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Introducing Network Science for Archaeology

1.1 WHAT ARE NETWORKS AND WHAT IS NETWORK SCIENCE?

Networks are nothing more than a set of entities and the pairwise connections among them. This simple definition encompasses a tremendous amount of variation from communication systems like the internet to power grids to neurons in the brain to road systems and flights between airports to our own social networks defined through familial ties, acquaintance, or any manner of interaction one could imagine. Over the last 20 years or so, academic interest in networks and the complex properties of network systems has grown by leaps and bounds. This has been mirrored by a growing excitement by the public in general (see best-selling works including Barabási and Frangos 2014 and Watts 2004). It is not uncommon these days to see networks and network visuals used as explanatory tools in news stories or popular articles shared across social media (another kind of network) exploring the complicated connections among characters in television shows, books, or people and organizations involved in news stories. Everyone, it seems, is excited about networks and networks are everywhere.

So, what is the big deal? Why have networks captured so much academic attention if the basic concept of a network is seemingly so simple? The real power of networks for researchers lies in their explanatory and predictive power across a wide variety of social and natural phenomena. There is a long tradition of social network analysis in the social sciences, and in particular sociology, going all the way back to the 1930s (see Freeman 2004 for a historical account). This work has shown that formally defining and measuring the properties and structure of social relationships often reveals features of social systems that are otherwise hidden if we only consider the attitudes and attributes of the people or other units involved. Since the late 1990s, a different set of network concepts have also taken hold among

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researchers interested in complex systems in physics, biology, and related fields (see Newman 2010). The excitement in this realm is largely focused on the availability of massive datasets and the emerging realization that networks comprising phenomena as diverse as the internet, the human brain, and even human and animal social networks are apparently governed by some common organizing principles and sometimes exhibit similar dynamics. Network science is a rapidly growing interdisciplinary field sitting at the intersection of these traditions of research, which promises to provide new insights along the edges of traditional disciplinary inquiry.

By way of example, showing the potential power of networks and what we can learn from them, we can turn to a classic study focused on one famous political dynasty, the House of Medici in the early Renaissance. Over the course of the first few decades of the 15th century, the House of Medici in the Republic of Florence rose from one of a number of wealthy families vying for power to a dynasty wielding unprecedented political, economic, and religious authority for centuries. The Medicis' influence eventually extended well beyond Florence, producing three Popes and numerous other high-ranking officials across the Italian peninsula and Europe. So, what explains the meteoric rise of the Medici dynasty? Was it purely their wealth? While the Medici family was among the wealthy families in Florence, there were many other rivals who equaled or surpassed them. Were the Medicis simply master strategists? To the contrary, historic accounts from the period describe Cosimo de' Medici in particular as enigmatic, reactive, and passive in dealings both public and private, with no apparent specific overarching goals (Padgett and Ansell 1993:1262–1263). Why, then, did the Medici dynasty rise so dramatically when so many others fell?

In the early 1990s John Padgett and Christopher Ansell set out to answer this question in an innovative and influential historical study focused on understanding the potential role of networks in the rise of the Medicis' political power and social influence (Padgett and Ansell 1993). Relying on the detailed work of historians outlining the business and personal dealings of the Florentine elite, Padgett and Ansell were able to reconstruct networks of marriage, economic relationships/business co-ventures, and patronage among the prominent 15th-century Florentine families (Fig. 1.1). This research revealed something surprising. While most of the prominent families were mutually connected in a single dense set of complex and overlapping relations, the Medici family consistently fell in a more intermediate position for different kinds of relations. Indeed, the Medicis had both more diverse connections (they married and created business ventures with many different families) and they tended to interact with families that were not otherwise interacting. Padgett and Ansell argue that this allowed the Medici family to develop

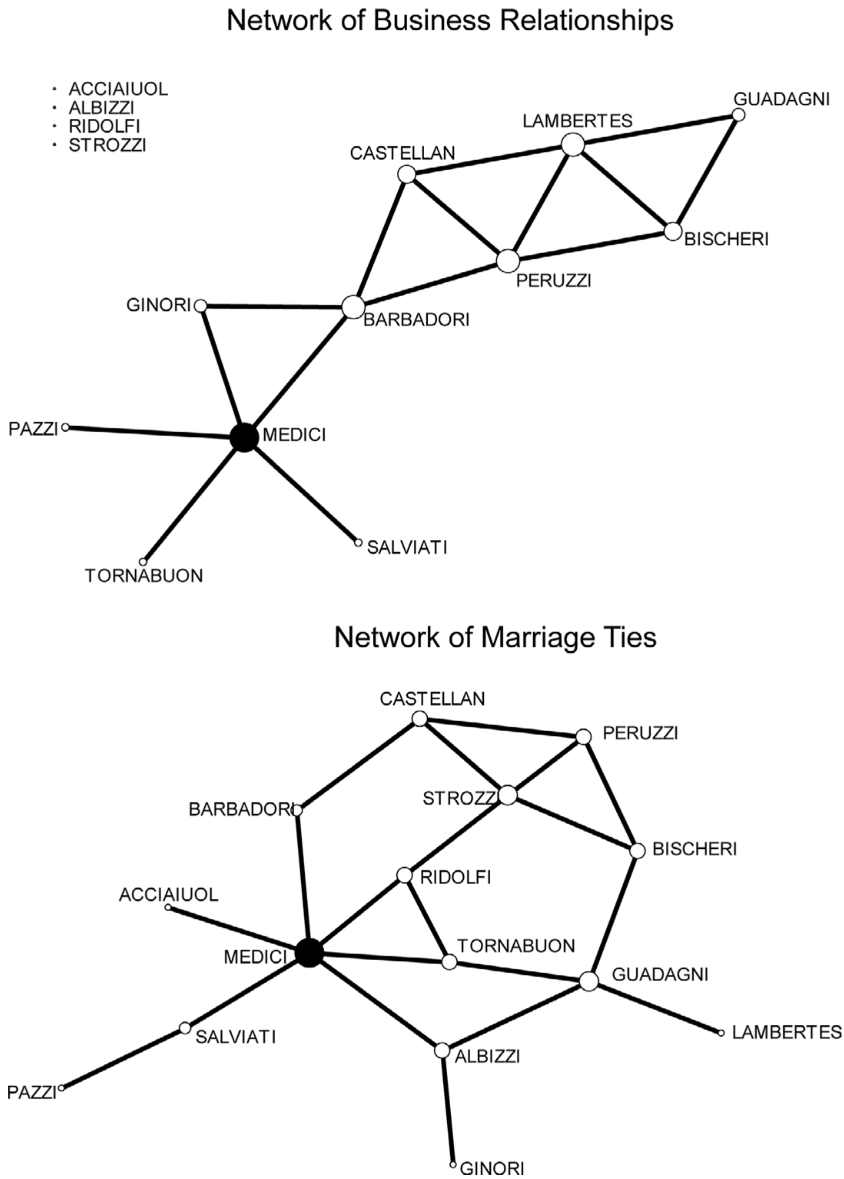

FIG. 1.1 Network diagrams showing business relationships and marriage ties among prominent families in 15th-century Florence based on data published by Padgett and Ansell (1993). Note that the Medici family in both networks has both more connections than other families and connects many families that are otherwise not connected.

