Hindawi Publishing Corporation
Journal of Archaeology
Volume 2013, Article ID 540912, 15 pages
http://dx.doi.org/10.1155/2013/540912

Review Article

Nonlinear Systems Theory, Feminism, and Postprocessualism

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Received 31 May 2013; Accepted 15 September 2013

Academic Editor: Yue-Xing Feng

This paper explores the insights that nonlinear systems theory can contribute to archaeological theory and method. Dynamical nonlinear systems theory, chaos theory, and complexity theory are first defined, and their interrelationships are discussed. Then chaotic processes are described and exemplified in processes relevant to archaeology. Some applications of nonlinear systems theory in archaeology are briefly reviewed. Next, it is argued that culture is a nonlinear system. Finally, an exploration of similarities, differences, and relationships between nonlinear systems theory, feminist theory, and postprocessual archaeology leads to suggestions for expansions and synergies among these theories.

1. Introduction

Nonlinear systems theory has transformed the dominant scientific paradigm in ways that have deep implications for archaeological theory and method. Nonlinear systems theory demonstrates that current archaeological analysis of patterns and processes is incomplete and so partial that our understanding of culture and cultural processes, especially evolution, is seriously compromised. The prevalence of nonlinear patterns and processes in culture and nature needs to be addressed by further development of archaeological theory and method. Comparison of nonlinear systems theory, feminist theory, and post-processual archaeology leads to suggested synergies, expansions, and areas of potential synthesis among these theoretical approaches.

This paper explores the insights that nonlinear systems theory can contribute to archaeological theory and method. Dynamical nonlinear systems theory, chaos theory, and complexity theory are first defined, and their interrelationships are discussed. Then, chaotic processes are described and exemplified in processes relevant to archaeology. Some applications of nonlinear systems theory in archaeology are briefly reviewed. Next, it is argued that culture is a nonlinear system. Finally, an exploration of similarities, differences, and relationships between nonlinear systems theory, feminist theory, and post-processual archaeology leads to suggestions for expansions and synergies among these theories.

2. What Is Nonlinear Systems Theory?

Paradigms limit the patterns and processes we can perceive and analyze from data. Nonlinear systems theory is a new scientific paradigm that developed out of the realization that apparently random variation can shape the irreversible evolutionary paths of complex systems. The recognition and analysis of chaotic systems and processes were not possible in the traditional scientific paradigm because it focused on regular recurring patterns and disregarded irregular variation as insignificant random "noise" [1]. Nonlinear systems theory involves some fundamental changes in normative scientific assumptions, theory, and methodology that have been widely adopted in archaeology.

The terms of dynamical nonlinear systems theory, dynamical systems theory, complexity theory, and chaos theory have often been used interchangeably, but they have been differentiated. Nonlinear systems theory is a paradigm in science that permits more accurate description and explanation of the evolution of most natural and cultural systems,

patterns, and processes. This is because most systems are nonlinear to some extent. Nonlinear systems theory encompasses the other theories, which address particular aspects of nonlinear systems. A dynamical system is a mathematical model of the time-varying behavior, or evolution, of an actual system ([2]: 2). Chaos and complexity are different but related kinds of behavior exhibited by nonlinear systems ([3]: 4–6). Complexity theory is concerned with complicated systems and processes that are not quite chaotic but are on the edge of chaos. Complexity and chaos both combine orderly and apparently stochastic elements, but complexity is more orderly than chaos ([4]: 366–370). In chaotic systems and processes, deterministic and apparently stochastic behaviors are interrelated, both being essential for the operation of a system or process ([4]: 16-17).

The hallmark of chaotic processes is that a small change within the system can lead relatively rapidly to a major change in the direction of the entire system. Chaotic systems are called "sensitive to initial conditions" because they can rapidly amplify small-scale apparently random perturbations into large-scale changes in the direction of evolution of the system. Further, the significant small-scale changes are generated deterministically by and within the system and do not require external stimulus ([3]: 6).

Nonlinear systems and processes are defined by their potential to become chaotic. Chaos was technically defined at the 1986 International Conference on Chaos by the Royal Society in London, as stochastic behavior occurring in a deterministic system. In layman's terms, this means that disorder can be produced in an orderly system. Within the classical scientific paradigm this is a paradox. How can apparently random behavior be produced by a deterministic system? ([4]: 17). The evolution of a deterministic system is in principle completely predictable, determined by knowledge of the parameters that describe the system, its time-evolution equations, and its initial conditions ([3]: 6). The evolution of chaotic systems cannot be predicted because the initial conditions cannot be accurately measured, and extremely small differences in initial conditions lead relatively rapidly to wide divergence in the evolutionary path of the system. Thus, the system has path dependence on the initial conditions [1].

Chaos theory focuses on qualitative analysis of nonlinear behavior that is unstable and aperiodic. Unstable systems never settle into a stable state that resists small perturbations. In aperiodic behavior no system variables ever repeat the same values, resulting in an irreversible evolution of the system. Unstable aperiodic behavior cannot be predicted because it never repeats and is more sensitive to small perturbations that our instruments can measure ([3]: 37). Unstable aperiodic behavior appears random when measured. History is a prime example of an unstable aperiodic process because it never repeats precisely and small, even individual changes can lead to a major change in the evolution of a culture and society ([2]: 4-5, 32–35; [5]: 51).

Perhaps the clearest example of an unpredictable chaotic system is the weather. In fact, modern chaos theory developed out of Lorenz's attempts to model the weather, which revealed how unmeasurably small differences in initial conditions led relatively rapidly to large divergences in the evolution of the weather system ([4]: 115–135).

Lorenz ([6]: 163) distinguishes between chaotic systems and nonlinear systems. While all chaotic systems are nonlinear, not all nonlinear systems are chaotic. Both are sensitive to initial conditions, but nonlinear systems may converge on an earlier stable state after a perturbation, while chaotic systems do not. Thus, the evolution of nonlinear systems may repeat a state and therefore be reversible in some sense, while chaotic systems never repeat a previous state and evolve irreversibly. In sum, all chaotic systems are nonlinear, but not all nonlinear systems develop chaos, although they have the potential to do so.

The characteristics of chaotic systems are captured in the definition of chaos theory as "the qualitative study of unstable aperiodic behavior in deterministic nonlinear dynamical systems" ([2]: 2). This definition captures the paradox that complex apparently random behavior can be found in relatively simple deterministic systems. According to Kellert ([2]: 5), these simple systems are described by less than five nonlinear differential equations, although the number is not specified by other authors (e.g., [3, 5]). Further, these equations do not include explicitly random terms that directly introduce stochastic variation into the system.

Nonlinear systems theory increases our understanding of processes involved in the complex behavior of real-world systems by describing nonlinear patterns in data, using nonlinear differential equations. By identifying nonlinear patterns in data we may be able to identify and understand the nonlinear processes producing these data. Nonlinear equations produce descriptive models of nonlinear processes by which chaos develops out of order and vice versa. Stability, instability, or chaos in nonlinear equations and systems is due to the rate of iteration. Low rates of iteration produce stability. As the rate of iteration is increased to higher values, the system is pushed into greater instability, leading to chaos.

Nonlinear differential equations model the evolution of the most common types of dynamical systems, differentiable ones, in which the variables analyzed change in a smooth or continuous fashion. The evolution of differentiable systems is modeled with nonlinear differential equations called the "evolution equations" that specify the rules controlling the changing states of the system, such as rates of change in variables controlling the spread of disease. Nonlinear differential equations are named for including nonlinear mathematical terms for rates of change. Differential equations create a qualitative description of the long-term behavior of a system in general rather than making precise numerical predictions of future system states ([2]: 3).

3. Nonlinear Processes Relevant to Archaeology

Archaeology includes applications of nonlinear systems theory, including complexity and chaos theories. Complex and chaotic systems evolve through nonlinear processes, including endogenous oscillation, sensitivity to initial conditions, iteration, positive feedback, negative feedback, bifurcations, diffusion, dissipation, and self-organization. Chaotic systems

endogenously create internal small oscillations. Then the system responds to the small-scale internal variations called initial conditions. Nonlinear systems' evolutionary paths are dependent on initial conditions. A system can rapidly evolve or diverge from a stable state through the interaction of nonlinear processes.

Nonlinear systems fundamentally evolve through iteration, in which the same mathematical operations are repeatedly performed on each system state to create the next state in an evolutionary trajectory. The previous state of the system becomes input that is operated on by a combination of positive and negative feedback to create the next state of the system ([7]: 178–195). The simplest example is a population system, in which the survival rate is the rate of iteration. Survival rate is a combination of the positive feedback of exponential birthrate, and negative feedbacks that dampen population growth through disease, starvation, war, infertility and other nonlinear processes. It is iteration that makes systems so sensitive to perturbations that they cannot be measured accurately enough to predict the resulting evolutionary trajectories ([2]: 29–35). Rapid iteration of a small perturbation can quickly lead to a bifurcation or branching off of the system in a new evolutionary direction ([3]: 17–19).

Nonlinear evolution through positive feedback can produce oscillation or dispersion among a number of system states, or attractors. An attractor is a state to which a system is drawn or attracted. In a stable state, a system oscillates in a basin centered around a single point that is called a fixed point attractor. A system such as a population may oscillate between two different size states in what is called a limit cycle, or limit cycle attractor. Chaotic patterns and processes often have fragmented attractors called strange attractors in which a number of different states are simultaneously attractive, creating a fragmented pattern in the system, exemplified by water turbulence in a stream with a number of rocks that create eddies ([5]: 8, 166-167, [4]: 85–114).

