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Finding a Place for Networks in Archaeology

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Abstract
Formal network analyses have a long history in archaeology but have recently seen a rapid florescence. Network models drawing on approaches from graph theory, social network analysis, and complexity science have been used to address a broad array of questions about the relationships among network structure, positions, and the attributes and outcomes for individuals and larger groups at a range of social scales. Current archaeological network research is both methodologically and theoretically diverse, but there are still many daunting challenges ahead for the formal exploration of social networks using archaeological data. If we can face these challenges, archaeologists are well positioned to contribute to long-standing debates in the broader sphere of network research on the nature of network theory, the relationships between networks and culture, and dynamics of social networks over the long term.

Keywords Social network analysis · Complex networks · Graph theory · Complexity science · Relational sociology · Material culture · GIS · Agent-based modeling

Introduction

Network methods and models are by no means new to archaeology, but such approaches have seen a rapid rise in recent years. There have been more archaeological network studies published in the past five years than in the previous 50 (Brughmans and Peeples 2017). This newly invigorated enthusiasm for networks in general and formal network analyses in particular echoes similar trends in many other fields over the last two decades (Borgatti et al. 2009; Freeman 2004; Knoke and Yang 2008; Newman 2011; Scott and Carrington 2011). The specific motivations for and implementation of network methods vary widely across research contexts, but a general optimism regarding the power of networks and network thinking has

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proliferated in the social, biological, and physical sciences as well as the popular imagination (Barabási 2002; Watts 2004b). At the same time, if this enthusiasm for network methods is not coupled with a greater concern for theory building and specific research agendas, the widespread excitement over networks may be short-lived (see discussions in Borgatti and Halgin 2011b; Knox et al. 2006).

In this article, I outline the past and current place of formal network studies in archaeology and provide a few reflections on the possible futures. I argue that archaeological networks are at a critical juncture and that, if such approaches are to continue to be influential, we must move beyond using networks largely as descriptive or exploratory tools to more frequently and more directly addressing substantive questions about the past that cannot readily be approached using other methods and models. This will require archaeologists to devote greater effort to both tailoring network tools to archaeological data and linking archaeological network studies to broader theoretical debates in the social sciences and beyond. Importantly, archaeologists are particularly well positioned to contribute to current and long-standing debates in the broader sphere of network research over the nature of network theory, the relationships between networks and culture, and the dynamics of social networks over the long term.

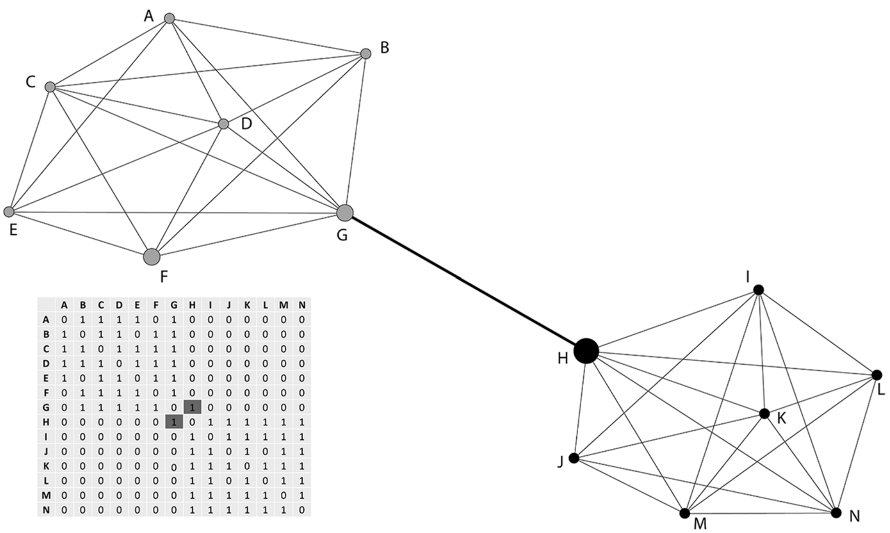
To limit this discussion to a reasonable scale, I focus here on archaeological studies that explicitly apply formal network methods and models to archaeological data. Thus, I largely exclude the many diverse works where networks are used primarily as metaphor (Hodder 2012) or general explanatory mechanism (Braun and Plog 1982; Dolwick 2009; Hodder 2012; Schortman and Urban 1987; see Knox et al. 2006 for a discussion of a similar divide in cultural anthropology), though the boundaries between such approaches have perhaps begun to blur in recent years (Hodder and Mol 2016; Schortman and Urban 2012). This discussion draws heavily on a comprehensive bibliography of formal archaeological network studies first compiled by Brughmans (2010, 2013a, 2014) and later expanded as part of a bibliometric review written for historians involved in network research (Brughmans and Peeples 2017). In many ways, this is an overview of an area of research in archaeology still in its adolescence, but as the discussion below illustrates, archaeological network studies are already quite diverse and show a great deal of potential for providing both new research directions and new insights from existing archaeological data.

I have organized the bulk of this review into three overarching sections. First, I provide a general discussion of the nature of formal networks and network theory, including a brief overview of terminology, a discussion of some of the most common network methods and models, and a historical perspective on the major traditions of network research in archaeology and beyond. I focus, in particular, on the nature of network theory, noting new developments and current debates in the social and physical sciences where archaeologists may have much to contribute. The next major section is focused on the conceptual and practical concerns associated with building networks from archaeological data. Here, I describe the process of abstraction through which archaeological data are connected to relational phenomenon and also provide an extended set of examples of many of the most common approaches to building and analyzing archaeological networks in the recent literature. The final major section is focused on the future of archaeological network research and, in particular, a few of the major challenges that we must face to move network methods and models forward.

Formal Networks and Network Theory

There are already several excellent published overviews of network techniques for archaeological audiences, so my coverage of specific methods here is somewhat brief (Brughmans 2010, 2012, 2013b; Collar et al. 2015; Knappett 2011, 2013a; Mills 2017). Although these past overviews are recent, quite a bit has changed in just the last few years, so I pay particular attention to the most recent trends. Beyond this, I provide an extended discussion of the major traditions of network research and network theorizing in the social sciences in general, as these topics structure much of the rest of this review.

At the most basic level, a network is simply a formal representation of the structure of connections among a set of actors. The most common method for visualizing and representing network data is the network *graph*, where actors are depicted as *nodes* or *vertices*, with lines representing connections among pairs of actors, also known as *edges* or *ties* (Fig. 1). Edges represent some specific kind of relationship between those actors. The kinds of relationships that can be represented in a network vary widely from direct interaction, to flows of information or goods, to general patterns of influence, geographic distance, or common affiliations in social and political groups. Both nodes and edges are often also further associated with additional attribute data that allow for the evaluation of variation in their underlying features



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	0	1	1	1	1	0	1	0	0	0	0	0	0	0
B	1	0	1	1	0	1	1	0	0	0	0	0	0	0
C	1	1	0	1	1	1	1	0	0	0	0	0	0	0
D	1	1	1	0	1	1	1	0	0	0	0	0	0	0
E	1	0	1	1	0	1	1	0	0	0	0	0	0	0
F	0	1	1	1	1	0	1	0	0	0	0	0	0	0
G	0	1	1	1	1	1	0	1	0	0	0	0	0	0
H	0	0	0	0	0	0	1	0	1	1	1	1	1	1
I	0	0	0	0	0	0	0	1	0	1	1	1	1	1
J	0	0	0	0	0	0	0	1	1	0	1	0	1	1
K	0	0	0	0	0	0	0	1	1	1	0	1	1	1
L	0	0	0	0	0	0	0	1	1	0	1	0	1	1
M	0	0	0	0	0	0	0	1	1	1	1	1	0	1
N	0	0	0	0	0	0	0	1	1	1	1	1	1	0

Fig. 1 A simple network graph displaying community structure (subgroups indicated by color) and a single bridging tie between these two communities. Node size is determined by betweenness centrality. The corresponding incidence matrix is shown in the bottom right with the bridging tie highlighted

(e.g., the size of the group defined as a node) or in associated outcomes (e.g., some measure of the relative success among actors in, for example, job seeking).

Formal network analyses typically involve both visual inspection of network graphs and the calculation of descriptive statistics for quantifying network structures, positions, and properties drawing on a broad array of tools, many of which were developed in the mathematical field of graph theory (discussed further below). Formal descriptive statistics are typically used to characterize salient aspects of networks at two scales—the graph (or whole network) level and node or edge level. Graph-level metrics include assessments of properties like *density* (i.e., the total number of possible connections that are active), the overall degree of clustering (i.e., the propensity for the formation of subgroups within the larger graph), or the degree of hierarchical structure present in a network. Node and edge-level metrics can be used to describe individual positions within the network, such as the degree to which a particular node is central or peripheral for different kinds of interactions, or the degree to which a node or edge falls within a dense cluster of relations or represents a *bridge* between such clusters. The most commonly invoked set of node and edge-level network metrics are known as *centrality* measures. These metrics are designed to characterize the relative importance of individual nodes, edges, and positions for directing or intercepting different kinds of flows through a network (Borgatti 2005; Butts 2009). Although there are many "off the shelf" tools available for characterizing networks structure and positions, it is important to carefully consider the choice of metrics, as specific measures are best suited for characterizing specific kinds of network processes. Perhaps the most common use for network analysis in the social sciences involves the calculation of such descriptive graph, node, or edge-level metrics and then comparisons of those measures to some external attribute or outcome to support inferences about the potential causes or consequences of network structure (Borgatti et al. 2009).

A Historical Perspective on Network Research in Archaeology and Beyond

Most applications of formal network methods in archaeology owe their origins to one of the three primary research traditions: graph theory, social network analysis, and complexity science. Each of these traditions represents well-developed fields in their own right, but there also has been considerable cross-pollination. Network studies of social phenomenon that resemble the kinds of analyses done today go back to at least the early 20th century (Moreno 1934 is often credited as the first; see Freeman 2004), but graph theoretic methods in discrete mathematics have a much longer history (back to 1736; see Biggs et al. 1976). The history of network methods in archaeology is quite diverse, and early applications were independently inspired from work in geography, mathematics, sociology, computer science, and many other fields. In more recent years, we are starting to see the emergence of a distinct tradition of archaeological network studies, including the development of methods and models specific to archaeological data (Brughmans and Peeples 2017).

Graph Theory

Graph theoretic methods are mathematical tools used to characterize the structure of pairwise relationships among entities, most often represented in the form of algebraic matrices. Graph theory is the mathematical bedrock of most formal network approaches. Graph-based methods were first tentatively applied to archaeological questions in the late 1960s. Most of the early discussions were limited to descriptive overviews in textbooks and methodological works (Clarke 1968; Doran and Hodson 1975). There also are a few early attempts at using graph-based methods for archaeological seriation (Jelinek 1960, 1967; Kendall 1969, 1971a, b). It was not until the mid-1970s, however, that formal graph-based methods began to be used specifically to explore patterns of interaction among social entities. Perhaps the earliest research in this vein was conducted by Terrell (1976, 1977a, b) and Irwin (1978), both working in Oceania. Their research was largely inspired by earlier work coming out of the New Geography (Chorley and Haggett 1967; Pitts 1965, 1978), biogeography, and population genetics (see commentary in Terrell 2013). In one early study, Terrell (1977b) created networks based on geographic proximity of Solomon Island communities using proximal point analysis (connecting nodes to their nearest neighbors) to systematically evaluate archaeological and human biogeographical patterns. Terrell argued that such geographic networks served as useful sources of hypotheses about potential interactions rather than reconstructions of "real" networks. Irwin (1978) used the geographic placement and size of archaeological sites in Papua New Guinea to explore the relative centrality of villages and hamlets in different inland and coastal settings and evaluate models for the development of exchange systems through time.

