Archaeological Modeling, Representational and Experimental

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Abstract: I distinguish, by specificity and representational function, several different types of archaeological models: phenomenological, scaffolding, and explanatory models. These take the form of concrete, mathematical, and computational models (following Weisberg's taxonomy), and they exemplify what Morgan describes as the "double life" of models; they vary significantly in the degree to which they are intended to accurately represent a particular target, or are media for experimental manipulation of idealized cultural processes. At the phenomenological end of the spectrum, representational models of data include typological constructs that selectively represent variability in archaeological data on several dimensions: formal (material), spatial, and temporal. Archaeologists also build phenomenological models of data drawn from non-archaeological sources – cultural and natural – that are relevant for interpreting archaeological data as evidence. Assemblages of these target and source models provide the necessary scaffolding for building and evaluating more ambitious explanatory and experimental models of cultural systems and processes, actual and hypothetical.

Archaeology is nothing if not a modeling discipline. Archaeologists model the data they recover from the archaeological record, the sources on which they draw to interpret these data, the specific events and activities that produced the surviving traces, and the encompassing social, cultural, ecological contexts and processes in which these events and activities took place. And yet there has been persistent ambivalence among archaeologists about models and modeling practices. Early advocates of modeling in archaeology were aligned with the emergence of a self-consciously scientific research program in the late 1960s and 1970s, the New Archaeology. But the defining commitment of the New Archaeology – to move beyond mere description of the record and interpretive speculation about the past; to realize genuinely explanatory understanding of the past – was most influentially articulated in terms of a vernacular logical positivism (Wylie 2002: Part 2). The explanatory goals of scientific inquiry were characterized in terms of covering-law models, and a programmatic commitment was made to design inquiry as a program of hypothetico-deductive testing; law-like generalizations about cultural systems and processes were to be systematically tested against archaeological data or, if established on other grounds, applied as explanatory principles to archaeological cases. In practice, however, it is typically models that even the most ardent archaeological positivists build and test, not isolated theoretical or factual claims, much less systems of laws or law-like propositions. They routinely make use of models, framed at a number of different levels of specificity, to explain events and conditions in the cultural past in terms of underlying mechanisms and historically specific processes rather than by subsuming particulars under general regularities. It is more productive, I argue, to think about archaeological practice as a genre of empirically grounded, investigative reasoning with and through models – a perspective elaborated by recent advocates of a "model-based archaeology" (Kohler and van der Leeuw 2007a).

This shift in analytic frame may seem straightforward enough but things quickly become complicated when you consider the range of constructs that archaeologists count as models; these are radically heterogeneous on a number of different dimensions. The task I take up here is to address the question: What are archaeological models? I propose a taxonomy of the kinds of models archaeologists build and use, distinguished by specificity and representational function. In the process I address two further questions: What do archaeologists use models to do? And, how do they learn from models? I take this to be scaffolding necessary for the normative epistemic task, which lies outside the scope of this paper, of addressing questions about what makes for a better or worse models and modeling practice in archaeology, given their diverse purposes.

1. Philosophical resources and archaeological parallels

In framing a taxonomy of archaeological models I draw on a point made with particular clarity by Morgan and Morrison in *Models as Mediating Instruments* (1999): that modeling practice is not well understood if you think of models primarily as tools for operationalizing theory, derived top-down from theory or constructed as "models of theory" for application to real world systems, or as simplified descriptions of phenomena that function as tools for systematizing data built, bottom-up, from the analysis of a specific body of data. Archaeological models are no exception; they are rarely constructed in either of these ways, and even when they approximate to these types of modeling practice their content is often much more complex. In Morrison and Morgan's terms, key classes of archaeological models are autonomous; they incorporate content that is not derived from or reducible to the data they represent or the theories they interpret. As such, they put archaeologists in a position to learn things about an archaeological subject that they could not have learned either from direct empirical investigation or by manipulating – testing, refining, applying – existing theory. That said, I find it useful to think of archaeological models as falling along a spectrum of degrees of abstraction (or idealization) and empirical specificity, with resolutely descriptive, data-systematizing models at the phenomenological end of the spectrum and highly idealized, theoretically motivated models at the other.

Morgan's recent discussion of the "double life" of models is a second useful resource, in this case for understanding the variability of purpose evident in archaeological models (Morgan 2012). She makes the case that models in economics figure both as objects of investigation and as tools for investigation; they support experimental as well as representational uses. As I will show, an important class of archaeological models is quite explicitly designed to support experimental manipulation; they are objects of investigation in Morgan's sense, rather than strictly representational tools. This is a point made in especially compelling terms by Kohler and van der Leeuw when they argue that the value of models, as constructs that mediate between "the real world and ourselves," is that they support the "joint exploration of the model and its target system" (2007: 4).

Finally, I draw on an older philosophical literature on models that anticipates, in some respects, recent philosophical thinking about models in science exemplified by Weisberg's *Simulation and Similarity* (2013), but is particularly useful in an archaeological context because of its focus on the role of analogical reasoning in the construction and use of models. The account of modeling developed by Harré (1970) and by Hesse (1970, 1974) brings into sharp focus the complexity of models themselves, and of the relationships that hold between models and their targets and sources. The taxonomy of archaeological models that I outline here presupposes their argument, now much expanded by Weisberg, that sentential and formal, mathematical models by no means exhaust the range of models that figure in the sciences. Iconic or "picturing" models, including what Weisberg describes as concrete models, play a crucial role in empirical inquiry: they "stand in for…mechanisms of nature of which we are ignorant"; they allow researchers to "picture possible mechanisms for producing phenomena" (Harré 1970: 54). Especially relevant here is the distinction Harré draws between two basic types of iconic model: homeomorphic models, in which source and subject are the same; and paramorphic models, in which these are different. A key feature of paramorphic models, where archaeological practice is concerned, is that they may be "multiply connected" (Harré 1970: 47-49); they incorporate elements drawn from a number of sources relevant for modeling different aspects of archaeological subjects that have no comprehensive contemporary analog.