Other nonlinear processes include the rapid even spatial spread of a phenomenon through diffusion, and dissipation of a closed system toward entropy, following the second law of thermodynamics. Self-organization is a nonlinear process that works to maintain an open system against the forces of entropy, by organizing environmental inputs in a far-from-equilibrium state ([8]: 140–145). Self-organization is exhibited in the development of pattern recognition in nonlinear artificial intelligence computer modeling (e.g., [9]).

Scientists have increasingly identified chaotic systems, patterns, and processes from the weather [6], heart rhythm [10] and kidney functioning [11] to predator-prey population interactions in ecological evolution [12, 13], and natural patterns of growth from plants to mountains and coastlines [14]. A number of nonlinear biological processes that are affected by social behavior have been identified, including disease epidemics [15–18], population growth, and migration [19]. Some of these nonlinear processes are relevant to archaeology either directly in researching cemeteries or as analogs of processes that can be analyzed in artifact assemblages.

A number of nonlinear cultural processes have been identified and modeled that are relevant to archaeology, including evolution [20, 21], learning [9], innovation [22, 23], diffusion, settlement pattern development ([24]: 50–53; [25, 26]; [27]), regional and urban development [24, 28], political movements, dynamics of population migration [29, 30], international security, the arms race and the outbreak of war [31–33], some economic patterns [34–37], and decision-making processes [38, 39].

3.1. Positive Feedback in Nonlinear Processes. Some of these nonlinear models have increased our understanding of mechanisms of change involved in phenomena relevant to archaeology. For instance, nonlinear epidemiological models suggest that historically recorded erratic yearly variations in disease frequency, instead of being due to random "noise," could result from increasing rates of contact in the winter and decreasing rates of contact in the summer [15–17]. Chaotic variation develops as a result of pushing the size of a parameter, such as rate of contact in a non-linear differential equation that includes competing terms for positive and negative feedback. Negative feedback limits the frequency of disease until it is overridden by continuing positive feedback to a key parameter, such as contact rate [18]. These models are relevant to archaeology because disease epidemics are one important source of temporal fluctuations in frequencies of gravestones in cemeteries, as well as number and size of settlements.

Nonlinear models of processes of individual social agency are of particular relevance to post-processual archaeology. Nonlinear models have been used to analyze individual decision-making processes in the context of corporations [29, 39, 40]. The field of artificial intelligence has also generated models of learning through neuronal self-organization into networks, which can also be applied to model individual agency in the development of social networks and organizations (e.g., [9]). Another model related individual learning processes to self-organization in cultural evolution [21].

Nonlinear processes of learning are particularly relevant to the post-processual concern for processes of individual social agency. A nonlinear model that could be directly applied in archaeological analysis describes how an initially rapid learning or rumor curve due to temporal or spatial positive feedback is followed by saturation and diminishing returns due to negative feedback [12]. The rapid learning curve is related to nonlinear processes of innovation and diffusion that archaeologists have analyzed (e.g., [23]). For archaeologists, this model might also be a useful analog in describing the pattern of early rapid increase in a popular style or technology, followed by slowing in the rate of adoption as the market is saturated. In archaeological research, change in artifact styles has been analyzed as a form of self-organization [41].

One application of nonlinear systems theory is relevant to historical archaeology of the fur trade. The predator-prey nonlinear system model has been used to explain the irregular annual variations in lynx and hare populations historically recorded by the 19th century Hudson's Bay Company, 1820–1930 [12, 13]. This model could also be applied as an analog in archaeology to map the kind of inverse relationship found in changing frequencies of artifact styles that represent alternative consumer choices [42].

3.2. Nonlinear Processes of Settlement and Market Development. Of particular relevance for post-processual archaeology are nonlinear models showing how individual idiosyncratic variation interacts inextricably with larger scale cultural and environmental processes to produce significant change. For instance, chaos scientists found that variations in large-scale geographical variables considered in Christaller models by themselves did not accurately model the development of settlement patterns. In computer simulations, even under ideal conditions, random elements of human behavior that formed the "initial conditions" of settlement development prevented the growth of an orderly hexagonal Christaller pattern. The orderly variables in the ideal model were not as important as random human behavior in determining the pattern of settlement development. This implies that the development of a settlement pattern cannot be adequately explained in terms of geographical variations in terrain or other large-scale variables. Individual variations in behavior, whether explainable or random, may be equally important to the development of a particular settlement pattern ([8]: 196–203). By including small-scale disorderly or random elements of human behavior that formed the "initial conditions" of settlement, more realistic nonlinear models were created ([24], Allen and Sanglier [25, 26]).

Nonlinear models of such self-organization processes in the growth of market areas and centers include the interaction between the random occurrence of entrepreneurs and the average dynamics of supply and demand ([24]: 50–53; [27]). Prior to nonlinear systems theory, LeBlanc (1969) used historical data to demonstrate the importance of individual idiosyncratic behavior in the initial geographical location and diffusion of early textile mills that were related to the development of urban 19th century areas in New England. The complex development of settlement patterns exhibits both the sensitivity to initial conditions and the irregular patterning at both small and large scales that are important aspects of non-linear models of chaotic processes.

Other kinds of relationships between stable and unstable system states are relevant to archaeology. Thom's catastrophe theory uses topology to model how stable systems can suddenly suffer from discontinuous nonlinear change as the result of a small variation, or trigger, that tips the balance of the system to another direction at a threshold point. Catastrophe theory has been used to model a stock market crash, prison riots, and decision-making processes. These kinds of cultural processes may produce archaeological remains [43].

3.3. Dissipative Systems. Stability and instability are dialectically related in dissipative systems, which counteract their progress toward entropy through processes of self-organization. Dissipative structures are open systems, such as plants, animals, and cultures, that maintain and renew themselves through processes of self-organization. Biological systems, including humans, are autopoietic, meaning that they constantly renew and maintain themselves and continuously adjust to environmental conditions, through the complex interaction of huge numbers of feedback loops. Dissipative systems organize and maintain themselves by cooperatively processing inputs from entropy in the environment (dead plants and animals), as in cooperative subsistence. Nonlinear equations describing dissipative systems show how order can develop out of the chaos in far-from-equilibrium conditions, such as devastating epidemics that decimate populations, or post-war disorganization. Dissipative structures include cultures, the growth of cities and of political movements [28, 29].

One dissipative structure that may be a model for an archaeological style horizon pattern is the soliton, a wave of water, air, or energy that does not disperse like most waves, but is bound together by coupling nonlinear interactions among the components of the wave, so that they do not separate, but retain their shape for unusual distances and periods of time. Solitons defy the classical physics principle of equipartition, the belief that energy in a system tends to disperse evenly and dissipate, resulting in the tendency towards entropy. Instead, solitons cause energy to bunch up within a system, maintaining local energy concentrations that can move through the system like ripples. Eventually the energy in solitons does dissipate through processes such as friction, returning again to chaos ([3]: 479).

The soliton model may seem similar to the process involved in archaeological horizons, in which styles maintain the same form as they spread rapidly within, or even across, cultures. As with solitons, style horizons are composed of interlinked components that are bound together in the style and do not separate as the style rapidly spreads over an unusual distance and period of time. Styles are often fuzzy or polythetic sets ([7]: 36-37; [44]) of elements with nonlinear linkages in that not all elements are always included in the manufacture of every artifact of the same style. Styles bunch up energy in the system into rapid reproduction of certain forms, and sometimes decorations, that constantly co-occur in the style and spread like ripples through cultures. Styles do eventually dissipate, but not immediately, and style elements may re-occur later.

3.4. Processes of Self-Organization. Nonlinear interactions can spontaneously self-organize into dissipative structures. Self-organization occurs through nonlinear processes that use iteration and feedback processes to couple system elements into coordinated action ([3]: 78-79; [8]: 112–129, 142-143). Self-organization involves cooperation, coordination and communication in systems from the scale of microtubules and mitochondria within cells, to individual decision-making, intracultural communication, and cooperation at the global scale, as in the UN (e.g., [29, 45, 46]).

Cooperative self-organization using chemical attractors to communicate is used by termites to coordinate in building mounds, and by slime molds to organize for migration to a new location when local food sources are exhausted. The communication of initially individual random behavior leads to behavioral coordination and cooperation among a number of individual organisms ([8]: 181–189).

Humans use both biological and cultural means of cooperative self-organization, communicating to produce

coordinated action in all sorts of organized behaviors. Nonlinear models of self-organization by individual social agents are of particular relevance to post-processual archaeology. Individual stochastic decisions have been analyzed in processes of cooperative self-organization of individuals into economic systems [46]. Nonlinear models from the field of distributed artificial intelligence have also been used to describe how individual social agents self-organize to create social organization [45]. Self-organization into dissipative sociocultural structures can leave archaeological remains, ranging from individual structures and graves to settlements and regional subsistence settlement systems (e.g. [47]).

Learning, cooperation, and satisficing strategies have been found to produce the greatest dynamic flexibility and responsiveness to change, which now appears more important for survival than the futile attempt to achieve any absolute static state of optimal fitness, which at best is only temporary. Optimization models overlook the incompleteness of information, the possibility that inertia may lead to systemic malfunctioning, and the possibility of systemic transformations that change the definition of the evolutionary problem ([8]: 207).

