Supporting Chronological Reasoning in Archaeology

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Abstract. This paper is a study on the formal representation of the information concerning archaeological finds and historical data that is relevant to the discourse about chronology. It aims at contributing to the theoretical foundations of chronological reasoning in Archaeology. Starting from the ontological analysis of the CIDOC CRM (ISO/CD21127), we define and classify elements of archaeological and historical evidence through the kinds of their chronological consequences and the complexity of chronological reasoning that they can support. Our work also aims at identifying broad categories that may allow for generalization and unification of the vast variety of methods discussed in the literature. Moreover, we identify five classes of evidence and background knowledge for temporal reasoning, and suggest a generalized interval-based formalism.

Keywords: archaeological theory, chronological reasoning, ontology, relative chronology, absolute chronology, dating methods

1. Introduction

Chronology is a major aspect of the archaeological process and a key issue to further inferences about actual and potential influence between people and the understanding of the evolution of cultures. Since the past is not accessible through direct observation, any dating of past events is based on different kinds of evidence and general knowledge about reality. Evidence and general knowledge provide input to inferences about chronological knowledge in a multi-step process as described by Jean-Claude Gardin (Gardin 1990). At some point in these inference chains, the transition is made between the description of reality and the mathematical expressions concerning known and unknown dates, their relationships and associated probabilities ("temporal consequences"). The diversity of kinds of evidence - ranging from effects like radio-carbon activity, teeth enamel abrasion, stratigraphy, material use, style, to historical records (correct or not obviously wrong ones) - is overwhelming. With very few exceptions, formal methods supporting chronological reasoning are conceived, developed, and applied in the context of very specific kinds of evidence.

In this paper we propose an approach that devises a general theory that examines all kinds of evidence and general knowledge about reality used in chronological reasoning, with respect to the kinds of mathematical expressions they can support. It is based on generalizations of an ontological and epistemological analysis of real world knowledge that links temporal consequences to their respective mathematical frameworks.

The potential benefits of such a theoretical approach are:

- To conceive as broadly as possible the applicability of the reasoning methods that are developed for specific cases.
- To develop more comprehensive reasoning systems.
- To assist in the selection of effective methods of reasoning and the related elements of documentation about evidence.
- To achieve semantic interoperability between cultural documentation and reasoning systems in order to exploit optimally present and future data for chronological reasoning.

Due to the early stage of our work and the limited available space for publication, this paper is rather intended to be a position statement and an invitation to discussion. We are well aware that there is an enormous number of details that need further analysis before any claim for true generalization is made. Nevertheless, we feel that we are on the right track, knowing for sure that a general theory like the one we are looking for can only be developed through a wider scientific debate.

The envisaged general theory would involve the following parts:

1. A model of the chronology-relevant elements of reality as perceived in the chronological discourse
2. A model of the relationships between dates and real world phenomena
3. A classification of the chronological argumentation
4. A formal framework for solving chronological problems

The remainder of this paper is organized as follows: In section 2, we address the fore mentioned parts 1 and 2. For part 1, we elaborate on the conceptualizations in and behind the CIDOC Conceptual Reference Model or ISO/CD 21127 (CRM), to which archaeologists have made an essential contribution (Crofts, Doerr, Gill, Stead and Stiff 2004). For the needs of part 2, we apply selected approaches from Computer Science and Artificial Intelligence. Part 3, as developed in section 3, is based on archaeological literature and discussion between archaeologists and computer scientists. A preliminary formalization on part 4 is developed throughout the paper.

2. A Model of Reality, Events, and Time

In this section, we address a model of reality, events and time as perceived in the chronological discourse.

2.1 Related work

Temporal reasoning problems arise in many areas of Artificial Intelligence (AI), including planning, reasoning about physical systems, discourse analysis, and analysis of time-dependent data.

