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Networks in Archaeology: Phenomena, Abstraction, Representation

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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.

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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

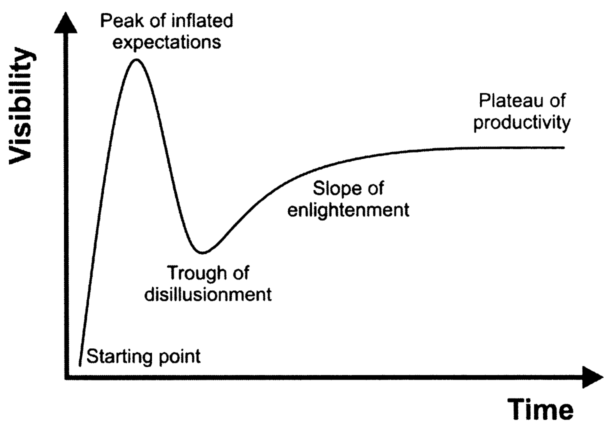

Fig. 1 Gartner's hype cycle for emerging technologies (modified after Fenn and Raskino (2008), Figs. 1–2): the moment of technological innovation is the starting point; expectations rise rapidly leading to a peak in visibility; followed by a negative hype period where the technology does not live up 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

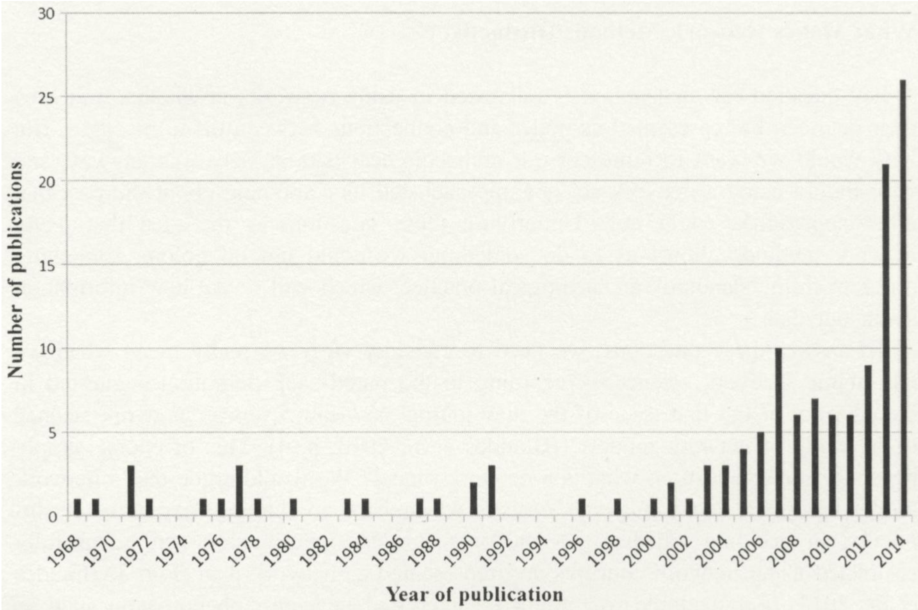

Fig. 2 Histogram of the number of published archaeological applications of formal network methods per year. Expanded version of Fig. 5 in Brughmans 2013. For references, see note at end of this paper

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 (underlined in the text).

What Makes Network Methods Distinctive?[1]

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

[1] Key concepts used throughout this introduction are underlined, and are defined in the glossary at the end of this introduction.