Some archaeologists continue to support optimization models of human behavior, in some cases as ideal rules that result in satisficing behavior [48]. Others have replaced the ideal model of a completely rational human being mechanically pursuing optimal use of available resources, maximizing efficiency and minimizing risks of loss, with a model of sufficiency, which is still rational, but not necessarily optimal or maximizing [49, 50].

Nonlinear systems theory adds irregular disorderly variation to the satisficing model, introducing the irrational, accidental, historical and specific microvariations that result in suboptimal behavior. Experimental research has found that even with complete information individuals and groups make sub-optimal decisions that are stochastic and nonlinear, due to misperceptions of feedback [29, 46, 51].

3.5. Nonlinear Evolutionary Theory. Recognition of the adaptiveness of cooperative self-organization is challenging the preeminence of competition in the Darwinian theory of evolution. Cooperativeness has been shown to be at least as important a survival strategy in adapting to external constraints as is competition. Innovative evolutionary theory has researched the survival advantages resulting from initially random behavior that leads to cooperation and self-organization in organisms, ranging from slime molds to humans in growing settlements [24–26].

In some cases cooperation among two species gave them a competitive advantage over other species, while in other cases cooperation among many species permitted all to survive. In some cases the evolution of two or more species became interdependent on each other, as in the coevolution of domesticated plants and animals and human cultures. Margulis and Sagan [52] have argued from previously overlooked evidence that early bacteria for which oxygen was toxic developed cooperative relationships with oxygen eating bacteria in order to survive. Oxygen-breathing plants and animals evolved from the development of symbiosis between non-oxygen-breathing and oxygen-breathing bacterial organisms. Beyond the Darwinian mechanisms of mutation, external natural selection, and gradualism, paleontological and biological evidence has been found for cooperation, symbiosis, self-organization, and small-scale agency. These mechanisms of change can create order from chaotic situations generated by the recurring mass extinctions of punctuated equilibria ([53]).

Resistance to entropy through cooperative self-organization is at least as important an evolutionary driving force as the environmental selective forces requiring adaptation in Darwinian evolution ([54]: 78). Further, contrary to Darwin's premise of unlimited growth in natural populations unless externally checked, biologists have found that natural populations grow and decline within self-regulated limit cycles that can be modeled with nonlinear differential equations ([53]: 124–129; [13]). Steven Jay Gould has theorized and analyzed the importance of historical contingency involving nonadaptive random change in processes of biological evolution. Concerning Darwinian evolution Gould ([55]: 120) has stated, "The synthetic theory. . .as a general proposition, is effectively dead, despite its persistence as textbook orthodoxy."

The evolution of self-organized forms out of entropy shows that everything, including order and chaos, is interconnected in holistic nonlinear ways. Bifurcations can lead either to chaos or to order. Stable cultural states may rapidly dissipate into chaos and entropy, as in the fall of civilizations. People can also cooperatively self-organize in a variety of cultural forms. Not only does the potential for chaos exist in regular orderly systems, but also within the complexity of chaos is the potential for coherent order. Nonlinear processes, including self-organization, connect order and chaos, entropy and evolution, in irreversible relationships, contradicting the classical scientific belief in the temporal reversibility of processes [53].

Nonlinear systems theory addresses interrelationships between chaos and order in the evolution of complex systems ([4]: 16–20). The evolution from order to chaos is exemplified in the fall and disintegration of complex civilizations such as the Maya, Aztecs, or Egyptians. Order can also develop out of chaos through other nonlinear processes, including the self-organization of dissipative structures and negative feedback. For instance, new cultures can develop from the chaos of war or devastating plagues [8]. Nonlinear systems theory offers an understanding of relationships among chaotic processes and orderly linear processes and theories that were previously considered to be opposites.

3.6. Identifying Nonlinear Cultural Processes in Archaeology. A number of previously-identified separate archaeological patterns can be recognized as nonlinear processes and are related to each other through nonlinear systems theory. The concept of a triggering mechanism for evolutionary change, such as an invention, can refer to a small-scale change that leads to a major change in the direction of an evolutionary trajectory. The concept of a threshold in the value of some

variables that results in large-scale culture change is also a nonlinear concept. Some context-specific archaeological theories relate a series of small scale changes, as in the process of domestication, to a threshold creating major system changes, such as the shift to herding and/or agriculture. Style horizons appear similar to solitons, and the process of diffusion can be modeled with nonlinear differential equations.

Stochastic or irregular variations in conjunction with orderly elements have been identified in some past cultural patterns. Pumain [28] showed that the historic growth of French cities developed into an orderly hierarchy that was generally accentuated over time but could change as a result of the stochastic introduction of industry or other innovations. Nonlinear modeling of dynamics in peer polities of early civilizations generally fits historic data concerning irregular variation in level of violence in societies, although the general simulation was not designed to fit any particular cultural context [56].

The use of nonlinear differential equations in archaeology has created more realistic models and simulations of past complex patterns and processes. However, the patterns generated by nonlinear equations do not yet entirely match available data [57]. Models generated by nonlinear differential equations do not precisely match the archaeological data for the development of the Mayan settlement pattern [58], the geographical spread of a historically documented epidemic ([59]: 250), or for discontinuous urban development in the late LaTene ([47]: 336-337).

There are several reasons why nonlinear differential equations generate models that do not precisely match patterns in archaeological data. In some cases small archaeological samples provide insufficient data to test computer-generated nonlinear models (e.g., [60, 61]: 212). More fundamentally, nonlinear mathematical equations model processes in general and do not capture much of the actual complexity of past cultures [57]. Hypothetical models generated by mathematical terms cannot precisely match the variations in actual archaeological patterns, because of the unpredictable nature of nonlinear patterns. It is impossible to precisely predict nonlinear patterns mathematically because by definition nonlinear systems and their patterns are not completely predictable. This fact explains why computer weather simulations cannot predict the actual path of nonlinear weather patterns with complete accuracy.

The primary utility of nonlinear modeling in archaeology appears to be in theoretical and methodological implications. For instance, the application of distributed artificial intelligence modeling was too abstract and general to fully address the self-organization of social complexity in the upper Paleolithic, but theoretical issues were raised [45]. A simulation based on a British late Bronze age exchange system for prestige goods generated patterns from limit cycles to chaos, depending on characteristics of production and the transaction rate. The model demonstrated a number of generic features, which may characterize exchange processes in different contexts and might explain some of the archaeological data [62]. Models were developed relating cultural evolution to individual learning processes [21] and intergenerational information transfer [63].

Nonlinear systems theory has been conceptually applied to gain greater insight into some archaeological patterns and processes. For instance, Hitchcock [64] has analyzed how Minoan domestic spaces combined regular recurring patterns of use and irregular variation in use. In this case nonlinear systems theory has conceptually expanded interpretation beyond the static identification of rooms with singular functions. Doonan [65] used a dynamic model to redefine the emergence of complex social systems in Archaic Italy, not as the result of any singular cause, but as the product of the complex interaction of a number of variable behaviors, using a dynamic nonlinear model permitted expansion of explanation beyond the single cause model to analyze complex variable behaviors as causative of complex social systems.

My research has related small-scale temporal variations in gravestone frequency to chaotic processes such as wars and epidemics. More importantly, a comparison of patterns of change across scales showed how both the gradual model of evolution and the punctuated equilibrium model result from the aggregation and averaging of small scale irregular variations. The process of cultural evolution appears more gradual than it actually is when small-scale oscillations in the system are averaged out. The sudden jumps in the punctuated equilibrium model of evolution can be produced by aggregating less extreme small-scale fluctuations in one direction into a longer time period. Thus, both the gradual and punctuated equilibrium models of evolution can be produced by the exclusive use of a large temporal scale of analysis. A multiscalar method was developed to reveal the actual process of change through oscillations in small temporal scales [42, 66, 67].

Nonlinear systems expand our ability to describe the irregularities in real-world patterns and processes in relation to their regularities or similarities. The identification of nonlinear patterns and processes that were not previously recognized as such can increase our understanding of the complexity of past cultural systems and their evolutionary trajectories. Further, the existence of other previously unknown nonlinear dynamics in many sociocultural systems and processes requires changes in archaeological thinking and practice.

4. Theorizing Culture as a Chaotic System

This section theorizes that culture meets the criteria of a nonlinear system. This means that cultural systems have the potential for chaos and other nonlinear processes and patterns. Some nonlinear cultural processes have already been discussed. Nonlinear systems theory provides a coherent framework that interrelates a number of nonlinear cultural characteristics and processes and also relates them to linear processes. All of the below criteria involved in the identification of chaotic systems and processes are interrelated.

First, culture is a nonlinear system because it is complex, dissipative, and self-organizing. Cultures use a number of processes in subsistence and manufacturing to prevent dissipation into entropy by self-organizing to gain inputs of energy from the natural environment and transform them into culture-sustaining products.

Second, many processes in cultural systems are too complex, discontinuous, and irregular to be accurately described or completely predicted from linear relationships among orderly variables, such as correlations or regressions. Chaotic systems and processes cannot be described and explained with linear cause and effect relationships, in which small changes produce small effects and large-scale causes are required to produce large-scale effects.

