Cultural Dynamics, Deep Time, and Data

Planning Cyberinfrastructure Investments for Archaeology

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ABSTRACT

Archaeological data and research results are essential to addressing such fundamental questions as the origins of human culture; the origin, waxing, and waning of civilizations and cities; the response of societies to long-term climate changes; and the systemic relationships implicated in human-induced changes in the environment. However, we lack the capacity for acquiring, managing, analyzing, and synthesizing the data sets needed to address important questions such as these. We propose investments in computational infrastructure that would transform archaeology's ability to advance research on the field's most compelling questions with an evidential base and inferential rigor that have heretofore been impossible. At the same time, new infrastructure would make archaeological data accessible to researchers in other disciplines. We offer recommendations regarding data management and availability, cyberinfrastructure tool building, and social and cultural changes in the discipline. We propose funding synthetic case studies that would demonstrate archaeology's ability to contribute to transdisciplinary research on long-term social dynamics and serve as a context for developing computational tools and analytical workflows that will be necessary to attack these questions. The case studies would explore how emerging research in computer science could empower this research and would simultaneously provide productive challenges for computer science research.

Los datos y resultados de la investigación arqueológica son esenciales para abordar cuestiones tan fundamentales como los orígenes de la cultura humana; el origen, crecimiento y decadencia de las civilizaciones y ciudades; la respuesta de las sociedades a los cambios climáticos a largo plazo y las relaciones sistémicas involucradas en los cambios antropogénicos en el medio ambiente. Sin embargo, carecemos de la capacidad para adquirir, administrar, analizar y sintetizar los conjuntos de datos necesarios para abordar cuestiones importantes como estas. En este trabajo proponemos que las inversiones en infraestructura computacional tienen la capacidad de transformar la habilidad de la arqueología para desarrollar la investigación en torno a las cuestiones más apremiantes de este campo con una base empírica y bajo el rigor de la inferencia científica que hasta ahora habían sido imposibles de lograr. Al mismo tiempo, la nueva infraestructura facilitaría el acceso a los datos arqueológicos a investigadores de otras disciplinas. Ofrecemos recomendaciones en torno al manejo de datos y su disponibilidad, la construcción de herramientas de infraestructura cibernética y a los cambios sociales y culturales en la disciplina. Proponemos financiar estudios específicos y concisos que demostrarían la capacidad de la arqueología para contribuir a la investigación transdisciplinaria sobre las dinámicas sociales a largo plazo y que sirvan de contexto para desarrollar herramientas computacionales y procesos de trabajo analíticos que son indispensables para abordar estas cuestiones. Los estudios de caso exploran como la investigación emergente en la ciencia de la computación puede potenciar este tipo de investigación y podría simultáneamente proveer retos productivos a la investigación en ciencias de la computación.

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BACKGROUND

The Place of Archaeology in Contemporary Science

Human societies are shaped by evolutionary processes and constrained by their natural and social environments, which they simultaneously modify. A fundamental challenge of science is to confront the complexity of human societies and their interactions with the natural environment. While societal responses to change are conditioned by contemporary stimuli, they are also contingent on a society's history and often have unintended consequences, in both the short- and long-terms. Systematic understandings of many of the complex processes that operate on centennial or millennial scales must, of necessity, use archaeologically derived data and knowledge. Archaeological data and research results are essential to understanding the origins of the human species and culture; the inception, waxing, and waning of civilizations; and societal responses to long-term climate change.

Archaeological research is a difficult, complicated endeavor. Archaeological data—the material remains of the past—are not only partial but also progressively depleted through time. Archaeologists must construct long chains of inferences to link the fragmentary physical record to whole, complex cultural systems. Moreover, archaeology is multidisciplinary in nature, incorporating in its fieldwork and laboratory research aspects of other fields, including geology, geography, biology, chemistry, and ecology, as well as cultural anthropology and history. While it is easy (and far too common) for researchers in other fields to "cherry pick" archaeological interpretations (e.g., Diamond 2005; cf. McAnany and Yoffee 2010), real understanding of human social dynamics and coupled human natural systems will come from coherent and complete arguments grounded in syntheses of several cases. It is critical to make archaeological data more accessible to researchers outside archaeology. To cite only a single example, ecologists examining the long-term effects of climate change need ready access to archaeological information on human activities and their impacts on biological systems. Archaeological investigations have unequivocally demonstrated that there have been enduring and substantial human impacts on what was previously thought to be the "natural" presettlement vegetation of such diverse areas as the United States (U.S.) Eastern Woodlands, the Southwest U.S. deserts, and the Amazon Basin. Absent archaeological data, essential ecological baselines would be wildly distorted (e.g., Briggs et al. 2006).

Archaeology, like other sciences, must be concerned simultaneously with the particular and with the general. Archaeology is a key source of information about what we might call the "facts of the past," and, absent recorded history, archaeology is often the *only* source. Archaeologists can answer particularistic questions such as "What was the economic basis of the Maya city of Tikal?" or "When was Cliff Palace in Colorado's Mesa Verde region abandoned?" At the same time, much contemporary archaeology is focused on attaining more general understandings of social dynamics. In such efforts, the particular facts of the past constitute the data used in the service of the broader questions. While it is impossible to perform controlled experiments on long-term social processes, it is possible to compare and contrast the data from different periods and locations that share commonalities, providing insights into the effects of variables through time. In rigorously examining more general explanations, reconstructed archaeological sequences thus appear as completed "experiments" in the operation of social and ecological dynamics played out in highly diverse social and natural environments. The more data points we have, the better our experiments; the better the experiments, the better chance we have of addressing fundamental questions about how human societies came to be and where they are headed.

The Need for Synthesis

Answering fundamental questions about human societies requires compiling, analyzing, and synthesizing large data sets. Through the first half of the twentieth century, an individual could command the archaeological literature for a large area. V. Gordon Childe, one of archaeology's grand synthesizers, commanded the literature for Europe and the Near East, which he synthesized in sweeping accounts of prehistory in works such as *Man Makes Himself* (1936) and *What Happened in History* (1942). Perhaps the last grand synthesizer in archaeology was Gordon Willey, who in the 1960s produced a seminal two-volume overview of New World prehistory (Willey 1966–1971).

With the explosion of research and data over the last 40 years, it has become impossible for an individual to have sufficient command of the archaeological literature in multiple geographical areas to do effective, large-scale synthesis. Advances in methods and technology have led archaeologists to collect many types of data and to gather and store vast quantities of fine-grained information. In response to laws and regulations protecting historic and archaeological properties, there has been an enormous increase in the scale and number of archaeological investigations. In the U.S. alone, cultural resource management (CRM) expenditures are on the order of a billion dollars annually (Altschul and Patterson 2010), with federal agencies sponsoring, on average, about 45,000 field projects per year since 2003 (Departmental Consulting Archeologist 2012).