Work on temporal reasoning can be classified in three general categories: algebraic systems; temporal logics; and logics of actions. Less formal but psychologically better grounded approaches are discussed in some of the AI works on planning, as well as in linguistics, and in psychological literature.
There is very little formal work on computing chronologies in Archaeology. General archaeological theories, like those elaborated by Gardin (Gardin 1990) and Hodder (Hodder 1999) do not dwell on chronology-specific considerations. The vast literature on actual chronologies does not formalize in a typical way the employed methods. A notable recent exception is the collection of papers edited by Buck and Millard (Buck I., Millard A., 2004).
Most formal work can be found in science – based techniques, such as radiocarbon dating, which rely heavily on statistical methods and especially on converting and calibrating "radiocarbon dates" into calendar dates (Aitken 1999;Renfrew and Bahn 2001). Formal work has also been done with classical statistics methods that make inferences by considering the likelihood of obtaining a particular set of observations on the basis of given values of the parameters in a probability model. In some cases, classical statistics methods and historical algebra are employed to represent and query historical indeterminacy (Dyreson and Snodgrass 1993). Quite popular is the Bayesian approach, that makes inferences based on *a posteriori* probability distributions of the parameters as given by Bayes' theorem. Bayesian analysis has first been applied to the analysis of chronological information, exploiting the related radiocarbon data for which the associated calendar dates are known *a priori* (Steier and Rom 2000; .Bayliss and Ramsey 2004; Buck 2004; Lanos 2004; Millard 2004). From a theoretical point of view, there is a frequent lack of understanding of the nature of the random processes that would justify the use of probabilistic methods.
Another area where formal work has been carried out is relative dating of archaeological contexts, as they appear in stratigraphy. This systematic approach, known as the "Harris-Matrix", was invented in the early 1970´s by Harris.(Harris 1989) The author describes layers as the smallest units of archaeological identification. Along with their spatial dimensions, these layers are associated with *formation events*. Spatial relationships are used to conclude on the temporal sequence of the respective events. In the paper entitled "Complicated relations and blind dating: Formal analysis of Relative Chronological Structures", M.K. Holst suggests a framework to combine stratigraphic information with temporal consequences derived from other structural relationships in and around excavated sites (Holst 2004). The author proposes a set of methods for formal treatment of archaeological evidence in relation to its asserted chronological consequences, coming thus, very close to the approach we postulate in this paper. His argumentation is however restricted to the kind of evidence that we call "order or traces", and ignores life-span information. In the paper "Applications of formal model choice to archaeological chronology building", S. K. Sahu describes a model choice method between prior models that may yield completely different posterior distributions, and stresses the importance of selecting the appropriate model (Sahu 2004). Obviously, future work on chronology should aim at combining all available dating methods and chronological knowledge that are applicable to a specific problem.
Apart from the Harris Matrix and the absolute dating methods, there is virtually no other epistemological analysis of how observation and background knowledge can be exploited for the assessment of temporal consequences. Even Holst (Holst 2004) does not analyze how the required "broadly contemporary" relationship is obtained, and why it cannot be reduced to a combination of more elementary pieces of evidence. It is such epistemological issues that we will attempt to investigate and illustrate here.

2.2 Events as meetings

Let us make the following assumptions about the perceived reality, similar to (Guarino 1998):
We define as *state of affairs* a specific distribution of *potentially* observable *items,* i.e. material items, conceptual items and events, as well as their associated *relations* and *qualities*[1], over space and time. An ontology can be seen as a model of *possible states of affairs.* The selection, the identity and the very nature of the items under consideration is a function of human perception, conceptualization and intended functionality (see also Hodder 1999). For example, we do not approach the history of a country on the basis of the flow of atoms and molecules within it, but we may do so, e.g., via the specific national laws valid in it.
The following ideas are an interpretation and extension of the CIDOC CRM, a model of possible states of affairs in the real world, in which historical and archaeological phenomena are abstracted as a network of *persistent items* that meet in space and time. P*eriods* are regarded as "...sets of coherent phenomena or cultural manifestations bounded in time and space. It is the social or physical coherence of these phenomena which identify an E4 Period[2], and not the associated spatiotemporal bounds."
An *event* is a special case of a period. It is compatible with the proper definition of a period, but moreover, it is a *meeting* of living or dead items that brings about a change of state at *any scale*. It is a *non-instantaneous, finite* process of a potentially *complex* nature. Consequently there exist neither minimal elements of events nor limits to their decomposition into subevents or to their composition into larger events or periods. In what follows, when speaking of events we imply periods (if not stated otherwise).
Events must be *contiguous* in space-time, in the sense that an event "happens within" a spatiotemporal kind of *coherence volume*, within which the living and dead participants "*meet*", i.e. they are in a position to interact - in analogy to the well-known concept in physics. For instance a discussion takes place in a room, in which we assume that everyone hears each other. It ends when the second last participant leaves. Its boundaries are fuzzy, but the more distant we are, the less relevant is the fuzziness of this coherence volume. Once finished, the same event cannot "restart".
Two *spatially* separated and not interacting phenomena are regarded as distinct events. Events *sharing a common participant* may be *aggregated* into a "superevent". The resulting coherence volume contains both the partial events and