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a coalition where everyone involved was connected *through* them, and thus they became the center of their socioeconomic sphere. Padgett and Ansell use historical accounts to convincingly argue that the individual decisions in this process leading toward the dominance of Medici authority were largely unintentional and were the product of dynamics common to a wide variety of network systems. Only after they were well established did the Medici family learn the true potential of what they had built.

The rise of the Medici family underscores a few important features about the nature of networks in general. First, networks and positions within them matter in a real, material sense. Beyond this, thinking about and formally tracking relations can often reveal surprising patterns that would otherwise be difficult or impossible to recognize through analyses focused on the attributes of the people or entities involved alone. The formal study of networks can tell us much about the relative importance and influence of the actors within that network as well as the processes behind significant changes in interaction over time. For archaeologists, the use of network concepts and network methods pushes us to think about the *relationships* driving social change in addition to exogenous processes that have often been given priority. The application of network science approaches to archaeological data has a great deal of potential to develop new insights into old questions as well as a whole body of well-developed and interesting research questions that are new to archaeology.

In this book, our goal is to both introduce network science and a wide variety of network methods for an archaeological audience, and also to make an argument for the importance of *relations* and *relational data* for understanding many natural and social phenomena that are of interest to archaeologists. In the remainder of this chapter, we set the stage by providing some basic definitions and concepts as well as a brief overview of the history of networks in archaeology, the place of network science in archaeological research, and the organization of this book.

1.1.1 *Basic Concepts*

For the purposes of this book, we define a **network** as a formal system of interdependent pairwise relationships among a set of entities (or actors). Networks are often represented and visualized as *graphs* with the actors in question depicted as a set of *nodes* or *vertices*, and the relationships among them drawn as lines, typically referred to as *edges* or *ties* (see Fig. 1.2). In this book we will use the term **node** to

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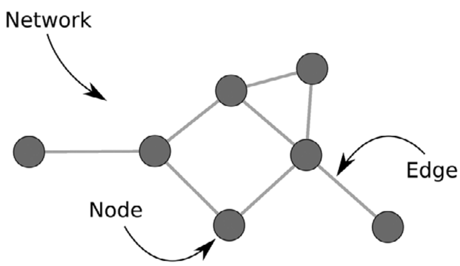

FIG. 1.2 Example network showing nodes and edges.

refer to the entities in a network and the term **edge** to refer to relationships between node pairs. In practice, many network researchers use the term *network* to refer to various kinds of network representations (like graphs and other mathematical notations), and for the sake of simplicity, we follow that general rule here. We do wish to note, however, the subtle but extremely important distinction between a network as a system of relations and a network representation as a formal abstraction of that system (see Chapter 3 for an in-depth discussion of the connection between networks, network data, and network representations).

A *network* is a formal system of interdependent pairwise relationships among a set of entities.

Networks involve the formal definition of *nodes* as the entities in question and *edges* as the relationships among them.

A *network representation* is a formal abstraction of a network created for the purposes of visualization or analysis. In this book, network representations are simply referred to as networks.

In this book we consistently use the terms *network*, *node*, and *edge*. However, alternative terms are common in other disciplines:

- A *network* is often called a *graph* in mathematics and computer science.
- A *node* is often called a *vertex* in physics, mathematics, and computer science, and an *actor* in sociology.
- An *edge* is often called a *link* in computer science, a *bond* in physics, and a *tie* or a *relationship* in sociology.

The nodes in a network can represent almost any kind of entity, from individuals or larger collectives (lineages, villages, corporations, nations, etc.) to objects,

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geographic locations, or even events. Likewise, the kinds of relationships that can be used to define edges are virtually endless, ranging from all manner of direct social interactions to biological relationships; flows of information, influence, or goods; shared participation in organizations or trends; and geographic proximity. Although the nature of nodes and edges in any given network representation can be quite variable, the important point is that they are defined using consistent criteria across all actors and relations within a given context.

Formal network research typically involves both the visualization of networks as well as the calculation of a broad range of statistics designed to quantify various aspects of network structure and node or edge position. **Network structure** is a general concept referring to the form and properties of a network. Are all actors connected or are there many isolated nodes? Is there a tendency for clustering or subgroup formation, or are all nodes connected in one dense set of relations? Are there intermediate nodes between otherwise separate clusters or are clusters wholly isolated from one another? Are some nodes more central to certain kinds of flows than others? There are a variety of network analytical tools designed both to represent such features of network structure (and many, many others we will discuss in the coming chapters) and to explain variation in such features at both the local (node/edge) and global (network-level) scales.

> *Network structure* refers to the general properties of a network including the overall patterns of relations, the presence/absence and nature of subgroups, the variation in the positions of actors within that network, and a broad range of other potentially salient features of organization.

1.1.2 *The Relational Perspective*

So, what makes networks special? Creating a network representation of some system of pairwise relationships can often be quite informative in and of itself. Network visuals are striking and can reveal important organizational principles of a system that are not otherwise apparent (see Chapter 6). We argue, however, that the true utility of network approaches lies in the **relational perspective** fundamental to the study of networks, that is, the underlying assumption that the nature and structure of *relationships* among actors are as important (or in some cases, more important) for understanding and predicting the behavior of actors in a network than the attributes of those actors themselves (see Chapter 8 for an extended argument). For example, the relational perspective suggests that in order to understand the role and importance in the Roman Empire of the province of Baetica in southern Spain, we cannot simply refer to the mineral wealth or agricultural potential of the region. Rather, we must consider how the region's position in the Roman transport system and the social relationships of its inhabitants that tied it to the capital of Rome were likely crucial in making it one of the most important and affluent regions in the Roman empire that eventually provided the first non-Italian emperors. Network methods and models help us formally describe and analyze such relational patterns.

Over the last two decades many archaeologists and material cultural specialists working in a variety of contexts have begun to shape what they see as a new direction in investigations of objects and identities sometimes glossed as "the relational turn" across many areas in the social sciences and humanities (see Harrison-Buck and Hendon 2018; Selg and Ventsel 2020; Van Oyen 2016). In our view, this relational turn does not represent a single paradigm but generally groups works that focus on the primacy of relations not just as drivers of social change but as constitutive components of persons and objects themselves. Within such perspectives entities and relations cannot be wholly separated and the agency of nonhuman entities is explicitly considered. Such relational perspectives draw on diverse theories and concepts including interpretive models like Actor-Network Theory (Latour 2005), entanglement theory (Hodder 2012; Hodder and Mol 2016), relational notions of personhood (Strathern 1988), and assemblage theory (DeLanda 2016), among many approaches. Some researchers have begun to consider the potential connections between such theoretical models and formal network methods and data (Knappett 2011, 2018, 2020; Knutson 2021; Van Oyen 2015, 2016) though empirical evaluations of such perspectives have been rare as of yet. In this book, we use the concept of the "relational perspective" in a somewhat narrower sense, focusing explicitly on the material role that relations in networks play in generating outcomes for actors within those networks. There is clearly overlap between formal network methods and broader notions of relationality that will likely continue to be explored (e.g., chapters in Donnellan 2020).

