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Past, Present, and Future of Complex Systems Theory in Archaeology

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Abstract
Throughout the history of archaeology, researchers have evaluated human societies in terms of systems and systems interactions. Complex systems theory (CST), which emerged in the 1980s, is a framework that can explain the emergence of new organizational forms. Its ability to capture nonlinear dynamics and account for human agency make CST a powerful analytical framework for archaeologists. While CST has been present within archaeology for several decades (most notably through the use of concepts like resilience and complex adaptive systems), recent increases in the use of methods like network analysis and agent-based modeling are accelerating the use of CST among archaeologists. This article reviews complex systems approaches and their relationship to past and present archaeological thought. In particular, CST has made important advancements in studies of adaptation and resilience, cycles of social and political development, and the identification of scaling relationships in human systems. Ultimately, CST helps reveal important patterns and relationships that are pivotal for understanding human systems and the relationships that define different societies.

Keywords Complex systems theory · Archaeological theory · Complex adaptive systems · Resilience · Sociopolitical organization · Inequality · Scaling theory

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Introduction

The interdisciplinary science of complexity and complex systems is a growing field with numerous applications across the natural and social sciences (Costopoulos 2001; Ellis 1998; Elsawah et al. 2020; Kauffman 1995; Ladyman et al. 2013; Levy 1994; Morrison 2008; Sawyer 2005). Within anthropology and archaeology, elements of complex systems theory (CST) have begun to make considerable contributions (e.g., Barton 2014; Esteve-Altava et al. 2011; Jacobson 2022; Kretzschmar 2015; Lansing 2003; Lansing and Cox 2019; Reynolds and Lewis 2019). Additionally, with the rise in quantitative methods like agent-based modeling and network analysis, complex systems science has further seeped into archaeological investigations (Ellen 2010; Kohler 2012; Lansing 2003; Mills 2017; Romanowska et al. 2021).

Perhaps some of the most substantial engagement with CST has been through complex adaptive systems approaches (or CAS), which is a subset of CST that looks explicitly at systems where adaptation to external and internal forces plays a larger role in emergent properties (Bliege Bird 2015; Lansing 2003; Mitchell 2009). While most human systems are adaptive, not all systems we interact with are (e.g., hurricanes, rivers, etc.). Given this fact, in this article I use the term CST to refer to a general body of theory about complex systems, *en masse,* and do not make a distinction between adaptive and non-adaptive systems (also see Mitchell 2009).

A theory of complex systems first requires a definition, of which there are many, for what constitutes a *complex* system. Ladyman et al. (2013, p. 57) present a particularly useful definition: "A complex system is an ensemble of many elements which are interacting in a disordered way, resulting in robust organisation and memory." This definition, while short, succinctly explains what a complex system is and how it differs from complicated or simple systems. Simple systems have one single path and one single outcome (e.g., a baking recipe, wherein each ingredient is added together in a specific order to create a new output); complicated systems have multiple paths and one single outcome (e.g., a car, which comprises multiple parts and mechanisms that have to work together to make the vehicle function); and complex systems have multiple paths, emergent properties, and self-organizing properties that can lead to multiple outcomes (e.g., air traffic control, which involves airport systems, airplanes, individual pilots, and traffic controllers and can subsequently affect other systems like governmental and emergency response).

Complex systems are not centrally controlled and do not always produce predictable outcomes due to internal and external interactions among different components of the system itself, which lead to adaptation and emergence of new states. As such, changes in a complex system are influenced by interactions taking place from the smallest to the largest scale, and different scales often result in different patterns. As such, pitfalls of earlier reductionist approaches (which have tendencies to assume systems are in a state of equilibrium and focus on singular scales of analysis) are incompatible with studies of complex systems. For example, causal determinism, which has a long history in anthropology (Arponen et al. 2019; Caspari 2009; Erickson 1999; Trigger 2006), has often led to overly simplistic, oftentimes incorrect conclusions. Sometimes this work also results in severely dangerous consequences (e.g., Fabian 2010). In contrast, studies of complex systems require frameworks that can simultaneously evaluate all scales of a system. This is one of the things that CST offers.

The theory of complex systems involves a series of general principles pertaining to how complex systems operate (see Table 1). Preiser et al. (2018), for example, identify specific characteristics of complex systems, including the fact that they have adaptive capacities (in the case of social systems), their behavior emerges from dynamic processes, they are open (and therefore at disequilibrium), and they are determined contextually. CST, then, refers to general principles that can help us study, describe, and explain complex systems dynamics and changes in these systems over time.

Based on the definition of complexity offered above, it is clear that humans are well defined by this term. We make decisions that do not always seem rational, defy many simple expectations from many quantitative models, and respond in nonlinear ways to interactions with our surroundings (social, ecological, and otherwise). However, we also form incredibly intricate structures in terms of social and political organizations, we respond to external stimuli in different ways, and human actions differ across scales of interaction. One of the main insights of CST is that regularity emerges at larger scales from chaotic interactions at smaller scales. Thus, CST, and complexity science more broadly, have much to offer archaeology in all its forms,

Table 1 List of characteristics and organizing principles of complex systems (after Ladyman et al. 2013)

Characteristic of complex systems	Related principle of complex systems theory
Multifaceted	Studies of complex systems involve numerous interactions among and between their various parts. This requires multiscalar and cross-scalar investigations.
Disordered and diverse	Interactions within and between complex systems are not centrally controlled or coordinated and can differ across different components of the system.
Structured	Complex systems are organized into multiple levels and properties that interact one another, often exhibiting regularities and symmetry that change periodically. Thus, studies of structure must involve scalar dimensions, including time.
Emergent feedback properties	Interactions within and between complex systems iteratively impact one another over time and lead to emergent structure and order at multiple scales.
Open systems in disequilibrium	Complex systems are not in equilibrium with environment and are often driven by external factors. They must be modeled using nonlinear methods that account for multiple levels of change
Historical memory	Information about historical events is usually stored within a complex system and plays a role in the trajectory of that system.
Adaptive properties	Many complex systems are adaptive, in that they can modify their behavior based on environmental states and existing historical knowledge of these conditions.

both quantitative and qualitative in focus. This framework can help unify investigations of humans between site-specific and regional scales to identify important patterns in human interaction, trends in social change, and responses to external events like war and climate change.

Indeed, the systems science origins of CST already have a long-established history with archaeology, as our discipline has long thought in terms of systems: social systems, political systems, economic systems, language systems, ecological systems, etc. CST, in contrast to earlier iterations of systems theory, emphasizes the importance of historical context, recognizes the agency of individuals, and can capture nonlinear dynamics (Barton 2014; Ladyman et al. 2013; Preiser et al. 2018). In these ways, CST offers a pathway forward to explore relationships between people, communities, societies, and their surrounding environments in ways that examine multiscalar and cross-scalar processes, helping alleviate simplistic conclusions and explore a range of possible mechanisms for social change, human adaptation, and human-environmental feedback dynamics.

In what follows, I synthesize the fundamental concepts of CST and the ways in which it can complement archaeological studies and bridge theoretical divides. Next, I trace the origins of systems thinking in archaeology and its relationship to CST. Then, I review the ways in which CST has already made significant contributions to archaeological research and the future potential of this framework within the discipline. Within this context, I also reflect on the different promises that have been made by earlier proponents of CST within archaeology and evaluate the progress made over the past few decades using these approaches. Overall, I aim to demonstrate how, regardless of the type of archaeology one practices, principles of CST are fundamental to the study of human systems and are often implicit within many extant modes of archaeological inquiry. Furthermore, many of archaeology's central questions are framed in ways that CST can (and has) directly addressed. The key becomes recognizing the ways in which CST can be more explicitly leveraged to advance archaeological research.

Foundational Principles of CST and Its Connection to Extant Archaeological Theory

Complexity science (from which CST is derived) has a long history but was largely propelled forward by the Santa Fe Institute beginning in the 1980s (e.g., Gell-Mann 1994, 1995; Mitchell and Hofstadter 1990; Mitchell et al. 1994; Nowak and Krakauer 1999; West 1984). CST accounts for unpredictability and nonlinearity (or "chaos," see Levy 1994; Lorenz 1963) and the emergence of new patterns through feedback loops and self-organizing behaviors. These dynamic interactions occurring at all levels within a system subsequently change with initial conditions and can behave in a range of (un)predictable ways. CST focuses on complex systems, which are *open* and do not always have definable borders and exchange energy and matter with external systems. Closed systems are in a state of equilibrium, or stability, wherein energy is maintained within the system (Fig. 1). Open systems, in contrast, are dynamic and require external sources of energy to be maintained.

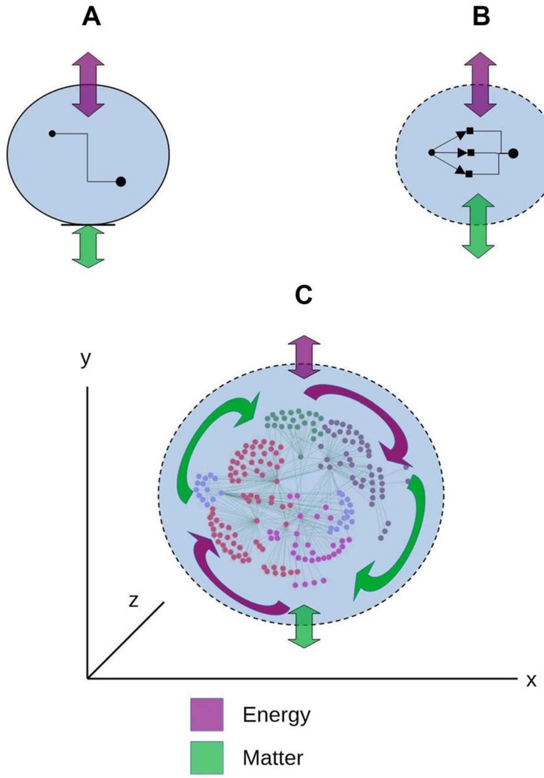

Fig. 1 Diagram of closed (**A**) versus open (**B**) systems and complex systems (**C**). Closed systems retain all matter (e.g., people, materials, etc.) but can exchange energy with outside forces. Open systems experience both energy and matter exchanges. Complex systems are a type of system (usually open) that exist on spatial (x, y) and temporal (z) scales and are defined by interactions among individuals within the system. Figure created by the author

Humans generally live within open systems, constantly being impacted by internal and external forces, exchanging energy, information, and other matter, and fluctuating between states of equilibrium and imbalance. As such, models that only look at equilibrium states limit archaeological understanding of far more complicated patterns and the mechanisms of human system dynamics.

Complex systems also undergo self-organization where "order supposedly emerges from disorder" (Richardson 2004, p. 76; Turner and Baker 2019). While earlier systems approaches (discussed more below) focused on patterns and structures within systems (e.g., Bertalanffy 1972), CST focuses on the *conditions* that lead to the emergence of patterns and structures (see Bintliff 1997, p. 87). Indeed, these are the very questions that archaeologists have long grappled with.

