Temporal Relations

Historical and scientific discourse about the past deals with different levels of knowledge regarding events and their temporal ordering that feed into chronology. Chronology is fundamental to understanding social and natural history, and reasoning about temporal relations and causality is directly related. An immense wealth of physical observations allows for inferring temporal relations and vice-versa. It is important to be able to document temporality both with regards to known dates but also according to relative positioning within a historical time line. The top-level properties of the CIDOC CRM relating to temporal entities support the documentation of: dates as time-spans or dimensions, mereological relations between temporal entities as well as a complete suite of topological relations.

Dates and Durations: When some absolute dates limiting a temporal entity are known, this can be documented by instantiating the *P4 has time-span* property and creating an instance of E52 Time-span. Dates should then be recorded as instances of E61 Time Primitive and related to the time-span through properties *P81 ongoing throughout* or *P82 at some time within*. Time is recorded as a span and not an instant in the CIDOC CRM. The choice of property *P81 ongoing throughout* allows the documentation of knowledge that a temporal phenomenon was occurring at least at all points of a known time-span. The property *P82 at some time within* allows the weaker claim that the phenomenon must have occurred within the limits of a particular time-span without further specifying as to when precisely. It is the default for historical dates, given, for instance, in years for events of much smaller duration. The actual mode of encoding the documented date is outside the scope of the CIDOC CRM, which defines this with a primitive class, E61 Time Primitive. Finally, the property *P191 had duration* can be deployed in order to document a temporal phenomenon with known duration but with less precisely temporal positioning. For instance, a birth may be known with the precision of a year, but with a duration of 3 hours. For documenting exact time-spans that are result of a declaration rather than observation, for instance in order to describe a time-span multiple events may fall into, the property *P170 defines time* allows for specifying the time-span uniquely by a temporal primitive, rather than by *P81 ongoing throughout* or *P82 at some time within* using an identical time primitive.

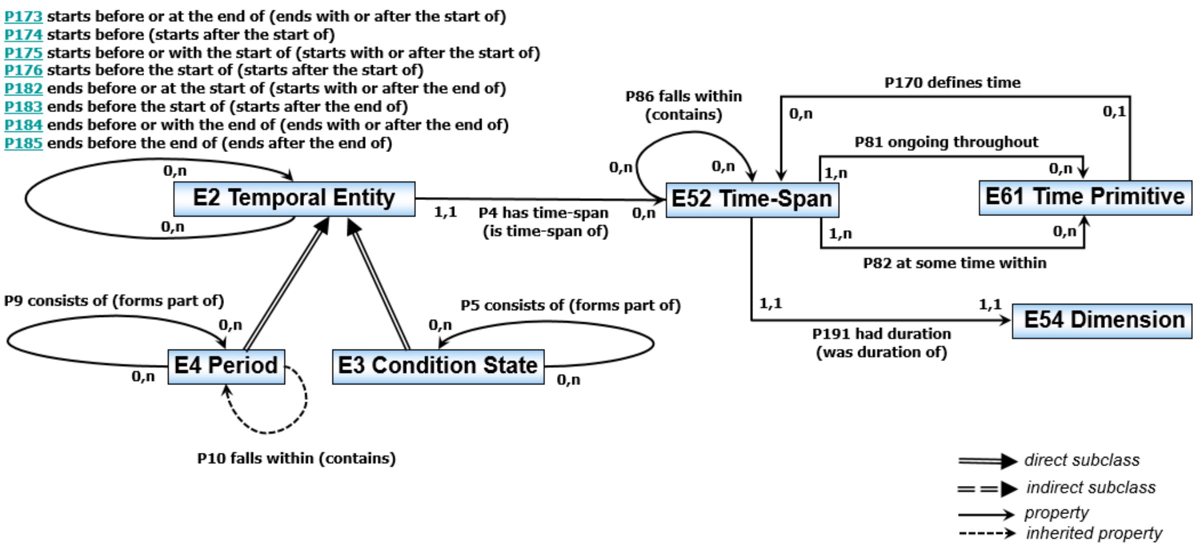

Figure 5: Basic CIDOC CRM Properties and Classes for Reasoning about Temporal Information