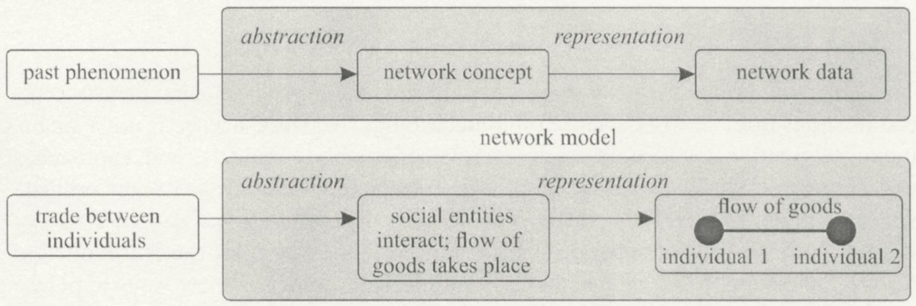

Fig. 3 *Top*: an abstract representation of a network model (adapted from Brandes *et al.* 2013, Fig. 1). Every network perspective for the study of the past includes these elements and processes. *Bottom*: an example of how a network model is used to explore a particular phenomenon

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.

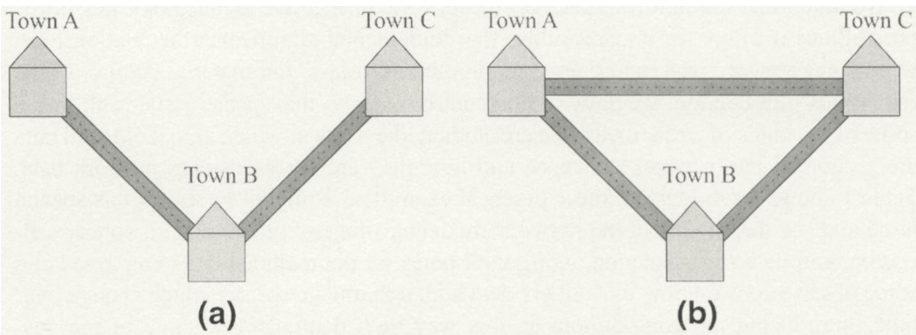

Fig. 4 Towns and connecting roads represented as network data. The hypothesis that the road from town A to town C *via* town B becomes unappealing will increase the probability that network (**a**) will evolve into network (**b**). This change will affect the opportunities of each town in terms of controlling 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 modeling 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.

Table 1 (continued)

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.

Table 1 (continued)

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 cut-off number of shared attributes.

Methods/tools: Standard social network analysis measures: 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.

Networks in the Past

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.

Network Concepts in Archaeology

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 inter-site 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.

Network Data in Archaeology

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.

A very 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."

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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, John M. 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.

Actor	See node.
Acyclic network	Defined as a directed network with no cycles. For example, the directed network in Fig. 5b is not acyclic because it includes the cycle 2-3-4-2. Examples of acyclic networks include citation networks and dendrograms.
Adjacency matrix	Defined as a way of representing a network where there is a row and a column for each node, and the values in the cells indicate whether an edge exists between a pair of nodes.
Affiliation network	See two-mode network.
Arc	See directed edge.
Average degree	See degree.
Average shortest path	See geodesic.
Betweenness centrality	A node's betweenness centrality is defined as the fraction of the number of geodesics passing through this node over the number of geodesics between all pairs of nodes in the network. Nodes with a high betweenness centrality are often considered to be important intermediaries for controlling

