Received: 9 April 2025 | Accepted: 22 April 2025

DOI: 10.1111/arcm.13095

ORIGINAL ARTICLE

Foreword – *Archaeometry* special issue on chronological modeling

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Abstract
It is well understood that archaeologists, by definition, always strive to assess time as precisely as possible. However, the lack of efficient temporal data interoperability limits our understanding of cross-cultural historical evolution. This Special Issue of *Archaeometry* on chronological modelling features nine contributions which, while not covering all existing methods, provide a useful snapshot of current research on formalisms, methods, and standards. We hope it will help spark a 'temporal turn' in archaeology, much like GIS initiated a 'spatial turn' in the field more than 30 years ago.

INTRODUCTION

Although many monographs and edited volumes have been devoted to the topic of time and archaeology in the last 3 decades, most of them followed a qualitative approach (Holdaway & Wandsnider, 2008; Karlsson, 2001; Le Goff, 2014; Lucas, 2005, 2015, 2021; Lyman et O'Brien, 2006; Murray, 1999; Stabrey, 2017; Thomas, 1996). Far fewer works have been devoted to quantitative and computational approaches to chronological modelling in archaeology. To the best of our knowledge, the latest volume to offer a *tour d'horizon* of such approaches is the indispensable *Tools for Constructing Chronologies. Crossing Disciplinary Boundaries*, edited by Buck and Millard in 2004. Twenty years after the publication of this milestone volume, we felt that time was ripe for a new survey of research on the topic.

INFORMING TIME

It is well understood that archaeologists, by definition, always strive to assess time as precisely as possible. However, although geographical information systems (GIS) facilitate spatial data

March 2025.

sharing and handle multiscalar data effectively, there is no "temporal information systems" (TIS) for historical and archaeological data. The lack of efficient interoperability in chronological data limits our understanding of cross-cultural historical evolution. Dedicating a special issue of *Archaeometry* to chronological modeling posits that a time metric can be assigned to the pace of human cultural evolution (Figure 1).

The idea of modeling time and space in the same way came during the Enlightenment, when prominent natural philosophers agreed on the possibility to give coordinates and relations of order to both time and space dimensions. On November 25, 1715, Leibniz wrote to Clarke, a supporter of Newton's views: "I hold *Space* to be something merely relative, as *Time* is; that I hold it to be an *Order of Coexistences*, as *Time* is an *Order of Successions*." (Clarke, 1717 p. 57). According to Leibniz, space groups together objects that coexist (a set), whereas time groups together events that follow one another (a sequence). Leibniz, Clarke, and Newton agree on considering that space and time are analogs, with events in time, and points in space. According to this scientific approach, it follows that measuring durations between events in time is the same as measuring distances between objects in space, just as there are analogies between spatial and temporal relations (Figure 2).

Peuquet's triad—the journalism axiom of "what, where, when"—and the logicist method in archaeology emphasize how combining "type-based," "space-based," and "time-based" views can be useful for modeling historical processes (Gallay & Gardin, 2009; Peuquet, 1994). If two events occurred closely in time and space, they are more likely to be related to one another (i.e., similar) than if they occurred at different times and places. That is what Crema, on the one hand, and Andreaki and Barceló, on the other, have argued regarding temporal data: "Events close in time are more likely to fall into the same archaeological period" and "Elements that are temporally close to each other should belong to the same cluster" (in this volume, respectively: Crema, 2024; Andreaki & Barceló, 2024). This is also what Tobler's First Law of Geography is about: "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). For archaeologists, two objects (*what*) close in time (*when*) and space (*where*) are probably more culturally related than distant objects. This principle of continuity

