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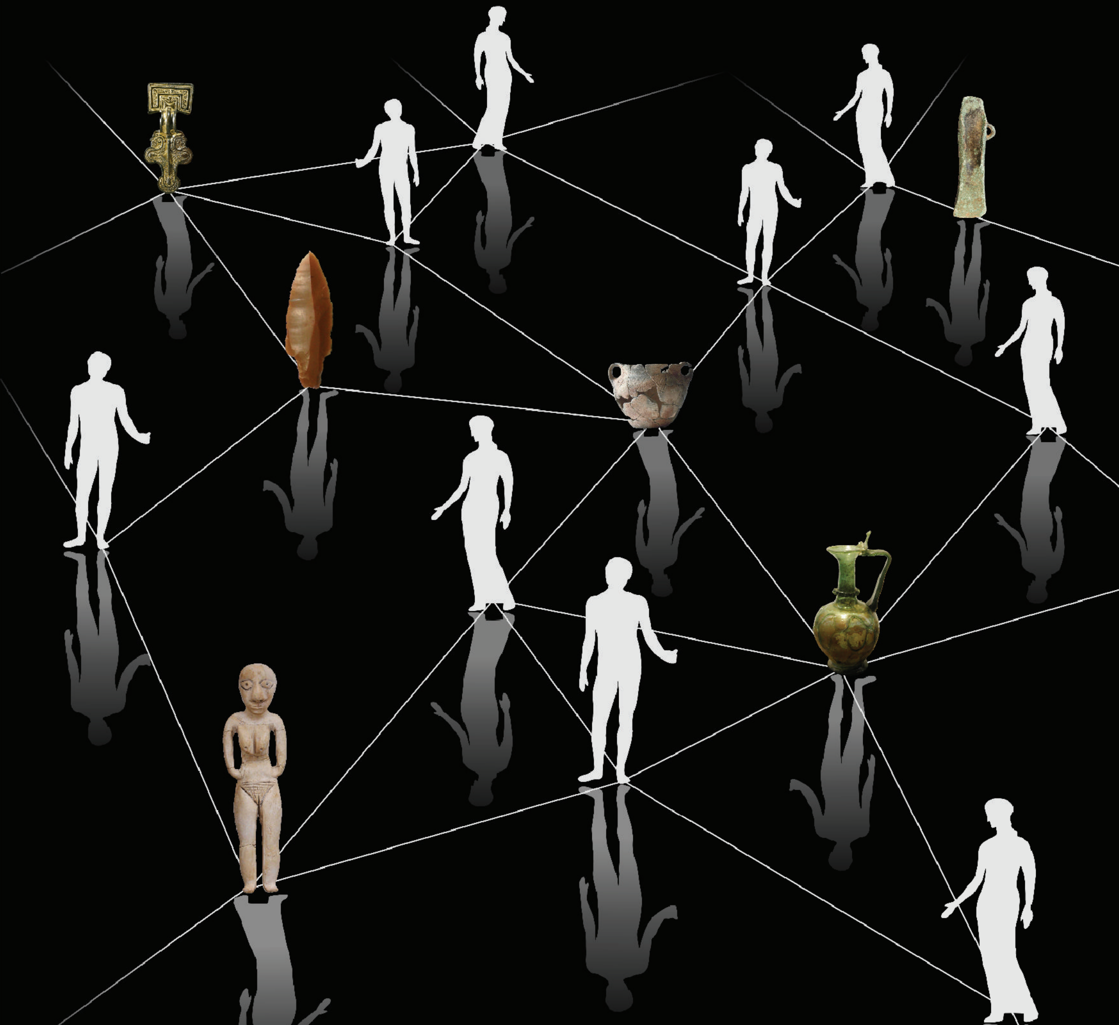

Social Network Perspectives in Archaeology

Edited by Sarah Evans and Kathrin Felder

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Volume 29.1 **Social Network Perspectives in Archaeology**

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The roots and shoots of archaeological network analysis: A citation analysis and review of the archaeological use of formal network methods

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Introduction

During the 2013 meeting of the Society for American Archaeologists the following slogan was confidently displayed throughout a symposium on network analysis: "Networks are awesome!"[1] Although this may be true, such a bold statement requires some qualification. A network analysis discussion forum at that same meeting revealed that there are very clear limits to the usefulness of archaeological network analysis[2]. Indeed, a number of archaeologists have recently surfaced a range of issues archaeological network analysts are struggling with (*e.g.*

[1] 'The Connected Past: Critical and Innovative Approaches to Networks in Archaeology'. Symposium held at SAA 2013 (3–7 April 2013, Honolulu), chaired by Tom Brughmans and Barbara Mills (and discussant Ian Hodder) (The Connected Past 2013).

[2] 'Re-connecting the Past: The Future of Social Network Analysis in Archaeology'. Forum held at SAA 2013 (3–7 April 2013, Honolulu), moderated by Angus Mol.

Isaksen 2013; Knappett 2011, 2013a). These issues in part result from the way archaeologists have adopted formal network methods. Two research traditions have been most influential to archaeological network analysts: social network analysis (SNA) and complex network studies in physics. In a recent review article (Brughmans 2013a) I argued that two critical challenges will need to be addressed in future archaeological network analysis. Firstly, a general unawareness of the historicity and diversity of formal network methods, both within and outside the archaeological discipline, or of suitable archaeological applications of known models and techniques, has resulted in a very limited methodological scope. Secondly, the adoption or development of network methods has very rarely been driven by specific archaeological research questions and is dominated by a few popular models and techniques, which has, in some archaeological cases, resulted in a routinized explanatory process (Brughmans 2013a: 654).

This paper aims to review how archaeologists are confronting these challenges. How influential were different network analysis research traditions to archaeologists? Has the methodological scope of archaeological network analysts widened in recent years? Do archaeologists have valuable and unique contributions to make to network science? Such a review demands an evaluation of the multi-disciplinary roots of archaeological network analysis, as well as of the innovative approaches championed in recent archaeological publications. Following a discussion of the particular challenges archaeologists are facing, I will trace how archaeologists have adopted formal network methods from other research traditions through a multi-disciplinary citation network analysis, and explore how these methods were adapted into innovative and critically applied archaeological approaches. It is hoped that such a multi-disciplinary review will help identify the benefits and limits of a diverse but fundamentally archaeological use of formal network techniques.

Since this article deals with formal network methods it is appropriate to provide a formal definition of what is meant by the term *network*. In this article I consider a network to be a set of nodes and the ties connected to these nodes. Ties can either have a direction or they can be undirected, which I will refer to as arcs and edges respectively. Further information on the nodes, arcs and edges is formalized as variables (Hanneman and Riddle 2005; Wasserman and Faust 1994). When placed into any archaeological research context this definition is not trivial, and a range of questions and problems instantly arise. What does the network mean? Is it derived from archaeological data? Does it change through time? Does it represent a past network and can we represent this network completely? What categorization is used to define nodes? Using the above as a definition of any real-world network would clearly be simplifying a complex reality, but it has proven to be immensely useful as a formal concept when applied critically. Some of the issues involved in doing so will be introduced below, although methods which do not conform to this definition will not be addressed in this article, to ensure the article remains focused.

The challenges

An in-depth discussion of the issues surrounding the archaeological use of formal network methods is outside the scope of the current article. It suffices to mention briefly the most frequently stated problems, those that led me to formulate the two challenges mentioned in the introduction above. Many of these issues can be usefully grouped into four broad categories: method, data, space and process.