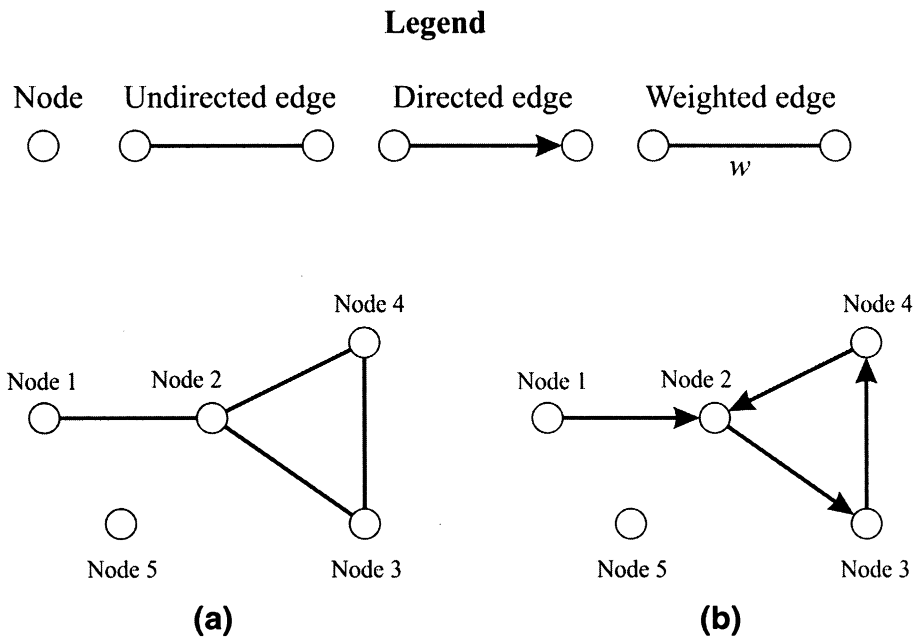

Fig. 5 Example network used in some of the definitions below to clarify network concepts

the flow of resources between other nodes, because they are located on paths between many other node pairs. The concept of brokerage is often mentioned in relation to betweenness centrality. Nodes which are incident to the *only* edge connecting two subsets of nodes in the network are in a position to broker the relationship between these nodes. These nodes will typically have a high betweenness centrality but not necessarily a high degree or closeness centrality. For example, in Fig. 4 if the only route between towns A and C travels through B, town B may be in a position to tax any goods traveling between them, to control what information travels between towns, or to isolate one or both. Betweenness centrality was first quantitatively expressed by Anthonisse (1971) and Freeman (1977).

Bipartite network — See two-mode networks.

Blockmodel — Defined as a partitioning into blocks of structurally equivalent nodes, where the blocks are connected by hypothesized edges.
In blockmodeling, the rows and columns of adjacency matrices are arranged so that structurally equivalent nodes are in adjacent positions in the matrix, and the edges between different blocks can be studied. First introduced by White, Boorman, and Breiger (1976).

Brokerage — See betweenness centrality.

Centrality Defined as a family of measures of the node's position within the network, which represent a ranking of nodes (see betweenness, closeness, degree, and eigenvector centralities). Centrality measures are used to identify the most important or prominent nodes in the network, depending on the different definitions of importance or prominence implemented in the network measure used.

Clique A clique is a subset of nodes in a network, where every pair of nodes is connected by an edge.
In the social sciences, only cliques of three nodes or more are usually considered. For example, in Fig. 5a, nodes 2, 3, and 4 form a clique of size 3. The definition of a clique is independent of whether it applies to the whole network or not. For example, a network can consist of multiple cliques, or an entire network can be one clique. The latter can also be called a complete network.

Closeness centrality The closeness centrality of a node is defined as the inverse of the sum of the geodesics of that node to all other nodes divided by the number of nodes in the network.
The closeness centrality of a node gives an indication of how close this node is to all other nodes in the network, represented as the number of steps in the network that are necessary on average to reach another node. Nodes with a high closeness centrality score could be considered important or prominent, since they can share and obtain resources in less steps than other nodes. Early quantitative implementations of closeness centrality are reviewed by Freeman (1979).

Clustering coefficient Defined as the number of closed triplets over the total number of triplets in a network, where a triplet is a set of three nodes with two (open triplet) or three (closed triplet) undirected edges between them.
The clustering coefficient represents the average probability that two nodes connected to a third node are themselves connected, and it is commonly used for this purpose since the publication of the "small-world" network model (Watts and Strogatz 1998). The clustering coefficient of a network is closely related to the concept of transitivity in the social sciences, which captures the notion that "a friend of a friend is a friend." Transitivity refers to the tendency of an open triplet to become a closed triplet.

Cohesion See density.

Complete network See clique.

Connected component Defined as a subset of an undirected network in which any pair of nodes can be connected to each other *via* at least one path, and where there can be no paths to any nodes outside this subset.
For example, in the undirected network in Fig. 5a, there are two connected components: node 5 and nodes 1, 2, 3, and 4.