In developing this taxonomy of archaeological models and modeling practices, I am influenced as well by the magisterial analysis, "Models and Paradigms in Contemporary Archaeology" (1972a) offered by the British archaeologist, Clarke, as the framework for an early and prescient collection of essays, *Models in Archaeology* (1972b), and by the distinctions drawn by Kohler and van der Leeuw in connection with the case they make for a "model-based archaeology" (2007). Both recognize the purpose-specific, partial nature of models. Clarke emphasizes the different functions served by models pitched at different levels of abstraction, lying on a continuum much like that posited by Morgan and Morrison for economics and the physical sciences (1999). Archaeological models include what Clarke calls "mind models" that function like Kuhnian paradigms; operational models that interpret these orienting conceptual models in observational terms; and models that systematize (selectively and economically) complex bodies of data, serving as heuristic devices for visualizing, manipulating, organizing, and comparing observations (Clarke 1972a: 2-5). Together, Clarke argues, models of these various kinds are a crucial resource for generating and articulating explanatory hypotheses. Taking up the cause of archaeological modeling thirty-five years later, the explanatory function of models is primary for Kohler and van der Leeuw: "a model here is just a candidate explanation" (2007: 1). However, invoking Levins on the impossibility of simultaneously maximizing generality, realism, and precision (1966), they also recognize a range of scales and degrees of abstraction in the models archaeologists devise to answer "'how' and 'why' questions" (2007: 1, 7). These are primarily marked by degree of aggregation; the key contrast for Kohler and van der Leeuw is between a new generation of agent-based models and earlier systems models (more of this ancestry shortly). Kohler and van der Leeuw also make a point that figures prominently in Clarke's brief for model-based modes of practice and converges directly on Weisberg's taxonomy of scientific models: that models come in a great many different forms. Their roster of mental, verbal, physical, and formal (mathematical and simulation) models is reminiscent of Clarke's argument that models can be constructed as physical "homomorphic parallels" between model and target or can take the form of formal (mathematical) representations of abstract systems of relationships inherent in the target (1972a: 41). In short, despite an emphasis on discontinuities, these programmatic arguments for "model-based" archaeology reflect significant continuities in evolving archaeological practice to which I hope the taxonomy proposed here does justice.

2. The challenges of archaeological modeling

Some advocates of the explanatorily ambitious New Archaeology did make the case for what they described as a "systems" rather than a "law and order" approach which put modeling at the center of archaeological inquiry (Flannery 1967; Sabloff 1981), which in some respects anticipated arguments made with considerable force in the U.K. by Clarke (1972a). In the discussions of modeling associated with the New Archaeology the emphasis was initially on theory-driven, "whole system" models, usually of an explicitly eco-determinist cast; these were intended to capture the essential causal and structural features of distinct types of cultural systems and the processes by which they adapted to the ecological contexts in which they took shape and evolved over time. But from the outset the constraints on "whole system" modeling and on the use of mathematical and simulation modeling techniques to operationalize archaeological theories of cultural process were recognized to be all but insurmountable in explanatorily interesting cases. In a classic statement dating to 1975, echoed in a number of later assessments, Doran and Hodson identified three pivotal problems. First, they observed, "models which are mathematically tractable are too simple for most archaeological problems" (Doran and Hodson 1975: 315). This is not just a technical constraint. Although computer technology was, even then, making possible simulations that could better cope with the computational challenges of modeling whole systems, a second more fundamental problem is that these models require a level of understanding of the conditions and processes modeled that is "only rarely met in archaeological work" (Doran and Hodson 1975: 315). Finally, an inescapable problem for archaeological modelers noted by Doran and Hodson and reiterated many times since is the "fundamental noisiness" of archaeological data which makes it difficult to empirically assess the descriptive and explanatory claims about the cultural past captured by or derived from these models (Aldenderfer 1991: 230).

Despite this early pessimism about the prospects of ever realizing the explanatory ambitions of the New Archaeology by means of modeling approaches, models are ubiquitous in archaeology. As Kohler and van der Leeuw put it, archaeologists "have drifted *in practice* toward what philosophers of science call a 'model-based' (Giere 1999) or 'semantic' (Lloyd 1988; Suppe 1977) approach to the task of explaining what happened, and why, in prehistory" (2007: 3). This in part due to the proliferation of fast, cheap computer technology but, even with the promise that Doran and Hodson's first problem might be resolved, the archaeological models that now answer the call to explanatory understanding are typically much more narrowly circumscribed than the whole system models initially advocated by allies and critics of the New Archaeology. This reflects, in part, a growing appreciation of the complexity of the human, social "ecodynamics" by which cultural systems modify as much as adapt to their environments (Kohler and van der Leeuw 2007a: 10). If anything, this makes Doran and Hodson's second two concerns even more acute. In response, archaeologists have shifted their focus to building and refining models of specific conditions and processes that are, or that could have been, responsible for specific types of event or forms of life to which the archaeological record bears witness. As Kohler and van der Leeuw describe the mandate for a "model-based archaeology" at this juncture, it is to understand "relatively small-scale" human systems, but to understand them in something closer to their full complexity: as "embedded within…the environments they inhabit and alter" (2007a: 2). At the same time, a broad cross-section of archaeologists have embraced a whole range of more prosaic modeling practices that are resolutely descriptive and phenomenological, but that are no less crucial to the broader explanatory goals of contemporary archaeology.

3. A taxonomy of archaeological models

With these conceptual resources in hand, consider some of the types of work-a-day models that abound in archaeology.

3.1. Phenomenological models of archaeological subject and source data

One prevalent use of models in archaeology is to characterize, in systematic terms, various types of archaeological data, and the diverse experimental and ethnohistoric sources on which archaeologists rely to interpret these data as evidence. These models take a range of forms: mathematical, computational, and in some cases concrete, to use Weisberg's categorization (2013: Chapter 2). They are typically homeomorphic models designed represent variability in the target or source domain. As such, they lie at the phenomenological end of the spectrum of model function marked by Morgan and Morrison although, I will argue, they incorporate much often unrecognized theoretical and interpretive content.

3.1.1. Models of archaeological data

Models of archaeological data typically represent variability on three dimensions: formal, material variability; the spatial distribution of artifacts and features within sites, or of sites and assemblages of artifacts across a region; and chronological trends in the appearance, frequency, and disappearance of artifact types, architectural styles, and cultural formations over time.

Material, formal variability in archaeological data is captured by descriptive typologies, ranging from highly specific artifact typologies aimed at systematizing local variability in material culture to expansive classification schemes that delineate trans-historical cultural formations and trans-regional cultural horizons. At the artifact-specific end of the spectrum, ceramic and lithic (stone tool) typologies have been especially crucial in many contexts as chronologically and spatially sensitive markers that came to anchor the characterization of "archaeological cultures" (from Childe 1929): distinctive assemblages of archaeological material – for example, stylistically distinctive artifacts, house forms, burial rites and subsistence practices that consistently co-occur – that were presumed to be the expression of distinct cultural configurations. So, for example, the late Neolithic culture(s) of western Europe that came to be known as the "Beaker people" were characterized archaeologically by a "package" of artifacts associated with a characteristic type of pottery, and the hunting-intensive Paleo-indian cultures of central North America were named for the distinctive Clovis and Fulsom projectile and spear points in terms of which they were first identified in the 1920s and 1930s. Broader syntheses of archaeological cultures, of the kind posited by Willey and Phillips for the Americas (1958), and by Childe for Europe (1957), characterize broad cultural horizons based on the sequence of appearance and distribution of these co-occurrent classes of archaeological evidence.