Overwhelmingly, archaeological investigations in the U.S. are publicly funded compliance projects; only a tiny fraction are supported by public or private research grants. Most compliance reports are not published, and so their results can be difficult to find. Yet these reports are filled with data tables and "facts of the past" (to say nothing of theoretical and methodological advances) and have enormous scientific potential that can—and must—be leveraged to advance our knowledge and understanding of the world (e.g., Dawdy 2009; Little 2002; Rockman and Flatman 2012; Sabloff 2008; Smith 2010).

Rather than compelling us to address the "big" questions, the tsunami of reports and data has had the opposite effect: most interpretations now focus on small regions and particular aspects of the archaeological record, such as ceramics or animal bones. We are metaphorically drowning in a sea of data. While abundant data have been collected that are relevant to examining such key issues as the complex and recursive interrelationships between human behavior and climate change, our attempts at such synthesis are frustrated by our practical inability to discover, acquire, manipulate, analyze and visualize those data, and present the results in ways that can be understood.

Infrastructure's Impact on Research

We propose investments in infrastructure that would transform archaeology's ability to advance research on the field's most compelling questions and that would enhance the infrastructure for transdisciplinary research on long-term social dynamics and the operation of coupled natural and human systems. At the same time, these investments would make key archaeological data accessible to researchers in other disciplines, such as ecologists looking at long-term biodiversity using dated animal and plant remains from archaeological sites, geographers interested in coupled social-ecological systems, economists studying the emergence or resilience of markets, and hazard specialists seeking to know how well people read different "signals" of impending change.

In considering the transformative potential of these investments, we can look for precedents in the past—as archaeologists are wont to do. Archaeology's widespread adoption of computers and statistical methods for data management and analysis in the 1970s did not simply make analysis more efficient; it genuinely transformed the ways in which research was conducted: the questions asked, the data collected, and the laboratory methods employed. Today, archaeologists are similarly poised to make dramatic advances in our understanding of coupled human and natural systems. Increasingly, we seek to address questions at ever-broader spatial and temporal scales that are directly relevant to contemporary science and society. But, as new and refined data collection and analytical techniques are being adopted, archaeologists are increasingly challenged as they acquire, manage, and analyze large volumes of disparate data. Major investments in cyberinfrastructure can again transform the questions we can address and the ways in which research is done by empowering us to much more effectively exploit the rich sources of data we already control.

Cyberinfrastructure and Scientific Workflows

Our ability to transform information and data into knowledge is continually being improved by cyberinfrastructure—the hardware, software, and people that constitute state-of-the-art information technology tools and services. Archaeology must look to these new technology-enabled methods for performing synthesis that will leverage the rich sources of already-collected data.

In recommending infrastructure investments, archaeology, like other scientific disciplines, needs to take into account the complete knowledge creation process, which includes research planning, data collection and organization, quality assurance, metadata creation (i.e., documentation that enables data to be interpreted and used), preservation (i.e., deposition of data and metadata in a secure repository), data discovery, data integration, and data analysis and visualization (Michener and Jones 2012). While much is yet to be accomplished, research sponsors and professional societies in many domains are now recognizing the value of supporting open access to data (Auer et al. 2007; Heath and Bizer 2011) and publications (Antelman 2004; Harnad and Brody 2004), as well as the scientific workflows that support replicable analysis and modeling (Gil et al 2007; Ludäscher et al. 2009).

Archaeology has begun to recognize and address the challenges entailed by confronting complex questions and a deluge of data. A 2004 conference (Kintigh 2006) confronted the promise and challenge of archaeological data integration and led directly to the development of tDAR: the Digital Archaeological Record (Digital Antiquity 2014), a repository for the digital records of archaeological investigations. tDAR enables some forms of data integration, while providing dramatically improved preservation and access to archaeological data and information. In Europe, substantial resources have been invested in a number of continent-wide initiatives linking computational research and archaeology, as well as the development of long-term digital archives for data; these include ARENA (2014; Kenny and Kilbride 2003), ARIADNE (2014), CARARE (Europeana 2014a), and the umbrella project of Europeana (Europeana 2014b). While expanding the content of such digital repositories and developing their analytical abilities are important foci for investment, they form only one part of a complex of interrelated needs that must be addressed.

WHAT ARE ARCHAEOLOGY'S GRAND CHALLENGES?

Below we recommend the investments in computational infrastructure that are needed to satisfy the disciplinary needs of archaeology, as well as other demands of the scientific community and contemporary society more broadly. In developing our recommendations, our premise was that the highest priority should be assigned to investments that enable us to address the most compelling questions.

Lacking a ready list of the big, unanswered questions in archaeology, we undertook an effort to identify the discipline's most important scientific challenges. Inspired by the National Science Foundation's (Guttman and Friedlander 2011) SBE2020 initiative, we crowd-sourced suggestions through email requests and listserv postings by the major North American and European professional associations (Kintigh 2013). In a summer 2012 workshop held at the Santa Fe Institute, a group of scholars with diverse interests and orientations augmented, refined, and prioritized the crowd-sourced suggestions, yielding a set of 25 grand challenges. These challenges have been disseminated to the archaeological community via publication in the community's major journal, *American Antiquity* (Kintigh et al. 2014a), and to the wider scientific community via publication in the *Proceedings of the National Academy of Sciences* (Kintigh et al. 2014b). Three of these challenges provide the focus for the proposed cases studies, outlined below.

While one might legitimately argue with the particulars of our list of grand challenges (Cobb 2014), we maintain that more general properties abstracted from these challenges can reasonably be used to guide our recommendations for infrastructure investments. The proposed grand challenges are not unique to archaeology; rather, they are social science questions whose answers require knowledge on temporal and spatial scales that only archaeology can provide. They derive from a conviction that understanding the cultural dynamics we observe today demands deciphering the long-term histories that produced them. Contrary to what some might have predicted, the challenges reflect a notable lack of concern with the earliest, the largest, and the otherwise unique. Instead, they focus on the dynamics of cultural processes and the operation of coupled human and natural systems. These cultural dynamics and environmental interactions undoubtedly involve complex, nonlinear relationships in which cause and effect are not readily distinguished. There was a strong consensus at the Santa Fe meeting that the grand challenges can be answered, but that they remain unresolved, in large part, because we lack the research infrastructure to grapple effectively with their complexity. Just finding and organizing the data to address these questions, which is only part of the challenge, would be beyond the capabilities of most researchers.

IMPEDIMENTS TO SYNTHESIS IN ARCHAEOLOGY

Having identified key characteristics of the grand challenges, it was clear that transformative progress demands a new focus on synthetic research by archaeologists, intensified collaboration with researchers from other disciplines, major investments in computational and social infrastructure to support synthesis, and development and application of new technologies for data visualization and exploration. We designed a second workshop, focused on the process of synthesis in archaeology, to explore these needs and to recommend investments in computational infrastructure that would transform archaeology's ability to meet its own challenges and to contribute to those faced by related sciences. Participants were a mix of archaeologists (all but one of whom had been part of the grand challenge workshop), computer and information scientists with expertise in key research areas, and a few others who are hard to classify (Table 1). The results of that productive meeting constitute the remainder of this article.