Perhaps inspired by these early studies, graph theoretic methods continued to be popular among anthropologists and archaeologists working in the Pacific (Hage 1977; Hage and Harary 1983, 1991, 1996; Hunt 1988). Direct applications of graph-based methods remained relatively rare in archaeology in general, however, averaging less than one publication per year throughout the 1980s through the mid-2000s. The few studies that were published, however, covered a broad geographic and temporal scope including Middle Uruk period Iran (Rothman 1987), the Mississippian period in the North American mid-continent (Peregrine 1991), Aztec Mesoamerica (Santley 1991), the Aegean Bronze Age (Broodbank 2000), and the Inka region in South America (Jenkins 2001). Importantly, although these studies were largely inspired by graph theoretic work in the geographical sciences, most early archaeological applications were clearly focused on addressing social questions about the interaction (especially economic interaction) among the inhabitants of settlements at various scales. For example, Peregrine's (1991) study of the Mississippian region used graph theoretic concepts to rank the centrality of different settlement locations along potential riverine corridors for transportation. Using these centrality metrics, he argued that the location of Cahokia at the point of maximum centrality (at the intersection of the Mississippi, Missouri, and Illinois Rivers) in this network allowed the inhabitants of this center to control the flow of goods and information across the network. In another study, Jenkins (2001) used the road system across highland Peru to define a transportation network among Inka settlements, arguing that Inka rulers planned and built facilities associated with both staple and wealth finance in different locations of varying centrality to take greater advantage of the flows of people and goods across that road network. In both examples, network position is seen as a key driver of the economic processes occurring at specific places and the prominence of specific settlements.

Social Network Analysis

Concurrent with the developments in geography and mathematics that inspired the studies discussed above, social network analysis (SNA) also began to emerge as a distinct field in the early 20th century. SNA refers simply to network studies focused on the structure of relations among social entities and typically involves the investigation of the substantive effects of network structure and position on variation in the attributes or outcomes for social actors within that network. SNA is most directly concerned with the interplay between the social processes that drive the formation of ties among actors and the consequences of network position and structure for those actors. This approach is quite broad and generally linked to a relational perspective that stresses the necessity of considering the nature and structure of interaction among actors rather than solely their attributes and attitudes if we are to fully understand any social phenomena.

SNA began as a loose set of related tools for visualizing and systematically comparing social structure and kinship that early practitioners called sociometry (Freeman 2004, pp. 31–42). Several different strands of research combined to create SNA as we know it today. Social anthropologists from the Manchester School of British social anthropology, in particular, made important contributions to the early development of SNA by conducting some of the first formal empirical studies of social networks (Barnes 1954; Bott 1955, 1957) and developing foundational theoretical concepts (Boissevain 1979; Mitchell 1969, 1974; see also Nadel 1957). By the 1950s and 1960s, social network researchers were beginning to apply formal graph theoretic methods to sociometric data, often collaborating directly with mathematicians (e.g., Barnes and Harary 1983; Harary et al. 1965). By the late 1960s, sociologists including White (2008) and his students in the Harvard Department of Social Relations started to tie all of these various threads together by connecting a general theory of structural relations with formal tools for quantitative measurement. By the mid-1970s, a distinct SNA paradigm with both specific theoretical approaches and methods was entrenched within sociology and closely related areas of organizational research. At the same time, network methods and models began to fall out of favor in anthropology due, perhaps in part, to their connections with structural theories that were unpopular among cultural anthropologists at the time (Knox et al. 2006).

Contemporary SNA studies are quite variable in terms of both the questions addressed and the methods used, so I cannot hope to cover the full range in this review. The approach I take here instead is to highlight briefly just a few of the most common kinds of network processes and properties SNA researchers have addressed, focusing in particular on models that inform the discussion of network theory and the archaeological examples in the subsequent sections. One of the most common goals for SNA is simply the documentation and visualization of social relations using formal network graphs. Visualizations are a key ingredient of SNA, and there is a voluminous literature on how relational data can be displayed to highlight different features of networks (Freeman 2000, 2005). Network graphs can reveal much about the structure of a network and can help identify actors in key positions. Such visualizations can be made even more powerful when coupled with tools for quantitatively characterizing the specific positions of nodes and edges like centrality metrics. Importantly, different centrality measures can help highlight different kinds of network positions and flows (Borgatti 2005). For example, degree centrality is a measure of the total count or weight of ties incident on a particular node. Thus, this measure is useful when direct connections are of primary importance for the network process represented in a particular graph (as in networks of comembership in groups). Betweenness centrality, on the other hand, measures the degree to which a node falls in an intermediate position along the shortest paths between other pairs of nodes. The characteristics of this measure make it particularly useful for examining the relative prominence of nodes for directing what is sometimes called a package delivery process (the movement of tangible goods/materials across a network to a known target).

SNA studies are often focused on exploring the social processes that drive structural tendencies in networks. This includes explorations of processes like *homophily*, the tendency for actors to develop and maintain connections with other actors who exhibit similar attributes (McPherson et al. 2001). The basic observation underlying this principle is that relations among social entities are more common among actors with similar characteristics than those with quite different characteristics. Homophily can drive the emergence of other network properties like *network closure*, or the tendency for "friends of friends" to also be connected (i.e., if A is connected to B and B is connected to C, closure describes the tendency for A to also be connected to C; see Coleman 1988). Many SNA studies are designed to understand how tendencies toward properties like homophily and closure and the positions they generate provide constraints or opportunities for actors in those networks. For example, many real-world social networks tend toward closure, with densely connected *cliques* (subgroups or clusters) and a small number of *bridging* ties spanning what would otherwise be gaps in network structure. Empirical studies in many different contexts suggest that actors in such bridging positions often accrue long-term advantages for themselves (Burt 1995; Granovetter 1973) or larger groups (Coleman 1988). As these few examples highlight, SNA studies are useful for documenting relational structure, exploring the underlying processes generating that structure, and evaluating the consequences of network positions for individual actors or the network as a whole.

SNA approaches to archaeological networks were proposed almost as early at the first flirtations with graph-based methods described above. In 1977, Irwin-Williams (1977) published an outline for using SNA methods and theoretical models to explore connections among Chacoan settlements in the U.S. Southwest based on material culture frequency data. The approach she outlines is quite similar to methods adopted by archaeologists in more recent years, though the lack of citations to her work suggest that most researchers involved in these later archaeological SNA studies were not initially aware of this earlier research. Irwin-Williams appears to have been inspired by the early work of British social anthropologists in particular but also cites geographic approaches to graph theory. As with graph-based methods, however, SNA did not catch on in archaeology in general until almost 30 years later.

SNA studies have become increasingly popular in archaeology over the last decade. Many of the most common applications involve the use of SNA tools for measuring network position and visualizing networks to address important archaeological questions at a variety of social scales. For example, Golitko and colleagues (Golitko and Feinman 2015; Golitko et al. 2012) conducted network analyses of a large database of geochemically sourced obsidian artifacts from Maya settlements using SNA methods for visualizing and characterizing the structural properties of exchange networks through time. These studies revealed important shifts in the geographic focus of exchange systems and the degree of network hierarchy, which suggests that shifts in regional economies may have contributed to (rather than resulted from) the demographic and political decline of inland Maya centers. In another study, Hart and Englebrecht (2012; see also Birch and Hart 2018; Hart 2012; Hart et al. 2016, 2017) used SNA visualization techniques for a series of sites in the northern Iroquoian region to build networks based on similarities in ceramic decorations and to evaluate two competing models of ethnogenesis. The authors constructed a series of networks to illustrate how ceramic similarity (used as a proxy for interaction) changed through time and argue that the results support a relatively recent period of ethnogenesis rather than the cladistic model of ethnic development that had previously been proposed.

A number of archaeological studies have explored SNA centrality metrics and their connection to other social processes. For example, Pailes (2014) created an intrasite network based on the trails between individual house clusters at the Cerro Prieto settlement in southern Arizona. He calculated a series of centrality measures using this network to assess the relative importance of each house cluster for different kinds of network flows. His work suggests that house clusters that are consistently central in the network include those houses with independent evidence of special status. In another series of studies, Mizoguchi (2009, 2013) created networks among Kofun period settlements in Japan based on shared ceramic traditions, noting that settlements in positions of high network centrality emerged as important locations in the burgeoning settlement hierarchy. From this, he argues that network position and centrality played a direct role in the development of this hierarchy and the increasing centralization of the region. Both studies suggest a relationship between network position and inequality in general.

Archaeologists are increasingly not just borrowing methods from SNA but also are beginning to use archaeological case studies to test models developed in sociology and other social sciences. This trend is due, in part, to ongoing collaborations between sociologists and archaeologists. The Southwest Social Networks project represents a collaboration among a diverse set of researchers with expertise in archaeology, sociology, geochemistry, and computer science (Mills et al. 2013a). This project is focused on exploring the nature and dynamics of social networks in the U.S. Southwest using SNA methods to create and evaluate material networks and explore models of social change and interaction from the broader comparative social sciences. Borck and colleagues (2015) used the related concepts of homophily and embeddedness (the structural integration of a node/group in the broader network) and modified versions of common SNA metrics to evaluate the role of network structures in the robustness or vulnerability of regional populations to environmental challenges. They found that regions marked by highly homophilous, homogenous, and isolated networks were more likely to experience population decline when faced with climate shocks than those areas with diverse and expansive networks. In another study, Peeples and Haas (2013) compared *brokerage* (i.e., intermediate) positions in networks of ceramic similarity to measures of settlement growth and longevity (used as proxies for social capital and success). Their study suggests that brokerage positions do not appear to confer advantage for the settlements in those positions; instead, brokered relationships tended toward closure through time (see Peeples and Mills 2018). Drawing on recent literature in sociology, the authors suggest that culturally contingent factors influencing how social relations are valued can alter the ways in which specific risks and rewards of network position play out. The goal of these studies is not just to answer questions of archaeological interest but to further use archaeological data to inform models in the social sciences more generally. This is an area of potential influence for archaeological network studies, as archaeologists have access to a broader range of social and political organizational settings than have typically been explored in SNA studies of similar social processes (see Peeples 2018).

Complexity Science Approaches

What I call complexity science approaches to networks (sometimes glossed as simply network science or complex networks; see Brandes et al. 2013) refers to a set of related network models largely developed in physics, mathematics, and computer science (Newman 2010, 2011). Such studies are part of a much larger interdisciplinary field focused on exploring the emergent properties and dynamics of complex systems in general (Ladyman et al. 2013). Complexity science as a distinct field goes back to at least the 1960s. The beginnings of this line of research are closely associated with researchers at the Los Alamos National Laboratory (and formerly the Manhattan Project) and organizations like the Santa Fe Institute. Beginning in the late 1990s with a number of highly influential publications (Barabási and Albert 1999; Watts and Strogatz 1998), work in this realm began to focus on networks as complex systems. This entailed the explorations of the nontrivial properties of networks that emerge through patterned connections among nodes that are not a product of the properties of those individual nodes or edges. A huge array of empirical studies in recent years have demonstrated that most large real-world networks exhibit some emergent properties, including networks in settings as diverse as the internet (Park 2005), connections among language families (Cong and Liu 2014), networks of air transportation (Rocha 2017), and even the human brain (Papo et al. 2014). The goal of such complex network approaches often is to identify and explore underlying generic processes or rules governing the impact of network structures on the behavior and evolution of those networks (Strogatz 2001). Notably, this work initially proceeded in almost total isolation from the long tradition of SNA studies (Scott 2011).

