

## Complex Systems and Archaeology

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A complex system, according to Mitchell, presents “large networks of components with no central control and simple rules of operation giv[ing] rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution” (2009:13). Such systems exhibit emergent and self-organizing behaviors. They commonly exhibit “frustration”—a condition in which it is impossible to satisfy all competing interests within the constraints imposed (Sherrington 2010). They frequently exist in far-from-equilibrium conditions. They are not merely complicated—meaning that they have many “moving parts”—but they also exhibit non-linear interactions involving structural contingencies or positive feedbacks. In this chapter I survey the implications for archaeology of the not-fully-formed theories of such systems, and the attempts by archaeologists to employ aspects of complexity theory, and its methods, in the study of prehistory.

Before beginning, though, I need to demarcate the territory. Many archaeologists immediately connect the term complexity with the cultural-evolutionary literature of the 1950s and 1960s, and the large literature in archaeology dealing with how “more complex” societies (meaning societies exhibiting inequalitarian social relations and political hierarchies) evolved from more egalitarian, smaller-scale societies. This is an interest of complexity theory—since it involves the emergence of new political actors, levels of organization, and social relations—but the scope of complexity theory is much broader, and encompasses even the smallest-scale human societies (and, for that matter, societies of ants, and networks of neurons inside an ant’s brain). Unlike many of the approaches outlined in this book, complexity theory is not first of all for and by archaeologists. It is therefore legitimate to wonder whether it has anything useful to offer us.

As we explore the territory covered by complexity theory we shall see that its borders are unguarded and its inhabitants diverse. Archaeologists—especially those with an evolutionary orientation—wander freely about, either selecting particular concepts or just drifting. Physicists, biologists, and economists are quite common. While abundant, mathematicians and computer scientists tend to be crepuscular because they are in such demand. Historians, political scientists, and ecologists likewise make important contributions to this community.

The web of interests connecting these diverse actors consists of—

- A real interest in theory seeking commonalities across levels of organization within a system, and across abiotic and biotic systems of various sorts;
- A special attraction to systems composed of many moving parts—dynamic systems—and the patterns that emerge from the interactions of these components through time;
- A quantitative orientation and a commitment to computation;
- Dissatisfaction with traditional, reductive practices as embodied by the positivistic, hypothesis-testing, highly analytic approach to science most of us learned in high school—especially since such approaches cope poorly with highly connected complex systems;

- An attraction to asking big, often transdisciplinary questions that may be shunned by disciplinary approaches, and a willingness to try to take a look at whole systems, even if it is a crude look (Gell-Mann 1994), particularly through the use of computer models.

Several additional characteristics of complexity research are reviewed by McGlade and Garnsey (2006). Here I begin by examining some of the roots of these tendencies in anthropology, archaeology, and elsewhere. Then we'll discuss in more detail some key concepts and methods in the study of complex systems (hereafter "CS"), with special attention to what archaeologists have done, or might do, with these approaches.

## **Some History**

### *Cybernetics and General Systems Theory*

The important involvement of some of anthropology's leading lights in the mid-20<sup>th</sup>-century development of cybernetics is a little known but fascinating story. Cyberneticians studied mechanisms for control and communication in both machines and living organisms. Cybernetics stood in relation "to the real machine—electronic, mechanical, neural, or economic—much as geometry stands to a real object in our terrestrial space" (Ashby 1956:2). In other words, cybernetics abstracted from real systems to attempt to study the general properties of all systems, with particular interest in processes such as feedback, stability, amplification, and regulation, accepting as underlying metaphor that a system is a machine of greater or lesser complexity. From the mid-1940s through the early 1950s a core group of about 20 scientists, including anthropologist-psychologist Gregory Bateson and ethnographer Margaret Mead, occasionally joined by Clyde Kluckhohn, met in a series of nine conferences funded by the Josiah Macy, Jr., Foundation to discuss the underpinnings of what came to be known as cybernetics (Heims 1991). Other members of the core group were mathematicians John von Neumann and Norbert Wiener. It is probable that Bateson's unique evolutionary and ecological orientation, his anti-reductionist tendencies, and his extremely wide-ranging interests, were all reinforced by these interactions.<sup>1</sup>

The Macy conferences eventually fell apart; a participant in some of the later less-productive meetings considered them no more than "bull sessions with a very elite group" (Mitchell 2009:297). But cybernetics, and its ally, general systems theory (von Bertalanffy 1950) made intriguing suggestions about how information and computation are embedded in living systems. Their cross-disciplinary analogies between machines and living organisms, and especially between the marvelous new digital computers and brains, informed a generation of research. Elements of cybernetics and general systems theory were incorporated into systems ecology,<sup>2</sup> systems analysis, artificial intelligence, and eventually the sciences of complexity.

And archaeology. The processualists engaged in a lively back-and-forth on the relative merits of a strict hypothetico-deductive approach versus a "systems" approach. Tuggle et al. (1972:9), on behalf of the latter, argued that "'processual analysis' does not center only upon the search for dynamic laws, but also on the

attempt to explain cultural phenomena in terms of system interrelationships. The system paradigm does not demand the use of laws and it accommodates the unique as well as the recurrent in the scheme of explanation.” North American archaeologists of a certain age probably gained an acquaintance with cybernetics through Kent Flannery’s influential “Archeological Systems Theory and Early Mesoamerica” (1968), published the same year as the first edition of David Clarke’s *Analytic Archaeology*. Both were major contributors to the stream of research reviewed here.<sup>3</sup>

### *Kent Flannery and Systems Theory*

Flannery cites Maruyama (1963) as his source for the idea that positive feedback (the “second cybernetics”) can amplify small deviations into large differences. In the case of highland southern Mexico, Flannery proposed that very small genetic changes in beans and especially in maize, perhaps brought on by increases in their range, initiated positive feedbacks within the wild-grass procurement system: “The more widespread maize cultivation, the more opportunities for favorable crosses and back-crosses; the more favorable genetic changes, the greater the yield; the greater the yield, the higher the population, and hence the more intensive cultivation” (1968:80). Flannery lauded cybernetics for encouraging archaeologists to think of cultures as systems, and for stimulating “inquiry into the mechanisms that counteract change or amplify it,” famously concluding that “it is vain to hope for the discovery of the first domestic corn cob, the first pottery vessel... Such deviations from the pre-existing pattern almost certainly took place in such a minor and accidental way that their traces are not recoverable. More worthwhile would be an investigation of the mutual causal processes that amplify these tiny deviations into major changes in prehistoric culture” (1968:85).