A number of factors conspire to frustrate synthetic research: the problems of preservation, discovery, and access; the difficulty of data integration; the variety and complexity of archaeological data and evidence; and disciplinary norms and pragmatics of data sharing and collaboration.

Data Preservation. Critical and irreplaceable archaeological data are in imminent danger of permanent loss. Digital data can be lost through media degradation and software obsolescence, or they may be discarded. An equally devastating loss of data—digital and otherwise—derives from inadequate documentation, or metadata, for databases or data sets. Frequently, the information needed to understand precisely what has been recorded, along with critical contextual information (such as sampling) is not systematically recorded. Too often, it resides only in the mind of the investigator. As investigators retire or die, or as the projects recede in time, this loss can be devastating (Michener et al. 1997). Despite the well-known fragility of digital data, there is often little concern for digital preservation of the research results once a project is completed. The loss is amplified now that archaeological reports, datasets, and images are generally born digital, with no paper backup.

Discovery and Access. Apart from issues of preservation, there are pervasive problems with discovery of relevant information resources and access to them. Most archaeological studies of the past several decades were not published, but were submitted to government agencies whose ability to track and disseminate them varies widely. Many important projects were executed before the digital age and only in rare cases have the results been digitized. It is impossible, of course, to repeat these investigations—archaeological contexts are destroyed by their excavation and what remains of the sites is often obliterated by the undertaking that triggered the investigation. We must take maximum advantage of the records and collections that remain.

TABLE 1. Synthesis Workshop Participants.

Participant	Affiliation (at the time of the workshop)	Discipline
Jeffrey H. Altschul	SRI Foundation & Statistical Research, Inc.	Archaeology
Peter Fox	Rensselaer Polytechnic Institute	Computer Science
Juliana Freire	New York University Polytechnic	Computer Science
Edward J. Hackett	Arizona State University	Sociology, Science & Technology Studies
Keith W. Kintigh	Arizona State University	Archaeology
Ann P. Kinzig	Arizona State University	Ecology & Sustainability
Timothy A. Kohler	Washington State University	Archaeology
Bertram Ludäscher	University of California, Davis	Computer Science
W. Fredrick Limp	University of Arkansas	Archaeology
Clifford A. Lynch	Coalition for Networked Information	Computer Science
William K. Michener	University of New Mexico & DataONE	Ecology & Informatics
Scott G. Ortman	Santa Fe Institute	Archaeology
Peter N. Peregrine	Lawrence University	Archaeology
Jeremy A. Sabloff	Santa Fe Institute	Archaeology
Melinda A. Zeder	Smithsonian Institution	Archaeology
John Yellen	NSF Archaeology Program	Archaeology (observer)

Technologies to effect preservation, discovery, and access of digital resources are now in place (e.g., tDAR in the U.S.; ADS (Archaeology Data Service 2014) in the United Kingdom (UK), and DANS (Data Archiving and Networked Services 2014) in the Netherlands). There are clear legal and regulatory requirements that federal agencies curate digital archaeological data resulting from their own activities, from permits, and from agency undertakings (Cultural Heritage Partners 2012). In a 2013 memorandum, the U.S. Office of Science and Technology Policy declared that the results of federally funded scientific research shall be "made available to and useful for the public, industry, and the scientific community" to the "greatest extent possible" (Holdren 2013:1). Despite this policy and the statutory and regulatory requirements, research and heritage management workflows do not move data and documents from the vast majority of investigations into these repositories as a matter of course. As a result, these data overwhelmingly remain inaccessible and at risk for loss.

Incentives to properly curate digital records are increasing in the academic sector (e.g., due to the National Science Foundation (NSF) and National Endowment for the Humanities requirements for Data Management Plans and some journal's demands that supporting data be accessible). Similar inducements for responsible digital data curation in the government and private sectors are rare.

Data Integration. Today, synthetic studies in archaeology typically rely on the published summaries of others' research, not on direct examinations of the data on which their arguments are based. As a result, erroneous conclusions can easily "become entrenched in the literature as 'facts' that serve as faulty premises of subsequent scientific arguments" (Kintigh 2006:570). These syntheses rarely employ primary data, because of lack of access to them and, at least as significantly, due to the difficulty of integrating data recorded using the often incommensurate systematics employed by different investigators. Creatively mining integrated sets of primary data will enable the detailed synthetic studies needed to approach important questions and will allow us to ferret out analytical or interpretive errors that have crept into commonly accepted understandings of the past. Improved best practices and standards for data acquisition (including the use of various technology-based capture mechanisms) will ease the challenges of integrating data from multiple investigators and sources going forward.

Data Complexity. In archaeology, systematic observations are recorded for many different classes of items: artifacts and architecture, plants and animals used by people, environmental indicators, and anthropic landscapes. Observations are made at a variety of scales, ranging from microscopic examination of a portion of a single object to archaeological sites and regional settlement patterns. Some observations come in textual form; others are systematic measurements or identifications of nominal categories, and still others are visual records, including photographs, three dimensional (3D) scans, and Light Detection and Ranging (LiDAR) images. Moreover, each observation is situated within a hierarchy of archaeological contexts, knowledge of which is essential for any interpretation. While there has been much attention to "big data" of late, we need analogous tools to deal with "complex data."

Data to Information to Knowledge. Many field decisions and analytical and interpretive steps separate archaeological *data*—our field and laboratory observations—from descriptive statements that become the interpreted archaeological "facts." Even more complex inferences separate the transformation of this descriptive *information* to *knowledge* concerning the operation of social and socio-ecological systems that is the ultimate target of archaeologists and other scientists who understand the importance of the long term. We need to consider how digital infrastructure can both assist and inform these analytical and interpretive tasks and make them more reliable and replicable. Reproducible research is a goal in many fields (Peng 2011) and should be a goal in archaeology. It requires that the data used, and the analytical workflows and algorithms that operate on them, be fully available and documented.

RECOMMENDATIONS

Overview

In our explorations of how archaeologists, working with a wide range of computer and information scientists, could produce transformative research, it was apparent that we will need: (1) improved data capture and availability; (2) cyberinfrastructure tool building; (3) new patterns of collaboration; and (4) social and cultural changes in the discipline. Recommendations for each of these sets of needs are laid out below.

In addition, we propose funding three synthesis case studies, each attacking one of the grand challenges. Each case study lays out a substantive challenge and foregrounds a suite of general issues of computational infrastructure that the case study should pursue. Case studies such as these would demonstrate archaeology's ability to understand the complex cultural and ecological interactions implicated in the grand challenges, and they would serve as productive contexts in which to develop and test a suite of computational tools and analytical workflows needed to attack these problems. The case studies would illustrate how emerging research in computer science can empower synthetic research, and they would simultaneously provide productive challenges for computer science research.