Third, many cultural processes can be modeled with the nonlinear differential equations that describe the behavior of chaotic systems. These equations, analogous to the laws and rules of culture, produce both "chaotic" variation and more orderly patterns that are interrelated in cultural processes. Therefore, disorderly variation is information that cannot be ignored without loss in accuracy of description and explanation.

Culture meets a fourth criterion of a chaotic system, because it is often "sensitive to initial conditions." This means that initial small scale, even individual variations in culture or environment, can lead to large-scale changes in the direction of cultural evolution. A small change in one variable can have a disproportionate impact on other variables.

Small-scale perturbations are more likely to be amplified into major cultural change in unstable cultures. The combination of chaotic and orderly elements in culture often creates some degree of cultural instability. However, since cultures are open systems they have the potential for sensitivity to initial conditions even in stable states. Small-scale variations produce large-scale change through nonlinear processes such as positive feedback and iteration. This process is exemplified in the rapid diffusion of technological innovations that have transformed human culture ([68]: 151–156).

Fifth, culture is a chaotic system because it can endogenously generate a great diversity in small-scale and individual variation from relatively few rules or laws of behavior. In contrast to the emphasis on exogenous causes in archaeological systems theory, chaos theory points out that, even without any external causes affecting a nonlinear system, positive feedback processes develop small scale endogenous variations into large-scale changes in the system ([2]: 12–22). Chaos theory emphasizes how the endogenous response of the system causes change, whether it is responding to exogenous or endogenous changes, or some combination of them. Many exogenous changes have no impact unless a response is developed endogenously, involving interpretation of an exogenous change to give it meaning. Exogenous change does not require a particular response. Choices exist and are made endogenously at the small scales of the individual and groups of individuals ([51]). Even the lack of response to exogenous change is an endogenous response that can have a large-scale cultural impact, as when a civilization falls due to a failure to respond to a small environmental change that spreads across a region.

Sixth, culture is a chaotic system because it evolves irreversibly. That is, cultural states, processes, and evolutionary trajectories are context-specific for different cultures, diverging even from shared initial conditions, and never repeating in precisely the same way or form, although there may be similarities among different cultural states or processes. Nonlinear patterns and processes vary uniquely for each culture. Cultural evolution is irreversible because of sensitivity to initial conditions that do not precisely repeat themselves ([8, 69]: 109–115).

Seventh, a culture's evolutionary path cannot be accurately predicted because initial conditions can never be precisely measured. Initial conditions cannot be measured precisely enough to completely capture the degree of sensitivity of chaotic systems to initial conditions. Researchers have found that iteration and positive feedback make chaotic systems so sensitive to initial conditions that it is impossible to measure the microvariations accurately enough to predict the resulting relatively rapid divergence of the evolutionary trajectories of chaotic systems. The impossibility of accurately measuring the variation in stochastic initial conditions that lead to completely different system states means that it is impossible to reliably predict long term future changes in a nonlinear system from its present state [4, 70].

5. Theoretical Implications: Comparing Nonlinear Systems Theory, Postprocessualism, and Feminism

This section compares some aspects of nonlinear systems theory, feminist theory, and post-processual archaeology in order to gain further insights about relationships, synergies, and potential areas of synthesis among these theories (Table 1). All three theories are revolutionary paradigms that have changed the questions asked in science and social science. Relationships among the critiques of science and social science in these theories have led to some similarities in the frameworks that each theory developed to create more complete and inclusive understandings of cultural complexity. The similarities and differences among these theories suggest some degree of synthesis may be possible by expanding both post-processual theory and nonlinear systems theory.

This section explores the deep implications of nonlinear systems theory for archaeological theory, including both processualism and post-processualism. In some cases, nonlinear systems theory leads to critiques of aspects of both processual and post-processual theory. In other cases, the implications of nonlinear systems theory suggest further development of some aspects of post-processual theory. Finally, nonlinear systems theory in some ways bridges the false dichotomy constructed between processual and post-processual theories, and shows how they are and could further be synthesized into a more productive theoretical approach than either offers by itself. Nonlinear systems theory combines a rigorous scientific methodology that is lacking in post-processual archaeology, with analysis of the importance of small scale stochastic variations of types that have been dismissed as random noise in processual analyses, which are limited to regular, recurring, or linear patterns.

Some critiques in feminist theory are relevant to nonlinear systems theory and post-processual archaeology. Of particular concern is how feminist theory reveals the deep cultural androcentrism underlying the degendered paradigms of

Table 1: Summary of comparison of nonlinear systems theory, feminist theory, and postprocessualism.

Nonlinear systems theory	Feminist theory	Postprocessualism
Critiques universal laws as ideal Context-specific cultural rules	3rd wave critique 2nd wave essentialism Historical variation in gender systems	VS ahistorical cross-cultural laws, determinism Context-specific cultural norms, rules
Incompleteness of reduction to parts Retains scientific determinism	VS science claim of neutral male objectivity Stronger objectivity through bias awareness	VS positivistic belief in neutral objectivity VS dichotomy between subject and object
Critiques order versus chaos dichotomy Chaos is stochastic variation in a deterministic system-dehumanized VS constructing structural dichotomies	Critiques gendered dichotomy between chaotic nature versus scientific order VS constructing structural dichotomies VS belief in innate gender dichotomy	Structuralism in cultural context Belief in deep cultural binary structures Belief binary thinking is innate Culturally structured gender dichotomy
Inclusive both/and thinking Spectrum interrelating order and chaos	Inclusive and/and theory of diversity Continuum of gender/sexual identities	Either/or thinking constructing differences Individual agency can change structures
VS only large-scale causes of large effects Small random variations have large effects Models of individual decisions in groups	VS only large scale causes of change Individuals cause major cultural change Individual free will with cultural limits	Research on cultural structures, large scales Only theorization of individual variability Individual variation within cultural structures
VS only external causes of change Internal small changes have large effects	VS only external causes of change Internal small groups cause major change	Research on cultural structuring of agency Neglect of nonlinear small group dynamics
VS ignoring random variation as noise VS linear patterns and processes Random variation leads to major change	VS deviant individuals as "exceptions" VS reduction of gender to social subsystem Inclusion of diversity in actions, viewpoints	VS ignoring random variation as noise VS systems theory adaptationism Pro variability, plural views, meanings
VS macroscale determining microscale Small differences in initial conditions Lead to major divergence in evolution Chaotic systems evolve irreversibly	VS macroscale determining microscale Development from small to large scale feminist organizations It is possible to lose gains in rights	VS macroscale determining microscale Research on cultural processes No evolutionary scale research Variation contingent on historical situation
Unmeasurable initial conditions So cannot predict nonlinear processes	VS generalizations overlooking diversity Legal and cultural processes of change	Static conceptions of social agency Individual and group processes change norms

Abbreviation Key: VS: versus, critiques.

nonlinear systems theory and post-processual archaeology. Aspects of post-processualism and nonlinear systems theory need to be regendered to reveal, critique, and address their sexist roots.

5.1. Reductionism and Benefits of Nonlinear Systems Theory for Processualism and Post-Processualism. First, nonlinear systems theorists have critiqued the dominant scientific paradigm for its inability to completely describe real-world nonlinear systems and processes. In the Newtonian mechanistic paradigm, the way phenomena functionally work is understood through the metaphor of a clock that can be taken apart and then reassembled by placing its constituent pieces back in correct relationship to each other. In Newtonian scientific ideology, phenomena are understood by analysis that reduces them to their constituent parts and linear relationships between these parts ([4]: 9).

The Newtonian paradigm is embodied in the theory and method of archaeological typology. Both processual and post-processual archaeology create typologies by analyzing material culture into their constituent attributes and linear relationships, such as correlations or factor analysis, among those attributes. Such analyses are fundamental to all archaeological typology. Correlations have been used to establish both processual functions of material culture and post-processual cultural meanings ([71]: 182-183).

The Newtonian worldview is also embodied in both processual and post-processual theoretical approaches. Processual anthropological systems theory analyzes culture into universal subsystems and linear relationships, such as correlations and regressions, that were used to infer subsystem functions of material culture, such as technomic, sociotechnic, and/or ideotechnic [72]. Feminists critiqued systems theory for reducing gender and ethnicity to part of the social system [73]. Post-processual archaeologists critiqued the adaptationist reductionism in systems theory but substituted the paradigm of structuralism, which reduces cultures to sets of binary oppositions often related to the western gender dichotomy ([71]: 4, 215). The reduction of the complexity of cultures to a set of structuralist dichotomies oversimplifies the complexity of culture even more than systems theory.

Nonlinear systems theory has shown that, contrary to the contentions of the Newtonian worldview, identifying major factors and linear relationships involved in cultural patterns and processes does not permit their complete description, explanation, or prediction. Rather than analyzing real-world patterns and processes into their parts to understand them, nonlinear systems theory models them holistically with nonlinear differential equations that require computers for their iteration. Nonlinear patterns and processes cannot be recognized with the use of linear equations such as regressions. Since nonlinear processes are prevalent in cultures as well as in nature, nonlinear systems theory needs to be adopted

in archaeology in order to more fully describe processes of change in the evolution of cultures.