In practice, most complex network studies have focused on a small number of measurable network properties that are extremely common in empirical settings across a wide range of contexts. For example, many real-world networks have what is known as *small-world* structure. In network terms, small-world networks have both short average path length and a high clustering coefficient (Watts and Strogatz 1998). In other words, in small-world networks the vast majority of nodes are not directly connected, but most nodes are still reachable from each other across a small number of moves. This is the underlying structural principle behind the famous experiments by Milgram (1967) and others (Travers and Milgram 1969; often glossed as the *six degrees of separation* studies), which showed that many randomly selected individuals could send letters through chains of acquaintances to a target individual unknown to them with only a small number of intermediates. Some real-world networks also display *scale-free* structure, meaning that distribution of degree for nodes follows a *power-law* (or at least a heavy tailed) distribution (Barabási and Albert 1999; Clauset et al. 2009). This is often attributed to the so-called rich get richer phenomenon where, as networks grow, new connections are preferentially attached to nodes that are already the most connected, such that a small number of nodes account for much of the connectivity in the network as a whole. Many complex network studies have focused on identifying and quantifying *community structure*. Community structure refers to the degree to which a network can be partitioned into discrete groups of nodes, each with dense overlapping connections within the group but with few edges that span community boundaries (Newman 2004). Community structure can impact the performance of networks in many ways including, for example, the rate at which biological (Salathé and Jones 2010) or social (Weng et al. 2013) contagions will spread across the network as a whole.

The few examples of emergent properties of complex networks outlined above merely scratch the surface of a huge field, but these popular models account for most recent archaeological applications. For example, several early influential studies in this vein were published in *Complex Systems and Archaeology* (Bentley and Maschner 2003b). This edited volume includes empirical and theoretical studies on a range of topics including the relationship between scale-free network structure and the emergence of inequality (Bentley and Maschner 2003a; Maschner and Bentley 2003) and the role of network structures in facilitating cascades of styles and cultural change (Bentley and Maschner 2003a; see also Bentley and Shennan 2003, 2005). Such models also have been popular for evaluating and interpreting material networks. For example, Sindbæk (2007) created a network among early Viking age settlements in southern Scandinavia based on the co-occurrence of artifact types and then evaluated the global properties of the network. From this he concluded that the network had both small-world and scale-free properties but that the particular form the network took (with geographic clustering and several hubs accounting for much of the flow) made it vulnerable to the loss of a few key nodes. Complex network studies also have addressed the network structures that drive or constrain the spread of innovations. Collar (2007, 2008, 2015) uses the concepts of small-world and scale-free network structures to investigate the network factors that influenced the spread (or lack thereof) of religious movements across the

Roman world. Physicists and complexity scientists have increasingly been directly involved in archaeological research focused on the nature and properties of complex networks, for example, collaborating with archaeologists to build and evaluate a series of simulated network models focused on the Middle Bronze Age in the Aegean using proximal point analysis, gravity models, and related geographic tools to assess potential and probable patterns of interaction and the robustness and vulnerability of maritime networks to different kinds of disturbances (e.g., Knappett et al. 2011; Rivers 2016; Rivers and Evans 2013, 2014; Rivers et al. 2013).

Studies of complex networks in archaeology have recently been combined with agent-based models (Bentley et al. 2005; Brughmans and Poblome 2016a; Graham 2005, 2006). Crabtree (2015) developed a simulation of several different modes of food exchange among Pueblo communities in southwestern Colorado, evaluating her results against a well-documented regional archaeological record. Her study suggests that, while small-world networks may be an efficient means for passing information across an entire network, compartmentalization of network structure may be more beneficial for survival at certain geographic scales in patchy environments such as the Colorado Plateau. Watts and Ossa (2016) used both agent-based modeling and empirical analysis of material networks to explore the processes underlying the exchange of ceramics in the Hohokam region of Arizona. They simulated networks using scale-free, geographic preferential attachment and open models and compared these simulations to their empirical results, concluding that the open (marketplace) model was the best fit (see also Ossa 2013). Studies such as these that both model and empirically evaluate network positions and processes show a great deal of potential and merit further attention in the future.

As noted above, the complexity science and social network analysis approaches that account for most applications of formal network analysis today are similar in that they define the structure of relationships among entities as a necessary component of explanations of the behavior and dynamics of those entities. However, these two research traditions owe their origins to quite different interdisciplinary concerns, and each approach tends to focus on different scales of data, analysis, and interpretation. Although there is certainly some variation, complex network approaches are most often focused on exploring the nature and consequences of global emergent properties of network structure like small-world or scale-free structure rather than the relative positions of individual nodes or edges within these networks. SNA approaches, on the other hand, are more often focused on the social processes that generate ties and structural positions as well as the properties of and outcomes for specific nodes and edges. The differences between these traditions have led to some unresolved tensions among scholars working in each area, but in recent years researchers have begun to combine insights from both approaches, a trend that is likely to continue (Scott 2011; Watts 2004a).

The Burgeoning Field of Archaeological Networks

Although there were many early tentative attempts at using network methods for archaeological questions, it is only over the last five to six years or so it has been possible to begin to chart the edges of a distinct and rapidly growing tradition of archaeological network research. Some of this recent rise in popularity can be attributed to the increased availability and accessibility of high-powered computing and software packages for conducting network studies (such as UCINET, Pajek, Gephi, Cytoscape, GraphViz, NodeXL, and many packages for the R platform such as igraph and statnet), but this new push likely also reflects the increasing popularity of network models in the sciences. Archaeologists, as voracious consumers of interdisciplinary method and theory, have enthusiastically applied both SNA and complexity science approaches to a range of archaeological topics. Even at this early stage, we are already starting to see some regional trends in the methods and models used. For example, researchers working in Europe largely cite complexity science approaches as the basis of their work, and they much more often assess formal network theories drawing on the emergent properties of network structure. Archaeologists working in the Americas more often cite SNA as their source of inspiration and apply methods and models from that field (see Brughmans and Peeples 2017).

At the same time, archaeologists are quite inclusive when it comes to using tools and concepts from the broader field of network studies. The edges between different approaches that structure network research in the social and physical sciences are perhaps becoming somewhat fuzzier in archaeology than in other arenas. For example, Kandler and Caccioli (2016) explored how emergent global structures in complex networks influence rates at which innovations are adopted or diffusion occurs. This work also drew on sociological and anthropological explanatory models focused on the roles of homophily and tie strength in such processes. Indeed, many of the most recent archaeological network studies are characterized by a fluid movement between models, methods, and theories from a broad range of network approaches rather than any one particular area (see commentary in Rivers 2016; cf. Brughmans 2013b). These are positive developments, but I would note that this kind of boundary-crossing work, though increasingly common, is not yet the norm. I argue that archaeological network researchers should devote substantial effort on developing approaches that combine a focus on the nature of ties and positions (SNA) as well as the underlying processes involved in the evolution of network structure (complexity science).

Archaeological network studies have many of the marks of a new specialization still on the rise (Brughmans and Peeples 2017), including a rapid increase in the number of publications ranging from influential book length overviews (Knappett 2011) to edited volumes (Brughmans et al. 2016; Knappett 2013b), special issues of journals (Collar et al. 2015; Evans and Felder 2014), numerous dissertations (Blair 2015; Borck 2016; Collar 2008; Johnson 2016; Lulewicz 2018; Peeples 2011; Phillips 2011; Swantek 2017; Torres 2012), and organized sessions at archaeological conferences (e.g., Society for American Archaeology, Computer Applications, and Quantitative Methods in Archaeology) and others focused on network studies in general (e.g., the International Network for Social Network Analysis Sunbelt conference). As I discuss further below, archaeologists are increasingly not just using network methods "off the shelf" but also building network models tailored specifically to archaeological data and archaeological research agendas. I see this as a positive development that bodes well for the future of archaeological network research, an area that merits substantial attention in the coming years.

Network Theory

One of the criticisms frequently leveled against network approaches in the social sciences is that network studies are simply a loose coalition of methods and descriptive tools without any independent theoretical underpinnings (see discussions of such criticisms in Borgatti et al. 2009; Borgatti and Halgin 2011b). This criticism is unfounded as the relational perspective offered by network approaches provides unique insights and testable ideas about the drivers and consequences of a wide range of social processes. Network approaches to social processes also have been criticized as being overly structural and for not adequately considering the influences of agency or culture (Emirbayer 1997; Emirbayer and Goodwin 1994). While it is true that structure is often emphasized over other kinds of attributes and identities in network studies (largely as a response to the perceived atomistic focus of earlier sociological models), network researchers are increasingly interested in explicitly exploring the interplay between networks, social capital, culture, and agency (Pachucki and Breiger 2010). This trend in many ways harkens back to earlier formulations of the network approach in anthropology and related fields (Knox et al. 2006; Mische 2011). I argue that this recent trend also offers substantial opportunities for archaeologists to contribute to the growing body of theory on the intersection of networks and culture in the social sciences in general.

The primary feature that separates network approaches from other kinds of inquiries into social processes is the emphasis on network structure as both product and driver of outcomes for actors within a network. In other words, the relational perspective suggests that attributes are not sufficient to explain variation in the successes or failure of actors in a given setting and that structural positions or structural characteristics of the network as a whole must be invoked to better understand such variation. In a classic historical network study, Padgett and Ansell (1993) used documentary materials to build networks of marriage, economic relationships, and patronage among elite families in 15th-century Florence. Their work shows that the dramatic rise in prominence of the Medici family was driven in large part by their advantageous positions in these networks rather than simply initial differences in class or social status. This insight is important in its own right, but ideally we want to move from this observation to a more general theoretical statement about the relationships between specific network processes or positions and their consequences.

Network theory, as the term is typically used, refers to the underlying assumption that some set of causes, effects, or associations can be described by or attributed to specific network mechanisms, positions, and processes (Borgatti and Halgin 2011b; see also Brandes et al. 2013 on *network science*). In other words, network theoretical statements are formal and testable expressions of dependencies among nodes, edges, attributes, outcomes, or global structures (or any combination thereof) in a network. Here, too, we see differences in the nature of theory building between the complex networks and social network analytical approaches described above. In general, complexity science approaches tend to build theories around explorations of the causes and consequences of network form (e.g., the generative processes involved in creating scale-free networks and their effects) while social network analytical approaches most often involve structural theoretical statements focused on the network causes and network effects of a particular phenomenon of interest (Marin and Wellman 2011, pp. 15–17).

Perhaps the best known example of a theory of network dependencies is Granovetter's (1973) "strength of weak ties" model. As Granovetter suggests, when two individuals are strongly connected in a social network they are likely to have largely overlapping social spheres due in part to tendencies toward closure and homophily. Thus, Granovetter argues that strong ties will seldom be a source of new information for an actor. Weak social ties (i.e., infrequently activated relationships), on the other hand, tend to bridge connections among actors who are themselves not connected and, thus, are more likely sources of novel information. From this it can be argued that having more weak ties may be an advantage under certain circumstances. Granovetter found empirical support for this theory in his investigation of job-seeking behavior. Specifically, in a study of career mobility in a Boston suburb, he determined that when individuals found a new job through referrals it was most often through infrequent contacts (i.e., weak ties) rather than their strongest connections. The "strength of weak ties" model has been particularly influential because it is quite generalizable and theorizes the processes that both generate and structure connections among actors (i.e., closure, homophily, and the creation of bridging positions) as well as consequences of particular relational structures and positions for those actors (i.e., individual advantage accrued through access to diverse information and resources). Many of the most widely used network theories take a similar form.