Method

Like any other formal techniques in the archaeologist's toolbox (*e.g.* GIS, radiocarbon dating, statistics), formal network techniques are methodological tools that work according to a set of known rules (the algorithms underlying them). These allow the analyst to answer certain questions (the network-structural results of the algorithms), and have clear limitations (what the algorithms are not designed to answer). This means that their formal use is fundamentally limited by what they are designed to do, and that they can only be critically applied in an archaeological context when serving this particular purpose. In most cases, however, these formal network results are not the aim of one's research; archaeologists do not use network methods just because they can. Instead one thinks through a networks perspective about the past interactions and systems one is actually interested in. This reveals an epistemological issue that all archaeological tools struggle with: there is a danger that formal networks are equated with the past networks we are trying to understand (Isaksen 2013; Knox *et al.* 2006; Riles 2001). In other cases, however, formal analysis is avoided altogether and concepts adopted from formal network methods are used to describe hypothetical past structures or processes (*e.g.* Malkin 2011). Although this sort of network thinking can lead to innovative hypotheses, it is not formal network analysis (see reviews of Malkin [2011] by Ruffini [2012] and Brughmans [2013b]). However, such concepts adopted from formal network methods often have a very specific meaning to network analysts and are associated with data requirements in order to express them. Most crucially, when the concepts one uses to explain a hypothesis cannot be demonstrated through data (not even hypothetically through simulation), there is a real danger that these concepts become devalued since they are not more probable than any other hypotheses. Moreover, the interpretation of past social systems runs the risk of becoming mechanized when researchers adopt the typical interpretation of network concepts from the SNA or physics literature without validating their use with archaeological data or without modifying their interpretation to a particular archaeological research context. This criticism is addressed at the adoption of formal network concepts only. It should be clear that other theoretical concepts could well use a similar vocabulary whilst not sharing the same purpose or data requirements, in which case I would argue to refrain from using the same word to refer to different concepts or explicitly address the difference between these concepts in order to avoid confusion.

Although it is easy to claim that the rules underlying formal network techniques are known, it is less straightforward to assume that the traditional education of archaeologists allows them to decipher these algorithms. Archaeologists are not always sufficiently equipped to critique the mathematical underpinnings of network techniques, let alone to develop novel techniques tailor-made to address an archaeological question. For many archaeologists this means a real barrier or at least a very steep learning curve. Sadly, it also does not suffice to focus one's efforts on the most common techniques or on learning graph theory. Like GIS, network analysis is not a single homogeneous method; it incorporates every formal technique that visualizes or analyzes the interactions between nodes (either hypothetical or observed), and it is only the particular nature of the network as a data type that holds these techniques together (Brandes *et al.* 2013). For this purpose it draws on graph theory, statistical and probability theory and algebraic models, as well as agent-based modelling and GIS.

A thorough understanding of the technical underpinnings of particular network techniques is not an option; it is a prerequisite for a critical interpretation of the results. A good example of this is network visualization. Many archaeologists consider the visualization of networks as graphs a useful exploratory technique to understand the nature of their data, in particular when combined with geographical visualizations (*e.g.* Golitko *et al.* 2012). However, there are many different graph layout algorithms, and all of them are designed for a particular purpose: to communicate a certain structural feature most efficiently (Conway 2012; Freeman 2005). These days, user-friendly network analysis software is freely available and most of it includes a limited set of layouts, often not offering the option of modifying the impact of variables in the layout algorithms. Not understanding the underlying 'graph drawing aesthetics' or limiting one's exploration to a single layout will result in routinized interpretations focusing on a limited set of the network's structural features.

Archaeologists who consider the application of network methods to achieve their research aims must be able to identify and evaluate such issues. Multi-disciplinary engagement or even collaboration significantly aids this evaluation process.

Data

Network analysis is by no means a method devoid of any theoretical considerations. Most interestingly, theoretical critiques are often triggered by issues concerning the role of archaeological data. This is usually a result of the material nature of archaeological data serving as proxy evidence for past human behaviour, which poses a number of challenges.

Firstly, imposing categories and sometimes hierarchical relationships on data is a prerequisite for any network analysis. This results in the assumption that categories can actually be defined with any certainty (Butts 2009), and from the need to establish data categories ahead of the analysis, rather than letting them emerge from the analysis (Isaksen 2013). Indeed, the definition of nodes, ties and the network as a whole can be considered the most crucial phase of any archaeological network analysis. However straightforward such definitions seem, doing so in a critical manner is not as easy as it sounds. For example, we could choose to follow a formal ceramic typology where each node represents a distinct type. When doing so we have to acknowledge that such typologies are modern constructs and that alternative categorizations can easily be developed. This in turn raises the issue that the network we analyze is not necessarily identical to the past networks we are trying to understand. For example, although in some cases it can be proven that particular ceramic types were used for particular purposes and in certain contexts, their meaning can nevertheless change through time, requiring a modification of our categorization (van Oyen *in press*).

Secondly, unlike network analysts in many other disciplines, archaeologists work with primary data sources of a material nature. Social network analysts often only consider inter-personal interactions, whilst archaeological network analysts are forced to consider *object-person* and *object-object* interactions. A range of interactionist theoretical perspectives exist to confront materiality, and archaeological network analysts are faced with finding a workable framework that combines both network theories and methods (Knappett 2011).

In summary, the decisions archaeological network analysts make when defining nodes and edges, when selecting or modifying analytical techniques and when interpreting the outcomes, are fundamentally influenced by their theoretical preconceptions. There is not a single right way to incorporate and interpret archaeological data in network approaches.

Space

The definition of nodes is not only dependent on data type categorization but also necessarily reflects the research questions being asked, revealing an issue of spatial scales. Do the past processes we are interested in concern interactions between regions, sites or individuals? How will this be represented in node, tie and network definitions? The ability of network approaches to work on multiple scales is often mentioned as one of the advantages of using formal network methods (Knappett 2011). In practice, however, archaeological network analysts have traditionally focused on inter-regional or macro-scales of analysis. Knappett (2011) argues that it is on the macro-scale that network analysis comes into its own and a recently published edited volume reveals this regional emphasis (Knappett 2013b). This insistence to work on large scales becomes quite unique in light of social network analysts' traditional focus on individual social entities in interaction. SNA provides a multitude of good examples of how network methods could be usefully applied on a micro- or local scale of analysis (*e.g.* ego-networks, see below). However, the nature of archaeological data, which rarely allows for individuals and their interactions to be identified with any certainty, should not be considered the only reason for this focus on the macro-scale. Arguably, networks lend themselves very well to exploring inter-regional interaction, and archaeologists have always had a particular interest in the movements and flows of people, resources and information across large areas. Moreover, many of the early applications of network methods in archaeology, which in some cases might have served as an example to more recent applications, concerned inter-regional interaction (*e.g.* Terrell 1976). One should acknowledge the importance of exploring how local actions give rise to larger-scale patterns if we are to benefit from the multi-scalar advantage of formal network methods (Knappett 2011).

It is not surprising that many archaeological network analysts are interested in exploring the dynamics between relational and geographical space (*e.g.* Bevan and Wilson 2013; Knappett *et al.* 2008; Menze and Ur 2012; Wernke 2012), given the importance of spatial factors in understanding archaeological data and archaeologists' traditional interest in geographical methods (*e.g.* Hodder and Orton 1976). Despite early work by archaeologists on geographical networks (for an overview see Chapter 2 in Knappett 2011), geographical space has been almost completely ignored by sociologists and physicists, resulting in a very limited geographical network analysis toolset for archaeologists to draw from (although see a recent special issue of the journal *Social Networks* [issue 34(1), 2012] and the review work by Barthélemy [2011], as well as techniques used in Space Syntax [Hillier and Hanson 1984]).