We expect these case studies to make clear progress on three grand challenge questions. The questions selected share several variables that crosscut many of the grand challenge problems: settlement size, settlement differentiation, demography, and key environmental indicators. These case studies will build generalizable cyberinfrastructure tools and strategies, e.g., for demographic reconstruction or climate analysis, that will be broadly useful in addressing these and many other grand challenges and related questions. All three case studies will engage multiple data sets that will have to be normalized to achieve reasonable comparability. While the normalization process will be partially automated, it will nonetheless require very substantial investments of human effort. All these syntheses will involve multiple iterations of analysis, inference, and critique.

The cyberinfrastructure-enabled workshops pioneered by the National Center for Ecological Analysis and Synthesis (NCEAS) offer a proven model that we propose to emulate in pursuing the three case studies. The NCEAS model employs working groups of 8–15 collaborators. Each working group combines and analyzes multiple data sets in order to address a fundamental, synthetic research question. A group meets in person two or more times a year over a period of two or three years (Hampton and Parker 2011), supplemented by email or other exchanges (e.g., Skype) to sustain the work. We suggest that each case study will need an organizer or small group of organizers assisted by a postdoc. For each case study, we propose at least three meetings over 18 months, with the first focusing

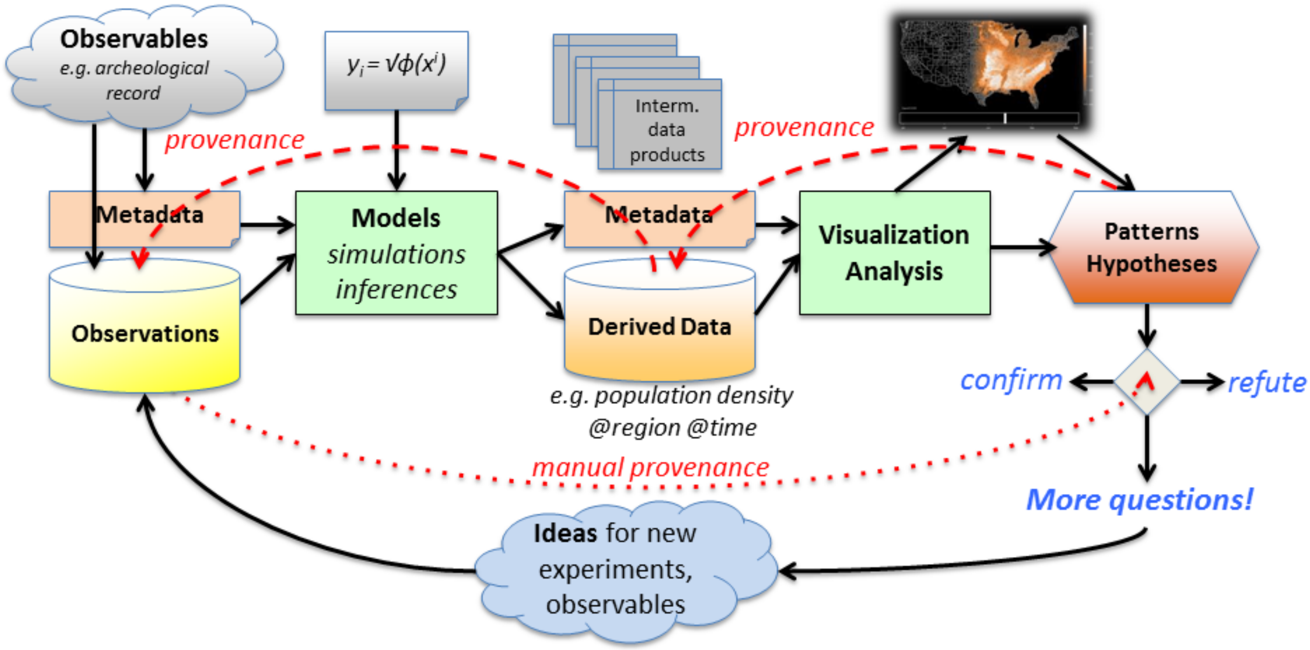

FIGURE 1. Inference and provenance pathways.

on hypothesis development and needed data resources; the second on data exploration and interoperability, hypothesis refinement, and analytical workflows; and the third on visualization, interpretation, testing, and theory-building. The working groups executing these case studies would involve archaeologists, computer scientists, and other relevant specialists, as well as individuals who could potentially apply the results. Each working group would have archaeology and computer science subgroups that, at each session, would work partly together and partly separately. Funding would be needed not just for the workshop meetings but also for cybertool development and data acquisition, cleaning, normalization, and analysis between the meetings.

Case Study 1: Organizational Complexity

Question: How and why do small-scale human communities grow into spatially and demographically larger and politically more complex entities?

Infrastructure Focus: Provenance and Inference Pathways, Models, and Workflows

How and why human organizations become more complex has long fascinated scholars. Indeed, this fundamental question is a common theme in NSF Archaeology Program research proposals and directly ties in with many other grand challenges. It also has been the subject of many large compliance projects, such as the Roosevelt Archaeological Project in Arizona (Dean 2000). Organizational complexity has been studied at scales from the growth of individual communities to the emergence of empires. It has been attacked in myriad individual projects, using diverse classes of data. In some key projects, relevant data were systematically recorded and are accessible in digital form. For most of these projects, the data will need to be systematized, digitized, documented, and integrated. In addition, it will be necessary to mine large cross-project databases, such as the artifact chemical compositional data held by the Missouri University Research Reactor. Finally, much of the relevant argument is embedded in the text of articles and reports that will need to be extracted in an analytically useful form using sophisticated natural language processing tools.

The synthesis efforts of this and the other case study working groups will run head-on into a problem that plagues archaeologists but fascinates computer scientists: the long inferential chains that archaeologists construct to link the observable archaeological and paleoenvironmental record with variables hypothesized to be related to complexity. These variables, in turn, are hypothesized to be interrelated in specific ways, ultimately leading to changes in social relations and organizations (Figure 1).

Efforts made by Timothy Kohler and his colleagues (2007, 2012) to model the development of ancient Puebloan societies in southwestern Colorado illustrate this complexity. To build their agent-based model, the investigators first created a series of resource-availability models for maize production, water, game, and fuel wood. Each resource-availability model encodes a multistep process (workflow) in which several environmental proxies are transformed and interrelated to produce independent variables. Similarly, archaeological data are transformed, based on a number of assumptions, into demographic inputs to the model. Assumptions are made about how households (the agents) behave in relation to resource availability, and in some versions of the model relationships among households may evolve as groups organize themselves and respond to environmental and social challenges with variable success. The model has great potential to explain the cultural trajectory and adaptability of ancient Pueblo society, but its power lies less in identifying the correctness of any single inferential pathway than in the possibility of studying multiple inferential pathways, each of which requires model outputs to be compared efficiently with appropriately organized archaeological data.