A few years later Flannery employed a similar perspective but a larger set of concepts to attempt to explain the origins of the state. He identified processes of segregation (“internal differentiation and specialization of subsystems”) and centralization (“degree of linkage between...subsystems and the highest-order controls”) (1972:409). These, he proposed, may be encouraged by mechanisms such as promotion (as in the case of an institution moving from special- to general-purpose) or linearization, in which lower-order controls are “repeatedly or permanently bypassed by higher-order controls” (1972:413). He treats the various “prime movers” proposed over the years as drivers for state formation (irrigation, warfare, population growth, etc.) as stresses that in various cases can select for these mechanisms, though systems can also evolve towards pathologies such as “hypercoherence” (e.g., Rappaport 1977) in which disruptions to any part cascade through the entire system.<sup>4</sup>

For Flannery the ultimate goal of such thinking was to establish the rules by which one could simulate the origin of the state, and he suggests 15 rules to be implemented in any such attempt. These focused mainly on structural changes to existing institutions, emergence of new institutions, and changing linkages among institutions—a focus on information and control very much in keeping with theory in cybernetics, though implemented by Flannery within an ecological framework.

The participants in the School of American Research's 1970 advanced seminar on prehistoric change (Hill, editor, 1977) saw three attractive features in systems theory (Plog 1977)—as a source of concepts; as a source of propositions describing the behaviors of systems; but most of all, for the analytic utility of simulation implementing a systems-theoretic approach (Plog 1977). Plog accordingly sketched a 16-step pseudo-code on behalf of the group outlining their understanding of the role of redistribution and warfare in the operation of the Hawaiian paramountcy. This did not, so far as I am aware, ever culminate in a simulation, but was intended as a thought exercise.

*David Clarke and Analytic Archaeology:  
Rescuing an Undisciplined Empirical Discipline*

David Clarke's ambitious *Analytic Archaeology* (1968) not only attempted to integrate systems perspectives into archaeology, but also to thoroughly systematize archaeological theory and put it in step with contemporary developments in geography, numerical taxonomy, and statistics, all of which were in full florescence, stimulated by newly available digital computers (Figure 1).

In his exposition for how cultures build up communication through material culture, decomposable into attributes and artifacts, and transmit these to successive generations he anticipates contemporary interests in building cultural phylogenies. Doran (1970:293) points out that Clarke's discussion of self-regulating properties of a cultural system "depends upon the amount of variety it shows; that is, upon the amount of information it contains or can transmit in some sense"—an extrapolation of a theorem in information theory due to Shannon and Weaver (1949). Clarke likewise develops a theory of how continuity (equilibrium) in societies can emerge from high levels of agreement or redundancy among "subsystems." Clarke's emphasis on "phase pattern regularities" and "time pattern regularities" as emergent properties at successively more general levels, moving from attribute, artifact, type, assemblage, culture, culture group, and techno-complex, resonate with metaphors used currently in describing complex systems. His repetitive images of networks of relationships and constraints, his attraction to abstraction and to models of all sorts, his fascination with how processes like diffusion could shape patterns seen in the archaeological record—all presage interests of later "complexity archaeologists." Moreover, in edited collections (Clarke 1972) he provided a rallying point for like-minded archaeologists. One wonders what this restless and original mind might have achieved, given more than 38 years. Aspects of this program were however kept alive and shaped by other researchers at Cambridge, including Colin Renfrew (e.g., 1973) and Sander van der Leeuw and James McGlade (e.g., 1997).

Not all archaeologists of this era with an interest in systems approaches agreed on how these approaches should be realized. In a prescient article, John J. Wood and R. G. Matson (1973) complained about the assumption or requirement of homeostasis in cybernetics (or general systems theory), their seeming requirement that sources of change always be outside the system, and their implicit functionalism. They suggested pursuing a more open model of system allowing for

change coming from within the system (as self-organization or morphogenesis), and one that emphasized relations of conditionality and constraint among the entities in the system. Following Buckley (1967) they called this the “complex adaptive systems” model.

### *The End of the Beginning*

These tendencies on both sides of the Atlantic saw their symmetric and logical culmination in the publication of two edited volumes on simulation in archaeology (Hodder 1978; Sabloff 1981). Although both were reviewed in a generally positive fashion (e.g., Lowe 1982), one gets the sense that the accomplishments of the case studies therein were a little underwhelming, given the possibly unrealistic expectations raised by the polemics of Flannery, Clarke and others.