Connection	See edge.
Cycle	Defined as a path in a directed network in which the starting node and ending node are the same. It is also called a closed path. For example, in Fig. 5b, the path 2-3-4-2 is a cycle. See also acyclic network.
Degree	The degree of a node is defined as the number of edges incident to this node. The average degree of a network is the sum of the degrees of all nodes in this network divided by the number of nodes. In a directed network, the indegree of a node refers to the number of incoming incident edges of a node. In a directed network, the outdegree of a node refers to the number of outgoing incident edges of a node. For example, node 2 in Fig. 5a has a degree of 3, while the same node can be said in Fig. 5b to have an indegree of 2 and an outdegree of 1.
Degree centrality	Defined as the centrality of a node based on the number of edges incident to this node. According to the degree centrality measure, a node is important or prominent if it has edges to a high number of other nodes.
Degree distribution	Defined as the probability distribution of all degrees over the whole network. The measure is commonly used to compare the structure of networks since the publication of the "scale-free" network structure (Albert and Barabási 2002, p. 49; Barabási and Albert 1999; Newman 2010, p. 243–247). In scale-free networks, the degree distribution follows a power-law.
Density	Defined as the fraction of the number of edges that are present to the maximum possible number of edges in the network. Cohesion is a commonly used concept which is often operationalized using the density measure. For other cohesion measures, see Wasserman and Faust (1994, 249–290).
Diameter	Defined as the length of the longest geodesic in the network.
Directed edge	Defined as an ordered pair of nodes, which is often graphically represented as an arrow drawn from a starting node to an end node. A directed edge is asymmetric. It connects a starting node with an ending node and cannot be traversed in the other direction. For example, all edges in Fig. 5b are directed edges.
Directed network	Defined as a set of nodes and a set of directed edges. A path through a directed network will need to follow the direction of the directed edges. For example, the network in Fig. 5b is a directed network.
Distance	See path length.
Dyad	Defined as any pair of nodes in a network that may or may not have an edge between them.

	For undirected edges, there are two possible dyadic relationships: connected, or not connected. For directed edges, there are four: unconnected; connected in one direction; connected in the other direction; and connected in both directions.
Edge	Defined as a line between a pair of nodes, representing some kind of relationship between them. Many synonyms exist to refer to an edge, including tie, arc, relationship, link, connection, and line. An edge can be directed or undirected, and weighted or unweighted. The concept "arc" is often used to refer to a directed edge.
Ego network	Defined as a network consisting of a node (called ego), the nodes it is directly connected to, and the edges between these nodes.
Eigenvector centrality	The eigenvector centrality of a node is defined in terms of the eigenvector centrality of nodes incident on it. More descriptively, instead of assigning a single centrality score to a node, a node's eigenvector centrality is defined in terms proportional to the nodes incident on it. A node with a high eigenvector centrality is a node that is connected to other nodes with a high eigenvector centrality. See Newman (Newman 2010, 169–172) for the procedure to calculate eigenvector centrality.
Embeddedness	A polyvalent concept that comprises two variants. The first is the structural integration of a node or any group of nodes within the network. Different measures for structural integration exist. The E/I index is one example of this, which is calculated as a ratio of the number of edges within a group of nodes (internal) and between groups of nodes (external). The second variant, as popularized in economic theory through the work of Polanyi (1944) and Granovetter (1985), relates to the intertwined nature of social, economic, political, religious, and cultural interactions. See Borck *et al.* (2015) and Hess (2004) for overviews of this concept.
Equivalence	See structural equivalence.
Geodesic	Defined as the path between a pair of nodes with the shortest path length. Sometimes referred to as the shortest path length between a pair of nodes. For example, the geodesic between nodes 1 and 3 in Fig. 5b is the path 1–3 with a length of 1. The average shortest path length is the average of all geodesics in a network.
Graph	See network.
Heterophily	Defined as a tendency of nodes to become connected to other nodes that are dissimilar under a certain definition of dissimilarity. For example, in Fig. 6a, a node with an attribute value represented in gray will have a tendency of being connected to a