Process

Many archaeological network studies treat networks as static snapshots. This is, at least in part, a result of the nature of archaeological data and our inability to observe past processes directly. Graph visualizations and many network analysis techniques further enforce this idea of a static network by exploring structural features of particular networks in isolation. However, the past systems we study were dynamic phenomena and the network approach used to understand these phenomena should reflect their changeable nature. In fact, one could argue that no network is truly static since our assumptions underlying the creation of ties imply flows of resources, which are dynamic processes taking place in a changing network.

Archaeological data often does not have the chronological accuracy to reconstruct an exact sequence of events: which ties and nodes appeared and disappeared in what order? A number of network modelling approaches exist that can help one deal with this issue, including agent-based modelling (*e.g.* Graham 2006), algebraic modelling (*e.g.* Menze and Ur 2012) and statistical modelling (*e.g.* Brughmans *et al.* under review; Lusher *et al.* 2013). Underlying all of these modelling approaches are clearly formulated assumptions of what a relationship means and what types of flows it allows for. They therefore require one to explicitly acknowledge the dynamic nature of past processes and the dynamic assumptions underlying the definition of ties.

But which model is best? Many models, representing different hypothetical processes, can be created that could all give rise to the same observed network. Since archaeologists cannot directly observe past processes, and given that our data are incomplete and are merely indirect proxies, how then can we ever claim that one model is more probable than any other? The problem of equifinality (the idea that multiple processes can have the same end result) is equally critical for network analysis as for any other technique in the archaeologist's toolbox. There are a few ways in which formal network methods can help us address this issue. Firstly, archaeological data (however flawed) used in statistical models can help us to identify very general processes that are more probable than others. Secondly, these models can help us to formally express otherwise ill-defined hypotheses and evaluate their likeliness given certain archaeological assumptions. Thirdly, they might not be able to prove certain processes, but models can definitely be used to negatively test or falsify certain hypotheses, or at least identify which processes are less likely than others (given our current knowledge). In this way, such models serve as experimental laboratories (Premo 2006). One has to acknowledge, however, that some past processes are unknowable given our current techniques and datasets. All archaeological approaches suffer from this disadvantage and network analysis is no exception.

Tracing methodological influence through citations

The emphasis on regional-scale studies, the material nature of our data and our focus on geographical structure and processes might give the impression that archaeological network analysis is principally different from network studies in other disciplines. However, some of the issues mentioned above, such as archaeologists' mainly considering static networks and their selection of a limited set of network techniques, clearly emerged through the adoption of network techniques from other disciplines. In fact, I will argue here that many of the above challenges are in no way unique to archaeology, and that other disciplines might offer us ways of dealing with them. A multi-disciplinary review is necessary, if we want to tease out the possible influences other disciplines have made to the archaeological use of formal network methods, how developments in these disciplines can help archaeologists overcome challenges, and how archaeologists can make unique contributions to network science at large.

In the second part of this article I will explore the origins of the challenges discussed in the first part, and how archaeologists can overcome them, by presenting the results of a citation network analysis and a review of recent archaeological literature. Citation network analysis is a particularly useful approach to explore the larger general trends in academic influence and might also make us aware of bodies of literature that have so far remained untouched by archaeologists. A literature review on the other hand allows a more detailed and qualitative look at particular cases of the adoption and adaptation of methods and their motivations. In the next section I will explore the multi-disciplinary influence on the adoption of network methods through these two approaches. A more elaborate and technical discussion of the citation network analysis performed here is presented in Brughmans 2013c. In this article I focus on the key results of this citation network analysis and discuss their relevance to understanding the challenges mentioned above.

In a citation network, nodes represent publications, and a directed edge (or arc) between two nodes indicates a citation (Eom and Fortunato 2011). In this case study, a citation is taken to represent influence and relatedness of subject matter (Newman 2010: 67–70). By extracting bibliographies from a select body of literature and creating such citation networks, the 'flow of influence' in these publications can be traced. However, it should be clear that the citation networks studied here are not considered to represent the full complexity of citation practices and the flow of influence. A number of limitations of this approach should be emphasized: the positive or negative nature of a citation is not considered explicitly in the analysis; purposeful non-citation cannot be analyzed; the available citation databases are heavily biased towards international peer-reviewed journals publishing in English; and my own selection of the boundaries of the citation network considered here affects the results. For these reasons, citation network analysis is here considered but one way of exploring the formal expression of academic influence and the spread of new techniques. This is why I will focus the citation network analysis on identifying the main paths of influence, whilst a close reading of the literature is considered invaluable for evaluating how and why certain publications were influential.

Citation network analysis: Data and method

The foundations of citation network analysis were laid by Garfield *et al.* (1964). Despite its long tradition, and although citation analysis is more commonly used in the field of anthropology (*e.g.* Choi 1988; Clark and Clark 1982; Robinson and Posten 2005), its use in an archaeological context has not been thoroughly explored yet. A number of studies use simple counts of citations or other bibliometric data to track trends in the archaeological sciences and compare the impact and evolution of archaeological journals (*e.g.* Butzer 2009; Marriner 2009; Rehren *et al.* 2008; Rosenswig 2005; Sterud 1978), or to evaluate the impact of gender differentiation in archaeology (*e.g.* Beaudry and White 1994; Hutson 2002, 2006; Victor and Beaudry 1992). Since in this article I aim to explore the multi-disciplinary influences on archaeological network analysts I will discuss two different types of citation networks: (1) all archaeological network analysis publications and (2) all publications cited by archaeological network analysts and the citations between them. 69 published examples of the archaeological use of formal network techniques known to me, and published before 2013, were included in the first network (from now on referred to as the 69 egos).[3] The selection was strongly influenced by my own knowledge of the topic, a bias that will be evaluated in the analysis.

Bibliographic data for these 69 egos were extracted from Thomson Reuters Web of Knowledge (WOK).[4] For publications that were not included in WOK this information was extracted manually. In order to create the second citation network the bibliographies of the publications cited by the 69 egos were extracted from WOK when available. Table 1 reveals that less than a third of these bibliographies could be found on WOK. This is caused by the WOK journal selection criteria, the absence of books and the bias towards English language publications, which form a second bias this study suffers from. The data extraction nevertheless resulted in a combined dataset of 33,556 publications linked by 42,993 citations. It was therefore decided to analyze this dataset as several networks with varying proportions of missing data. Table 2 presents summary information on the different networks analyzed separately in this study.

	Egos	Cited by egos
Total publications	69	1859
Extracted from WOK	28	449
Extracted manually	41	0
Missing bibliographies	0	1410

Table 1. Count of egos and neighbouring publications that could be found in WOK and those whose bibliographies had to be extracted manually. The last row 'missing bibliographies' refers to the number of publications that were cited by the egos but that could not be found on WOK.

[3] The term 'ego' is commonly used to refer to individual nodes that are the focus of a study. In SNA the study of so-called 'ego-networks' refers to ego nodes, their direct connections and the relationships between them. This type of network is used when the local social context of individuals is compared (Marsden 2002). Since in this study we are interested in the direct context of archaeological network analysis studies, the term egos can be usefully adopted to refer to these studies.

[4] WOK (Web of Knowledge 2013) provides access to the most comprehensive citation databases and is the most commonly used resource for citation network analysis (Newman 2010: 68).