The presumption that formal (material) variability of this kind has inherent cultural significance has been a matter of sharp contention within archaeology since at least the 1940s and 1950s, when Brew and Ford, and later Spaulding articulated sharply opposing views about what these models of data represent: that they are selective, purpose-specific impositions by the analyst (Brew 1946; Ford 1954), as opposed to culturally salient features of the archaeological record that archaeologists "discover" (Spaulding 1953a, b; see Adams and Adams 2008 and Wylie 2002 for analysis of this debate). To illustrate the contingency and purpose-specificity of typological systems, Ford offered a thought experiment: a variety of house forms on the fictional Island of Gama Gama characterized by a range of different traits (e.g., roof style, construction on stilts, size, layout) whose variability is continuous across time and space. Although regularities in the distribution and association of these material traits can certainly be identified empirically (indeed, "statistically discovered," as Spaulding had insisted), it is possible to carve material culture at different joints. Shifting the selection of traits will yield different patterns of association and spatial/temporal distribution, and often enough their variability is continuous so that different boundaries can be drawn between types (1954). Brew's point was that archaeological typologies are tools of analysis, constructed as needed to address particular archaeological questions. The typologies that served archaeologists initially in modeling spatial and temporal relations within and between classes of archaeological data may not be a plausible proxy for cultural identity, or be useful in tracking shifts in technologies, subsistence practice, trading relations or social status, to name just areas of archaeological interest.

Spatial distribution models vary dramatically in scale, target, form and purpose. They include, for example, spatial auto-correlation models that delineate artifact drop-zones around hearths and in activity areas, and a range of other models that capture the spatial relations between key features within archaeological sites. Classic examples are models that represent regularities observed in the orientation of burials and associated grave goods in mortuary sites (see the example of a Roman period cemetery in the UK discussed below), and the patterned clustering of functionally distinct rooms in Southwestern pueblos that was the basis for Hill's posit of generationally stable households at Broken K Pueblo (1968), an early demonstration project for the New Archaeology. They include, as well, models of an architectural "grammar" of the kind developed by Glassie for Middle Virginia folk housing: an inventory of geometric forms structured by a basic unit of measurement (the diagonal constitutive rectangles and squares) and a set of grammatical rules for assembling these into canonical house forms (1975). At a regional scale archaeologists develop formal and computational models of the distribution sites or visible features on the landscape, now facilitated by widespread use of geological information systems (GIS). For example, spatial packing models (imported from quantitative geography) were developed to capture the proxemics of settlement hierarchies which, in turn, were the basis for positing regional chiefdoms in Neolithic Europe (Renfrew and Shennan 1982). More recently, landscape archaeologists have developed richly interpretive spatial models of the sacral (rather than political) landscapes in which Neolithic and Bronze Age monuments like Stonehenge are embedded (Parker Pearson and Ramilisonina 2008; Whittle 1997). A related example that incorporates experimental elements (of which, more below) is Llobera's delineation of corridors of movement between Neolithic Galician mamoas, identified both in terms of ease of movement, given regional topology, and the viewscape afforded travellers along these pathways (Llobera 2015). In these cases, digital repositories of spatial data and the analytic power of GIS analyses are a crucial resource; predictive modeling of where archaeological sites of various kinds are likely to occur is now a key component of cultural resource management (Verhagen and Whitley 2011).

Chronological models represent the appearance and disappearance, and related changes in the form and frequency of specific types of material culture over time, and at scales ranging from individual artifact types, cross-type styles and assemblages, to broad cultural formations. The locus classicus for such models is Kroeber's decidedly non-archaeological seriation of changes in fashion in which he determined that, despite the perception of rapid and dramatic change, the proportions that define what is fashionable change very slowly and predictably; his test case was the evolution of styles in women's formal wear from 1845 to 1915 (Kroeber 1919). Influential examples developed to illustrate of these seriation principles in archaeological terms include Deetz and Dethlefsen's classic analysis of changes in the frequency of decorative styles in New England tombstones; they demonstrated the same regular "battleship curve" in stylistic changes over time as had Kroeber (1967). Another example that continues to be used as a basis for building finegrained chronologies in historical archaeology is Binford's formal model of a regular pattern of change in the mean bore hole diameter of clay tobacco pipes produced in Europe and North America between 1600 and 1900, described as "deterministic and mathematical" by Clarke (1972a: 18). Although physical dating techniques are now predominantly the basis for archaeological chronologies, tradition-specific seriation models continue to be a key resource in many contexts. Indeed, although it was widely assumed that local, "relative" chronologies would automatically be replaced when radiocarbon dating was introduced – the "first radiocarbon revolution" (initiated by Libby in the 1950s) – in fact, discrepancies between these systems have been pivotal in raising questions about the accuracy of absolute chronologies that generated the painstaking, sixty-year process of calibrating radiocarbon dating curves – the "second radiocarbon revolution" (Manning 2015: 130-140).

The challenge of establishing spatial-temporal control dominated the initial construction of typological systems in most contexts of archaeological research, but this by no means exhausts the purposes for which they are used. As Boozer observes in a discussion of the "tyranny of typologies" (2015), once these phenomenological models were developed, practitioners often lost sight of the purposes they were designed to serve. They became entrenched as the dominant medium of communication within archaeology; they configure reporting conventions and set the framework for the comparative analyses that were the basis not only for regional models of cultural diversity and evolution, but also the fine-grained analogical comparisons that underpin interpretive claims about the evidential significance of archaeological data. Often they persist even when accumulating data undermines the distinctions they draw and as focal questions change, requiring analysis in terms of traits that track other dimensions of variability. As the disconnect between these models of data and evolving research agendas becomes increasingly strained, the central point made by Brew in the mid-1950s is more relevant than ever: that in constructing typologies archaeologists must choose among a great many observable, measurable traits, so any one selection necessarily reflects specific investigative purposes. In analysis of a problematic typology of domestic Romano-Egyptian house forms, Boozer draws attention to the ramifying downstream consequences of failing to keep the contingency of these models of data clearly in view, reifying them as representations of a fundamental cultural reality and treating them as the framework within which all subsequent research must be conducted (2015: 104-106).

3.1.2 Models of non-archaeological sources

A second important genre of phenomenological modeling in archaeology is of the data drawn from non-archaeological sources on which archaeologists rely to interpret archaeological data as evidence. These are also typically homeomorphic models, in this case of natural or cultural processes that are presumed to be responsible for (or that could have been responsible for) the production, deposition, and preservation or degradation of the types of material that make up the archaeological record: "N-transform" and "C-transform" models, to use language introduced in the 1980s by Schiffer in connection with widely influential account of archaeological inference (1987).