Mereological relations: The documentation of the part-whole relationship of temporal phenomena is crucial for historical reasoning. The CIDOC CRM distinguishes under temporal entities two immediate specializations: E4 Period is a high-level concept for the documentation of temporal phenomena of change and interactions in space and time, comprising but not limited to historical periods such as Ming or Roman, and is further specialized in rich hierarchy of more specific processes and activities. The second specialization is E3 Condition State*,* a rather specific class for the documentation of static phases of physical things. The CIDOC CRM so far does not describe a higher-level class of static phases, because they are normally deductions from multiple observations, problematic in information integration and vulnerable to non-monotonic revision. For both classes, two different mereological relations are articulated: The property *P9 consists of* is used to document proper parthood between instances of E4 Period, i.e., to describe how the phenomena that make up an instance of E4 Period can causally be subdivided into more delimited phenomena. In contrast, the property *P10 falls within*, explained further in the section about spatiotemporal relations, describes only a non-causal co-occurrence in the same spatiotemporal extent. The property *P5 consists of* indicates, in analogy, proper parthood between instances of E3 Condition State.

Topological Relations: A lot of semantic relations have implications on the temporal ordering of temporal entities. For instance, meeting someone must occur after birth and before death of the involved parties. Information can only be transferred after it has been learned. On the other side, direct information about temporal order has implications on possible or impossible semantic relations. This form of reasoning is of paramount importance for research about the past. It turned out that the popular temporal relations defined by (Allen, 1983), which the CIDOC CRM had adopted in previous versions, are not well suited to describe inferences from semantic relations, as detailed in the section "Temporal Relation Primitives based on fuzzy boundaries" below. Instead, the CIDOC CRM introduces a theory of fuzzy boundaries in time that enables the accurate interpositioning of temporal entities between themselves taking into account the inherent fuzziness of temporal boundaries. This model subsumes the earlier introduced Allen temporal relations which may continue to be used in extensions of the CIDOC CRM.

Spatiotemporal Relations

Treating space and time as separate entities is normally adequate for describing events and where things are. When more precise documentation and reasoning is required about phenomena spreading out over time, such as Bronze Age, a settlement, a nation, moving reference frames such as ships, things being stored in containers and moved around, built structures being partially destroyed, rebuilt and altered etc., space and time must be understood as a coherent continuum, the so-called spacetime. This is not a familiar concept for many users, and those not interested in such details may therefore skip this section.

However, the respective model the CIDOC CRM adopts constitutes a valid interface to the OGC standards, as elaborated in CRMgeo (Doerr & Hiebel 2013) and important for connecting to GIS applications. The key class CIDOC CRM provides for modelling this information is E92 Spacetime Volume. E92 Spacetime Volume is used to document geometric extents in the physical spacetime containing actual or possible positions of things or happenings, in particular in those cases when the changes of place to be documented cannot be reduced to distinct events, because the spatial extent changes continuously. The higher-level properties and classes of CIDOC CRM that centre around E92 Spacetime Volume allow for the documentation of: relations between spacetime volumes, relations to space and time as separate entities, and treating the exact extent of physical things and periods in space at any time of their existence as spacetime volumes. Its use is particularly elegant for the description of temporal gazetteers.

Defining a Spacetime Volume: There are three ways to define a spacetime volume:

1 the property *P169 defines spacetime volume* should be used to declare a spatiotemporal container for some things or happenings in terms of spatial coordinates that may vary over time, be it in discrete steps or continuously with the help of spacetime expressions. The latter are instances of E95 Spacetime Primitive, a primitive class for expressing values in data systems not further analysed in the CIDOC CRM.

2 Instances of E4 Period are regarded to be specialized instances of E92 Spacetime Volume that are formed by the spreading out of the phenomena that make up an instance of E4 Period. As such they are fuzzy but in general observable.

3 The continuous sequence of spatial extent that the matter of an instance of E18 Physical Thing occupies in the course of time, defines a spacetime volume unique to it from the beginning of its existence to its end, which can also be understood as its trajectory through the universe The property *P169 defines* allows for referring to this spacetime volume, in order to document its additional properties. As such this spacetime volume is fuzzy but in general observable. It is not easy to make a mental picture of the spacetime volume of a physical thing, but the construct simplifies all reasoning about where things have been.