> The *relational perspective* at the core of formal network approaches is the notion that the structural properties of networks and variation in the positions of nodes and edges in a network are just as important for explaining or predicting the behavior of the actors of that network as the attributes of the social actors themselves.

1.1.3 *Network Science and Network Theory*

One criticism often directed toward network research is that it is simply a loosely defined set of methods and mathematical tools and does not constitute an explicit approach with its own unique theoretical underpinnings, research agendas, and insights (see discussion in Borgatti and Halgin 2011b; Borgatti et al. 2009). Are networks simply tools to get a job done or do networks also offer a fundamentally new theoretical perspective? In this book, we argue that we can have it both ways to a certain extent (see also Peeples 2019). Network approaches can be profitably used as analytical tools to address a number of traditional archaeological research concerns (a hammer and some nails), but network approaches also offer exciting novel research agendas beyond the realm of traditional archaeological questions (the plans to build a fancy new gazebo). In this book, we attempt to walk the fine line between these two perspectives, exploring both the practical methodological aspects of the network approach as well as what we see as the deeper theoretical insights the approach has to offer. We suggest that network perspectives and network methods have the potential to open up archaeological investigations to a broad array of important topics that have, as of yet, seen considerably less attention than they deserve (see also discussions in Brughmans 2013b; Mills 2017; Peeples 2019).

So, what then is the "network science" where this book gets its title? Here we borrow a useful definition from the inaugural issue of the journal *Network Science*. Brandes et al. (2013:2) define **network science** as "the study of the collection, management, analysis, interpretation, and presentation of relational data." That seems simple enough: network science offers specific methods and tools to deal with relational data consisting of entities and relations, and relations are important for understanding a broad range of phenomena. Network science provides tools to collect the data necessary to create formal network representations and explore and interpret network structures. For example, in one recent study, Golitko and Feinman (2015) used network science methods and visualization tools to explore the procurement and distribution of pre-Hispanic Mesoamerican obsidian (see also Golitko et al. 2012). This involved collecting data on the frequency of occurrence of objects made from different obsidian sources at a number of important sites and creating a network representation based on the shared frequencies of objects from those sources. In this network representation, sites were defined as nodes and strong similarities in site assemblages based on obsidian sources were represented as edges. They subsequently used this network to explore the relative centrality (importance) of specific sites and areas for directing flows of obsidian across the region, producing results that led to new archaeological insights.

As this brief example illustrates, network science *methods* are certainly useful, but we argue that where the rubber really meets the road when it comes to network

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science is when we use these methods to explicitly explore network theories. **Network theories** are formalizable and testable expressions of dependencies (or contingencies) among nodes, edges, attributes, outcomes, or global network structures, or any combination thereof (see Chapter 8). In other words, network theories are formal statements about how one part of a network system or one kind of relationship in a network can influence the development, spread, or decline of some other salient feature of that system or the actors within it (see Chapter 3). As with any theoretical concept in archaeology, network theories can come from traditional archaeological concerns or may be derived from expectations based on the properties of networks themselves. In either case, the application of network theories in archaeology (or any field for that matter) typically involves two basic components: (1) the development of a model for abstracting network concepts and techniques to study a real-world phenomenon as network data and (2) a formal evaluation of the network dependencies, contingencies, and/or relational processes described by a network theory using network data.

This process of abstraction is, of course, not unique to network research. As archaeologists we study diverse phenomena involving past human behavior, but we typically cannot study these phenomena directly. Instead, we must always abstract the phenomenon we are interested in exploring using archaeological concepts and develop tools for representing such concepts using archaeological data. Network approaches to archaeology are no different. For example, let's say we are interested in exploring how the position of a settlement within a regional transportation system influenced the growth of that settlement. In this case, the general archaeological concept we are interested in exploring is the movement of people and resources across a region using transportation corridors, and the implications of this movement for settlement growth. The notion of the "position" of a settlement in relation to such flows can be abstracted using the network concept of "centrality," which refers to a broad set of approaches used to describe the relative importance of nodes for directing or receiving flows across a network (see Chapter 4 for further discussion). In order to represent this concept using archaeological data we could then define a simple point-to-point (settlement-to-settlement) network using sites as nodes and roads connecting them as edges, perhaps with some additional considerations of the length or formality of road segments. From here we have got our network data (derived from archaeological data) and the path ahead is relatively straightforward. We can calculate and evaluate relative differences in network centrality and compare these to attributes of settlements including their size or rates of growth to evaluate our relational theories.

As the discussion above suggests, modeling and abstracting archaeological data into network data is therefore a fundamentally archaeological thing to do. It involves a constant dialogue among archaeological data, disciplinary knowledge, archaeological theory, and network concepts (see also Section 1.2). In archaeological applications of network science, network theories can include theories about how a network structure evolves, how processes and flows take place in relation to the network structure, how all aspects of the network affect the behavior and opportunities of the nodes and edges, or many more relational questions. Network theories can describe how relational aspects of the past phenomenon of interest functioned, or they can be theoretical arguments about why it is appropriate to use network concepts and data to abstract and represent a given phenomenon. Both of these are network theories. For example, in Golitko and Feinman's (2015) study described above, the authors theorize that top-down control of obsidian production and distribution by major settlements resulted in the important positions of these settlements in the obsidian distribution network: this is an archaeological theory about relational aspects of a past phenomenon. They also suggest that network centrality measures are appropriate representations of these relative importance positions of major centers: this is a theoretical argument about the appropriateness of using particular network methods and representations to address the question at hand in a given context.

To put it simply, **network science in archaeology** is the study of network models and network theories developed for an archaeological research context, and formally expressed and tested using network methods. Although network science techniques without explicit network theories may sometimes offer useful analytical explorations, the ability of such methods to lead to new insights into past human behavior is significantly enhanced *when theory and method are combined*. We cannot emphasize enough that network science can only make unique contributions to our understanding of past human behavior when archaeologists let their use of network science be guided by the specific nature of archaeological research contexts, critical evaluations of archaeological data, and careful considerations of relational theories (see Chapter 8).

Network science is the study of the collection, management, analysis, interpretation, and presentation of relational data.

Network theories are formal and testable expressions of dependencies among nodes, edges, attributes, outcomes, or global network structures or any combination thereof. They express why and how relationships matter in a certain research context.

Network science in archaeology is the study of network models and network theories developed for an archaeological research context, and formally expressed and tested using network science methods.