Based on these principles, archaeologists can look at CST as a framework for understanding the emergence of different configurations of human society. The central tenets of CST can be broadly articulated: If a human system is complex, we must understand its current configurations (i.e., structures left in the archaeological record) as emergent properties that result from multiscalar interactions between the whole system (e.g., culture or society), its parts (i.e., people and their decisions), and surrounding systems interactions (e.g., other societies, external environments, etc.). Additionally, the result of any emergent properties may be unique to that system because of initial conditions, internal contexts (e.g., human agency), and external influences (e.g., environmental events), but underlying factors can be translated (e.g., cultural norms, scaling laws, etc.) that result in similar patterns in other systems. As such, incorporating emic perspectives is required for understanding the processes by which specific configurations emerged.

As Larsen-Freeman and Cameron (2008, p. 201) write, complexity theory "is antithetical to the common reductionist approach in science, which relies on the central principle that one can best understand an object of inquiry by taking it apart and examining its pieces. From a complexity theory perspective, knowing about the parts individually is insufficient because we are interested in understanding how the interaction of the parts gives rise to new patterns of behavior." In contrast to structural-functionalists and many early processual archaeologists, studying similarities and differences between artifacts, architecture, and other materials cannot explain the entire underpinning of a cultural system; but it can provide important local context that may or may not translate to understanding broader trends. In other words, *studying the parts of a system is insufficient because we must also understand how those parts interact and the consequences of those interactions across space and time*.

Based on the central principles of CST, it becomes clear that studies of this nature require engagement with alternative viewpoints: because systems are ultimately dynamic, they change, sometimes unpredictably, based on very specific contextual elements at large and small scales. Additionally, because complex systems are *open,* they are inherently out of equilibrium and are actively influenced by, and interact with, other adjacent systems. Due to the fact that these interactions can cause adaptations and changes in other systems, from the standpoint of hypothesis testing, we must make predictions based on probability and proximate causation, rather than looking for any one, single explanation.

Furthermore, initial reactions will not remain static, and while we can hypothesize about what might happen, we cannot always predict if, when, or in what order these events will necessarily transpire. Therefore, when deriving hypotheses regarding CST, we must assume that feedback effects can result in numerous possible reactions, which in turn, can cause further cascading effects. This leads to the emergence of system properties and change. The recent explosion of Bayesian statistical approaches within archaeology (Otárola-Castillo and Torquato 2018) and advances in simulation methods have greatly aided researchers' ability to address some of these uncertainties. Such methods can help falsify some hypotheses on the basis of contextual variables and probability, allowing for greater confidence in predicting how specific organizational forms can and have emerged.

Importantly, CST forces us to think beyond simple explanations of cause and effect related to social change (e.g., climate change causes political instability). Rather, it enables us to study the "nature and properties" of different contexts in the physical and social world that enable the emergence of specific organizations of social life and the ways in which they can be reconfigured (Bentley and Maschner 2001; Bintliff 1997). As such, examining the archaeological record in terms of complex systems enables researchers to look for patterns of social form, changes over time, and comparisons in these properties between places. This has great power to enhance our understanding of human societies, both in terms of local interactions and global trends.

A Brief History of Complex Systems Science and Archaeological Thought

Systems thinking and archaeology share a long history. Since the 19th and 20th centuries, archaeologists, anthropologists, and sociologists understood that human societies could be influenced by external forces, and some researchers, like Durkheim (1893; Trigger 2006), even noted that any change to one part of a social system would cause subsequent changes in other parts of the system. The structuralist paradigm (e.g., Levi-Strauss 1963; Lévi-Strauss and Needham 1969; Mauss 1990) assumed that culture was governed by strict structural elements, wherein a cultural system could be understood by looking at patterns of order, opposition, and similarity to other cultural systems (Trigger 2006). Similarly, functionalism, with its emphasis on understanding general cultural organization from an analysis of individual materials (e.g., Malinowski 1922, 1945; Radcliffe-Brown 1924, 1952), focused on patterns of connection between elements within a cultural or social system (Trigger 2006).

Cultural ecology and ecological anthropology directly investigate the relationship between human and environmental systems (e.g., Harris 1966; Steward 1955; Steward and Setzler 1938; White 1988). Within this paradigm there were researchers who understood the ability for cultural systems to adapt through self-organization and that we could understand these processes of change only by looking for subsequent changes in archaeological materials like pottery (e.g., Caldwell 1958). Cultural ecology soon spawned new interest in settlement patterns, and while views among its practitioners differed, such investigations emphasized the study of the emergence of behaviors, rather than specific bounded cultural groups (Trigger, 2006).

The introduction of Marxism into anthropological inquiry was also clearly impacted by a systems-level understanding of society, wherein shifts in economic and material distributions offset power dynamics and cause changes within the social system as a whole (Patterson 2004; Price 1982; Roseberry 1997). In many ways, these notions of understanding a cultural system by investigating its parts aligns with the tenets of general systems theory (GST) that emerged in the mid-20th century. The foundational ideas of systems theory were laid out by Bertalanffy (1928; 1972, p. 410), a biologist, who stated that the main task of biology "must be to discover the laws of biological systems (at all levels of organization)." This idea later became formalized as GST, which was chiefly concerned with formulating and deriving "general principles that are applicable to 'systems' in general" in order to concretely define systems relationships, changes, organization, and similarities (Bertalanffy 1968, 1972).

The use of GST within archaeology largely aligned with the processual movement. Researchers were interested in using systematic methods to derive quantifiable "truth" about the past through the study of archaeological materials to understand the mechanisms of past human societies (e.g., Binford and Binford 1968;

Flannery 1972; Renfrew 1972; Thomas 1972; Watson et al. 1971). In many ways, systems thinking aligned with a push toward the establishment of *systematics*, or metalanguage that permitted for subdisciplines and outside fields to communicate about ideas in identical terms (Binford 1965; Dunnell 1971; Lyman et al. 1997; Rodin et al. 1978). The formalization of concepts provides links between theoretical and empirical realms and permits the establishment of explicit units that archaeologists could analyze and compare, perhaps most notably with ceramic typologies (e.g., Phillips et al. 1951). By doing so, researchers could understand how specific parts of a cultural system can help glean insight on the overall system. By the 1950s and 1960s, systems theory and approaches were widespread, but not all researchers were conscious of this fact. Some argued that systems theory didn't need to be introduced to archaeologists; rather its influence needed to be exposed to those who were unaware of its impact and could provide new techniques and approaches to move the discipline forward (Rodin et al. 1978, p. 753).

Much as structuralist and functionalist approaches lost favor in archaeology, earlier iterations of systems theory garnered mixed reviews and heavy criticism among some archaeologists (see Ellen 2010). GST, akin to structural-functionalism, is rooted in the idea that an entire system could be understood if you identified its different parts and relations between them. This is not to say that multivariate explanations were ignored by archaeologists using systems approaches; quite to the contrary, many researchers fully acknowledged that major transitions resulted from an accumulation of different factors (e.g., Clarke 1972; Flannery 1967, 1968). The problem was that archaeologists did not have the computational tools necessary to fully evaluate multivariate causation (Bentley and Maschner 2007). Nonetheless, major criticisms of early archaeological theory (and processualism, specifically) centered on the idea that "scientific" investigations could identify universal laws of human behavior.

Indeed, the concept of universal truths was a major component of the post-processual turn and postmodern critique across the social sciences (see Ortner 1984; Trigger 2006). Researchers also pointed out that GST was hampered by functionalist notions and led to deterministic assumptions that could not account for human agency (Crumley 2005; Stein 1998). Even before the watershed volume *Writing Culture* (Clifford and Marcus 1986) was published, anthropologists and archaeologists were criticizing systems theory (e.g., McGuire 1983), and social scientists, at large, were pointing out its often-mechanical descriptions of human systems and its inability to understand nonlinear relationships (see Turner and Baker 2019; Yawson 2013).

One example comes from the work of archaeologists using Wallerstein's (1974) world-systems theory to understand ancient societies. Researchers like Kohl (1987) realized that ancient human systems only *partially* resembled modern world systems, that the rigid core-periphery structure espoused by Wallerstein was less stable at different points in history, and that ultimately, human systems are open, with constant flows of people and information (e.g., Anthony 1990; Trigger 2006; Wolf 1982). Indeed, the difference between open and closed systems (i.e., equilibrium) represents a fundamental difference between GST and CST (Kauffman 1995). While computational limitations placed on earlier researchers using GST necessitated the assessment of closed systems (Bentley and Maschner 2007), the nature of interacting, open systems is not a new concept (e.g., Binford 1965; Moran 1990; Price and Brown 1987; Rappaport 1971; Sahlins 1958; Smith and Flannery 1986; White 1988), and researchers have long understood human systems to be constantly changing (e.g., Eerkens and Lipo 2005; Premo and Scholnick 2011; Shennan 2002; Tattersall 2008). But the limits of computational technologies during the mid-20th century made assessing disequilibrium states difficult or impossible, with most archaeologists and anthropologists opting to instead use simpler models set at equilibrium (e.g., Dyson-Hudson and Smith 1978; O'Connell and Hawkes 1981; Smith et al. 1983; Winterhalder 1981).

One of the fundamental concepts that emerged from the ontological turn of the 1980s is the fact that every study, scientist, and story has elements of truth (or "partial truths," *sensu* Clifford 1986), but not the whole truth, as it is ultimately biased by some aspect of the observer, analyst, or mode of interpretation. Thus, an epistemological crisis was revealed: how can we truly know anything? Over the course of the past several decades, philosophers and social scientists have wrestled with these questions (e.g., Clifford and Marcus 1986; Derrida 1980; also see Ortner 1984, 2016). Ultimately, to understand any phenomenon requires a melding of perspectives and approaches, as each will reveal different (sometimes contradictory) information.

This very idea aligns well with the principles of CST. One of its underpinning principles is that *local context and memory are pivotal*, which strongly aligns with concepts espoused by anthropologists and archaeologists since the turn of the 20th century (see Boas 1896, 1932) and the postmodern movement in the late 20th and early 21st centuries (e.g., Brück 2005; Hamilton et al. 2006; Ingold 1993; Shanks and Tilley 1989; Tilley 1994). CST, akin to the postmodern critique, holds that understanding the world requires consultation of different units, scales, and methods to fully grasp the intricacies of relationships between different actors and their surrounding environments.

Following this idea, studies of system dynamics require interdisciplinary approaches and community engagement (which I discuss more below). CST is, by definition, an interdisciplinary framework, bridging the gap between the social, physical, and natural science, humanities, and other fields. Archaeology, too, has long been developing into a multidisciplinary field, incorporating methods and theories from ecology, geology, biology, geosciences, and chemistry, among others. Additionally, qualitative approaches remain invaluable, as ethnographic, historical, and other sources of information provide unique perspectives on the world and how it operates that are essential to understanding (as much as possible) and incorporating emic perspectives into research design and interpretation.

While advocating for adopting CST more explicitly into archaeological thought, I do not mean to suggest that it should replace other extant perspectives. Rather I emphasize how CST is deeply compatible with many of the frameworks currently employed by archaeologists and where explicitly using CST principles can provide important nuances in our interpretations and help derive new hypotheses about emergent social phenomena. As such, one of the more useful ways of incorporating

CST into future archaeological research is in tandem with other well-established theoretical bodies.