The relational underpinnings of network approaches like those described above are embedded in a broader tradition of relational thinking in the social sciences with a long history in many fields. Mische (2011) provides a detailed history of relational sociology, which was one of the major undercurrents in the development of social network studies as they exist today. Knox and colleagues (2006) provide an account of similarly influential developments in cultural anthropology. According to both accounts, early formal attempts at exploring social networks in the 1940s through the 1960s were focused on emphasizing the importance of relational structure *in tandem* with the attributes and identities of actors in networks (White 2008). Structure and agency were both seen as essential to understanding social processes (but their argument was that structure had been overlooked). As network analyses became increasingly formal and mathematical through the 1970s with the incorporation of tools from graph theory, researchers began to focus their efforts on those aspects of network structure that could most readily be directly quantified (Brint 1992). Unfortunately, this "methodological virtuosity has come at the price of relative inattention to theoretical underpinnings" (Knox et al. 2006, p. 128). In the excitement over formal characterizations of network structure, attitudes, attributes, and agency were left in the dust (Santoro 2008).

Since the 1990s, many network researchers in the social sciences have begun to return to the dual focus on network structure and agency/culture that was so important to the initial formalization of the network approach and SNA in particular. Much of this work is centered on what Mische (2011) calls the "New York School" of relational sociology. This turn was perhaps most pronounced in studies of historical sociology, collective action, and social movements

(Emirbayer 1997; Kim and Bearman 1997; Krinsky and Mische 2013; White 1992, 2008; see Tilly 1978 for an earlier take on this approach). Contemporary network theorists in this tradition are increasingly concerned with social networks as cultural constructions. In this line of research, the risks and rewards associated with network positions are not strictly determined but are instead seen as culturally and historically contingent. Thus, the causes and consequences of network structure cannot be examined without consideration of the content, meanings, and histories of social ties. Work in this vein has focused on how networks can serve as conduits for the spread of cultural developments as well as forces shaping culture. A large body of research has investigated how networks of frequent interaction set the stage for the formation of collective identities that can then spread beyond their relational context to become social categories in their own right (e.g., McAdam et al. 2001; Nexon 2009). I (Peeples 2011, 2018) have recently explored this model in an archaeological context, suggesting that an appreciation of both relational networks and categorical distinctions can help us move beyond some long-standing debates in archaeology over the nature of social identity. This general approach to combining considerations of networks and culture is increasingly popular in sociology (Pachucki and Breiger 2010) and as Knox et al. (2006) note, anthropologists are well positioned to contribute to this conversation. I would add that archaeologists, in particular, have the potential to explore the co-development of networks and culture over the long term and add new perspectives to this burgeoning area of network theory.

In addition to drawing on network theories from the broader social and physical sciences, another profitable area of development for archaeological network studies is the translation of well-developed archaeological models and theories into formal network models. This can take a wide variety of forms. Knappett (2011) used networks to formalize archaeological approaches to interaction and the role of material culture in mediating interactions by drawing on theoretical models including actor network theory (see also Van Oyen 2016a). Several researchers have relied on popular practice-based approaches to exploring shared identities through archaeological data to formally explore similarities in material culture and texts and to build networks based on shared communities of practice or consumption (Blair 2015; Blake 2014; Mills 2016; Munson 2015; Peeples 2018). Cochrane and Lipo (2010) used methods developed by quantitative sociologists to define and analyze phylogenetic networks based on material culture to evaluate evolutionary models of culture change. These applications of network methods are quite diverse and run the gamut from evolutionary theory to postprocessual theory. These examples, however, all represent attempts to address specific archaeological theoretical concerns from a formal relational perspective in that they conceptualize *interaction* as essential for understanding the social phenomenon at hand. These and many examples discussed below also illustrate how network theory and methods can provide new insights into archaeological questions that would be difficult to directly address using traditional approaches.

Building Archaeological Networks

To build a formal social network we need two things: a well-defined set of social actors and a means for identifying or measuring some specific kind of relation among every pair of actors. In many social network studies focused on contemporary settings, these two things are relatively straightforward to obtain. Common techniques include the use of questionnaires, interviews, direct observations of interactions, or careful readings of documents to identify and characterize connections among some sample of individuals in a clearly bounded context for interaction. When such direct evidence of relations is unavailable, as is typically the case for archaeological network investigations, what other kinds of proxies might we use to define the boundaries of networks and evaluate the structures of interaction?

Although networks have only recently gained popularity in archaeology, there is already a dizzying diversity of data and methods that have been used to generate formal networks. As Collar et al. (2015; drawing on perspectives from Brandes et al. 2013) note, the creation of all archaeological networks involves a process of abstraction where a network phenomenon of interest is defined, that network phenomenon is conceptualized in terms of some measurable proxy, and then the network is formally represented and analyzed. This process of abstraction can take many different shapes, but I argue it is essential for archaeological network analysts to clearly describe all data and assumptions and to take such abstractions into account when designing analyses of the resulting networks. The most common forms of archaeological networks in recent publications tend to draw on some combination of geographic, material cultural, documentary data, or simulations. Here I first discuss the two fundamental challenges for creating networks—defining actors and setting boundaries, and measuring and interpreting social relations—and then provide an extended discussion and additional perspectives on some of the most common approaches (as well as a few rarer approaches) for building networks from archaeological data.

Specifying Boundaries, Defining Nodes, and Measuring Relations

The first hurdle any network study must overcome is what is sometimes called the boundary specification problem. How do we determine which actors (nodes) to include in a network and which to exclude to address a particular question? In SNA, solutions to this problem are often characterized as falling along a continuum between "realist" and "nominalist" network definitions (Laumann et al. 1992). The realist approach is focused on identifying well-defined groups where the actors involved clearly recognize their membership outside any consideration of their social ties. This often includes institutions like schools, prisons, corporations, or even situations where larger collectives interact such as the United Nations. Typically, in such settings the goal is to characterize a "total network" including all substantively involved actors and all of the relations among them. This is, clearly, difficult to achieve at a very large scale. The study by Pailes (2014) discussed above, focused on the network of trails among all house clusters at a single archaeological site, provides a good archaeological example of a realist approach to boundary definition. In a similar study, Wernke (2012) explored changes in the nature of intrasite transportation corridors across the colonial transition in a single settlement in highland Peru, arguing that network approaches to transportation are most appropriate at extremely well-preserved and well-documented sites (or portions of sites) where such a total network can be achieved. Indeed, it is primarily at the scale of individual sites or small regions where realist boundary definitions have been applied to archaeological studies.

On the other side of the spectrum we have nominalist approaches where the researcher, rather than the social setting, imposes boundaries on network inclusion based on her own theoretical or methodological concerns. The methods most relevant to archaeological studies involve the use of event- or attribute-based strategies for network formation. In a contemporary setting one could create a network among all attendees of a given meeting, all members of a particular professional society, or all people who live in a house of a particular style. Most archaeological networks fall fairly close to the nominalist end of the spectrum, with boundaries set based on traditional archaeological regional constructs, the presence/absence of particular kinds of features at archaeological sites, or, more frequently than we would like, data availability. Nominalist network boundaries are widely used in SNA and defensible as networks, which unlike social groups "have no natural boundaries" (Borgatti and Halgin 2011b, p. 1169). At the same time, we should not mistake an analysis constrained by the researcher's goals and data availability as an exploration of a complete network (see Lemercier 2015 for a similar discussion of boundary specification in historical network analyses).

Earl and Keay (2007) provide one of the few explicit discussions of the varied decisions that are involved in specifying network boundaries in their study of connectivity among urban Iberian and Roman towns in southern Spain. They first compiled a complex relational database including information on nearly 400 sites from many sources and then used a range of tools (fuzzy set theory along with linguistic operators and various data management platforms) to define a subset of sites that met their criteria as both urban and dating to their period of interest. The authors are clear that their own definition of the relevant sample may have substantive impacts on their subsequent analyses. In their studies of networks in the U.S. Southwest, the Southwest Social Network team defined networks among settlements dating to their period of interest including only those known and well-documented sites with more than 12 rooms within a predefined study area (Mills et al. 2013a, b). Thus, in these examples, if there were important drivers of network structure generated through interactions among nonurban sites in southern Spain, or among smaller settlements in the U.S. Southwest, or beyond the predefined study area in either case, they would be, by definition, missing from all formal analyses. Unfortunately, in most archaeological network studies, the nature of boundary definition is often only cursorily addressed. This is particularly problematic. Laumann et al. (1992) note that the scale of analysis and the constraints of the sample fundamentally influence network structure and the kinds of questions that are most appropriate to address with a given dataset. Beyond this, many of the most common methods and metrics used in network analysis assume the analyst has access to a complete network with well-defined boundaries and should be used with extreme caution where these criteria are not met (Wasserman and Faust 1994, p. 33). Mills et al. (2015) suggest that one potential way to address the boundary specification problem in archaeological contexts is to conduct analyses at multiple nested scales and to make inferences taking the similarities and differences across scales into account (see also Orser 2005). This is, however, only a partial solution, and boundary specification is a topic that merits substantial attention in future archaeological network studies.

Once the boundaries of a given context have been chosen, the next step is to define the units of analysis that will be used as nodes in a formal network. Most SNA studies outside archaeology are focused on interactions among individuals, but it is relatively common to define nodes as larger collectives (like families or organizations or nations; see Knoke and Yang 2008). As already illustrated above, network approaches have been used to explore connections at a variety of scales from individual structures or features, to archaeological sites, to larger regions. In the vast majority of recently published archaeological network studies, however, nodes are defined at the site or settlement level. This, of course, comes with all the long-standing concerns in archaeology about how to properly define sites or settlements as loci of specific kinds of activities in the past. Beyond this, we should be particularly careful in applying network methods designed for evaluating actor-to-actor interactions to archaeological site data. As Bernardini (2007) notes in his study of networks of ceramic exchange among Hopi villages in Arizona, when we track the movement of pottery between discrete villages, we are not tracking direct interactions from village to village but instead the residues of multiple accumulated interactions among individuals or small social groups who lived in those villages (see also Mills 2016). This is generally true of most material culture-based approaches to archaeological networks, as we are often constrained by the scale of data availability. Under such circumstances, it is appropriate to avoid methods and network metrics that rely on the identification of specific directed interactions and instead focus on those approaches appropriate for identifying patterns in general network flows and positions.

Most formal networks are what are known as *one-mode* networks where all nodes are of a single class (e.g., connections from person to person or site to site). A *two-mode* network, on the other hand, is one in which there are two distinct classes of node under consideration (Fig. 2). Most two-mode networks are also defined as *bipartite*, meaning that edges are only defined between pairs of nodes that fall into different classes. Examples of two-mode, bipartite networks include networks based on person-to-event connections (with ties drawn between people and the events they attend) or site-to-artifact type connections (with ties between sites and the specific types of materials/artifacts they contain). Two-mode networks are often collapsed into their constituent one-mode counterparts (e.g., Breiger 1974), as there are many more readily available tools for analyzing one-mode data, but this is not necessary (and some information is lost in the process). Direct analyses of two-mode networks are relatively rare in archaeological applications, but Knappett (2011) illustrates that such an approach is a particularly good fit for networks based on material culture data as it allows for formal engagement with archaeological theories on how objects mediate interactions

