Networks in Archaeology: Phenomena, Abstraction, Representation

Anna Collar & Fiona Coward & Tom Brughmans & Barbara J. Mills (2015)
Journal of Archaeological Method and Theory 22: 1-32
DOI 10.1007/s10816-014-9235-6

A. Collar (*) Department of Classical Archaeology, Aarhus University, Jens Chr. Skous Vej 5, Aarhus 8000, Denmark
e-mail: annacfcollar@gmail.com
F. Coward, Department of Archaeology, Anthropology and Forensic Science, Bournemouth University, Christchurch
House, Talbot Campus, Fern Barrow, Poole, Dorset BH12 5BB, UK
T. Brughmans, Department of Computer and Information Science, University of Konstanz, Box 67, 78457 Konstanz,
Germany
B. J. Mills, School of Anthropology, University of Arizona, 1009 E South Campus Drive, Tucson, AZ 85721-0030,
USA

Keywords Archaeology. Network science . Social network analysis, Relational archaeology

Abstract
The application of method and theory from network science to archaeology has dramatically increased over the last decade. In this article, we document this growth over time, discuss several of the important concepts that are used in the application of network approaches to archaeology, and introduce the other articles in this special issue on networks in archaeology. We argue that the suitability and contribution of network science techniques within particular archaeological research contexts can be usefully explored by scrutinizing the past phenomena under study, how these are abstracted into concepts, and how these in turn are represented as network data. For

this reason, each of the articles in this special issue is discussed in terms of the phenomena that they seek to address, the abstraction in terms of concepts that they use to study connectivity, and the representations of network data that they employ in their analyses. The approaches currently being used are diverse and interdisciplinary, which we think are evidence of a healthy exploratory stage in the application of network science in archaeology. To facilitate further innovation, application, and collaboration, we also provide a glossary of terms that are currently being used in network science and especially those in the applications to archaeological case studies.

NB Key concepts used throughout this introduction are defined in the glossary at the end of this introduction.

Don't Believe the Hype?

Gartner's hype cycle (Fenn and Raskino 2008), a model for the life cycle of emerging technologies (Fig. 1), shows how on its emergence, a technological innovation is surrounded by inflated speculations and enthusiasm about its prospects. This is then followed by a period of disillusionment, where the innovation does not seem to live up to expectations, until finally its place in a domain becomes more completely understood, allowing it to be used to its full potential. The hype cycle model is arguably just part of the perhaps more commonly known logistic curve of diffusion of innovations and/or adoption of technologies, but the concept allows us to situate the recent surge in the use of formal network methods in archaeology (Fig. 2) within a longer term framework of their gradual diffusion across the discipline. Network methods have been used by archaeologists at least since the 1960s, but only in the last decade or so have they become more widely applied: does this imply that they are heading toward the lofty peak of inflated expectations? Or have we already struggled past this point to race down the slope on the other side, toward the trough of disillusionment?

Much of the biological and cultural worlds that people inhabit are organized into networks of nodes (from neurons, to individuals, to groups) and the relational ties or

edges that connect them (Newman 2010). A major idea within network science is that the position of a node within a network both constrains and creates opportunities for future action (Borgatti et al. 2013, p. 1). An increasing number of scholars are arguing that network science—used here to cover network concepts and methods drawn from a variety of disciplines—can make innovative contributions to archaeology, while acknowledging the many challenges that face

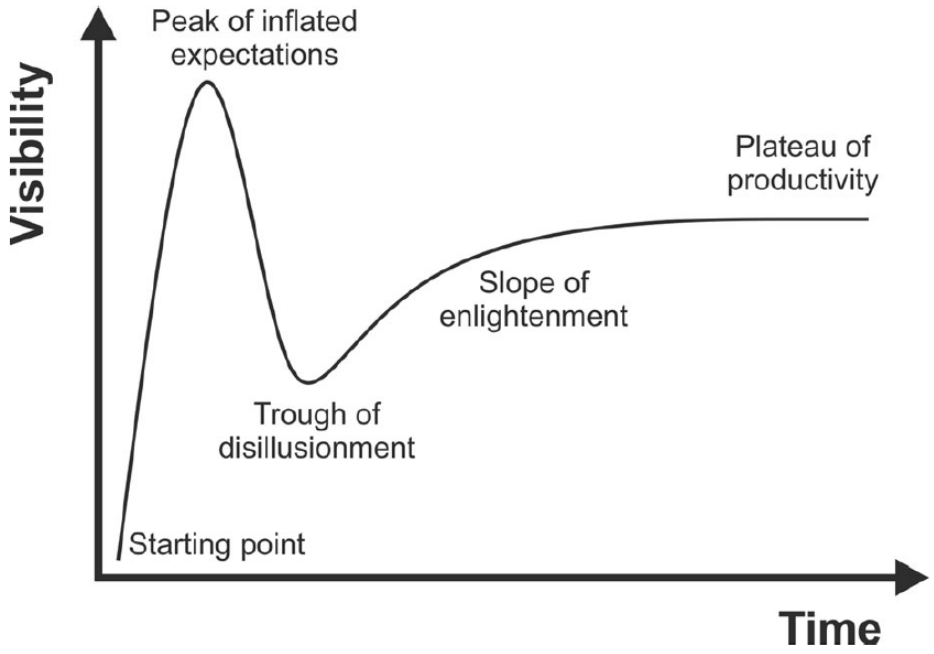

Fig. 1 Gartner's hype cycle for emerging technologies (modified after Fenn and Raskino (2008), Figs. 1–2): the moment of technological innovation is the starting point; expectations rise rapidly leading to a peak in visibility; followed by a negative hype period where the technology does not live up to expectations; the technology matures and its potential is better understood. Note that this curve is a model, and that it does not represent the full life cycle of technologies, which could still fail or increase after these initial patterns.

archaeologists using formal network methods (Brughmans 2014; Brughmans et al. 2015; Isaksen 2013; Knappett 2011; Knappett 2013; Peeples et al. 2014). However, how can we claim to properly understand the role network science can play in the archaeological research process if our expectations are inflated, or if we are wading through a personal trough of disillusionment? Where

precisely are we on the hype curve? As the editors of this special issue on network science in archaeology we would like to think we have reached the slope of enlightenment and that—if we squint a bit—we can catch a glimpse of the consolidation phase represented by the plateau of productivity, but perhaps we are still in the initial phase of optimism marking the near foothills of the peak of inflated expectations. The Gartner hype cycle teaches us an important lesson regardless: although only some innovations reach the plateau of productivity, all initially face this difficult traverse, and going through these ups and downs is both an inevitable and a necessary process. Here, then, we will attempt to go beyond the positive (or indeed negative) hype, and attempt to focus on what network concepts and methods really contribute to archaeological research.

The papers in this special issue all thus illustrate how using network methods in archaeology can contribute to a new stage of productivity. We will not therefore list the advantages and disadvantages of using network concepts and methods in our discipline (e.g., Brughmans et al. 2015), but instead present positive examples of the ways in which using these concepts and methods allows us to ask and answer new archaeological research questions—moving us beyond the hype toward a better understanding of the potential role of networks more broadly within archaeology. We also provide a glossary to clarify and standardize new or unfamiliar terms.

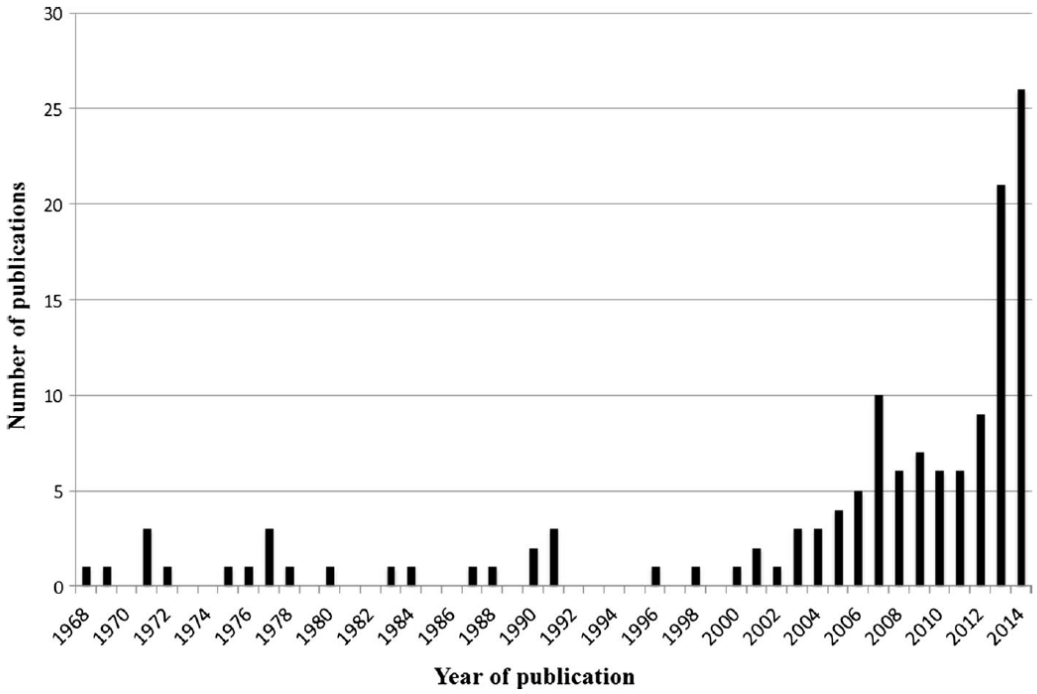

Fig. 2 Histogram of the number of published archaeological applications of formal network methods per year. Expanded version of Fig. 5 in Brughmans 2013. For references, see note at end of this paper

What Makes Network Methods Distinctive?

A key question for archaeologists interested in using networks is whether and how their data can be represented as nodes and connections between them, or edges. But why would we want to represent our archaeological data as networks anyway, and why should using a network science approach tell us something about the past that other approaches could not? Underlying these questions is the idea that using network methods allows us to do something we could not do before, something different from "standard" archaeological practice, which will reveal new information about our data.