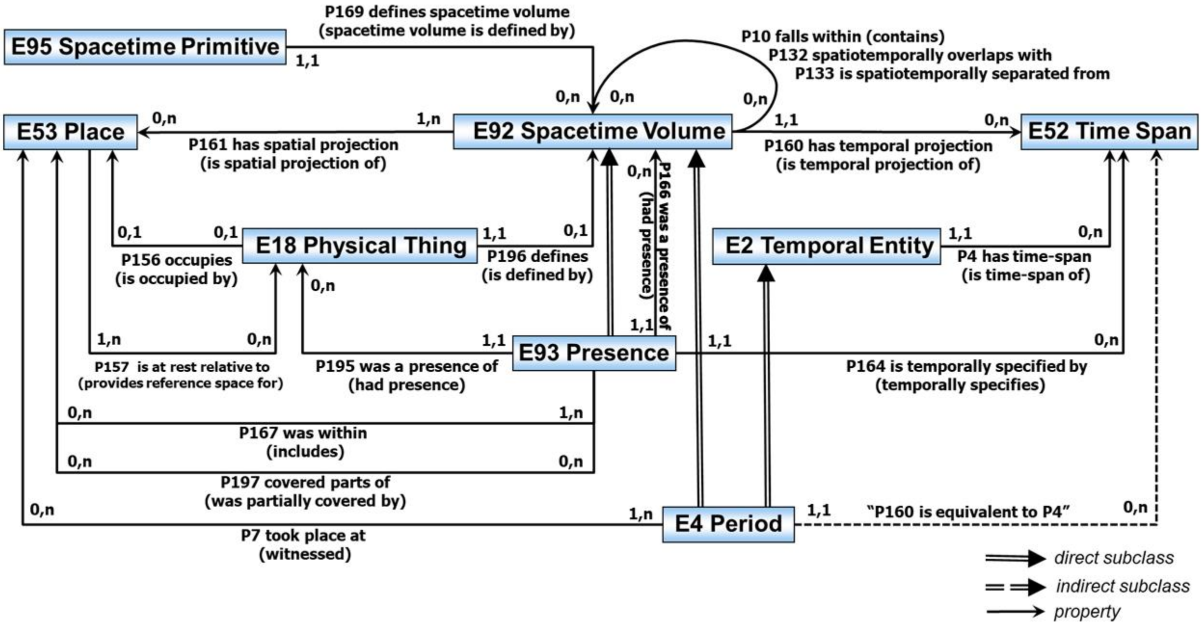

Figure 6: Basic CIDOC CRM Properties and Classes for Reasoning with Spacetime Volumes

Relations with Places and Physical Things: The property *P161 has spatial projection* associates a spacetime volume with the complete spatial extent it has occupied during its time-span of definition. Due to relativity of space, the definition of an instance of E53 Place must be relative to some physical thing as geometric reference. This can explicitly be documented with the property *P157 is at rest relative to*. If the place where something is at a certain point in time is given in multiple reference spaces in relative movement, such as with respect to a ship versus to the seafloor, these differently defined places may later move apart. Therefore, a spacetime volume, even though uniquely defined, can have any number of spatial projections, depending on the reference space. Currently, the GPS system defines a default reference space on the surface of Earth. In art conservation and other descriptions of mobile object of fixed shape, it is useful to refer to the precise place a physical thing occupies with respect to itself as reference space via *P156 occupies*, for further analysis. *P156 occupies* constitutes a particular projection of the spacetime volume of this thing. In contrast, the property *P53 has former or current location* only describes that a thing was within a specific place given in some reference space for an undefined time.

Relations with Time-Spans and Periods: The property *P160 has temporal projection* associates a spacetime volume with the complete temporal extent it has covered comprising all places of its definition. In contrast to places, the reference system of time is unique[8] except for the choice of origin. For instances of E4 Period and its subclasses, which inherit *P160 has temporal projection,* the property is actually identical with the property *P4 has time-span* inherited from E2 Temporal Entity*,* because is describes the temporal extent of the phenomena

8 This holds for applications in the scope of the CIDOC CRM, which are in the non-relativistic area, but not strictly, for instance, for satellites.

that make up an instance of E4 Period. Therefore, it is recommended to use *P4 has time-span* for instances of E4 Period and its subclasses, rather than *P160 has temporal projection*.

