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ARTICLE

Current Key Intersections between Theoretical and Computational Archaeology

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Abstract

Computational archaeology and theoretical archaeology often appear as separate domains within the field, each driven by distinct methodologies and objectives. Through the lens of discussions held at the 2021 Central European Theoretical Archaeology Group (CE-TAG) conference and analysis of a follow-up questionnaire, this study explores the current trends and intersections between these areas to identify opportunities for meaningful integration. We highlight key challenges, such as the theoretical underpinnings of computer-assisted methods, the epistemological implications of data-driven approaches, and the need for open-science practices. Our findings emphasize the importance of mutual understanding and collaboration, particularly in research and education, in bridging divides and enhancing the synergy between these domains. By addressing shared concerns such as bias, scalability, and methodological transparency, we propose a framework for fostering innovation in both computational and theoretical archaeology while maintaining their shared goal of interpreting the human past.

Resumen

La arqueología computacional y la teoría arqueológica se presentan frecuentemente como dos ámbitos claramente diferenciados, cada una con sus propios métodos y objetivos. A partir de las discusiones mantenidas durante el congreso del Grupo de Teoría Arqueológica de Europa Central (CE-TAG) en 2021, así como de las evaluaciones de un cuestionario desarrollado al efecto, el presente trabajo explora las tendencias e intersecciones actuales entre las áreas mencionadas para identificar oportunidades de integración. Resaltamos los desafíos más importantes, como las derivaciones teóricas de métodos computacionales, las implicaciones epistemológicas de los enfoques basados en datos, o la necesidad de prácticas de ciencia abierta. Nuestros hallazgos enfatizan la importancia de la colaboración y comprensión mutua, particularmente en investigación y educación, para tender puentes y reforzar las sinergias entre ambos dominios. Enfocándonos en problemas compartidos, como los sesgos, la escalaridad o la transparencia metodológica, proponemos un marco de trabajo para fomentar la innovación tanto en la arqueología computacional como en la teoría arqueológica, manteniendo su objetivo común de interpretar el pasado humano.

Keywords: computational archaeology; data; open science; politics of science; theoretical archaeology

Palabras clave: arqueología computacional; data; ciencia abierta; política científica; teoría arqueológica

From the calibration of ^{14}C dates to the use of complex nested models for the prediction of archaeological sites or the modeling of past human–environment interactions, computer-aided methods have become commonplace in archaeology. In addition, there has been an increase in the use of scientific and quantitative methods summarized under the term "third science revolution" (Kristiansen 2014), resulting in a (big) data-driven approach to archaeology. The sheer presence of data and the new analytical possibilities enabled by the use of computers are fundamentally changing archaeological science (Kintigh et al. 2015). Similar developments have already had a major impact on the way knowledge is produced and understood in other disciplines across both natural sciences and the humanities. However, the use of data by each discipline varies based on its specific questions, data, financial possibilities, and history. The literature to date dealing with the relationship between computer-assisted methods and their embedding in archaeological theories and narratives has not yet succeeded in closing the gap created by the unsynchronized pace at which methods and theories are developing (Perry and Taylor 2018). It is sometimes claimed that the multitude of data and the new possibilities of evaluation make theoretical considerations completely obsolete and the interpretations to some extent self-evident and even that data can replace theory. One might think that death of archaeological theory is again being proclaimed or at least suggested (see also Bintliff and Pearce 2011). Yet, throughout the history of the discipline, archaeology has repeatedly drawn on anthropology, the humanities (Ingold 2013; Shankland 2020), and the natural sciences.

The very fact that, by using new methods, we are adopting new narratives from other disciplines demands an intensive examination of their theoretical implications. These methods may involve basic knowledge of regional geography; fundamentals of biological, anthropological, and social sciences; and the results yielded by enhanced statistical applications, making it difficult to gather and interpret expert knowledge in an interdisciplinary research design. This raises the question: What are the most important issues that theoretical archaeology must address not only to make the best use of the technical progress to date but also to stimulate further disciplinary advances and to provide answers to relevant research questions? Such considerations were raised as early as the 1960s, when the integration of new (often quantitative) methods and approaches in archaeology sparked a surge in theoretical discourse (e.g., Clarke 1968). In spatial archaeology, the advent of geographic information systems (GIS) in the 1980s and their proliferation in archaeology in the 1990s led to increased interest in landscape archaeology, settlement patterns, and the intrasite distribution of artifacts (e.g., Allen et al. 1990). By extension, encountering the limits of GIS applications in interpreting human perception and the use of space spurred on the development of experimental approaches, psychology, and phenomenology (Hamilton et al. 2006). Yet, many have concluded that the approaches of postprocessual archaeologies are similarly "scientific" in that they aim at reproducibility, replicability, and rigorous data analysis (e.g., Marwick 2017; VanPool and VanPool 1999). The extent and quality of the current changes that the discipline is undergoing require us to ask these questions again.

Our major goal here is to address these challenges and identify the trends and pressing issues both for archaeologists and for the wider scientific community. Building on the topics raised at the international conference on theoretical approaches in computational archaeology (CA) held in October 2021 in Brno (Czech Republic) as part of the Central European Theoretical Archaeology Group (CE-TAG), we discovered that there is, above all, a need for an epistemological discussion. At the same time, it has become evident that it is the concept of a "model" that represents a meaningful intersection of theory with quantitative and computer-based methods.

In the following, we explore the theoretical and methodological issues raised by the topics discussed at that conference and the results of a questionnaire circulated among academics and students. We conclude with a discussion of likely future directions for theoretical archaeology, which is challenged by computer applications, data, and quantitative revival, and of its possibilities and limitations.

Themes and Discussions

At the seventh annual CE-TAG meeting, we explored the theoretical potential of computer-assisted and quantitative archaeological research to contribute to modern and interdisciplinary archaeology. We focused on the last two decades, during which the use of computer methods and "Big Data" in archaeological research greatly increased. This development resulted in a significant shift in research on the human past and an increasing number of publications covering a broad spectrum of topics using methodical approaches that produced large datasets, enabling patterns to be found in their quantification (e.g., Lock 2003; Nakoinz and Knitter 2016) or applied (agent-based) simulation approaches (e.g., Barceló and Castillo 2016; Wurzer et al. 2015). At the same time, those involved in more humanities-oriented archaeology criticized these research approaches for disregarding potential theoretical connotations or even "dehumanizing" the discipline (e.g., Hodder 1991, 2012). It seemed as if the two camps were in conflict, mostly based on the "cultural emphasis" of one group and the "gloss-over-culture attitude" of the other. Yet, both research approaches can inform one another and are greatly needed to disentangle the multifaceted picture of the past (e.g., Ribeiro 2019). Indeed, the "third science revolution" in archaeology (Kristiansen 2014) should be defined by such collaboration.

We identified three major pillars of archaeological research, which were not restricted to computational approaches but rather build the shared foundation of most archaeological subdisciplines: (1) data management, concerned with the collection of large datasets facilitated by currently available tools; (2) implications for chronology; and (3) interpretive implications of computational approaches for understanding socioenvironmental interactions. This article's central question addresses how theoretical developments in the discipline can accompany, steer, and control the trajectory of methodological progress, and vice versa.