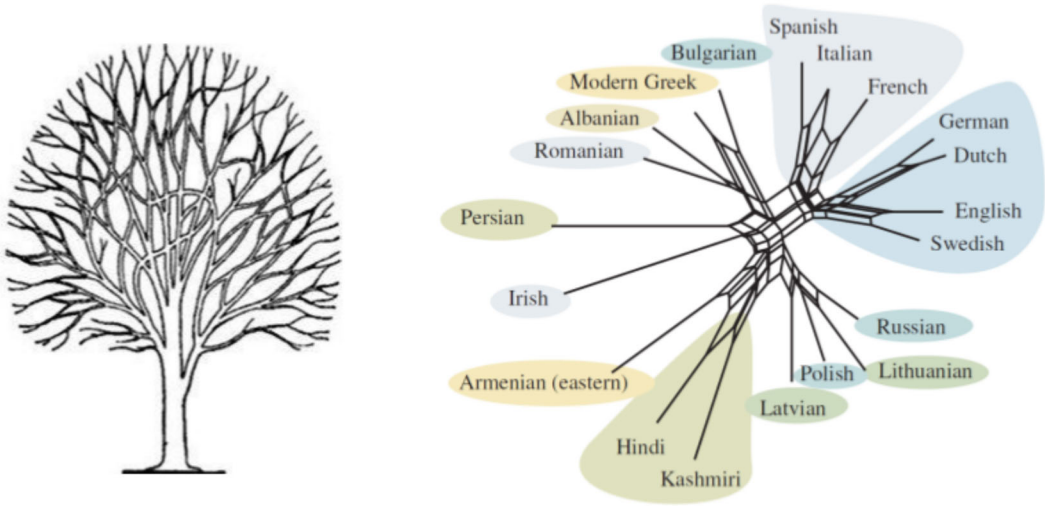

FIGURE 1 Cultural evolution modeling. On the left-hand side: *Tree of Life and Tree of the Knowledge of Good and Evil—That is, of Human Culture* by Kroeber (1948). On the right-hand side: split graph of Indo-European typological data by Gray et al. (2010). Cultural transmission is a mixed transmission that involves vertical (branches) and horizontal transmissions (branches anastomosis). Cultural transmission traits can be quantified through computational processes and quantitative indices (D-score in the case of a split graph) and modeled with admixture graphs.

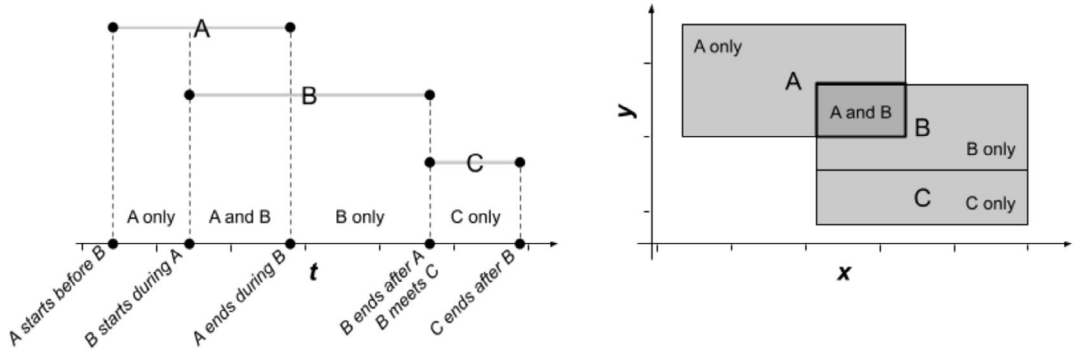

FIGURE 2 The equivalence in space–time binary topological relationships is as follows: on the left-hand side, time is represented as one dimensional (*t* axis), black dots represent begin and end events (zero-dimensional), and grey lines represent timespans (one-dimensional). On the right-hand side, space is represented as two-dimensional (*x* and *y* axes), grey polygons represent areas (two-dimensional). Topological relationships between A, B, and C can be deduced from their begin and end events (temporal) and their coordinates (spatial).

also lies at the heart of seriation (Petrie, 1899), in which observed archaeological features can be chronologically reordered according to their attribute proximities.

CROSS-DATING

When two time spans are chronologically disjoint, meaning they do not share intersections, their relationship can be described using temporal relations such as "Before" and "After" (Allen, 1983). Two other unambiguous temporal binary relations are: "Meets/Met By" (i.e., sequence) and "Equal" (i.e., full synchrony). Conversely, the temporal relation "contemporary" necessitates further explanation (Lucas, 2015). Clarification of temporal binary relations is the focus of one of the papers in the special issue (Levy, 2025). Assessing precisely the degree of contemporaneity between archaeological facts is one of the biggest challenges of chronological modelling. For example, to what extent were two kings exchanging diplomatic letters—say, a Hittite king and an Egyptian Pharaoh—contemporaneous?