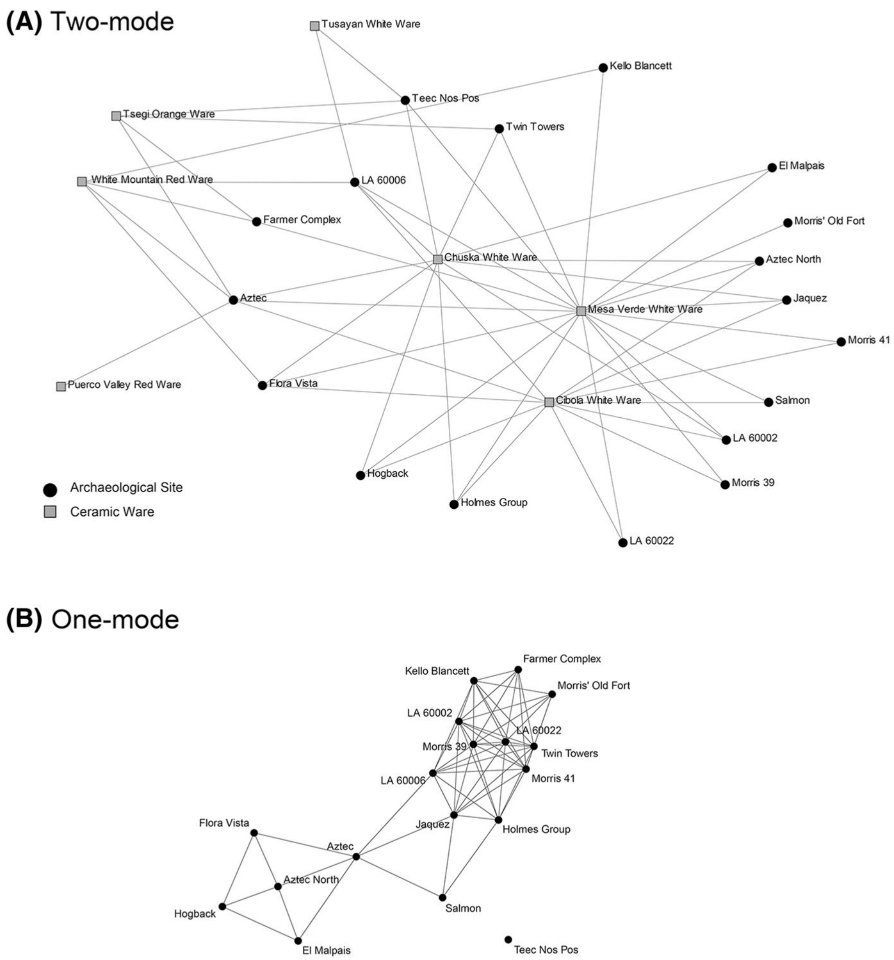


Fig. 2 A) An example of a two-mode network representing connections among archaeological sites and painted ceramic wares (≥ 5% in site assemblage) in the Middle San Juan region of the U.S. Southwest (c. AD 1050–1100) and B) the corresponding one-mode projection for sites sharing ≥ 75% similarity for ceramic counts by ware

among individuals and larger groups (see also Brughmans and Poblome 2016b; Graham and Weingart 2015; Mol et al. 2015). Beyond this, two-mode networks have proven useful in explorations of patterns of raw material consumption by allowing for the creation of networks that connect geographic sources of materials with consumer sites and allow for formal investigations of the network processes that drive or constrain resource use (Mills et al. 2013a; Phillips 2011). Direct analysis of two-mode (and multimode) networks is currently an area of growth in network studies in general (Field et al. 2006; Opsahl 2013), and it is essential that archaeologists invest more effort into exploring these approaches (see Blair 2015; Lulewicz and Coker 2018).

The final major component necessary to build a network is the definition of some consistent means for measuring and interpreting relationships among pairs of nodes. As summarized by Knoke and Yang (2008, p. 12), the kinds of relations considered in studies of social networks are quite varied and can include economic transactions, direct or indirect communications, shared sentiments, authority/power relations, kinship, or other kinds of instrumental relations. The specific type of relation that a researcher measures depends on the question at hand. If the goal is to create a network of economic interactions among corporations, then the data considered may include contracts or payments among companies. If the goal is exploring interlocking connections among individuals involved in those corporations, a better measure may be ties based on shared members of boards of directors. The key requirement is that a clear argument linking a network process and specific data can be made.

The definition of network relations is somewhat less straightforward in an archaeological context than in many other areas where network approaches have been applied. Archaeologists are seldom privy to direct information about specific patterns of interaction and instead must rely on material proxies and chains of interpretive connections that link the artifacts and features we recover to the social processes we are interested in exploring. Indeed, many archaeological proxies for relations among entities may be better understood as statements of the *probability* that a connection existed rather than a social tie in the strict sense. One common class of network model used for archaeological data already discussed in some detail above involves the use of the geographic locations of nodes and assessments of the nature of travel between them. The underlying assumption of networks generated using such data is that greater geographic proximity may increase the likelihood of other kinds of social relations that are the phenomena we are actually interested in (or at least this can be used as a workable null model). No matter what data are used, we must carefully consider how we conceptualize the links between our evidence and the relational phenomenon we wish to explore to avoid treating network methods as a "black box" (Isaksen 2013; Sindbæk 2013). Fortunately, archaeologists are not alone in this struggle, and there are a variety of techniques available for investigating interactions when actors and relations cannot be directly observed or easily documented.

One particularly relevant method for defining networks from proxy data from contemporary network studies is the use of *affiliation* (or co-affiliation) data (Borgatti and Halgin 2011a). Affiliation data, in this context, refers to information that documents the memberships of actors in particular groups or their participation in specific events. The basic argument underlying the use of such data is that common affiliations either constitute a social tie worth investigating or alternatively, that co-participation in groups or events provides opportunities for other kinds of relations to develop among the actors involved. This is often treated as a probabilistic statement about the likelihood that two actors who share common affiliations also interact in other ways. In a classic early anthropological affiliation study, Davis et al. (1941) used the society pages of a local newspaper in "Old City" in the U.S. Deep South to identify women who attended various society events. From this they defined a formal network among these women suggesting that co-participation in events could be used to reconstruct the likely social circles (see Breiger 1974). Such affiliation data can be used to create *two-mode* networks (connecting actors to affiliations), but perhaps more frequently, affiliation networks are collapsed into one-mode (actor-to-actor) networks of co-affiliation where the connections represent the strength of similarities between pairs of actors. This approach is particularly useful in contexts where we cannot get direct access to the actors involved in a network, such as so-called "dark networks" of illicit activity (e.g., Everton 2012) or, of course, archaeological networks.

Most recent archaeological networks represent the use of affiliation data in one form or another, but this important point has seldom been explicitly recognized or discussed in detail. In one rare account, Sindbæk (2013, see also Sindbæk 2015) notes that networks based on shared affiliations (usually in the form of artifacts) have particular properties that make it difficult to precisely define network positions, structures, and communities without some external means of evaluating the context of shared affiliations. Beyond this, affiliation networks do not distinguish between social proximity and social similarity, instead treating them as one and the same (Borgatti and Halgin 2011a). This is not meant to suggest there is no way forward, and indeed affiliation networks are extremely common and useful in many areas of network research. The use of such data requires special attention, however, when we design analyses for characterizing network structure and positions (Faust 1997; Field et al. 2006; Opsahl 2013). Borgatti and Halgin (2011a) provide an excellent guide to the intricacies of affiliation networks that archaeologists should explore in greater detail. As they note, the next frontier for exploration of affiliation networks is the creation of methods tailored specifically to the direct analysis of two-mode affiliation data. Archaeological data provide a natural fit for such methods, but few analyses have taken advantage of such techniques.

Data and Methods for Constructing Archaeological Networks

The most common kinds of data used to build archaeological networks can be grouped into four basic categories: geographic data, documentary data, material cultural data, and simulations. Here I briefly outline many different ways archaeologists have built networks using these various kinds of data (and combinations thereof), noting in particular how relations have been conceptualized and the different kinds of questions that have been addressed with different kinds of data. Throughout, I highlight several recent studies that I argue should inspire future research, but this discussion is by no means exhaustive.

Geographic Data

Most of the earliest applications of network methods in archaeology involved the use of settlement locations and geographic data, and these models remain popular today. One common class of model involves the creation of potential travel networks using site locations and the geographic or travel-cost distances among pairs of sites to identify possible vectors of movement across a landscape. This includes the relatively simply graph theoretic point proximity models used by Terrell (1977b) described above, as well as the more complex gravity models and approaches that build on work in economic geography and spatial ecology (e.g., Bevan and Wilson 2013; Evans 2016; Menze and Ur 2012; Rivers et al. 2013). Perhaps not coincidently, many of the earliest geographic archaeological network studies focused on island communities (Broodbank 2000; Hage and Harary 1991, 1996; Irwin 1978; Terrell 1976, 1977b), where many of the complexities of defining nodes and travel between them are perhaps more straightforward than in other settings.

In more recent years, there have been several studies that incorporate geographic information systems (GIS) techniques to explore likely paths and travel costs between pairs of settlements in different kinds of physiographic environments (e.g., Mackie 2001; Verhagen et al. 2013). In most cases, these geographic models are used as null models of potential connectivity, which are subsequently compared to available archaeological evidence to evaluate fit and to infer the underlying processes generating "real" networks of interaction. In a particularly innovative study, White and Barber (2012) describe what they call the FETE (from everywhere to everywhere) model, which allows them to identify the most traversed paths in a landscape with topographic and land cover constraints, irrespective of start and end points. In other words, their model helps them highlight likely networks of movement across a landscape rather than simply from place to place. They applied this method in prehispanic Oaxaca, noting a strong correspondence between archaeologically documented vectors of exchange and their model of movement, as well as new potential vectors highlighted by their model that suggest directions for future research. In another regional study in northern Mesopotamia, Menze and Ur (2012) created a network among settlements, taking both their geographic locations as well as their sizes into account through the use of exponentially truncated power function models. They then compared this network to a series of trails between sites previously documented using remote sensing methods to parameterize their network model. These analyses suggest that the incorporation of attributes, including site size, provides a better fit for documented paths than simple nearest neighbor assumptions. They further argue that the role of settlement size as a driver of interaction likely means that the centrality of large sites would have helped to stabilize those settlements (by concentrating resource flows) even as they breached the limits of their local environments.

Another class of model that has frequently been applied to archaeological data includes the analysis of transportation networks defined on the basis of archaeologically documented roads, trails, or other corridors for travel between sites or features (e.g., Jenkins 2001; Pailes 2014; Peregrine 1991; Wernke 2012; see also Ferreira-Lopes and Pinto-Puerto 2018). Isaksen (2007, 2008, 2013) published a series of studies in this vein, exploring the nature of Roman transportation systems by combining data from many sources, including archaeologically documented roads, compilations of riverine/water transportation corridors, and historic documents like the Antonine Itineraries (see also Graham 2006). Using networks generated via these varied data, Isaksen explored the centrality of different locations across the broader network to investigate how network position influences the political status of settlements and also how network cliques do or do not conform to designations like provincial boundaries. One important point that has not been adequately explored in archaeological investigations of such transportation networks is the impact of missing data. Indeed, similar studies in contemporary contexts suggest that analyses of network flow in such transportation networks are particularly vulnerable to missing nodes and edges. Methods have been developed in other fields for probabilistically imputing missing connections in such networks, and these methods likely hold potential for archaeological analyses (e.g., Asif et al. 2016). Other projects in this vein that show the potential for such models for both applied research and education include the ORBIS interactive mapping project that provides a web-based mapping system allowing users to interactively explore the economics of transportation across the Roman world (Scheidel and Meeks 2017).

GIS tools also have been used to define and formally explore networks of intervisibility among sites and features. Swanson (2003), working in the Paquimé region of northern Mexico, used network methods to explore a series of hilltop features that had previously been hypothesized as a fire-signaling network. Swanson created networks based on shared lines of sight among these features and generated random networks to compare to the observed network. From this, he argued that the observed network was ideally positioned for signaling. In another recent study, Bernardini and Peeples (2015) used network methods and visibility analysis in the greater U.S. Southwest to explore the dynamics of "sight communities" connecting settlements based on their common views of prominent peaks. They relied on theoretical concepts developed via research on geographic cognition and argue that network methods can help archaeologists formally explore how people experienced landscapes by defining and comparing the degree to which they shared common visual anchors. As this suggests, network methods have the potential to help archaeologists more formally evaluate phenomenological models of landscape use (see Brughmans and Brandes 2017; Van Dyke et al. 2016). Brughmans et al. (2014, 2015) present a series of analyses exploring the role of intervisibility in site placement for Iron Age and Roman period sites in southern Spain. Notably, these studies use a set of tools called exponential random graph models (ERGM) to simulate and evaluate different archaeological hypotheses regarding the processes that influence visibility. ERGM models are powerful tools frequently used in the broader field of network science to model network formation and support statistical inferences about the underlying processes driving the evolution of positions and structures. These models are the state of the art in the field but have only recently been applied to archaeological data (Amati et al. 2017; Brughmans et al. 2014, 2015). This represents a potential new frontier for network analysis in archaeology that should be investigated further, not just for geographic networks but for all kinds of data.