To answer these questions, we need to consider what we really mean when we talk about "network science." According to the pared-back definition suggested in the editorial of the first issue of the new journal Network Science, "network science is the study of network models" (Brandes et al. 2013, p. 4). This of course simply

begs the further question: what is a network model? We would argue that a network model represents the conceptual process researchers go through, explicitly or implicitly, in deciding whether the phenomena under investigation can be usefully abstracted using network concepts and represented as network data (Fig. 3; Brandes et al. 2013). For example, we might be interested in a past phenomenon such as patterns of trade in prehistory. A certain level of abstraction is required to view this in terms of network concepts, and to determine whether this alternative conceptualization will lead to new insights. For example, “past trade” can be conceptualized and abstracted as the aggregate pattern of individual social entities engaging in multiple interactions through which the flow of goods and commercial information takes place. Abstraction of past phenomena into network concepts in this way requires scholars to clearly and explicitly define the conceptualizations they use in order to come to their conclusions.

The next step in the network modeling process is to formulate specific representations of these concepts as network data. In our trade example, social entities can be represented as nodes and the connections that allow for, or arise out of, the flow of commercial information and goods between them can be represented as edges, linking the nodes together. Not only does this step allows for the “translation” of archaeological data into network data, but in the absence of sufficient empirical data, it also allows scholars to formally represent their hypotheses, formally analyze them and explore their implications, and specify what forms of network they would expect to see should new archaeological data become available in the future.

Figure 3 presents network data as the end result of the process of abstraction, suggesting it serves merely to represent network concepts. However, network data have distinguishing characteristics of their own in that they allow us to represent dynamic processes and their effects. Brandes et al. argue that what makes network data different is the assumption that the presence of one edge may affect any other edge

in the network: for binary networks, the presence or absence of an edge may depend on the presence or absence of other edges; in valued networks, the weight of edges may depend on that of other edges (Brandes et al. 2013, p. 10). Quite literally, then, from a

network perspective relationships matter: it is the relationships that constitute a network, and that change its structure. This makes it clear how fundamental the theoretical assumptions underpinning representations of networks are to network science: when representing their data as a network, scholars must formulate exactly how they envisage some ties as dynamically affecting others.

The following hypothetical example of a road network illustrates the key features of network data further. If roads connect town A with town B and town B with town C (Fig. 4a), all road-bound traffic between towns A and C will need to pass through town B. A researcher may note from empirical data, or simply hypothesize, that over time a new road appears, directly connecting A and C. To explore processes of network change, the researcher must formulate and weigh a range of hypotheses: for example, a direct road between A and C is more likely to emerge if the road via B becomes unappealing for some reason. Perhaps the direct route is shorter, the inhabitants of town B levy a toll on traffic, the bandits are terrifying, or the potholes are terrible. Such hypothetical scenarios do not merely change network structure by altering the relationships between individual nodes, but will also affect the future development of that network. For example, adding a new road may mean that the traffic passing through town B decreases, decimating the commercial opportunities of its inhabitants and casting the town into interminable decline.

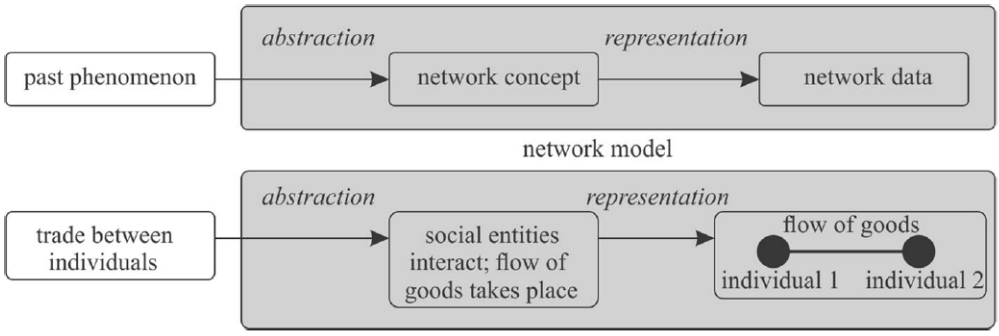

Fig. 3 Top: an abstract representation of a network model (adapted from Brandes et al. 2013, Fig. 1). Every network perspective for the study of the past includes these elements and processes. Bottom: an example of how a network model is used to explore a particular phenomenon.

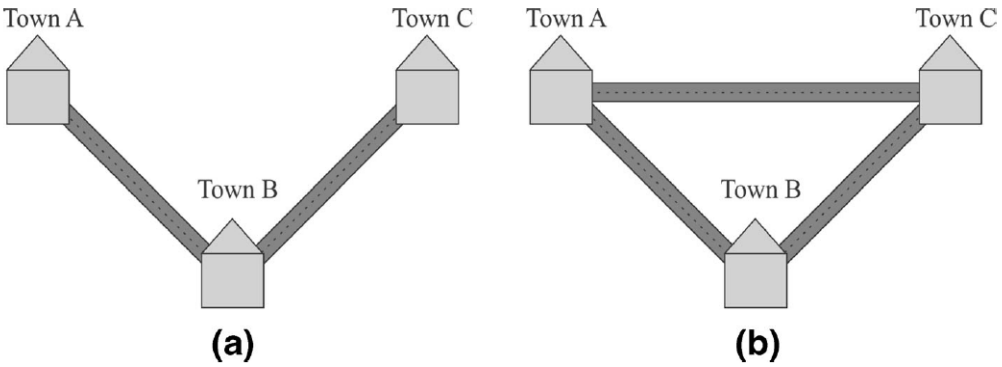

Fig. 4 Towns and connecting roads represented as network data. The hypothesis that the road from town A to town C via town B becomes unappealing will increase the probability that network (a) will evolve into network (b). This change will affect the opportunities of each town in terms of controlling the flow of resources (goods, people, information), and might in turn trigger further network change

What's New for Archaeologists?

The foregoing provides a good starting point for identifying the potential that concepts and methods from network science offer archaeology. Network science is not a single, monolithic entity, but denotes a diverse set of methods, models, and approaches concerning the study of the management, representation, and analysis of network data which represent our hypotheses about how and why relationships matter. It is not limited to the analysis of networks or the study of social networks, nor is it limited to the representation of data, nor to the fact that it offers researchers new ways to phrase

research questions. The central potential of network science for archaeology is that it places relationships at the heart of our analytical techniques.

Does this suggest that archaeology needs a dedicated toolkit of network science methods? The discipline uses a range of formal methods already: for example, geographic information systems (GIS) is the study of the management, representation, and analysis of spatial data, the assumption being that spatial data is somehow different from other types of data and merits the development of a methodological toolkit dedicated to its study. GIS was adopted and adapted from other disciplines and is now commonly used in archaeology because we frequently deal with spatial data, because we ask research questions that require the analysis of spatial data, and because archaeologists find visualizations of the spatial distribution of archaeological data useful for visual exploration and communication. Precisely the same arguments can be made for networks—we frequently deal with relationships, we ask research questions that require the analysis of relationships, and archaeologists find visualizations of relationships in archaeological data useful for visual exploration and communication.
As with GIS, network concepts and methods were originally drawn from other disciplines and are still in the process of being adopted and adapted to the specifics of archaeological data. However, although archaeologists currently need to draw from the suite of techniques and models designed by practitioners in the interdisciplinary field of network science, this does not relegate archaeological network analysis to a subfield of network science, and there is much potential for the development of specifically archaeological network techniques and methodologies, as the papers in this special issue demonstrate.

We argue that the innovative aspect of network science for archaeology lies in the possibilities it offers for understanding the fundamental significance of relationships, within and between past (and present) individuals, groups, and material culture. In the rest of this introduction, we draw on the contributions to this special issue to illustrate

some of the kinds of phenomena that are studied, the ways in which archaeological data are abstracted into network concepts, and how they are represented as network data. Table 1 shows a summary of these practical examples, listing all papers in this special issue and the three steps in the network modeling process: phenomenon, conceptualization, and data representation, along with notes on the methods/tools employed and some observations on how the authors deal with dynamic networks which change over time. Introducing the contributions in this way both demonstrates some of the new ways in which using network science has allowed archaeologists to address their research questions, and also draws out the underlying similarity of the modelling processes involved across a broad range of disparate case studies.

Table 1 Summary of how network approaches are used in the articles in this issue

Borck, Mills, Peeples & Clark
Phenomenon: Persistence vs. depopulation of the pre-Hispanic North American Southwest
Conceptualization: Similarities of proportions of ceramic wares as evidence of more direct and/or intensive interactions between settlements. Having high population levels and/or more extensive links with other groups or open social networks is more adaptive and results in survival and persistence rather than migration/depopulation.
Data representation: Sites/nodes are connected by edges extrapolated from high levels of similarity (determined using the Brainerd-Robinson coefficient) in decorated ceramic wares at those sites.
Methods/tools: Standard social network analysis measures e.g., homophily, embeddedness; External – Internal (E-I) index calculated at multiple analytical scales to examine individual regions' embeddedness in the overall network.
Temporality: Sites are divided into 50-year chronological time slices, taking into account the date ranges for each site and ceramic type and estimated population of each site.

Visualization: Maps of sites and of secondary network data (E-I indices); plots of geographical variation in network properties across the region under study. Separate network visualizations for each time slice; weighted edges and different-shaped nodes for different cultures/geographical regions.
Brughmans, Keay & Earl
Phenomenon: Intervisibility of Iron Age and Roman sites in southern Spain Conceptualization: Intervisibility of sites could be the result of deliberate positioning of sites to signal between them and/or to the control of outlying sites by central ones. More prominent sites could thus be more attractive to later Roman arrivals. Data representation: Individual sites are nodes, connected with directed edges representing probable lines of sight from an observer on one site to an observed point at another site. Methods/tools: Intervisibility of sites is determined using a GIS according to a probability threshold determined via sensitivity analysis. Generated networks are analyzed using standard network measures e.g., density, degree centralization, clustering coefficient. Simulations of intervisibility networks generated without topographical constraints are compared with archaeological data to evaluate which factors are most significant in producing the observed patterns. Temporality: Five distinct time slices determined separately using the archaeological record. Visualization: Maps of sites; various site location properties and secondary network data (global network measures e.g., clustering coefficient, density, degree, arc probability) presented as graphs; network visualizations, geographically based, different variations of the same data using different thresholds for edges (not chronological).
Crabtree
Phenomenon: Food exchange and sharing among prehistoric Ancestral Pueblos in the American Southwest.