Studying Socioecological Systems: Complex Adaptive Systems and Panarchy Theory

One of the central ways CST has made its way into archaeological inquiry is through complex adaptive systems (CAS), which are a subset of CST approaches that look explicitly at systems where adaptation to external and internal forces plays a larger role in emergent properties (Mitchell 2009). Given that human systems are adaptive, CAS has been especially useful for understanding cycles in social organization and how they are impacted by surrounding complex systems (like climate and ecological systems). Common frameworks in CAS are resilience theory and panarchy (Allen and Starr 1982; Bradtmöller et al. 2017; Gunderson and Holling 2002).

Resilience theory stems directly from CST; it operates under the assumption that stability and change are both central characteristics in relationships between social and ecological systems and seeks to explain the source and consequences of change at different levels of a system (Bradtmöller et al. 2017; Holling 1973; Redman and Kinzig 2003; Walker et al. 2004). Panarchy refers to a specific set of nested hierarchical structures under which resilience theory can operate and captures multi- and cross-scale relationships between information and energy transfer through a system. This is often referred to as an "adaptive cycle model" (Fig. 2). While useful as a heuristic device, it is not always a simple task to quantify these models and test them against empirical data, and much work done with panarchy models has been qualitative (Sundstrom and Allen 2019).

The concept of "nested feedback" is central to CST, overall, as it seeks to understand multiscalar and cross-scalar emergent properties. As such, a key strength of CST is that its concepts can be applied at and between multiple scales simultaneously. This sets it apart from many other bodies of archaeological theory where this is not possible.

For example, many archaeological investigations pertaining to socioecological dynamics use evolutionary frameworks like niche construction theory (Fuentes 2016; Laland and O'Brien 2010; Quintus and Allen 2023; Zeder 2016) and human behavioral ecology (Codding and Bird 2015). These frameworks are quite compatible with the tenets of CST, but they must be integrated together to achieve a multiscalar, contextually dependent investigation of systems interaction that is inherent in CST (see Bliege Bird 2015).

Niche construction theory, which is borne out of evolutionary biology (e.g., Jones et al. 1994; Odling-Smee et al. 2003; also see Spengler 2021), emphasizes that organisms can increase their fitness through active modification of selective pressures within their environment. These modifications are not isolated in their effects, however, and can create feedback loops between human and broader ecological systems (Laland and O'Brien 2010; Odling-Smee et al. 2003). Much akin to CST, niche construction theory directly incorporates vital considerations such as the dynamic nature of systems relationships and adaptive capacities resulting from emergent

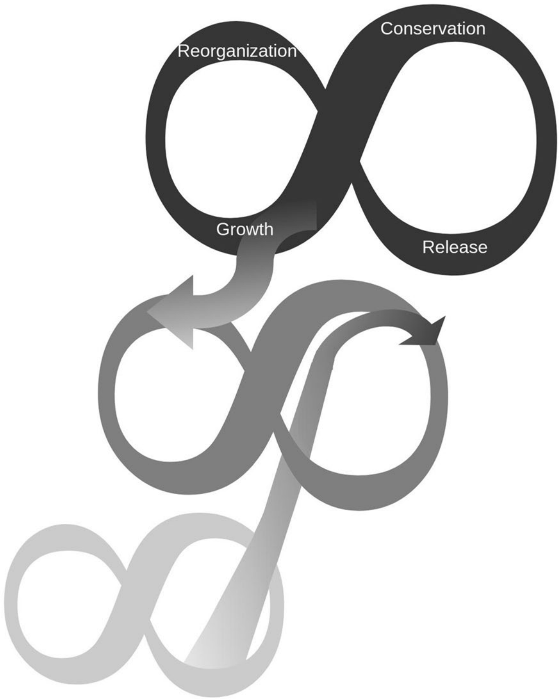

Fig. 2 Illustration of a panarchy model with nested feedback cycles in a system with three levels. Interactions at small scales can affect those at larger scales, and interactions at larger scales can inhibit or accelerate adaptations at smaller scales. The adaptive cycle itself consists of four main phases: (1) release, in which the system becomes increasingly fragile until it devolves into a new form, losing energy and matter; (2) conservation, in which the system begins to accumulate and store additional energy and material; (3) growth, in which the system begins to expand to encompass new elements; and (4) reorganization, in which resources are reorganized into a new system (which may or may not resemble the old system). Figure created by the author and adapted from Gunderson and Holling (2002), Sundstrom et al. (2023), and Redman and Kinzig (2003)

behavior (Preiser et al. 2018). However, it has been criticized for its highly descriptive but limited explanatory capabilities that stem from its focus only on larger scales of interaction (Iovita et al. 2021) and its inability to explain initial conditions (e.g., how people gain necessary information to change their surroundings successfully [Stiner and Kuhn 2016]). While niche construction's focus on large scales is not necessarily a shortcoming, if we tightly define the nature of the questions we are asking by considering emergent properties at a range of scales (*sensu* CST), we can gain a fuller understanding of systems relationships than any one scale can provide (as different scales are interdependent).

To accomplish this using other standard evolutionary models is more difficult, requiring the incorporation of multiple models that aid in explanation and provide different scales of analysis. For example, optimal foraging theories (e.g., Charnov 1976; Fretwell and Lucas 1969; MacArthur and Pianka 1966), which make assumptions about behavior related to social and environmental resources, have been applied to archaeology quite extensively (e.g., Bird et al. 2016; Davis et al. 2020; Jazwa et al. 2017; Robinson et al. 2019). Many scholars now advocate merging human behavioral ecology and niche construction theory in search for answers about human-environmental dynamics (Bliege Bird 2015; Codding and Bird 2015; Mohlenhoff and Codding 2017; Ready and Price 2021; Stiner and Kuhn 2016; Thakar and Fernandez 2023). In addition to providing greater explanatory power to niche construction theory, the two frameworks also serve to investigate interactions at small, moderate, and large spatiotemporal scales. According to CST, this permits for a greater comprehension of the complexity of human-environmental systems interactions.

A recent study by Wren et al. (2023) provides an example by showing how optimal foraging models can be modified and improved using agent-based modeling simulations. This approach allows archaeologists to examine the local-scale dynamics captured by human behavioral ecology while also capturing long-term effects and emergent behavior over larger scales of space and time. In other words, agent-based models take the starting assumptions of how people will behave and then permits for the emergence of new behaviors and organizations through interactions between individuals, communities, and populations over time. Multiple scales of interaction are examined simultaneously and reveal different patterns of behavioral change and decision making that would not be visible when examined individually. This kind of work provides a good example of how CST can be integrated with and bolster extant bodies of archaeological theory by introducing stochasticity to examine emergent behaviors and properties. Greater engagement with CST can enhance archaeological research by exposing nonlinear relationships and the processes by which behavior and social organizations develop and change.

Questioning the Prevalence of Hierarchy and Western Orthodoxy: Anarchy and Heterarchy

While an entire subset of CST has been widely applied within archaeology to study socioecological dynamics, there are other ways in which CST has featured within the discipline, largely through philosophical frameworks like anarchism and heterarchy. Social scientists have long been interested in the emergence of social and cultural systems (e.g., Durkheim 1895; Spencer 1860; also see Trigger 2006). However, the frameworks used to examine the emergence of new organizational forms vary widely. A detailed look at all of these philosophical and theoretical approaches goes beyond the scope of this article, but I focus on a few key examples where CST has (or has the potential to) shed new light on old questions.

One example stems from anarchy theory, which emerged alongside other critiques of capitalism (e.g., Marxism) to explain the emergence of power dynamics in society (Borck and Sanger 2017; Graeber 2004; McLaughlin 2007). While anarchism looks at power as an *emerging* characteristic influenced by a multitude of factors, Marxism focuses primarily on class conflict and resource exploitation (Borck and Sanger 2017; Graeber 2004; Sanger 2023). Nevertheless, Marxist philosophy also emphasizes the importance of historical context, local conditions, and the interconnection between humans and nature (Marx and Engels 1970; Roseberry 1997). Already, we can see important parallels between social theory and complexity theory, wherein systems must be understood in fluid, contextualized terms where feedbacks between actors can lead to the emergence of new organizational forms.

Anarchism's focus on emerging properties aligns it strongly with complexity frameworks, as they reject the notion of parts defining the whole (cf. GST) and instead subscribe to the idea that societies (or social systems, in general) are the result of the interactions among its components (i.e., people and their practices). As such, the state of a system is always at the mercy of its actors, leading to a process where ends and means are simultaneously in flux (Borck and Sanger 2017).

Going deeper, anarchism focuses on multiscalar processes, wherein bottom-up and top-down actions influence one another (Angelbeck and Grier 2012; Furholt et al. 2020; Graeber 2014). One salient example of this is in what Graeber and Wengrow (2021) define as "institutional flexibility." In a system of institutional flexibility, individuals consciously cycle between hierarchical and heterarchical power dynamics by creating and disassembling relationships. There are numerous examples of such relationships in ethnographic, historical, and archaeological contexts (see Graeber and Wengrow 2021; Jackson 2005; Lévi-Strauss 1944; Lowie 1948; McGuire and Saitta 1996; Sanger 2023). I am not the first to note the parables between anarchy and complexity science. Maldonado and Mezza-Garcia (2016) point to similarities between the two in terms of their "absence or critique to control [and] the importance of self organization." As they state: "the sciences of complexity are *stricto sensu*, sciences of the anarchic, in the sense that they deal with non-governable systems" (Maldonado and Mezza-Garcia 2016, p. 57).

Concepts of anarchy theory also align in some ways with those of heterarchy. Heterarchy offers a contrasting perspective on power relations in modern and historical contexts compared to traditional hierarchy models. Rather than view organization in terms of hierarchical power structures, heterarchy looks at unranked relationships between elements within a system (or when there can be multiple kinds of rankings) (Crumley 1995; McCulloch 1945). Importantly, heterarchy does not exclude the principle of hierarchy; instead, it offers a framework in which hierarchy is one possible power dynamic that can emerge rather than being the default (Grauer 2021). The concept has proven useful for archaeologists in a range of studies seeking to understand power and other social dynamics (e.g., Crumley 1995; Davies 2009; DeMarrais 2013; Grauer 2021; Moonkham et al. 2023; O'Reilly 2003).

CST is deeply intertwined with many of these kinds of frameworks and provides important ways to model important sociopolitical processes and challenge preconceptions that are inherent in Western modes of thought. Anarchy theory, for example, has shown how individuals and small community groups can construct social organizational forms that counteract centralized political power (Clastres 1989; Furholt et al. 2020; Graeber 2004; Scott 1976, 2017). By combining these insights with those offered through CST, we may be able to identify scaling relationships and other important properties that allow for such sociopolitical systems to emerge, and importantly, what limitations result in the breakdown of such systems. As the world grapples with political unrest and the rise of centralized, autocratic governments, archaeological research can provide a range of examples of the different ways in which such political systems emerged and how they were replaced.