Archaeologists rely on an enormously broad range of other fields, from ethnography and history to biomedicine, ecology, and physics for the background knowledge necessary to build these models. But as useful as these resources are, often archaeologists find that the cultural and/or natural processes of interest to them have not been intensively studied, or not studied at scales or in contexts relevant to archaeological questions. The fields of experimental archaeology and ethno-archaeology have grown up in response to these limitations. At the C-transform end of the spectrum, the Kalinga Ethnoarchaeological Project is one example of a long-running research program in which archaeologists have undertaken their own ethnographic research with the aim of documenting methods of production, exchange networks, and patterns of cultural transmission, in this case, of ceramic technology (Longacre and Hermes 2015). A recent report on this project includes a directional graph of household pottery exchange: a phenomenological model of ethnographic data relevant to the question of whether shifting patterns in ceramic production and exchange can serve as a proxy for intensification in a craft-based agricultural economy (2015: 43). N-transform modeling includes, for example, the uses archaeologists make of well established geological models of soil formation and erosion processes to understand archaeological deposits. But here again archaeologists often develop their own models of the impact that, for example, the activities of burrowing animals and insects can have on archaeological features and stratigraphy: "bioturbation" and "faunalturbation" (Holliday 2004: 271-276). A classic example is Stein's model of the rate at which earthworms can completely turn over an archaeological midden, obscuring archaeological features and redistributing cultural material (1983). A number of experimental archaeologists have taken this a step further, building concrete models designed to provide insight into the processes by which particular classes of artifacts could have been produced or transformed over time into distinctive types of archaeological deposit. Bell (2015) describes a number of experimental projects in England and Europe that involve full-scale recreations of key archaeological features, like earthworks and mounds, house structures and middens, which are then monitored, sometimes over decades, for patterns of erosion and collapse. The identification of weed complexes that are diagnostic of different types of early Neolithic farming practices in Europe (described below) depends on phenomenological models of bio-ecological conditions under which weed and food crop species co-occur, and the results of agricultural experiments designed to model the impact on these plant assemblages of different plant husbandry regimes (Bogaard 2004, 2015).

Recent developments in archaeometalurgy, dietary studies, and radiocarbon dating, among other areas, also illustrate the complexity of putting external resources to work in archaeological contexts, particularly when this requires modeling physical or bio-chemical processes that are affected by and that reciprocally shape human activities. For example, Pollard and Bray (2015) make the case that provenience studies of European Bronze Age metal artifacts has run aground; the complexity of the chemical composition of these artifacts undermines a long-running program of analysis aimed at linking individual artifacts or assemblages to particular sources of raw material. Rather than persist in the attempt to disentangle a signal linked to origin from the noise of degradation – an approach they describe as narrowly scientific – they argue for an alternative that takes as its point of departure the assumption that the chemical components of these objects are themselves dynamic, the product of jointly social and technological/material histories of circulation, reuse, repurposing. To this end they identify distinct types of copper based on the presence or absence of trace elements that reflects the differential effects on them of oxidation and interaction under conditions of repeated melting, mixing, and recycling: a phenomenological model of variability in the chemical composition of this class of material (2015: 118-120). Similarly, complex phenomenological modeling is required to make use of stable isotope and trace element analysis of skeletal material as a basis for reconstructing dietary profiles; in an example discussed below, this involved modeling the clines in the chemical composition of groundwater across England and Europe in order to estimate the geographical origins and lifetime travels of individuals buried in a late Romano-British cemetery. Finally, the process of refining radiocarbon dates likewise depends on integrating evidence relating to physical, climatic, ecological conditions that can affect the ratio of radioactive to stable carbon in organic matter recovered from archaeological contexts: for example, fluctuations in atmospheric carbon levels, carbon sinks, patterns of carbon uptake, sources of contamination. While these N-transform models focus on factors affecting the radiocarbon signal itself, the characteristic approach of the "third radiocarbon revolution" has been a "pragmatic Bayesianism" (Manning 2015: 140-141; Bayliss and Whittle 2015: 217-218): a strategy of modeling the probability distributions for a range of radiocarbon dates that could have been produced by an organic sample. This approach takes into account not only N-transform processes that affect the measured ratio of stable to radioactive carbon in a sample, but also multiple lines of archaeology-source evidence including, for example, stratigraphic superposition and seriation.

These examples of phenomenological models – models of data associated with archaeological subjects and sources – illustrate the now well-established point that seemingly straightforward descriptive, representational models are actually quite complex conceptually. Even when, on the face of it, they seem to be abstracted directly from the phenomena, and their source and subject is ostensibly the same, they incorporate substantial purpose-specific theoretical and interpretive, as well as descriptive, content.

3.2. Scaffolding models: measurement tools and guides to interpretation

The complexity of phenomenological models arises, not just because their targets and sometimes their sources are complex, but because their purposes are complex; they are intended to serve a number of inferential and investigative purposes beyond systematizing the data they represent. Models of source data are intended to capture projectable relations between the physical traces that survive in the archaeological record and the antecedent events, conditions, and processes that produced them. Well constructed, they are mediators in a rather different sense than that introduced by Morgan and Morrison; they function in archaeological interpretation as auxiliary hypotheses that mediate the interpretation of archaeological data as evidence relevant for positing and testing hypotheses about the archaeological target of interest: cultural events and activities, conditions of life, systems and processes. Here are two examples in which archaeologists make use of phenomenological models of source and subject data in this scaffolding sense, as *measurement tools or interpretive guides*.

The Roman Diaspora Project. In this project archaeologists make sophisticated use of an array of N-transform and C-transform models to specify the likely origins and lifetime travel of individuals buried in a late period Roman cemetery in Winchester, U.K. (Eckardt et al. 2009, Leach et al. 2009). The catalyst for this study was an interpretation, dating to the 1970s, of the formal traits of burials in this cemetery – skull morphology; epigraphy, statuary, and associated artifacts; and patterns of spatial orientation and distribution – that were taken to be markers of cultural affiliation and status associated with degree of "Romanization," resistance to Roman rule, and North African or Eastern European origins as "incomers." The Diaspora project team undertook to develop dietary profiles based on isotope and trace element analysis of bone marrow and dental cores that allowed them to determine where individuals were likely born and spent their early years, as well as where they had lived and traveled. This analysis depends crucially on two types of phenomenological models mentioned earlier: models of cross-continent clines in the mineral composition of groundwater, and of the isotopic signatures of various types of diet. The upshot was that several individuals who had been identified originally as incomers had most likely been born and raised in the vicinity of the cemetery where they had been buried; others who most likely originated in North Africa were buried in graves that had been interpreted as elite; and several children proved to have originated outside the region where they were buried. These scaffolding models were, then, the basis for characterizing the status and mobility of individuals buried at Winchester in terms that pose a substantial challenge to the earlier interpretation of their remains and the canonical, text-based accounts of population diversity and mobility in he Roman Empire that had informed this interpretation (Eckardt et. al 2009; Leach et. al 2009).