Not surprisingly, many archaeological interpretations involving complexity founder on the middle-range theory used in the lengthy inferential chains linking observations with expected outcomes. Critical evaluations of arguments often focus more on methodological weaknesses than on the underlying social theory. To advance the debate on social complexity (and numerous other topics), we need new ways of evaluating inferential pathways. Fortunately, computer scientists are interested in problems of provenance, dependency, and inference and are developing cyberinfrastructure tools that can be adapted to archaeology. For computations that correspond to *queries*, the database community has developed numerous provenance approaches to explain *why* and *how* a result was derived from input data, and *where* in the input the result data came from (Cheney et al. 2009). Similarly, for *scientific workflows*, advanced methods to capture, store, query, visualize, and analyze provenance have been developed (Anand et al. 2012; Davidson et al. 2007).

This Organizational Complexity working group might choose to begin with a number of (at least seemingly) well-understood empirical cases that occupy a limited range of the complexity spectrum. (This effort might build on the Rise of Early States Project, now underway at the Santa Fe Institute, which is developing synthetic digital databases on the rise of early states in Mesopotamia, Oaxaca, and the Southern Andes, as well as larger comparative ones.) For each of the selected variables of interest (such as demography or economic organization), it would be useful to start with the relevant observations (e.g., site size and settlement differentiation) and make explicit the inferential pathways that lead to the derived dimensions of interest. It would then be possible to do well-grounded comparisons among the cases, and—through the application of different inferential pathways with the recorded observations—to explore the sensitivity of any conclusions to uncertain assumptions. This is in contrast to what is now (of necessity) the typical mode of synthesis in archaeology, which is to compare the *interpretations* of the original investigators, not the *primary data* of the original investigations. Maintaining the provenance of the inferences would not only document any results obtained, but would also allow later additions of cases to the analysis and reevaluation, should it become clear that faulty or dubious assumptions had been embedded in the results.

Case Study 2: Human Responses to Climate Change

Question: How do humans perceive and react to changes in climate and the natural environment over short- and long-terms?

Infrastructure Focus: Data Federation, Visualization, and Tool Building

Archaeologists have long been concerned with how environmental change affects human societies. Over the last 50 years, social scientific perspectives that viewed the environment as determining or strongly constraining cultural responses have yielded to more dynamic, systemic understandings that see the environment as shaping and simultaneously being shaped by human societies.

In posing this challenge, Kintigh et al. (2014a:18–19) note that:

> People constantly monitor aspects of the environment and respond to perceived change by integrating their observations with their goals, their knowledge, and their life experiences. While considered responses will often improve outcomes in a given year, such decisions can result in alterations of the environment that are highly detrimental in the long term. Furthermore, it appears quite difficult to respond appropriately to environmental changes that are sufficiently slow that they cannot be perceived in a single lifetime—such as shifts in the Earth's temperature, sea levels, stream flows, and soil chemistry— even in complex societies that maintain permanent records of environmental observations.
>
> Archaeologists are reasonably successful in documenting societal reactions to short- and long-term environmental change. Most interpretations are, however, post hoc, functional explanations of why a particular culture made the choices that it did. Case by case, these interpretations may seem compelling, but they have proven extremely difficult to generalize.

Work would likely start by seeking correlations between environmental changes and roughly contemporary social changes. When more direct evidence on past climates is not available, sentiment analyses employing computational methods to extract weather-related references in historic-period textual sources might detect climate change (e.g., though more frequent mentions of "drought" or "famine" in period texts).

While plausible associations have often been offered in the literature, generalizable statements about how people respond to long-term climate change will require a shift from case or regional studies to large-scale comparative research. It will require archaeological data at multiple scales, relevant to regional settlement systems, subsistence, economic and social organization, social networks, demography, and technology. Both high-resolution case studies and extensive data on settlement locations will be essential. Areas investigated by previous NSF Biocomplexity and Coupled Natural and Human Systems (CNH) grants are likely good ones from which to start. Indeed, Margaret Nelson is leading a current NSF-CNH grant attempting a synthesis for the Southwest U.S. that is tackling a number of issues closely related to this challenge (Nelson et al. 2010). A NSF Human Social Dynamics grant, and subsequent research led by Barbara Mills, has synthesized a large amount of data on social networks for this same area (Mills et al. 2013). Both these projects relied heavily on information gleaned from CRM reports.

Along with archaeologists, the working group might involve experts on climate, ecology, agronomy, and geology, as well as applied anthropologists who have studied how modern groups perceive and respond to climate change. The working group will need access to a broad range of environmental and paleoenvironmental data at the finest spatial and temporal resolution possible for each empirical case. Much of the environmental data, of course, will reside in locations other than archaeological data repositories (e.g., the National Oceanic and Atmospheric Administration [NOAA] or the United States Geological Survey [USGS]). Thus, this case study would make a logical testbed for federating archaeological and natural science data repositories—which is to say, effecting transparent data exchange (interoperability) of archaeological data centers with those of allied fields.

Because knowledge of the environment is essential to addressing many of the most compelling issues, this working group would be an excellent context in which to build reusable cybertools. This study could provide a test case for building reusable tools that create new ways of visualizing the complex, multivariate, time-dependent relationships being investigated in modeled and actual data. We also envision building a map-based tool that would extract and process environmental and paleoenvironmental data to produce the best possible reconstructions (with available data) for a given place and time (Bocinsky and Kohler [2014] provide a recent example). Temporally sequential visualizations overlaying macroregional-scale demographic or social data on landscapes cued with key paleoenvironmental indicators could foster new and important insights regarding possible correlations. The same environmental reconstruction tool, with appropriate visualizations, would prove invaluable to archaeologists and other scientists attacking a great diversity of questions. It would also provide an attractive avenue for bringing the results of archaeological research to the public.

Case Study 3: Long-term Urban Dynamics

Question*:* How can systematic investigations of prehistoric and historic urban landscapes shed new light on the social and demographic processes that drive urbanism and its consequences?

Infrastructure Focus: Modeling, Data Integration, and Visualization

As a settlement form, cities have been immensely successful since their initial emergence more than five millennia ago (Mumford 1968). Today, more than 50 percent of the world's population lives in urban settings, and the trend towards urbanization is expected to continue. Archaeologists can provide models of the long-term growth of cities that will be useful to modern urban analysts (e.g., Smith 2010, ed. 2012) and can illuminate human responses to both abrupt and gradual climate changes at a variety of spatial and temporal scales. Through methods such as simulation and visualization, such urban timelines can be significantly enhanced and strengthened.

This proposed study of urban dynamics entails comparison of the long-term stability and change in 20 or so ancient cities, from the Old and New Worlds, with and without historical records, and in diverse environmental settings. It will develop a Geographic Information System (GIS) that would track for each city, through time, (1) population; (2) areal extent; (3) the intracity distribution of different classes of architecture and artifacts; (4) the flows of materials into and out of the city; (5) environmental setting; and (6) climate.