1.2 WHERE DOES NETWORK SCIENCE FIT IN ARCHAEOLOGY?

So far we have covered what network science is and how it differs from other approaches. But how does it fit with what we do as archaeologists? Where should we position network methods and models in our research process and thinking? In this section we will provide an abstract overview of how network science might be incorporated in a generalized archaeological research process. We intentionally do not go into many specifics here. In Chapter 2 we provide a wide range of archaeological examples of the use of network science for studying past relational phenomena to give you a sense of the current landscape of archaeological network research.

Figure 1.3 offers a graphical representation of our argument regarding the place of network science in the archaeological research processes. The first thing to notice is that *doing network science in archaeology* is necessarily *doing archaeology*. Network science applied to archaeological research is a subset of archaeological research: it does not happen in isolation, it is not immune to the limitations of archaeological data nor does it replace archaeological theory. Just like any other formal or informal approach applied to our discipline, network science cannot be considered a black box positioned outside our discipline – a black box into which

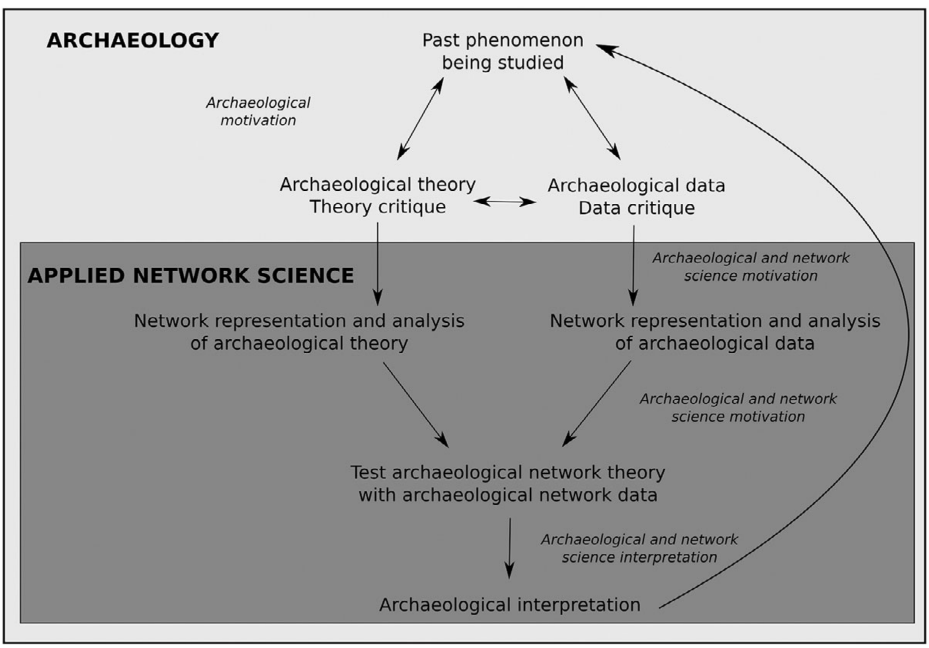

FIG. 1.3 Generalizing abstraction of a typical archaeological network research process.

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archaeological theories and data are inserted, and out of which a ready-made archaeological interpretation comes. Every step of the process of network science demands archaeological argumentation and a keen awareness of the specific properties and limitations of archaeological data. Why is network science necessary in this archaeological research context? What limitations do archaeological data impose on my use of network science techniques or models? Can my archaeological theories be appropriately represented using network science concepts and tools? Failing to address these questions is bad network science *and* bad archaeology. Doing critical network science research inevitably requires us to do critical archaeological research. In this book we will guide you through the process of doing **critical archaeological network research**, by continually emphasizing the archaeological questions you should be asking yourself as part of critical network science.

All archaeological research aims to help us better understand a particular past phenomenon related to human behavior. This is why in the abstract research process shown in Figure 1.3 we have placed the past phenomenon under study at the top. Archaeologists collect data to explore this past phenomenon and we formulate theories to describe that past phenomenon, with data and theory engaging in a constant dialogue. For example, if we wish to study the movement of individuals through ancient Pompeii (Fig. 1.4), we must first collect and critically assess information about past excavations of the town. Perhaps this data collection will suggest areas where we might be missing parts of the town plan or other data, triggering fresh excavations or other additional research. In our evaluation of these data, we will identify structures that will help us reconstruct the town plan. Critical assessments of this archaeological information will allow us to attach varying degrees of uncertainty to each element of this reconstruction. From here, we can develop expectations about how Romans entering the town might have moved around within it: for example, based on our knowledge of Roman towns in general, we might suggest that the forum had a gravitational pull or funneling effect on all movement through the town.

So far we have merely described archaeological research: there is nothing particularly "networky" about the previous paragraph. We could start introducing network science into this research process at this point in two ways: *modeling archaeological data* and *modeling archaeological theories*. To *model our data* of Pompeii's town plan with a network representation, we might consider representing each road junction as a node and each road as an edge (Fig. 1.4) to create a spatial road network (see Chapters 3 and 7). The structural properties of the network as a whole and of each node's position can subsequently be studied using exploratory network analytical techniques and metrics (see Chapter 4). We might similarly

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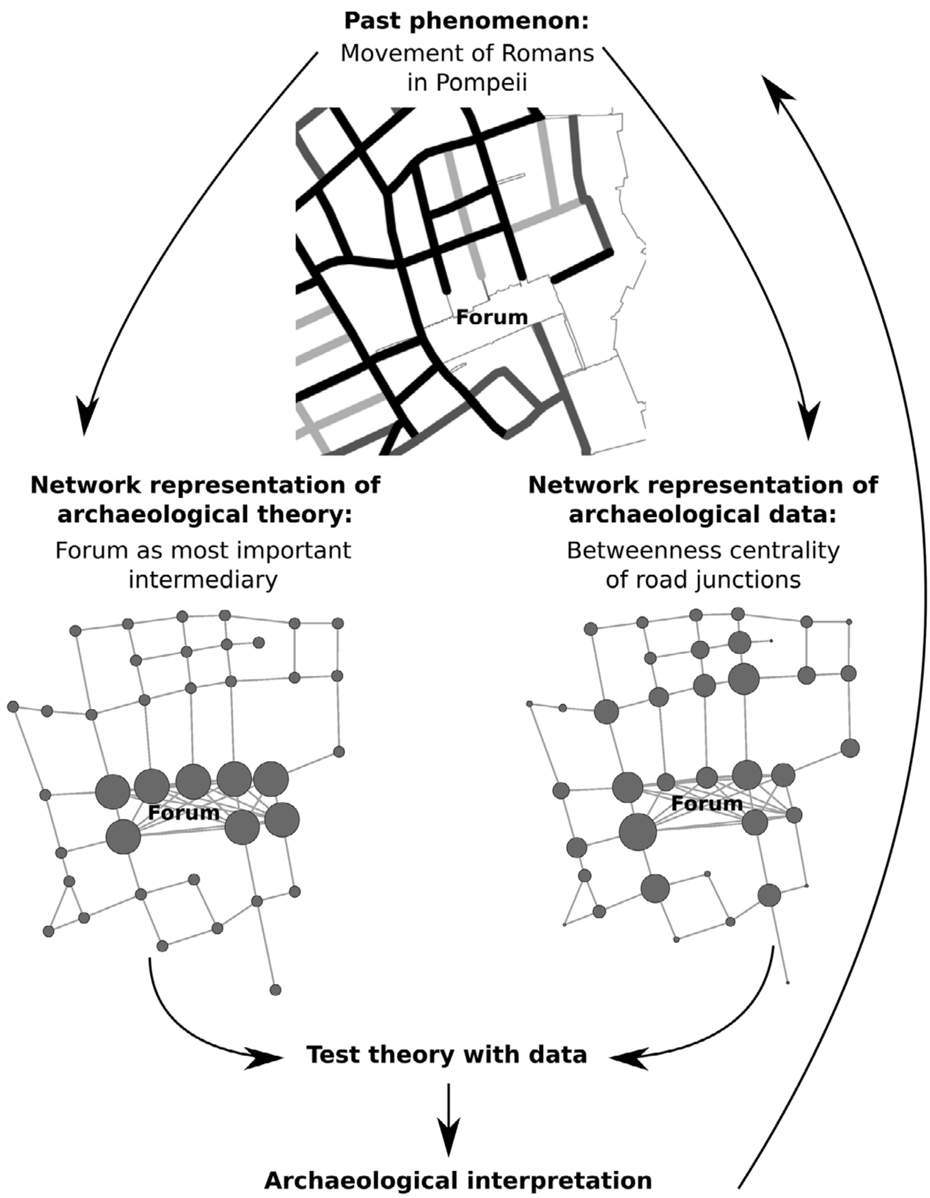