Documentary Data

Historical network research is a rapidly growing and diverse field in its own right that deserves more discussion than I can offer here. Historians in general face many of the same challenges as archaeologists in creating and evaluating networks, in particular, the need to abstract formal characterizations of "actors" and "connections" from proxy data of varying quality (Lemercier 2015 provides a useful overview of recent approaches and perspectives). Common approaches to using documentary data to build networks include notarial records of contracts, marriages, court cases, and other official filings to define connections among people or larger entities. The work by Padgett and Ansell (1993) on Renaissance Florence discussed above provides one influential example of this approach. A number of other studies have created "who-to-whom" networks based on a corpus of correspondence to formally explore the structure of connections among senders and receivers (e.g., Cline and Cline 2015; Orser 2005). Alexander and Danowski (1990) used 280 letters written by the Roman senator Cicero (c. 68–43 BC) to explore the structure of communication among his network of contacts and suggested that the structure of communication networks cast doubt on the traditional view of a sharp division between the two classes of Roman elites (senators and knights).

In other studies, networks are defined using diverse and fragmentary data assessed through traditional methods of historiography. Düring (2016) recently published an analysis of networks among persecuted Jews and their support networks in Berlin during the Second World War based on a wide variety of sources, including survivor accounts and historical reconstructions focused on particular people/groups. In this study, Düring defines different kinds of assistance (forging documents, accommodation, food/food stamps, help to escape, etc.) and systematic qualitative assessments of the intensity of help and influential actors within these networks. Düring argues that network analytical techniques can be used to identify many of the same influential actors defined through traditional historical research methods. He suggests a more useful approach involves comparisons of formal network analyses and traditional historical observations, which provides opportunities to explore "unused potential" (e.g., actors who were structurally positioned to provide assistance but did not). Archaeologists would be well served by exploring such approaches to combining diverse datasets into single networks, as these methods are currently much more developed in historical network analysis than in archaeological network research.

In many studies, the line between historical and archaeological networks is fairly blurry. This is particularly true for explorations of architectural inscriptions. For example, Munson, Scholnick, and others (Munson 2015; Munson et al. 2014; Munson and Macri 2009; Scholnick et al. 2013), using data generated as part of the Maya Hieroglyphic Database Project, published a series of network studies that use inscriptions on Classic Maya stelae and other monuments to address a wide variety of questions ranging from the nature and scale of sociopolitical interactions to the cultural evolution of ritual practices. For these analyses, the authors constructed networks based on mentions of cities in inscriptions located at other cities, also noting the specific context in which these mentions occurred (e.g., antagonistic, diplomatic, kinship). By documenting the semantic context of mentions, this team has been able to explore the specific content and nature of social ties and, further, to identify how different kinds of interactions resulted in different kinds of network structures and positions. Research like this shows a great deal of potential, but substantial challenges that remain include developing methods to account for differences in sampling effort and temporal variation (challenges this team is currently working to address).

In other recent studies, documentary evidence is not used as the primary basis for defining shared affiliations; documents are instead used to bolster interpretations of networks generated using other kinds of material evidence (Isaksen 2007; Sindbæk 2007). For example, Sindbæk (2007) created material networks among early Viking settlements in southern Scandinavia based on shared artifact styles and interpreted the structure of these material networks in light of historically documented accounts of travel across the region and beyond. He argued that a careful reading of documented interactions can help us make stronger inferences about features of network structure that may be ambiguous when material culture is considered alone. In another innovative study, Graham (2006) used several accounts in the Antonine Itineraries of travel across the Roman provinces to help build an agent-based model (ABM) of the diffusion of materials and ideas across the greater Roman world. He used this ABM to identify differences in nature and scale of diffusion across different regions of the Roman Empire. The use of documents along with other material evidence or simulations for providing what Sindbæk (2013) calls "contextual readings" of networks is an area that shows great potential.

As historical network research is currently also on the rise, this is an area where collaborations among archaeologists and historians may thrive in the years to come (see Brughmans and Peeples 2017). The international Historical Network Research (HNR) group has recently compiled extensive bibliographies of historical and archaeological network research that they have made available online (http://historicalnetworkreserach.org/hnr-bibliography/). HNR also has recently started *The Journal of Historical Network Research* with the inaugural issue published in 2017.

Material Cultural Data

Perhaps the most common approach to building archaeological networks in recent years has involved the use of material cultural remains. This is quite a diverse area of research in its own right, but most studies fall into one of the three categories: networks based on artifacts sourced using geochemistry or similar methods; the presence/absence, frequency, or similarities of artifacts types/styles between nodes; and similarities based on detailed technological/design characterizations of individual objects or classes of objects. These different lines of material evidence provide insights into different kinds of interactions and social processes (e.g., transactions/exchange, shared patterns of consumption, shared contexts of social learning) but generally fall under the definition of affiliation networks as described above.

Networks based on the movement of objects that can be attributed to specific origins through compositional analyses or related methods are, in many ways, a perfect fit for network analyses. Indeed, network terminology and graphical representations have a long history in such provenance studies (e.g., Evans 1989), even if formal network methods are new. When properly sampled, such sourced objects allow us to explore both the direction and volume of flows of materials among geographically defined sources. This is particularly useful where sources can be attributed to small geographic zones. For example, Bernardini (2007) took advantage of the enviable resolution of ceramic chemical compositional studies in the Hopi region of northern Arizona where chemical sources can, in some cases, be attributed to single villages. Using a large compositional database, he was able to build directed networks (where the direction of edges between nodes are indicated) of ceramic circulation and calculate centrality statistics to document changes in the scale of ceramic circulation through time. This study shows that even within this relatively small region, patterns of interaction as measured by ceramic circulation varied considerably among areas separated by only tens of kilometers. As Bernardini notes, ceramic circulation does not necessarily only indicate exchange and may represent population movement, the use of geologically similar materials, or other processes. Although general network graphs have sometimes been used for the purposes of visualization in similar regional ceramic chemical composition studies (e.g., Schachner et al. 2011), the use of formal network models is rare. This is an area that should be explored further in the future. Importantly, it is likely that network methods applied to existing data would allow researchers to glean new insights, though the scale of geological resolution will necessarily constrain the scale at which networks can be defined (see issues discussed by Gjesfjeld and Phillips 2013).

Several recent archaeological network studies are based on investigations of obsidian. Obsidian is a particularly good candidate for provenance analysis as small geological sources are often chemically distinct, and it can be cheaply sourced using a variety of techniques (Shackley 2005). One feature that makes obsidian and similar materials different from sourced ceramics, however, is that the locations where such materials are obtained are not necessarily the same as the nodes that we are often interested in tracking. Thus, such materials are particularly good candidates for two-mode (bipartite) network analyses. Phillips (2011), in his study of obsidian circulation among Kuril Island communities in northeast Asia, applied methods for analyzing bipartite affiliation networks connecting sites to chemically identified obsidian sources. This approach allows him to explore connections among island communities based on the shared use of specific sources. In the U.S. Southwest, Mills et al. (2013a) created a two-mode network connecting settlements and obsidian sources, parameterized based on expectations generated by a geographic model of the cost of travel across the landscape. Specifically, they connect settlements to sources and value ties based on the degree to which such connections over- or underestimate specific sources in relation to what would be expected based on travel time from each site to each source. In another study, Blair (2015) uses both one and two-mode analyses to explore the distributions of chemically characterized glass beads recovered from burials at the 17th-century Santa Catalina de Guale Mission located on St. Catherine's Island off the coast of Georgia. Blair suggests that the comparison of both one and two-mode networks is a profitable approach that has the potential to reveal aspects of community structure that would be difficult to identify without both types of networks. When the questions at hand revolve around the economic interactions among sites or regions, it also can be useful to collapse affiliation data derived from such sourced objects into one-mode networks. For example, Golitko and others (Golitko and Feinman 2015; Golitko et al. 2012) used similarities in the proportions of different obsidian sources recovered at sites as a measure of the strength of connections among them. I describe this similarity approach in more detail below.

Another common approach to building material cultural networks in archaeology is the use of artifact occurrences or frequencies as affiliation data. In many cases, this approach entails simply connecting nodes when they share a specific class of object (Mizoguchi 2009, 2013; Sindbæk 2007) or weighting connections based on the number of shared features (Blake 2013, 2014; Coward 2010, 2013). The underlying assumption in this affiliation-based approach is that shared material cultural styles or classes of objects suggest possible social ties among the inhabitants of the places where these objects were recovered. One of the advantages of such relatively simple methods is that they often can be applied at large scales using data from a diversity of sources, even when some of the specifics of collection and sampling strategies are not known.

Where data on the relative frequencies of objects from systematic collections are available, however, there are other options. In recent years, a set of common procedures for defining affiliation networks based on archaeological frequency data has emerged. This method involves converting assemblages of artifact counts by type or some other classification into a matrix of similarities among pairs of sites/contexts (most often using the Brainerd-Robinson coefficient of similarity). This matrix is often subsequently binarized to define the presence or absence of an edge above some threshold of similarity. This set of operations has been used in a wide variety of contexts and for many types of material cultural data (Blair 2015; Freund and Batist 2014; Golitko and Feinman 2015; Golitko et al. 2012; Gravel-Miguel 2016; Hart 2012; Hart and Engelbrecht 2012; Hart et al. 2016; Irwin-Williams 1977; Jennings 2016; Mills et al. 2013a, b, 2015; Östborn and Gerding 2014; Peeples 2011, 2018; Peeples and Haas 2013; Terrell 2010a; Weidele et al. 2016). Data structured in this way have been used to understand and visualize the "texture" of social relations in a given context and to address specific questions about the structure of interaction at various scales using traditional network metrics like centrality measures. For example, Mills et al. (2013b) calculated eigenvector centrality for ceramic similarity networks in several temporal intervals in the San Pedro Valley of Southern Arizona (c. AD 1200–1450). They note that sites in the best-watered portions of the region tended to be characterized by high network centrality early on, but this pattern changed after a period of migration. They conducted these analyses using both painted and plain ceramics, which showed somewhat different patterns that suggest the values ascribed to different categories of goods may have entailed different kinds of relational processes.

Justifications for the use of such similarity networks vary, but frequently the argument is that similarities in the frequencies of materials recovered at two sites suggest similarities in practices of consumption. In other words, the argument is not that high similarities in discard necessarily represent direct interaction among those units of analysis but only that the inhabitants of sites/regions with similar assemblages were more likely to have interacted than the inhabitants of sites/regions with dissimilar assemblages (see Mills 2016; Peeples et al. 2016a). This collapsing of social proximity and social similarity is justifiable under many circumstances and is a common assumption of affiliation studies in SNA more broadly; this analytical decision also necessitates careful consideration in the design of subsequent analyses (Borgatti and Halgin 2011a). Importantly, networks of similarity are decidedly *not* exchange networks, though they have erroneously been discussed this way in many recent publications. There is considerably more work to be done to better understand the properties of such similarity-affiliation networks and the connection between shared material culture and different kinds of social relations. I would argue that the popularity of this set of procedures poses some danger of creating the "black box" that Sindbæk (2013) warned us about unless we direct greater effort toward addressing these concerns.

