Building a better past with the help of agent-based modeling

J. Daniel Rogers and Wendy H. Cegielski

With a few exceptions, the distant past is an anonymous land occupied by people who made things and left behind a cryptic record of broken pieces. Even when the written word comes into play in human history and we can read the hieroglyphs naming an Egyptian pharaoh and describing royal achievements, the majority of human experience remains unknown and unrecoverable. Archaeologists usually excavate to gather physical evidence from ruins, monuments, and artifacts, which become data streams for the interpretation of past societies. Basic excavation is supplemented by a variety of scientific and historical research methods, all of which are far removed from observing the actual experiences of individuals in the past.

The result is that aggregated categories such as households, neighborhoods, cities, nations, and civilizations become the units of analysis. These categories are incredibly important, but they are often used because finer analytical levels are unavailable. Furthermore, the aggregate categories are typically implemented under expectations of classical science, such as equilibrium outcomes that assume normal distributions as well as

Fig. 1. Agent-based modeling is a powerful means for archeologists to explore the connections among individual action, intangible social entities, and broader interpretations at any time scale. If used more widely, ABM could free practitioners from many traditional limitations and make findings translatable to the general scientific public. Image courtesy of Wendy Cegielski and Jay Etchings (Arizona State University, Tempe, AZ).
linear assumptions of cause and effect about rates of change or adaptive processes. These approaches only scratch the surface of complex human dynamics.

Unless fine-grained behaviors can be accounted for, the use of standard inferences and analogies only adds more layers of unknown bias to interpretations. Essentially, the past is understood through conceptual tools developed before the mid-20th century. However, innovative computational methods provide a way out of this old conundrum by introducing new ways of conceptualizing scale and pattern, exploring social change, and utilizing large data sets.

Although we focus here on archaeology, it is not alone in facing the challenges of using second-hand observation, incomplete data, and coarse-grained inferences—consider histonography, the study of earth processes, paleobiology, ecology, and astrophysics. All these fields and more develop diachronic interpretations without direct observation of the processes under study.

ABM and computational methods, in general, capture the dynamics of new research concepts coupled with the potential of incorporating ever-increasing realms of knowledge.

The good news for the study of human history is that, even with these challenges, digital data from a vast array of analytical categories (physical, chemical, biological, spatial, social, and psychological) are now becoming accessible on a large scale. In parallel, a new generation of computational tools is in place to develop large models and take advantage of massive data sets. In particular, over the last few years agent-based modeling (ABM) has matured into a powerful way to explore data and the connections among individual action, intangible social entities, and broader interpretations at any time scale. Indeed, the use of ABM is a fundamentally new way to explore the dynamics that constitute all social actions. ABM, if used more widely, can have an immensely beneficial impact on building a better past by freeing practitioners from many traditional limitations—and by making findings translatable to the general scientific public (see also PNAS Opinion by Altschul et al. ref. 3).

Computing Power
Basic ABM in the social sciences is an object-oriented computational simulation situated in a spatial environment and populated by agents with characteristics and behaviors that mimic individual humans, social groups, or organizations. The agents may learn and adapt and are not restricted by categorical thinking or equilibrium assumptions. ABM produces results that reflect stochastic complexities, much like human history. Routinely, the analysis of dynamics at a small scale, at the level of individual agents or small groups, leads to a rejection of linear assumptions when applied to the macro level of cultural change. Like any model, computational or not, ABM is an abstraction of the system of interest.

Archaeologists have never been shy about using computers to their full potential. In the 1960s and 1970s mainframes were exploited not only to facilitate multivariate statistics but also to create simulations. Aside from these early studies, the real explosion in published research occurred after 2000 and even more so after 2007 (5, 6). Recent studies generally incorporate one or more overlapping themes, including historical, social complexity, complexity science, formation processes, human ecology, and evolutionary processes.

The most common and arguably the most influential developments are the long-term studies that focus on a single region to analyze broader social patterns while demonstrating a close correlation with empirical data. These studies have focused on the fundamental relationships between humans and the environments in which they live. Examples include the Long House Valley project (7) and the Village Ecosystem Dynamics Project (8), both in the US Southwest. In Europe and Asia, the Mediterranean Landscapes Dynamics Project (9) and the Mason-Smithsonian Joint Project on Inner Asia (10) have contributed additional perspectives. These projects and others have extended the ABM dialogue by demonstrating the method’s utility in diverse contexts. Each of these projects has interdisciplinary institutional underpinnings that allow sustained effort.

Across the behavioral and social sciences, the use of simulations and ABM has a similar time depth but still faces many of the same challenges seen in the study of past societies. Early classic studies in economics and international relations with some of the characteristics of ABM include Thomas Schelling’s Micromotives and Macrobehavior (11) and research on international conflict by Alker and Brunner (12). The idea of computational social science, as both a methodology and an interdisciplinary paradigm, now includes textbooks and several introductions to ABM methodology (13, 14). The volume and diversity of work underway speak to a growing awareness within mainstream disciplines, although acceptance remains elusive. The low rate of acceptance is largely the result of a lack of familiarity with the method and the challenge it represents to existing paradigms.