Farming practice in Neolithic Eastern Europe. The objective of this project was to adjudicate between competing models of the farming practices that had been adopted in various locales as agricultural subsistence patterns were taking shape in Eastern Europe through the Mesolithic and Neolithic transition 10,000 years ago (Bogaard 2004). Each of these models had some support, and each had different explanatory implications for understanding the impact of this major transition in subsistence practice on settlement patterns, material culture, social relations, and population mobility. It had proven difficult to discriminate between these competing models not least because the contemporary analogues for each type of practice involve suites of plants – cultigens and weeds – now adapted to ecological settings that have been continuously reconfigured through millennia of intensive human activity. To determine which types of farming practice were adopted at various junctures and in different locales, Bogaard developed a series of scaffolding models of functional plant ecology that incorporate the phenomenological models of experimental and bio-ecological data mentioned earlier. These scaffolding models represent the distinctive complement of weeds associated with each type of crop and crop management, for example, intensive rather than extensive agriculture, shifting rather than fixed-plot cultivation, and spring rather than winter cropping (2004: 154-159). The background knowledge from plant science and archaeobotany provided an initial set of posits about these weed complexes, refined through a program of experimental archaeology designed to recreate hypothesized Neolithic farming practices and document their ecological viability, labor demands, yield, and archaeological signatures. Bogaard thus constructs archaeological proxies for the major crop husbandry models on offer and uses these lower level scaffolding models as the basis for systematically assessing the representational plausibility of each of them in specific prehistoric contexts.

In these two cases archaeologists build an assemblage of homeomorphic phenomenological models of source as well as archaeological data that, together, serve as scaffolding for the interpretation of archaeological data as evidence of specific past events and practices. As interpretive scaffolding, these models serve as the basis for analogical arguments that make possible systematic comparisons between the sources of interpretation (natural and/or cultural processes observed in the present) and the archaeological targets or subject of interpretation (Shelley 1999; Wylie 1985, 2002). While no one line of evidence based on scaffolding models is likely to be decisive, they can be used very effectively, in combination, to build and test broader reconstructive and explanatory claims about the past. The principle at work here is that such "cables" of argument will be compelling to the extent that the scaffolding used to construct distinct lines of evidence are causally and epistemically independent of one another; this "vertical independence" is the key to ensuring that they have the capacity to be mutually constraining (Wylie 2011: 387).

3.3. Reconstructive and explanatory models

As these examples suggest, assemblages of scaffolding and phenomenological models are the basis for building explanatory models of the cultural past of the kind that are identified as the central goal of archaeology. These last are *complex paramorphic models* either of particular archaeological targets (specific past cultures) or of generalizable types of cultural system or cultural process. Consider three reconstructive models that address explanatory questions, and that bring into sharp focus two key dimensions on which archaeological modeling varies: in degree of idealization as opposed to representational fidelity to a specific subject past; and in the non-representational use of models in an experimental mode, as objects of investigation.

Representational models: the Desert Archaic simulation. This is a classic whole-system simulation of prehistoric subsistence practice in the Great Basin (U.S.) known as the "Desert Archaic" that was developed by Thomas (1972), in the spirit of the New Archaeology, to determine whether the Shoshone seasonal round documented in the 1930s could be projected back in time: whether it could be treated as, in effect, a homeomorphic model of the subsistence practices of antecedent, archaeologically identified cultures in the region. Thomas' strategy was, first, to develop a computational model of the source: Steward's 1938 ethnographic account of the seasonal round of Shoshone foragers in the Great Basin. He then "reduce[d] the activities [modeled] to their correlative tool assemblages," ran this single year model a thousand times, corrected for the impact of less frequently available resources, and in this way generated aggregate patterns of artifact deposition for the region. He then tested the model output against the results of archaeological surveys in the region, establishing that drop patterns for most artifact classes did conform to expectations, most strikingly in case of sites located in open areas where they had not previously been archaeologically documented. This process also threw into relief several empirical and inferential weaknesses inherent in his model, for example, the tool types differentiated by edge angle proved not to be reliably diagnostic of the functionally different types of site posited by the model. In short, one result of testing the expectations generated by his simulation of the Shoshone ethnohistoric seasonal round was to make it clear that the lithic typologies on which archaeologists conventionally relied in this region – phenomenological models of this class of archaeological data – were too coarse-grained with respect to tool function to be reliable scaffolding for the interpretation of these data as evidence relevant to questions about subsistence practice.

This reconstructive, explanatory model is explicitly representational and homeomorphic, at least aspirationally; it is intended to capture 'how actually' Shoshone foragers exploited the resources afforded by the Great Basin over the thousand year period pre-contact. It is credible to the extent that the models of data (source and subject) used to generate test outcomes are themselves well established and fit for purpose, and to the extent that they are also causally and epistemically independent of the overarching model they are meant to test. The principle at work here is that the material signature posited for each element of the Shoshone seasonal round should not nepotistically ensure that archaeological data will conform to expectation; I describe this elsewhere as a requirement of "vertical independence" (Wylie 2011: 381).

Hybrid representational and experimental models: Gila Naquitz (The Early Mesoamerican Village). This is a more sophisticated computational model of the evolution of the foraging and farming practices of a hypothetical microband developed by Flannery and Reynolds in the mid-1980s (1986); it answers Flannery's earlier call for attention to modeling approaches when the New Archaeology was taking shape (1967). One goal of this modeling exercise was to simulate the process of incremental change in subsistence practices evident in the archaeological record of a cave site in the Oaxaca valley (8,700-6,600 BC). The simulation developed was, in this respect, a representational model built up from an assemblage of subsidiary homeomorphic scaffolding models; Flannery and Reynolds report that they did "everything we could think of to make the model realistic" with respect to to the climate and paleoecology of Gila Naquitz, and the "wide spectrum" repertoire of foraging resources exploited by its late Holocene occupants that had been documented archaeologically (1986: 436). In addition, however, this model incorporates a crucial experimental component; Flannery and Reynolds manipulate key elements of the model to test the impact of different intergenerational processes of community learning from trial and error in face of fluctuating climatic and ecological conditions (1986: 441). Flannery's larger purpose is to assess the credibility of competing explanatory accounts of how and why agriculture developed, apparently independently, in a great many locales around the world at roughly the same time (10,000-5,000BC). He argues that archaeological and paleo-ecological evidence calls into question conventional appeals to exogenous forcing factors like environmental crisis, and urges archaeologists to consider the explanatory potential of accounts that posit more gradual processes by which incipient agriculture emerged as an extension of foraging practices, driven as much by internal social processes as by pressures to adapt to climatic variation in the early Holocene.

Flannery and Richard's strategy was to develop a computational model in two stages, simulating first the evolution of wide spectrum foraging in the area of Gila Naquitz, and then the emergence, in this context, of incipient agriculture. To make these models as realistic as possible, the repertoire of subsistence activities represented in each of these two stages was based on archaeological data that establish what resources were being exploited when the cave at Gila Naquitz was occupied; the climate was modeled as generating wet, dry, and average years randomly, based on paleoclimatic data; and the assignment of values to such variables as availability, yield, labor requirements and dietary return for the dozen key sources of food exploited by the microband was based on scaffolding models of region-specific archaeological and paleoecological data. In addition, Flannery and Reynolds developed several hypothetical subroutines to model the information-sharing and decision-making practices by which the hypothetical foragers could learn from trial and error experimentation with different resource collecting schedules and modifications to their repertoire of collecting strategies. This jointly realistic and experimental simulation was initially run for foraging strategies alone and showed rapid improvement in efficiency until, after about 500 iterations, it proved hard to improve on the established pattern; at this point positive feedback for change shifted to negative feedback encouraging conservatism. Then they introduced several archaeologically documented incipient agricultural strategies to the repertoire – for example, clearing thorn forest to allow weedy plants (beans, and squash) to colonize, and deliberately planting maize and squash seeds – and simulated another learning process. In this second stage simulation the foraging strategies of the hypothetical microband gradually shifted, incorporating the full suite of agricultural strategies until they reached stable performance in 550 iterations.