Relationship between Theoretical and Computational Archaeology: Questionnaire

To obtain a better overview of the most important issues, we conducted a survey a few months after the 2021 conference. In addition to collecting demographic data, it posed just one open-ended question to respondents: "*What do you consider to be the most important issues in computational and quantitative archaeology that need to be addressed in depth by theoretical archaeology?*" We deliberately kept this single question broad so participants could identify any themes, challenges, or opportunities they saw as critical—unconstrained by predefined categories. Additionally, posing only one substantive question helped minimize respondent burden and thus encouraged a higher completion rate.

The questionnaire was disseminated through the mailing lists of 73 institutions and nine professional associations; we received 121 answers. The returned questionnaires seemed to capture a fairly good cross section of the field in terms of age, gender, and academic status, although not surprisingly, scientists working in academia are overrepresented.

As shown in Figure 1, most respondents belonged to the 30–39 age group, indicating a majority were in the midst of an active professional and research life. There was a slight male majority (57.5%), whereas 37.5% identified as female, and a small number identified as gender variant or declined to specify. PhD holders comprised the largest educational group (62.8%), followed by master's graduates (28.9%), with fewer respondents at the bachelor's or professoral (or qualification) level. Reflecting the academic skew, 70.2% worked in academia, with students comprising another 9.9%; those working in museums, heritage management, and commercial archaeology each constituted about 3%.

Respondents were from 26 countries, with a clear bias toward those from Central Europe and Germany, in particular (Figure 2). The geographical dominance of Germany most likely reflects the extensive distribution of the questionnaire through German-speaking archaeology networks and the larger number of German-speaking and Germany-based scholars in Central Europe. It does not necessarily signify a disproportionately greater interest in theoretical issues or computer-aided archaeology among scholars based in Germany.

Notably, more than three-quarters of respondents considered themselves familiar with computational methods (78.5%) and connected to current theoretical debates (77.7%). About half (48.8%) had attended a specialized conference on computational archaeology within the last five years, and 37.2% had attended a conference on theoretical archaeology. Many also participated in events such as the annual meeting of the European Association of Archaeologists, the Society for American Archaeology, or the Union Internationale des Sciences Préhistoriques et Protohistoriques.

Sixty percent of respondents felt that the methods of computational archaeology and their application are not theoretically reflected sufficiently (Figure 3). This concern underscores the central motivation

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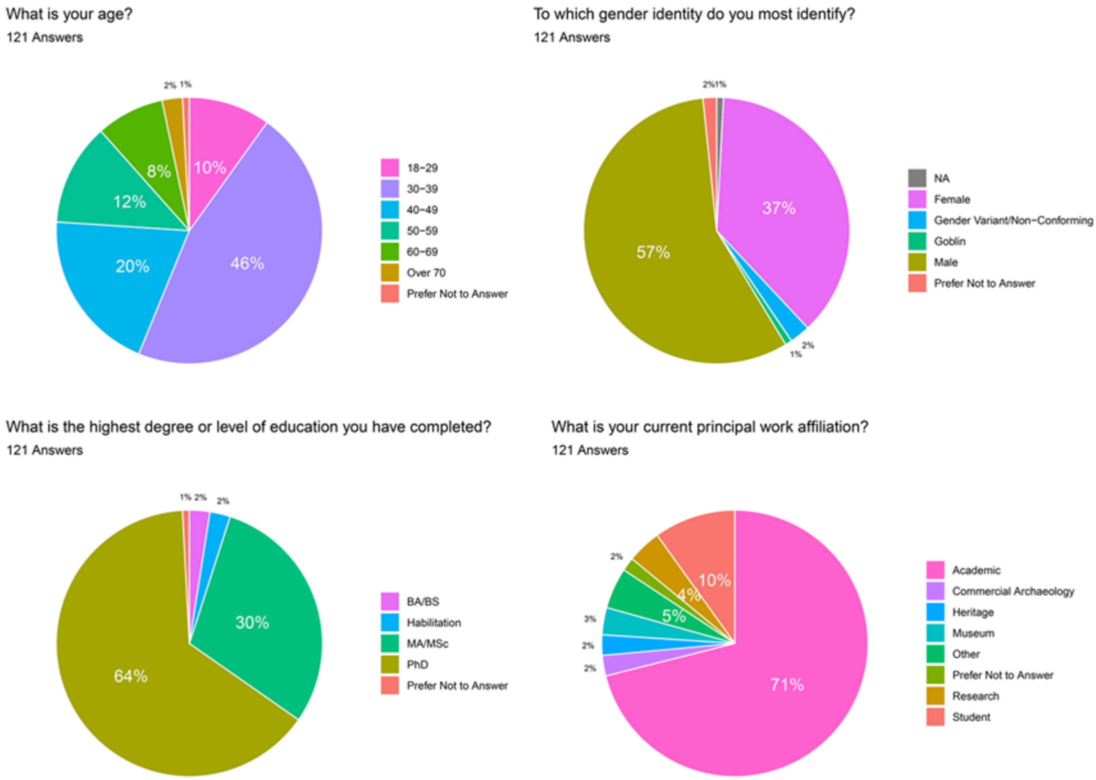

Figure 1. Demographic composition of the survey respondents, based on questionnaire data.

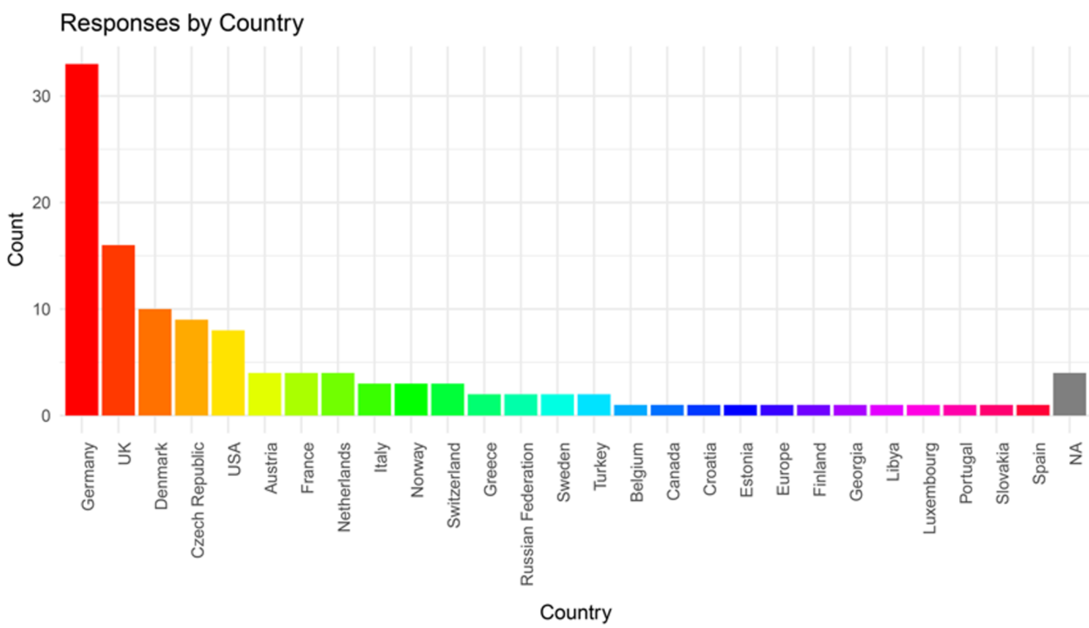

Figure 2. Geographic distribution of survey respondents, as reported in the questionnaire.