One more approach to material cultural networks that has developed in recent years involves the use of technological characterizations of specific artifacts and classes of objects to track patterns of relational connections based on similarities in production practices, which presumably indicate *some* kind of interaction and shared contexts of learning. Much work in this vein builds practice-theoretic models popular in the anthropology and archaeology of technology, including a huge literature on communities of practice and the chaîne opératoire approach (Dobres and Hoffman 1994; Gosselain 2000; Van der Leeuw 1993; Wenger 1998; see also Van Oyen 2016b). Watts (2013) conducted detailed analyses of lithic reduction methods on a sample of projectile points from the Tonto Basin in central Arizona and identified the likely work of individual flint knappers. He then used these data to simulate networks among settlements in the region based on the distribution of work attributed to specific knappers. I (Peeples 2011, 2018) conducted technological characterizations of corrugated cooking and storage pottery from a number of sites in the Cibola region of Arizona and New Mexico to generate a network among settlements based on similarities in production practices. I found that similarity was closely tied to geographic distance, with a few exceptions that may indicate patterns of regional population movement. In a similar study, Golubiewski-Davis (2018) applied an innovative approach to 3D scanning a set of central European Bronze Age swords and used a variety of statistical approaches to define and analyze formal networks based on swords with similar attributes. Based on this work, there were four distinct areas in central Europe within which sword makers shared technological knowledge during the Bronze Age. Such approaches define relations among nodes based on similarities in technological practices; the similarities may indicate common contexts of learning or frequent interaction. They even may allow us to identify individuals in the archaeological record.

Simulations

The final common approach to archaeological networks in recent studies involves the use of simulations. Works discussed above (Evans 2016; Knappett et al. 2011; Rivers 2016; Rivers and Evans 2013) used simulations to construct and test a range of plausible geographic models against our knowledge of the archaeological record. Similarly, Kandler and Caccioli (2016) used a simple simulation of small-world and scale-free network structures to explore how such structures influence the adoption of innovations. Agent-based models have become increasingly common in archaeological network studies (e.g., Brughmans and Poblome 2016a; Cegielski and Rogers 2016; Crabtree 2015; Graham 2006; Graham and Weingart 2015; Ossa 2013; Watts and Ossa 2016). Such simulations allow us to test ideas about the nature and scale of interactions as well as the consequences of such interactions. One important role that such simulations studies are well suited to play is to help us better understand the possible and probable processes that generate network structures and positions.

For example, Graham and Weingart (2015) developed an agent-based model focused on Roman economic interactions and explored the evolution of interaction under a range of plausible assumptions about the way the extractive economy operated. This experimentation facilitates the consideration of the underlying processes that may have generated network structures in the archaeological record, as well as the identification of areas of equifinality. Thus, this model helps focus and improve inferences drawn from empirical networks. This is an area of network research with a great deal of potential.

Other Approaches

There are several rarer uses of network methods and models in archaeology that merit mention. For example, Johnson (2016) used SNA techniques on skeletal biodistance data from the Moquegua Valley in Peru to formally explore patterns of biological relatedness within a regional context. This is the first such bioarchaeological analysis of which I am aware. Beyond this, network methods also have recently been used to reconstruct and analyze food webs in archaeological contexts to understand the interactions among different species based on "what-eats-what" relations (Crabtree et al. 2017; Dunne et al. 2016). Network and graph-based methods have proven useful for addressing other kinds of archaeological questions that are not necessarily focused on traditional relational questions. Merrill and Read (2010) used graph-based methods and matrix algebraic techniques to identify overlapping sets of cohesive artifacts to reveal intrasite activity areas and site structure within a Mousterian habitation site from the Levant. Munson (2015), drawing on practice-theoretic concepts, used network analytical techniques to untangle a complicated stratigraphic sequence at a southern Maya temple center. Beyond this, common methods for analyzing "space syntax" in archaeology (Hillier and Hanson 1989; Mol 2012) also rely on graph theoretic concepts. It is likely that similar uses of network and graph-based methods for spatial and temporal analysis will increasingly find a place in archaeology.

Archaeologists have begun using network tools to investigate the nature of scientific publication and collaboration in archaeology in general (e.g., Sinclair 2016). Brughmans (2010, 2014; Brughmans and Peeples 2017) has explored patterns of publication in the burgeoning specialization of archaeological network studies to show the evolution of specific tools and theories and, more generally, to illustrate that recently popular archaeological applications of network research represent only a small fraction of the methods that have been applied in the past. Jørgensen (2016) used bibliometric methods to explore a recent corpus of archaeological publications to evaluate the nature of the divide between science and humanities approaches in the field in general (see Schich et al. 2009 for a study in classical archaeology). Tsirogiannis and Tsirogiannis (2016) have recently applied network methods to the investigation of the illicit trade of Italian and Greek antiquities. Peeples et al. (2016b) used network methods to explore the impact of cultural resource law on archaeological knowledge in the U.S. Southwest. Mickel (2016) used SNA methods along with topic modeling to investigate the long history of collaborative research at Çatalhöyük, Turkey, to help understand the role of interaction in the development of archaeological method and theory. As these examples highlight, network methods have a great deal of potential for helping us not only address archaeological questions but also to understand the relational and structural processes driving generation of archaeological knowledge.

Combining Approaches

The diverse approaches to building and analyzing archaeological networks using different kinds of data have been quite informative on their own, but another recent trend that holds substantial potential is the combination and comparison of networks based on different lines of evidence. I have already described several ABM studies that have been compared to empirical material cultural and documentary networks (Brughmans and Poblome 2016c; Graham 2006; Ossa 2013; Watts and Ossa 2016). Terrell (2010a, b, 2013), in his work in Oceania, has demonstrated the potential of evaluating networks based on material culture to linguistic and genetic network analyses, noting in particular the interpretive potential of mismatches between different lines of evidence. Another set of recent approaches involves the combination of material and geographic networks (e.g., Coward 2013, 2016; Hart 2012; Hill et al. 2015; Orengo and Livarda 2016). Hart (2012) compared networks of ceramic similarity among northern Iroquoian sites, finding that there was little correspondence between connections suggested by material culture and geographic proximity (see Hill et al. 2015 for a similar exploration in the U.S. Southwest). Mills et al. (2013a) combined ceramic similarity networks, geographic networks, and two-mode networks based on obsidian source determinations to explore how the process of long-distance migration in the late prehispanic period reshaped the nature of long-distance interaction across the western U.S. Southwest. Comparative approaches such as these are likely to provide new and exciting insights and should be greatly expanded in the coming years.

Challenges and Opportunities for Archaeological Network Studies

Archaeological network research is a diverse and vibrant field already making headway toward answering new and old questions in archaeology in innovative ways. The question remains, however, where do we go from here? I see three important challenges facing archaeological network researchers as the specialization continues to develop (see also Brughmans et al. 2016): the advancement of network methods and network definitions appropriate for the constraints of archaeological data, the development of better methods for tracking and interpreting network change through time at various temporal scales, and the development of a better understanding of the complex relationship between material culture and social relations. These are, of course, not the only tasks that lie ahead, but if we can face these challenges, archaeological network studies will not only remain relevant over the long term but perhaps even offer a transformative new perspective for understanding the complex nature of social relations and social change in the past and present.

Adapting Network Methods to Archaeological Data (and Vice Versa)

Over the last few years, we are seeing a growing literature focused specifically on exploring many of the previously untested aspects of archaeological network methods. As the discussions above have illustrated, there are some peculiar features of archaeological network data that are not well served by widely available analytical tools. Importantly, many recent methodological advances in archaeological network research have been driven by collaborations among archaeologists and network specialists in physics, sociology, computer science, and other fields. Here, I highlight a few areas where such work has already begun to make an impact.

One common feature of the archaeological record is incomplete data. Archaeological network researchers must often build networks based on an incomplete sample of nodes within our selected boundaries because we lack information on specific contexts or those contexts have been destroyed. Beyond this, even when we do have information, it is often incomplete (due to sampling issues, differences in recording conventions, etc.). With so many known unknowns and unknown unknowns, how can we make confident inferences about interaction using archaeological data? Some researchers have begun to focus on developing solutions to the problem of missing data using quantitative approaches for inferring missing nodes and edges. Bevan and Wilson (2013) adapted spatial analytical methods developed in ecology to model inhomogeneous point processes to simulate the potential locations of missing settlements in a geographic network on the island of Crete. Tsirogiannis and Tsirogiannis (2016) drew on algorithmic models for estimating missing edges in a network representing the movement of goods across the illicit Greek and Italian artifact trade. This last example, focused on the illicit artifact trade, suggests another area of network research that archaeologists would be well served to explore further. Specifically, there is a growing field of "dark network" research focused on creating and analyzing networks in arenas such as terrorist organizations or the drug trade (see Everton 2012). Researchers in this realm are faced with many of the same issues as archaeologists, such as unknown missing information and information of varying quality about specific nodes and/or edges, and have developed a suite of tools to help tackle such challenges. Many of the relevant methodological advances in the "dark networks" realm have yet to trickle into archaeological network research. This is an area of potential future growth (see Peeples 2017).

In addition to inferring missing data, other researchers have developed tools for tempering interpretations of networks based on fragmentary data. Gjesfjeld (2015) used a bootstrap simulation approach and sensitivity analysis to assess the impact of missing nodes in a network of hunter-gatherers in the Kuril Islands of northeastern Asia and to assess error associated with key network metrics (see also Mills et al. 2013a; Peeples et al. 2016a). Groenhuijzen and Verhagen (2016) assessed the robustness of betweenness centrality measures in a least-cost network among settlements in the Dutch Roman *limes* using a related approach to iteratively simulate subsamples from the larger settlement database and evaluate the stability of their node-level centrality measures. Collins-Elliot (2017) recently used techniques for Bayesian estimation to account for sampling error in assessments of similarity in glass vessel assemblages from Republican and Augustan Roman settlements. Such

Bayesian approaches hold considerable promise for archaeological data where we are often plagued by the vagaries of sampling (see Mills et al. 2018; Peeples and Roberts 2017).

Several recent studies have focused on the properties and key features of similarity networks (affiliation networks) that are quite common in archaeology but relatively rare in network studies in general. For example, Peeples and Roberts (2013) used ceramic similarity networks from the U.S. Southwest to explore the sensitivity of several common node-level and global network metrics to the creation of binary networks from weighted data. They suggest that under many common circumstances it is preferable to calculate such descriptive statistics from the full weighted network rather than binarized versions that are more useful for visualization. Weidele et al. (2016) have taken the visualization of such similarity networks further by exploring methods that allow for the creation of valued graphs that preserve important features of the underlying similarity structure. Östborn and Gerding (2014) developed a set of methods for creating general similarity networks and statistically assessing deviations from random patterns. Habiba et al. (2018) recently published an interesting analysis exploring different kinds of similarity metrics and their influence on the definition and analysis of such networks. As discussed above, there are many properties of similarity-based affiliation networks that require the use of special care with their analysis; this is an area where archaeologists could benefit by collaborating with researchers in other fields with longer histories of using such data (Borgatti and Halgin 2011a; see also Prignano et al. 2017).