[1] see also (Gangemi, Guarino, Masolo and Oltramari 2003)
[2].In CIDOC/CRM notions (classes or entities) are identified by numbers preceded by the letter "E" and are named using noun phrases (nominal groups) using title case (initial capitals).The E4 Period class comprises sets of coherent phenomena or cultural manifestations bounded in time and space

the shared participant's trajectory between these events. It is worth noting, that the extent of the coherence volume depends on the kind of event - take, e.g., an overseas phone communication, which covers some 70.000 km and part of an hour, versus a mosquito bite, which covers several millimeters and some seconds.

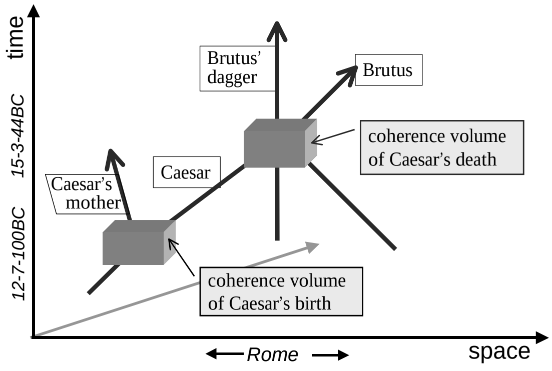

Fig. 1 Historical events as meetings

The concept of "meetings" is extraordinarily powerful: Chronology concerns and involves events (The Columbia Electronic Encyclopedia 2003). "Dating" an object actually means approximating the coherence volume of some event(s) in which the object *was present*. Knowledge about all other participants present in the same event may help to constrain this event. There follow some examples of how events can be interpreted as meetings:

1. Historical events: e.g. Caesar's birth can be regarded as his first meeting with his mother, which also begins his existence. The coherence volume of his birth can be estimated by both the room and the whole day of his birth. Caesar's murder can be described as a meeting of Caesar, Brutus, Brutus' dagger and others. Whereas Caesar's existence finishes, Brutus, his dagger and the others continue to exist after the event. The coherence volume of Caesar's murder can be approximately placed within some hours on the Forum Romanum. The event can be seen as an aggregation of different subevents, such as the individual stabbings by the senators (see also Pianesi and Varzi 1996). Unbeatably, a latest boundary for the end of the murder is when Caesar's body was burned on the Forum, which may be seen as part of the murder or not.