	Local scale	Meso scale		Global scale
	Archaeological applications	Ego-network		Combined dataset
		WOK data network	All data network	
Number of nodes	69	518	1928	33556
Number of arcs	128	1489	3987	42993
Missing bibliographies	0	0	1342	33032
Connected components	9	6	1	2
Isolated nodes	6	3	0	0
Average number of citations	3.71	5.75	4.14	2.562

Table 2. Simple network measures for all networks in the case study.

Citation among archaeological network analysts

The analysis of the 69 egos revealed that archaeological applications of formal network methods before the 1990s are rare. The last decade in particular has seen a strong increase of applications, which are rarely influenced by the older ones, and there are strong differences in citation densities between the groups of old and more recent archaeological applications. The chronological visualization of this network and the results of the input domain measure are the best examples of this (fig. 1). The input domain represents the number of all other nodes that are connected to a given node by a path (de Nooy *et al.* 2005: 193). Notably, while older publications normally receive a higher score, in the current network it is the more recent archaeological applications that receive the highest scores, in particular those in the early 2000s which pioneered the adoption of popular network models from physics. According to most of the network measures used, the higher citation density caused the recent applications to be most prominent. It is tempting to interpret this in light of the observation that many of these recent applications use a limited set of similar network techniques (in particular the popular small-world [Watts and Strogatz 1998] and scale-free [Barabási and Albert 1999] network models, developed by physicists and marking the start of an increase in the multi-disciplinary interest in networks). This methodological similarity does not explain the higher citation density, however, since popular methods were mainly adopted from a few non-archaeological publications. In fact, the high citation density was largely the result of a few recent review publications (Brughmans 2010, 2012; Knappett 2011), which were also almost exclusively responsible for the few citation links bridging the recent (early 2000s onwards) and the older applications (1970s–1990s). To explore their impact (and at least in part to evaluate the bias of my own knowledge of archaeological network analysis publications as represented by the bibliographies of Brughmans [2010 and 2012]) these publications were removed from the citation network and a co-citation network was created of the remaining publications (fig. 2).[5]

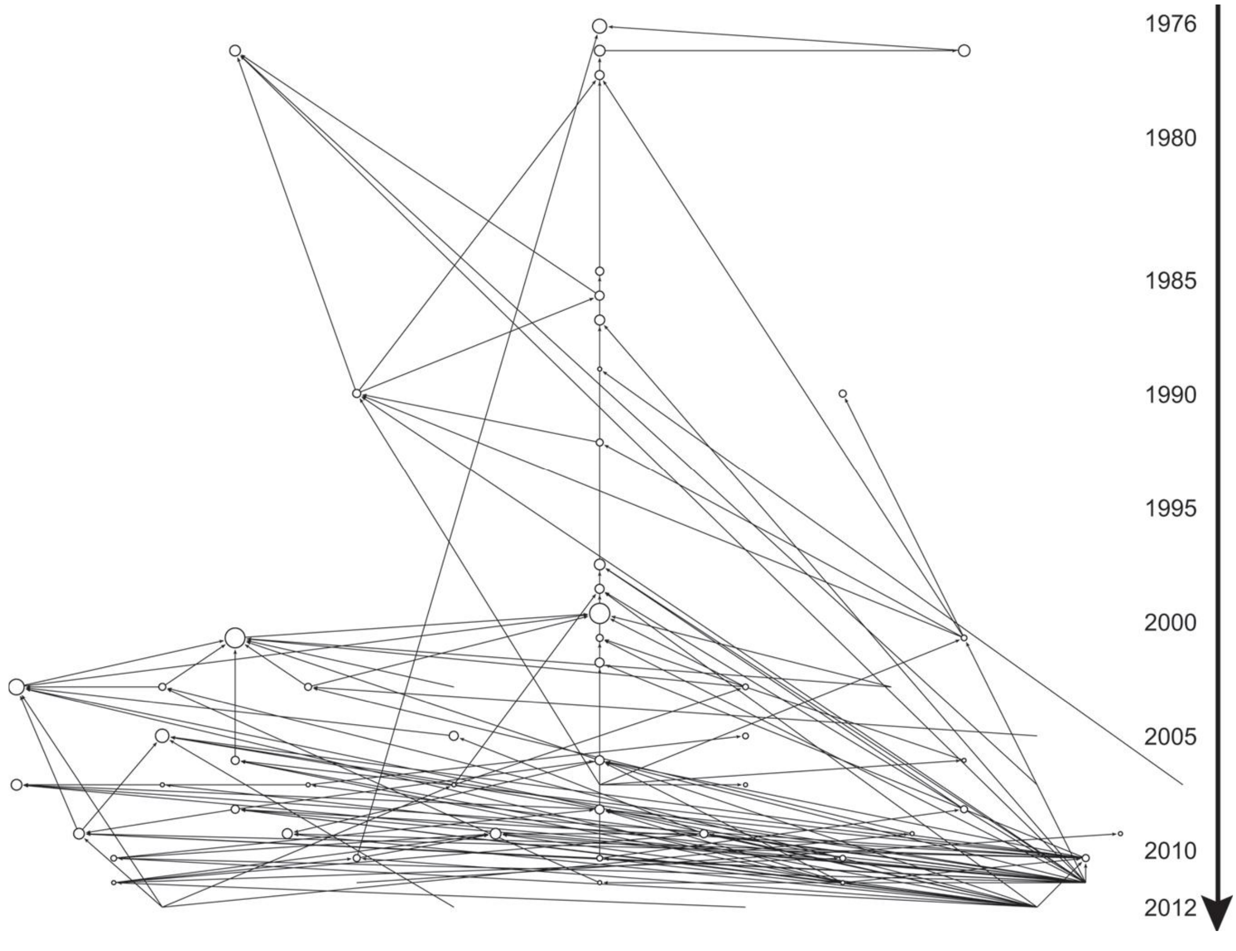


Figure 1. Chronological visualization of the local scale network of the 69 archaeological applications of network methods before 2012. Nodes represent publications and arcs represent citations. The size of nodes represents the relative input domain scores. Nodes are positioned along the Y-axis according to their date of publication. The positioning of nodes along the X-axis does not reflect any logic other than avoiding the overlap of nodes and arcs to make the patterns more visually 'readable'.

[5] In a co-citation network edges are drawn between a pair of nodes if they are both cited by the same paper(s). Co-citation networks are considered a good indicator for clusters of papers that deal with related topics (Newman 2010: 116–117).