The Late Bronze Age in the Ancient Near East and the Aegean is arguably the epitome of cross-dating in archaeology, as attested by the wide literature concerning its chronology. This period is characterized by diplomatic letters, and other written sources, documenting Egyptian and Mesopotamian royal genealogies and long-distance interconnections between civilizations located in the Eastern Mediterranean. Imported decorated ceramics and other luxury goods, many of which are stratified, enable numerous chronological deductions and cross-cultural comparisons. Not to mention the more common material culture that enables the building of local chronologies. Anchoring local and regional chronologies to *absolute confirmed dates* ("anchor" dates), such as the Thera-Santorini eruption that spread ash through the Eastern Mediterranean, using tephra dating, is one of the upcoming challenges for this period (in this volume: Panagiotopoulos & Trognitz, 2025).

TOWARD A "RAILWAY TIME" IN ARCHAEOLOGY

Efficient chronological alignments also require the use of shared standards and unambiguous definitions. Indeed, the dating of a piece of material culture (a pottery vessel for example) is always multi-aligned: It can be related to a stratigraphic unit containing other objects, to a site

stratigraphy, to seriation, to artifact types found in other archaeological cultures, and finally to absolute dates (say, radiocarbon dates). Building from material culture always requires handling various chronological frameworks, such as regional timelines, stratigraphic diagrams, similarity matrices between objects, summed probabilities of radiocarbon dates, and the many temporal relations linking these archaeological facts. Use of ontologies and controlled vocabularies, such as the CIDOC-CRM (ISO 21127[i]), help make dates and chronological statements explicit and reusable by capturing their stated fuzziness independently of their time granularity and chrono-cultural context (in this volume: Stead, 2024). Dates—whether fuzzy or accurate—can be correctly expressed using the EDTF ISO standard (ISO 8601-2[ii]), whereas UNESCO recommends to base the time scale on the proleptic Gregorian calendar (see ISO 8601[iii]) and to express dates in BCE/CE (Before Common Era/Common Era). Archaeology aggregates the material culture in space–time containers labelled "periods" (Le Goff, 2014). Time–space linked open data gazetteers such as PeriodO (perio.do; Golden & Shaw, 2016) and ChronOntology (chronontology.dainst.org; Schmidle, 2021) also help clarify period definitions.

Nowadays, Bayesian modeling, by integrating prior archaeological knowledge (e.g., stratigraphic sequences) with date probability distributions (e.g., radiocarbon), has proven to be an effective tool for narrowing the possible time span of assessed archaeological events (in this volume: Buck & Juarez, 2024). Bayesian modeling is particularly useful for partially ordered sets (*posets*) such as site stratigraphies, "chaînes opératoires," and genealogies of individuals. Relationships between discrete elements of these time posets (respectively a stratigraphic unit, an action, and a person's lifespan) can be modelled using directed acyclic graphs (DAGs). For example, in the Harris matrix shown in Figure 3 (implicitly a DAG), the temporal relationship between Layer 403 and Layer 404 is unknown (e.g., 404 might be anterior or