Conceptualization: Individuals with surplus food share with others; such food sharing is adaptive and selects for social aggregation (or, in negative scenarios, depopulation).

Data representation: Agents exchange with other agents, creating directed ties between individuals that are represented as nodes.

Methods/tools: Agent-based simulations are used to model the effects of reciprocal exchange on household placement, size and stability. The model which produces results most closely resembling the archaeological record is analyzed using network methodologies and concepts, including network diameter, path length, degree, clustering coefficient, etc.

Temporality: Chronological time blocks predetermined by the broader context of the author/project and based on the archaeological record. Simulation includes "built-in" multi-scalar temporality which decisions made about exchange and trade on a "seasonal" basis and decisions about relocation on an "annual" basis. New generations/households are formed at regular (but unspecified) intervals.

Visualization: Present plots/graphs of the output of ABMs; map of study area; node size represents indegree and outdegree; color of node interconnectedness.

Golitko & Feinman

Phenomenon: Procurement and distribution of pre-Hispanic Mesoamerican obsidian

Conceptualization: Long-distance flows of raw material; centrality of major centers might imply top-down control of production and distribution, even distribution following geographical least-cost rules might imply a more dispersed network of trade.

Data representation: Obsidian flows (edges) between sites (nodes); similarity between obsidian frequencies at nodes is used to "weight" edges (subject to a minimum "cutoff" value).

Methods/tools: Diachronic social network analysis; centrality measures; geographical least-cost pathways.

Temporality: Separate networks are generated for predetermined chronological time blocks based on the archaeological record.

Visualization: Network visualizations with nodes arranged both by geographical coordinates and by relational organization (spring embedding is the routine chosen).
Gjesfjeld
Phenomenon: Adaptiveness of social relationships and exchange relationships among hunter-gatherers, particularly in challenging environments such as the Kuril Islands of Northeast Asia during the Epi-Jomon and Okhotsk cultures. Conceptualization: Similar geochemical signatures of pottery assemblages from Kuril Island sites imply exchange relationships between those sites; these relationships were adaptive and so likely to become more intensive and less fragmented over time. Data representation: Sites/nodes are probabilistically linked by common membership of a group sharing ceramics made of clay from a common origin. Methods/tools: Sensitivity analysis in the form of repeated bootstrapping with random sampling is used to assess the extent to which "removing" nodes from the network affects the overall network pattern, particularly network centrality (degree, betweenness and eigenvector are all measured). Temporality: Two separate networks generated corresponding to two archaeologically distinct cultural historical periods, supported by graph correlation between the networks indicating significant differences between them. Visualization: Map; cluster analysis of similarities and differences in material culture; scatter graph of secondary network data (principal components); primary and secondary network data metrically as tables; network visualizations (in each case, two networks, one relational, one geographical, per time period, node size representative of degree centrality in some, in others width of line indicates strength of relationships); graphs of secondary network data (how network measures change as nodes are removed); boxplot.
Graham & Weingart
Phenomenon: Trade and exchange of bricks in the Roman economy.

Conceptualization: Individual brick makers stamp bricks made of particular fabric or fabrics, which are sold elsewhere; the distribution of the stamps of individual brick makers demonstrates the reach of trade from the kiln. Data representation: Individual stamped bricks with the stamp of the same maker are the nodes, linked by edges representing various relationships (common findspots; common fabrics, etc.); this two-mode network is later collapsed into a one-mode network. Methods/tools: Standard network characteristics are calculated, including average shortest path length and clustering coefficient. Two-mode networks. Archaeological networks are compared with random networks to determine the archaeological network does not represent a "small world" in this case. Agent-based simulations are used to generate social networks that are compared with the archaeological networks as a means of assessing the plausibility of the model (the Roman economy as "bazaar"). Temporality: Network is parsed by four rough dynastic periods. Temporality is built into the ABM in cycles of searching for and harvesting resources and asking for help from other nearby agents. Visualization: Screenshot of Netlogo model; output of different resource bases used in ABM. Various network measures are presented metrically in tables. No network visualization per se is presented.
Mol, Hoogland & Hofman
Phenomenon: How do the inhabitants of the small island of Saba, North-Eastern Caribbean, fit into the broader economy and lifeways of the archipelago as a whole? Conceptualization: Similarities and differences between the material cultures of sites reflect frequency/intensity of contact/relationships between them. Data representation: Sites (nodes) are connected firstly by geographical distance (within a variable cut-off point, sites are "linked") by potentially multiple edges if archaeological and historical evidence points to the movement of ideas or goods between them; at the intra-site level, individual sites/burials/house structures

become the nodes, connected into multi-scalar two-mode networks by edges derived from material culture similarities.

Methods/tools: Minimum distance networks; Ego networks; betweenness centrality; multi-scalar networks incorporating a variety of different types of node, from "site" to individual "find." Two-mode networks.

Temporality: All sites are roughly contemporary; dating/phasing not explicitly considered.

Visualization: Map; Ego networks; minimum distance networks, i.e., geographically based visualization (betweenness centrality indicated by color of node). Spatial intra-site diagrams; two-mode ego networks with nodes differently shaped to indicate what kind of entity it represents (here node size correlates with betweenness centrality, and node color indicates the different nature of the exchange systems).

Östborn & Gerding

Phenomenon: Diffusion of fired bricks across the Mediterranean region during the Hellenistic period.

Conceptualization: The contexts of brick use are similar between sites closely linked in the diffusion network among which the innovative technology spread, and change over time and with distance, so that contexts with higher levels of similarity in brick attributes are likely to have been linked more closely.

Data representation: Contexts (which may include several from individual sites) become nodes, linked by shared attributes including dating, structural use, "binding," size category, subject to a (variable) minimum cutoff number of shared attributes.

Methods/tools: Standard social network analysismeasures: path length and network diameter. Similarity levels were systematically varied to determine the optimum level of similarity in order to exclude potentially false positives.

Temporality: Dating phase is included as an attribute which can be strictly enforced as a link or not.

Visualization: Images of fired bricks; maps with sites plotted by chronological time slice; graph of temporal distribution of fired bricks and kinds of contexts in each

time slice; geographical networks at different probabilities; networks in which only the shortest paths are represented; dots on maps in which the dots are altered to show various network properties; graph of median edge lengths at different thresholds; histograms of network measures/degrees; plots of network measures at different similarity levels.

Archaeologists are perhaps primarily concerned with material culture. This inevitable focus on the physical remains has encouraged some particular ways of thinking about the past and about past phenomena—the archaeologists of the early twentieth century were accused by the "New" Archaeologists of the 1960s and 1970s of having forgotten about the people who made and used the artifacts they studied and typologized. In contrast, the New Archaeologists asked different kinds of questions of their material culture, seeking to understand past social phenomena such as dynamics of trade and exchange, population rise and fall, or regional interactions and systemic change.

Equally in turn, however, processual archaeology has been accused of cultural materialism, whereby the materials and the processes they can illuminate have been given precedence over the intention behind and the meanings of the objects. The postprocessual turn in archaeology sought to redress this, refocusing on the roles of individual agency and social imbalances in accounting for past phenomena, as well as seeking to explore networks of meaning and symbolism in material culture.
The past phenomena that are most often studied using network science approaches show similarities to those studied by the processual school of thinking, although many of the interpretations of relationships fit comfortably within postprocessual approaches.

Knappett (2011) has framed this in terms of the multi-scalar ways in which materials intercede between people and even how things may interact with other things. We find in this volume, for example, the study of population growth, migration, and regional interaction within changing environmental conditions explored in the paper by Borck

et al. (2015); food exchange and settlement patterns simulated in the paper by Crabtree (2015); production and exchange of a variety of different kinds of raw materials, goods, and practices in those by Golitko and Feinman (2015), Gjesfjeld (2015), Graham and Weingart (2015), and Mol et al. (2015); the diffusion of technological processes (Östborn and Gerding (2015)); and site interconnections, power, and intervisibility, as studied by Brughmans et al. (2015). This kind of abstraction is aided by the archaeological record, since sites or assemblages of material culture form natural nodes, and seeking to focus on the dynamics by which they come to be characterized the way they are is an extremely fruitful line of analysis, yielding new interpretations and posing new research questions, as all these papers demonstrate in different ways.

A criticism that can be leveled at many existing applications of network science in archaeology is that the network models used are not concerned with the individual decision making and interactions that constituted most people's normal lives, and that these interactions thus become subsumed under the grand narrative of long-term culture processes. But what is also clear from the studies presented in this volume is such interactions can be incorporated into formal methods, and that there is space for elements of the postmodern critiques in archaeological network analysis. The paper by Graham and Weingart focuses on the stamps of individual brick makers in the Roman Empire. In addition, both this paper and that by Crabtree use agent-based modeling (ABM) techniques to simulate networks based around the actions and interactions of individuals. Meanwhile, the paper by Mol et al. demonstrates the potential of network methods for exploring the interplay between the actions of individuals and the grand narrative of the longue durée by comparing site-to-site networks with ego networks revolving around individual actions and interactions derived from intra-site analyses. Such ego networks can be useful for providing a multi-scalar view of site assemblages by abstracting, combining, and visualizing the relationships between different types of material culture that might usually be separated out into different levels. This allows network interpretations to break away from traditional scales of analysis, so bringing the roles of the individual into the

picture more clearly. These fully worked methodological contributions point the way toward a richer and more detailed understanding of the interactions that make up networks in archaeology, which, taken alongside other more theoretical research that use networks as a heuristic device for thinking about agency, relationships in material culture, and between people and things (Hodder 2011, 2012; Knappett 2011, 2015; Latour 2005)—might help to bring us closer to the "thick description" as argued for by Geertz (1973).