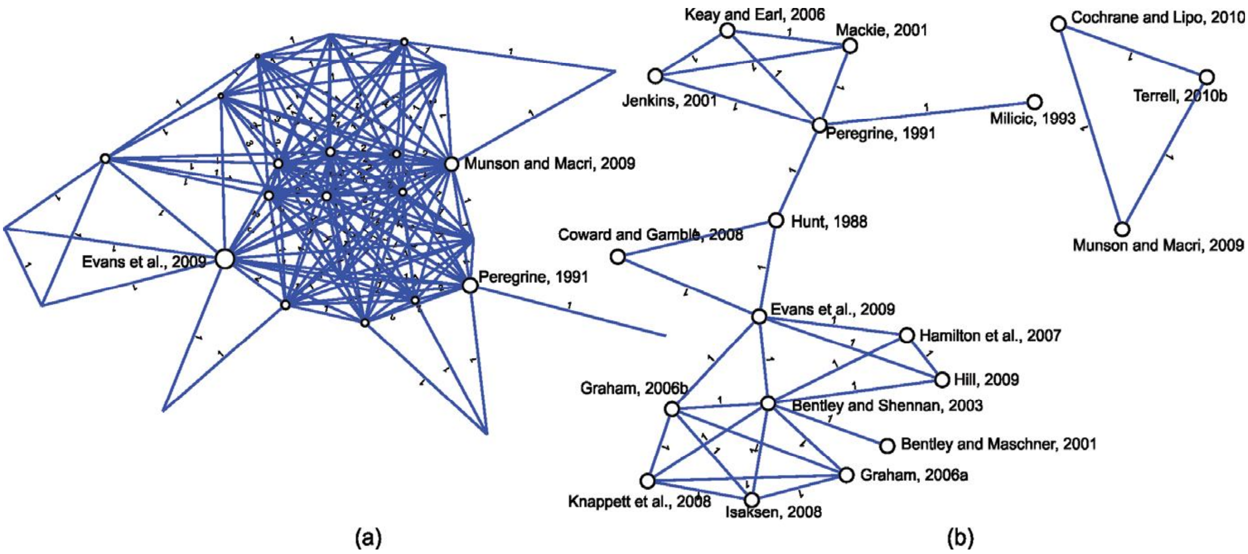


Figure 2. Co-citation network of the local scale network (a) with and (b) without three recent review publications (Brughmans 2010, 2012; Knappett 2011). Size of nodes in network (a) represent betweenness centrality: the proportion of all shortest paths between pairs of other nodes that include this node (de Nooy *et al.* 2005: 131).

This revealed that pairs of publications rarely cite the same sources, and the majority of clusters in this network can be attributed to authors citing their own previously published work, or to topical, national and institutional contacts between authors. Therefore, there seems to be limited mutual influence between recent archaeological applications of network methods (or at least the authors did not make possible influence explicit through citation).

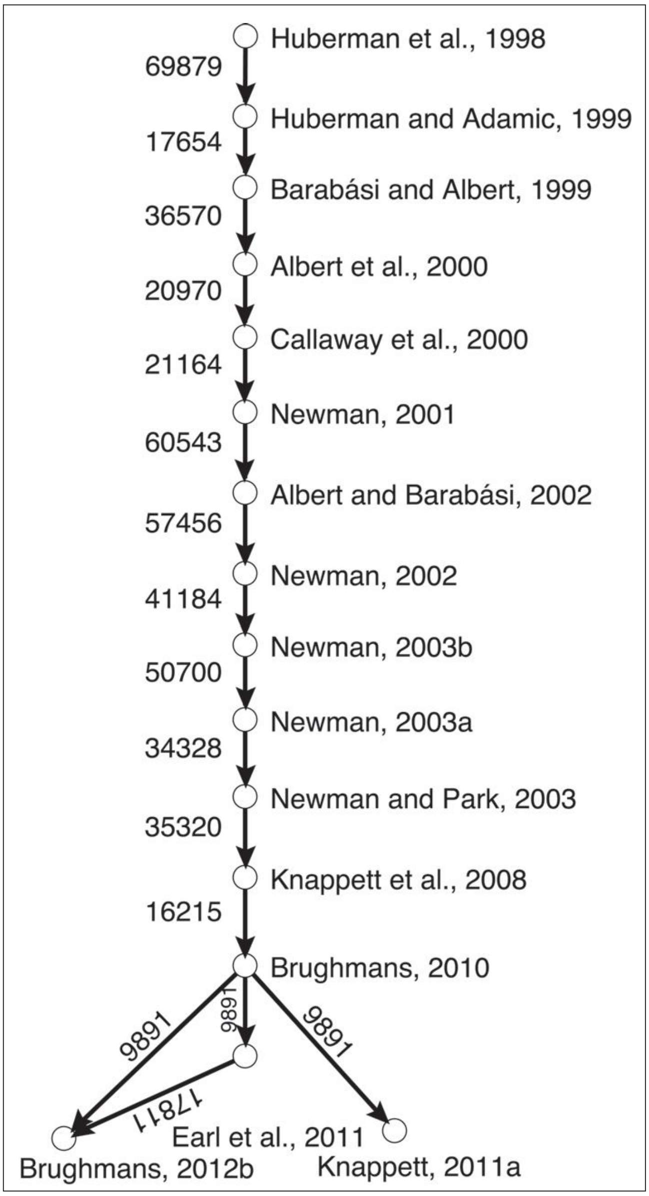
Multi-disciplinary influences

The citation patterns of the multi-disciplinary works cited by archaeologists revealed that key methodological influences came from outside the archaeological discipline. A few network models (Barabási and Albert 1999; Watts and Strogatz 1998) and methodological textbooks (Scott 1997; Wasserman and Faust 1994) by physicists and social network analysts were cited by most of the archaeological network analysts. Indeed, only in a few cases were formal network techniques adopted from publications other than these highly influential ones. The citation network analysis revealed that these publications were not only influential to archaeologists but were in fact key authorities in a wide range of disciplines. Using a measure called 'citation weights',[6] a path of the most common citations can be extracted (figs

[6] The citation weights measure identifies the path traversed by the largest number of other paths (Hummon and Doreian 1989). This path can therefore be considered the most important path of influence (as represented through citation) (Hummon *et al.* 1990: 464).

3–5). These paths again emphasize the few popular publications mentioned above. Indeed, they reveal the 'main paths of influence', as understood by this measure, as the connecting citations that are most frequent within this network only. However, they also reveal a number of other publications, influential among non-archaeologists, that elaborated on these authorities but that have been largely ignored by archaeologists. The vast majority of these publications were written by physicists, which in part reflects the WOK dataset used (being more representative of the physical sciences than of the social sciences). However, it also reflects the increased interest in network science among physicists in the last decade after the publication of Watts and Strogatz (1998) and Barabasi and Albert (1999). These two publications have been very influential to archaeological network analysts, at least in part because of their popularity in other disciplines, whilst the other physics publications identified by the citation paths have been rather neglected by archaeologists. As far as SNA is concerned, the citation networks seem to indicate that SNA publications only influenced archaeologists after the emergence of these two popular physics papers, even though the SNA literature has been around for much longer. Archaeologists mainly drew on technical SNA textbooks (*e.g.* Wasserman and Faust 1994) and a few popular theories (*e.g.* Granovetter 1973), but until recently (as argued below) did not venture much further into the very diverse range of SNA techniques.

The citation networks revealed disciplinary and topical clusters of publications that include research areas tangential to the egos that might well have innovative and useful archaeological applications. In short, this large citation network re-contextualizes the archaeological use of formal network methods within wider research communities and holds the potential to guide future discovery and adoption of published formal methods that have proven useful in different fields of research. Further detailed exploration of the citation network is necessary since the results presented here clearly over-emphasize the most often cited publications. One interesting small-scale pattern, for example, is that older archaeological applications from the 1970s and 1980s were mainly influenced by geographers (*e.g.* Haggett and Chorley 1969), even though SNA was already well-established at that time.