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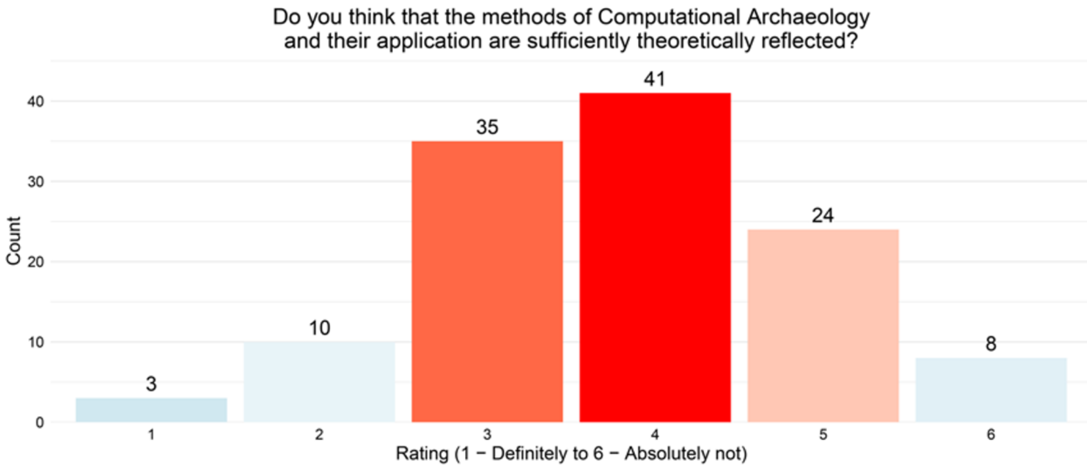

Figure 3. Ratings of theoretical reflection on computational methods in archaeology. Rating ranged from 1–Definitely to 6–Absolutely not.

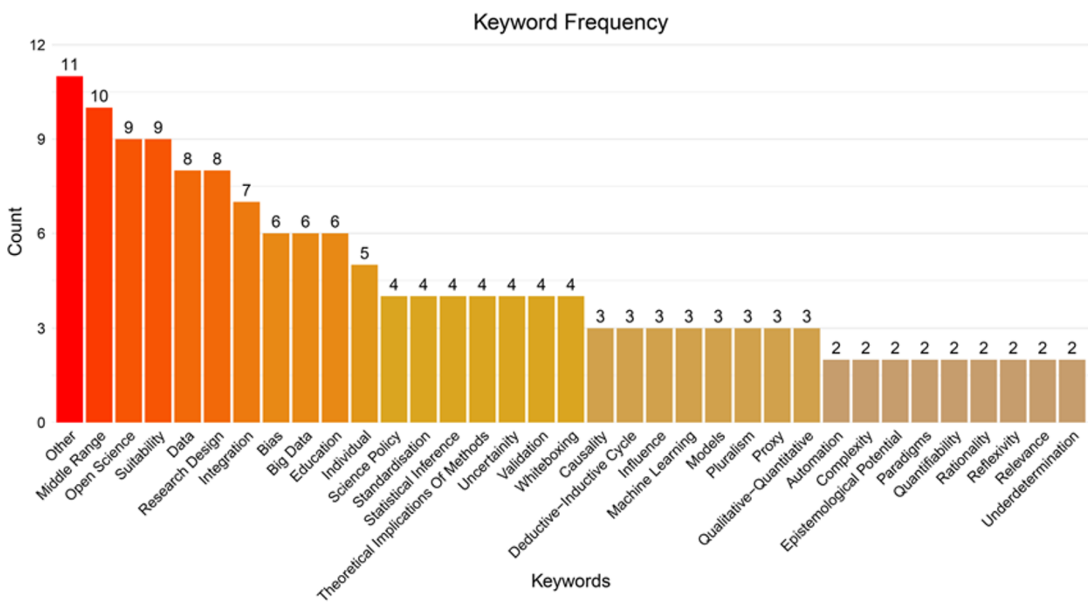

Figure 4. Number of responses pertaining to different topics (e.g., open science, ethics, reflexivity), illustrating the variety of fields where respondents see a need for stronger theoretical engagement with computer-assisted methods.

behind our study: to investigate how theoretical archaeology can better engage with the expanding domain of quantitative and computer-based approaches.

From the single open-ended question, we received a diverse array of responses, varying in scope and specificity. To manage this breadth, we coded the submissions using keywords (Figure 4) before categorizing them into overarching themes (Figure 5).

To do so, we employed an iterative, hermeneutic procedure. We began by reading through all the responses in full, noting any clearly articulated themes that emerged. Each distinctly expressed topic was assigned one or more keywords, and more ambiguous answers were coded with best-fit keywords or—when existing ones did not apply—assigned new keywords that captured the underlying ideas. In some cases, participants wrote minimal or nonsubstantive comments (e.g., “I don’t know”), which we categorized as NA. Answers raising unique or idiosyncratic points were tagged as Other.

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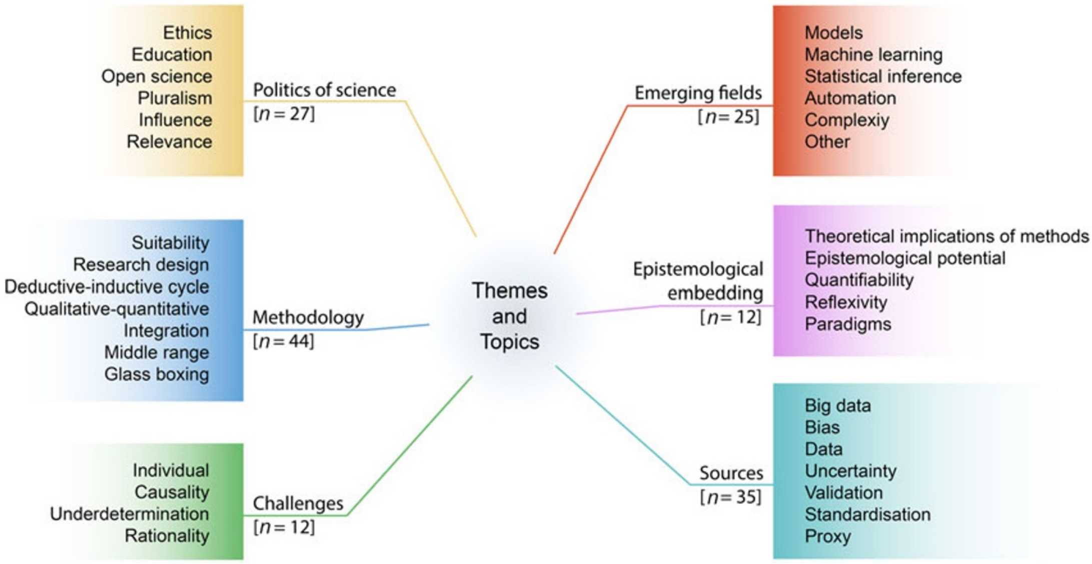

Figure 5. Categorization of responses to the single open-ended survey question, illustrating how we grouped them into overarching themes (e.g., methodology, data, politics of science). Each theme's frequency reflects how many respondents mentioned related issues.