The same year Hodder’s edited volume appeared, Merilee Salmon, a philosopher of science with a special interest in archaeology, asked “what can systems theory do for archaeology?” and concluded, not much. She argued that in archaeological applications the notion of “system” was not adequately defined. Following Rapaport (1972), she saw no general characteristics of various sorts of systems that were not simply consequences of their definition as a system. She found Flannery’s 1968 article on domestication interesting, but suggests that the sorts of positive and negative feedbacks he proposed were available as concepts before the development of cybernetics. In general, she saw the “systemic approach” in archaeology as potentially productive, but does not wish any of this credit to go specifically to the successes of general systems theory: “attention generated by the program of the general systems theorists has been instrumental in expanding our conception of systems and their importance, but we cannot look to [it] for an explicit methodology” (Salmon 1978:178).<sup>5</sup>

Finally, Salmon drew a strict line of demarcation between general systems and theory and what she calls “mathematical systems theory.” This she considers to be a “pure mathematical theory” (1978:178) originally intended to help construct digital computers which were beginning to be used with some success, at the time of her writing, to model biological systems. (She would apparently characterize any formal [mathematical] model of any system as being part of “mathematical systems theory” though of course most would regard this as a method, not a theory.) Her quite legitimate worries with such approaches included the fact that the points of contact between such systems of equations and the world they reference may be few and vague, and the fit between their predictions and the world quite rough.

And suddenly she sounds very contemporary: “Archaeology, even more than biology, studies extremely complex systems whose boundaries are not well defined. Modeling always ignores some, often fundamental, aspects of a system in order to focus on others. No one model should or does model every feature of a system. Whether a model is good or bad depends partly on our purposes in constructing the model. Unless the components of a system and their systemic relationships are well understood it is difficult to decide which features may be ignored in constructing useful models. ... Much more must be known about crucial components of biological systems and their important relationships before they can be modeled successfully. And biologists, not systems theorists, are the ones who are equipped to do this sort

of work. I believe that archaeology is in a position similar to that of biology in this respect” (1978:179).

In the end she rejects mathematical models as “too simple to be applied with much success to the complex systems that interest archaeologists. Mathematical Systems Theory is limited by its own lack of mathematical richness to applicability to only rather simple real systems... It has limitations that make it applicable to few, and only very simple, real systems. It is *not complex enough* to handle the sorts of situations that interest archaeologists” (1978: 174, 181; emphasis added).<sup>6</sup>

Trouble was brewing on other fronts as well. Only eight years after editing a volume in which he was cautiously optimistic about its prospects, Hodder (1986) does not even mention simulation in an influential review of current approaches in archaeology—a disinterest Chippindale (1993:34) attributes to a destructive tendency for archaeologists to consume one theory or technique after another, without being able to make any of them work. But Hodder, and other post-processualists, had become dissatisfied with a failure of processualism generally to be sufficiently contextual and historical, to account for active agency, and to progress beyond a “surface” level and a focus on function in order to approach cultural meanings.<sup>7</sup>

With many archaeologists thus looking the other way, the larger scientific community’s interests in complexity rather suddenly galvanized in the early 1990s (Figure 2). Articles examining simple computational systems called cellular automata (Wolfram 1984) or defining concepts such as self-organized criticality (Bak et al. 1988) or the edge of chaos (Kauffman and Johnsen 1991) led the way but were soon joined by more empirical studies, including for example complexity-inspired analyses of food webs (Pimm et al. 1991) and approaches to simulating the evolution of cities using cellular automata (White and Engelen 1993). Computational approaches to the problem of emergence of cooperation in human societies (Axelrod 1984), building on earlier uses of game theory to study animal conflicts (Maynard Smith 1974) opened a vast strand research that to date has had less effect on archaeology than it should. These conceptual developments were enhanced by increasing speed and availability of computers, the development of object-oriented languages, and by the mid-1990s the availability of platforms for agent-based modeling. Before long, archaeologists too began to explore these new concepts and tools (e.g., Bentley and Maschner 2003; Kohler and Gummerman 2000).

### **Central Concepts**

Most of these new approaches break systems down into their constituent interacting entities. Instead of dealing with abstract variables describing system organization, they instead focus on how these entities interact with each other, and how various characteristics of the systems in which they are embedded arise from these interactions, which are often spatialized and local. Moreover, these entities can be heterogeneous, even within classes. Depending on the problem, entities might be individuals, households, villages, cities, or all of those.

This way of thinking is much more in line with how most of us think about societies than is the earlier systems paradigm. It not only highlights what we usually

consider to be the agents of interest; it also provides a natural framework within which to consider questions that are perennial favorites for archaeologists, who for good reasons are drawn to questions of origins. How does a community arise from a collection of independent households? How do norms arise where previously there were none? Or how, as Adam Smith (1761/1985:201) wondered, can “two savages, who had never been taught to speak, but had been bred up remote from the societies of men...begin to form that language by which they would endeavour to make their mutual wants intelligible to each other....”?

### *Emergence*

Emergence as a concept may seem non-problematic to most archaeologists, as we can readily imagine, for example, the emergence of a new technology or a new level of sociopolitical hierarchy. With a little more difficulty we can visualize the invisible hand guiding the emergence of stable prices and a product distribution possibly beneficial to all from the self-interested interactions of producers and consumers. Emergent properties are also commonly identified in physical systems: convection cells emerge as we heat a pan of water on the stove, and a characteristic slope of a sandpile (its angle of repose, or critical slope) emerges as we add sand to its top. It's not hard to be convinced, following Anderson (1972), that more is often different: classical physics for example must arise from the rules of quantum physics, even though it works differently; chemistry in turn doesn't contradict any of those rules, but adds new ones.

Yet although virtually everyone agrees that “emergence relates to phenomena that arise from and depend on some more basic phenomena yet are simultaneously autonomous from that base” (Bedau and Humphreys 2008:1) there are many open questions about the concept, and neither researchers nor philosophers have converged on a more specific and comprehensive definition. Indeed it seems likely that various classes of emergent phenomena need to be identified and more specifically defined. Do we mean precisely the same thing when we say that phase changes emerge as we cool water from 100° C to 0°; that thoughts and feelings somehow emerge from the biochemical and electrical interaction of neurons in our brain; that segregation can emerge from the local interactions of agents who are quite tolerant of living in integrated neighborhoods (Schelling 1978); or that chiefdoms may emerge from competition among tribes? So while complexity theorists have difficulty avoiding use of the term “emergence” since they are attracted to systems exhibiting it, they treat the concept with some caution. Characterizing a property as emergent is at best a general description and never an explanation.