Archaeologists are increasingly taking their analytical fate into their own hands and working to adapt existing network methods to archaeological data and to develop new methods designed specifically to confront the vagaries of the archaeological record. The publications cited above are merely the tip of the iceberg, and there are many more investigations in this arena currently underway. In particular, the European Research Council-funded NEXUS 1492 project includes a number of collaborators specializing in computer science who are involved in ongoing collaborations with other teams of researchers who are conducting empirical archaeological network research to improve and develop new archaeological network methods and models (Amati et al. 2017; Brughmans and Brandes 2017; Brughmans et al. 2017; Habiba et al. 2018; Weidele et al. 2016; see http://www.nexus1492.eu). At a recent Computer Applications and Quantitative Methods in Archaeology conference in Atlanta, Brughmans and Peeples organized a workshop (see Peeples 2017 for the web version of this workshop) and two sessions explicitly focused on dealing with the uncertainties in archaeological network data. Such methodological work is an area of rapid development in archaeological networks that likely will expand in the coming years.

Tracking Network Dynamics at Varying Temporal Scales

Although we have long recognized that networks and social relations can and do change through time, traditional approaches to network representation and modeling in SNA and the social sciences broadly (especially prior to the 2000s) have tended to focus on single observations or "snapshots" of complex networks that collapse temporal variation for the sake of analytical consistency. On the other end of the spectrum, studies of social networks from the complexity science perspective are often focused on understanding the evolution of networks by modeling the generative processes underlying global network structures (e.g., small-world or scale-free structure; see Snijders 2011). As of yet, there are relatively few *empirical* network studies that investigate the changing structural positions of individual actors or sets of actors in networks within the context of such broader evolutionary network processes. Although recent work is encouraging (e.g., Ryan and D'Angelo 2017; Suitor et al. 1997; Wissink and Mazzucato 2017), most empirical network studies based on multiple longitudinal observations tend to focus on change in networks through time on the order of days, weeks, months, or a few years at most. Thus, we have very few examples of how network structures and positions change over the long term. This is undoubtedly an area where archaeologists could make major contributions.

Many recent archaeological network studies focused on change through time have tended to take the "film strip" approach of lining up multiple network snapshots to evaluate network dynamics and temporal dependencies. This typically takes the form of creating a sequence of networks by assigning sites or portions of sites to specific archaeological phases and examining how the broad structural properties of networks change across those phases. For example, Coward (2010) divided her sample of Epipaleolithic and early Neolithic sites in the Near East into a series of 1,000-year intervals. Her nodes are not complete site assemblages but instead discrete radiocarbon-dated contexts that can be assigned to a particular interval. Similar phase-based procedures have been used in many of the studies discussed above (e.g., Gjesfjeld 2015; Golitko et al. 2012; Hart and Engelbrecht 2012). Lulewicz (2018) also has recently shown the promise of Bayesian methods for compiling and adjusting regional radiocarbon chronologies to improve the resolution of network data with his work in southern Appalachia. Such phase-based approaches allow us to track how networks evolve across broad temporal periods; these methods are, of course, constrained by the chronological resolution of the sample at hand.

Over the last several years, a number of new methods have been introduced that have the potential to help us get beyond the chronological limitations of traditional archaeological phases. Roberts et al. (2012) have developed a set of methods for chronologically apportioning artifact assemblages into smaller temporal intervals based on cross-dates. Specifically, this method takes the date range for a site and the cross-dated date ranges and frequencies for each artifact type recovered from that site and assumes a normal popularity curve (or any other theoretical or empirical distribution) for each type through time to estimate the likelihood that each artifact found at a site was deposited in a given interval (see also Fentress and Perkins 1988). This method not only helps improve chronological resolution but also allows sites occupied in partially overlapping intervals to be directly compared where their occupation spans intersect. This method has proven quite useful for examining change in networks at the scale of human generations in the U.S. Southwest (Mills et al. 2013b, a, 2015) and likely could be applied elsewhere. Network studies also might be well served by exploring methods for dealing with chronological uncertainty in other areas of archaeological research, such as the aoristic approach to spatial analysis used by Crema (2012) or recent work by Ortman (2016; Ortman et al. 2007) that applies empirical Bayesian methods to divide site occupations into smaller chronological intervals for population reconstructions. Such methods are not limited to areas where high-resolution chronologies are already available, as de Pablo and Barton (2015) have developed a set of related empirical Bayesian methods for apportioning the use-lives of sites based on surface lithic assemblages with varying degrees of chronological control and expert knowledge. The application of such methods has the potential to help us track change in networks through time with greater precision than has previously been possible (see Mills et al. 2018).

Despite these recent improvements in methods, we are left with a number of nagging questions. Specifically, what does it mean to create a network that represents interaction in a period of dozens or several hundred or even thousands of years? Interactions tracked within such broad time slices certainly do not represent social networks in the strict sense but may instead provide general indications of the strongest vectors of interaction on average across an interval. Does this difference mean that we should be cautious in applying network methods designed to deal with static, short intervals? How might we test the impacts of chronological resolution on network models (see Peeples et al. 2016a)? Importantly, archaeologists are privy to information over much greater time scales than researchers in most other fields. What can we say about how networks change over the long term that cannot be said with other kinds of data? The complexities of networks built with varying degrees of temporal resolution have not yet seen the attention they deserves, but I hope this will be an area of growth in the coming years.

The Complicated Relationship Between Material Culture and Social Connections

One important point in many of the examples of archaeological networks that I have described in this review is the complex relationship between material culture and specific inferences about social connections in the past. Specifically, what does it mean to create a network based on shared material cultural styles or technologies? How do people use material culture to establish and maintain affiliations? What is the relationship between such materially defined affiliations and interaction or shared identity? This is certainly not an area unique to formal network studies, and there is a voluminous literature on the ways in which material remains are used to define social boundaries, identities, and interactions at a variety of scales (see Knappett 2011), including many influential ethnoarchaeological studies of the relationship between material culture and different kinds of interaction and influence (David and Kramer 2001; Hegmon 2000; Kramer 1985; Stark 2003).

Such work has been used to great effect in a variety of areas of archaeological research but, as of yet, has seen limited direct consideration in formal archaeological network studies. There is potential here, however, and much of this literature is directly relevant to some of the most vexing questions facing network researchers. For example, Bowser and Patton (2008) explore the relationships between stylistic similarity and age and kin relations among women potters in the Amazon using methods quite similar to archaeological similarity networks described above. Their work demonstrates that the nature of material cultural similarities and their relationship to kin groups changes over the life course of individual potters in complex ways. Terrell (2010a), working in the Sepik coast of Papua New Guinea, used ethnographic material cultural collections from the early 20th century to investigate the correspondence between material cultural and linguistic boundaries. His work illustrates that archaeologists may be hard pressed to reconstruct such linguistic patterns using only material culture, suggesting that we may need to temper our interpretations of network models generated using similar data. Careful attention to studies such as these has the potential to help us better understand what our archaeological network models can and cannot tell us. Such materially focused ethnographic research on the nature and content of social ties and network structures has a great deal of potential, not only for archaeological research but for investigations of affiliation networks generally. Importantly, the ethnography of social networks is an area of growth in other fields as well (e.g., Berthod et al. 2017), and archaeologists would be well served to pay attention to such developments. The next step will be for archaeologists and ethnographers to more directly collaborate on projects explicitly focused on tracking how formally defined social networks (as reckoned by people themselves) relate to patterns of material similarity, production, and consumption at various scales. Along similar lines, ethnoarchaeological research focused on understanding the nature of social boundaries, identity, and ethnicity has been quite productive and influential in studies of these issues in archaeology in general (e.g., Gosselain 2000; Hodder 1978; Wiessner 1997); I argue that we are past due for a materially focused ethnoarchaeology of formal social networks.

Conclusions: Finding a Place for Networks in Archaeology

Throughout this review, I have painted a fairly rosy picture of the prospects for and promise of network approaches to archaeological research. As a researcher closely involved in the development of this specialization, I am quite optimistic. This is not to say there will not still be some bumps in the road ahead. In particular, the excitement over archaeological networks has led to a proliferation of studies that could perhaps be best classified as the proverbial hammer looking for a nail. This is not unlike the early days of archaeological adoptions of other fancy new methodological and theoretical toys. Where we find ourselves today in archaeological network research is perhaps not too different from where studies of GIS in archaeology were 15 to 20 years ago (see Conolly and Lake 2006; Wheatley and Gillings 2002). GIS over the years has grown from the new kid on the block to a common and extremely useful set of tools for addressing a wide variety of archaeological concerns applied in studies with diverse theoretical underpinnings. My hope is that archaeological applications of network methods can make a similar transition in the coming years. Beyond this, changes in the nature of network thinking and network theory outlined above suggest that network researchers in a number of fields are increasingly interested in topics that are clearly within the wheel house of archaeologists (e.g., change through time, networks and culture, social identity, socioenvironmental interaction, complex adaptive systems, the material manifestations of social networks).

Archaeologists need to begin to devote greater effort toward using network studies, not just to address archaeological questions but to take our seat at the table in broader conversations among network researchers in general.

At this point in the development of archaeological network studies, it is important that we critically reflect on what archaeological network studies offer that is truly new and how network methods and network thinking can be improved to move the field forward. What do networks do for archaeological research that other traditional approaches do not? Perhaps the most frequently discussed advantage of "network thinking" in archaeology, and in the social sciences broadly, is that the reliance on relational perspectives pushes us to think not only about the attributes of individual artifacts, sites, or regions but instead how the structure of interactions among such social entities constrain or facilitate social change at various scales. Such a perspective challenges traditional notions of societies that consist of hierarchically nested territorially defined units and instead forces us to grapple with the complexities of interaction at various scales. Network thinking has the potential to get us out of the trap that Wolf (1982, p. 6) called the "billiard ball" model of societies, cultures, nations, and the like, where such entities were given names and boundaries and treated as if they had objective reality outside the relations among the people who comprise such arbitrary designations (see Peeples 2018). Such a shift in thinking encourages us to view the materials we recover as tied up in transactions among people rather than cultures or societies, and this further pushes us to ask new questions of the past. In this way, network thinking offers a potentially revolutionary new paradigm for archaeological research that allows us to formally and quantitatively explore the interdependence of interaction, influence, social structure, and the outcomes associated with network positions and properties in ways otherwise not possible.

Network approaches offer new and exciting opportunities for archaeology to become part of a broader ongoing interdisciplinary conversation in the social, physical, and behavioral sciences. As of yet, most archaeological network studies have been guided by archaeological concerns and largely focused on developing new ways of addressing existing archaeological questions (though I describe several exceptions above). The broader field of network research, however, is replete with formal and testable models focused on describing the risks and rewards of different kinds of network positions or the drivers of network properties like small-world structure. Such work is a vast trove of potential new and exciting questions for archaeological research that go beyond traditional disciplinary concerns. How does network structure influence network function over the long term? How do complex network structures emerge and expand at local and global scales? How are such processes influenced by political and organizational complexity? How does network position influence the stratification of influence or success among individuals or larger groups and the development of inequality?

Surely archaeology has much to offer the broader field of network science as well. Network researchers are increasingly interested in the potential effects of history and culture on the nature of network evolution and network processes (e.g., Knox et al. 2006; Mische 2011; Pachucki and Breiger 2010). If we stick to networks in contemporary settings alone, are we not missing the tremendous diversity and range of social settings offered by the archaeological record? Might we potentially draw incorrect conclusions about the ubiquity of network properties or phenomena if we limit ourselves to contemporary social and political settings? From this, I argue that archaeology has a special role to play in the future of network studies, and the social sciences more generally, as the only direct source of information on human societies beyond the scope of historic records and the tremendous diversity of human societies over the long term (see also Smith et al. 2012). For such a research program to reach its full potential, archaeologists will need to pay closer attention to their own social networks and make concerted efforts to reach out to scholars working on related issues in other fields to develop collaborations, to attend conferences in other disciplines to present and absorb new work, and, importantly, to publish archaeological network research in nonarchaeology venues. If we can live up to the challenges outlined here, archaeological networks research is poised to make major contributions to the discipline and beyond.

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