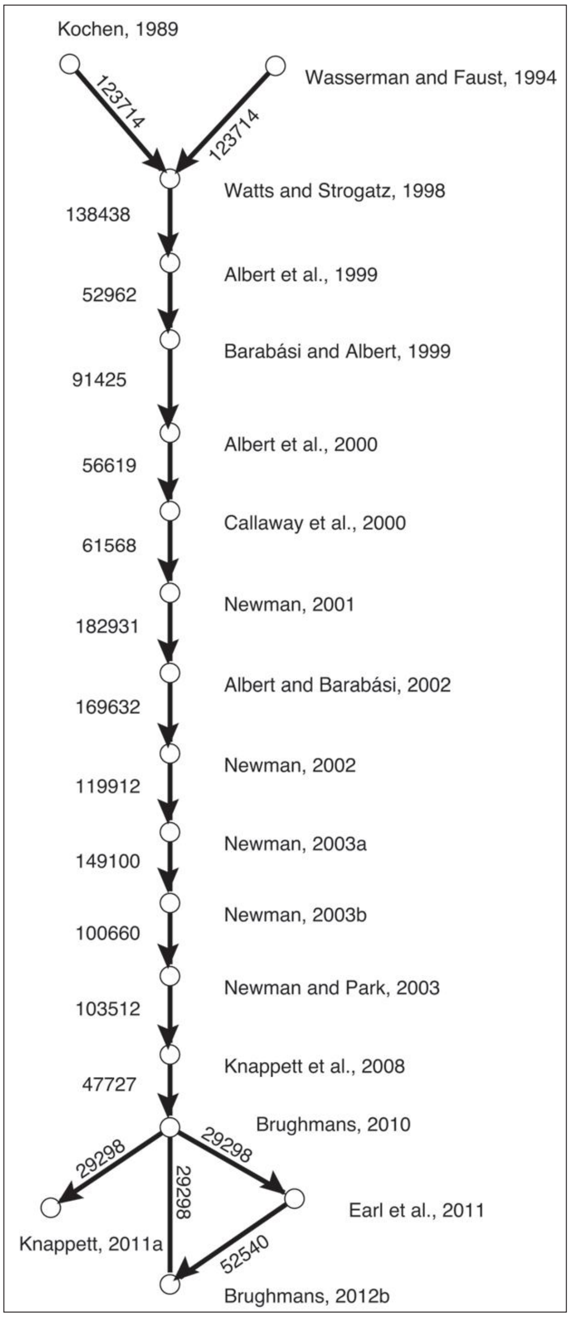


Figure 3. (left). Citation weight path of the meso-scale WOK data network. This network includes all egos and only the publications they cite that could be found on WOK so that it is completely representative of all citations between them. Nodes represent publications, arcs represent an inversed citation (*i.e.* 'X is cited by Y') and arc weights represent the number of paths passing through it.

Figure 4. (right). Citation weight path of the meso-scale all-data network. This network includes all egos and all the publications they cite. Because the bibliographies of the vast majority of these could not be found on WOK this network misses many citations. Nodes represent publications, arcs represent an inversed citation (*i.e.* 'X is cited by Y') and arc weights represent the number of paths passing through it.

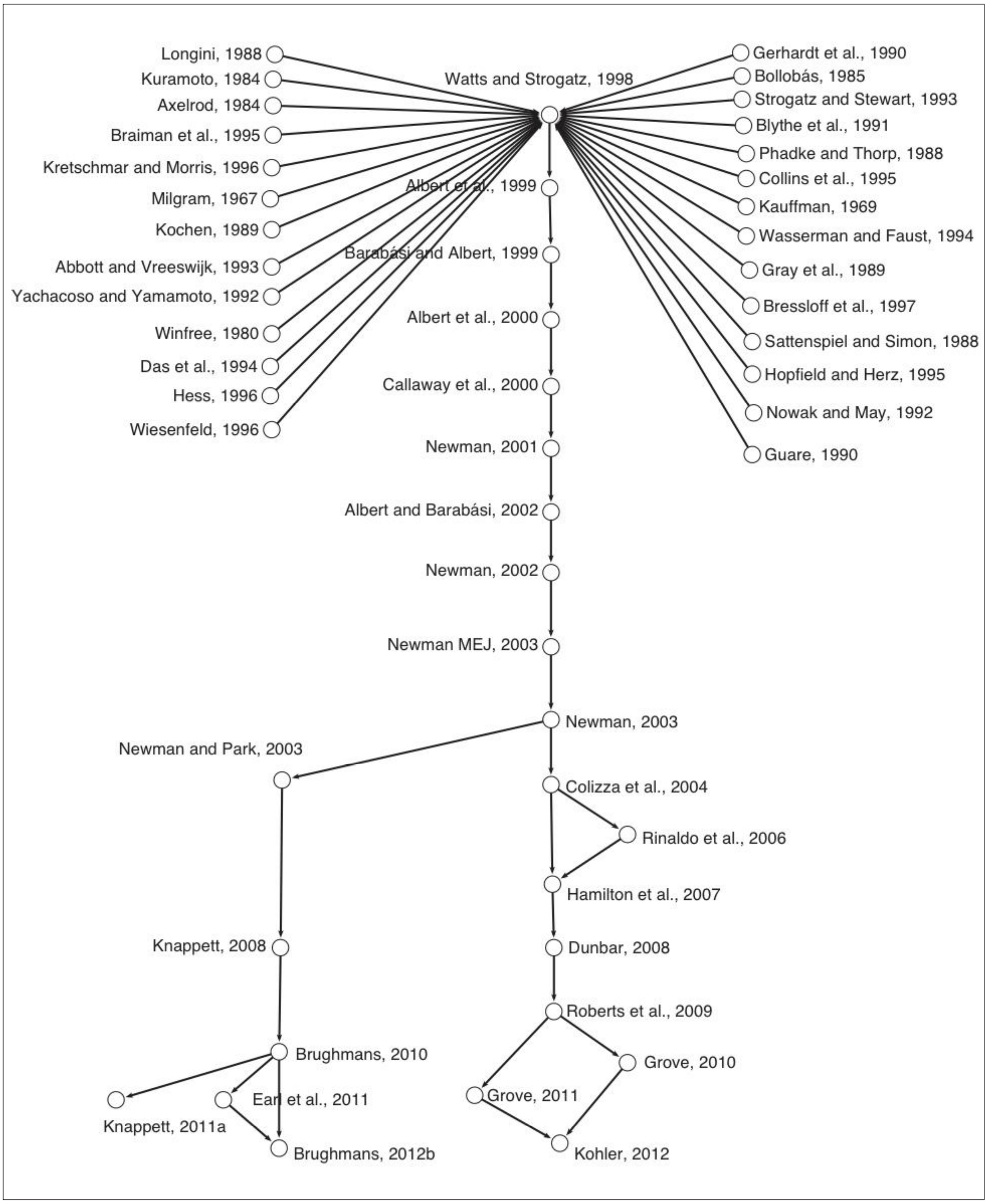


Figure 5. Citation weight path of the global scale network (including all egos, all publications they cite, and all publications cited by the latter that could be found on WOK). Nodes represent publications, arcs represent an inversed citation (*i.e.* 'X is cited by Y') and arc weights represent the number of paths passing through it.