FIG. 1.4 Abstract example of an applied archaeological network research process using a subset of the Pompeiian town plan (excerpt from Poehler 2017: Fig. 6.2). The past phenomenon under study is the movement of people in Pompeii. Our archaeological data can be analyzed as network data by representing road junctions as nodes and road segments as edges. Network data can also be used to represent the archaeological theory of the importance of the forum junctions for mediating the movement of people by representing hypothesized importance of junctions as node attribute values (here represented by node size). The properties of the dataset can be analyzed using an exploratory network analysis technique that is an appropriate representation of the theorized process: betweenness centrality (a measure of the importance of a node sitting on intermediate paths across the network [see Chapter 4], here represented by node size). Comparing theorized node attribute values with betweenness centrality scores allows us to test the theory and interpret the results to gain insights into the past phenomenon.

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model our theory of movement through Pompeii by attaching an attribute representing the theorized importance of each junction to all nodes in this network and assigning higher importance values to junctions along the forum as compared to other junctions in the town plan (Fig. 1.4). We can then again use network metrics to study this formal network representation of our theory: What are the relationships between our attributes of interest (e.g., distance from the forum) and the structural positions of nodes in the network? Network science allows us to formally express such archaeological network theories, and it allows us to explore what the implications are of our theory for its constituent parts: the roads, junctions, and the Romans that moved over them.

From here, network science tools and techniques can be used to evaluate archaeological theories with archaeological data. A crucial prerequisite for this step is critical evaluation of both archaeological theory and archaeological data: you need to make a convincing argument that a particular archaeological theory is testable with a particular archaeological dataset; you need to explicitly design an analysis that enables this test to be performed; and you need to evaluate the reliability of the archaeological evidence for addressing this theory. Network science offers formal tools to implement such analyses. To facilitate this process, consider asking yourself the following questions:

- What past processes are of interest and how can they be represented using my archaeological dataset?
- What archaeological or relational theory might explain the patterns in my archaeological dataset?
- How could the theory of interest be represented and evaluated using archaeological evidence?
- What are the limits of the data and/or what further archaeological data would I need to collect in order to fully evaluate this theory or represent the network process of interest?

Once we are ready to formally test network theories using archaeological data, there are several ways we might proceed. In many contexts, we can evaluate a network theory directly by representing our archaeological dataset as a network. This approach could be used to test our theory about the importance of the forum and the two main roads in Pompeii. We could use betweenness centrality (see Chapter 4) to calculate in our network representation of archaeological data how important every junction and road was as an intermediary in the movement of people (Fig. 1.4). We could subsequently compare these centrality values from our analysis with those of our formal representation of our archaeological theory to determine whether the forum does indeed have a higher centrality as predicted by our theory. Formal network theories can also be tested without explicitly creating a network representation from archaeological data. For example, Bentley and Shennan (2003) evaluated network theories focused on cultural transmission using a non-network representation of data patterns in pottery designs from Neolithic Europe. Specifically, they developed expectations for the emergence and popularity of material cultural styles over the course of cultural evolution under different kinds of transmission based on a general stochastic network model and then tested this model using assessments of the frequencies of pottery motifs through time. As this suggests, one can evaluate network models without conducting "network analyses" using archaeological data in the most conventional sense.

Even though formally testing theories in the way we outline here is a constructive way to improve our understanding of past human behavior, do not despair if this is not immediately possible in your research context. Indeed, network science approaches have much to offer archaeological research even if we are not yet prepared or able to directly test formal theories with data. For example, we can use network science concepts and models to formally represent or explore the implications of our archaeological theories in abstract, or we can create exploratory network representations of our archaeological data to get a general sense of structural patterning in our archaeological data before defining our theories or questions. In this way, network science approaches to archaeology can help us explicitly think through and develop our theories, help us better understand and perhaps refine or reformulate our questions, and help us develop predictions of the archaeological patterns we would expect to see as the outcome of our theories in case one day the data necessary to test these theories are available. Network science tools similarly help us explore our archaeological data, understand underlying patterns, and perhaps guide data correction or new data collection.

With the abstract research process described here we aim to illustrate where network science fits in archaeological research on the most general level. Such a network research process in practice should be part of a multi-method approach to understanding past human behavior: there is no reason why every aspect of archaeological network research should be dominated by exclusively network data and tools. Network science offers tools that are sometimes appropriate because they allow the archaeologist to do something they want to do or could not do any other way. But if non-network statistical or spatial analysis techniques are more appropriate for representing an archaeological data pattern, then these should be used alongside network methods.

Network science can only make constructive contributions to archaeological research when it is inserted into the archaeological research process in appropriate places. What counts as appropriate is determined by the theories being evaluated, data critique and research context, and a critical understanding of the network science concepts and tools themselves.

> Doing *critical archaeological network research* requires archaeological argumentation at every step of the network science application process. Why is network science necessary in this archaeological research context? What limitations does my archaeological data critique impose on my use of network science? Can my archaeological theories be represented using network science concepts and tools?