Nonlinear systems theory could expand the scope of processual systems theory to more accurately describe and explain interactions between cultural and natural systems, because they are nonlinear systems. This expansion would be facilitated by the fact that nonlinear systems theory expands the systems framework rather than completely rejecting it. In addition, nonlinear systems theory, while critiquing many aspects of traditional science, from the dichotomy between order and chaos to the focus on large scale external causes of large-scale changes, remains fundamentally scientific and deterministic, holding that simple rules in cultural systems lead to small-scale stochastic variation that was previously inaccurately dismissed as "noise." Nonlinear systems theory also upholds the scientific belief in the possibility of objectivity and the ability to make accurate observations with the senses and measurement, producing data that are not theory-laden. This contrasts with the post-processual belief that all data production involves interpretation that is fundamentally theory-laden and presentist.

Nonlinear systems theory could synergistically expand post-processual archaeology's ability to describe and explain nonlinear processes because both theoretical approaches are concerned with the complex relationships between the relatively few simple rules governing systems and small-scale or individual variation. Nonlinear differential equations generate stochastic variation from relatively few simple rules. Thus, nonlinear equations might be able to express how cultural rules such as ideals and norms lead to the generation of diversity in actual behavioral practices. Both processualism and post-processualism adopted the earlier archaeological practice of analyzing cultural norms, which post-processualism further connects to dichotomies supposedly deeply structuring cultures. Both paradigms analyze cultures in terms of their deeper structure, whether culture is reduced to a system, or to a set of structural dichotomies. Neither processualism nor structuralism leaves much room for social agency or for processes of culture change ([71]: 30-31, 61, 207-208).

5.2. The valorization of External Large-Scale Causes and Devaluation of Small-Scale Internal Variation. Nonlinear systems theorists have critiqued the normative scientific assumption that large-scale causes are required to produce large-scale effects, as well as the dismissal of small-scale internal systemic fluctuations as insignificant "noise" ([8]: 178). Feminist archaeologists have similarly critiqued the processual overemphasis on external large-scale causes of cultural evolution, and the frequent dismissal of individual deviations from norms as insignificant "exceptions." The valorization of the large-scale and external can be related to the association of these qualities with men and men's political history, while the devaluation of the small-scale and internal can be associated with the devaluation of women's small-scale internal housework ([74]: 102). Feminists early critiqued Binford's argument that large-scale cultural institutions control internal variation due to variables such as gender and ethnicity ([75]: 221 critiqued by [73]: 6; [76]: 22-23). Both these critiques are congruent with the post-processual critique of the processual minimization of individual social agency.

Nonlinear differential equations may address the disjunction in archaeology between the post-processual goal of identifying individual social agency and widely used macroscale scientific methods. The mathematical methods of correlation and statistical significance that are widely used in archaeology are based on the normative scientific assumption that large scale causes are required to produce large-scale effects. In one scientific example, nonlinear patterns of climate change are modelled at the global macroscale, although they result from microscale changes. Statistical methods such as averages and correlations identify the significance of data as part of a large-scale pattern, such as an artifact type or associations from which culture-wide functions and meanings can be inferred (e.g., [71]: 185). While it is useful to statistically identify large-scale cultural patterns, this does not methodologically address small-scale or individual variability or agency, which are important in nonlinear processes. Significant small-scale or individual variations may be statistically averaged out in large-scale trends.

Nonlinear differential equations may be useful to adopt in post-processual archaeology because they model how small-scale variation that could be identified with individuals can causally lead to large-scale culture change. This means that archaeologists need to develop methods to realize the post-processual goal of identifying individual variations in producing material culture rather than discarding such variations as statistically insignificant random "noise." Archaeologists need to pay attention to infrequent and unique aspects of material culture in order to be able to identify individual social agency. Post-processual theorizing of social agency may be enhanced with the concept of small-scale or even individual initial conditions that iterate to create a rapid divergence in the direction of a culture's evolutionary path.

5.3. Internal Small-Scale Social Agency in Large-Scale Change. Nonlinear systems theory, feminist theory, and post-processual archaeology theorize the complex relationships between cultures and small-scale or individual social agency. All three theories posit some degree of reciprocal relationship between nonlinear systems that generate small or individual variations and the agency of individuals in changing the structure or evolutionary direction of a cultural system. In all three theories small-scale and individual variations are theorized to be produced within cultures, constrained by cultural rules, norms, laws, structural dichotomies, or habitus.

On the other side of the equation, all three theories posit the existence of individual social agency, with some differences. A number of applications of nonlinear systems theory are congruent with the post-processual concern for individual social agency. In particular, the field of distributed artificial intelligence analyzes cooperative self-organizing processes involved in individual learning (e.g., [21, 77]), and business applications have analyzed individual nonlinear decision-making processes in small group contexts (e.g. [29, 39]). Nonlinear models of distributed artificial intelligence

have also been used to analyze individual social agency in self-organizing social structures. Post-processual archaeology could use these nonlinear models to expand its ability to analyze individual social agency in relationship to larger social groups.

Post-processual archaeology could benefit from incorporating nonlinear processes that link small changes due to individual social agency to cooperative self-organizing processes in groups ([8]: 312-313). Post-processual archaeology has reduced all change processes to individual social agency, neglecting small-group dynamics in nonlinear cooperative self-organizing processes that are not simply the aggregation of a number of individual agent actions. Post-processual theorizing has focused on the short-term history of individual agency, as well as long-term history and structuralism, but has neglected analyzing processes at the mid-scale of conjunctural history or Braudel's moyenne duree, including the nonlinear processes of diffusion, demographic trends, economic cycles, and political processes ([71]: 104, 140, 144). Systems theory included many kinds of nonlinear processes, including innovation, triggers, thresholds, and horizons, which could beneficially expand post-processual analyses of the moyenne duree connecting individual social agency with Braudel's [78] longue duree.

Much of nonlinear systems theory uses a depersonalized language of "internal small-scale variation" and "initial conditions" that could benefit from the post-processual humanization of systems theory. Nonlinear differential equations modeling specific past cultural systems could describe small fluctuations that correspond to historically documented actions of particular individuals. This might be possible for nonlinear systems theory to address particular historical individuals or groups, as can feminist history and post-processual archaeology.

Feminist and post-processual theorizing of social agency may provide humanizing insight into nonlinear differential equations modeling the self-organization involved in cultural processes such as the growth of cities and political movements. Individual unique changes can be the initial conditions and triggers that are iterated through positive feedback in cooperative self-organized small groups and networks until at some threshold a tipping point is reached that transforms the direction of a culture's evolution. In fact, my feminist research on domestic reform exemplifies a nonlinear process of cultural transformation initiated by individuals and propagated in small-scale women's socio-political organizations that developed into large-scale organizations and global networks creating major cultural change ([79, 80]: 121-122).

Nonlinear systems theory could expand its focus on how the system generates and responds to apparently random variations with the further feminist concern about how individual people and social groups act as social agents to create change by transforming their cultural context. The diversity among individual and group actions researched by postmodern feminists is a source of small-scale irregular variation, or oscillation in nonlinear systems. Thus, nonlinear systems theory is congruent with an inclusive feminist approach that analyzes the diversity in small group and individual behaviors ([80]: 119).

Both nonlinear systems theory and feminist theory have found that small-scale or individual random/idiosyncratic behaviors are sufficient conditions to create large-scale change within a system. However, feminists have theorized individual free will more than either nonlinear systems theory or post-processual archaeology [81]. The degree of individual free will may be easier to analyze from documents than from archaeological data.

5.4. Critiques of Universal Laws. Nonlinear systems theory, postmodern feminist theory, and post-processual archaeology all involve critiques of the scientific search for ahistorical universal laws advocated in positivism (e.g., [82]: 27; [7]: 15-16, 54, 428-429, 468–470; [83]). However, all three paradigms do posit the ability to generalize about system-wide laws, rules, or norms within a particular culture. Comparing the critiques in the three theories suggests areas of synergy and possible expansion of both nonlinear systems theory and post-processual archaeology.

Both feminist and post-processual archaeologists have critiqued the construction of ahistorical cross-cultural laws that over-generalize similarities among cultures and overlook significant contextual differences ([74]: 102). While arguing that the universal laws constructed by processual archaeologists are trivial, post-processual archaeologists argue for the validity of historical laws within a particular cultural context, following on Binford ([71, 75]: 11). Feminists have further shown that universal overgeneralizations can be politically significant in supporting modern inequalities. Modern gender inequalities have been legitimated and naturalized by projecting them as universal in the past. Post-modern feminists have deconstructed stereotypic monolithic binary oppositions of women versus men by analyzing the complexity in gender systems created by intersections of gender with race, ethnicity, class, religion, and other social factors ([84]: 129-130).

Comparison of nonlinear systems theory, post-processual theorizing, and feminist theory suggests synergistic expansions of each theory. Nonlinear systems theory could be expanded to include the critique of the comparative cross-cultural method of overgeneralizing and essentializing that supports the development of universal cultural generalizations and laws ([71]: 11). Nonlinear systems theory and post-processualism could both gain insight from the feminist critiques of the process of constructing universal generalizations about essential biological gender dichotomies through the projection of western categories onto other cultures ([84]: 130).