The adequacy of the model as a representation of the real system should be evaluated in two ways, Flannery and Reynolds argue. First, as with Thomas' model, it should be assessed in terms of the correspondence of model outcomes with actual outcomes documented archaeologically – specifically, outcomes not built into the original simulation. Key measures of success were congruence in the relative emphasis on each plant species exploited for both models; the order in which changes in practice and shifts in emphasis emerge in the case of incipient agriculture model; and in the time frame for stabilization in both models. Second, Flannery and Reynolds add an assessment of model robustness that depends on experimental manipulation of model parameters and inputs. For example, to assess the role and plausibility of the multigenerational learning processes they had built into the foraging model they disabled the information feedback loop and found that performance peaked early but then oscillated in a manner quite unlike anything suggested by the archaeological record. They also changed the environmental conditions and population density under which agricultural strategies were adopted and found that the random alternation of wet, dry, and average years is a crucial stimulus for the experimentation and learning processes that, in the simulation, give rise to incipient agriculture. Under conditions of substantially greater climatic or populational stress the hypothetical band proved to be more conservative, while under conditions of lower stress the band's subsistence strategies fluctuated without the directional intensification of practice observed archaeologically.

This, then, is a computational paramorphic model poised between modeling 'how actually' and 'how possibly' incipient agriculture took shape in the Oaxaca valley. It incorporates a number of subsidiary homeomorphic models – analytic and descriptive models of climate, ecology, subsistence strategy – but reaches beyond them to model archaeologically enigmatic socio-cognitive factors. As such, this model is autonomous in the sense outlined by Morrison and Morgan (1999) and, given this autonomy, it manifests the double life discussed more recently by Morgan (2012). The simulation developed by Flannery and Reynolds serves both as a tool for investigating the archaeological subject, for which representational adequacy is key, and as an object of investigation in its own right. Experimental manipulation of the model generated a number of insights into causal dynamics of the system that could not be directly investigated, and suggests that intergenerational learning from trial and error can result in extensions of foraging practices that ultimately transform them into agricultural practices. In short, exploration of the hypothetical world of the model provides at least preliminary support for their more general contention that you do not necessarily need to posit a prime mover external to the system to account for major cultural transformations; these may well be explicable in terms of incremental changes in a number of interlinked social practices and ecological conditions.

Sophisticated models designed to simulate complex, path-dependent interactions between multiple causal and ecological factors, including decision making processes and social dynamics, have since been developed in a number of connections. In a recent optimal foraging model of the Pleistocene colonization of Sahul (Australia-New Guinea), O'Connell and Allen are explicit in rejecting "minimalist" models that downplay the cognitive and technological sophistication of these incoming foraging populations (2012: 5). Their model incorporates ethnographically and ecologically informed sub-models of decision-making that had reciprocal impact on the complex environments the entered, under conditions of short-term climatic instability (2012: 12). Contributors to *Model-Based Archaeology* likewise emphasize the complexity of the processes by which human populations modify their environments and, in turn, reconfigure their practices and technologies in response to environments they have in part created (Kohler et al. 2007: 61). Their agent-based models are built up from a great many scaffolding models that are as realistic as possible, given available archaeological and paleoecological data, but also incorporate what Kohler et. al refer to as "cultural algorithms" (2007: 89). These models are then a platform for simulating the impact of various types of stress and shifts in social organization or learning process. For example, Wilkinson et al. (2007) develop a baseline model of an Early Bronze Age Mesopotamian settlement that they describe as a plausible, but "'static' view of settlement and land use" (2007: 192). They then build agent-based simulations that incorporate a number of key behavioral patterns (reciprocal exchange, kinship and subsistence activities) in order to explore the effects of chronic or acute labor shortages and disease on settlement population and household viability. These simulations are not representational, but they provide an insight into factors that affect settlement sustainability "from the standpoint of the individual household agents" rather than at the level of the settlement as a whole and its "aggregate properties" (2007: 203, 201). They illustrate "different evolutionary trends that households can follow" within the same socio-ecological environment, and in the process bring into focus conditions under which aggregate system behavior can abruptly change as a consequence of agent-level decisions that push the system toward "a hidden resource threshold" (2007: 206).

Experimental models: Hopi agriculturalists in the U.S. Southwest. This is a suite of even more hypothetical 'how possibly' models developed by Hegmon (1991) and Robertson (1997) to explore the impact of different food sharing practices on the survival rates of households in a small-scale farming community, and the potential for (some of) these practices to generate stratification (Robertson 1997: 13). Although they rely on well established phenomenological and scaffolding models of the paleoecology, settlement patterns, and social organization in the prehistoric Southwest, their purpose is not to model the actual or potential dynamics of any particular ancestral Hopi farming community. Rather it is to investigate various properties and dynamics of the model itself. Hegmon's initial model is a highly idealized computational model designed to simulate the survival rates of a dozen households in a hypothetical farming community that practices traditional ethnographically documented Hopi-style maize farming on three different kinds of fields under typical Southwest conditions of crop yields in wet and dry years. She asks what the survival rates for individual households would be if, rather than sharing food in dry, low-yield years, each household kept its own produce to itself, if they shared only in years of scarcity, or if all households consistently pooled their produce. For multiple runs of twenty-year simulation cycles she found that households had only a 45% survival rate if they relied exclusively on their own produce. By contrast, on a "restricted sharing" scenario the survival rate was 80% for households in communities of four or more households. Pooling all produce generated equivocal results.

A related model developed by Robertson (1997) relies on the same basic set-up but simulates the effects, over time, of two different sharing arrangements: an egalitarian, "credit-dispersing" strategy by which the shortfall of individual households is met through redistribution of a pool of total community surplus, and a "credit concentrating" procedure by which the household with the largest surplus has the first opportunity to redistribute, starting with households with the smallest shortfall and meeting the needs of as many deficit households as its surplus permits. Robertson finds that "restricted sharing practices not only enhance household survival rates but also have the potential to lead to the growth of rather high levels of both debt and credit without any overt political maneuvering" (1997: 13). For 100 runs of forty-year simulation cycles most households canceled out their credit or debt to one another, but some households did significantly better than others. Crucially, Robertson reports that these results were not tightly correlated with differences in the quality of the fields allocated to a household, and that they are robust even under the credit dispersing strategy, with some amplification under the credit concentrating strategy.