1.3 TRENDS IN ARCHAEOLOGICAL NETWORK RESEARCH

Network research has a long history in the physical, behavioral, and social sciences, but it is only recently that network approaches have gained a major foothold in archaeology. The number of published works focused on the formal analysis of networks in archaeology has increased nearly threefold over the last 10 years (Fig. 1.5) and we see indications that archaeological network research is still on the rise. In this section, we briefly outline the history of network research in archaeology, including what we see as some of the most important recent trends. This brief overview only scratches the surface, however, and we refer readers interested in the history of networks in archaeology to several recently published overviews (Brughmans 2013b; Brughmans and Peeples 2017; Mills 2017; Peeples 2019) that cover various topics in greater detail.

Network approaches as they exist today owe their origins to three major traditions of research: (1) graph theory, (2) social network analysis, and (3) complexity science. Although there is considerable overlap among these areas of research, each also has its own unique research agendas, methods, and tools. Importantly, network methods and models have found their way into archaeology several times somewhat independently over the last 50-plus years or so, inspired by each of these three major traditions.

Graph theory is the mathematical field focused on studying the formal structure of pairwise relationships among entities, often in the form of algebraic matrices. The beginnings of graph theory go back all the way to 1736 when the mathematician Leonhard Euler wrote the first formal theorem (see Biggs et al. 1976). Graph

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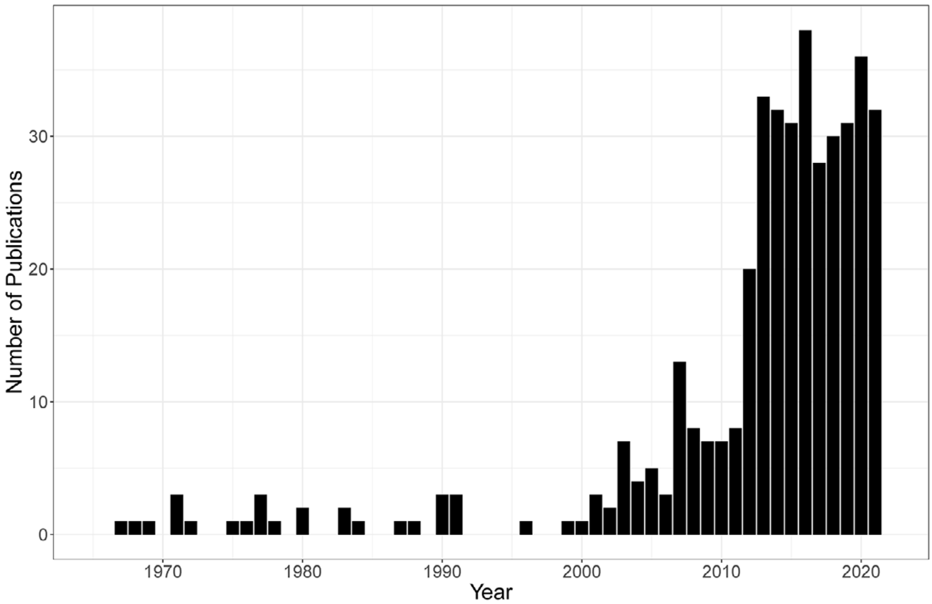

FIG. 1.5 The number of published formal archaeological network studies per year between 1965 and 2021 (using data updated from Brughmans and Peeples 2017).

theory is, in many ways, the mathematical foundation of all other network approaches and has widespread applications in the physical sciences generally for the quantification and explorations of connected systems. In the 1960s and 1970s, a number of geographers began to pick up on graph theoretic concepts and methods to describe and analyze patterns of human land use and settlement (e.g., Chorley and Haggett 1967; Pitts 1965, 1978). By the late 1970s, largely inspired by these geographic studies, a few archaeologists also began to attempt to apply graph-based models to explore archaeological data. The earliest formal graph theoretic studies in archaeology were conducted by John Terrell (1976, 1977) and Geoffrey Irwin (1978), both working in Oceania. These studies relied on the creation of simple graphs based on the geographic proximity of settlements to serve as useful sources of hypotheses about potential interaction among island communities. Indeed, in these early studies, graphs were not seen as "real" networks representing a past reality in any sense but instead as null models that could be used to evaluate archaeological data. Although graph theory remained popular in the archaeology of the Pacific (Hage 1977; Hage and Harary 1983, 1991; Hunt 1988) for a number of years, graph-based methods never took off in archaeology as they did in other closely related fields. This is perhaps, in part, because graph-based models for network data are largely focused on documenting network structures but offer little

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guidance in terms of testable models and expectations for the outcomes of such network structures. Between the 1980s and the early 2000s, a small number of graph theoretic studies were published in archaeology focused on many different parts of the world, but these amounted to far fewer than one publication per year (e.g., Broodbank 2000; Jenkins 2001; Peregrine 1991; Rothman 1987; Santley 1991).

Social Network Analysis (SNA) refers to a long tradition of exploring formally defined social relations that has its origins in a number of developments in the early and mid-20th century, including the study of kinship and social structure (sociometry; Moreno 1934; see also Freeman 2004) and the Manchester School of British social anthropology emerging in the 1950s (e.g., Barnes 1954; Bott 1955, 1957; Mitchel 1969; Nadel 1957). Researchers working in this realm were interested in exploring the complex relationships between social structure and social differentiation, and began to develop a number of formal tools for describing variation in social structure toward that end. Many of these early methods shared much in common with contemporary approaches to graph theory, and indeed, early social network scholars began to collaborate with mathematicians to develop these ideas further (e.g., Barnes and Harary 1983; Harary et al. 1965). By the 1970s, SNA had emerged as a distinct paradigm focused on developing both a general theory of structural relations as well as increasingly diverse quantitative tools designed to analyze social structures using network data. SNA today is a vibrant field with numerous dedicated journals and conferences and a dizzying array of methods and applications. Research under the heading of SNA is most often focused on exploring the importance of structural relations among individuals (though not entirely so) and in particular the social processes driving structural tendencies in networks.

Interestingly, SNA was suggested as a potentially useful approach for exploring patterns of interaction among archaeological settlements by Cynthia Irwin-Williams (1977) almost as early as the very first applications of graph-based methods described above. Although SNA methods rapidly gained popularity in the social and behavioral sciences broadly in the 1970s and 1980s, it is not until recently that we see any substantial impact in archaeological research. Beginning only a little over 10 years ago, we have begun to see the proliferation of a number of archaeological studies explicitly inspired by SNA models and methods coming largely out of sociology (e.g., Bernardini 2007; Birch and Hart 2018; Golitko et al. 2012; Hart 2012; Hart and Engelbrecht 2012; Mills et al. 2013a, 2015; Peeples and Haas 2013). Several recent projects represent collaborations among archaeologists and sociologists (such as the Southwest Social Networks Project; Mills et al. 2013a, 2018; see Section 2.8.2). Archaeologists have used tools for quantification and visualization developed in SNA to address archaeological questions at a variety of scales. For example, Mills and colleagues (2013a, 2013b, 2015) in a series of studies have used SNA methods and theories to explore the impact of a major period of migration on the nature of regional social relations across a large portion of the US Southwest. Although many archaeological forays into SNA largely represent the use of these methods to address traditional archaeological concerns, there have also been several recent studies that explicitly test SNA theories in an attempt to engage in debates beyond the typical borders of archaeology (e.g., Birch and Hart 2018; Borck et al. 2015; Lulewicz 2019; Peeples and Haas 2013), a trend we hope will continue.