ABM and computational methods, in general, capture the dynamics of new research concepts coupled with the potential of incorporating ever-increasing realms of knowledge. These new methods upend the sequential rigidity of the classical scientific method. It is now possible to hypothesize the actions of highly detailed individual agents, to incorporate dependencies between those agents, and to simultaneously test a multiplicity of scenarios in a simulated laboratory, moving beyond classical mathematical or statistical approaches. The use of ABM represents a potential paradigm shift, not just for the study of the human past but also for the social sciences. To apply a familiar tale to illustrate the potential of computational simulations: Sometimes our greatest innovations occur during impromptu discussions. Imagine being able to access every inspired bar-napkin conversation that every social scientist ever had and having them available...
at all times for your next conversation. This is the power of the dynamics and scale that can be captured in computational simulation.

**Effective Approach**

ABM is not a miracle cure, but there are five areas in which it can make a difference:

1. Social processes can be investigated at any spatial or time scale—from individuals to world systems;
2. ABM development facilitates data standardization and encourages collection of larger data sets;
3. The ubiquitous need to build data categories can revolve around topics of interest rather than pre-existing interpretive constructs;
4. Material links to social dynamics can be more thoroughly investigated; and
5. New hypotheses can be easily developed to focus future field research.

A demonstration of how ABM can transform a social science is evident when considering fundamental research quandaries. Archaeology focuses on social dynamics described as culture changes, the origins of civilization, the origins of agriculture, and other similar themes. Restrictions in the study of such themes are imposed by the necessity to create intermediate interpretive tools such as artifact typologies and chronology. Although fundamental to archaeology, chronology also confounds attempts to interpret behavior and process. Chronology is a typology of sequential information placed into blocks of time. Studying the differences between blocks is a form of data aggregation, which makes it difficult to generalize between levels of investigation because of data loss (16).

Furthermore, chronologies are themselves theories that tend to become standardized, thus automatically supporting some interpretations and rejecting others. Time periods hundreds of years long are compared when ideally much finer resolution is needed. For instance, archaeology often studies patterns of settlement to interpret local economies, trade networks, and political systems. An essential question to ask is, “Are the sites contemporary in each time block?” For the analysis to be valid, contemporaneity must be established. Archaeologists often just accept that contemporaneity cannot be established and instead bolster the argument with other lines of evidence. Sometimes archaeologists are forced to look the other way because in most instances detailed chronologies are absent.

The typical approach to a problem such as unknown contemporaneity is to push both ends of the data spectrum—expand the scope outward and increase the details inward. This involves locating and excavating more sites and conducting more specialized studies to develop fine-grained chronology. Doing so could take a long time or is impossible because of data lost to dams, highways, urban sprawl, or sea-level rise. By approaching temporal dynamics first through simulation, ABM can generate hypotheses and interpretations without data aggregation at scales ranging from seconds to millennia and without years of additional survey and excavation. Refined hypotheses promote focused fieldwork driven by the best available data sets.

**No Panacea**

Can ABM ever replace basic fieldwork methods? Absolutely not. ABM will not discover a royal tomb (although it might help), but neither will excavating 100 royal tombs capture the structure and dynamics of early states. To make matters worse, the archaeological record is a finite resource. A recent study has shown that, as the number of archaeologists has grown, fieldwork has increased, yet the rates of discovery in many segments are in decline, and Surovell et al. (17) predict that future archaeology will increasingly focus on existing museum collections or return to sites previously studied. We agree, but we also add computational methods as part of the vision for future archaeology.

Combining ABM with shifts already underway in fieldwork has the potential for truly novel insights (9). Even with these advantages, ABM-based research is not mainstreamed within the social sciences. Some reasons why center on the fact that results from ABM often do not match the standard terminology, scope of research questions, complexity of results, or validation by established research methods. There is also a common skepticism that questions whether science-based computation is compatible with fields of research closely tied to the humanities (18). Even for steadfastly skeptical research areas, ABM meshes well with the focus on individual agency or action emphasized in such areas of social theory as feminist theory, critical theory, and post-structuralism (5).

A conceptual mismatch continues to exist partly because ABM often uses a bottom-up form of social science that is neither entirely deductive nor inductive but represents a third methodology described as generative. In this approach, the model itself is an elaborate hypothesis constructed to study emergent pattern through the actions of individual agents (19). Complexity science and the study of complex adaptive systems have influenced the development of social science ABM (20). The stochastic nature of ABM results, unexpected outcomes, and the ability of small causes to make big changes challenge fundamental theories in archaeology, such as how states and empires originate, how to interpret settlement systems, and even how we understand the very distribution of artifacts in a site.

Although scientific methods are rejected by some segments of the broader research community that studies the human condition, the good news is that a major shift is underway. The change is fueled by a new generation of interdisciplinary scholars who see computational methods as the norm. Several universities in East Asia, Europe, and the United States have created and sustained interdisciplinary centers that foster computational social science and serve as a basis for a burgeoning research community (21).
Much is at stake as we rethink how to study the past. Past societies embody the prototypes and roots of many contemporary challenges, from poverty to conflict to climate change. The past provides analogs but has a much greater potential that should not be ignored. We have the opportunity to build a more dynamic approach to the past and use it to better understand our present challenges.