The working group would include archaeologists, modelers, specialists on ancient climate and environment, and modern urban analysts/planners. The initial challenge will be to effectively integrate data from many cities over long periods of time in ways that can be sensibly compared. Both modeling and advanced visualization will be central to the task of disentangling complex human interactions through time and space. It will be important to relate periods of beneficial or negative environmental contexts with periods of stability and social change. Of course, we will need to look at both endogenous and exogenous sources of disturbance. When there are evident declines, we'll want to assess time lags and compare recovery rates, as well as to examine collapses. When possible associations are identified in the aggregate data, it will be important to have access to an infrastructure that will allow us to drill down to relevant subgroups and individual cases to refine our arguments.

Such a study might seem such an obvious thing to do that surely it must have already been done. Scholars have certainly compared ancient cities (Cowgill 2004; Marcus and Sabloff 2008; Smith 2012). Until recently, however, it has not been possible to work at this scale (with this many cities), nor has it been feasible to perform analyses and comparisons that rely so heavily on spatialized primary data. Ortman et al. (2014) showed that urban settlement in the Valley of Mexico in precolumbian times exhibits the same superlinear and sublinear types of scaling in relation to settlement size predicted by algorithms developed for modern cities by Geoffrey West, Luis Bettencourt, and their colleagues (Bettencourt 2013; Bettencourt et al. 2007; West et al.1999). Since this recommendation was developed, Michael Smith has initiated a substantial comparative urbanism study that is creating a strong foundation for the even more ambitious efforts of this urban dynamics working group.

Data Capture and Availability Recommendations

Data Access and Preservation. A key premise of our efforts is that better leveraging of existing data is essential to transformative progress in archaeology. Archaeological data are, and will be, most effectively maintained in a disciplinary data center or digital repository. Disciplinary repositories are able to maintain and use detailed archaeological metadata in ways that promote discovery and access, robust data integration, analysis, long-term preservation, and federation with related data sources (see below) in ways that would not be possible in institutional, museum, or more general-purpose repositories. While sustainable disciplinary repositories are in place (e.g., tDAR and ADS), the effectiveness of the synthetic efforts proposed here will depend in large part on the size and content of their data stores, as well as on research access to archaeological site inventories maintained by states and other jurisdictions.

The first task is to build digital content in relevant repositories; at present, digital data from only a miniscule fraction of academic or CRM projects conducted in recent decades are maintained in a digital repository. For a given set of research objectives, targeted legacy data (both data sets and documents) will need to be digitized and moved into a disciplinary repository. In addition, sponsoring or permitting agency mandates are needed to move documents and data, including contextual data, from *all* new projects into a disciplinary repository so that their irreplaceable information is preserved and available for future research. As central elements of the data infrastructure, disciplinary digital repositories need baseline support for operations, for long-term preservation, and for software development. As field data collection procedures move from partially to fully digital, the data centers will need to automate direct incorporation of these data streams.

As data in diverse forms (e.g., documents, images, databases, GIS) enter these repositories, vexing problems of data ownership will need to be confronted and solved in order that the results of archaeological investigations can be thoroughly shared as disciplinary ethics demand (Society for American Archaeology 1996), instead of being restricted—in principle or in practice—as matters of personal (or corporate) possession. In this task, it will be useful for the professional organizations and the repositories to work with agencies sponsoring or requiring the work to demand that documentation of the archaeological record be freely accessible to qualified scholars and archaeologists.

Make Available Key Data Sets. In addition to targeted legacy data sets, some data sources are so widely used that investment is warranted to incorporate or federate them so that they can be effectively used by many projects. These include data on the archaeological samples from the University of Arizona Laboratory for Tree Ring Research and chemical composition databases used in sourcing artifacts, such as the Missouri University Research Reactor INAA data and the Berkeley Geoarchaeological XRF Lab. To the extent that the data are not proprietary, it would also be tremendously useful to capture information from commercial radiocarbon and other laboratories. A challenge in all these cases will be to incorporate the contextual information needed to make the individual specimens maximally useful (which, in many cases, is not held by the relevant lab).

Data Integration. While tDAR provides useful data integration tools (Spielmann and Kintigh 2011) for structured data sets, we need data integration capabilities that are smarter and easier to use, and that can work with other sorts of data, notably data encoded in text. In particular, data integration technologies must be developed that incorporate analytical workflows that can track provenance and automate the exploration of alternative paths. The complexity of archaeological data and the complexity of the dynamics that we hope to understand will demand new social and computational technologies to empower the needed synthesis. While there is no turn-key solution for this complex integration problem, there has been a substantial amount of prior work on the integration, alignment, and mapping of databases (Halevy et al. 2006), taxonomies (Thau et al. 2008), and ontologies (Choi et al. 2006), to name a few. Semantic integration approaches (Bowers and Ludäscher 2004; Doan and Halevy 2005) and methods that combine data- and process-integration (Ludäscher et al. 2006) provide promising starting points towards realizing the vision depicted in Figure 1.

Interoperability and Federated Data. Archaeological research has involved multiple disciplines since the nineteenth century. In the ordinary course of research, archaeologists rely on such specialists as geomorphologists, climatologists, botanists, zoologists, demographers, physical anthropologists, statisticians, and geochemists, not to mention ethnographers, historians, and sociologists. In recent years, archaeologists have worked to systematically integrate this interdisciplinary research, rather than to relegate it to a series of appendices in final reports. These interactions remain essential for interpreting and understanding the archaeological record. Indeed, this dependency has only increased in recent decades. While it is not sensible to maintain worldwide topographic or climatological data directly in an archaeological database, it is important to be able to access those kinds of data efficiently. The answer is to federate, i.e., to effect interoperability of archaeological data centers with those of allied fields. A key step in this direction will be for tDAR to become a member node of DataONE (2014), a NSF-funded, distributed framework of repositories of observational data concerning life on earth and the environment that sustains it (Michener et al. 2012). Through that federation, archaeological data and knowledge at multiple levels of inference can be represented and exposed in ways that are useful for scholars in other fields. A particularly interesting aspect of the challenge of federating archaeological data is the need, in some areas, to integrate material typically considered part of the humanities rather than the sciences: art, architecture, history, and the like.

Cyberinfrastructure Tool-building Recommendations

Natural Language Processing. Enormous quantities of archaeological information and knowledge are embedded in often lengthy reports and journal articles. Gray literature and published reports are filled with data tables, descriptions, and interpretations of archaeological contexts and finds, but only a tiny fraction of these publications are digitally accessible. Capturing the information contained in these reports is essential because they often constitute the *only available documentation* of the excavation of important sites that are now thoroughly excavated, destroyed, or otherwise unavailable.