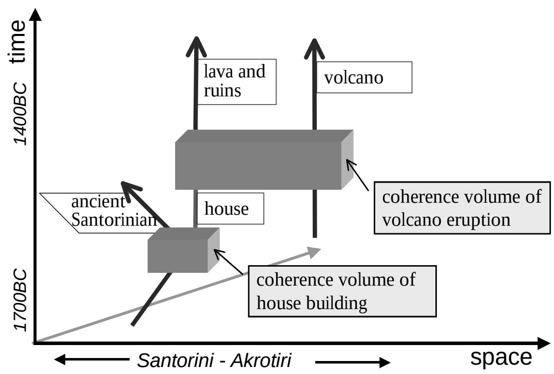

Fig. 2 Deposition events as meetings

2. Deposition events can also be seen as meetings. Let us assume, that a Bronze Age inhabitant of Akrotiri, Thera has built a house (1st meeting), that was later destroyed and covered by ashes from the explosion of the local volcano (2nd meeting). Consequently, the archaeological notion of "context formation" can be abstracted as a set of meetings. Note the analogies to the first case, which may support a similar system of chronological consequences: birth - building, murder – destruction, Caesar – house; participants coming into being, ending or surviving in the events.
3. Finally, information exchange forms fine meetings too: e.g., the well-known Marathon runner that witnessed the Greek victory (1st meeting). He ran to Athens, where he transmitted this message to someone else and died (2nd meeting). The message survived, and "infected" more and more people in subsequent meetings like a disease. Note that a message is immaterial, a "Conceptual Object" in the CIDOC CRM, which can exist on multiple carriers at different places at the same time.

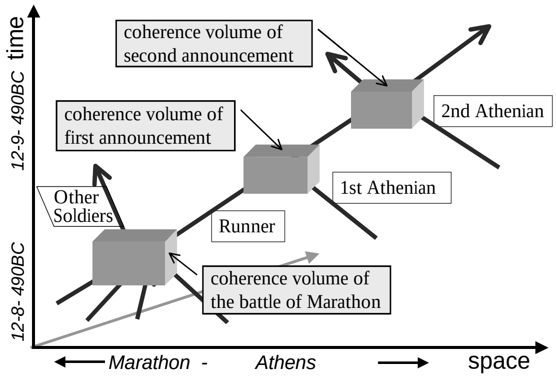

Fig. 3 Information exchange as meeting

Obviously, one can build relative chronologies between participants in meetings, only based on the knowledge of which items were created, destroyed or "survived" events, completely independent of the nature of the event and the participant. For this purpose, the CIDOC CRM (Doerr 2003) classifies an open set of familiar relationships such as "used object, produced" by these three fundamental properties:

1. P12 occurred in the presence of (was present at)
2. P92 brought into existence (was brought into existence by)
3. P93 took out of existence (was taken out of existence by)

It is this kind of ontological generalization we seek in order to shape a general theory of chronology. The CRM describes most of it. Areas not sufficiently covered by the CRM are explicitly mentioned in this text. In the next section, we describe a model of events and time that is compatible with the above definition of an event. In section 3, we describe all the ontological generalizations we found. They all end-up in relationships of events and periods.

2.3 Events and time

A precise mathematical foundation is a foremost requirement for establishing a well-founded chronology framework. This section introduces a mathematical model intended to support temporal reasoning for chronology. The proposed model provides the formal machinery for both representing and reasoning with imprecise temporal knowledge.

Our temporal reasoning framework is based on an *Event/Time structure ETS* defined as *ETS = (E, TM, h, π)*, where:

- *E* is a denumerable set of discrete events or periods.

- *TM* is a linear time model defined as the 6-tuple $TM = (D, T, u, l, \leq)$, where:
  - *D* is the set of Julian dates *d* regarded as real numbers (i.e. given in years, milliseconds or any granularity of time).
  - $T \subset (D \times D)$ is a set of convex time intervals specified by their endpoints.
  - $u(t),\ t \in T$ is a function mapping the greater (upper) interval endpoint to an element of D.
  - $l(t),\ t \in T$ is a function mapping the smaller (lower) interval endpoint to an element of D.
  - $\leq$ is the complete temporal order on *D*
- *h* is a function mapping every element $e \in E$ to an element $t \in T$, which represents the true time *throughout* which the event or period *is happening*.
- π is a function mapping every element $e \in E$ and $d \in D$ to a probability distribution function *f* that returns the probability of an event or period to be happening ("on-going") at time *d*.

Time intervals are either the true (albeit unknown or undetermined) intervals of the events, or approximations of the latter. We assume that the true temporal extent of an event cannot be observed, but that it is possible for a suitable observer to identify dates $d \in D$ that are definitely before or after the true endpoint of an event. Semantic relationships between events and absolute dating give rise to sets of "temporal consequences" that relate or approximate the endpoints of the true intervals of the events under consideration. In more detail, this model allows for describing the following determination relationships of an interval $t \in T$ with an event *e*:

(D1) Indeterminacy: $i(t,e) \Leftrightarrow h(e) \subset t$.