The post-processual critique that universal laws do not take historical context into account could be expanded with the explanation in nonlinear systems theory that universal scientific laws only apply under ideal conditions. For instance, the universal law of gravitation needs to be qualified according to actual context, such as air resistance and height above earth, in order to be accurately applied to different real-world processes. The ideal nature of universal laws is due to

the generalization from particular situations that is required to generate universal laws. The fact that universal laws are ideal explains why they do not fully explain any particular historical situation or process. Nonlinear differential equations have been useful in showing how context-specific rules and initial conditions can be iterated to more accurately model the actual historical path of a process than is possible using universal laws. Nonlinear differential equations could be used in post-processual archaeology to methodologically implement the theorizing that historical laws are useful, by analyzing real data.

5.5. Nonlinear Evolutionary Theory. Nonlinear systems theory has significantly increased our understanding of cultural as well as biological evolution ([53, 68]: 87–109). Nonlinear systems theory and feminist theory both critiqued the focus on competition in Darwinian evolutionary theory, and the neglect of the importance of cooperation. Feminists have more specifically critiqued the focus on male competition in early hominid evolution ([54]: 94–97).

Some significant connections and synergies are possible between the post-processual theorizing about Braudel's [78] longue duree and the nonlinear systems theory of evolution. Nonlinear systems theory has revealed that an inaccurate scientific belief that evolution was reversible had supported the search for ahistorical laws. The nonlinear systems theory contention that evolution, including cultural evolution, is irreversible is congruent with the post-processual theorizing about historical contingency due to cultural context. Post-processual theorizing could be enhanced with nonlinear systems theorizing about the irreversibility of cultural evolution and its connection to the critique of universal laws. Post-processual archaeology could be expanded with the nonlinear systems theory contention that the evolutionary path of nonlinear systems, including cultures, cannot be completely described or explained because the initial conditions cannot be measured accurately enough. Initial conditions could correspond to individual or social group variations in behavior.

Nonlinear systems theory and post-processualism are both concerned with microvariation and deny the existence of a disembodied cultural evolutionary trajectory, hurtling through space and time with the macroscale determining the microscale. The implication is that post-processual theorizing could be expanded beyond static conceptions of social agency and structuralist constructions of cultures to incorporate nonlinear evolutionary processes that dynamically model interrelationships sought by post-processualists among long, medium, and short-scale processes (e.g. [71]: 136).

Post-processual multiscalar theorizing could be enhanced by adopting a multiscalar temporal method of analysis that reveals how small scale variation aggregates to create the appearance either of Darwinian gradual evolution or the discontinuous jumps in the punctuated equilibrium model of evolution. Analyses in finer temporal scales increase our understanding of the processes of culture change underlying these evolutionary models. Methodologically it is important to use short temporal scales that do not average out small-scale variations in larger scale temporal trends [42, 66, 67].

5.6. Critiques of the Western Dichotomy between Order and Chaos. Most fundamentally, nonlinear systems theory critiques the foundational western assumption of a dualistic opposition between order and chaos ([4]: 5). Orderly patterns, such as trends, are considered to be the significant cultural message or signal, while irregular variation is considered as meaningless irrelevant noise that obscures the orderly patterns ([3]: 6-7). Scientists researching nonlinear patterns and processes have critiqued the western dichotomy between order and chaos by showing how these apparent opposites are dialectically interrelated [1, 4, 6, 70]. However, orderly patterns are still very predominantly constructed from analyses of archaeological data, with statistically insignificant variation being dismissed as random meaningless noise.

Feminist critiques of sexist cultural dualisms reveal how the dichotomy between order versus chaos is gendered at a deeper cultural level. Feminist research has revealed how orderly objective scientific reasoning has been valorized as male in binary opposition to subjective reasoning that has been devalued as irrational, chaotic, and female, at least since the Enlightenment ([85]).

Merchant ([86]: 168–172) researched how Francis Bacon (1561–1626) defined men's scientific method as the use of male-identified rational objectivity to conquer and subjugate female-identified chaotic nature. She revealed that Bacon made an analogy between men's interrogation of witches and the scientific method of interrogating mother nature through torture with mechanical devices in order to extract the truth. Thus, the supposedly objective rational scientific method justified superstitious religious men in torturing and burning women accused of witchcraft.

The cultural construction of science as orderly, objective, and rational as opposed to devalued chaotic, subjective, and emotional reasoning is as flawed as the gender dichotomy on which these binary oppositions are based. On the basis of the sexist dominant gender ideology Rene Descartes (1596–1650) gendered the field of mathematics as male [85]. The belief that men are more rational and capable of mathematics and science than women has persisted to the present day [87].

Western gender ideology has long justified patriarchy through fundamental beliefs in numerous interrelated gendered dichotomies, including culture/nature, sacred/profane, order/chaos, rational/emotional, and mind/matter. The association of women with chaotic emotion and nature was used by men's governments to deny women higher education until well into the nineteenth century. In 1873, a retired Harvard Medical School professor argued that women's reproductive organs would be damaged if they used their brains too much by trying to overreach their innate inability to grasp the higher reasoning in mathematics and science. Since at least 1400 feminists have been arguing that women deserve education because women's mental abilities are equal to men's ([88]: 192–219; [89]: 56).

Nonlinear systems theory could deepen its critique of the scientific dichotomy between order and chaos with feminist research showing the connection of this scientific dichotomy to the older culturally constructed gender dichotomy valorizing men as orderly, rational, objective, and cultural in opposition to women, devalued as chaotic, irrational,

subjective, and natural. Further, nonlinear systems theory could include the feminist critiques of the gender dichotomy that is the source of the dichotomies between order versus chaos ([80]: 118).

Feminist theory has further critiqued the gendered dichotomy between male-associated objectivity versus female-associated subjectivity [90]. Within nonlinear systems theory, the impossibility of absolute objectivity is discussed in the context of the Heisenberg principle from quantum physics but is not connected to the feminist gendered critique of objectivity ([8]: 298–300; [91]: 113). The limited scientific critique in nonlinear systems theory is probably related to its development within the hard sciences of physics and mathematics. Feminist critique has shown that these fields most strongly conflate actual scientific practice with the ideology of absolute objectivity [90].

Post-processual archaeology is similar to feminist theory in arguing against the western dichotomy between objectivity and subjectivity. However, post-processualism degenders the dichotomy and focuses on the subjective reconstruction of the past in the present and the social and political value of archaeology in modern power strategies ([71]: 207, 223). Post-processualism needs to address the significance of the cultural gendering of this dichotomy, which creates a hierarchy between male-identified objectivity and female-identified subjectivity that needs to be critiqued and corrected. Objectivity will retain its higher status as long as its sexist roots are not critiqued.

Nonlinear systems theory and feminist theory are similar in following their critiques of gendered oppositions with arguments that the binary terms form complementary dialectical relationships. That is, nonlinear systems theory argues that order and chaos are inextricably interrelated, and feminists argue that men's and women's roles are complementary and interdependent. Further, nonlinear systems theory and feminist both model the range of these interrelationships as a continuum (see below). Post-processualism has critiqued determinism ([71]: 7), but might consider modifying this position based on the dialectical interrelatedness of deterministic and stochastic elements in nonlinear processes and systems, including culture.

5.7. Critiques of Structuralism. Structural anthropology, initiated by Claude Lévi-Strauss, holds that the world is deeply, innately, structured in pairs of binary oppositions that are modeled on the western gender dichotomy ([71]: 45). In historical archaeology, Deetz [92] has contended that binary thinking is universal and biological. Post-processual archaeology interprets deep cultural structures from material culture, based on structural and symbolic anthropology ([71]; 215).

In critiquing the implicitly gendered western dichotomy constructed between order and disorder, nonlinear systems theory critiques structuralism. Postmodern feminists have critiqued the construction of gender as a universal set of binary oppositions and in some cases have further critiqued the paradigm of structuralism ([84]: 129-130; [81]). Further, feminists contend that other western cultural dichotomies, particularly race, are based on the gender dichotomy ([93]: 46).

Some feminists have further critiqued the paradigm of structuralism for constructing whole cultures on the model of gendered binary oppositions. Structuralism fails to distinguish dualistic ideology from the greater diversity of alternative ideologies and actual cultural practices. Although a number of gender, racial, and other cultural ideologies, especially in the West, are dualistic, some cultural subgroups and non-Western cultures have constructed nonbinary ideologies and practices. At a deeper level structuralist binary thinking in categories of p or not p needs to be replaced with inclusive and/and feminist thinking concerning the full range of diversity in individual variation ([74, 84]: 129).

Post-processual archaeology is limited by its use of the paradigm of structuralism, despite critiques of the lack of convincing evidence for dualistic interpretations of artifacts in some prehistoric cultures. Both post-processual theory and nonlinear systems theory have critiqued the static nature of structuralist constructions of culture and their inability to address change and cultural evolution ([71]: 68, 90; [8]: 205).

5.8. Inclusive Worldviews and Continuum Models. Nonlinear systems theory and feminist theory both critique structuralism and have instead developed inclusive worldviews and continuum models to represent actual variation along dimensions. Nonlinear systems theory has critiqued the traditional scientific dichotomy between order and chaos. Stewart ([4]: 22) has constructed a continuous spectrum of system states that combine order and chaos to varying degrees. Similarly, an inclusive feminist theoretical approach critiques culturally constructed gender dichotomies and instead models the complex interactions of social dimensions as intersecting continuums, including gender, sexuality, and race ([84]: 129-130).