After developing a preliminary set of keywords, we organized them using a mind map, grouping together semantically related or overlapping concepts. This visualization helped us see which topics co-occurred, which ideas clustered around one another, and where gaps existed. We then refined the keyword list to better reflect all identified topics and applied these updated keywords to responses that had not yet been accurately categorized. Finally, we aggregated the keyword groups into a set of overarching themes—providing a coherent framework for subsequent analysis. In the next several sections, we explore these themes in detail, incorporating individual feedback to highlight key insights.

Politics of Science

By "politics of science" (Figure 5; keywords: ethics, education, open science, pluralism, influence, and relevance), we refer to the broad factors shaping archaeological research and its position within wider academic and public spheres. Traditionally, such concerns have been explored within theoretical archaeology. Yet the politics of science is also deeply intertwined with everyday research practice when funding bodies may be nonspecific or stipulate, for instance, open-science principles.

Open science emerged as the most frequently cited topic. Respondents emphasized the importance of free access not only to publications and data but also to reproducible research workflows (Marwick 2017; Marwick et al. 2017). In some cases, the responses simply named this topic (and often exclusively) as *the* most important issue. These answers underscore the value of theorizing the preconditions and effects of open dissemination: Which initiatives genuinely improve scientific knowledge, and how can ethical and practical barriers—such as protecting sensitive site coordinates—be managed? Although these discussions reflect archaeology's broader embrace of global open-data trends, they are especially salient in computational work, where the reproducibility of complex analytical pipelines greatly depends on transparent methods.

Education was another leading issue, given that the proliferation of computer-assisted approaches demands broader digital literacy. If theoretical archaeology is to guide the application of these new methods, coding skills and critical reflection on algorithmic assumptions must become part of basic archaeological training (Marwick et al. 2020; Scherjon et al. 2019). This need is intensified by the recent public adoption of AI tools such as generative large language models (GLLMs), which are tools trained on massive text data to produce human-like text responses. Although it remains unclear whether

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GLLMs will most affect computational workflows or interpretive practices, several scholars (Cobb 2023; Tenzer et al. 2024) predict a growing focus on digital literacy so that professional expertise can counter superficial analyses, outdated narratives, and potential "hallucinations." Moreover, AI alignment issues—training algorithms toward specific research goals—could demand new ethical and theoretical frameworks, especially as archaeology grapples with large, potentially skewed datasets (e.g., Casini et al. 2023).

Turning to *ethics*, participants highlighted resource inequalities (gender, funding, infrastructure) that can limit who benefits from computational tools. Collaboration offers one remedy: sharing not only data but also computational resources can help offset disparities, although such initiatives must integrate open-science safeguards to protect sensitive archaeological data.

Similarly, discussions of *plurality* (*multivocality*) reflected concern that quantitative methods might perpetuate Western scientific paradigms in the sense of foundational paradigms (Clarke 1968); respondents asked how to include alternative epistemologies and whether contradictory analytical results can coexist in a more inclusive interpretive space.

Although fewer in number, responses on *influence* and relevance noted that digital methods have the potential to reshape archaeological questions and interpretations, often having broader impacts than immediately obvious because of the ubiquity of digital and computer-based processes; for instance, 3D technologies may affect how artifacts and sites are presented to the public, or macro-archaeological research may catalyze dialogue with other disciplines (Perreault 2019). The underlying challenge is to ensure that these shifts promote deeper collaboration rather than reinforce existing biases. Indeed, the long-standing tradition of archaeology contributing "interesting problems" (e.g., seriation) to other fields suggests there is potential for truly bidirectional exchanges—but also for unintended oversimplifications.

Overall, the politics of science aspect reported in our survey highlights a dual imperative: harnessing the momentum of open science and digital advances while maintaining caution about ethical, educational, and plurality concerns. For computational archaeology, this means consciously embedding theoretical reflection at every stage—funding, data collection, analysis, and dissemination—to preserve archaeology's nuanced view on the human past.

Epistemological Embedding

Computer-based methods shape, limit, and guide archaeological research. Survey responses emphasized that although digital tools can greatly enhance scholarly inquiry, they also necessitate explicit theoretical reflection—an aspect often overlooked.

A recurring theme was reflexivity, also in the sense of the *implications* of using computer-based methods. For example, Perry and Taylor (2018) advocated for integrating critical self-awareness into digital workflows, thereby encouraging the use of methods that foreground introspection and iterative critique.

Another focal point concerns *paradigms*, the ways in which existing theoretical frameworks are translated into and sometimes reshaped by computational analyses. These ways can be demonstrated by visibility analyses. They were designed around the importance of visual perception for both social interaction and individual understanding of the world (Gillings and Wheatley 2020). It could also be argued that the availability of computers played a decisive role in the development of processual archaeology or GIS for landscape archaeology in the 1980s and 1990s (e.g., Allen et al. 1990; Clarke 1968).

Quantification is a prerequisite for computer-assisted methods. Participants questioned the extent to which quantification is feasible—or desirable—when dealing with complex cultural phenomena. Technical solutions, such as fuzzy logic that handles partial truths beyond simple binary true/false categories, semi-quantification, or data aggregation/assimilation that merges newly collected observational data with computational models to refine or adjust existing prediction all help in addressing ambiguity, yet their theoretical legitimacy still demands scrutiny.

Finally, the limits and possibilities of the *epistemological potential* of computational archaeology emerged as an overarching concern. One extreme insists that everything is quantifiable—viewing computers as able to tackle once-intractable problems—whereas those holding the opposite position contend that core aspects of human life lie beyond statistical description. Striking a balance between these views requires a systematic appraisal of computational methods.

Methods

Most responses focused on concrete research practices and emphasized four topics—middle-range theories, suitability, research design, and integration—alongside considerations of transparency, inductive/deductive approaches, and qualitative/quantitative interplay.

Aspects of *middle-range* theories were mentioned frequently. Survey participants often emphasized the need to link theory with data and application through mid-level frameworks (Arponen et al. 2019). Machines only execute precise instructions, so well-articulated mid-level concepts become critical in bridging broader theory and specific computational tasks. A telling case is Verhagen and Whitley's (2012) emphasis on the complexities of using middle-range theory in predictive modeling. Although they see considerable value in linking interpretive notions, such as population pressure or territorial claims, to cause–effect relationships, they caution that translating these into formal model parameters is far from straightforward. In particular, uniformitarian assumptions about how past societies used landscapes can be difficult to uphold, and observational biases pose obstacles to validating theoretical constructs. Thus, the real challenge lies in operationalizing social and cognitive processes, an endeavor that, when explicitly tackled, can yield more robust, truly theory-driven models.