These uses of CST demonstrate that it does not require computational skills and quantitatively rigorous methods for archaeologists to derive value. While a vast majority of CST literature (especially on resilience and CAS) is driven by quantitative approaches and computational methods, complexity is not merely a quantitative approach. Qualitative and quantitative researchers, alike, can, have, and should use CST to make significant advances in archaeology, as discussed below.

A Review of CST in Archaeological Research

CST has permeated archaeological studies increasingly over the past two decades (Bintliff 1997; Bentley et al. 2005; Crabtree et al. 2021; Davis 2020; Jacobson 2022; Kohler 2012; Kohler and Gumerman 2000; Lansing 2003; Lansing and Cox 2019). Most notably, CST has been directly invoked in studies that focus on three major categories: (1) studies of adaptation, resilience, and sustainability of social, economic, and political systems; (2) cycles of social and political (d)evolution; and (3) the identification of scaling relationships in human systems that can allow greater cross-cultural comparison between societies and time periods. In many instances, these categories are not distinct, as studies can tackle many of these concepts simultaneously (e.g., Baggio et al. 2016; Bradtmöller et al. 2017; Burke et al. 2021; Davis et al. 2023; Strawhacker et al. 2020). Such scholarship has been aided by methodological developments like social-network analysis, simulation-based modeling methods, and greater interdisciplinarity among archaeological research teams.

Ultimately, a complexity framework helps reveal important patterns and relationships that are pivotal for understanding human systems and the dynamics that define different societies. In what follows, I focus on archaeological literature that uses CST principles (or complexity science frameworks, generally) in the framing of research questions and/or interpretation of their results. This is, by no means, an exhaustive, all-encompassing account, and there are many other examples of archaeological research that uses or aligns with CST.

Methods and Approaches that Capture Complexity

Complexity science evolved in tandem with computational innovations like simulation modeling (Romanowska et al. 2019), and as archaeologists have adopted new methods and technologies, the use of CST has likewise increased. As d'Alpoim Guedes et al. (2016a) indicate, the two primary approaches to studying complex systems in archaeology come from network science and agent-based modeling, as both allow researchers to characterize feedback loops between human and external systems and can accommodate stochasticity and heterogeneity. While a full review and overview of these methods goes beyond the scope of this article (for more details see Brughmans 2010, 2013; Hartmann 1996; Peeples 2019; Romanowska et al. 2021), I summarize the most relevant aspects of these methods as they pertain to the uptake of CST within archaeological research.

Given that CST is mainly concerned with the structure of systems and how these structures emerge, adapt, self-organize, and change over time, advances in network science and network analysis have been pivotal for the expansion of complexity science. Network analysis methods, which emerged from graph theory in the 1960s, operate on the assumption that there are important relationships between entities, objects, and ideas, and that these relationships must be examined, rather than the entities in isolation, to understand behavior in a meaningful way (Brughmans 2013; Wasserman and Faust 1994). Furthermore, network studies encapsulate multiple scales of interaction that can occur between people, objects, and ideas, including how organization emerges and transforms over time (Knappett 2011).

One particular kind of network approach that has been increasingly utilized by archaeologists is social-network analysis (SNA). SNA is primarily focused on identifying social processes that create specific structures and connections between entities (Peeples 2019). SNA is increasingly used alongside other methods like simulation modeling and within CST frameworks (for a detailed overview, see Peeples 2019). Indeed, much of network science is influenced by complexity science because it "forces one to think explicitly about how things relate and how local interaction between individual entities might give rise to patterning on a system-wide scale" (Brughmans 2013, p. 642).

Another suite of methods that are central to advancing CST, especially within archaeology, are simulation models. Simulation can be defined as a formalized, artificial representation of real-world systems that also account for temporal dimensions (Hofmann et al. 2011; Romanowska et al. 2019). Additionally, simulation methods serve a variety of different purposes that can aid scientific research: they can help investigate the processes by which systems emerge and change; they can develop and test hypotheses, models, and theoretical frameworks; they can be used for pedagogy by helping others understand a specific process; and they can be used to aid experiments or in lieu of real-world experimentation (Hartmann 1996). The advancement of computer-processing capabilities has led to the subsequent acceleration in the complexity that simulations and other models can incorporate, and while simulations are always simplified abstractions, some can get quite complicated and computationally expensive.

Agent-based models are one particular form of simulation modeling that have allowed for CST to be applied more directly to archaeological investigations (e.g., Andrei and Kennedy 2013; Balbo et al. 2014; Beekman 2005; Davies et al. 2019; Dean et al. 2000; Djurdjevac Conrad et al. 2018; Kohler and Gumerman 2000; Romanowska et al. 2021). Agent-based models are stochastic models, meaning that they operate under probability distributions and can introduce heterogeneity, which is important for studies of cognition and transmission (for a detailed overview, see Romanowska et al. 2019). Agent-based models require more computational processing capabilities than other simulation approaches, however, and due to their multilevel structure, they can be more difficult to analyze and interpret (Grimm et al. 2006). Nonetheless, they have proven quite capable of providing important insight and nuance to archaeological research by introducing human agency and random variability into assessments of cultural change, thereby improving earlier models based on closed systems (e.g., Bentley et al. 2005; Romanowska et al. 2019; Wren et al. 2023).

Bayesian inference offers another means by which to evaluate complex systems, as such approaches inherently require historical information (McElreath 2020; Otárola-Castillo and Torquato 2018; Palacios and Barceló 2023). One of the key strengths of Bayesian approaches is that they allow for new and existing data to be combined to make predictions. In this way, Bayesian methods allow for estimations of the probability that a given hypothesis is true based on prior, historical data, and these results can be updated as new information is collected. Furthermore, when coupled with simulation methods like agent-based modeling, Monte-Carlo, and Approximate Bayesian Computation (Crema et al. 2014), the use of Bayesian inferences can greatly aid the modeling of complex systems (e.g., Marsh 2015; Rubio-Campillo et al. 2017). In part, it is because these approaches account for uncertainty, which is inherent in complex systems, and it incorporates information from the whole system under investigation, not a subset of data in isolation (Otárola-Castillo et al. 2022).

Ultimately, CST is highly quantitative, and its progress has been largely dependent on advances in computational processing and methods development. The integration of computational methods in archaeology is hardly new (e.g., Carneiro 1970a; Laflin 1982; Lock 2003; Polla and Verhagen 2018; Thomas 1973), but archaeology, as a field, often lags many years or decades behind others in terms of the adoption of new technology. For example, network approaches were slow to integrate into archaeological research for several reasons, including an overall unawareness of network methods and established models and a lack of question-driven uses of network models early in archaeological history (Brughmans 2013). CST has followed a similar trajectory, but as the discipline becomes more interdisciplinary, the adoption of novel techniques like agent-based models, social-network analysis, and others have led to increased use of CST principles in archaeological investigations.

Nonetheless, integrating CST into archaeological studies does not *require* computational methods. As I mentioned previously with respect to theoretical and philosophical positions on heterarchy and anarchy, CST can find its way into archaeological inquiry in qualitative ways as well. Principles of CST can also be assessed using specific kinds of data collection methods that capture complexity (i.e., multiscalar relationships, historical contexts, change and adaptation over time, etc.), none of which inherently require intensive computational training. For example, survey and excavation procedures can be designed to capture information at different scales (e.g., Davis et al. 2021). In so doing, we can better understand the connections between regional patterns and local-scale behaviors, helping bridge a divide between micro- and macroscale investigations (*sensu* Sawyer 2001, 2004) and long-standing debates over the most effective approaches to studying the archaeological record (e.g., Anschuetz et al. 2001; Bailey 1981, 2008; Dunnell 1992; Dunnell and Dancey 1983; Rick et al. 2022).

Similarly, the integration of multiple sources of evidence from geology, ethnography, climatology, among others, can greatly expand our capacity to measure complex systems interactions. Comparing regional or global trends in climatic and environmental conditions, for example, can tell us important things, but these are not always relevant to smaller scales of community interaction (e.g., d'Alpoim Guedes and Bocinsky 2018; Strawhacker et al. 2020). Likewise, a sediment core from a single archaeological site can tell us plenty about the nature of conditions for people at that specific time and place, but it does not necessarily reflect trends that impacted distant neighbors and communities farther away. By consulting and combining datasets that crosscut time and space, we can form a better picture of how human societies emerge, respond to external stressors, and change.

Below, I provide a synthesis of major research pathways in which CST has made significant contributions in recent years. While many of these studies rely, at least in part, on computational methods like those just discussed, many also incorporate more qualitative approaches that account for multiple scales of interaction and feedback effects over time.

Cycles of Social and Political (D)evolution: Societal "Complexity" and the Emergence of Power Structures

The study of how hierarchical systems of political control emerge (particularly in terms of state formation and collapse) are central avenues of archaeological inquiry (Kintigh et al. 2014). This long history also poses a particular challenge for studies of "complexity," as we must disentangle notions of "societal complexity" with those of "complex systems" (see Daems 2021; Dan-Cohen 2020). The two uses of the term 'complex' are not the same and, in many ways, are mutually exclusive. "Societal complexity" is largely rooted in views of social evolution wherein societies evolve into different (usually deemed "superior") forms with greater levels of hierarchy and technological capacity (e.g., Service 1962; Spencer 1860). This teleological definition of complex is counterintuitive to the definition of complexity espoused by CST.

Researchers like Daems (2020, 2021; also see Kohler et al. 2022) have written on some of these issues and tried to demonstrate how "societal complexity" can be redefined along the lines of complex systems, emphasizing the capacity for information transfer and peoples' ability to self-organize into new forms that can process information in different ways. This view of complexity is more in line with this article: it is a description of a system's capacity to process information and self-organize; it is not a description of overall development or social organization (cf. Service 1962; Spencer 1860).

Despite differences in terminology over the past century, questions regarding social development and change have long intrigued researchers and have led to entire subdisciplinary foci on the causes of societal collapse and hierarchical emergence (e.g., Costanza et al. 2007; Ramenofsky 1982; Tainter 1988, 2014). CST approaches allow researchers to reexamine older theories on the emergence of "states" and other hierarchical power structures. For example, Carneiro's (1970b) notion of "environmental circumscription" associates the emergence of hierarchical organization with environmental conditions (i.e., resources) and people's control over those resources. The emphasis on *emergent* phenomena and their causes is in line with CST, but adequate testing of Carneiro's work continues with mixed results, largely because initial conditions and local context are crucial (e.g., Feinman and Carballo 2018; Gavrilets et al. 2010), as is the ability to consider multiple levels of interaction between and among political systems and the people they encompass.

Turchin et al. (2018) demonstrate how assumptions from CST can help reevaluate earlier hypotheses (like Carneiro 1970b) regarding state formation and the factors that lead to hierarchical political organization. The researchers use time-series regression to evaluate emergent patterns in sociopolitical organization and compare these results to empirical datasets from the archaeological record. This approach allowed them to find nonlinear associations between their various predictor variables and some support for the idea that population is an important factor in the rise of political hierarchy. Ultimately, they conclude that initial conditions of social systems will influence overall outcomes and stress the importance of examining "large, dynamic, time-series data culled from a wide temporal and geographical sampling of past societies" (Turchin et al. 2018, p. 15). While the study was designed to test overarching theories of state formation, more concrete results would likely have been obtained by constructing a well-defined system with less temporal and geographic variation to assess different hypotheses.