(D2) Determinacy: $d(t,e) \Leftrightarrow h(e) \supset t$.

(D3) Indeterminacy of begin: $b(t,e) \Leftrightarrow l(h(e)) \in t$.

(D4) Indeterminacy of end: $e(t,e) \Leftrightarrow u(h(e)) \in t$.

Fig. 4 depicts an illustration of the determination relationships.

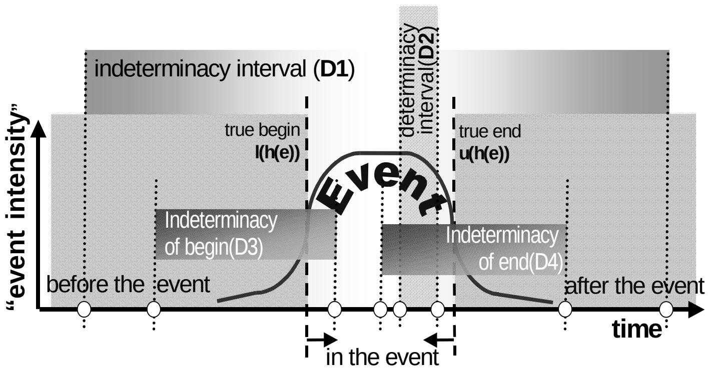

Fig. 4 Illustration of determinacy and indeterminacy intervals

Determinacy actually means that the event is "on-going" throughout and beyond the given interval. Further, we discuss the following temporal relationships between two time intervals $t_1, t_2 \in T$:

(R1) $t_1 < t_2 \Leftrightarrow \forall d_1 \in t_1: d_1 < l(t_2)$.

(R2) $t_1 \leq t_2 \Leftrightarrow \forall d_1 \in t_1: d_1 \leq u(t_2)$.

(R3) $t_1 \geq t_2 \Leftrightarrow \forall d_1 \in t_1: d_1 \geq l(t_2)$

Finally, we declare an addition of a time interval *t* with an interval *li* of temporal duration values *l:*

(S1) $t + li = \{ d \in D: \exists d1 \in t, l \in li \wedge d = d1 + l \}$

This model can be used as the basis for establishing an interval algebra (along the lines of Allen 1983, Cowley and Plexousakis 2000a, 2000b) for indeterminate time and, subsequently, for formalizing interval based chronological reasoning.
It should also be possible to refine this model into a spatiotemporal one, by replacing temporal bounds with spatiotemporal bounding volumes. This exceeds, however, the frame of this paper. Any spatiotemporal theory should however comply with the respective temporal one, in that any temporal bounds equal the end points of the projection of a corresponding spatiotemporal bounding volume to the time axis, and any probability distribution over time equals the partial integral of the corresponding spatiotemporal probability distribution over space. Under these conditions, any of the results of the latter should become a mere refinement of those of a temporal theory.

3. Chronological Reasoning

Dating means approximating the temporal bounds of the coherence volume of some event. (We regard that all models treating events as points in time are in principle inconsistent with reality and *not observable*). "Dating" an object means dating some event in which the object *was present*, such as its production or historical use. The goal of chronology is the determination of minimal indeterminacy time-intervals for the begin and end of each event or period in a system under consideration. This goal may be *refined* by the determination of the probability of each event or period to begin or to end at a certain time. The latter is obviously *consistent* with the former, if the respective probabilities are zero outside the given intervals and sum up to unity inside. In both cases, begin and end of events may be contracted to a notion of "instantaneous happening", in particular for events of irrelevant duration with respect to the scale under consideration.
We understand the Process of Chronology as the minimal temporal confinement of *all possible* chronology-relevant states of affairs consistent with the given evidence ("possible pasts"), or of the *most probable* state of affairs consistent with given evidence. The results of both cases are of interest. In the following, we shall only sporadically mention the refinement of interval models with probabilistic models. Even though more theory exists on the latter, we regard the former as a prerequisite and necessary bound for a sound probabilistic theory.
In case the given evidence is contradictory - in that it results in no possible past - one may resort to either questioning the quality of the selected elements of evidence, or assigning probability values to the truth of those, until a possible past emerges. Such an approach could be regarded as both, a spiral reasoning as in (Hodder 1999), or as a modification of a reasoning chain as Gardin describes (Gardin 1990). We prefer the latter view, distinguishing, in contrast to Hodder, the historical process, in which knowledge is acquired, from the reasoning chain, by which knowledge is justified at a certain point in time. As (Feyerabend 1993) points out, the difference between the two is common to all sciences, even though it is frequently pretended to be the same, and the historical process itself is in truth rarely objective.