Suitability of data, methods, and parameters was the second-most frequently mentioned issue, which included aligning the scale of the data with the research question. In archaeology, which bridges the humanities and sciences, our data are physical and material, with their meaning emerging only through specific questions, evaluation, and interpretation. Therefore, it is essential to use methods and data from the outset that are truly suited to answering research questions originating from the humanities-focused aspects of archaeology.

The responses summarized under the topic of *research design* follow a similar direction as those regarding suitability. In the field of computer-aided methods, in which entire conferences can revolve around the topic of the most appropriate cost surface calculation or other GIS-based tools, central archaeological questions are potentially sidelined. There is also the danger of creating undue simplifications. Overly simplified models risk oversimplified narratives, yet excessive complexity can obscure relevant correlations. Certainly, good examples of both can be found in the current aDNA discussion and the evaluation of principal component analyses of genetic patterns (Slatkin 2016). Questions must therefore be well formulated, and the main aims of the research must be clear before the appropriate methods are chosen.

Another cluster of responses called for stronger *integration* across disciplinary boundaries, such as uniting archaeology, the paleosciences, and sociocultural anthropology. Evolutionary archaeology was mentioned as a field in which theory effectively intertwines with computer-aided methods and quantification. The incorporation of methods from other disciplines has led to increasingly specialized sub-archaeologies, including archaeo-informatics, that risk becoming siloed. Theory-based research could make a more concerted effort to fold them into mainstream archaeological discourse.

Still another key theme was overcoming "black-box" approaches by *glass boxing*: fully disclosing methods and assumptions. Yet transparency alone does not guarantee broad understanding, because specialized knowledge is often required to adequately critique complex software or statistical routines. Using push-button analytical tools without critical theoretical engagement clear influences how data are handled and how they lead to an interpretable result; for example, various GIS or statistical methods at first glance produce results that are easy to interpret visually, but the whole analytical procedure may not be fully understood by every team member. Achieving genuinely "glass-box" practices may require better training, shared vocabularies, and active engagement between technical specialists and theoretical archaeologists.

Finally, respondents noted that bridging *deductive/inductive* or *qualitative/quantitative* divides remains an ongoing challenge. How can data be transformed into information, and how can qualitative

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statements be extracted from quantitative data and these transformed into relevant narratives? Although quantitative data can always be "downscaled"—for example, through classification—it is more important to generate relevant qualitative data than to merely relabel numbers.

Sources

Quantitative and computer-assisted methods often lack the built-in uncertainty that is tied to qualitative or traditional interpretations. Because data are frequently used verbatim, attention to data quality, character, and validity is crucial (35 responses to this aspect made it the second-most mentioned topic after methodology). To prevent overinterpretation, theoretically supported buffers must be deliberately incorporated.

The most obvious and most frequently mentioned aspect within this topic area is the *data* itself. Managing and representing data emerges as a central concern, parts of which we already discussed. A genuine archaeological challenge is handling time-related data, notably how to integrate absolute and relative dating: this is an area where theoretical archaeology could offer valuable insights. An issue relating to research design is how data collection predefines investigations. Much of our data are nominal, representing existential quantification (∃x). As one respondent remarked, "*Data does not speak for itself, only in the context of scientific practices*." A specific archaeological data theory essentially specifies a general information theory. Translating general principles into field-specific necessities appears to be a desirable goal, as inferred from the responses.

Recent shifts in archaeological practice have prompted discussions about Big Data, partly spurred by Kristiansen (2014) but also reflecting an ongoing transformation in archaeology. Although the term (De Mauro et al. 2015) may not perfectly fit the archaeological record, it can apply when large spatial datasets or varied types of data accumulate. Most survey responses simply named Big Data without specifying its pitfalls, yet one warned that broad-scale analysis may gloss over environmental and cultural variability. Here, the evaluation of massive datasets, not just their size, becomes the real challenge. After all, our research can be conducted easily on a multiscalar basis (e.g., Bevan and Conolly 2006; Hodos 2022).

Both big and not-so-big data carry *biases* from the way information is collected, processed, or distributed, which was the topic of six responses. Again, most answers simply mention this issue without much explanation. One response mentions both algorithmic bias and training data bias. This points to the fact that all evidence (inductive) is a basis for hypothesis generation and testing (deductive), so that any bias is always in the end driven by data. The response "*bias through data and narratives*" highlights this. Finally, the reference to "*research bias including differential access*" emphasizes that an unequal bias landscape also results from an unequal research landscape. We assume that the best way to minimize these biases is to compensate for such inequalities through sharing information, discussions, and academic exchange. Theoretical archaeology can help us scrutinize these blind spots and propose more equitable practises.

Validation refers to the inductive–deductive cycle and the use of "*subsequent field/material data*" to review the "*results of computational methods*" and the "*validation of models*." In this way, the "reliability" of CA may be verified. It is useful to distinguish at least two levels of validation: (1) verifying that a given computational pattern or correlation is indeed present in a dataset, something that can often be established with a high degree of certainty through defined technical procedures and providing the means to reproduce the respective analyses, and (2) judging whether a specific interpretation or explanatory model accurately captures the social, cultural, or historical phenomena in question. The second level can run into "absolute truth" issues, because interpreting complex human behaviors rarely permits final proof. Instead, we can ask whether a model or interpretation is useful, robust, or consistent with known evidence in a given research context (Dewey 1941:178).

Uncertainty in models and data is perceived as another problem. Obviously, uncertainty must be considered when using statistical and computer models. But is there a need for a general theory of uncertainty in archaeology that goes beyond quantitative approaches? Is it even possible to develop such a theory?

Standardization is one way to mitigate some of the uncertainty by making decisions about classification at the time of data recording, rather than after data collection. However, doing so can

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risk oversimplification. The researcher's primary task is to translate complex reality into scientifically manageable information, inherently simplifying it. The increasing volume of data from excavations and investigations tends to delay these necessary decision-making processes. As scientists, we are expected to make such—often imperfect—decisions and thereby to make data available for higher-level analyses. At the same time, multiple or coexisting standards can reflect a healthy multivocality, in which region-specific practices or different theoretical perspectives and research questions shape classification systems. Rather than forcing a single uniform standard, archaeology could benefit from developing robust interfaces (e.g., interoperable ontologies) that allow diverse standards to communicate with one another. It would be preferable to implement classifications and standardizations upfront while building in pathways for translation between alternative systems and providing the scientific community with the means to critically evaluate these decisions. Focusing on practical aspects of standardization—such as data formats and thesauri—is only secondarily a theoretical consideration. Every decision regarding standardized documentation affects how information is made available and becomes data for further analyses. Therefore, any standards we adopt should be explicit and transparent to enhance the reliability of the data (Reiter et al. 2024).

Proxies (and by extension nominal indicators) were mentioned only a few times. This surprised us because, in our opinion, all the archaeological data are just proxy information. We suggest that the goal of archaeological research lies beyond counting and categorizing finds and features—and for all questions beyond that, the material remains represent nothing more than proxy data. Even though nominal indicators may seem more discrete than proxies, both serve to bridge interpretive theory and measurable evidence. Therefore, we consider a theory of proxies (and indicators) as a very important field of activity, possibly going far beyond what is commonly used and understood as a proxy in archaeological practice.