In all these examples, from the broad-scale diachronic analyses of millions of pieces of ceramic data offered by Borck et al., to the localized, site-level picture of individual interactions in the Caribbean presented by Mol et al., it is the relationships between the nodes that are brought to the fore: using network science methods allows all the diverse phenomena under study to be viewed afresh, in terms of the interactions that underlie them. This can provide a meaningful bridge between the processual and postprocessual approaches that are now part of archaeology's legacy.

How are these past phenomena translated into abstracted network concepts? A number of network models have been previously used and applied in archaeology—including the "small world" and "scale-free" networks. The small world concept (Watts and Strogatz 1998) has often featured in archaeological network analysis, perhaps partly because of its fame and its common use in many other disciplines, and it has proved a useful model in many cases. However, the papers in this special issue highlight the fact that network science in archaeology is already reaching beyond these low-hanging fruit and demonstrating beyond doubt that the small world is not a one-size-fits-all model.

All the network concepts that are used here offer new ways to get at the realities of past interactions and relationships, and demonstrate a level of criticism and reflexivity of method which support the notion that the use of networks in archaeology is moving toward the slope of enlightenment.

The paper by Borck et al. uses the concepts of embeddedness and homophily to look at population resilience and system collapse across a large area of the American Southwest. They extract relationships between sites—used as a proxy for groups of people—to think about processes of population migration and stability in the face of environmental crisis. Likewise, Crabtree's paper uses the exchange of food goods in the American Southwest as a proxy for social relations, exploring aggregation and occupation in contrast to dispersion and abandonment. She interprets the clustering of households into settlement groups as being based around the function of sharing foods and so contributing to better life expectancy. She uses dendrochronological data to generate predictions of annual soil productivity and uses this as the basis for an agent based model in which people follow food resources and the simulated results are compared with the real data.

The paper by Gjesfjeld takes a similarly socio-ecological perspective, using ceramic data from the Kuril Islands near Japan as a proxy for exploring intra-archipelagian social relationships and social aggregation and fragmentation in environmentally extreme conditions, assuming that these relationships reflect adaptive behavior. He conceptualizes this through the use of network centrality measures, and offers critical evaluation of network models by bootstrapping and repeatedly generating the models to ensure a level of robustness. Intra-regional exchange, production, and trade are also the focus of several other papers here: Golitko and Feinman generate regional networks of material culture similarity as a proxy for the exchange networks through which obsidian circulated in Mesoamerica. They argue that the properties of networks and nodes, such as centrality, reflect economic relationships and power relations (hierarchical or heterarchical) between ancient settlements. In a similar vein, Östborn and

Gerding offer another example of a network based on similarities in material culture and technological practices that explores the diffusion of innovative technologies: in this case, Hellenistic fired bricks, as a proxy for differential access to information,

potentially indicative of hierarchical political and social relationships between sites and levels of society. While the Graham and Weingart paper also looks at bricks, it does so in a very different way, highlighting the variety of ways in which network methods can be applied. They focus on testing a model of the Roman economy as a multi-scalar "bazaar" incorporating actors at a variety of scales from the small-time peddler to the grand merchant. Here, the makers' stamps and fabrics of bricks become proxies for origins and patterns of trade, allowing the exploration of networks of production and patronage via network properties such as clustering and path length. Their analysis of the archaeological data is complemented by their use of an ABM to generate network data directly from hypotheses about the individual behaviors of actors in the bazaar. Interestingly, the ABM data do not match the archaeological data very well, and neither really supports the hypothesis that the Roman world was a "small world." This mismatch between model and archaeological reality points to a valuable tool for testing hypotheses about past processes.

In contrast, Mol et al. take network analysis in a different direction: alongside intersite networks based on geographical proximity, they also use ego networks based on intra-site assemblages to explore local networks, using multiple different kinds of material culture—from ceramics to burials to zooarchaeological data—to produce a "thick" network picture of multiple different interactions within and between groups in the Caribbean.

Finally, Brughmans et al. use a network method in a strikingly different way, focusing not on material culture but on the properties of the sites themselves: exploring inter-site connections and visibility and comparing this data with known routes through the landscape of southern Iberia. Their use of site visibility data as a proxy for exploring changing political power relations and political control of the landscape highlights the fact that multiple different processes could have given rise to the edges in our network, and hence that multiple models could describe the network data under scrutiny, but some are better at this than others.

Finally, then, how are these network concepts, as approximations of the past phenomena under study, turned into network data? A key issue here is the difference between the distinct analytical stages of representation and visualization.

“Visualization” is the depiction of archaeological data as network data. However, before this can occur, the distinct step of representation must take place, in which scholars specify how the network concepts they have developed to explore the past phenomena they wish to understand (as described above) can be translated into network data in the form of nodes and edges, and combinations of these. At the core of this translation from concept to data representation is the decision-making process by which the archaeologist decides what they are calling “nodes” and what they consider to be the “edges” between those nodes.

Avery common approach, demonstrated by many of the papers in this special issue, is to use sites as nodes. Sites form natural nodes because of their relative boundedness, discreteness, and stability and persistence over archaeologically observable timescales, as well as their common use by archaeologists as analytical concepts. They offer the opportunity for mesoscale analysis of interactions: probably the level at which archaeologists most often work, due to the diachronic nature of the archaeological record and a historic interest in systemic level processes. However, the papers in this volume nevertheless formulate very different conceptions of the edges that link the nodes, and in fact as Mol et al. demonstrate, there is no need to restrict oneself to just one scale of analysis—while sites are used as nodes in part of their analysis, they go on to experiment with finer scales of analysis, using for example burials and house structures as nodes alongside sites.

Such two-mode analyses offer greater opportunities for including multiple kinds of nodes within a single network. For example, while Mol et al. start from a one-mode analysis at a regional level, using sites as nodes, they then focus in more tightly on some nodes in particular to examine intra-site relationships in material culture and how these connect into the broader network. To do this, they use a two-mode,

genuinely multi-scalar representation and indeed visualizations incorporating sites, objects, and contexts as nodes. Similarly, Graham and Weingart's paper uses individual stamped bricks, the stamp of a particular manufacturer, common findspots, and common clay fabrics as different kinds of nodes. Although they later collapse their multi-nodal networks into a one-mode network connecting individual stamped brick finds, including multiplex modes of representation at an early stage of their analysis allows them to explore complexities in the relationships under investigation. Graham and Weingart's paper also introduces a still finer scale of analysis, similarly employed by Crabtree, in which individual agents are used as nodes in agent-based simulations. Although such simulations do not allow us to access real individuals in the past, they do allow us to begin to account for individual agency and the role individuals play in creating and maintaining networks, and allow us to test the plausibility of our assumptions about individual actions and interactions against the archaeological record itself.

Of course, what links the nodes together is as fundamental a question as how the nodes are characterized themselves. Perhaps unsurprisingly for archaeologists, most of the papers in this special issue use various aspects of material culture and inferred material culture practice to create the edges in their network, the exception being Brughmans et al. who use visibility to integrate their sites into a linked network. This representation of the network edges is particularly innovative as it marries network analysis with the rich tradition of spatial analysis and landscape interpretation in archaeology, and highlights the potential of contextualizing network studies with more perceptual approaches.

The use of material culture as the edges in the network is by no means straightforward, however, and the maturity and diversity of the approaches represented in this special issue highlight this very clearly. One common approach is to measure similarities in material culture between sites (Borck et al.; Mol et al.; Golitko and Feinman; Graham and Weingart; Östborn and Gerding). These

approaches are largely networks of consumption, drawing on the networks of materials used and discarded (or lost) at archaeological sites (Mills et al. 2014).

However, other commonalities can also be used to link nodes. For example, alongside direct evidence for common manufacturers in the form of brick stamps, Graham and Weingart include information on origins, findspots, and fabrics in their multiplex networks—an approach that draws on networks of both production and consumption. Gjesfjeld's paper demonstrates another potential way of linking nodes/sites together, using principal components analysis to separate out groups using similar raw materials in their ceramic traditions.

Even when using "simple" similarity measures, analysts must make decisions about whether and how to weight their edges to indicate variable strength of relationships between nodes, as demonstrated for example in the paper by Golitko and Feinman, who use frequency of material culture similarity to do this. Edges can also be characterized as having directionality, i.e., as indicating flow from one node to another that is not necessarily reciprocated. Crabtree, for example, uses directional edges in her networks to illustrate patterns of exchange between individuals. Indeed, much of the work on compositional analysis in archaeology can be effectively represented through directional networks. Conceptualizing archaeological data as network data in this way allows the data to be analyzed using a suite of different techniques and methods drawn from network science—these are dealt with in detail elsewhere and so will not be covered here (see Newman 2010; Scott and Carrington 2011; Wasserman and Faust 1994); many are demonstrated in the contributions to this volume. However, one important element of the process, and one that needs to be recognized as a distinct stage of analysis, is visualization. It might perhaps be assumed that producing a visual image of "a network" would be a final and relatively straightforward step in analysis once decisions have been made about how to represent the archaeological data as network data—and indeed, visualizations are relatively straightforward to create in many different software packages. However, they are not necessarily an end in themselves, and both the rationale for and form of visualization must be carefully

considered if the resulting image is to achieve its aim and not simply end up as a so called “spaghetti monster”—a network so dense and complicated that it is extremely difficult to comprehend.

First, visualization offers the opportunity to reassess a dataset and the appropriateness of the assumptions made in conceptualizing that dataset as a network, making it an important part of the iterative process of analysis—not necessarily the end stage. Second, although (or perhaps because) network visualizations are both fairly easy to make and can be extremely appealing as a novel way of viewing connectivity in datasets, careful thought must go into them. Most of the papers in this special issue have chosen to represent their network data as a network visualization. However, the choices that have been made about how to present the visualizations are diverse. Each technique highlights different aspects of the data that the author(s) are concerned with, and enable the reader to access and assess structural properties and information about relationships between entities.