Any formal method is *internally* objective, directed and not cyclic. Only a thorough understanding of the points where subjective assumptions enter the formal system allows for tracing the effect of justified, subjective, alternative opinions and separate it from a simply wrong formalism. In this paper, we will no further consider such revision processes, which can also be formalized (see Flouris, Plexousakis and Antoniou 2004).

Primary evidence for the existence of past events are either their products, permanent traces, placement of objects or reports in written or oral historical records (information). In addition, qualities of objects such as state of decay, chemical alteration, deformation (e.g. glass) provide evidence for chronology. Finally, background knowledge about physical laws, assumed to be global and diachronic, and about social laws, assumed to be valid in the respective context, complements the reasoning. In the following, we classify evidence and background knowledge by their specific chronological consequence.

3.1 Absolute Chronology

Absolute chronology can only have three kinds of sources:

1. Historical records relating an *observation* to a *known calendar*, an astronomic event or any other event that can be dated absolutely.
2. Matching a *temporally unique pattern* of a partial sequence of traces with a complete, known sequence, such as dendrochronology, patterns in polar ice, in order to date the completion event of the partial sequence.
3. Calculation of temporal distance via the *state of an "aging" process* with known effect on an object *from the present* to the starting event, such as radio - carbon, potassium-argon, uranium series, mutation rate of mitochondrial DNA, thermoluminescence etc.

Sources 2.and 3., provide indeterminacy intervals (D1), i.e., outer bounds, for the happening time of the event with fixed dates, frequently refined by probability distributions within this interval. Quantum effects, such as radio - carbon, actually yield extremely low, but non-zero probabilities outside any reasonable interval, a theoretical complication not further looked into here. The only reasoning possible is the intersection of such intervals (or combination of probabilities) yielding narrower intervals (or sharper probability distributions). *It will not provide any information about the duration of an event or period.*

We regard the historical act of observing or witnessing an event as part of a larger coherence volume of the observed event (a "meeting"). Therefore knowledge about time-points when the event was actually on-going might be regarded as a case as described in section 3.3. For reasons of simplicity however, we assume that an observer may find for even a completely unstructured event, such as a simple move from one place to another, dates that fall within or outside its happening interval. From these dates, approximations of inner and outer bounds (D1, D2), begin and end (D3, D4), as well as of duration may be found.

Sources 1., 2., may also provide periodic date ranges, such as Olympic Games, months, seasons as with the flowers found on Tut-Ankh-Amun's mummy. They can be expanded into finite series of possible absolute intervals, and thereby be dealt with the same formalism.

3.2 Relative Chronology by Event Order

A first form of *relative chronology* concerns direct evidence about the temporal ordering (sequencing) of multiple events. It can only have three kinds of sources:

1. *Historical records* temporally relating an observation of an event to another event (e.g. kings lists, sequences of figures on totem poles).
2. Observation of the *order of traces* of different events that indicate their temporal sequence, such as: stratigraphy, necessary vertical construction sequences; things found inside a closed space, the systems of scratches from glaciers with different directions in Labrador, where the previous are partly destroyed by the following. The order is derived from relative location such as overlaying, partial replacement, obstruction and inclusion, may be even chemical diffusion. Reasoning can be extraordinarily complicated, with arguments about accessibility etc. (Holst 2004). The CIDOC CRM provides no adequate description for the relevant observable relationships.
3. "Causal" relationships between events, i.e. *necessary prerequisites* of an event to have happened. For instance, participation in a meeting must be at/after creation and at/before destruction of all participants (people and things such as strata, objects, tools, buildings, vehicles etc.). Transfer of information via meetings must be at/after the creation of information and its information carriers (people, objects), and at/before the loss of the last carrier. An object/information found distant from its origin must have been moved before, such as the knowledge about the victory in Marathon.