Discussion and conclusions: Confronting the challenges ahead

The citation network reveals a rather fragmented picture of archaeological network analysts seemingly working in isolation in their respective sub-disciplines (as far as the archaeological use of their network methods is concerned), despite clear methodological similarities, whilst frequently engaging with developments in other disciplines. This idea of isolation sheds light on the processes of adoption and (published) uses of formal network methods by archaeologists. The early adopters knew of each other's network-related work but their methodology was peripheral to the key topics being discussed in their sub-disciplines (Irwin, *pers. comm*; Terrell, *pers. comm.*). Therefore, in addition to an obvious technological barrier, this sub-disciplinary isolation and, in some cases, intentional non-citation might have led to a limited exposure of network-related work (Cochrane, *pers. comm.;* Irwin, *pers. comm*; Terrell, *pers. comm.*). On the other hand, the newer generation of archaeological network analysts that emerged in the last decade managed to achieve a wider exposure, at least in part because now the technologies (software, the internet, big data, hardware) were readily available. The impact of the World Wide Web and social media on influencing the renewed uptake of formal network methods cannot be overstated; they serve as examples to researchers of how networks in the present affect our actions on a daily basis. These technological changes affected researchers in all disciplines and I believe a growing academic influence should also be considered an important factor (*e.g.* through the popularity of certain network models, or popular-science publications by Watts [2003] and Barabási [2002]). Indeed, the more recent applications often use techniques published by physicists, and the adoption of new techniques follows the trends in physics (but also SNA) with a short delay (Brughmans 2013a, 2013c).

The results of the citation network analysis are also directly relevant to explaining some of the challenges formulated above. This study confirms that two research traditions have been most influential to archaeological network analysts: social network analysis (SNA) and complex network studies in physics. Although SNA is the older of the two research traditions, archaeologists have only started adopting formal network methods more frequently after the emergence of a few popular complex network models in physics. SNA, with its long history in the social and behavioural sciences and its focus on the analysis of social phenomena, has a formalized set of the most commonly applied network techniques that comes with its own vocabulary and jargon developed to address social networks. Many archaeological network analysts have adopted this vocabulary along with the techniques, but the challenges mentioned above reveal that its meaning requires further discussion when used in the context of archaeological networks. The popular models adopted from physicists, on the other hand, introduced the issue of equifinality and the need to consider processes of interaction rather than seemingly static observations. The citation networks clearly showed that some methods and models in both SNA and physics are significantly more often applied (or at least cited) than others, and archaeologists have initially focused on these few popular approaches that have proven their worth in other disciplines (*e.g.* small-worlds, centrality measures). The citation analysis also revealed a number of other publications along the 'main paths of influence' that have received less attention by archaeologists but have received a very high number of citations from other disciplines. Indeed, the citation networks proved revealing as an exploratory tool to investigate the overlap in citation practices by archaeologists and researchers from other disciplines, and in particular to identify and explore groups of publications that have so far been largely ignored by archaeologists.

This fragmentary picture and over-emphasis on popular techniques is changing rapidly, however. It must be said that the citation network only reveals the situation up to 2011 (with only two publications from 2012). Since then a good number of innovative and critical archaeological network studies have been published which might considerably shake up citation patterns. Indeed, these most recent publications (mentioned below) express a critical awareness of some of the challenges discussed at the beginning of this article and suggest new ways of addressing them. Many of these publications combine network techniques with other tools in the archaeologist's toolbox to develop a methodological framework tailor-made to address their archaeological questions. In most of these cases new research questions can be asked thanks to the network perspective, and sometimes the network approach and results themselves give rise to new questions that were not considered before.

The need to clearly reflect on the meaning of relationships, the definition of nodes and the implications of these decisions has now become common practice among archaeological network analysts (*e.g.* Golitko *et al.* 2012). In some cases, the issue of categorization is addressed explicitly by exploring networks of different typologies (Peeples 2011), using different similarity indices (Cochrane and Lipo 2010), and by exploring the effects of our methodological decisions through a sensitivity analysis (Peeples and Roberts 2013). Archaeologists have also traditionally been interested in spatial analysis, significantly more so than social network analysts. A number of recent publications explore the interface between spatial and topological network approaches even further (*e.g.* Bevan and Wilson 2013; Menze and Ur 2012; Mills *et al.* 2013; Wernke 2012). These geographical approaches, as well as studies incorporating materiality (*e.g.* Knappett 2011) and those taking a long-term perspective (*e.g.* Mills *et al.* 2013), promise to make valuable archaeological contributions to network science in general. In addition to drawing on established archaeological approaches, however, archaeologists are increasingly exploring new network techniques developed in different disciplines. A good example of this is the use of structural equivalence or blockmodelling techniques by Scholnick and colleagues (2013), allowing them to identify groups of nodes that occupy a structurally similar position in the network.

Although many challenges remain unsolved, recent archaeological work nevertheless shows much more diversity in the application of formal network methods. This wider methodological scope is not only desirable, it is necessary. In the editorial of the first issue of the new journal *Network Science*, Ulrik Brandes and colleagues (2013) argue that network data is fundamentally different from tabular or dyadic data since it concerns dependencies among network variables (variables describing ties between a pair of nodes, where the presence of one tie may influence the presence of another). They argue that because of this a distinct corpus of quantitative techniques is needed to analyze this relational data type. Archaeological network analysts have illustrated that in archaeology we are also confronted with this network data type, and that techniques developed by network scientists are a necessity to help archaeologists tackle this data. Given all this, one can now consider networks to be indeed awesome! By recognizing the particular nature of network data, by maintaining a multi-disciplinary perspective and by confronting the challenges ahead, I believe archaeologists are well on their way to harnessing the full potential network science has to offer to our discipline. Moreover, archaeologists' focus on the relationships between material culture and people, their ability to explore cultural change over the long-term, and their challenge of dealing with very different material data types might hold the promise of valuable and unique contributions from archaeology to network science in general.

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References

Barabási, A.-L. 2002. *Linked: The New Science of Networks.* Cambridge: Perseus.

Barabási, A.-L. and Albert, R. 1999. Emergence of scaling in random networks. *Science* 286: 509–512.

Barthélemy, M. 2011. Spatial networks. *Physics Reports* 499(1–3): 1–101.

Beaudry, M. and White, J. 1994. Cowgirls with the blues? A study of women's publication and the citation of women's work in Historical Archaeology. In Claassen, C. (ed.), *Women in Archaeology*. Philadelphia: University of Pennsylvania Press, 138–158.

Bevan, A. and Wilson, A. 2013. Models of settlement hierarchy based on partial evidence. *Journal of Archaeological Science* 40(5): 2415–2427.

Brandes, U., Robins, G., McCranie, A. and Wasserman, S. 2013. What is network science? *Network Science* 1(01): 1–15.

Brughmans, T. 2010. Connecting the dots: Towards archaeological network analysis. *Oxford Journal of Archaeology* 29(3): 277–303.

Brughmans, T. 2012. Facebooking the past: A critical social network analysis approach for archaeology. In Chrysanthi, A., Flores, M.P. and Papadopoulos, C. (eds), *Thinking Beyond the Tool: Archaeological Computing and the Interpretative Process.* (British Archaeological Reports International Series S2344). Oxford: Archaeopress, 191–203.

Brughmans, T. 2013a. Thinking through networks: A review of formal network methods in Archaeology. *Journal of Archaeological Method and Theory* 20: 623–662.

Brughmans, T. 2013b. Review of Malkin, I. 2011. A small Greek world: Networks in the Ancient Mediterranean. *The Classical Review* 63(01): 146–148.

Brughmans, T. 2013c. 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., Keay, S. and Earl, G.P. Under review. Exponential random graph models for archaeology, a case study on visibility networks in Iron Age and Roman southern Spain.

Butts, C.T. 2009. Revisiting the foundations of network analysis. *Science* 325(5939): 414–416.

Butzer, K.W. 2009. Evolution of an interdisciplinary enterprise: The Journal of Archaeological Science at 35 years. *Journal of Archaeological Science* 36(9): 1842–1846.

Choi, J.M. 1988. Citation analysis of intra- and interdisciplinary communication patterns of anthropology in the U.S.A. *Behavioral & Social Sciences Librarian* 6(3–4): 65–84.