### *Self-Organization*

Let's go back to our sandpile and continue to dribble sand onto the top of the cone. As the slope reaches its critical value we will find that there are many small avalanches, fewer medium-sized ones, and the occasional really large one. Avalanches reduce the slope, but adding more sand builds it up again, so we can say

that the sand pile's slope is "attracted" to the critical value. If we graph the distribution of sizes of avalanches on these piles, moving from small to large on the x-axis, and if both the y-axis (the frequency of avalanches of various sizes) and the x-axis are logarithmic, the distribution follows a straight line with a slope of approximately -1.

Per Bak and his colleagues used this system to define the concept of self-organized criticality—"self-organized" since the slope is attracted to its critical value without any external management. The distribution of avalanche sizes is said to follow a power law. While this may not seem very remarkable or even interesting in this particular case, what is remarkable is how commonly power-law-like distributions emerge in a variety of apparently unrelated contexts. Indeed, they are often said to be a characteristic of complex systems.

With living systems in mind, Stuart Kauffman developed the superficially similar idea of evolution to the "edge of chaos." The governing ideas here were developed using simple computational models (random Boolean networks and NK fitness landscapes) whose behaviors Kauffman analyzed in a long series of articles, many summarized in Kauffman (1993). Random Boolean networks (RBN) are briefly but lucidly described by Mitchell (2009:282-284) and elsewhere I have used them as abstract models for reciprocal exchange systems (Kohler et al. 2000). They consist of  $N$  nodes, each having a state of either 0 (inactive) or 1 (active) connected to other nodes (including possibly a self-link). The linkages between nodes are directional, though if node A links to node B, it is possible (but not required) that B also links to A. The number of links coming into each node (that is, the in-degree) is called  $K$ . Each node is governed by one of two rules: OR or AND. For example, a node in a state of 0 governed by OR with an in-connection to two other nodes, one of which is in a state of 1, will, in the next time step, take on a value of 1, since the switch to activity depends on only one of its connections being active in the previous step. If the rule were AND, the switch to activity would require both connected nodes to be active in the previous time step. These networks can be in only a finite number of states (though that number might be very large) and one way to characterize their behavior is to measure how many discrete time steps they require to return to a particular state entered earlier. Once this happens, since these networks are deterministic, they will continue to cycle through that same space of possibilities. This is called the cycle length, and any realized cycle is called an attractor of the system.

Among the many things Kauffman and his colleagues learned about such networks through simulation using various values for  $N$  and  $K$ , and random wiring and logic, is that their typical long-run behavior is very dependent on the value of the in-degree measure  $K$ . In general, these networks exhibit three regimes of behavior: ordered, complex, and chaotic. When  $N=K$  their behavior is maximally disordered, with high sensitivity to initial conditions (the original states of the nodes), and very long state cycles. When  $K=1$ , the networks tend to fall apart into discrete, structurally isolated loops—the maximally ordered regime. Of special interest is the  $K=2$  case, in which the networks exhibit what Kauffman (1993:198-202) calls complex behavior, at the (somewhat metaphorical here) "phase transition" between order and chaotic regimes. He proposes that we take these



networks as abstract models for  $N$  genes being regulated by  $K$  other genes, suggesting that  $K=2$  epistatic interactions provide the most desirable compromise between stability and limiting damage from errors, and an ability to adapt. Less cautiously he has sometimes proposed that all living systems are driven to an analogously similar “edge of chaos” either by processes of self-organization, adaptation, or both. Objections arise to these broader claims, however, when they refer to levels of organization such as ecosystems that cannot plausibly act as units of selection (Levin 1999:183-184).

### *Innovation*

These interests in emergence and self-organization are also leading to new approaches to understanding innovation in sociocultural systems that depart from the variation—selection account received from Darwinian theory. Beginning from a recognition of the importance of *organizations* in sociocultural systems (versus *populations* in Darwinian theory), Lane, Maxfield et al. (2009) develop a theory of the processes peculiar to sociocultural systems that seeks to explain the innovation cascades (and, therefore, rapid change) they commonly exhibit. Especially important are innovations to which individuals or organizations can attribute new kinds of functions, even though these innovations may have begun only as a “better-faster-cheaper” means of carrying out an existing function. Gutenberg’s press is used as an example. Organizational transformations then promote the proliferation of the innovation (for our example, through the use of travelling representatives to peddle the newly printed books). As the new artifacts are used, novel patterns of human interaction develop around them (as the peddlers make their whereabouts known and people buy their wares). These interactions lead to new “attributions of functionality” describing what participants are or might be getting from the interactions—as when the presses conceived the idea of using the same printing technology that made books possible to produce flyers advertising the whereabouts of the peddlers and their wares. Finally, these new artifacts (the flyers) are in fact produced, and we are back again where we started in the cycle of innovation—though of course, in this case and many others, these innovations would continue to ramify endlessly. Brian Arthur (2010) points out that new technologies are quite commonly novel combinations of existing technologies, a combinatorial process which would tend to enhance such cascades.

Lane, Maxfield et al. (2009:37-40) call this entire cycle “exaptive bootstrapping.” Their approach can be linked to findings from scaling exercises that show consistent differences between biological and social systems with respect to activities linked to innovation. van der Leeuw et al. (2009) and White (2009) explore some implications of this approach for understanding human social evolution. In important ways these suggestions return us to V. Gordon Childe’s (1936) conception of the neolithic and urban revolutions as (in part at least) idea-driven transformations connected to hinge points in the rate of accumulation of knowledge and productivity.

### **Methodological Attractors**

To date archaeologists interested in complex systems have brought three main approaches to their analyses: scaling studies, agent-based modeling, and various network-based methods. These are not necessarily independent; agent-based models, for example, might generate social networks which in turn could be examined for scaling behavior.