Geographical visualizations are often helpful, as they place the network into an archaeologically recognizable context. Almost every paper here provides a map, orienting the reader in space and time, and many present visualizations of networks in which the nodes are arranged by geographical coordinates. However, many also include visualizations of networks organized according to other criteria in which, for example, the nodes are arranged so that the distance between them reflects the strength of the relationships between them. Such visual juxtaposition of geographical and other network layouts allows readers to see the potential impact of geography on material and social relationships in the datasets under investigation (e.g., Brughmans et al.; Östborn and Gerding; Golitko and Feinman; Gjesfjeld; Mol et al.; see also Mills, Clark et al. 2013).

Separate network visualizations are also often presented for distinct time slices, again aiding comparison between visualizations (e.g., Borck et al.; Golitko and Feinman; Gjesfjeld). Other papers present a series of visualizations comparing the

results using different threshold values where edges between nodes are present or absent depending on a minimum threshold value (e.g., Brughmans et al.; Gjesfjeld; Östborn and Gerding). The benefits of visualization must be balanced with decisions on what is lost in the thresholding of ties, and in some cases often weighted and unweighted tie analyses can both be used (e.g., Peeples and Roberts 2013).
The visualizations of nodes and links can also be tailored to demonstrate the properties of individuals and the properties of interconnections within the network. The width and/or color of edges can be scaled to provide a visual guide to the strength of weighted networks, as seen in the visualizations in papers by Borck et al., Gjesfjeld, and Golitko and Feinman. Similarly, the size, shape, and color of nodes can be adjusted to reflect a variety of attributes of the nodes. Primary attributes such as the nature of the entity depicted by the node (e.g., site/material culture object or class by Mol et al.; geographical region and/or cultural affiliation by Golitko and Feinman, and Borck et al.) and secondary attributes such as the node's centrality or degree (Mol et al.; Crabtree; and Gjesfjeld), and even interpretations such as the nature of the exchange system each node is inferred to be part of (Mol et al.) can be visually conveyed in this way.

However, it is clear from the papers here that traditional network visualizations are only one of the ways in which both primary and secondary network data can be presented: almost all the papers also employ a range of other well-known data analysis techniques used in archaeology to highlight those aspects of the networks they wish to emphasize. Indeed, Graham and Weingart's paper does not include a traditional network visualization at all, relying on tabular presentation of metrics, a graph plotting the output of their agent-based models over time and a screenshot of their computational implementation of those models.

Other means of visualization seen here include the use of color-coded maps by Borck et al. to demonstrate changing external-internal (E-I) index values across their study region, thus mapping the geographical variation in network properties across the area. Still other types of visualization can also be seen—notably, Östborn and Gerding

are the only authors to include an image of the actual material culture used to create the networks, while Mol et al. include a plan of one of the sites they study, used as a basis for creating the intra-site elements of their multi-scalar two-mode network. It is clear, then, that visualization is far from straightforward; although the traditional network visualization, whether geographically or relationally organized (or indeed both), remains deservedly popular, many decisions must be made about which and how many networks to produce visualizations of, and what information, if any, is to be conveyed about the attributes of edges and nodes. It is also clear that there are many other options for conveying information about network data than traditional network visualizations.

Conclusions

In this introduction, then, we have pulled apart the processes that the authors of the papers in this special issue have gone through to first abstract the phenomena they study into network concepts, and then to represent those concepts as data. This has demonstrated how abstraction and representation processes determine the usefulness of network methods for addressing research questions. Different network data can be constructed from the same archaeological data, and different network conceptualizations and network data can be formulated for exploring the same phenomena. We could conclude that the multi-vocality of network approaches is a significant virtue: they reveal different things, allow for different insights into past phenomena through different conceptualizations, and allow one to work on multiple (conceptual and/or geographical) scales. However, some approaches might be more suitable than others, and it is the way in which we abstract the phenomena we are interested in and the way in which we see connections in our data that will determine their success.

It is important to stress again the fact that network methods are part of an archaeological research process, not a replacement of it. Network methods provide a set of techniques that may potentially prove useful at multiple different stages of the analytical and interpretive process. The abstraction of past phenomena into concepts is

something all archaeologists do routinely, and formulating assumptions about how and why relationships matter should always be motivated by archaeological theory and reasoning.

Second, network science methods incorporate techniques that are already frequently used by archaeologists, or that are an element of commonly used methods. For example, a Harris matrix can be considered a network representation of the theoretical assumptions known as the laws of stratigraphy. Formal methods should be selected for their ability to perform necessary tasks no other method can do, and can often complement one another when used in combination.

Third, some of the more familiar elements of network science can also be of considerable use. For example, in some cases similar, more commonly used statistical techniques might be an alternative and perhaps ultimately a better means of manipulating archaeological data. However, the representation of archaeological data as network data and the use of exploratory network techniques are a valuable form of exploratory data analysis, as the process of representing archaeological data as networks, exploring them visually, and thinking about relationships and their implications can lead to new insights and questions.

Such a process may also bring about a new attempt to understand how structure and practice interact since one of the major results of network approaches in other disciplines is how actors (nodes) influence, and are influenced by, the position of other actors within the network. Archaeology's ability to marshal datasets that can be both spatially and temporally expansive allows us to analyze networks in a dynamic way. Moreover, there is room for considering things or artifacts as actors within a network approach, such as within the two-mode network analyses suggested by Knappett (2011). Some things certainly did have agency to individuals and groups in the past and representing that interaction formally may be one way to explore relationships of people and things.

As the articles in this issue show, we are at the beginning of an exciting process with a healthy diversity of approaches. The future of network theory in archaeology depends on continuing to explore the various ways in which network science can produce new questions and new answers. We need to think more deeply about datasets, collaboration, and sharing of data, because large datasets are particularly well-suited to analysis through network concepts and methods. Having said this, as several of the articles demonstrate, small datasets can still deliver important insights. The diversity in scales, concepts, approaches, and applications that we have seen already bodes well for networks in archaeology being more than "hype."

Acknowledgments

The authors are grateful to the contributors to this special issue and to all speakers at the session of the Society of American Anthropology in Hawaii in 2013 from which this special issue is derived, including the discussant Ian Hodder. We would also like to thank Catherine Cameron and James Skibo for their help in compiling and editing the contributions.

Glossary

This glossary contains definitions of concepts used in the individual papers of this special issue. For each concept, we first provide a formal definition, often followed by a description of the main use of the concept or its implications. The network represented in Fig. 5 is used to illustrate a number of concepts. Where examples drawn from figures are provided, we refer to connected nodes by their number separated by a hyphen (e.g., 1–2 indicates that node one is connected to node 2). A key reference work for most of the concepts described here is that by Wasserman and Faust (1994), in which more elaborate descriptions, mathematical formulations, and additional bibliographic resources can be found. A limited number of additional primary sources are given in this glossary and included in a separate bibliography below.

The glossary presented here benefited greatly from discussions with members of

the algorithmics group at the Department of Computer and Information Science of the University of Konstanz, JohnM. Roberts Jr., and the contributors to this special issue. It is coauthored with Habiba. The authors of this paper are solely responsible for any remaining mistakes in this glossary.

Glossary is available at:
https://archaeologicalnetworks.wordpress.com/resources/#glossary

References

Albert, R., & Barabási, A. (2002). Statistical mechanics of complex networks. Reviews of Modern Physics, 74 (January), 47–97.

Anthonisse, J. M. (1971). The rush in a graph. Amsterdam: Mathematische Centrum.

Barabási, A.-L., & Albert, R. (1999). Emergence of scaling in random networks. Science, 286(5439), 509– 512. doi:10.1126/science.286.5439.509.

Borck, L., Mills, B. J., Peeples, M. A., & Clark, J. J. (2015). Are social networks survival networks? An example from the Late Prehispanic U.S. Southwest. Journal of ArchaeologicalMethod and Theory ,22(1). doi:10.1007/s10816-014-9236-5.

Borgatti, B., Everett, M. G., & Johnson, J. C. (2013). Analyzing social networks. Los Angeles: Sage.

Brandes, U., Robins, G., McCranie, A., & Wasserman, S. (2013).What is network science? Network Science, 1(01), 1–15. doi:10.1017/nws.2013.2.

Brughmans, T. (2013). Networks of networks: a citation network analysis of the adoption, use and adaptation of formal network techniques in archaeology. Literary and Linguistic Computing, The Journal of Digital Scholarship in the Humanities, 28(4), 538–562.

Brughmans, T. (2014). The roots and shoots of archaeological network analysis: a citation analysis and review of the archaeological use of formal network methods. Archaeological Review from Cambridge, 29(1), 18–41.

Brughmans, T., Collar, A., & Coward, F. (2015). Introduction: challenging network perspectives on the past. In T. Brughmans, A. Collar, & F. Coward (Eds.), The

connected past: challenges to network studies of the past. Oxford: Oxford University Press.
Brughmans, T., Keay, S., & Earl, G. P. (2015). Understanding inter-settlement visibility in Iron Age and Roman Southern Spain with exponential random graph models for visibility networks. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9231-x.
Crabtree, S. (2015). Inferring ancestral Pueblo social networks from simulation in the Central Mesa Verde. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9233-8.
Fenn, J., & Raskino, M. (2008). Mastering the hype cycle. How to choose the right innovation at the right time. Boston: Harvard Business Press.
Freeman, L. C. (1977). A set of measures of centrality based on betweenness. Sociometry, 40(1), 35–41.
Freeman, L. C. (1979). Centrality in social networks. I. Conceptual Clarification. Social Networks, 1, 215–239.
Geertz, C. (1973). Thick description: toward an interpretive theory of culture. In C. Geertz (Ed.), The interpretation of cultures: Selected essays (pp. 3–30). New York: Basic Books.
Gjesfjeld, E. (2015). Network Analysis of archaeological data from Hunter-Gatherers: methodological problems and potential solutions. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9232-9.
Golitko,M., & Feinman, G. M. (2015). Procurement and distribution of Pre-Hispanic Mesoamerican Obsidian 900 BC–AD 1520: a social network analysis. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9211-1.
Graham, S., & Weingart, S. (2015). The Equifinality of archaeological networks: an agent-based exploratory lab approach. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9230-y.
Granovetter, M. (1973). The strength of weak ties. American Journal of Sociology, 78(6), 1360–1380.
Granovetter, M. (1985). Economic action and social structure: the problem of embeddedness. The American Journal of Sociology, 91(3), 481–510.