While Turchin and colleagues (2018) demonstrate how time-series analysis can help identify general patterns in the emergence of political hierarchies, a recent study by Shin et al. (2020) makes use of another set of CST principles: scale and local historic context. Shin and colleagues undertook an investigation of scale in the development of hierarchical sociopolitical systems using a combination of local-level datasets generated by researchers in different areas around the world and aggregated information derived from these datasets. The authors then used a variety of statistical approaches, including principal components analyses and a variety of simulation-based statistical models to parse through this information to try and derive general rules pertaining to the development of sociopolitical systems. Overall, their findings align with earlier studies that suggest increasing population sizes led to the development of hierarchical structures (Feinman 2012; Johnson 1982; Kosse 2000). However, Shin et al. (2020) also emphasize that there are transitional zones between scales of population and information-processing capabilities that must be crossed before such structures can develop. This conclusion required an approach (i.e., CST) that could look at and between different scales of interaction that were overlooked by many prior studies.

Furthermore, their analysis leads to another important finding that many Holocene-era societies in the Americas maintained scales that (almost by design) did not breach that scaling threshold. While the reason for this is likely multifaceted, the authors list two potential explanations: (1) the absence of load-bearing domesticates (like horses, cattle, etc.) in the Americas, and (2) that we are asking the wrong question entirely about social development. The latter point could also have been reached using a completely different set of social theory (i.e., anarchy): change your frame of reference and ask *why societies in the Americas may have consciously chosen to avoid reaching a societal scale (in terms of information transfer and population levels) where innovations seen elsewhere were necessary* (Graeber and Wengrow 2021; Sanger 2023). Because CST permits for the evaluation of multiple scales of interaction simultaneously, the authors were able to reach this similar conclusion as well as uncover general rules of sociopolitical development that many earlier researchers uncovered decades ago (e.g., Carneiro 1970b). This demonstrates not only the importance of consulting a range of theoretical perspectives but also the utility of CST as an analytical framework that can be leveraged to understand the intricacies of emergent social, political, and economic patterns among human societies.

While Shin et al. (2020) reveal interesting trends regarding the nature of human societies and information-processing capabilities, their approach is not without its problems. A recent collection of articles highlights some of the issues that can arise in aggregations of global information: many local intricacies can be obscured, overlooked, and misinterpreted. For example, Wernke (2022) highlights how the unique systems of information management employed by the Inka were incorrectly labeled as "absent" within the database used by Shin et al. (2020). Wernke argues that implicit ethnocentric biases toward the Western Hemisphere's norms have distorted the interpretation of many places around the world, including South America. This speaks to a larger issue in archaeology, generally, regarding inclusivity and engagement with local communities, which I discuss in more detail below. Briefly, Wernke highlights an important necessity among researchers and a key principle of CST: any attempt to understand complex systems *requires* input from regional specialists and local communities in order to correctly identify and classify cultural institutions and systems properties.

Along these lines, proponents of complexity theory within archaeology have tried to challenge ethnocentric orthodoxy through alternative viewpoints. One example comes from Crumley (2005), who uses the principle of heterarchy to investigate social organizations. Crumley notes that, historically, among older systems theorists and anthropologists, hierarchy has been associated with order. She argues that heterarchy, and complexity theory, more broadly, can serve as a much-needed correction to this line of thinking and can accommodate history and individual agency into studies of power structure. Indeed, this is one of the very things that practitioners of anarchy theory advocate (e.g., Graeber and Wengrow 2021; Sanger 2023).

Grauer (2021) presents one example of how heterarchy has been used to advance archaeological understanding of social and political relationships. The author investigates the political relationships surrounding access to water resources in Belize between AD 750 and 1100. Using a series of excavations and city-wide surveys at the site of Aventura, Grauer documents water access that crossed between hierarchical levels, indicating that all levels of society had some access to this resource, which was not the case at many other Maya cities. Grauer (2021) argues that heterarchical models are more compatible with ancient Maya worldviews because they do not assume that humans can impose direct control over the environment. As such, a heterarchichal framework affords the ability to shift power to nonhuman actors (for example, ancestors, which are central actors in Maya ontologies). Furthermore, a heterarchy model of power dynamics also permits for multiscalar evaluation of power that can cut across social level, gender, and age.

The implications of a heterarchical power dynamic could potentially explain why Aventura managed to thrive during a period when many other urban centers were undergoing sociopolitical reorganization and ecological downturn. As Grauer (2021, p. 10) finds, "[p]ower was not derived from restricting access to water, even in times of drought," but rather each household had their own ability to access water, regardless of social or economic standing. This, in turn, may have increased the city's resilience to changing regional ecological and political conditions.

In sum, archaeological research using CST has provided important insight to the factors that can help explain the emergence of unique social and political organizational structures. Use of CST frameworks has highlighted the importance of initial conditions and local histories in attempts to understand the emergence of sociopolitical structures. CST has also helped identify relationships between thresholds in population size and interactions and transitions between different sociopolitical states. Of equal importance, CST has challenged orthodox viewpoints on order, thereby permitting for alternative interpretations on the nature of hierarchy and the possibility of nonhierarchical power structures to constitute equally plausible forms of sociopolitical organization. Along these lines, the use of heterarchical power as a framework has allowed for multiscalar investigations into political systems, including the ability to identify simultaneously competing power structures at play within different levels of society (e.g., Grauer 2021; Moonkham et al. 2023).

Studies of Adaptation, Resilience, and Sustainability

Perhaps one of the most abundant examples of how CST has been integrated into archaeological studies is through literature on resilience and sustainability among socioecological systems. Entire volumes and countless books and articles have been published in the past several decades on this topic (e.g., Allen et al. 2022; Bradtmöller et al. 2017; Costanza et al. 2007; Faulseit 2016; Fisher et al. 2009; Gunderson and Holling 2002; Jacobson 2022; LeFebvre et al. 2022; O'Brien 2017; Ullah et al. 2019). Indeed, many prior reviews of complexity theory in anthropology have focused on CAS approaches and case studies of resilience among different human societies (e.g., Bentley and Maschner 2003; Bradtmöller et al. 2017; Lansing 2003; Redman 2005; Redman and Kinzig 2003; Thompson and Turck 2009; Turck and Thompson 2016; Weiberg 2012).

Dearing (2008), for example, uses a resilience theory framework to investigate socioenvironmental systems interactions over time in Yunann, China, demonstrating how paleoenvironmental records, when linked with climatic and anthropological data, reveal important information about socioenvironmental systems dynamics. The author identifies a series of different scales of systems interactions, including a centennial–millennial cycle of land use and erosion, a decadal–centennial land-use flooding cycle, and a seasonal–annual monsoon-flooding cycle, each of which change human and ecological responses. Additionally, the authors note that interpretations on the overall health of the system change when human–environmental relationships are examined at different temporal scales. When the environmental context of the modern Yunnan landscape is compared at a centennial scale with land use and flooding cycles, the system appears healthy; but when it is compared to millennial-scale events of land use and erosion cycles, the system appears degraded (Dearing

2008). Overall, Dearing concludes that the modern environmental system in Yunnan lies in a steady but degraded state, suggesting that it is resilient to climate change but greatly susceptible to changes in land-use practices (e.g., loss of paddy farming systems).

In another study, Barnett et al. (2020) use a variety of paleoclimatic, paleogeographic, and paleo-oceanographic datasets to reconstruct past sea levels and environmental conditions. The authors utilize this multiproxy, interdisciplinary approach to improve understanding of nonlinear and variable responses to sea level changes during the Holocene. Given local variation (in terms of environmental and geological conditions and cultural behaviors), the best practices for adapting to climate change are likewise diverse. As such, the researchers conclude that local cultural and societal perspectives are (and will remain) critical in developing successful adaptive responses to climate change (Barnett et al. 2020). Indeed, this way of thinking is not only significant for archaeology but also for conservation biology, ecology, and environmental science, where top-down policies can be greatly improved by engaging with local communities and gaining important cultural and historical context (e.g., Allen et al. 2022; Fletcher et al. 2021; Razanatsoa et al. 2021; Westerman et al. 2012). Counter to this kind of thinking, CST requires a consideration of emergent properties that arise at different scales in a system and the feedback dynamics that result from these reconfigurations. Top-down thinking doesn't work with CST because it *only* considers a single scale of action and its consequences but not the consequences at other scales that will inevitably *respond* to this interaction in ways that may vary from the scale under consideration.

Take, for example, a governmental policy initiative that restricts all fishing access in a lake because commercial fishing operations are decimating fishery productivity. While commercial fishing is causing an imbalance to the ecosystem, the local communities have fished in this area for generations, creating a symbiotic system in which fisheries are kept stable through human intervention. The government policy will help correct for commercial fishing operations (a larger-scale interaction), but it will also destabilize the community and local fishery resilience as they are now intertwined with local communities living in that region. By looking across scales, these consequences can be realized before they happen and may help lead to different solutions. Within archaeological contexts, the framework offered by CST allows us to understand cascading impacts of regional-scale events on local-scale systems and vice versa (e.g., Crabtree et al. 2021; Davis et al. 2023; Dearing 2008; Xu et al. 2020).

Recent research by Xu et al. (2020) exemplifies how CST helps make archaeology increasingly relevant for addressing ongoing and future societal and ecological challenges. Xu and colleagues demonstrate how for thousands of years humans have occupied a narrow range of temperature zones around the world. They then show that current projections in climate warming will place billions of people outside historically livable ranges. This, in turn, would cause cascading demographic changes and societal effects without adequate climate-change mitigation efforts in the present. This kind of research by archaeologists fits well within other studies of complex systems that examine vulnerabilities of populations to a variety of socioeconomic and environmental crises (e.g., d'Alpoim Guedes et al. 2016a; Martini et al.

2022; Omodei et al. 2022; Silva et al. 2022) and is thus pivotal for expanding interdisciplinary collaborations between archaeology and other fields.

The integration of CST principles to study emergent behaviors can also be seen in recent studies that demonstrate the importance of understanding multiscalar interactions through local conditions and local community behavior. For example, d'Alpoim Guedes and Bocinsky (2018) demonstrate how local climate conditions are more important than global or regional trends for understanding the experiences of ancient farming communities as these conditions are most significant in impacting crop yields. One of the challenges among environmental archaeologists is to determine how paleoclimate datasets (which often record regional climatic trends) relate to local-scale conditions (but see Contreras et al. 2018). The authors use paleoclimate data and a method of interpolation to map local environmental proxies and estimate variations in their values over different time scales (see d'Alpoim Guedes et al. 2016b). This allowed for both local and regional conditions to be assessed over time (capturing changes in spatial and temporal scale). Overall, d'Alpoim Guedes and Bocinsky (2018) demonstrate how, at a general level, populations in Asia used a variety of strategies to buffer against crop failure, including crop diversification, storage, and economic specialization. However, on a local level, changes in climate impacted communities in different ways (also see Petrie et al. 2017), as variations in crop returns and the overall landscape were impacted uniquely. Looking at multiple scales, the authors argue, can "help archaeologists situate the culturally resilient strategies they developed in the climatic context in which they took place" (d'Alpoim Guedes and Bocinsky 2018, p. 8).