The inclusive approach of nonlinear systems theory in researching how order and chaos are interrelated in real-world processes and systems could be deepened with feminist epistemology, recognizing that reasoning is a continuum that includes the full range of combinations of objectivity and subjectivity. Post-processualism has similarly recognized that the cultural dichotomy between objectivity and subjectivity needs to be dissolved but has failed to recognize that it is fundamentally gendered in a power hierarchy that also must be dissolved.

6. Conclusion

Comparison of nonlinear systems theory, post-processual archaeology, and feminist theory has revealed a number of synergies and areas of potential synthesis among these paradigms. A number of nonlinear patterns and processes have been shown to be relevant archaeologically, either directly or indirectly as analogs for archaeological processes. Further, it has been argued that many processes previously identified in archaeology are nonlinear processes. It has been briefly argued that culture meets the criteria of a nonlinear system, including the potential for chaos.

If culture and cultural processes are nonlinear, then archaeological theory and method needs to be expanded with nonlinear systems theory and methods in order to be able to analyze nonlinear processes. Comparison of nonlinear systems theory, feminist theory, and post-processual archaeology has shown major areas of congruence and synergy that suggest areas of potential synthesis among these theories. Differences among these theories have led to suggestions for potential expansions of these paradigms.

Acknowledgments

The author would like to thank Peter Allen, David Landy, Erik Mosekilde, Gottfried Mayer-Kress, Mike Schiffer, Peter Senge, and John Sterman for encouraging her to pursue her research on the implications of nonlinear systems theory for archaeological theory and method. This paper has also benefited from comments by Chris Beekman and Steve Lansing. Of course any errors are the author's responsibility.

References

[1] J. Gleick, *Chaos: Making a New Science*, Viking Penguin, New York, NY, USA, 1987.

[2] S. H. Kellert, *In the Wake of Chaos: Unpredictable Order in Dynamical Systems*, University of Chicago Press, Chicago, Ill, USA, 1993.

[3] R. C. Hilborn, *Chaos and Nonlinear Dynamics: An Introduction for Scientists and Engineers*, Oxford University Press, Oxford, UK, 2nd edition, 2000.

[4] I. Stewart, *Does God Play Dice? The New Mathematics of Chaos*, Blackwell, Malden, Mass, USA, 2nd edition, 2002.

[5] P. Smith, *Explaining Chaos*, Cambridge University Press, Cambridge, UK, 1998.

[6] E. N. Lorenz, *The Essence of Chaos*, University of Washington Press, Seattle, Wash, USA, 1993.

[7] D. L. Clarke, *Analytical Archaeology*, Columbia University Press, New York, NY, USA, 2nd edition, 1978, Revised by Bob Chapman.

[8] I. Prigogine and I. Stengers, *Order out of Chaos*, Bantam Books, Toronto, Canada, 1984.

[9] A. Henri, "Self-organizing networks: weak, strong, and intentional," Paper presented at the Conference on Dynamical Description and Human Systems, University of Cambridge, December 1990.

[10] R. Pool, "Is it chaos, or is it just noise?" *Science*, vol. 243, no. 4887, pp. 25–28, 1989.

[11] K. S. Jensen, E. Mosekilde, and N.-H. H. Rathlou, "Self-sustained oscillations and chaotic behaviour in kidney pressure regulation," in *Laws of Nature and Human Conduct: Specificities and Unifying Themes. Discoveries 1985 Symposium*, I. Progogine and M. Sanglier, Eds., Task Force of Research Information and Study on Science, Brussels, Belgium, 1985.

[12] R. Pool, "Ecologists flirt with chaos," *Science*, vol. 243, no. 4889, pp. 310–313, 1989.

[13] M. Toro and J. Aracil, "Qualitative analysis of system dynamics ecological models," *System Dynamics Review*, vol. 4, no. 1-2, pp. 56–80, 1988.

[14] B. Mandelbrot, *The Fractal Geometry of Nature*, W.H. Freeman, San Francisco, Calif, USA, 1982.

[15] J. L. Aron and I. B. Schwartz, "Seasonality and period-doubling bifurcations in an epidemic model," *Journal of Theoretical Biology*, vol. 110, no. 4, pp. 665–679, 1984.

[16] D. Holton and R. M. May, "Distinguishing chaos from noise," in *The Nature of Chaos*, T. Mullin, Ed., pp. 149–183, Clarendon Press, Oxford, UK, 1993.

[17] R. Pool, "Is it healthy to be chaotic?" *Science*, vol. 243, no. 4891, pp. 604–607, 1989.

[18] W. M. Schaffer and M. Kot, "Differential systems in ecology and epidemiology," in *Chaos*, A. V. Holden, Ed., pp. 158–178, Princeton University Press, Princeton, NJ, USA, 1986.

[19] R. Reiner, M. Munz, and W. Weidlich, "Migratory dynamics of interacting subpopulations: regular and chaotic behavior," *System Dynamics*, vol. 4, no. 1-2, pp. 179–199, 1988.

[20] P. M. Allen, "Dynamic models of evolving systems," *System Dynamics Review*, vol. 4, no. 1-2, pp. 109–130, 1988.

[21] R. G. Reynolds, "Why does cultural evolution proceed at a faster rate than biological evolution?" in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 269–283, Routledge, London, UK, 1997.

[22] P. M. Allen, "Models of creativity: toward a new science of history," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 39–57, Routledge, London, UK, 1997.

[23] S. van der Leeuw, "Archaeology, material culture and innovation," Paper presented at the Conference on Dynamical Description and Human Systems, University of Cambridge, December 1990.

[24] P. M. Allen, *Cities and Regions as Self-Organizing Systems, Models of Complexity*, Gordon and Breach, Amsterdam, The Netherlands, 1997.

[25] P. M. Allen and M. Sanglier, "Urban evolution, self-organization, and decision making," *Environment & Planning A*, vol. 13, no. 2, pp. 167–183, 1981.

[26] P. M. Allen and M. Sanglier, "Dynamic models of urban growth," *Journal of Social and Biological Systems*, vol. 1, no. 3, pp. 265–280, 1978.

[27] M. Sanglier and P. M. Allen, "Evolutionary models of urban systems: an application to the Belgian provinces," *Environment & Planning A*, vol. 21, no. 4, pp. 477–498, 1989.

[28] D. Pumain, "City-sized dynamics in urban systems," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 97–118, Routledge, London, UK, 1997.

[29] E. Mosekilde, E. R. Larsen, and J. D. Sterman, "Chaotic dynamics produced by human decision making behavior," Paper presented at the Conference on Dynamical Description and Human Systems, University of Cambridge, December 1990.

[30] J. Sturis and E. Mosekilde, "Bifurcation sequence in a simple model of migratory dynamics," *System Dynamics Review*, vol. 4, no. 1-2, pp. 208–217, 1988.

[31] G. Mayer-Kress, "A nonlinear dynamical systems approach to international security," in *The Ubiquity of Chaos*, pp. 181–195, Proceedings of the AAAS Annual Conference, San Francisco, Calif, USA, 1989.

[32] A. M. Saperstein, "Chaos—a model for the outbreak of war," *Nature*, vol. 309, no. 5966, pp. 303–305, 1984.

[33] A. M. Saperstein and G. Mayer-Kress, "A nonlinear dynamical model of the impact of SDI on the arms race," *Journal of Conflict Resolution*, vol. 32, no. 4, pp. 636–670, 1988.

[34] R. H. Day, "Chaos and evolution in economic growth," Paper presented at the Conference on Dynamical Description and Human Systems, University of Cambridge, December 1990.

[35] P. Chen, "Empirical and theoretical evidence of economic chaos," *System Dynamics Review*, vol. 4, no. 1-2, pp. 81–108, 1988.

[36] B. Mandelbrot, "The many faces of scaling: fractals, geometry of nature and economics," in *Self Organization and Dissipative Structures*, W. C. Schieve and P. M. Allen, Eds., University of Texas, Austin, Tex, USA, 1982.

[37] S. Rasmussen, E. Mosekilde, and J. D. Sterman, "Bifurcations and chaotic behavior in a simple model of the economic long wave," *Systems Dynamics Review*, vol. 1, no. 1, pp. 92–110, 1985.

[38] E. Mosekilde, E. R. Larsen, and J. D. Sterman, "Coping with complexity: deterministic chaos in human decision making behavior," in *Proceedings of the Symposium, Characterising Complex Systems: Interdisciplinary Workshop on Complexity and Chaos*, H. Bohr, Ed., World Scientific, Singapore, 1989.

[39] J. D. Sterman, *Business Dynamics: Systems Thinking for a Complex World*, Irwin/McGraw-Hill, 2000.

[40] E. Mosekilde and S. Rasmussen, "Technical economic succession and the economic long wave," *European Journal of Operational Research*, vol. 25, no. 1, pp. 27–38, 1986.

[41] R. A. Bentley and H. D. G. Maschner, "Stylistic change as a self-organized critical phenomenon: an archaeological study in complexity," *Journal of Archaeological Method and Theory*, vol. 8, no. 1, pp. 35–66, 2001.

[42] S. M. Spencer-Wood, "Cultural complexity, non-linear systems theory, and multi-scalar analysis," in *Debating Complexity: Proceedings of the 26th Chacmool Conference*, Archaeological Association, University of Calgary, 1993.

[43] T. Poston and I. Stewart, *Catastrophe Theory and Its Applications*, Dover, New York, NY, USA, 1996.