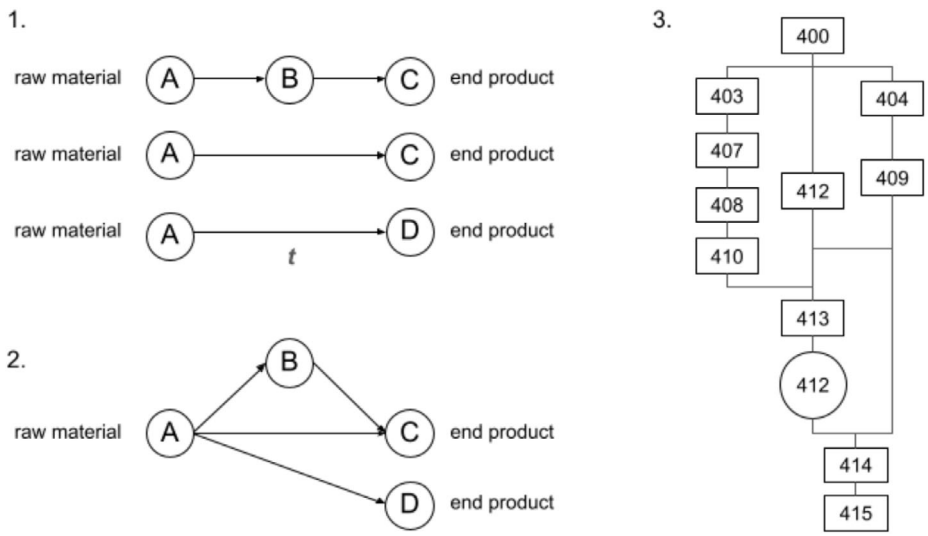

FIGURE 3 Directed acyclic graphs (DAGs) modelling of different time sequences where each node represents an event or a time span. On the left-hand side, Subfigures 1 and 2, chaînes opératoires (COs) comparison for different knapping techniques, where nodes represent actions in a sequence: preparation of the nucleus (A), thermal treatment (B), pressure debitage (C), and percussion debitage (D). Subfigure 1 represents all execution paths (or complete paths) and Subfigure 2 represents the same paths aggregated into a process graph. On the right-hand side, Subfigure 3, the Harris matrix of a site stratigraphy, arrows of time are not marked but are implicit, with more ancient layers at the bottom of the stratigraphy (Harris's *law of superposition*). Two COs or two site stratigraphies can be compared using graph theory: One can compare their length (number of nodes), their number of common nodes, their number of common edges, and so on. The more complex these sequences are, the more likely it is that two different cultures sharing time series had cultural interactions. All of these sequences are closely linked to the concept of path dependence—what one might call the "biography" of an object or a site (in this volume: Andreaki & Barceló, 2024).

posterior to 403), but we know that they are both anterior to layer 400 and posterior to layer 413 (Figure 3). A Bayesian network uses Bayesian probabilities and DAGs to integrate uncertain and incomplete archaeological data.

In contrast to this probabilistic approach, one can use deterministic algorithms to build chronologies. For example, chronological network analysis (CNA) uses a deterministic approach where the best fit of each date is computed by propagation of constraints on dates and temporal relations (Levy et al., 2021).

These approaches are implemented in software for Bayesian analysis, such as OxCal (Ramsey 2009) and ChronoModel (this volume: Noukpoape et al., 2025), as well as in software for deterministic methods, such as GroundHog and ChronoLog (this volume: Falk, 2025, and McIvor et al., 2025, respectively). These tools enable the construction of large regional models by integrating numerous heterogeneous and uncertain temporal sequences.

The integration of all the formalisms, methods, and standards discussed above could spark a "temporal turn" in archaeology, much like GIS initiated a "spatial turn" more than 30 years ago.

ACKNOWLEDGEMENTS

We would like to warmly thank all the contributing authors for their excellent papers and for their patience throughout the reviewing process. We also thank the reviewers for their thorough work, as well as Prof. Shadreck Chirikure and Mrs. Samantha Bowring for their assistance during the editorial process.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/arcm.13095.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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ENDNOTES

[i] International Organization for Standardization. (2023). *ISO 21127:2023, Information and documentation — a reference ontology for the interchange of cultural heritage information*. https://www.iso.org/standard/85100.html

[ii] International Organization for Standardization. (2019). *ISO 8601-2:2019, Date and time — representations for information interchange — Part 2: Extensions*. https://www.iso.org/standard/70908.html

[iii] International Organization for Standardization. (2019). *ISO 8601-1:2019, Date and time — representations for information interchange — Part 1: Basic rules*. https://www.iso.org/standard/70907.html

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How to cite this article: Huet, T., & Levy, E. (2025). Foreword – *Archaeometry* special issue on chronological modeling. *Archaeometry*, 1–6. https://doi.org/10.1111/arcm.13095