Despite their reliance on realistic, if highly idealized, baseline models of the regional ecology and of ancestral Hopi farming practices, these models are constructed primarily for purposes of experimentation, not to simulate the dynamics of any actual archaeological community as in the case of the models developed by Thomas (1972), Flannery and Reynolds (1986), or Wilkinson et al. (2007). The value of these models is heuristic; they allow Hegmon and Robertson test hypothetical claims about the cumulative effects that different social arrangements could potentially have on the distribution of wealth in Southwestern communities that cannot be directly tested archaeologically. In the process, they show that significant social stratification can emerge without having to introduce the mechanisms of a chiefdom-style political formation. Kohler et al. (2007) describe similar goals in connection with an agent-based simulation of the performance of farming households in the context of a suite of highly realistic, archaeologically constrained resource models of the environment in which prehispanic settlement patterns would have evolved in southwestern Colorado (AD 600-1300). Their ultimate goal is to understand archaeologically documented cycles of colonization, settlement concentration, and depopulation in the region (2007: 63) but their primary interest in the simulation is in "abstract properties of the simulated exchange systems" (2007: 96). They defer assessment of the archaeological plausibility of these simulations, noting that their discussion of factors that make a difference in this simulation "is purely hypothetical"; the value of the simulation is its "power…to show us alternative worlds" which, even if they did not exist, "may be able to tell us many things about the worlds that did" (2007: 99-100).

4. Conclusions

I draw three conclusions from this taxonomy of archaeological models.

First, the diversity of archaeological modeling practices reinforces analyses developed in other contexts, most pointedly, in philosophical terms, by Weisberg in *Simulation and Similarity* (2013), and by Kohler and van der Leeuw in their brief for model-based archaeology (2007). What counts as adequacy in model construction depends fundamentally on what the model in question is meant to do, and this is an irreducibly pragmatic issue: a matter of research priorities, technical capabilities, empirical and interpretive resources.

Second, reconstructive and explanatory models of the cultural past are assemblages of smaller scale phenomenological and scaffolding models that, together, represent specific factors, variables or processes presumed to constitute the archaeological target, whether this is a particular event, a local set of practices, or large-scale cultural systems and long-term processes. Taken as a whole, these assemblages are multiply connected paramorphic models; they are constructed analogically, and their content derives from homeomorphic models of subject-domain archaeological data and of source-domain data drawn from a diverse array of other fields.

Finally, models at one scale, or models of one dimension of a cultural system or life-world, are the basis for testing and refining models pitched at other scales or that represent other dimensions of the target. Claims about the empirical, theoretical credibility of an explanatory account of the past typically concern the credibility of model components, themselves narrowly specified models of particular aspects of the past cultural context or process or system under study. On a modeling approach, evidential constraints are thus diffuse, impinging on archaeological understanding of the cultural past at a number of points; testing model outputs against source data or archaeological data may suggest the plausibility of the model as a whole, but more immediately it establishes the credibility of specific elements of the assemblage. The hypothetico-deductive account of confirmation and testing that was vigorously advocated by New Archaeologists and still influences programmatic debate in archaeology captures little of what matters in this process of building, refining, manipulating and assessing explanatory models in archaeology. When these models are compelling, their credibility arises from mutually constraining and reinforcing relations among subsidiary models rather than from any one self-warranting epistemic foundation.

References

Adams, W. Y., & Adams, E. W. (2008). *Archaeological Typology and Practical Reality: A Dialectical Approach to Artifact Classification and Sorting*. Cambridge: Cambridge University Press.

Aldenderfer, M. (1991). The Analytical Engine: Computer Simulation and Archaeological Research. *Archaeological Method and Theory, 3*, 195–247.

Bayliss, A., & Whittle, A. (2015). Uncertain on Principle: Combining Lines of Evidence to Create Chronologies. In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 213-242). London: Routledge.

Bell, M. (2015). Experimental Archaeology at the Crossroads: A Contribution to Interpetation or Evidence of 'Xeroxing'? In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 42-58). London: Routledge.

Bogaard, A. (2004). *Neolithic Farming in Central Europe: An Archaeobotanical Study of Crop Husbandry Practices*. New York: Routledge.

———. (2015). Lessons from Modeling Neolithic Farming Practice: Methods of Elimination. In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 243-254). London: Routledge.

Boozer, A. L. (2015). The Tyranny of Typologies: Evidential Reasoning in Romano-Egyptian Domestic Archaeology. In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 92-109). London: Routledge.

Brew, J. O. (1946). The Use and Abuse of Taxonomy. In J. O. Brew (Ed.), *The Archaeology of Alkali Ridge, Southeastern Utah* (pp. 44-66). Cambridge, Massachusetts: Harvard University Press.

Childe, V. G. (1929). *The Danube in Prehistory*. Oxford: Oxford Univesity Press.

———. (1957). *The Dawn of European Civilization* (6th Edition ed.). London: Kegan, Paul.

Clarke, D. L. (1972a). Models and Paradigms in Contemporary Archaeology. In D. L. Clarke (Ed.), *Models in Archaeology* (pp. 1-60). London: Methuen.

———. (Ed.). (1972b). *Models in Archaeology*. London: Routledge.

Deetz, J. F., & Dethlefsen, E. S. (1967). Death's Head, Cherub, Urn and Willow. *Natural History, 76*, 29-37.

Doran, J. E., & Hodson, F. R. (1975). *Mathematics and Computers in Archaeology*. Edinburgh: Edinburgh University Press.

Eckardt, H., Chenery, C., Booth, P., Evans, J. A., Lamb, A., & Müldner, G. (2009). Oxygen and Strontium Isotope Evidence for Mobility in Roman Winchester. *Journal of Archaeological Science, 36*, 2816-2825.

Flannery, K. V. (1967). Cultural History versus Cultural Process: A Debate in American Archaeology. *Scientific American, 217*(1), 119-122.

Flannery, K. V., & Reynolds, R. G. (1986). Simulating Foraging and Early Agriculture in Oaxaca. In K. V. Flannery (Ed.), *Gila Naquitz: Archaic Foraging and Early Agriculture in Oaxaca, Mexico* (pp. 433-508). New York: Academic Press.

Ford, J. A. (1954). Comment on A. C. Spaulding, 'Statistical Techniques for the Discovery of Artifact Types. *American Antiquity, 19*(4), 390-391.

———. (1954). On the Concept of Types. *American Anthropologist, 56*, 42-57.

Glassie, H. (1975). *Middle Virginian Folk Housing*. Knoxvill TN: University of Tennessee Press.

Harré, R. (1970). *The Principles of Scientific Thinking*. Chicago: University of Chicago Press.

Hegmon, M. (1991). The Risks of Sharing and Sharing as Risk Reduction: Interhousehold Food Sharing in Egalitarian Societies. In S. A. Gregg (Ed.), *Between Bands and States* (pp. 309-329). Carbondale Illinois: Southern Illinois University Press.

Hesse, M. (1970). *Models and Analogies in Science*. Notre Dame, Indiana: Notre Dame University Press.

———. (1974). *The Structure of Scientific Inference*. London: Macmillan.

Hill, J. N. (1968). Broken K Pueblo: Patterns of Form and Function. In L. R. Binford & S. R. Binford (Eds.), *New Perspectives in Archaeology* (pp. 103-142). Tucson: University of Arizona Press.