Understanding the individual and local level of systems interactions (e.g., social networks) has been greatly aided by complexity science and CST, most notably, perhaps, in the form of network science (Peeples 2019). New approaches are opening avenues to examine the interrelationships between individuals, groups, and societies in the emergence, reorganization, and (d)evolution of socioeconomic, political, and technical networks across time and space. With the introduction of network science methods into archaeology (Mills 2017; Östborn and Gerding 2014; Peeples and Roberts 2013; Wasserman and Faust 1994), there has been an explosion of investigations into the internal dynamics of social, political, and economic networks and the emergence of new organizational forms.

One example is a study conducted by Baggio et al (2016). The researchers use network analysis methods to examine the influences of social and ecological contexts on social connections at the community and household scale. By incorporating these multiple scales of investigation, they examine a range of possible scenarios for the effects of changing network connections at individual and community levels and their effects on the overall resilience of a social system to external shocks (e.g., climate change, resource depletion). They demonstrate that, contrary to many environmentally deterministic ideas, the breakdown of social relationships causes more issues in terms of societal resilience than environmental downturn.

Similarly, Gauthier (2021) uses network approaches and spatial statistical methods that measure interaction to understand the role that social networks and connections play in buffering a society against variability in climatic and environmental conditions. The study finds that social interactions do appear to increase the ability of human populations to withstand environmental change. However, the exact degree to which different social ties buffered against environmental stress varied across regions and at different scales (local to regional).

In another study, Davis et al. (2023) use similar CST and network approaches, coupled with oral history records from southwest Madagascar, to examine the role of political and climatic variability on social-network organization. They demonstrate that shifts in climatic and political conditions correlate with reorganization of social networks between archaeological sites. As such, local responses to regional climatic and political trends served adaptive functions to cope with new, often unstable, conditions. Specifically, stresses caused by hypervariable conditions led to increased density in the clustering of social ties and the emergence of a core-periphery structure, which not only can help reduce risk but also can result in centralized, hierarchical power. As conditions became more stable, the social networks once again reorganized, easing the core-periphery structure. Overall, the study demonstrates not only how global and regional conditions can influence local-scale interactions but also how local historical knowledge is essential to understanding social networks and adaptive strategies.

In sum, there has been a great deal of literature focusing on resilience of social and political systems using CST. Among CST's greatest contributions to this research are the identification of local-scale and regional-scale patterns of coevolution between humans and landscapes, wherein emergent behavior can create buffers against climate change at the cost of an overreliance on human intervention; in some cases, the opposite patterns are true. Researchers have uncovered important strategies for coping with climate change and environmental instability (e.g., Baggio et al. 2016; d'Alpoim Guedes and Bocinsky 2018; Douglass and Rasolondrainy 2021), identified feedback mechanisms between human activities and ecosystem functioning (e.g., Dearing 2008; Redman and Kinzig 2003; Ullah et al. 2019), and identified potential shifts in where humans will be able to live as climatic conditions change in the present based on historical trends (e.g., Xu et al. 2020). Such insight holds important lessons for contemporary society, where conservation initiatives sometimes ignore the role of local communities in managing ecosystem productivity (e.g., Fletcher et al. 2021; Westerman et al. 2012). This work also illuminates the need to incorporate local and regional scales to understand the ways social networks can act as buffers against internal and external threats facing portions of a population.

The Identification of Scaling Relationships in Human Systems: Improving Cross-Cultural Comparisons

Another area where CST is contributing to archaeology is in the identification of scaling laws, particularly among urban systems (Bettencourt et al. 2007, 2008; Ortman et al. 2014). Scaling laws try to establish a functional relationship between two or more entities where each quantitatively scales in relation to the other (Bettencourt et al. 2008; Johnson 1981; Ortman et al. 2020; Stauffer 1979; West 2017). For example, a commonly identified scaling law demonstrates that socioeconomic institution

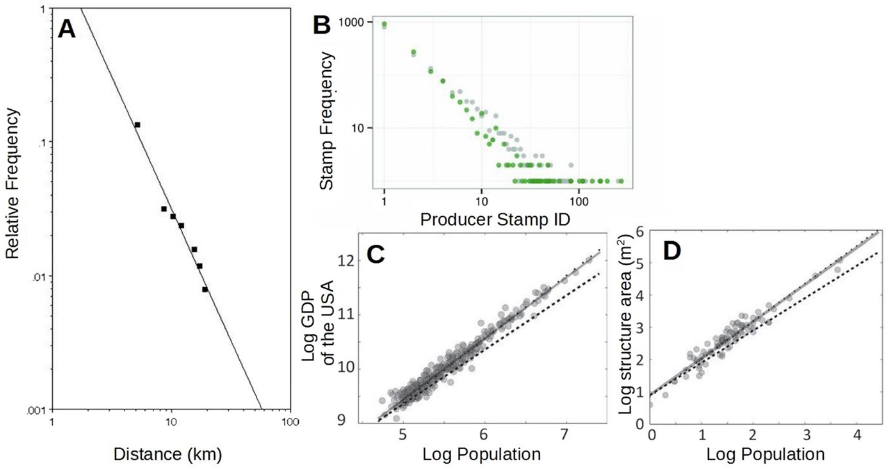

Fig. 3 Examples of power-laws found in the archaeological record: **A** shows power-law distribution of distances between Ju/'hoansi hunter–gatherer campsites (after Brown et al. 2007); **B** shows power-law distribution found among olive-oil markets in the Roman Empire showing that most production was centered around a small number of sellers (after Rubio-Campillo et al. 2017); **C** and **D** show power-laws of scaling between economic output with population in the modern day USA (**C**) and the prehispanic Andes (**D**) (after Smith 2019)

development correlates with the size of the population and overall size of territorial control of a governing system (e.g., Bettencourt 2013). Power-laws are a type of scaling relationship wherein one dataset scales at the power of another. In archaeology, CST and scaling theory have been applied to the study of a variety of phenomena (Fig. 3), but among the most widely applied uses is in urban scaling.

Urban scaling seeks to understand nonlinear urban properties (e.g., wealth and infrastructure) and how they change in relation to population and city size (Bettencourt et al. 2020). Formal mathematical relationships of this kind were developed through decades of interdisciplinary work focused on primarily modern (but also ancient) urban systems (e.g., Altaweel and Palmisano 2019; Bettencourt et al. 2007, 2008; Lobo et al. 2013, 2020; Schläpfer et al. 2014) and has since been applied to a variety of archaeological contexts (e.g., Ortman et al. 2014, 2020; Ortman and Coffey 2017; Squitieri and Altaweel 2022).

Ortman et al. (2014) are among the first to develop a general scaling theory for archaeological settlements. Using urban scaling theory developed previously (e.g., Bettencourt et al. 2007), the authors develop a model of settlement scaling that they apply to an archaeological dataset consisting of >1500 archaeological settlements from the Basin of Mexico spanning the past two millennia. Settlement scaling theory developed by Ortman et al. (2014) argues that socioeconomic properties present in human systems emerge from individuals' choices in spatial arrangement that balance movement cost with social interactions (also see Ortman and Coffey 2017). The authors find that the scaling relationships (which are derived from modern contexts) also apply to ancient settlement systems. As such, there appear to be "fundamental processes behind the emergence of scaling" in human settlements across time

(Ortman et al. 2014, p. 7). Furthermore, the identification of this scaling relationship lends support to the notion that all human settlement systems function in the same manner, but that specific forms and scales of economics are emergent properties resulting from interactions among individuals within settlements as opposed to specific technological, political or economic factors" (Ortman et al. 2014, p. 7).

Such insights are incredibly important, as they aid the ability of archaeologists to compare ancient and contemporary societies at different scales on equal terms (Ortman and Coffey 2017). In a time when archaeologists are in need of connecting with the public and explaining in clear terms why what we do is useful to modern society, such approaches offer clear examples of how the past can inform modern and future human goals. Additionally, the insights provided by scaling theory (the results of Ortman et al. 2020, in particular) run fundamentally opposed to prior deterministic assumptions that complexity within human societies requires some sort of "revolution" in technological, economic, or political innovation (e.g., Flannery 1972; Meggers 1960; White 1988; also see Trigger 2006). While these variables may play a role, scaling is ultimately an emergent property resulting from social and other systems interactions (Bettencourt et al. 2007; Ortman et al. 2014; Ortman and Coffey 2017).

Scaling relationships have also been identified in studies of the Roman market economy. Rubio-Campillo et al. (2017) used Bayesian models to identify a power-law distribution among market structures of olive-oil trade during the Roman Empire. Power-laws indicate that the economic system was self-organized with a degree of hierarchy in its structure (Newman 2005). The authors suggest that the presence of power-law relationships could not be the result of random chance, as it requires the investment of a "large amount of resources and fine control over the system" (Rubio-Campillo et al. 2017, p. 1248). As such, the authors suggest that Rome had a "densely interconnected" free market system.

Another example of how scaling theory has been applied to archaeology is Squitieri and Altaweel (2022), who use urban scaling combined with metrics of inequality (Gini and Atkinson coefficients) to examine changes in inequality within urban systems during and prior to the establishment of empires in the Near East. The authors demonstrate that changes in house size attained similar scaling relationships with those observed in modern populations and that urban infrastructure often changed at a comparable level to overall population sizes. Additionally, Squitieri and Altaweel (2022) show how house sizes increased more rapidly during periods of empire rule, and metrics of inequality demonstrate that disparities in wealth also accelerated during these periods. The authors caution, however that their results only reflect general patterns and that regional and local-scale nuances likely exist that current data cannot capture.

Scaling relationships offer, perhaps, one of the best ways in which archaeology can be directly involved in studies of contemporary phenomena. A common struggle for archaeology has been to demonstrate its value to the current and future world (e.g., Smith 2021). By using the archaeological record to identify patterns that transcend history and scales of social and political organization, we can contribute to important topics like sustainability, the rise of political extremism, economic volatility, among others. Scaling theory, and CST more broadly, offer one means to identify such relationships and enable archaeology to contribute to greater interdisciplinary collaborations.

Complex Systems Approaches and the Prospect of Engaged, Interdisciplinary Archaeology

A significant amount of scientific research has moved toward increased interdisciplinarity in recent years, with research teams encompassing a range of backgrounds and expertise to examine increasingly complicated questions (e.g., Crabtree and Dunne 2022; d'Alpoim Guedes et al. 2016a; Silva et al. 2022; Van Noorden 2015; Weart 2013). Because of the nature of complexity, any investigations into these kinds of systems will inevitably exceed the capabilities of any lone researcher, both in terms of methodological training and background knowledge. As such, research using CST as a framework requires collaboration between fields and allows archaeologists to increase their interaction with other disciplines, answer fundamental questions that are shared by other fields, and increase the overall impact of archaeological research.