Hess, M. (2004). “Spatial” relationships? Towards a reconceptualization of embeddedness. Progress in Human Geography, 28(2), 165–186.
Hodder, I. (2011). Human-thing entanglement: towards an integrated archaeological perspective. The Journal of the Royal Anthropological Institute, 17(1), 154–177.
Hodder, I. (2012). Entangled: An archaeology of the relationships between humans and things. Oxford: Wiley-Blackwell.
Isaksen, L. (2013). “O what a tangled web we weave”—Towards a practice that does not deceive. In C.Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 43–70). Oxford: Oxford University Press.
Knappett, C. (2011). An archaeology of interaction: Network perspectives on material culture and society.Oxford: Oxford University Press.
Knappett, C. (Ed.). (2013). Network analysis in archaeology: New approaches to regional interaction. Oxford: Oxford University Press.
Knappett, C. (2015). Networks in archaeology: between scientific method and humanistic metaphor. In T. Brughmans, A. Collar, & F. Coward (Eds.), The connected past: Challenges to network studies of the past. Oxford: Oxford University Press. (in press)
Latour, B. (2005). Reassembling the social: An introduction to actor-network-theory. Oxford: Oxford University Press.
Lorrain, F., & White, H. C. (1971). Structural equivalence of individuals in social networks. Journal of Mathematical Sociology, 1, 49–80.
Mills, B. J., Borck, L., Clark, J. J., Haas, Jr., W. R., Peeples, M. A., & Roberts, Jr. J. M. (2014). Multiscalar perspectives on Southwest social networks, A.D. 1200–1450. American Antiquity.
Mills, B. J., Clark, J. J., Peeples, M. A., Haas, W. R., Roberts, J. M., Hill, J. B., Shackley, M. S. (2013). Transformation of social networks in the late pre-Hispanic US Southwest. Proceedings of the National Academy of Sciences of the United States of America, 1–6. doi:10.1073/pnas.1219966110
Mol, A. A. A., Hoogland,M., & Hofman, C. L. (2015). Remotely local: ego-networks of late pre-colonial (AD 1000–1450) Saba, Northeastern Caribbean. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9234-7.

Newman, M. E. J. (2010). Networks: An introduction. Oxford: Oxford University Press.
Östborn, P., & Gerding, H. (2015). The diffusion of fired bricks in Hellenistic Europe: a similarity network analysis. Journal of Archaeological Method and Theory, 22(1). doi:10.1007/s10816-014-9229-4.
Peeples, M. A., Mills, B. J., Roberts, J. M., Jr., Clark, J. J., & Haas, W. R., Jr. (2014). Analytical issues in the application of network analyses to archaeology. In T. Brughmans, A. Collar, & F. Coward (Eds.), The connected past: Challenges to network studies of the past. Oxford: Oxford University Press.
Peeples, M. A., & Roberts, J. M., Jr. (2013). To binarize or not to binarize: relational data and the construction of archaeological networks. Journal of Archaeological Science, 40(7), 3001–3010.
Polanyi, K. (1944). The great transformation. The political and economic origins of our time. Boston: Beacon.
Scott, J., & Carrington, P. J. (2011). The SAGE handbook of social network analysis. London: Sage.
Wasserman, S., & Faust, K. (1994). Social network analysis: Methods and applications. Cambridge: Cambridge University Press.
Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of “small-world” networks. Nature, 393(6684), 440–442. doi:10.1038/30918.
White, H. C., Boorman, S. A., & Breiger, R. L. (1976). Social structure from multiple networks. I. Blockmodels of roles and positions. American Journal of Sociology, 81(4), 730–779.

References included in Fig. 2

Alexander, C. (2008). The Bedolina map: an exploratory network analysis. In A. Posluschny, K. Lambers, & I. Herzog (Eds.), Layers of perception: Proceedings of the 35th international conference on computer applications and quantitative methods in archaeology (CAA), Berlin, Germany, April 2–6, 2007. (Kolloquien zur Vor- und Frühgeschichte, Vol. 10) (pp. 366–371). Bonn: Dr. Rudolf Habelt GmbH.

Allen, K.M. S. (1990). Modelling early historic trade in the eastern Great Lakes using geographic information systems. In K. M. S. Allen, S. W. Green, & E. B. W. Zubrow (Eds.), Interpreting space: GIS and archaeology (pp. 319–329). London - New York - Philadelphia: Taylor & Francis.

Barthélemy, M. (2014). Discussion: social and spatial networks. Nouvelles de l'archéologie, 135, 51–61.

Bentley, R. A., & Maschner, H. D. G. (2003). Complex systems and archaeology. Salt Lake City: University of Utah Press.

Bentley, R. A., & Maschner, H. D. G. (2007). Complexity theory. In R. A. Bentley, H. D. G. Maschner, & C. Chippendale (Eds.), Handbook of archaeological theories (pp. 245–270). AltaMira Press. doi:10.1016/j.ijnurstu.2010.09.012.

Bentley, R. A., & Shennan, S. J. (2003). Cultural transmission and stochastic network growth. American Antiquity, 68(3), 459–485.

Bentley, R. A., & Shennan, S. J. (2005). Random copying and cultural evolution. Science, 309, 877–878. doi: 10.1126/science.309.5736.874b.

Bentley, R., Lake, M., & Shennan, S. (2005). Specialization and wealth inequality in a model of a clustered economic network. Journal of Archaeological Science, 32(9), 1346–1356. doi:10.1016/j.jas.2005.03.008.

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

Bevan, A., & Crema, E. R. (2014). Une modélisation géographiquement explicite d'interaction culturelle. Dialectes crétois modernes, archéologie de l'âge du Bronze. Nouvelles de l'archéologie, 135, 45–50.

Bevan, A., & Wilson, A. (2013). Models of settlement hierarchy based on partial evidence. Journal of Archaeological Science, 40(5), 2415–2427. doi:10.1016/j.jas.2012.12.025.

Bintliff, J. (2004). Time, structure, and agency: the Annales, emergent complexity, and archaeology. In J. Bintliff (Ed.), A companion to archaeology (pp. 174–194). Oxford: Blackwell.

Blake, E. (2013). Social networks, path dependence, and the rise of ethnic groups in pre-Roman Italy. In C. Knappett (Ed.), Network analysis in archaeology: new approaches to regional interaction (pp. 203–222). Oxford: Oxford University Press.
Blake, E. (2014). Dyads and triads in community detection: a view from the Italian Bronze Age. Nouvelles de l'archéologie, 135, 28–31.
Branting, S. (2007). Using an urban street network and a PGIS-Tapproach to analyze ancient movement. In E. M. Clark, J. T. Hagenmeister (Ed.), Digital discovery: Exploring new frontiers in human heritage.
Proceedings of the 34th CAA conference, Fargo, 2006 (p. 87–96). Budapest.
Broodbank, C. (2000). An island archaeology of the early Cyclades. Cambridge: Cambridge University Press.
Brughmans, T. (2010). Connecting the dots: towards archaeological network analysis. Oxford Journal of Archaeology, 29(3), 277–303. doi:10.1111/j.1468-0092.2010.00349.x.
Brughmans, T. (2012). Facebooking the past: A critical social network analysis approach for archaeology. In A. Chrysanthi, M. P. Flores, & C. Papadopoulos (Eds.), Thinking beyond the tool: Archaeological computing and the interpretative process. British Archaeological Reports International Series (pp.
191–203). Oxford: Archaeo press.
Brughmans, T. (2013a). Thinking through networks: a review of formal network methods in archaeology. Journal of Archaeological Method and Theory, 20, 623–662. doi:10.1007/s10816-012-9133-8.
Brughmans, T. (2013b). Networks of networks: a citation network analysis of the adoption, use and adaptation of formal network techniques in archaeology. Literary and Linguistic Computing, The Journal of Digital Scholarship in the Humanities, 28(4), 538–562. doi:10.1093/llc/fqt048.
Brughmans, T. (2014). The roots and shoots of archaeological network analysis: a citation analysis and review of the archaeological use of formal network methods. Archaeological Review from Cambridge, 29(1), 18–41.
Brughmans, T., Isaksen, L., & Earl, G. (2012). Connecting the dots: an introduction to critical approaches in archaeological network analysis. In M. Zhou, I. Romanowska,

Z. Wu, P. Xu, & P. Verhagen (Eds.), Proceedings of computer applications and quantitative techniques in archaeology conference 2011, Beijing (pp. 359–369). Amsterdam: Amsterdam University Press.
Brughmans, T., Keay, S., & Earl, G. (2012). Complex networks in archaeology: urban connectivity in Iron Age and Roman Southern Spain. Leonardo, 45(3), 280.
Clarke, D. L. (1968). Analytical archaeology. London: Methuen.
Classen, E. (2004). Verfahren der “Sozialen Netzwerkanalyse” und ihre Anwendung in der Archäologie. Archäologische Informationen, 27, 219–226.
Classen, E. (2008). Early Neolithic social networks in Western Germany. In A. Posluschny, K. Lambers, & I. Herzog (Eds.), Layers of perception. Proceedings of the 35th international conference on computer applications and quantitative methods in archaeology (CAA), Berlin April 2-6 2007. Kolloquien zur Vorund Frühgeschichte, Vol. 10. Bonn: Dr. Rudolf Habelt GmbH. 372+CD-ROM.
Classen, E., & Zimmerman, A. (2004). Tessellation and triangulations: Understanding Early Neolithic social networks. In K. F. Ausserer (Ed.), Enter the past: proceedings of the 30th CAA conference held in Vienna, Austria, April 2003. Oxford, 467–471.
Cochrane, E. E., & Lipo, C. (2010). Phylogenetic analyses of Lapita decoration do not support branching evolution or regional population structure during colonization of Remote Oceania. Proceedings of the Royal Society B, 365, 3889–3902.
Collar, A. C. F. (2007). Network theory and religious innovation. Mediterranean Historical Review, 22(1), 149–162. doi:10.1080/09518960701539372.
Collar, A. C. F. (2008). Networks and religious innovation in the Roman Empire. PhD thesis, University of Exeter.
Collar, A. C. F. (2013a). Religious networks in the Roman Empire: The spread of new ideas. Cambridge: Cambridge University Press.
Collar, A. C. F. (2013b). Re-thinking Jewish ethnicity through social network analysis. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 223–246). Oxford: Oxford University Press.
Collar, A. C. F., Brughmans, T., Coward, F., & Lemercier, C. (2014). Analyser les réseaux du passé en archéologie et en histoire. Nouvelles de l’archéologie, 135, 9–13.