### *Scaling and the Nearly Ubiquitous Power Law*

A very wide range of phenomena—from the frequencies of baby names to numbers of sexual contacts to the sizes of cities and frequencies of words in a text—correspond at least approximately to a power law (Bentley and Maschner 2008). In such a distribution (briefly mentioned above) the frequency of any phenomenon (such as the word “it” in a text) is inversely proportional to its rank in the frequency of all words in the text. Indeed, this statistical regularity was first made generally known for words in texts by Harvard philologist George Kingsley Zipf (1949), and later generalized by the late Benoit Mandelbrot, who also connected this regularity with his fractal geometry (Mandelbrot 1977:239-245; see also 272-273 for Mandelbrot’s reflections on Zipf’s career).

As Bentley and Maschner put it, “many see [the ubiquity of these distributions] as profound...whereas others caution that it could be a mathematical coincidence” (2008:247). One such cautionary note is that many distributions that have been described as conforming to a power law do not, on more rigorous mathematical scrutiny (Clauset et al. 2009). Of course, for some purposes this may not really matter; it may simply be of more importance that a distribution be power-law-like in having a “fat” or “heavy” right tail.

Of more concern is the difficulty of identifying the process(es) giving rise to such distributions. For example, it seems likely that the fact that personal wealth distributions in many societies, or the sizes of firms, follow power-law-like distributions is more attributable to a “rich get richer” phenomenon than to the sort of “invisible hand” guiding the process described by Per Bak and his colleagues. A rich-get-richer phenomenon probably also explains why Maschner and Bentley (2003) were able to show that corporate household size on the north Pacific coast of North America is power-law-like, and why Bentley and Shennan (2003) could suggest with similar tools that those with prestige are likely to garner even more prestige. See Grove (2011) for more discussion of plausible generating processes for such relationships.

In general it is becoming less exciting to discover that some new phenomenon conforms to a power-law-like distribution than it is to begin to use the scaling parameters of those distributions in a comparative fashion to provide insight into the processes generating the distributions. Recently a new kind of scaling study has arisen with this idea in mind. Instead of graphing a rank (in a frequency distribution) against a measure of size or frequency, as Zipf did for word frequencies and many archaeologists have done for site sizes, the idea here is to generalize this approach for any quantity of interest  $Y$  (for example, the number of

patents granted) in relationship to some measure  $N$  of size of the system (for example, city populations):

$$Y \approx cN^\beta \quad (1)$$

where  $c$  is a constant and  $\beta$  is the exponent (or power) from which the power law derives its name. When  $\beta = 1$ , the relationship scales linearly; values for  $\beta < 1$  are called sublinear, and values  $> 1$ , superlinear. Bettencourt et al. (2007) found that the relationship between recent patenting activity and the population sizes of U.S. metropolitan areas scales superlinearly, with a value for  $\beta$  of about 1.29, meaning as cities grow in size, their patenting activities grow more rapidly than do their populations. This is what economists call increasing returns to scale. Since that time, other researchers have found superlinearities for other aspects of cities that have to do with knowledge or money generation and other creative activities (including crime!), even though other aspects of cities often scale sublinearly (gas stations or hospitals) or linearly (doctors or pharmacies) with size (e.g., Helbing et al. 2009). On the other hand, various aspects of biological systems (e.g., metabolic rates, life-spans) tend to scale sublinearly with average body mass (e.g., West et al. 1997) though here too the mechanisms responsible are still debated (Savage et al. 2010).

A similar willingness to play creatively with such distributions, in conjunction with simulations beginning from recently hypothesized mean sizes of nested groups from Hill and Dunbar (2003), has allowed Grove (2010) to identify the recurrent group sizes hypothesized as responsible for forming a nested, hierarchical structure in the sizes of Bronze Age stone circles in Ireland (Figure 3). These nested levels may appear, in part at least, because of constraints on information processing or communication bandwidths that are general to human societies (Hamilton et al. 2007; Johnson 1982).

### *Agent-Based Modeling*

Many useful applications of systems-style (equation-based) modeling in archaeology continue to appear and could legitimately be reviewed in this chapter. Space limits require me to focus on a newer style of simulation provided by agent-based models, which is particularly congenial to a CS archaeology. In such simulations, the “system” is broken down into its constituent interacting agents from whose behaviors and interactions various systems-level properties may emerge. Although the earliest experiments with agent-based models in the social sciences were very abstract and general (like Axelrod’s repeated prisoner’s dilemma tournaments or Schelling’s studies of neighborhood segregation) two more empirical projects in the prehispanic U.S. Southwest helped introduce agent-based modeling to archaeologists. One, in Long House Valley of northeastern Arizona, is described by Dean et al. (2000) and Axtell et al. (2002; see also comment by Janssen 2009). The other, the Village Ecodynamics Project, is set in southwestern Colorado (Kohler et al. 2000, 2007).

Although different in detail, both projects seek to make various systems-level properties such as the local population trajectories, or the placement and sizes of residential sites, emerge from the interaction of households with each other and with the dynamic environments they inhabit. Both benefit from the high-resolution chronologies and climate proxies made possible by tree-rings.

Studies such as these value realism with respect to some particular setting at the expense of generality. Since it is difficult to evaluate very general models precisely because they are *not* fit to any specific setting, a potential advantage to these more empirical approaches is that they may allow us to rigorously evaluate a general model by first “instantiating” it in a local setting, and then assessing how well its predictions fit the data from that archaeological record. For example, my colleagues and I have instantiated an abstract evolutionary public goods game developed by Hooper et al. (2010) in our study area in southwestern Colorado between A.D. 600 and 1300 (Kohler et al. 2011). We find that this model fits the available data for the rise of leadership in our area during its first 300 years reasonably well, though we identify the need for additional mechanisms to explain the more hierarchical systems that appear there after A.D. 1070.