Complex network approaches (or complexity science approaches to networks) are the most recent major tradition in network research to develop. This approach largely developed out of work in physics and computer science, going all the way back to the 1960s, but began to emerge as a distinct research tradition in the early 2000s (Newman 2010, 2011). Complex network approaches are focused on exploring the emergence of nontrivial properties of networked systems that are not a property of the individual nodes or relations in that network. Many of the most influential findings in this body of research are focused on the generalizability of networks. In other words, complex network approaches are often focused on the features that are common across all manner of networks. For example, a great deal of work has focused on identifying and explaining the emergence of small-world structure in networks. Small-world networks are networked systems where most nodes are not connected to each other, but almost every node is reachable from almost every other node across only a few steps (Watts and Strogatz 1998; see Chapter 4). Small-world structures have been argued to emerge in a wide variety of real-world networks, suggesting that the principles driving their emergence may be a function of certain kinds of networked relationships generally rather than any specific context or the attributes of nodes or edges in those networks. Complex network approaches are often focused on explaining "global" or graph-scale network properties such as these rather than individual positions, which are more often the focus of SNA studies.

Interest in complex network approaches in archaeology rose in the early 2000s along with a general interest in complex systems. Much of this interest spurred from an influential volume called *Complex Systems and Archaeology* published in 2003 (Bentley and Maschner 2003), which included a number of case studies that involved testing complex network models using archaeological data. In recent years, a number of archaeologists have begun to collaborate with complexity scientists from other fields. For example, the archaeologist Carl Knappett has collaborated with physicists Ray Rivers and Tim Evans on a series of network models focused on

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the Bronze Age in the Aegean. This work involved the creation of a series of complex network models to assess the potential patterns of interaction and the robustness of maritime networks to a variety of disturbances (Knappett et al. 2011; Rivers 2016; Rivers and Evans 2013; Rivers et al. 2013).

Over the last decade or so it has been possible to speak of a distinct and growing body of **archaeological network research** drawing on each of the major traditions briefly described above. This trend is due in part to the increasing availability of software tools for analyzing and visualizing network data (e.g., UCInet, Pajek, Gephi, and many packages for the R and Python platforms; see discussion of software in Appendix B) but is also partly a response to the increasing popularity of network models in the broader social and natural sciences. Archaeologists have been quite cosmopolitan in applications of network science, drawing on the massive body of interdisciplinary network research to develop useful new methods for addressing old archaeological questions as well as a whole suite of new questions we were not asking even a few years ago; many of these will be elaborately discussed in the next chapter.

As we write today there are numerous sessions and papers on archaeological networks at just about every major national and international conference as well as one annual community-led conference (The Connected Past: http://connectedpast.net) explicitly dedicated to the explorations of networks in archaeology and history. Every year there are numerous dissertations and theses applying network science to archaeological data, as well as book-length treatments of network research and journal special issues (e.g., Brughmans et al. 2016; Collar et al. 2015; Knappett 2011, 2013, 2014; Lozano et al. 2017). Recent work includes numerous exciting applications of network scientific tools to archaeological data and a burgeoning literature focused on the unique challenges of applying network methods and models to archaeological data (e.g., Brughmans et al. 2016). Importantly, archaeological network practitioners have already begun to breach the boundaries of archaeology and regularly present at conferences like the International Network for Social Network Analysis (INSNA) Sunbelt conference focused on the study of social networks generally. We see these all as positive developments and suggest that the future bodes well for network science in archaeology (see also Peeples 2019).

1.4 HOW TO READ THIS BOOK

We decided to write this book because both of us have frequently been approached by archaeologists with a general interest in network techniques or a sense that

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relational data may help them address interesting questions, but with no notion of where to begin. There are numerous recently published historical overviews, perspective pieces, and calls for the increased importance of networks in archaeology (e.g., Brughmans 2010, 2013b; Collar et al. 2015; Mills 2017; Peeples 2019), but to date, there is no single manual or guide that helps you along the path from archaeological question to archaeological data to network data to network analysis to useful results. Our goal with this book is to provide an overview of the state of the art in archaeological network studies including examples and detailed discussions of the kinds of questions that can be addressed as well as the unique challenges of deriving and analyzing network representations from archaeological data to help readers make these connections. We have attempted to keep this book practical in that we address specific problems and provide solutions for issues that archaeological network analysts are likely to face. At the same time, we have devoted substantial attention to describing what particular methods do (though we have largely relegated mathematical formulas to the glossary) and, perhaps most importantly, when it would or would not be appropriate to apply a given method to a given problem. Throughout this book we present new key concepts and terms in **bold** text where they first appear and provide definitions in boxes as well as in the glossary at the end of the book.

Even in a field as young as archaeological network studies, we cannot hope to be comprehensive. Instead, we have chosen a broad range of topics selected to highlight the diversity of approaches already in the literature and what we see as many of the most important potential future directions. We want to give our readers all the basic tools necessary to collect, manage, and analyze archaeological network data and address substantive questions on their own. We illustrate these approaches throughout with archaeological case studies and shorter examples explored in boxed vignettes. Beyond this, we want readers to come away with a general understanding of network methods and models that will allow them to confidently venture out into the broader network science literature beyond the borders of archaeology to find new and exciting theories, methods, and research questions. We have also created a detailed online companion to this book that provides datasets, additional examples, and the information necessary to replicate the analyses in this book.

We have written this book to be both a useful general introduction to the world of archaeological networks as well as a handbook for readers who have more experience with these approaches. *If you only have one hour* to find out what archaeological network research is, then read this chapter (congratulations, you've made it this far) and Chapter 2 along with the summaries of all other chapters.