Challenges

It is true that accomplishing all the possible tasks discussed so far is a considerable challenge for both theoretical and computational archaeologists. However, there are specific areas, or possible assumptions and conditions of these procedures, that make them particularly challenging. Therefore, we group together 12 responses that address specific challenges.

One of these concerns the role of an *individual* within large datasets, the possibilities for subjecting individual social actions to quantitative analysis, and how to avoid treating exceptions or "outliers" as mere noise. Appropriate approaches to these specific questions do exist. Examples include agent-based models (ABMs) and simulations that focus on the actions of individuals as agents to assess their effect on the system as a whole ("emergence"). Theoretical questions here may be whether these approaches are sufficient, what other approaches need to be considered, and how they could better contribute to the understanding of human behavior.

A second challenge is *causality* or *determinism*. Although it is widely accepted that all historical processes are multifaceted, many archaeological explanations still reduce events to a single, overarching cause. Computational models exacerbate this tendency if they force complex phenomena into simplified causal chains. Balancing the need for a workable model with the inherent multiplicity of the past remains an ongoing dilemma.

A closely related issue is *rationality*, reflecting the frequently invoked assumption that humans act on the basis of complete information and clear incentives. In archaeology as in other social sciences, that people always act logically or economically should represent a baseline or reference model, rather than a blanket claim. In other words, rational models ask, "What if past agents were guided purely by cost-benefit thinking?" and then compare the outcomes to observed patterns. Such models can be useful starting points for exploring deviations from an idealized scenario. It is also important to distinguish between formal/logical rationality (i.e., internal consistency of decisions) and "reasonable assumptions" (e.g., treating humans as cost optimizers); sometimes economic theory uses those assumptions as an axiom. In reality, social or symbolic motivations can override purely economic decisions, leading to settlement patterns that defy cost-based predictions. Such discrepancies underscore the importance of incorporating cultural contexts into computational frameworks.

Finally, *underdetermination* was explicitly mentioned twice. This term is now primarily linked to temporal and spatial scales, where the processes that should be recorded and reconstructed must match the resolution that we can achieve with our sources. After the original publication (Perreault 2019) calling for a focus on large-scale questions and the analysis of large-scale data, it is certainly more of an encouragement to pursue CA more intensively. But is such a—perhaps naïve—statistical evaluation of timespans encountered in archaeological practice theoretically viable? A discussion of the topic of underdetermination can also include examining the extent to which it exists at all and can be determined.

Emerging Fields

The last overarching theme comprises emerging areas stemming from computational approaches and quantitative inquiry, along with a few "other" topics mentioned only once. We argue that such topics can potentially represent the major mainstream topics of the future.

Statistical inference was mentioned most frequently. Some respondents called for reducing the emphasis on visualization and incorporating more rigorous inferential statistics; another named the interpretation of *p*-values. The latter is currently being discussed in applied statistics in general (most recently, see Courtenay 2024); from the archaeological point of view, it would be interesting to evaluate *p*-values with regard to the negative evidence in the archaeological record. Approaches that go beyond traditional *p*-values, such as Bayes factors and simulation-based significance tests, offer potentially richer insights. Bayes factors, for instance, enable the direct comparison of competing models, helping archaeologists weigh different interpretive frameworks (e.g., a cultural vs. environmental explanatory model) in light of the data's likelihood under each scenario. Likewise, simulation-based methods, widely used in spatial or point-pattern analysis, can incorporate domain-specific factors like taphonomic processes, biases in site detection, or uneven sampling intensities. By generating many synthetic datasets under varying assumptions, these tests compare observed patterns to distributions that account for archaeological realities. Such tools move beyond binary "significance" to illuminate how well each model aligns with the underlying archaeological record—and they can better capture the uncertainty inherent in complex, fragmentary data.

From our perspective, *models* were mentioned surprisingly infrequently, with only three references. The tasks identified with regard to theory were conceptualization and validation, as well as the fact that (independent) models are suitable for establishing the link between archaeological patterns and causal processes. Providing that link is precisely where we see the strength of models: their ability to mediate the close relationship between theory and data, between deduction and induction, and between high- and low-level hypotheses. Previously, the use of models was much more widespread, particularly within processual archaeology, but archaeological theory moved away from them. This shift most likely occurred because many epistemological tools are not perceived as models at all, even though they are precisely that (Clarke 1972; Nakoinz and Hinz 2015). Therefore, models provide an excellent starting point for a deeper theoretical investigation of computer-assisted and quantitative archaeological practice.

Machine learning using algorithms that identify patterns in data received the same number of mentions as models in our survey. Many research and heritage practices—in archaeology, for example, the location of potential sites using remote sensing tools (e.g., Argyrou and Agapiou 2022) or the classification of archaeological objects (e.g., Korokhina 2024)—are currently being revolutionized. The AI boom will also create a surge in advanced machine-learning approaches. Before using those approaches, it is necessary to develop a theorization at an early stage before it is surpassed by reality. The supposed objectivity of machine-learning methods needs to be questioned from a theoretical point of view (Tenzer et al. 2024), as does the bias in the archaeological data itself. The same can be said about *automation*.

The final topic that was mentioned more than once is *complexity*, often framed as an antidote to deterministic narratives. Complexity research recognizes emergent phenomena as facts and is thus well suited to archaeological research. Another facet is the complexity of archaeologically observable past societies and of the conditions and effects of their emergence (e.g., Daems 2021). However, its core assumptions also demand careful theoretical and methodological grounding within archaeology.

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Finally, a range of other topics—including aDNA, navigation theory, Bayesian statistics, and multimaterial additive manufacturing—reveal the extensive domain in which computational archaeology now operates. Although many originate from other disciplines, archaeology's theoretical frameworks must adapt to—or critically evaluate—such specialized innovations. The widespread sense that some questions remain "theoretically underdeveloped" underscores a collective desire for more explicit reflection on the interplay between novel methodologies and long-standing archaeological aims.

Summary

Questions concerning methodology, sources, and data were considered to be the most important. In absolute terms, various aspects of middle-range theory, suitability of methods, data, integration, and research design stood out. In the area of the politics of science, open science was the topic most mentioned. Next were issues about bias, Big Data, the individual, and education. All other aspects mentioned were represented in the third order with a maximum of four mentions. Although the research efforts of many computational archaeologists are theoretically very well informed, theoretical archaeology can significantly contribute to many areas of computer-assisted and quantitative archaeology.

Key Intersections for Computational Archaeology

The answers to our questionnaire and the final discussion during the seventh CE-TAG conference identified some practical actions researchers may take to explore and engage with the interface between theoretical and computational archaeology. We were able to identify commonly shared—and, for sure, proclaimed—shortcomings currently connected to CA. However, we are also convinced that there is no reason to abandon or reduce the endeavors associated with computational approaches; instead, we should engage more, especially on the theoretical level, with CA because of its potential to reveal knowledge about the past. We, however, are not calling for a simplistic union between theory and computational approaches in archaeology, even though the building of bridges between the two is widely advocated. However, we can identify several pathways that may help us lay foundations for integrating CA better in current theoretical research and for formulating strategies on how to improve communication and mutual understanding between archaeologists working with and without advanced computer-aided methods.