Another recent example of an empirically rich agent-based model is Griffin and Stanish’s (2007) instantiation of a general fission/fusion model for polity formation in the Lake Titicaca basin. A related model has also been proposed by Gavrillets et al. (2008), and Griffin (2010) has since generalized the Titicaca model and assessed its behavior using scaling tools. All of these focus on the problem of how we can explain the cycling phenomenon often seen in early polities, and also show how it is possible in agent-based models to generate new levels of organization from lower-level entities.

At the same time, applications of agent-based modeling of a more general, conceptual nature by and for archaeologists seem to be increasing rapidly. Here is a small sample displaying the diversity of problems being addressed:

- as a means for evaluating arguments for selection of lithic materials based on quality, optimization, or risk management, Brantingham (2003) developed an agent-based model for stone raw material procurement in which agents simply sampled the materials they encountered in a random walk;
- Premo and Hublin (2009) show how a process of culturally mediated migration in the Pleistocene could result in the low levels of genetic diversity found in modern humans;
- Powell et al. (2009) extend a version of Henrich’s (2004) model for the demographic conditions allowing “cumulative adaptive evolution” to suggest how number and size of subpopulations in a metapopulation, and the degree of migration among them, affect cultural complexity. Their results suggest that the transient appearance of increased symbolic and technological complexity in various areas of Eurasia and Africa, prior to their fixation around 45,000 years ago, is plausibly explained by such demographic factors; and
- Premo and Kuhn (2010) somewhat similarly show how local group extinctions could explain the very slow rates of cumulative culture change

and low total cultural diversity in Lower and Middle Paleolithic stone tool assemblages.

Note how all these studies—and others that could be cited—use agent-based modeling to explore the consequences for the archaeological record of some specific process, or set of processes, extended over a long period (and often across space). This is a task that is usually too difficult for the human mind to perform accurately unless the proposed processes are extremely simple. Thus agent-based models will often be useful as we attempt to reconstruct the processes responsible for the patterns we perceive in the record.

Most of the models produced so far by archaeologists feature “reactive” agents that receive input, process it, and produce an output according to the rules provided by the programmer. Costopoulos (2008) and Lake (2004) call for use of more “deliberative” agents “characterized by a wide diversity of individual viewpoints, strategic goals, and even belief systems” (Costopoulos 2008:278). Although this would indeed address some of the critiques that post-processualists originally levied against systems theory and other aspects of processualism, so far at least most modelers in archaeology have shown a preference for the relative clarity and interpretability provided by simpler agents, preferring to focus on the complexities arising from the interactions among these agents.

### *Networks*

If scaling studies and agent-based modeling have recently emerged as promising methods whereby archaeologists can approach complexity, we might say that the use of networks in archaeology is in the process of emerging. One index of this is that it is easier to find creative quantitative applications of network concepts in recent dissertations (e.g., Hill 2009; Phillips 2011) than in current publications. Many of the seminal papers on network research are made available in Newman et al. (2006) and the major theoretical developments briefly reviewed by Newman (2003). As for agent-based modeling, the study of networks was really not possible prior to ready access to high-speed computation. Network studies have been particularly transformed by the huge digital databases formed by and accessed through the web.

Network scientists have developed various ways to characterize any network based on measures such as the distribution of numbers of linkages among the nodes (degree distribution), the extent of clustering (or transitivity) in a network, and the extent to which networks are resilient to the removal of one or more nodes. Examinations of large numbers of social, informational, technological, and biological networks have shown that “small-world effects”—discovered by Stanley Milgram in the 1960s (Milgram 1967)—are quite common. In such networks most pairs of nodes can be connected by a relatively short path through the network, even if the network is very large. This property is called high transitivity. Power-law degree distributions (“scale-free” networks) also turn up very regularly in citation networks, the world wide web, metabolic networks, and power grids, for example (Newman 2003:13-14). Network researchers generally attribute this property to preferential attachment, a variant of the “rich-get-richer” phenomenon mentioned

above; researchers are more likely to cite a paper that is already commonly cited than to dig a possibly equally relevant article out of obscurity. According to Newman (2003:30) this property was in fact first identified in citation networks, by Price (e.g., 1976), who called it the principle of cumulative advantage.

Although a vast number of archaeological studies invoke network concepts verbally, very few attempt to rigorously apply “network thinking.” Bentley and Shennan (2003) explored some connections between network models and cultural transmission theory. Tim Evans et al. (2009) develop an approach from statistical physics to graph an “archaeology of relations” in the Middle Bronze Age Cyclades. Their approach allows them to take as input to the model the known locations of archaeological sites (which become the nodes in the network) with important output from the model being the population sizes and most likely linkages among those sites. Essentially, they seek to define a state for the system that minimizes energy expenditure within constraints imposed by the locations of the sites (as given by the archaeological record, generally coarse-grained to the level of the island), the distances between sites, and parameters that control degree of site independence or self-sufficiency. In addition, they penalize (but do not prohibit) long-distance contacts. A graphical product of this work is shown in Figure 4.

### **Trajectories**

Some additional promising approaches can be glimpsed on the horizon. In a time when people can point their phones at a mountain and be told that they are viewing Mont Blanc, archaeologists could do a much better job of recognizing patterns in data! Simon Dedeo et al. (2010) develop an approach to extracting the payoffs to and the strategies used by primates from observations of their conflicts over time. This can be contrasted with normal uses of game theory, in which the strategies and payoffs are posited in advance, and then the dynamics of the interactions over time are deduced. Dedeo et al. call their approach “inductive game theory.” I mention this not as a method that can be ported directly to archaeology, but as an example of the directions in which a CS archaeology might take us as we attempt to infer behaviors from time-series data on material associations.