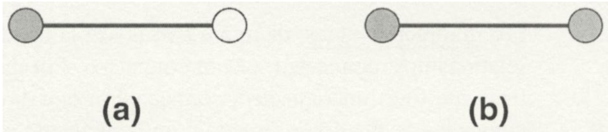

Fig. 6 Nodes with two different attribute values, represented as the *white* or *gray fill* of nodes. **a** Heterophily represents a tendency of nodes being connected to other nodes with a different attribute value. **b** Homophily represents a tendency of nodes being connected to other nodes with the same attribute value

	node with a different attribute value represented in white.
Homophily	Defined as a tendency of nodes to become connected to other nodes that are similar under a certain definition of similarity. For example, in Fig. 6b, a node with an attribute value represented in gray will have a tendency of being connected to a node with the same attribute value.
Indegree	See degree.
Isolates	Defined as nodes in a network which have no incident edges. For example, node 5 in Fig. 5a is an isolate.
Line	See edge.
Link	See edge.
Network	Defined as a set of nodes and a set of edges. In mathematics, a network is referred to as a graph, while networks often consist of social nodes and edges, and are referred to as social networks in the social sciences.
Node	Defined as an atomic discrete entity representing a network concept. A vertex (plural vertices) is a commonly used synonym to refer to a node. The term actor is sometimes used as a synonym for nodes in the social sciences.
One-mode network	See two-mode network.
Outdegree	See degree.
Path	Defined as a walk between a pair of nodes in which no nodes and edges are repeated. For example, nodes 1 and 3 in Fig. 5b are connected by the path 1-2-3.
Path length	Defined as the number of edges in a path. For example, nodes 1 and 3 in Fig. 5b are connected by the path 1-2-3, which has a path length of 2.
Power-law	Defined as a mathematical relationship between two entities where the frequency of one entity varies as a power of the second entity. More formally, the probability of a node with degree k is proportional to k^{a}. Commonly used to describe the degree distribution of networks with a scale-free structure (Barabási and Albert 1999). When a network's degree distribution follows a power-law, it implies that few nodes have a much higher degree than all other nodes in the network and most nodes have a very low degree. Nodes

with a very high degree, sometimes referred to as "hubs" in the network, significantly reduce the average shortest path length of the network.

Relationship See edge.

Shortest path See geodesic.

"Small-world" network A small-world network is defined as a network in which the average shortest path length is almost as small as that of a uniformly random network with the same number of nodes and density, whereas the clustering coefficient is much higher than in a uniformly random network (a uniformly random network is defined as a network in which each edge exists with a fixed probability *p*).

The small-world network structure as described here was first published by Watts and Strogatz (1998). This structure illustrates that relatively few edges between clusters of nodes are needed to significantly reduce the average shortest path length. It implies that resources can flow between any pairs of nodes in the network relatively efficiently, while maintaining a high degree of clustering.

Social network See network.

Strongly connected component Defined as a connected component in a directed network.

In a directed network, a connected component is always either strongly or weakly connected. For example, in Fig. 5b, node 5 is a connected component, while the set of nodes 1, 2, 3, and 4 are not because node 1 cannot be reached by a path from the other nodes.

Strong tie A number of theoretical network models used in the social sciences rely on a distinction between strong and weak ties (particularly those drawing on Granovetter 1973). The distinctions between the two, however, are rarely formally defined. In general, strong ties are used to describe frequently activated relationships (such as family/kin ties) whereas weak ties are used to describe infrequently accessed connections (acquaintances). Strong ties tend to be among actors with similar sets of overlapping relationships whereas weak ties more often connect sets of actors who would otherwise be unconnected. In weighted networks, thresholds on the distribution of weights across a network as a whole are often used to define strong *vs.* weak ties though there are no consistent rules used for this distinction.