Event order information allows for the creation of temporal networks constraining the true time intervals of events e_i, e_j, such as: $h(e_i) < h(e_j)$, $h(e_i) \leq h(e_j)$, $h(e_i) \geq h(e_j)$.

Temporal networks can be combined with elements of absolute chronology. The result is an enhanced set that may: a) refine absolute intervals, b) provide new absolute intervals for relative (variable) intervals, and c) turn some relative intervals into absolute ones.

It seems that direct information about *temporal equality* can only appear indirectly as the result of identifying two events as one. This could be a result of definition, as in the case of the breakdown of periods into phases, or of recognizing two objects as parts of the same whole (Holst 2004), which in turn results in identifying their creation events as identical, rather than their creation times. Multiple evidence may provide a system of upper and lower bounds that evaluates *more or less into equality*.

Event order does not provide any information about the duration of an event or period.

3.3 Relative Chronology by Event Inclusion

A second form of relative chronology we recognize as distinct concerns primary evidence of *temporal inclusion*. A larger, on-going process ("superevent") contains sub-processes ("subevents") that can be dated individually (relatively or absolutely), e.g., a single killing that is part of a battle or the deposition of one object in a matrix. This containment can have only three kinds of sources:

1. *Historical records* of actual observations.
2. *Inclusion of traces* (deposition inclusion, inclusion in built or other rigid structure, a skull on a battle field, etc.).

3. "causal" relationships i.e., necessary constituents of an event to happen, or background knowledge of the characteristic processes at that time, such as the steps of a lost-wax casting.

Inclusion information introduces a new quality: It provides constraints to the *latest beginning* and *earliest end* of the container process i.e. the dating of each subevent e_i provides a least constraint for the super event e_l to be *on-going*: $h(e_i) \subset h(e_l)$.
If at least two subevents are known, they provide *lower bounds* for the *duration* of the superevent. The larger the number of known subevents, the better the approximation of the event duration. The formalism has to deal now with inequalities involving outer *and* inner bounds. We suppose that Holst's "broad contemporary" relationship (Holst 2004) is actually an inference based on multiple inclusion relationships, and should therefore be an outcome rather than an input of the proposed formalism.

3.4 Relative Chronology by Temporal Distances

The third form of relative chronology concerns primary evidence of *temporal distance and duration.* Temporal distance and duration information that is not derived from absolute chronology is relatively rare. It can have only three kinds of sources:

1. Historical records of actual observations, implying the use of a calendar with unknown absolute determination.
2. Calculation of *temporal distance* by relating the size of an effect to an estimated rate of change, such as a change rate of style/ technological skills, deposition rates, tooth abrasion between birth and death. Discrete changes form a particular case, such as relative dendrochronology. Estimations of the traveling time of people, goods, information or technology, based on the assumed transfer speed, also fall in the same category (Note that the use of transfer speed may require to take into account distances as variables!).
3. Background knowledge of maximum or average durations such as human life and generation time-span, average use period of clay pots etc.

Knowledge about temporal distances is in turn associated with indeterminacy intervals about maximal/minimal duration (or a respective probability distribution). Adding temporal distance to the reasoning described so far requires *summation* of temporal bounds, a new element in the formula, such as: $h(e_i)+li \leq h(e_j)$. These systems are also called "floating chronologies" (Buck and Millard 2004). Periodic distances, such as "at one of his following anniversaries" may be developed into a series of possible distances, as described in section 3.1.