Clark, B.M. and Clark, S.E. 1982. Core journals in anthropology. *Behavioral & Social Sciences Librarian* 2(2–3): 95–110.

Cochrane, E.E. and 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.

Conway, S. 2012. A cautionary note on data inputs and visual outputs in social network analysis. *British Journal of Management* 25(1): 102–117.

Eom, Y.-H. and Fortunato, S. 2011. Characterizing and modeling citation dynamics. *Public Library of Science ONE* 6(9): e24926.

Freeman, L.C. 2005. Graphic techniques for exploring social network data. In Carrington, P.J., Scott, J. and Wasserman, S. (eds), *Models and Methods in Social Network Analysis.* Cambridge: Cambridge University Press, 248–268.

Garfield, E., Irving, H.S. and Richard, J.T. 1964. T*he Use of Citation Data in Writing the History of Science*. Philadelphia: Institute for Scientific Information.

Golitko, M., Meierhoff, J., Feinman, G.M. and 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. 2006. Networks, agent-based models and the Antonine Itineraries: Implications for Roman archaeology. *Journal of Mediterranean Archaeology* 19(1): 45–64.

Granovetter, M.S. 1973. The strength of weak ties. *American Journal of Sociology* 78(5): 1360–1380.

Haggett, P. and Chorley, R.J. 1969. *Network Analysis in Geography*. London: Arnold.

Hanneman, R.A. and Riddle, M. 2005. *Introduction to Social Network Methods.* California: University of California Riverside.

Hillier, B. and Hanson, J. 1984. *The Social Logic of Space.* Cambridge: Cambridge University Press.

Hodder, I. and Orton, C. 1976. *Spatial Analysis in Archaeology.* Cambridge: Cambridge University Press.

Hummon, N.P. and Doreian, P. 1989. Connectivity in a citation network: The development of DNA theory. *Social Networks* 11(1): 39–63.

Hummon, N.P., Doreian, P. and Freeman, L.C. 1990. Analyzing the structure of the centrality-productivity literature created between 1948 and 1979. *Science Communication* 11(4): 459–480.

Hutson, S.R. 2002. Gendered citation practices in American Antiquity and other archaeology journals. *American Antiquity* 67(2): 331–342.

Hutson, S.R. 2006. Self-citation in archaeology: Age, gender, prestige, and the self. *Journal of Archaeological Method and Theory* 13(1): 1–18.

Isaksen, L. 2013. "O what a tangled web we weave" – Towards a practice that does not deceive. In Knappett, C. (ed.), *Network Analysis in Archaeology. New Approaches to Regional Interaction.* Oxford: Oxford University Press, 43–70.

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

Knappett, C. 2013a. Introduction: Why networks? In Knappett, C. (ed.), *Network Analysis in Archaeology. New Approaches to Regional Interaction.* Oxford: Oxford University Press, 3–16.

Knappett, C. (ed.). 2013b. *Network Analysis in Archaeology. New Approaches to Regional Interaction.* Oxford: Oxford University Press.

Knappett, C., Evans, T. and Rivers, R. 2008. Modelling maritime interaction in the Aegean Bronze Age. *Antiquity* 82: 1009–1024.

Knox, H., Savage, M. and Harvey, P. 2006. Social networks and the study of relations: Networks as method, metaphor and form. *Economy and Society* 35(1): 113–140.

Lusher, D., Koskinen, J. and Robins, G. 2013. *Exponential Random Graph Models for Social Networks*. Cambridge: Cambridge University press.

Malkin, I. 2011. *A Small Greek World: Networks in the Ancient Mediterranean*. Oxford and New York: Oxford University Press.

Marriner, N. 2009. Currents and trends in the archaeological sciences. *Journal of Archaeological Science* 36(12): 2811–2815.

Marsden, P.V. 2002. Egocentric and sociocentric measures of network centrality. *Social Networks* 24(4): 407–422.

Menze, B.H. and 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): E778–787.

Mills, B.J., Clark, J.J., Peeples, M.A., Haas, W.R., Roberts, J.M., Hill, J.B., Huntley, D.L., Borck, L., Breiger, R.L. and Clauset, A. 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.

Newman, M.E.J. 2010. *Networks: An Introduction*. Oxford: Oxford University Press.

Nooy, W. de, Mrvar, A. and Batagelj, V. 2005. *Exploratory Social Network Analysis with Pajek.* Cambridge and New York: Cambridge University Press.

Peeples, M.A. 2011. *Identity and Social Transformation in the Prehispanic Cibola World: A.D. 1150-1325*. Unpublished PhD dissertation submitted to Arizona State University.

Peeples, M. A. and 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.

Premo, L.S. 2006. Agent-based models as behavioral laboratories for evolutionary anthropological research. *Arizona Anthropologist* 17: 91–113.

Rehren, T., Grattan, J. and Klein, R. 2008. Going strong, and growing. *Journal of Archaeological Science* 35(2): 213.

Riles, A. 2001. *The Network Inside Out.* Ann Arbor: University of Michigan Press.

Robinson, W. and Posten, P. 2005. Literature use of scholars publishing in leading anthropology periodicals. *Behavioral & Social Sciences Librarian* 23(2): 1–17.

Rosenswig, R. 2005. A tale of two antiquities: Evolving editorial policies of the SAA journals. *The SAA Archeological Record* 5(1): 15–21.

Ruffini, G. 2012. Review of Malkin, I. 2011. A small Greek world: Networks in the Ancient Mediterranean. *American Historical Review*: 1643–1644.

Scholnick, J.B., Munson, J.L. and Macri, M.J. 2013. Positioning power in a multi-relational framework: A social network analysis of Classic Maya political rhetoric. In Knappett, C. (ed.), *Network Analysis in Archaeology. New Approaches to Regional Interaction*. Oxford: Oxford University Press, 95–124.

Scott, J. 1997. *Social Network Analysis: A Handbook.* London: Sage.

Sterud, E. 1978. Changing aims of Americanist Archaeology: A citations analysis of American Antiquity 1946-1975. *American Antiquity* 43(2): 294–302.

Terrell, J.E. 1976. Island biogeography and man in Melanesia. *Archaeology and Physical Anthropology in Oceania* 11(1): 1–17.

The Connected Past. 2013. *The Connected Past: People, Networks and Complexity in Archaeology and History*. Website: http://connectedpast.soton.ac.uk, accessed on 31 May 2013.

Van Oyen, A. In press. Networks or work-nets? Actor-Network Theory and multiple social topologies in the production of Roman terra sigillata. In Brughmans, T., Collar, A. and Coward, F. (eds), T*he Connected Past: Challenging Networks in Archaeology and History.* Oxford: Oxford University Press.

Victor, K. and Beaudry, M. 1992. Women's participation in American Prehistoric and Historic Archaeology: A comparative look at the journals American Antiquity and Historical Archaeology. In Claassen, C. (ed.), *Exploring Gender Through Archaeology*. Madison: Prehistory Press, 11–22.

Wasserman, S. and Faust, K. 1994. *Social Network Analysis: Methods and Applications.* Cambridge: Cambridge University Press.

Watts, D.J. 2003. *Six Degrees: The Science of a Connected Age*. London: Vintage.

Watts, D.J. and Strogatz, S.H. 1998. Collective dynamics of "small-world" networks. *Nature* 393(6684): 440–442.

Web of Knowledge. 2013. *What It Is.* Website: http://wokinfo.com/about/whatitis, accessed on 31 May 2013.

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.