Holliday, V. T. (2004). *Soils in Archaeological Research*. Oxford: Oxford University Press.

Kohler, T. A., Johnson, C. D., Varien, M., Ortman, S., Reynolds, R. G., Kobti, Z., . . . Yap, L. (2007). Settlement Ecodynamics in the Prehispanic Central Mesa Verde Region. In T. A. Kohler & S. E. van der Leeuw (Eds.), *The Model-Based Archaeology of Socionatural Systems* (pp. 61-104). Santa Fe, NM: SAR Press.

Kohler, T. A., & van der Leeuw, S. E. (2007a). Introduction: Historical Socionatural Systems and Models. In T. A. Kohler & S. E. van der Leeuw (Eds.), *The Model-Based Archaeology of Socionatural Systems* (pp. 1-12). Santa Fe, NM: SAR Press.

———. (Eds.). (2007b). *The Model-Based Archaeology of Socionatural Systems*. Santa Fe, NM: SAR Press.

Kroeber, A. L. (1919). On the Principle of Order in Civilization as Exemplified by Changes of Fashion. *American Anthropologist, 21*(3), 235-263.

Leach, S., Lewis, M., Chenery, C., Müldner, G., & Eckhardt, H. (2009). Migration and Diversity in Roman Britain: A Multidisciplinary Approach ot the Identification of Immigrants in Roman York, England. *American Journal of Physical Anthropology*. doi: 10.1002/ajpa.21104

Levins, R. (1966). The Strategy of Model Building in Population Biology. *American Scientist, 54*(4), 421-431.

Llobera, M. (2015). Working the Digital: Some Thoughts From Landscape Archaeology. In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 173-188). London: Routledge.

Longacre, W. A., & Hermes, T. R. (2015). Rice Farming and Pottery Production Among the Kalinga: New Ethnoarchaeological Data from the Philippines *Journal of Anthropological Archaeology*, 38: 35-45. doi: 10.1016/j.jaa.2014.09.005

Manning, S. W. (2015). Radiocarbon Dating and Archaeology: History, Progess and Present Status. In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 128-158). London: Routledge.

Morgan, M. S. (2012). *The World in the Model: How Economists Work and Think*. Cambridge: University of Cambridge Press.

Morgan, M. S., & Morrison, M. (Eds.). (1999). *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge: Cambridge University Press.

Morrison, M., & Morgan, M. S. (1999). Models as Mediating Instruments. In M. S. Morgan & M. Morrison (Eds.), *Models as Mediators: Perspectives on Natural and Social Science* (pp. 10-38). Cambridge: Cambridge University Press.

O'Connell, J. F., & Allen, J. (2012). The Restaurant at the End of the Universe: Modelling the Colonisation of Sahul. *Australian Archaeology, 74*, 5-16.

Parker Pearson, M., Cleal, R., Marshall, P., Needham, S., Pollard, J., Richards, C., . . . Richards, M. (2007). The Age of Stonehenge. *Antiquity, 81*, 617-639.

Parker Pearson, M., & Ramilisonina. (1998). Stonehenge for the Ancestors: The Stones Pass on the Message. *Antiquity, 72*, 308-326.

Pollard, M., & Bray, P. (2015). The Archaeological Bazaar: Scientific Methods for Sale? Or: 'putting the "arche-" back into archaeometry? In R. Chapman & A. Wylie (Eds.), *Material Evidence: Learning from Archaeological Practice* (pp. 113-127). London: Routledge.

Renfrew, C., & Shennan, S. (Eds.). (1982). *Ranking, Resource and Exchange: Aspects of the Archaeology of Early European Society*. Cambridge: Cambridge University Press.

Robertson, I. G. (1997). Sharing, Debt, and Incipient Inequality in Small-Scale Agricultural Economies: A Computer Simulation. Presented at the 62nd annual meeting of the Society for American Archaeology (Nashville TN).

Sabloff, J. A. (2008). *Archaeology Matters: Action Archaeology in the Modern World*. Walnut Creek, CA: Left Coast Press.

Salmon, M. H. (1978). What Can Systems Theory Do for Archeology? *American Antiquity, 43*, 174-183.

Schiffer, M. B. (1987). *Formation Proceses of the Archaeological Record*. Albuquerque, New Mexico: University of New Mexico.

Shelley, C. (1999). Multiple Analogies in Archaeology. *Philosophy of Science, 66*(4), 579-605.

Spaulding, A. C. (1953a). Review of *Measurements of Some Prehistoric Design Developments in the Southeastern States* (Ford, 1952). *American Anthropologist, 55*, 588-591.

Spaulding, A. C. (1953b). Statistical Techniques for the Discovery of Artifact Types. *American Antiquity, 18*(4), 305-313.

Stein, J. K. (1983). Earthworm Activity: A Source of Potential Disturbance of Archaeological Sediments. *American Antiquity, 48*(2), 277-289.

Steward, J. H. (1938). *Basin-Plateau Aboriginal Sociopolitical Groups* (Vol. 120). Washington D. C.: Bureau of American Ethnology.

Taylor, W. W. (1948). *A Study of Archeology*. Carbondale Illinois: Southern Illinois University Press.

Thomas, D. H. (1972). A Computer Simulation of Great Basin Shoshonean Subsistence and Settlement Patterns. In D. L. Clarke (Ed.), *Models in Archaeology* (pp. 671-703). London Methuen.

Verhagen, P., & Whitley, T. G. (2012). Integrating Archaeological Theory and Predictive Modeling: A Live Report from the Scene. *Journal of Archaeological Method and Theory, 19*(1), 49-100.

Weisberg, M. (2013). *Simulation and Similarity: Using Models to Understand the World*: Oxford University Press.

Whittle, A. (1997). Remembered and Imagined Belongings: Stonehenge in its Traditions and Structures of Meanings. *Proceedings of the British Academy, 92*, 145-166.

Wilkinson, T. J., Gibson, M., Christiansen, J. H., Widell, M., Schloen, D., Kouchoukos, N., . . . Tenney, J. (2007). Modeling Settlement Systems in a Dynamic Environment: Case Studies from Mesopotamia. In T. A. Kohler & S. E. van der Leeuw (Eds.), *The Model-Based Archaeology of Socionatural Systems* (pp. 175-208). Santa Fe, NM: SAR Press.

Willey, G. R., & Phillips, P. (1958). *Method and Theory in American Archaeology*. Chicago: University of Chicago Press.

Wylie, A. (1985). The Reaction Against Analogy. *Advances in Archaeological Method and Theory, 8*, 63-111.

———. (2002). *Thinking from Things: Essays in the Philosophy of Archaeology*. Berkeley, California: University of California Press.

———. (2011). Critical Distance: Stabilising Evidential Claims in Archaeology. In P. Dawid, W. Twining & M. Vasiliaki (Eds.), *Evidence, Inference and Enquiry* (Vol. Proceedings of the British Academy 171). London: Oxford University Press.