Coward, F. (2010). Small worlds, material culture and ancient Near Eastern social networks. Proceedings of the British Academy, 158, 449–479.
Coward, F. (2013). Grounding the net: social networks, material culture and geography in the Epipalaeolithic and early Neolithic of the Near East (~21–6,000 cal BCE). In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 247–280). Oxford: Oxford University Press.
Coward, F., & Gamble, C. (2008). Big brains, small worlds: material culture and the evolution of the mind. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363(1499), 1969–1979. doi:10.1098/rstb.2008.0004.
Doran, J. E., & Hodson, F. R. (1975). Mathematics and computers in archaeology. Edinburgh: Edinburgh University Press.
Dunn, H. (2014). Population genetics and the investigation of past human interactions. Archaeological Review from Cambridge, 29(1), 42–66.
Earl, G., & Keay, S. (2007). Urban connectivity of Iberian and Roman Towns in Southern Spain: a network analysis approach. In J. T. Clark, & E. M. Hagenmeister (Eds.) Digital discovery: Exploring new frontiers in human heritage. Proceedings of the 34th CAA conference, Fargo, 2006 (pp. 77–86).
Evans, S., & Felder, K. (2014). Making the connection: changing perspectives on social networks. Archaeological Review from Cambridge, 29(1), 9–17.
Evans, T., Knappett, C., & Rivers, R. (2009). Using statistical physics to understand relational space: a case study from Mediterranean prehistory. In D. Lane, D. Pumain, S. Van Der Leeuw, & G. West (Eds.), Complexity perspectives in innovation (pp. 451–479). Dordrecht: Springer.
Fulminante, F. (2012). Social network analysis and the emergence of central places: a case study from Central Italy (Latium Vetus). BABesch, 87, 27–53.
Fulminante, F. (2014). The network approach: tool or paradigm? Archaeological Review from Cambridge, 29 (1), 167–178.
Gamble, C. (1999). The Palaeolithic societies of Europe. Cambridge: Cambridge University Press.
Gjesfjeld, E., & Phillips, S. C. (2013). Evaluating adaptive network strategies with geochemical sourcing data: a case study from the Kuril Islands. In C. Knappett (Ed.),

Network analysis in archaeology: New approaches to regional interaction (pp. 281–306). Oxford: Oxford University Press.
Golitko, M., Meierhoff, J., Feinman, G. M., & Williams, P. R. (2012). Complexities of collapse: the evidence of Maya obsidian as revealed by social network graphical analysis. Antiquity, 86, 507–523.
Graham, S. (2005). Agent-based modelling, archaeology and social organisation: the robustness of Rome. The Archaeological Computing Newsletter, 63, 1–6.
Graham, S. (2006a). EX FIGLINIS, the network dynamics of the Tiber valley brick industry in the hinterland of Rome, BAR international series 1486. Oxford: Archaeopress.
Graham, S. (2006b). Networks, agent-based models and the Antonine Itineraries: implications for Roman archaeology. Journal of Mediterranean Archaeology, 19(1), 45–64.
Graham, S. (2006).Who's in charge? Studying social networks in the Roman brick industry in Central Italy. In C. Mattusch & A. Donohue (Eds.), Common ground: Archaeology, art, science, and humanities—Proceedings of the XVI International Congress of Classical Archaeology, Oxford (pp. 359–362).
Graham, S. (2009). The space between: the geography of social networks in the Tiber valley. In F. Coarelli & H. Patterson (Eds.), Mercator Placidissimus: the Tiber Valley in Antiquity, new research in the upper and middle river valley. Edizioni Quasar: Rome.
Graham, S. (2014). On connecting stamps—network analysis and epigraphy. Nouvelles de l'archéologie, 135, 39–44.
Graham, S., & Steiner, J. (2007). TravellerSim: growing settlement structures and territories with agent-based modeling. In J. T. Clark & E. M. Hagenmeister (Eds.), Digital discovery: exploring new frontiers in human heritage. Proceedings of the 34th CAA conference, Fargo, 2006 (pp. 57–67). Budapest: Archaeolingua.
Hage, P., & Harary, F. (1983). Structural models in anthropology. Cambridge: Cambridge University Press.
Hage, P., & Harary, F. (1991). Exchange in Oceania: A graph theoretic analysis. Oxford: Clarendon.

Hage, P., & Harary, F. (1996). Island networks: communication, kinship and classification structures in Oceania. Cambridge: Cambridge University Press.
Hiorns, R. W. (1971). Statistical studies in migration. In F. R. Hodson, D. G. Kendall, & P. Tăutu (Eds.), Mathematics in the archaeological and historical sciences, Proceedings of the Anglo-Romanian conference, Mamaia 1970 (pp. 291–302). Edinburgh: Edinburgh University Press.
Hunt, T. L. (1988). Graph theoretic network models for Lapita exchange: a trial application. In P. V. Kirch & T. L. Hunt (Eds.), Archaeology of the Lapita cultural complex: A critical review (pp. 135–155). Seattle: Thomas Burke Memorial Washington State Museum Research Reports no. 5.
Hutchinson, P. (1972). Networks and roman roads: a further Roman network. Area, 4(4), 279–280.
Irwin, G. (1978). Pots and entrepôts: a study of settlement, trade and the development of economic specialization in Papuan prehistory. World Archaeology, 9(3), 299–319.
Isaksen, L. (2007). Network analysis of transport vectors in Roman Baetica. In J. T. Clark & E. M. Hagenmeister (Eds.), Digital discovery: Exploring new frontiers in human heritage. Proceedings of the 34th CAA conference, Fargo, 2006 (pp. 76–87). Budapest: Archaeolingua.
Isaksen, L. (2008). The application of network analysis to ancient transport geography: a case study of Roman Baetica. Digital Medievalist, 4, http://www.digitalmedievalist.org/journal/4/isakse.
Isaksen, L. (2013). “O what a tangled web we weave”—Towards a practice that does not deceive. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 43–70). Oxford: Oxford University Press.
Jenkins, D. (2001). A network analysis of Inka roads, administrative centers, and storage facilities. Ethnohistory, 48(4), 655–687.
Jiménez, D., & Chapman, D. (2002). An application of proximity graphs in archaeological spatial analysis. In D. Wheatley, G. Earl, & S. Poppy (Eds.), Contemporary themes in archaeological computing (pp. 90– 99). Oxford: Oxbow Books.

Kendall, D. (1969). Incidence matrices, interval graphs and seriation in archeology. Pacific Journal of Mathematics, 28(3), 565–570.
Kendall, D. G. (1971a). Seriation from abundance matrices. In F. R. Hodson, D. G. Kendall, & P. Tăutu (Eds.), Mathematics in the archaeological and historical sciences, Proceedings of the Anglo-Romanian conference, Mamaia 1970 (pp. 215–252). Edinburgh: Edinburgh University Press.
Kendall, D. G. (1971b). Maps from marriages: an application of non-metric multi-dimensional scaling to parish register data. In F. R. Hodson, D.G. Kendall,&P. Tăutu (Eds.), Mathematics in the archaeological Networks in Archaeology 29
and historical sciences, Proceedings of the Anglo-Romanian conference, Mamaia 1970 (pp. 303–318). Edinburgh: Edinburgh University Press.
Knappett, C. (2011). An archaeology of interaction: Network perspectives on material culture and society. Oxford: Oxford University Press.
Knappett, C. (2013a). Network analysis in archaeology: New approaches to regional interaction. Oxford: Oxford University Press.
Knappett, C. (2013b). Introduction: why networks? In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 3–16). Oxford: Oxford University Press.
Knappett, C. (2014). Avant-propos. Dossier: Analyse des réseaux sociaux en archéologie. Nouvelles de l'archéologie, 135, 5–8.
Knappett, C., Evans, T., & Rivers, R. (2008). Modelling maritime interaction in the Aegean Bronze Age. Antiquity, 82(318), 1009–1024.
Knappett, C., Evans, T., & Rivers, R. (2011). The Theran eruption and Minoan palatial collapse: new interpretations gained from modelling the maritime network. Antiquity, 85(329), 1008–1023.
Kohler, T. A. (2012). Complex systems and archaeology. In I. Hodder (Ed.), Archaeological theory today II (pp. 93–123). Cambridge: Polity Press.
Leidwanger, J. (2014). Maritime networks and economic regionalism in the Roman Eastern Mediterranean. Nouvelles de l'archéologie, 135, 32–38.
Lock, G., & Pouncett, J. (2007). Network analysis in archaeology session introduction: an introduction to network analysis. In J. T. Clark & E. M. Hagenmeister