What More Has Computational Archaeology to Offer?

CA is well integrated into archaeological research and, from a certain perspective, currently seems to dominate the field: most archaeologists use some kind of computer applications, and many investigations are not feasible without the use of computer-aided techniques ranging from documentation, both in the field and labs, to data analysis and visualization. We are also convinced that CA can grow in its responsibility and abilities to handle the current "grand challenges" of archaeology (Kintigh et al. 2014) while not losing sight of the need to reflect on the epistemological embedding of its methods, applications, and the politics of science.

One of the advantages of CA is its potential to bridge the gap between quantitative and qualitative research approaches and scales: critical and reflective approaches based on sociocultural anthropological standpoints should be integrated into CA, given its general openness toward any kind of datasets and its wide range of methodological possibilities (Perry and Taylor 2018). For example, anthropological understandings of kinship can be integrated into collections and analyses of aDNA datasets (e.g., Brück 2021), and reflective thinking can be incorporated into the premises used for ABM (e.g., Wunderlich and Laabs 2023). The potential to connect different levels of scale that we observe in CA is thus linked to the potential to connect different disciplines.

Another important aspect is that archaeology ultimately finds evidence in patterns of material culture distributions. For example, CA is frequently used in spatial analysis to find and highlight statistical patterns and distributions that provide information on past spatial use (e.g., Gillings et al. 2020). Computational methods may extend the interpretation of data beyond assessing the validity of results and the potential "strength of signal" suggesting patterns of spatial use: one could also use that data to recognize and understand a change in human behavior and to determine to what extent present-day archaeological views on change may align with those of past peoples (Crelin 2020).

Conversely, there are multiple ways in which theories and theoretical approaches can be integrated into quantitative approaches of CA. We agree with Perry and Taylor (2018) that theoretical approaches that focus on the reflections of one's self, one's data, method, or the ideology of a given scientific paradigm should play a far stronger role in CA than is currently the case. After all, quantitative approaches need to be backed up and reflected on by qualitative data and theoretical approaches. Hypothesis-generated research questions must lead to an investigation seeking to answer it, which means engaging in the deductive–inductive cycle. Computer-based quantitative studies should be question driven and thus theory driven.

Open Science

Open science (OS), as already mentioned, is becoming essential and in archaeology must also include the theoretical considerations that lead to interpretations and narratives. However, it is strongly linked to the digitalization and computerization of science in general (Science Europe and German Research Foundation 2018), and its principles (Open Science 2023)—open methodology, open source, open data, open access, open peer review, and open educational resources—do not necessarily cover the need to open up the theoretical part of science. This may be sufficient for many natural sciences that are based on the "scientific method" per se and do not follow any specific or only generally accepted schools of thought. They may also have less need to think about the epistemological foundations of their scientific methods, because humans as acting subjects are less central to their work.

This is not true for humanities nor for archaeology. To make sense of the material remains we excavate and to turn them into knowledge, we need a whole chain of data transformations before we can infer human action. This chain of inferences must necessarily use deductively constructed top-down assumptions that we must use as gap fillers. Of course, the openness about theory can be redundant and need not be formulated anew in each publication, but the basic models that play a major role in one's own research agenda should be stated. In our effort to make sense of the past, we deal with uncertainty not only in data analysis but also in those basic models we employ. Therefore, we need to make our middle-range theories explicit.

Of course, CA is strongly involved in pushing novel agendas into archaeology, which requires analytical procedures and datasets to be explicit and available. CA has the possibility to be a role model in archaeological science and open many existing black boxes. It should also be a role model for collaboration, transparency of methodology, data sharing and accessibility, as well as good and reproducible scientific practices (see also Perry and Taylor 2018). Because CA studies might be under suspicion of skewing data and using methods to produce results that fit initial research questions and narratives, many of them already follow the ideas of OS and publish their datasets and methodology following the rules for reproducible research. This is demonstrated, for example, by the ever-growing list of papers using and publishing R code in Ben Marwick's "CRAN Task View: Archaeological Science" (Marwick et al. 2022). Archaeology would benefit from adopting most OS principles, because the preparation and processing of most archaeological data are of central importance, whether advanced computational methods are used or a written description is the result. A task for a theoretically oriented CA (or a CA-oriented theory) would therefore be to devise ways to reveal precisely these theoretical foundations in the same manner as is evolving today with the methodology of analyses.

In terms of practical implementation, a range of open-science guidelines, platforms, and tools already exist to help archaeologists make their work more accessible and reproducible. For instance, the Open Science Framework (OSF) offers free, versioned hosting for data, code, and project documentation. "The Turing Way" provides a broad-based handbook on reproducible research in data science, which is largely adaptable to archaeological workflows. Open Context and the *Journal of Archaeological Data* offer curated, peer-reviewed data sharing specifically for archaeology, and Marwick et alia's (2017) discussion of OS practices in archaeology and the "CRAN Task View: Archaeological Science" (Marwick et al. 2022) demonstrate how reproducible code and data can be integrated into research design.

Caution Is Needed

What became clear in the survey results is that CA is perceived as being a field that tends toward positivism and believes in the superiority of ever larger datasets and smarter algorithms. There is some truth to this view. However, we must also remember that often the data itself and the theoretical model associated with it inspire the notion that any data analysis must lead to significant results and that the more sophisticated the method used for data analysis, the more credible it is. It therefore seems necessary to promote processes for evaluating and validating the data and theories, as well as the methodology used. This applies to both quantitative and qualitative approaches, as well as to research projects conducted on a large or small scale. Bias cannot be eliminated in any kind of archaeological research, but it is equally present in quantitative and qualitative approaches.

Developing a Common Language

Something that should unite all archaeologists is the desire to create a representative image of past societies based on our most up-to-date knowledge, regardless of the spatial or temporal extent of the past under investigation. This may be more of an ideal than a reality, but it should be an ideal that most of us agree with. To achieve it, we use all kinds of archaeological data and transform this information into a narrative using different methods and theories.

Archaeology is a discipline that engages in many ways with issues of multidisciplinary and public interest. As such it needs to seek a common language with experts from different disciplines, as well as the public. Researchers and other members of academia who are actively involved in continuous education can approach a common language through education. Common vocabularies can be developed and shared through the educational systems offered by universities, and the extensive possibilities offered by summer schools, online tutorials, and online courses provide a basis for developing increased understanding between researchers from different disciplines. Despite the opportunities that arise from shared understanding, consideration must be given to the obstacles that stand in the way of sustainable implementation.

The teaching of archaeology at universities covers in most cases a wide range of necessary topics and competences, and it would be unrealistic to expect every single institute and department to offer an extensive range of courses specifically on CA and archaeological theory. Yet, basic knowledge in both areas should be firmly anchored in the undergraduate curricula. As Garstki (2022) points out, a study program should challenge digital and other archaeological skill sets regularly so students can achieve literacy in them. A very concrete but serious obstacle to digital literacy is the lack of coding skills among most archaeologists. In other disciplines, such as astronomy or biology, an introduction to basic programming techniques and data science is now a standard part of undergraduate education. Why should a science as open and interdisciplinary as archaeology lag behind? In the age of AI, basic digital literacy will grow in importance in working with future CA approaches. As mentioned earlier, it will take an effort on all sides to bridge the gap that currently seems to divide at least parts of the archaeological community.