3.5 Categorical or Typological Dating

All previous forms of dating are based on the observation of particular items and factual relations ("material facts" in Guizzardi, Herre and Wagner 2002). The last form of relative chronology we could identify in this work is what we call "categorical dating". It is based on a two-step process: One or more objects o_i are classified by a type or category C. The category is associated with a kind of events, the total of which can be dated by some outer bounds, i.e. the dating of the category. Then it is assumed that the particular objects date within the respective date range of their category. (Dating of categories is not described by the CIDOC CRM.) We have found three prominent forms:

1. It is assumed that the creation events $p(o_i)$ of all o_i of one type C of items (material or immaterial) *fall within* the spatiotemporal extent of a specific minimal period $P(C)$:
   $P(C) := inf\{ t \in T : \forall o_i \in C \Rightarrow h(p(o_i)) \subset t \},$
   where *inf* denotes the infimum (i.e., least upper bound) of all such sets with respect to set inclusion.
   This process combines the uncertainties of *classification* (deviation from prototypes) with the uncertainty of the actual distribution of the creation of *such things* within the respective period. Once the classification is assumed to be valid, the problem reduces to the dating of the period, as described in the previous sections.
2. It is assumed that the production events of one type of things *are all after* the production events of another type of things, such as archaic and classic styles. This leads to the relative dating of two objects respectively.
3. It is assumed that the production events of one type of things have a characteristic *temporal distance* from the production events of another type of things, typically by subjective estimations of the *speed of evolution*, such as style, technological skills.

We cannot go into further detail here. A reliable basis for the dating of a category seems to be either historical records or rich statistical evidence. Other arguments are based on subjective estimations of evolution. Basically all cases in 3.1 to 3.4 have parallels on the categorical level. However, the characteristic differences of reasoning on factual and categorical level must not be overseen !

4. Summary: Observation and Temporal Reasoning

We have identified five classes of evidence and background knowledge for temporal reasoning. They give rise to distinct mathematical forms of temporal consequences. The latter are simple and meaningful, in the sense that they seem to support a notion of the minimal elements of direct observation against inferences of more complex relationships that seem *not to be directly observable*. In particular true temporal equality seems to be not observable, e.g. two people born simultaneously - a case distinct from the equality of indeterminacy intervals, e.g. people born in the same year. Further work must clarify, if these assumed minimal elements are sufficient to explain the construction of all temporal relationships discussed in literature. Each class seems to systematically have three kinds of sources: records of historical observation, current material evidence, and background knowledge. Each class and kind of source seems to be well - distinct. We assume, that the interval-based formalism proposed here can be translated, in a more or less systematic way, into a probabilistic approach.

5. Conclusions

This is a preliminary study intended to support a more generalized theory of chronological reasoning in archaeology. We have classified evidence, as found in literature, by regarding the mathematical form of temporal consequence into categories supporting:

1. Absolute chronology
2. Relative chronology by event order
3. Relative chronology by inclusion
4. Relative chronology by temporal distances
5. Categorical dating

We are encouraged in our vision that the vast diversity of existing chronological reasoning methods can actually be classified into a relatively small, well-defined set of principles and kinds of elementary observations. This will in turn permit to establish a general mathematical problem formulation embracing the other forms.

Fundamental to this is a further elaboration of the ontology of the implied concepts, such as the definition of events, and the epistemology, such as observability of properties. Only a few extensions of the CIDOC CRM seem to be necessary to provide a model for appropriately documenting chronology-relevant evidence and background knowledge.

The interval-based formalism suggested here is based on the idea of non-instantaneous, complex events with fuzzy boundaries. The fuzziness is formally described as the inability to observe the true event boundaries. Ontological relationships between events map to temporal consequences in the form of relationships between true and observed interval boundaries. The formalism has still to be fully developed. It must be verified, if it actually covers the reality of archaeological evidence appropriately from the ontological, epistemological and mathematical point of view. In the sequence, the relationship and compatibility of probabilistic and interval-based formalism may be studied. Finally, the revision process of the belief in observations and records has to be integrated in a systematic way. From the computer science and mathematics point of view, all this seems to be feasible. Even though we hardly believe that such a "world formula" would ever be solvable, the simplicity of the "primitive" relationships discussed here seems to suggest that reasonable approximations can be calculated for many cases not yet thought of, that the correctness of current methods can be validated and that relationships of different methods can be better understood. However, the major contribution should be an insight in the interplay of formalism and subjective assessment.

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