(Eds.), Digital discovery: exploring new frontiers in human heritage. Proceedings of the 34th CAA conference, Fargo, 2006 (pp. 71–73). Budapest: Archaeolingua.
Mackie, Q. (2001). Settlement archaeology in a Fjordland archipelago: Network analysis, social practice and the built environment of Western Vancouver Island, British Columbia, Canada since 2,000 BP. BAR international series 926. Oxford: Archaeopress.
Menze, B. H., & Ur, J. A. (2012). Mapping patterns of long-term settlement in Northern Mesopotamia at a large scale. Proceedings of the National Academy of Sciences of the United States of America, 109(14), E778–E787. doi:10.1073/pnas.1115472109.
Mills, B. J., Clark, J. J., Peeples, M. A., Haas, W. R., Roberts, J. M., Hill, J. B., Shackley, M. S. (2013). Transformation of social networks in the late pre-Hispanic US Southwest. Proceedings of the National Academy of Sciences of the United States of America, 1–6. doi:10.1073/pnas.1219966110
Mills, B. J., Roberts, J.M., Clark, J. J., Jr., Haas,W. R., Huntley, D., Peeples,M. A., & Breiger, R. L. (2013b). In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 181– 202). Oxford: Oxford University Press.
Mizoguchi, K. (2009). Nodes and edges: a network approach to hierarchisation and state formation in Japan. Journal of Anthropological Archaeology, 28(1), 14–26. doi:10.1016/j.jaa.2008.12.001.
Mizoguchi, K. (2014). Evolution of prestige good systems: An application of network analysis to the transformation of communication systems and their media. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 151–179). Oxford: Oxford University Press.
Mol, A. A. A. (2014). Play-things and the origins of online networks: virtual material culture in multiplayer games. Archaeological Review from Cambridge, 29(1), 144–166.
Mol, A. A. A., & Mans, J. (2013). Old boy networks in the indigenous Caribbean. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 307–333). Oxford: Oxford University Press.

Müller, U. (2010). Zentrale Orte und Netzwerk Zwei Konzepte zur Beschreibung von Zentralität. In C. Dobiat,
P. Ettel, & F. Fless (Eds.), Zwischen Fjorden und Steppe. Festschrift fur Johan Callmer zum 65. Geburtstag (pp. 57–67). Rahden: Verlag Marie Leidorf GmbH.
Müller, U. (2012). Networks of towns—networks of periphery? Some relations between the North European Medieval town and its hinterland. In S. Brather, U. Müller, & H. Steuer (Eds.), Raumbildung durch Netzwerke? Der Ostseeraum zwischen Wikingerzeit un Spaetmittelalter aus archaeologischer und geschichtswissenschaftlicher Perspektive (pp. 55–78). Bonn: Dr. Rudolf Habelt GmbH.
Munson, J. (2013). From metaphors to practice: operationalizing network concepts for archaeological stratigraphy. Journal of Archaeological Method and Theory. doi:10.1007/s10816-013-9181-8.
Munson, J. L., & Macri, M. J. (2009). Sociopolitical network interactions: a case study of the Classic Maya. Journal of Anthropological Archaeology, 28(4), 424–438. doi:10.1016/j.jaa.2009.08.002.
Nelson, E. S., & Kassabaum, M. C. (2014). Expanding social networks through ritual deposition: a case study from the Lower Mississippi Valley. Archaeological Review from Cambridge, 29(1), 103–128.
30 Collar et al. Orser, C, Jr. (2005). Network theory and the archaeology of modern history. In P. Funari, A. Zarankin, & E. Stovel (Eds.) Global archaeological theory SE - 7 (pp. 77–95). Springer US. doi:10.1007/0-306-48652- 0_7.
Orton, C. (1980). Mathematics in archaeology. London: Collins.
Östborn, P., & Gerding, H. (2014). Network analysis of archaeological data: a Systematic Approach. Journal of Archaeological Science.
Peeples, M. A. (2011). Identity and social transformation in the prehispanic Cibola world: A.D. 1150-1325. Ph.D. dissertation, Arizona State University.
Peeples, M. A., & Roberts, J. M. (2013). To binarize or not to binarize: relational data and the construction of archaeological networks. Journal of Archaeological Science, 40(7), 3001–3010. doi:10.1016/j.jas.2013.03.014.

Peregrine, P. (1991). A graph-theoretic approach to the evolution of Cahokia. American Antiquity, 56(1), 66–75.
Phillips, S. C. (2011). Networked glass: Lithic raw material consumption and social networks in the Kuril islands. University of Washington, Seattle: Far Eastern Russia. Unpublished PhD dissertation.
Pouncett, J., & Lock, G. (2007). A vector-based approach to the integration of geophysical and test-pitting data: Phasing the South Cadbury Environs Project. In E. M. Clark & J. T. Hagenmeister (Eds.), Digital discovery: Exploring new frontiers in human heritage. Proceedings of the 34th CAA conference, Fargo, 2006 (p. 97–106). Budapest.
Riede, F. (2014). Eruptions and ruptures—a social network perspective on vulnerability and impact of the Laacher See eruption (c. 13,000 BP) on Late Glacial hunter-gatherers in northern Europe. Archaeological Review from Cambridge, 29(1), 67–102.
Rivers, R., & Evans, T. S. (2013). What makes a site important? Centrality, gateways and gravity. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 125–150). Oxford: Oxford University Press.
Rivers, R., & Evans, T. S. (2014). New approaches to Archaic Greek settlement structure. Nouvelles de l’archéologie, 135, 21–28.
Rothman, M. (1987). Graph theory and the interpretation of regional survey data. Paléorient, 13(2), 73–91. doi:10.3406/paleo.1987.4430.
Santley, R. S. (1991). The structure of the Aztec transport network. In C. D. Trombold (Ed.), Ancient road networks and settlement hierarchies in the New World (pp. 198–210). Cambridge: Cambridge University Press.
Schich, M., & Coscia, M. (2011). Exploring co-occurrence on a meso and global level using network analysis and rule mining. In Proceedings of the ninth workshop on mining and Learning with Graphs (MLG ’11). San Diego: ACM.
Schich, M., Hidalgo, C. A., Lehmann, S. J., & Park, J. (2009). The network of subject co-popularity in Classical Archaeology. Bollettino di Archeologia Online, 49–57.
Scholnick, J. B., Munson, J. L., & Macri, M. J. (2013). Positioning power in a multi-relational framework: A social network analysis of Classic Maya political rhetoric. In

C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 95–124). Oxford: Oxford University Press.
Schweizer, T., Hage, P., Harary, F., Houseman, M., Kent, S., & Wolfe, A. W. (1997). Embeddedness of ethnographic cases: a social networks perspective. Current Anthropology, 38(5), 739–760.
Shuchat, A. (1984). Matrix and network models in archaeology. Mathematics Magazine, 57(1), 3–14.
Sindbæk, S. M. (2007a). Networks and nodal points: the emergence of towns in Early Viking Age Scandinavia. Antiquity, 81(311), 119–132.
Sindbæk, S. M. (2007b). The small world of the Vikings: Networks in Early Medieval communication and exchange. Norwegian Archaeological Review, 40, 59–74.
Sindbæk, S. M. (2009). Open access, nodal points, and central places: maritime communication and locational principles for coastal sites in south Scandinavia, c. AD 400–1200. Estonian Journal of Archaeology, 13 (2), 96. doi:10.3176/arch.2009.2.02.
Sindbæk, S. M. (2013). Broken links and black boxes: Material affiliations and contextual network synthesis in the Viking world. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 71–94). Oxford: Oxford University Press.
Stoner, J. (2014). “Extending the self” through material culture: private letters and personal relationships in second-century AD Egypt. Archaeological Review from Cambridge, 29(1), 129–143.
Swanson, S. (2003). Documenting prehistoric communication networks: a case study in the Paquimé polity. American Antiquity, 68(4), 753–767.
Terrell, J. E. (1976). Island biogeography and man in Melanesia. Archaeology and Physical Anthropology in Oceania, 11(1), 1–17.
Terrell, J. E. (1977a). Geographic systems and human diversity in the North Solomons. World Archaeology, 9(1), 62–81.
Terrell, J. E. (1977b). Human biogeography in the Solomon Islands. Fieldiana Anthropology, 68(1), 1–47.
Terrell, J. E. (2010a). Language and material culture on the Sepik Coast of Papua New Guinea: using social network analysis to simulate, graph, identify, and analyze social

and cultural boundaries between communities. The Journal of Island and Coastal Archaeology, 5(1), 3–32.
Terrell, J. E. (2010b). Social network analysis of the genetic structure of Pacific islanders. Annals of Human Genetics, 74(3), 211–232. doi:10.1111/j.1469-1809.2010.00575.x.
Terrell, J. E. (2013). Social network analysis and the practice of history. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 17–42). Oxford: Oxford University Press.
Van der Leeuw, S. E. (2013). Archaeology, networks, information processing, and beyond. In C. Knappett (Ed.), Network analysis in archaeology: New approaches to regional interaction (pp. 335–348). Oxford: Oxford University Press.
Van Oyen, A. (2014). Les acteurs-réseaux en archéologie: État de la question et perspectives futures. Nouvelles de l'Archéologie, 135, 14–20.
Verhagen, P., Brughmans, T., Nuninger, L., & Bertoncello, F. (2013). The long and winding road: Combining least cost paths and network analysis techniques for settlement location analysis and predictive modelling. In Proceedings of computer applications and quantitative techniques in archaeology conference 2012, Southampton (pp. 357–366). Amsterdam: Amsterdam University Press.
Wernke, S. A. (2012). Spatial network analysis of a terminal prehispanic and early colonial settlement in highland Peru. Journal of Archaeological Science, 39(4), 1111–1122. doi:10.1016/j.jas.2011.12.014.
Zubrow, E. B. W. (1990). Modelling and prediction with geographic information systems: a demographic example from prehistoric and historic New York. In K. M. S. Allen, S. W. Green, & E. B. W. Zubrow (Eds.), Interpreting space: GIS and archaeology (pp. 307–318). New York: Taylor & Francis.