[44] B. Kosko, *Fuzzy Thinking: The New Science of Fuzzy Logic*, Hyperion, New York, NY, USA, 1993.

[45] J. Doran, "Distributed artificial intelligence and emergent social complexity," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 283–298, Routledge, London, UK, 1997.

[46] R. Reiner, "Quantitative social science: the master equation approach," Paper presented at the Conference on Dynamical Description and Human Systems, University of Cambridge, December 1990.

[47] S. van der Leeuw and J. Mcglade, "Structural change and bifurcation in urban evolution: a non-linear dynamical perspective," in *Time, Process, and Structured Transformations*, J. Mcglade and S. van der Leeuw, Eds., pp. 331–373, Routledge, London, UK, 1997.

[48] T. A. Kohler, J. Kresl, C. van West, E. Carr, and R. Wilshusen, "Be there then: a modeling approach to settlement determinants and spatial efficiency among late ancestral pueblo populations of the Mesa Verde region, U.S. southwest," in *Dynamics in Human and Primate Societies: Agent-Based Modeling of Social and Spatial Processes*, Santa Fe Institute and Oxford University Press, Oxford, UK, 1999.

[49] M. Jochim, "Optimization models in context," in *Archaeological Hammers and Theories*, J. A. Moore and A. S. Keene, Eds., Academic Press, New York, NY, USA, 1983.

[50] A. Keene, "Biology, behavior and borrowing: a critical examination of optimal foraging theory in archaeology," in *Archaeological Hammers and Theories*, J. A. Moore and A. S. Keene, Eds., Academic Press, New York, NY, USA, 1983.

[51] J. D. Sterman, "Misperceptions of feedback in dynamic decision making," *Organizational Behavior and Human Decision Processes*, vol. 43, no. 3, pp. 301–335, 1989.

[52] L. Margulis and D. Sagan, *Microcosmos*, Summit Books, New York, NY, USA, 1986.

[53] A. Robert and G. Stanciu, *The New Biology*, New Science Library, Boston, Mass, USA, 1988.

[54] S. J. Goerner, *Chaos and the Evolving Ecological Universe*, Taylor and Francis, New York, NY, USA, 1994.

[55] S. J. Gould, "Is a new and general theory of evolution emerging?" *Paleobiology*, vol. 6, no. 1, pp. 119–130, 1980.

[56] H. R. Erwin, "The dynamics of peer polities," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 57–97, Routledge, London, UK, 1997.

[57] R. Rosen, "Are our modeling paradigms nongeneric?" in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 383–296, Routledge, London, UK, 1997.

[58] C. T. Brown and W. R. T. Witschey, "The fractal geometry of ancient Maya settlement," *Journal of Archaeological Science*, vol. 30, no. 12, pp. 1619–1632, 2003.

[59] E. B. W. Zubrow, "Clusters of death, pockets of survival: dynamic modeling and GIS," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 216–264, Routledge, London, UK, 1997.

[60] H.-P. Francfort, "Archaeological interpretation and non-linear dynamic modeling: between metaphor and simulation," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 151–176, Routledge, London, UK, 1997.

[61] S. Mithen, "Simulating mammoth hunting and extinctions: implications for North America," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 176–216, Routledge, London, UK, 1997.

[62] J. McGlade, "The limits of social control: coherence and the chaos in a prestige-goods economy," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 298–333, Routledge, London, UK, 1997.

[63] G. C. P. King and A. G. Lindh, "Fractal environmental changes and the evolution of culture," in *Time, Process, and Structured Transformations*, J. McGlade and S. van der Leeuw, Eds., pp. 254–269, Routledge, London, UK, 1997.

[64] L. A. Hitchcock, *Minoan Architecture: A Contextual Analysis*, vol. 155 of *Studies in Mediterranean Archaeology*, Paul Astrons, Jonsered, Sweden, 2000.

[65] O. Doonan, "Chaos in the cemetery: complex adaptive systems and social reproduction in archaic Italy," *Archeological News*, vol. 21-22, pp. 61–72, 1997.

[66] S. M. Spencer-Wood, "Culture and the chaos paradigm," Paper presented at the 1st Joint Archaeological Congress, in the Symposium 'Current Issues in Archaeological Theory and Method', Baltimore, Md, USA, January 1989.

[67] S. M. Spencer-Wood, "Non-linear dynamics in cultural processes: implications for theories of culture and cultural evolution," Paper presented at the Conference on Dynamical Description and Human Systems, University of Cambridge, December 1990.

[68] E. Laszlo, *Evolution: The Grand Synthesis*, New Science Library, Boston, Mass, USA, 1987.

[69] D. Ruelle, *Chance and Chaos*, Princeton University Press, Princeton, NJ, USA, 1991.

[70] J. P. Crutchfield, J. D. Farmer, N. H. Packard, and R. S. Shaw, "Chaos," *Scientific American*, vol. 254, no. 12, pp. 46–57, 1986.

[71] I. Hodder and S. Hutson, *Reading the Past: Current Approaches to Interpretation in Archaeology*, Cambridge University Press, Cambridge, UK, 3rd edition, 2003.

[72] L. R. Binford, "Archaeology as anthropology," *American Antiquity*, vol. 28, no. 2, pp. 217–225, 1962.

[73] A. Wylie, "Gender theory and the archaeological record: why is there no archaeology of gender?" in *Women and Production in Prehistory*, M. W. Conkey and J. M. Gero, Eds., Basil Blackwell, 1991.

[74] S. M. Spencer-Wood, "A feminist agenda for non-sexist archaeology," in *Quandaries and Quests: Visions of Archaeology's Future*, L. Wandsnider, Ed., pp. 98–114, Southern Illinois University Press, Carbondale, Ill, USA, 1992.

[75] L. R. Binford, *Working at Archaeology*, Academic Press, New York, NY, USA, 1983.

[76] M. W. Conkey and J. D. Spector, "Archaeology and the study of gender," *Advances in Archaeological Method and Theory*, vol. 7, pp. 1–38, 1984.

[77] G. M. P. O'Hare and N. Jennings, Eds., *Foundations of Distributed Artificial Intelligence*, Wiley Interscience, New York, NY, USA, 1996.

[78] F. Braudel, *The Mediterranean and the Mediterranean World in the Age of Phillip II*, Collins, London, UK, 1973.

[79] S. M. Spencer-Wood, "Diversity in 19th century domestic reform: relationships among classes and ethnic groups," in *Those 'Of Little Note': Gender, Race and Class in Historical Archaeology*, E. M. Scott, Ed., pp. 175–208, University of Arizona Press, Tucson, Ariz, USA, 1994.

[80] S. M. Spencer-Wood, "Strange attractors: non-linear systems theory and feminist theory," in *Exploring Social Theory in Archaeology*, M. B. Schiffer, Ed., pp. 112–126, University of Utah Press, Salt Lake, Utah, USA, 2000.

[81] S. M. Spencer-Wood, "Feminist theory," in *The Encyclopedia of Historical Archaeology*, C. E. Orser, Ed., pp. 205–209, Routledge, London, UK, 2002.

[82] L. R. Binford, "Archaeological perspectives," in *New Perspectives in Archaeology*, R. Sally and R. L. Binford, Eds., pp. 5–32, Aldine, Chicago, Ill, USA, 1968.

[83] P. J. Watson, S. A. LeBlanc, and C. L. Redman, *Explanation in Archaeology: An Explicitly Scientific Approach*, Columbia University Press, New York, NY, USA, 1971.

[84] S. M. Spencer-Wood, "Toward the further development of feminist historical archaeology," *World Archaeological Bulletin*, vol. 7, pp. 118–136, 1995.

[85] S. Bordo, "The cartesian masculinization of thought," *Signs*, vol. 11, pp. 439–456, 1986.

[86] C. Merchant, *The Death of Nature: Women, Ecology and the Scientific Revolution*, HarperCollins, New York, NY, USA, 1980.

[87] M. Baenninger and N. Newcombe, "Environmental input to the development of sex-related differences in spatial and mathematical ability," in *Taking Sides: Clashing Views on Controversial Issues in Sex and Gender*, E. L. Paul, Ed., pp. 97–100, McGraw-Hill/Dushkin, Guilford, Conn, USA, 2nd edition, 2002.

[88] G. Lerner, *The Creation of Feminist Consciousness: From the Middle Ages to Eighteen-Seventy*, Oxford University Press, New York, NY, USA, 1993.

[89] B. M. Solomon, *In the Company of Educated Women*, Yale University Press, New Haven, Conn, USA, 1985.

[90] L. Code, *What Can She Know? Feminist Theory and the Construction of Knowledge*, Cornell University Press, Ithaca, Greece, 1991.

[91] M. Schroeder, *Fractals, Chaos, Power Laws*, W.H. Freeman, New York, NY, USA, 1991.

[92] J. F. Deetz, "Material culture and worldview in colonial Anglo-America," in *The Recovery of Meaning: Historical Archaeology in the Eastern United States*, M. P. Leone and P. B. Potter Jr., Eds., pp. 219–234, Smithsonian Institution Press, Washington, DC, USA.

[93] M. Bloch, "From cognition to ideology," in *Power and Knowledge*, R. Fardon, Ed., pp. 21–48, Scottish Academic Press, Edinburgh, Germany, 1985.