From Reflection to Action

The discussions outlined here highlight deep interconnections between theoretical archaeology and computational practice. In this section, we translate these connections into more concrete, step-by-step suggestions. Although some themes—like open data or transparent workflows—are relevant to many scientific disciplines, we highlight here how they can be adapted to the context and challenges of archaeological research.

A major step forward is to integrate theoretical reflection directly into research design, ensuring that computational methods are neither applied in isolation nor chosen purely for their novelty. Rather than formulating research questions only after collecting or modeling data, researchers benefit from co-developing hypotheses with both theoretical specialists and computational experts at the very outset of a project. Early collaboration helps prevent situations where methods are retrofitted to existing datasets; it simultaneously clarifies the epistemological frameworks in which data and models will be interpreted. For instance, when planning a GIS-based project on regional settlement patterns, inviting experts on social agency and landscape phenomenology to initial workshops can refine the choice of parameters (e.g., anisotropic cost surfaces or agent-based simulation of daily movement) and ensure that relevant theoretical assumptions such as the role of past perceptions of space are carried into the computational design.

Agent-based models are a prime example of incorporating theory early in CA; one example is Chliaoutakis and Chalkiadakis's (2020) agent-based trading model for Bronze Age Crete. In their approach, autonomous, utility-seeking household agents occupy a virtual landscape modeled on the Minoan world around Knossos, enabling researchers to investigate how socioenvironmental factors shape intersettlement networks. Crucially, the authors tested two spatial interaction submodels (XTENT and Gravity) to see how theoretical assumptions about settlement "importance" (e.g., prestige, population, or longevity) affect trading ties. They found that privileging importance over proximity (via the Gravity model) aligned more closely with archaeological evidence of Minoan site hierarchies and the disruptions sparked by the Theran volcanic eruption. By examining network properties like centrality and clustering, the study highlights how theory-driven computational designs can reveal fresh insights into the organization, adaptability, and resilience of past societies.

Meaningful collaboration, however, depends on an adequate level of digital literacy across the archaeological community. To build this capacity, university curricula can include structured instruction in basic programming (e.g., R or Python), as well as hands-on introductions to open data repositories or agent-based modeling platforms. Practitioners who are already working in the field can benefit from short, targeted workshops, potentially offered by digital humanities centers or professional associations, that pair conceptual debates about rational versus nonrational decision-making with practical coding exercises. For example, a workshop might first address how cultural beliefs influence Bronze Age trade patterns and then guide participants through coding an agent-based model in NetLogo that incorporates nonrational decision rules. By coupling theoretical discussions with direct experience in implementing models, such activities encourage archaeologists to see computational methods less as black boxes and more as flexible tools subject to critical scrutiny.

Central to these critical and reflective approaches is the commitment to transparent, open, and collaborative practices. Archaeological data are inherently shaped by layers of interpretive decisions—ranging from field documentation conventions to classification systems—and making datasets and code available for reuse and replication can help demystify these processes. Researchers may publish software scripts, annotated data tables, or 3D models on platforms such as GitHub, Zenodo, or the Open Science Framework, accompanied by clear project documentation and references to theoretical assumptions. In cases where data sensitivity is a concern (e.g., in revealing precise site locations), strategies like sharing coarsely gridded coordinates or requiring formal data-use agreements can balance reproducibility with ethical obligations. When made open, these computational workflows illuminate the choices involved in data cleaning, classification, or model parameterization—allowing both specialists and nonspecialists to evaluate the validity and potential biases of the resulting analyses.

Although this article cannot provide an exhaustive manual for implementing open science, it is important to emphasize that practical, detailed guidelines already exist. In addition, archaeologists can tap into several established frameworks to simplify and standardize their adoption of open-science practices. For instance, the FAIR Data Principles (Findable, Accessible, Interoperable, Reusable) offer clear criteria for structuring and archiving datasets, and the UNESCO Recommendations on Open Science provide a global roadmap for ethically sharing research outcomes. In Europe, the ARIADNE infrastructure illustrates effective data curation and repository models. Aligning local initiatives with these or similar frameworks can accelerate the integration of open-science principles, fostering a more cohesive and collaborative archaeological community.

To further reduce the risk of hidden or unintended biases, it is helpful to institutionalize reflexivity within the entire research workflow from project design to publication. One practical approach is to include short, explicit "reflexivity statements" that identify the theoretical stance, the known limitations of datasets, and potential uncertainties or interpretive leaps. These statements can also outline how the results will be "ground-truthed" against secondary datasets, ethnographic analogies, or historical records. For example, a predictive site-location model might be validated by random checks in the field, discussions with community stakeholders, or the close reading of textual evidence. Such iterative cross-checking goes beyond merely reporting error margins or *p*-values; it acknowledges that interpretive frameworks shape how we collect and evaluate data in the first place.

Finally, theoretical pluralism can be nurtured by consistently trying out multiple interpretive or computational scenarios to ensure that no single approach—processual, postprocessual, evolutionary, or otherwise—dominates the narrative unchallenged. CA, in particular, offers opportunities for comparing how different theoretical assumptions translate into diverging model outcomes. By systematically experimenting with alternative interpretations, such as contrasting a rational-actor view of resource use with a culturally embedded perspective, archaeologists can reveal both the implicit norms that govern a model's construction and the patterns that persist across various assumptions. This openness to multiple working hypotheses is especially valuable for illuminating the complexities of human behavior hidden behind aggregate patterns in large-scale datasets.

Taken as a whole, these interconnected strategies—integrating theory early, improving digital literacy, adopting transparent practices, fostering reflexivity, and championing pluralism—represent an evolving framework for promoting innovation in CA. They go beyond merely acknowledging the importance of theory or data sharing, instead insisting that practices like cocreated research design or reflexivity statements become routine. Although not every project can implement all these measures, even incremental progress—such as publishing a modest reflexivity note or sharing code with a clear README—can shift the culture toward a more critically engaged, ethically grounded, and interdisciplinary mode of inquiry.

Conclusion

As a discipline primarily concerned with the human past, archaeology needs to remain conscious of its main goals to answer contextually and generally relevant research questions. In the history of the discipline there were periods when archaeology derived its relevance and validity of its conclusions from positioning itself closer to the natural sciences, such as in the 1960s with the New Archaeology and around the 2000s in its turn to complex computational modelling. Today, however, the capacity of archaeology to reveal long-term patterns and provide wide-ranging cross-cultural reflections remains its most valid contribution, exemplified in sociospatial studies or studies of human–environmental interaction (Kintigh et al. 2014).

The major concern of archaeologists remains how to identify suitable methodologies for addressing specific issues and answering research questions. Given that "computational archaeology" is a methodological denomination, it should perhaps make itself redundant as a subfield in its own right and instead seek ways to shape computational analyses to better suit the interpretive and social nature of the archaeological inquiry.

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