As archaeology has accumulated vast quantities of all sorts of data over the last few decades, especially from what we in the US call cultural resource management, it is imperative that we develop more powerful techniques for building linkages among these datasets and analyzing them as a totality. Projects such as Digital Antiquity (<http://www.digitalantiquity.org/>) and Archaeological Data Services (<http://ads.ahds.ac.uk/>) are beginning to make these data accessible; to us falls the interesting task of addressing them creatively and with useful result.

### **Conclusions: Relationships of CS with Other Archaeologies**

I have portrayed CS approaches as partially descendant from processualism via their connections with systems theory and simulation. The connections of CS archaeology with evolutionary archaeology (defined broadly) are also obvious. Indeed, complex systems of living agents are often called complex *adaptive* systems.

It is difficult (and often pointless) to differentiate these two perspectives. Nevertheless—just as Kauffman’s work tries to show how processes of self-organization generate structure on which selection can act—archaeologists beginning from a CS perspective may be more willing than evolutionary archaeologists to study processes constraining selection, or more prone to identify processes not envisioned by the modern synthesis, as I briefly noted for the papers on innovation from Lane et al. (2009).

John Bintliff considers CS to provide an integrative perspective for archaeology:

I have placed the theory under integrative programs because one of its chief appeals for contemporary archaeology... lies in the centrality of a subtle role for individual agents, unique events, in constant dialectic with constraining and enabling structures of their social and environmental context.... Significantly, as forms of social life unfold into larger and more elaborate variations, new properties of culture appear which are not observed in simpler versions (emergent complexity). The advantages of the culture historical, processual, and post-processual paradigms are all available within the theoretical umbrella of chaos-complexity [Bintliff 2008:160].

Whether or not one agrees with Bintliff, what seems obvious is that a CS perspective offers a completely open, rapidly evolving, and non-dogmatic set of approaches to the archaeologist eager to embrace computation for clarifying the structure and behavior of the complex systems our ancestors created and inhabited.

#### NOTE

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<sup>1</sup> Harries-Jones (1995:103-144) explores Bateson's ambivalent relationship with cybernetics. Bateson was fascinated by the role of feedback—a key principle of cybernetics—in ecological systems, and how cybernetics elevated the role of information, in conjunction with feedback, to allow for self-organization. He also saw a correspondence between feedback and learning. His opposition to the more mechanistic, deterministic, and control-oriented aspects of cybernetics led him, though, to consider noise and error as having creative possibilities for systems, rather than as nuisances to be eradicated.

<sup>2</sup> Ecology was of great interest to many students in U.S. graduate schools in the 1960s and 1970s. There these students were exposed to systems approaches through texts such as E. P. Odum's (1972) *Fundamentals of Ecology*, and his brother H. T. Odum's energy-flow simulations (e.g., 1960).

<sup>3</sup> Space limits force selectivity here. Many other archaeologists, especially in the 1970s, employed aspects of cybernetics or systems theory either in their empirical research, or in their theorizing, including Hill (1977), Watson et al. (1971), Wright (1977), and Zubrow (1975); see also Plog (1975) and references therein.

<sup>4</sup> Those interested in the networks joining people and ideas may find a link with Bateson here as well, since Rappaport, a colleague of Flannery's at Michigan, was on sabbatical at the East-West Center, where he interacted with Bateson while writing his first pieces employing cybernetics concepts in the late 1960s (Rappaport 1971); perhaps he in turn influenced his younger colleague.

<sup>5</sup> Jim Doran comes to a rather similar conclusion about cybernetics, though he is much more hopeful about the potentially constructive role of "the use of the computer to construct and test a 'simulation' of some complex system evolving in time" (1970:296).

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<sup>6</sup> There is an ironic historic twist to Salmon's critique. Her authority on mathematical systems was Arthur Burks (1975), who helped in aspects of the design or implementation of the first important digital computers ENIAC and EDVAC. Eventually he joined the faculty at the University of Michigan, helping found the "BACH group" (**B**urks, Robert **A**xelrod, Michael **C**ohen, and John **H**olland), an important precursor to both the Santa Fe Institute and Michigan's Center for the Study of Complex Systems.

<sup>7</sup> See Wobst (2010) for another view of the reasons for the demise of the first wave of simulation. Some current approaches in complex systems attempt to address many of the post-processual critiques, though the reconstruction of cultural meanings may be beyond any archaeology except in special circumstances.





Fig. 1. David Clarke in 1972. Photograph by Tim Frost.