A substantial fraction of journal content is now available digitally through JSTOR and commercial services. The task of prioritizing, digitally capturing, preserving, and making accessible important legacy reports and the tens of thousands of reports generated annually is certainly daunting. However, the problems are primarily social and economic. We know how to do these things and have established digital repositories that do them effectively (e.g. ADS, tDAR, and DANS). And experience shows that, from a pragmatic standpoint, it is far easier to get the reports submitted and processed than it is to acquire and thoroughly document formal databases. Nonetheless, there is a huge amount of expensive work to be done. Although a start has been made on automated classification of articles (Jeffrey et al. 2009; Tudhope et al. 2011), achieving the necessary access to textual presentations of information in archaeology still represents a major challenge.

Beyond automated metadata generation, we must be able to discover and extract relevant data, information, and knowledge embedded (in complex ways) within archaeological texts. Google-like word searches will not solve this problem, especially for longer documents. Human indexing of even a small amount of this information is obviously not a realistic option. The development and application of sophisticated (computational) natural language processing capabilities will be essential for discovery, analysis, and synthesis. This will require extracting and representing information contained in the natural language texts in a formal knowledge representation language. Because key relationships among concepts may never be stated directly in words, the knowledge extraction will have to take into account the semi-standardized structure of these reports and relationships implied by the hierarchy of chapters and section headings. This extraction and query processing will further require inference from formally represented generic knowledge of archaeology. Relevant work is being done in computer science (Hackenberg et al. 2010; Tari et al. 2012), but the archaeological context offers some additional challenges.

Modeling and Simulations. Modeling is playing an increasing role in understanding complex systems, and modelers may be critical intermediaries in addressing transdisciplinary questions. Models, both simple and complex, will serve as key components of our inferential pathways at different conceptual levels. Both agent-based and dynamical models have proven useful in addressing more complex issues (Anderies et al. 2008; Kohler and van der Leeuw 2007), and models may require elaborate computational preprocessing to create inputs that also need to be reproducible.

With the tools available today, each model can be seen as the product of careful individual craftsmanship, and documentation is often incomplete or idiosyncratic. Provenance documentation of model parameters is one obvious and important task for cyberinfrastructure development. Different sorts of models interact with theory and data in very different ways, and it is important to better understand and describe the ways in which modelers and modeling efforts can best articulate with other components of the overall research agenda. Taking this a step further, an industrial-scale model development toolkit could automate many model-building tasks and facilitate sensitivity analyses, documentation, and assessment of alternative outcomes. Finally, as modeling plays an increasing role in research, we need to archive models and the data behind the models in appropriate repositories such as openABM (2014) and tDAR, respectively.

Recommendations for Social and Cultural Changes in the Discipline

Disciplinary Change. Social and cultural change in science occurs through several distinct but interacting mechanisms. Some changes are set in motion through the deliberate actions of science policymakers or scientific societies, while others are the result of collective social behavior in the form of scientific social movements. Still others are the emergent or serendipitous outcome of interactions that are difficult to predict. National science policy, in combination with the informal "science policy" efforts of professional societies, can set in motion the events that transform a discipline.

Technologies transform sciences. Major national investments in telescopes or observatories (including observatory networks such as the National Environmental Observatory Network or the Long Term Ecological Research sites) can transform their sciences by enabling measurements of certain sorts while excluding or defunding alternatives (Hackett 2011). Underlying the policies and the associated investments was a change in the conceptualization of ecological processes from something akin to natural history or plant sociology to something resembling the physical flow of matter and energy (Hackett and Parker 2015a, 2015b).

Place matters, too, and the qualities of place that matter arise through a combination of the unplanned social dynamics of scientists and deliberate social planning. The proposal that led to the funding behind the National Center for Ecological Analysis and Synthesis (NCEAS), for example, incorporated elements of previous plans from workshops and scientific societies. The small-group structure and dynamics of collaboration, shaped by organizational context and purpose, accomplish the transgressive or transformative science that is at the heart of any profound change in a scientific discipline. Trust, intimacy, emotional energy, and similar qualities of group interaction are vital in this process.

Science does not take place in a vacuum. Scientific inquiry is shaped and influenced by political, economic, and social events and processes. For example, energy exploration and extraction in the U.S. is transforming large regions, requiring federal land managing agencies to investigate and develop new ways of managing cultural resources that focus less on individual actions, such as constructing a well pad, fence line, or road, and more on programmatic landscape-scale approaches. Multidimensional predictive models of site location, drones outfitted with photogrammetric and remote sensing technology to identify and map archaeological resources, and digital-only site recording are discipline responses to competitive pressures to make the archaeological process more efficient and more accurate.

Finally, the process of doing science is also the process of creating the conditions under which science is done. Deeply innovative science may entail innovations in these conditions. Following the ecology examples, the promise of NCEAS and the faith demonstrated by this national investment were fulfilled through the actions of scientists and practitioners who, in the course of doing their work, were also engaged in organizing science, transforming culture, and enacting science policy.

Knowledge Structuring and Management. Investments are needed to support effective data extraction, preservation, sharing, and reuse. We must address standards and formats for knowledge representation and the development of ontologies, controlled vocabularies, and related information management tools. These investments will underpin and support many of the other recommendations presented here.

For some classes of data, standards are so well established that their use should be expected in any professional work. For example, the International Standards Organization (ISO) and Federal Geographic Data Committee (FGDC) provide spatial metadata standards (Federal Geographic Data Standards Committee 2014). The National Park Service (2014) is leading an effort under the FGDC umbrella to develop metadata standards for cultural resource-specific spatial data. In all cases, adherence to best practices in data collection and recording will lead to important gains in data usability. The Archaeology Data Service and Digital Antiquity have produced *Caring for Digital Data in Archaeology: A Guide to Good Practice* (2013, 2014), which provides excellent guidance.

While there is too much diversity in the archaeological record to recommend fully standardizing data collection and recording protocols, research efforts will be substantially enhanced to the extent that user communities follow standards that they, themselves, establish. In Europe, numerous standards efforts are in place or underway, including the CIDOC Conceptual Reference Model (International Council of Museums (2014). Internationally, the Arches Project is building "an information system … to inventory and manage immoveable cultural heritage" (Getty Conservation Institute 2014). In the U.S., the Digital Archaeological Archive of Comparative Slavery (2014) has done this quite effectively for an important research context. Communities may also develop and adopt analytical ontologies that will greatly facilitate the incorporation of legacy data in data integration and synthesis (Spielmann and Kintigh 2011 provide an example with archaeozoological data). We believe that, in many cases, useful standards will most effectively develop within research communities because the benefits will accrue most directly to those communities. Financial support for such user community efforts would move this process forward much more rapidly than would otherwise be possible.