The idea of interdisciplinarity stretches well beyond scientific collaborations across academic disciplines and touches on the need to engage with other stakeholders involved in research programs. CST emphasizes multiscalar levels of interaction and emergent properties that result from historical memory and interactions among systems components (i.e., individuals). Much as the post-processual turn emphasized "partial truths" and the stark contrasts between emic and etic perspectives, CST requires engagement with all levels of a system depending on the questions asked and the phenomena under investigation. As such, we must engage with the members of a system whose actions define that system (i.e., local actors), and their perspectives need to be included to understand the larger system they encompass and create. Studies using complexity frameworks therefore require community collaboration and engaged archaeological practice that emphasizes two key concepts.

Complex systems are historically contextualized. Because complex systems are adaptive, time is an essential characteristic. In the context of human systems, this means that to understand past occurrences, we need an intimate knowledge of the system (i.e., local traditions, customs, and worldviews) and its initial conditions (i.e., local history). Local, indigenous, and descendant communities who are keepers of such records are, thus, invaluable for understanding these initial conditions, which we can then use to model and test archaeological theories.

One of the criticisms levied against GST was the fact that it did not include (or even consider) non-Western concepts and worldviews. The argument was even made that unless "multiple epistemologies" were truly engaged with systems theory, such an approach would ultimately fall short of solving any problems in cross-cultural contexts (Rodin et al. 1978, p. 755). By emphasizing the complexity inherent in systems interactions, CST requires historical and multiscalar context. For human systems, local knowledge becomes fundamental to drawing any conclusions or starting any investigation of human dynamics.

Complexity science prioritizes collaborative research and learning designs. The underlying assumptions of CST revolve around multiscalar connections and contextual importance. Thus, the practice of complexity science prioritizes research and learning models that are collaborative, merge multiple perspectives, and are founded on partnership interactions that can capture heterogeneity in thought and interpretation (Morrison 2008). This speaks to a fundamental aspect of the future of archaeology: we must integrate the perspectives of the public, local, indigenous, and descendant communities, and other stakeholders, but not only for the sake of academic discovery. We need to truly have an *exchange of ideas*, whereby all parties are actively involved in research design and implementation and come away with new perspectives, knowledge, and understanding of the topic of interest (e.g., Douglass et al. 2019).

While the use of complex systems approaches can help push for decolonization efforts and diversification of perspectives, studies can (and are) still conducted without local collaboration. The theoretical framework of complex systems requires balanced perspectives to derive hypotheses about system formation and development. In its application, however, the theory must be met with practice: the study of complex systems should be integrated with indigenous praxis and worldviews and utilized within a collaborative research environment (e.g., Alleway et al. 2023; Davis et al. 2023; Douglass and Rasolondrainy 2021; Pisor and Jones 2021; Pisor and Ross 2022). This is important not only for broadening our perspectives and challenging Western ontologies but also for addressing the inequities and injustices within archaeological practice, and academic research more generally (Nicholas 2008; Supernant and Warrick 2014).

Promises Made, Promises Kept? The Impact of CST and Its Future in Archaeological Thought

Principles behind CST are directly relatable to (and entrenched within) other extant theoretical frameworks applied within different archaeological circles. To this point, CST is well suited to address nearly all of the "grand challenges" posed for archaeological research by Kintigh et al. (2014). As illustrated in Fig. 4, nearly every major category of the grand challenges aligns with one or more foundational principles of CST, and in most cases, there have been at least a handful of studies focused on specific grand challenges that have used CST approaches, explicitly, in recent years.

It is also worth noting just how many of the grand challenges engage with key CST principles: *emergence* of social inequalities, agricultural economies, and cultural and biological responses; *feedbacks* between human and environmental systems; *adaptation* of behavior, culture, and society to external interactions with climatic and environmental systems; *multiscale effects* of systems interactions, both in terms of spatial and temporal dimensions; and *local context* via identity formation and its role in shaping social systems. Systems thinking, and CST in particular, are deeply ingrained within the very questions archaeology, as a discipline, is invested in studying. It is clear that CST has a central role to play in understanding human history, and it can help address longstanding research questions and develop new avenues for research that archaeologists have yet to investigate.

Fig. 4 Shows how CST aligns with many of the grand challenges in archaeological research (as presented by Kintigh et al. 2014). Examples of archaeological research that have used CST to address some of these questions are also presented: MS = multiscalar interactions; EP = emergent properties; SO = self-organization; A = adaptation; FL = feedback loops; SS-D = stable states and disequilibrium; LHC = local history and context; GL = general laws. Figure created by the author ▶

Since the early 21st century, several notable publications have advocated for the integration of CST into archaeological thought and, in so doing, made a series of promises about what this framework would allow researchers to accomplish. Scholars have argued that concepts from complexity science could bridge the gap between micro- and macroscale investigations of social systems (Sawyer 2001, 2004) and reinvigorate archaeology's conceptual base (Redman and Kinzig 2003); they also have suggested that CST is the only available framework that could integrate culture history, processualism, and post-processualism (Bentley and Maschner 2007; Bintliff 1997). A question in need of consideration after nearly two decades is how well have these predictions and promises held up.

The Promise of Reinvigorating Conceptual Thinking

Based on the literature reviewed here, many researchers are making use of the concepts of CST, but not all who use these principles use them equally. Many uses of CST are largely interpretive, using notions of emergence and adaptation to frame nuanced interpretations of archaeological findings but not necessarily in deriving testable hypotheses (e.g., Barnett et al. 2020; Petrie et al. 2017). Others use CST to frame important studies that investigate coevolutionary feedback cycles and emergent properties of social and political systems (e.g., Davis et al. 2023; Dearing 2008; Kohler et al. 2012; Thompson and Turck 2009). What is clear is that CST is helping spur interdisciplinary thinking, which can be viewed as a "reinvigoration" of the conceptual base of archaeological research (*sensu* Redman and Kinzig 2003). However, the exact way in which this is taking place is not necessarily as Redman and Kinzig originally anticipated.

Redman and Kinzig (2003) stated that resilience theory (and CST principles) would contribute to archaeological thought in three main ways: (1) substantively, it would allow for a greater understanding of the mechanisms by which human societies operate and allow for predictions into the future of human systems; (2) theoretically, it would provide a framework and means by which to share ideas across traditional disciplinary boundaries; and (3) individually, researchers would become more attuned to their own perspectives and biases, which would help them embrace alternative views from other disciplinary backgrounds. Twenty years later, there have certainly been improvements in the understanding of human societal mechanisms and forecasting of changes to human societies (e.g., Hooper et al. 2010; Kemp et al. 2022; Xu et al. 2020). There have also been many new discoveries regarding human behavior, demographics, and the emergence of sociopolitical organization that have emerged from collaborative projects rooted in CST (e.g., Crabtree et al. 2021; Davis et al. 2023; Djurdjevac Conrad et al. 2018; Ortman et al. 2020; Shin et al. 2020). Nevertheless, more can be done with the concepts and frameworks provided by

Grand Challenges (Kintigh et al. 2014)	CST Principles	Relevant Literature
Emergence, communities, and complexity 1. How do leaders emerge, maintain themselves, and transform society? 2. Why and how do social inequalities emerge, grow, persist, and diminish? 3. Why do market systems emerge, persist, evolve, and fail? 4. How does the organization of human communities at varying scales emerge from and constrain the actions of their members? 5. How and why do small-scale human communities grow into spatially and demographically larger and politically more complex entities? 6. How can systematic investigations of ancient urban landscapes shed new light on the social and demographic processes that drive urbanism and its consequences? 7. What is the role of conflict in the evolution of complex cultural formations?	1. EP, FL, SS-D, A, SO 2. EP, A, SS-D, SO 3. EP, A, SS-D, SO, MS 4. MS, SO, FL 5. EP, SO, A, SS-D 6. MS, LHC, FL 7. EP, A, FL	Bentley 2003; Gavrilets et al. 2010; Oka et al. 2017; Ortman et al. 2020; Ortman and Coffey 2017; Rubio-Campillo et al. 2017; Shin et al. 2020; Turchin et al. 2018
Resilience, persistence, transformation, and collapse 1. What factors have allowed for differential persistence of societies? 2. What are the roles of social and environmental diversity in creating resilience and how do their impacts vary by social scale? 3. Can we characterize social collapse or decline in a way that is applicable across cultures, and are there any warning signals that collapse or severe decline is near? 4. How does ideology structure economic, political, and ritual systems?	1. FL, LHC, SS-D 2. LHC, MS, FL, GL 3. GL, SS-D 4. LHC, SO, EP	Barton et al. 2010; Dearing 2008; Gavrilets et al. 2010; Petrie et al. 2017; Redman and Kinzig 2003; Ritchison et al. 2020; Turck and Thompson 2016
Movement, mobility, and migration 1. What processes led to, and resulted from, the global dispersal of modern humans? 2. What are the relationships among environment, population dynamics, settlement structure, and human mobility? 3. How do humans occupy extreme environments, and what cultural and biological adaptations emerged as a result? 4. Why does migration occur and why do migrant groups maintain identities in some circumstances and adopt new ones in others?	1. EP, FL, A, SS-D, MS, GL 2. FL, LHC, MS 3. EP, A, SO, LHC, SS-D 4. LHC, EP, SS-D, FL, GL	Barton et al. 2010; Crabtree et al. 2021; Djurdjevac Conrad et al. 2018; Gauthier 2021; Romanowska et al. 2021
Cognition, behavior, and identity 1. What are the biophysical, sociocultural, and environmental interactions out of which modern human behavior emerged? 2. How do people form identities, and what are the aggregate long-term and large-scale effects of these processes? 3. How do spatial and material reconfigurations of landscapes and experiential fields affect societal development?	1. EP, FL, A 2. EP, SO, LHC, MS 3. MS, FL, SS-D	Arrow et al. 2000; Bentley and Maschner 2001; Barton et al. 2010; d'Alpoim Guedes and Bocinsky 2018; Graham 2006; Lobo et al. 2022
Human–environment interactions 1. How have human activities shaped Earth systems? 2. What factors affect population growth in prehistory and history? 3. What factors drive health and well-being in prehistory and history? 4. Why do foragers engage in plant and animal management, and under what circumstances does management lead to domestication? 5. Why do agricultural economies emerge, spread, and intensify, and what are the relationships among productive capacity, population, and innovation? 6. How do humans respond, perceive, and react to abrupt environmental change over different time scales?	1. FL, EP, SS-D 2. FL, A, GL 3. FL, GL 4. LHC, FL, EP 5. EP, SS-D, A, SO, MS 6. MS, LHC, FL	Barton et al. 2010; d'Alpoim Guedes and Bocinsky 2018; Gauthier 2021; Graham 2006; Marsh 2015; Petrie et al. 2017; Ritchison et al. 2020; Strawhacker et al. 2020 Xu et al. 2020

CST, but further advancement requires interdisciplinary collaboration and/or training, which is a common plea but difficult to achieve.