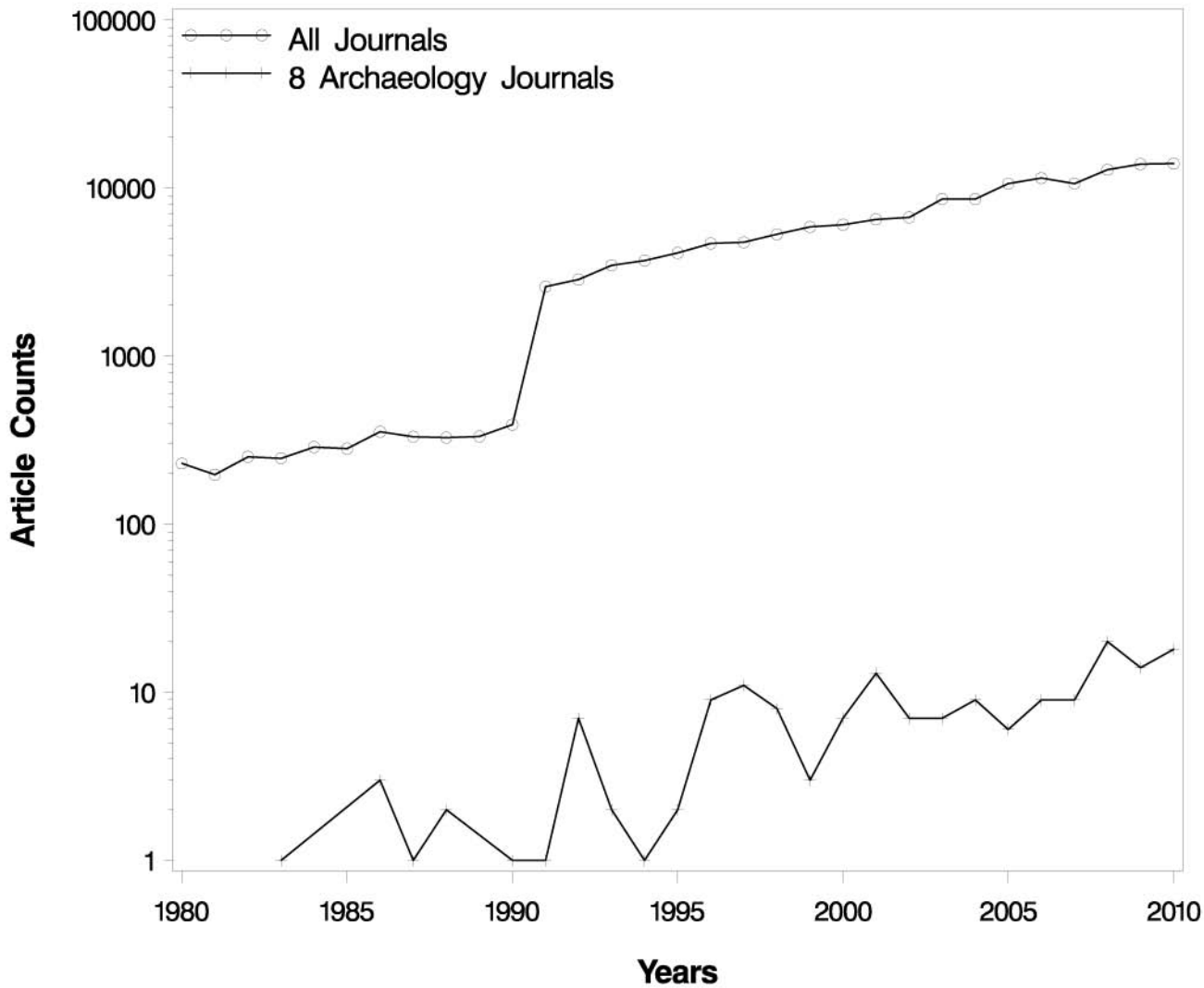


Figure 2. Papers with "complexity" in title or topic from 1980-2010 in journals indexed by ISI Web of Knowledge.©  
Note logarithmic y axis.

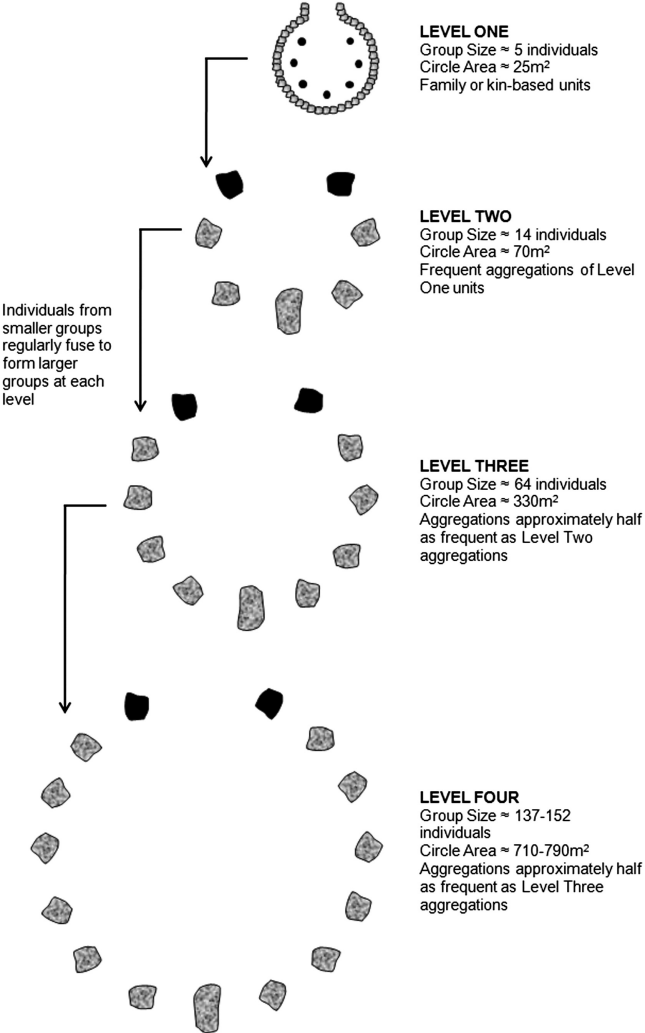


Fig. 3. Proposed group sizes associated with stone circles of various sizes in Bronze Age Ireland. Each higher level incorporates lower-level groupings, with higher-level groupings occurring proportionally less frequently. (Reprinted from *Journal of Archaeological Science* 37, M. Grove, Stone circles and the structure of Bronze Age society, 37, p. 2619, 2010, with permission from Elsevier and the author.)

Figure 4. Network formed among Middle Bronze Age Cycladic sites by taking the size of the vertices (sites) to be proportional to the total weight of ingoing edges. Width of an edge reflects the strength of interactions in the direction indicated by the arrow. (Output from the model described in Evans, T., C. Knappett, and R. Rivers 2009. Using statistical physics to understand relational space: a case study from Mediterranean prehistory, in D. Lane, S. van der Leeuw, D. Pumain, and G. West (eds) *Complexity Perspectives in Innovation and Social Change*. Dordrecht: Springer. By permission of the author.)