Training and Community Development in Information Technology. For any infrastructure to be effective, the relevant research communities need access to training necessary to use it and, equally, must see compelling advantages to engaging with it. Research community development and training will have both sociological and technological components. It will need to address a range of needs, from those of students to those of established researchers and scholars. It will need to serve closely interacting research teams, institutions, and virtual research communities. Archaeology will need to establish a viable career track for archaeological information professionals. Training will undoubtedly include both graduate and in-service training, much of which may be accomplished online. Also needed are face-to-face programs that could connect archaeologists and computer scientists, perhaps modeled on the NSF Short Courses on Research Methods (QualQuant 2014) or the summer program of the Inter-university Consortium for Political and Social Research (2014). The current NSF-sponsored Spatial Archaeometry Research Collaborations project (Center for Advanced Spatial Technologies 2014) is a useful example. In this effort, highly experienced researchers, field instruments, and analytical software are available to research projects through a peer-reviewed competition. Successful projects expand their spatial analytical recordation and analysis capabilities, and their project staff and students receive on-the-ground training in these next generation skills.

Engage the Heritage Management Community. In the U.S. and many other countries, archaeological investigations are, overwhelmingly, conducted by CRM professionals responding to governmental mandates. A focus on defined, key research challenges—such as the grand challenges discussed above—provides the opportunity for academic and applied archaeologists to collaborate productively in ways that serve the public interest. By aligning research efforts with widely accepted research challenges, the results of archaeological compliance projects could directly inform issues of interest to the discipline and the public. The cumulative weight of individual project results would greatly enhance empirical support and broaden theoretical approaches, leading to synthetic statements that would not otherwise be possible.

Of course, research is not a one-way street. While data from CRM projects are being aggregated by teams addressing synthetic challenges, their results will provide applied archaeologists with a more focused set of research questions and data needs that can be incorporated into individual projects. Archaeological research can effectively progress on multiple scales simultaneously, from large-scale synthetic questions to site-specific ones. For archaeologists working in CRM, aligning their research with discipline-wide efforts will make their work more efficient, more productive, and, quite possibly, of greater competitive value.

Embedding shared research challenges within the current heritage management workflow is more a social than an archaeological problem. Sponsoring agencies and other stakeholders need to be convinced that utilizing these challenges will lead to more efficient and effective management of archaeological resources. Archaeologists working in heritage management will need to be convinced that work contributing to the challenges is expected by the sponsors and valued by the discipline. This outcome is best achieved through a structured dialogue among academic and applied archaeologists designed to find ways of recording and making accessible the archaeological data needed to address the grand challenges within current business practices. Cybertools that enable archaeologists to objectively distinguish levels of research significance in the archaeological record and to manage those resources better, as well as computer applications that allow the public to perceive the benefits of heritage studies through a better and deeper understanding of the past, will be essential to convince sponsors of the merits of making necessary changes in practice.

Recommendation of Development of an Archaeological Synthesis Center

Scientific synthesis is a process whereby data, concepts, and theory are combined in new ways to generate original knowledge and insights (Pickett et al. 2007). Although single researchers may attempt synthesis, teamwork greatly accelerates the process by focusing the diverse expertise of a broad array of researchers on a challenging problem. This is best accomplished at centers devoted to synthesis that provide a neutral location with access to the computational and analytic capabilities, logistical support, and spatial arrangements necessary for a team of diverse individuals to engage in open dialogue, to intensely explore and analyze data and concepts, and to make rapid progress on exciting questions (Carpenter et al. 2009; Hackett et al. 2008). Synthesis centers now exist for many disciplines; most are based on the model developed at the National Center for Ecological Analysis and Synthesis, a NSF center established in 1995 (Hackett and Parker 2015a, 2015b) .

Archaeology is poised to benefit from the creation of a center that would focus on synthesis of the plethora of data, concepts, and theories that come from archaeology and many related disciplines. Information about the process of synthesis now exists that can guide the creation of such a center. For example, analysis of NCEAS working groups demonstrated that productivity as measured by numbers of publications was most closely related to the numbers of meetings that a working group held, followed by the number of different institutions that participated in the working group (Hampton and Parker 2011). In addition to the physical place for supporting intense in-person working groups, an Archaeology Synthesis Center would, like other synthesis centers, need access to state-of-the-art cyberinfrastructure, including support for virtual meetings in between the face-to-face meetings. Informed by the experience of conducting the pilot projects proposed above, NSF should establish an Archaeological Synthesis Center.

AN INFORMATICS PERSPECTIVE ON THE POSSIBILITIES FOR ARCHAEOLOGY

In 2009 Tony Hey and his colleagues at Microsoft Research released a volume of essays titled *The Fourth Paradigm: Data Intensive Scientific Discovery*. It placed currently developing capabilities for a data intensive science research paradigm in the context of the great historical research paradigms, experiment (and observation) and theory, and more recently, computational science. The nature of archaeology is such that it can make only limited use of raw computational power unless that power is effectively harnessed to exploit archaeology's rich but highly complex data sources and models that respect locality and temporality. In this vision, the archaeology of the future will increasingly depend on linking modular simulations of diverse phenomena operating at widely varying scales with model predictions tested against the available material evidence. To validate our understandings of archaeological contexts and cultural processes it will be necessary to diachronically visualize and analyze the complex interactions of modeled individual and collective behavior with reconstructed built environments, ecological systems, climatic regimes, and similar structures. Where substantial documentary evidence survives, large-scale computational analysis of that body of evidence may provide key evidence to parameterize our models and simulations. Achieving such a vision will only be possible if archaeology and related disciplines embrace and push the state of the art in information and data management.

The other striking potential is for archaeology as an integrative science. The scientific challenges discussed here are all integrative challenges—they demand a multi-disciplinary response, and the integration of data and models from work in a wide range of disciplines. Yet someone needs to take the lead in developing the integrative framework for these contributions. As indicated above, the demands of such a framework can drive important research and tool development in computer science and informatics. However, the intellectual leadership to attack the substantive challenges will have to come from archaeologists creatively and intensively collaborating with scholars in many other fields.

CONCLUSION

Archaeological research results are essential to addressing such fundamental questions as the origin of human culture, the origin, waxing, and waning of civilizations and cities, the response of societies to long-term climate changes, and the systemic relationships implicated in human-induced changes in the environment. Today, archaeologists lack the capacity for analyzing and synthesizing large data sets needed to address these fundamental questions. Here, we have proposed investments in computational infrastructure that would transform archaeology's ability to advance research on the field's most compelling questions with an evidential base and inferential rigor that have heretofore been impossible. More precisely, these investments would enable both academic and applied archaeologists to participate fully and effectively in the transdisciplinary collaborations that will be essential. Achieving these research outcomes will also demand further development of organizational frameworks, such as a synthesis center, that can support these collaborations and enable them to succeed, to the benefit of archaeology, allied disciplines, and science and society more broadly.

We need to imagine and work toward an infrastructure of archaeology that not only would permit effective and ready access to detailed results of past investigations, but that would also empower synthetic research that is unthinkable at present. Although some recommendations will be expensive and difficult to implement, for others great progress requires only changes in policy or minor shifts in resource allocation. Implementing the recommendations offered here would dramatically improve and accelerate archaeology's ability to build reliable reconstructions of past societies, and it would transform our ability to contribute to compelling social science questions and to crucial debates on contemporary issues.

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