For example, archaeologists can integrate themselves into larger studies of Earth systems and forecasting for the contemporary and future world. CST provides a framework that allows for trans- and interdisciplinary discussion, and recent studies are beginning to show the power of integrating archaeological perspectives into broader studies of human society (e.g., Allen et al. 2022; Altschul et al. 2017; Burke et al. 2021; Kemp et al. 2022; Xu et al. 2020). The call to leverage data from the past to inform on modern issues is not new but has been reinvigorated in recent years, in many cases by scholars employing complex systems approaches (e.g., Barnett et al. 2020; Crabtree and Dunne 2022, 2023; Silva et al. 2022).

Archaeologists are already making more nuanced interpretations using CST, but there are also important questions that can be asked using this framework. For example, it is often demonstrated and argued that people in the past managed to live sustainably under certain conditions, but can these approaches work effectively in the modern world (see Nicoll and Zerboni 2020)? Studies of scaling relationships and assessing the degree to which ancient strategies can effectively be applied in the present is an important research avenue to which CST can make important contributions. Furthermore, future studies focused on the emergence of (in)equality may offer unique insight to the factors involved in preserving or destabilizing different status quo of social, economic, and political organization. Such investigations require CST as they necessitate understanding of nonlinear dynamics, emergent properties, and alternative lenses to view organizational forms that may have differed significantly from contemporary preconceptions.

The Promise of Bridging the Gap Between Micro- and Macroscales

In the social sciences, a fundamental challenge for researchers has been the study of sociality from micro- and macroscales. Speaking within the context of sociology, Sawyer (2001, 2004) describes a gap in studies of microscale and macroscale sociality and suggests that studies of emergence can help bridge this divide by looking at mechanisms by which social systems emerge. Within archaeology, CST has certainly afforded the ability to narrow this scalar gap, as numerous case studies have demonstrated (e.g., Crabtree et al. 2021; Contreras et al. 2018; d'Alpoim Guedes and Bocinsky 2018; Dearing 2008; Gauthier 2021; Ortman and Coffey 2017; Shin et al. 2020). By highlighting multiscalar and cross-scalar interactions, CST has allowed archaeologists to gain important insight about the nature of resilience among social and environmental systems, identify common trends (i.e., scaling laws) that are shared between different societies, and provide important nuances to earlier conclusions about social and political development.

The ways in which researchers have attempted to bridge scales of analysis varies. Some have developed methods to capture processes occurring at different scales of interaction (e.g., Crabtree et al. 2021; Contreras et al. 2018; d'Alpoim Guedes et al. 2016b; Davis et al. 2021; Gauthier 2021; Kohler et al. 2012), while others are developing theoretical approaches to attain general patterns that are shared at different scales (e.g., Bettencourt 2013; Gunderson and Holling 2002; Hooper et al. 2010; Ortman and Coffey 2017; Shin et al. 2020; West 2017). Future attention should be placed on merging the theoretical developments with methodological ones. I have argued for this elsewhere in terms of advancements in remote sensing archaeology (Davis 2021; Davis and Douglass 2020), but many of the points translate well to this discussion. Primarily, methodological advancements that permit the collection of new information must be met with new theoretically derived questions that can make the most use of these technological developments. Practitioners of CST are already starting to do this in strides, particularly among computational approaches like simulation modeling and network studies, which have longer histories tied to complexity science. A true test of CST's utility within archaeology will be the expansion of mixed-methods studies that blend qualitative and quantitative data to address questions about emergent human systems. Such studies are already appearing and making important insights about human behavior (e.g., Andrei and Kennedy 2013; Bliege Bird and Bird 2020; Davis et al. 2023; Petrie et al. 2017; Reynolds and Lewis 2019).

The Promise of Merging of Processual and Post-processual Thought

Given the broad applicability of CST to archaeology, this framework also highlights that the division between processual and post-processual thought is a "false dichotomy" based on uncertainty and positivism (Bentley and Maschner 2007). This idea led Bentley and Maschner to suggest that the framework may be the only one that can unify these schools of archaeological practice. Ultimately, complexity theory relies on both general laws of a system's behavior and the reality that agency requires nuances when we make predictions about a future state of that system. As demonstrated above, CST has started to live up to this promise, but greater integration of qualitative and quantitative approaches is needed.

CST sits in opposition to teleological thought, simple cause-effect relationships, and *sine qua non* arguments. A distinction is required, however, between definitions of determinism in philosophy and physics. Complex systems, by definition, can be both deterministic and random (Crumley 2005; Ladyman et al. 2013), but physics defines determinism as the idea that a set of fundamental laws (i.e., mathematical formulas) can describe all processes within a system but their solution will be unique given initial conditions (van Strien 2021). In philosophy, determinism, or causal determinism (Hoefer 2003), is the idea that human decisions and actions are caused by outside forces (opposed to free will and agency). Thus, while complex systems can be deterministic, this only refers to the idea that their properties can be partially explained by some set of mathematical laws and not that humans have no agency.

An important aspect of complex systems approaches is that they inherently require considerations of agency; even under identical conditions, outcomes can change due to general stochasticity within the system that are created by local-scale (i.e., group and individual) actions and/or external influences. As agents within a system respond to internal and external changes, these responses do not always follow a single, well-defined rule. As such, complexity approaches avoid pitfalls of earlier processualist and systems-type frameworks that focused on closed systems with no room for influence by internal forces and assigned ultimate power to external forces like environment, economics, or technology. While such structures ultimately have great influence on societies, the individuals who create these systems cannot be ignored. As a result, CST limits the capacity for research to succumb to conclusions rooted in causal determinism where a system and all of its parts (including human behavior) is driven by an outside force. Rather, human systems are simultaneously influenced by a myriad of internal and external factors.

Another area where CST can blend processual and post-processual thought is within the context of equifinality. CST can be thought of, in some ways, as a combination of the evolutionary concepts of gradual and punctuated equilibrium (Gould and Eldredge 1977), wherein gradual and rapid change can both occur and alter the system (Bentley and Maschner 2007). These changes are not predictable, and thus, CST operates on the idea that it is difficult (and sometimes impossible) to accurately predict the future or past of a system, even when every rule of the system is known, because of stochastic internal processes. This fact is essential for the problem of equifinality when you look at this concept's inverse.

As Bentley and Maschner (2007, p. 256, emphasis original) explain: "by trying to reconstruct the past from evidence available in the present, there can be an infinite number of possible histories because we do not *perfectly* understand the present state." A fundamental methodological and theoretical challenge for archaeologists is to understand how the archaeological record is created and the processes that result in the current configuration of materials that we have to interpret. But CST explains two fundamental truths that are often viewed in opposition by processualists and postprocessualists. (1) There *is* a single history of events that led to the current observable state of the archaeological record. As such, the archaeological record is defined by a single answerable course of events (*sensu* positivist thought). (2) These events are never fully knowable (*sensu* postmodernism) because of uncertainty introduced into the system through its emergent properties.

This may seem counterintuitive, but it must be remembered that the goal of CST is to explain emergent properties and their effects on a system, not to predict the past, current, or future state of that system. By using the methods available from complexity science, particularly simulation methods, we can study the different processes by which the archaeological record could have emerged into its current state, and through this process, narrow down possible explanations for the record we see before us. By improving how we study, record, and understand the archaeological record and its formation, we can improve our interpretations of human behavior that are captured in this resource.

Conclusion

Archaeologists have always been interested in transitional periods in human history: how did agriculture emerge? What caused a society to collapse? What factors led to the rise of inequality and hierarchy? The commonality between these research problems is that they all focus on periods of disequilibrium within human societies. The first attempts to study many of these phenomena were often simple models of closed systems, which are inherently in equilibrium. Such frameworks have led to incredible insights on human behavior, its external and internal influences, and a range of variables that can change how people and societies react to different circumstances (e.g., Dyson-Hudson and Smith 1978; O'Connell and Hawkes 1981; Smith et al. 1983; Winterhalder 1981; Winterhalder et al. 2010). But closed-system models can only get you so far. The sheer fact that optimality models often fail to fully explain human systems are proof of this: humans don't act in a vacuum.

By using open systems (and inherent disequilibrium) as a starting point, we can learn not only the ways in which different phenomena are related but also what combinations of factors give rise to many of the states of most interest (i.e., emergence and collapse of sociopolitical and economic structures). CST can also help identify why some local patterns contrast widely with regional patterns and vice versa. It is within this space, in particular, where complexity approaches have the greatest potential for the future of archaeological research. Ultimately, such investigations require collaborative approaches. This includes not only interdisciplinary academic collaborations but also local community collaborations and engaged research practices.

Additionally, the insights offered by CST have permitted archaeologists to identify general patterns of social structural emergence that are similar across societies of different scales (Ortman et al. 2014, 2020). This kind of research is exceptionally important because it allows us to find patterns that transcend specific case studies. This, in turn, can help identify commonalities among human systems and broaden the applicability of many archaeological studies across time and space.

CST manages to blend processual and post-processual ideas, as it allows for explanatory governing laws of a system but also demonstrates how emergent properties spurred by interactions among individual components of the system lead to unpredictable outcomes. This does not mean that results are not translatable or transferable to other locations or points in time. In contrast, comparative studies are still incredibly useful, as they can tell us about the kinds of relationships that transcend spatial, temporal, or cultural bounds, and it is here that we can find archaeology's most significant contributions to modern issues. However, every system will evolve in unique ways, even if the underlying rules of that system are identical. In essence, CST is amenable to the idea of "processual-plus" archaeology (*sensu* Hegmon 2003), wherein research integrates different theoretical perspectives to capture post-processual themes with systematic, quantitative methods.

This raises a particularly important point about complexity science and its applications to archaeology: it is not only for the quantitative researcher. While CST is, by definition, a quantitative framework, its emphasis on memory and history demands the inclusion of qualitative elements. The history of archaeological thought is often discussed as a dichotomy between qualitative/postmodern approaches and quantitative/processual approaches; but neither can fully encapsulate human systems. Rather, the quantitative and qualitative must be used in tandem, as they seek to explain the same things in different ways, helping bolster research by broadening perspectives and providing important nuance and context.

Finally, CST affords the opportunity to demonstrate not only how every culture is different but also how seemingly unrelated populations can provide valuable insight to issues occurring to globalized society in the present, as complexity dynamics at one scale are unequivocally relevant to others. While scales of interaction may differ, comparative analyses can shed light on how different relationships emerge and what kinds of cascading effects they can have.

In sum, CST offers archaeologists an invaluable framework in which to investigate some of the most substantial questions facing our discipline. As Biskowski (2004, p. 421) wrote in *Journal of Anthropological Research* nearly 20 years ago about CST: "Complexity is not merely a trendy subject. It lies at the foundation of most things archaeologists study: it cannot go away." As methods and technologies have improved, our ability to harness CST has likewise increased, leading to significant insight into humanity and society in the past and present. The world is a complicated place, with many entangled components (e.g., Hodder 2016), and CST offers a means by which to peer into that complexity and make sense of the chaos that unfolds.

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