Chapter 2 provides an extended discussion of the kinds of evidence that archaeologists have used to create network representations and several examples of what has been done with such networks. *If you have a little more time* and want to get an idea of how to apply network science to a range of archaeological cases, we suggest you continue by reading Chapter 3, which focuses on both the process through which archaeological data are collected and abstracted to network data as well as the general features of networks as analytical objects and network data. The first three chapters of the book also cover a number of important topics on the appropriate selection of methods and models for a range of common research problems in archaeology. *If you are already familiar with network science and archaeological applications* and want help identifying and applying specific methods in your own archaeological research, then read the middle chunk of the book: Chapters 4–7. These chapters focus on a series of analytical topics: exploratory network analysis, sampling and uncertainty assessment, network visualization, and spatial networks. Some of the methods presented are already commonly applied to archaeological network research, whereas others represent novel directions for future studies (in particular, Chapter 5). We do not expect that all readers will work through these middle chapters line by line, but instead, this portion of the book can be considered more of a reference and guide to good practice for a range of common and not so common techniques. For each of these middle chapters we have provided brief case studies illustrating the major concepts and approaches as well as a series of exercises designed to let you evaluate your own comprehension (with answers and worked examples provided at the end of the book as well as in the online companion). *If you want to engage with the mathematical implementations* of these techniques, in addition to reading Chapters 4–7, follow up on the references in the further reading lists and see the equations in the glossary. Finally, Chapter 8 provides our own perspective on the potential *future(s) for network science in archaeology* including where we think the field can/should go both methodologically and theoretically to overcome a wide range of challenges. This chapter also returns to the point made here in the introductory chapter about the importance of combining network methods and explicit network theories, but we discuss this issue in more practical terms building on the concepts introduced in the rest of the book. We hope the last chapter serves as both a jumping-off point and an inspiration for readers to expand on what they have learned here; archaeological network science is a young field and there is a need for new creative approaches to explore and expand its limits.

Because software for managing and analyzing network data tends to change quite rapidly, we have decided not to tie the main text of this book to any particular software package (we provide brief descriptions of some current common software packages in Appendix B). Instead, we present the basic theoretical justifications for and "nuts and bolts" descriptions of the approaches covered here and refer readers to the *associated online companion* for the specific analytical details. This online companion is quite elaborate and provides tutorials and examples of the analyses discussed in this book primarily using the R programming language (R Core Team 2021). These examples will be periodically updated by the authors and, importantly, also include a public commenting feature so that those who use this book can contribute, ask questions, and even develop related exercises designed for courses or for self-teaching. We hope the online appendix and the associated open source data, code, and tutorials will develop into a thriving ecosystem of archaeological network practitioners. In order to help that happen, we have also designed the online companion to be a clearinghouse for open archaeological network datasets. We have populated this resource with many of our own published datasets, including those used in this book, and we hope others will do the same.

A number of datasets and case studies are used repeatedly throughout the book to illustrate network concepts and methods, and Section 2.8 introduces the data used. These have been selected to offer geographically and temporally varied examples, as well as to demonstrate how network methods might be used in very different research contexts or to study diverse phenomena. They include Roman roads, ceramic design and technology from the US Southwest, Medieval sites in the Himalayas, archaeological publications, and Iron Age and Roman sites in southern Spain.

1.5 SUMMARY

- Our goal in this book is to both introduce network science and a wide variety of network methods for an archaeological audience and also to make an argument for the importance of relations and relational data for understanding many natural and social phenomena that are of interest to archaeologists.
- A network is a formal system of interdependent relationships among a set of entities.
- A network representation is a formal abstraction of a network created for the purposes of visualization or analysis. In this book, network representations are simply referred to as networks.
- Network representations involve the formal definition of nodes as the entities in question and edges as the relationships among them.
- Network structure refers to the general properties of a network including the overall patterns of relations, the presence/absence and nature of subgroups, the

variation in the positions of actors within that network, and a broad range of other potentially salient features of organization.
- The relational perspective at the core of formal network approaches is the notion that the structural properties of networks and variation in the positions of nodes and edges in a network are important for explaining or predicting the behavior of the actors of that network in addition to the attributes of the actors themselves.
- Network science is the study of the collection, management, analysis, interpretation, and presentation of relational data.
- Network theories are formal and testable expressions of dependencies among nodes, edges, attributes, outcomes, or global network structures or any combination thereof. They express why and how relationships matter in a certain research context.
- Doing critical archaeological network research requires archaeological argumentation at every step of the network science application process. Why is network science necessary in this archaeological research context? What limitations does my archaeological data critique impose on my use of network science? Can my archaeological theories be represented using network science concepts and tools?
- Network science can only make constructive contributions to archaeological research when it is inserted into the archaeological research process in appropriate places. What defines those appropriate places is determined by the archaeologist's theories, data critique and research context, as well as by a critical understanding of the network science concepts and tools themselves.
- Network approaches as they exist today owe their origins to three major traditions of research: (1) graph theory, (2) social network analysis, and (3) complexity science. Each of these has influenced archaeological research independently several times over the last 50 years or so.

Further Reading

The following resources provide detailed accounts of the history and applications of archaeological network research using a broad array of examples.

Brughmans, Tom 2010 Connecting the Dots: Towards Archaeological Network Analysis. *Oxford Journal of Archaeology* 29(3):277–303.

2013 Networks of Networks: A Citation Network Analysis of the Adoption, Use and Adaptation of Formal Network Techniques in Archaeology. *Literary and Linguistic Computing, The Journal of Digital Scholarship in the Humanities* 28(4):538–562.

Brughmans, Tom, Anna Collar, and Fiona Coward 2016 *The Connected Past: Challenges to Network Studies in Archaeology and History*. Oxford University Press, Oxford.

Brughmans, Tom, Barbara J. Mills, Jessica L. Munson, and Matthew A. Peeples 2023 *The Oxford Handbook of Archaeological Network Research*. Oxford University Press, Oxford.

Brughmans, Tom, and Matthew A. Peeples 2017 Trends in Archaeological Network Research. *Journal of Historical Network Research* 1(1):1–24.

Collar, Anna, Fiona Coward, Tom Brughmans, and Barbara J. Mills 2015 Networks in Archaeology: Phenomena, Abstraction, Representation. *Journal of Archaeological Method and Theory* 22(1):1–32.

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

2013 *Network Analysis in Archaeology: New Approaches to Regional Interaction.* Oxford University Press, Oxford.

2014 Avant-propos. Dossier: Analyse des réseaux sociaux en archéologie. *Nouvelles de l'archéologie* 135:5–8.

Mills, Barbara J. 2017 Social Network Analysis in Archaeology. *Annual Review of Anthropology* 46:379–97.

Peeples, Matthew A. 2019 Finding a Place for Networks in Archaeology. *Journal of Archaeological Research* 27:451–499.

In addition to the above archaeological resources, the following general network texts provide excellent introductions to the history of network research, network science, and some of the most common applications.

Barabási, Albert-László, and Jennifer Frangos 2014 *Linked: How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life*. Basic Books, New York.

Borgatti, Stephen P., and Daniel S. Halgin 2011 On Network Theory. *Organization Science* 22(5):1168–1181.

Brandes, Ulrik, Garry Robins, A. N. N. McCrainie, and Stanley Wasserman 2013 What Is Network Science? *Network Science* 1(1):1–15.

Coscia, Michelle 2021 The Atlas for the Aspiring Network Scientist. www.networkatlas.eu.

Freeman, Linton C. 2004 *The Development of Social Network Analysis: A Study in the Sociology of Science*. Empirical Press, Vancouver.

Knoke, David H., and Song Yang 2008 *Social Network Analysis*. 2nd ed. SAGE, Los Angeles.

Scott, John, and Peter J. Carrington 2011 *The SAGE Handbook of Social Network Analysis*. SAGE, London.