Structural equivalence Defined as two nodes are structurally equivalent if they have identical edges to and from all other nodes in the network (see Lorrain and White 1971).

Structural equivalence is used to identify nodes which have the same position in a network. It can be used to inform blockmodeling. In the social sciences, the structural similarities

	identified through structural equivalence are used to study social positions and social roles.
Tie	See edge.
Transitivity	See clustering coefficient.
Two-mode network	Defined as a network in which two sets of nodes are defined as modes. In a two-mode network, nodes of one mode can only be connected to nodes of another node. Two-mode networks are sometimes referred to as bipartite networks. The definition of modes depends on the research context. In the social sciences, two-mode networks are often used as a representation of affiliation networks, where one mode represents individuals and the other mode represents institutions or other concepts these individuals are affiliated with (given the definition of affiliation within the research context). For example, individuals may be affiliated to political parties, or be members on different boards of directors. The most common example of the use of two-mode networks in archaeology is to represent sites as one mode and the artifact types found on sites as a second mode. Two-mode networks can be transformed into two different one-mode networks by focusing on either one of the two modes. In a one-mode network, only the nodes of one of the two modes is included, and pairs of nodes are connected by an edge if both have a connection to at least one node of the other mode in the two-mode network. For example, the two-mode network in Fig. 7a (where two different modes are represented as nodes with a different color) can be transformed into a one-mode network of only gray nodes (Fig. 7b) or a one-mode network of only white nodes (Fig. 7c).
Undirected edge	Defined as an unordered pair of nodes, which is often graphically represented as a line drawn between the pair of nodes. An undirected edge is symmetric. Typically just called an edge. For example, all edges in Fig. 5a are undirected edges.

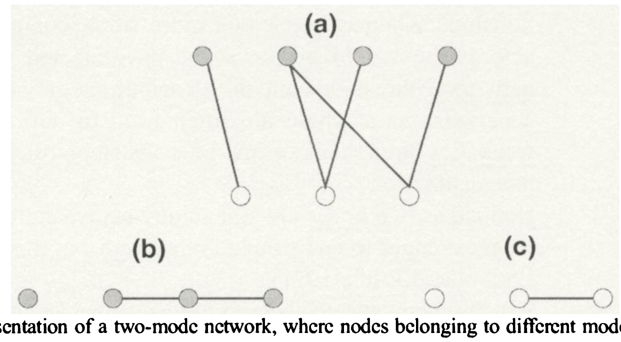

Fig. 7 **a** Representation of a two-mode network, where nodes belonging to different modes are represented with a *white* or *gray* fill. **b** One-mode representation of the gray mode in the two-mode network of **a**. **c** one-mode representation of the white mode in the two-mode network of **a**

Undirected network	A set of nodes and a set of undirected edges. An undirected network is symmetric. For example, the network in Fig. 5a is an undirected network.
Unweighted edge	Defined as an edge which is not weighted. Typically just called an edge. See also weighted edge.
Unweighted network	Defined as a set of nodes and a set of unweighted edges.
Valued network	See weighted network.
Vertex	See node.
Walk	A walk between a pair of nodes is defined as any sequence of nodes connected through edges which has that pair of nodes as endpoints. In contrast to a path, nodes and edges can be repeated in a walk. For example, in Fig. 5b, a walk between nodes 2 and 3 could be 2-3-4-2-3.
Weakly connected component	Defined as a connected component in a directed network where the directionality of edges is ignored. In a directed network, a connected component is always either strongly or weakly connected. For example, in Fig. 5b, there are two weakly connected components: node 5 and nodes 1, 2, 3, and 4.
Weak tie	See strong tie.
Weighted edge	Defined as an edge with a value associated to it. These values are often real numbers but they can also be any concept connecting the end nodes of the edge. The definition of an edge weight depends on the research context. Weights could be represented as an attribute of an edge. Thresholding can be applied to select a subset of edges with a given edge weight.
Weighted network	Defined as a set of nodes and a set of weighted edges.

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