Relations of Presence: Instances of E93 Presence are specialized instances of E92 Spacetime Volume that are identical with the spatial evolution of a larger spacetime volume specified by *P166 was presence of*, but delimited to a, normally short, time-span declared by *P164 is temporally specified by*. In other words, they constitute “snapshots” or “time-slices” of another spacetime volume, such as the extent of the Roman Empire during 30AD. They are the basic construct to describe exactly where something was or happened at a particular time (-span), in connection with the property *P161 has spatial projection.* In particular, it allows for describing the whereabouts of mobile objects, be it in the storage of a museum, a palace, deposited in the ground, or transported in a container, such as the bone of a saint. For ease of use, a shortcut *P195 was presence of* is defined directly to E18 Physical Thing, bypassing the definition of its spacetime volume.

Topological Relations: Finally, the Model defines truly spatiotemporal topological relations. *P10 falls within (contains)* is the complete inclusion of one spacetime volume in another. It should not be confused with inclusion in the spatial and temporal projection, which may be larger. E.g., in 14 AD, Mesopotamia was not within the Roman Empire. Further, the properties *P132 spatiotemporally overlaps with* and its negation *P133 is spatiotemporally separated from* are fundamental to argue about temporary parthood, possible continuity etc.

Temporal Relation Primitives based on fuzzy boundaries

It is characteristic for sciences dealing with the past, such as history, archaeology or geology, to derive temporal topological relations from stratigraphic and other observations and from considerations of causality between events. For this reason, the CIDOC CRM introduced in version 3.3 the whole set of temporal relationships of Allen's temporal logic (the now deprecated properties P114 to P120). It was regarded at that time as a well-justified, exhaustive and sufficient theory to deal with temporal topological relationships of spatiotemporal phenomena relevant to cultural historical discourse. Allen's temporal logic is based on the assumption of known, exact endpoints of time intervals (time-spans), described by an exhaustive set of mutually exclusive relationships.

Since many temporal relations can be inferred from facts causal to them, e.g., a birth necessarily occurring before any intentional interaction of a person with other individuals, or from observations of material evidence without knowing the absolute time, the temporal relationships pertain in the CIDOC CRM to E2 Temporal Entities, and not their Time-Spans, which require knowledge of absolute time. If absolute times are known, deduction of Allen's relation is a simple question of automated calculus and not the kind of primary scientific insight the CIDOC CRM, as a core model, is interested in. However, their application turned out to be problematic in practice for two reasons:

Firstly, facts causal to temporal relationships result in expressions that often require a disjunction (logical OR condition) of Allen's relationships. For instance, a child may be stillborn. Ignoring states at pregnancy as it is usual in older historical sources, birth may be *equal to* death, *meet* with death or be *before* death. The knowledge representation formalism chosen for the CIDOC CRM however does **not allow** for specifying **disjunctions**, except within queries. Consequently, simple properties of the CIDOC CRM that imply a temporal order, such as *P134 continued*, cannot be declared as subproperties of the temporal relationship they do imply, which would be, in this case: "before, meets, overlaps, starts, started-by, contains, finishes, finished-by, equals, during or overlapped by" (see *P174 starts before the end of*).

Secondly, nature does not allow us to observe equality of points in time. There are three possible interpretations to this fact. Common to all three interpretations is that they can be described in terms of fuzzy boundaries. The model proposed here is consistent with **all** three of these interpretations.

1. Any observable phenomenon that can be dated has a **natural temporal extent** with **fuzzy boundaries** of **gradual transition** from not existing to definitely existing and then to no longer existing.
2. These fuzzy boundaries can also be interpreted as the time intervals about which experts, even with a complete knowledge of the described phenomenon, may not agree as to whether this phenomenon is already ongoing or not, or still ongoing or not.
3. Under a third interpretation, the fact that an instance of E2 Temporal Entity is ongoing is **not observable** within the fuzzy boundaries.

Consider, for instance, a birth. Extending over a limited and non-negligible duration in the scale of hours it begins and ends gradually (1), but can be given alternative scientific definitions of start and end points (2), and neither of these can be determined with a precision much smaller than on a scale of minutes (3). The fuzzy boundaries **do not** describe the relation of incomplete or imprecise knowledge to reality. Assuming a lowest granularity in time is an approach which does not help, because the relevant extent of fuzziness varies at a huge scale even in cultural reasoning, depending on the type of phenomena considered. The only exact match is between arbitrarily declared time intervals, such as the end of a year being equal to the beginning of the next year, or that "Early Minoan" ends exactly when "Middle Minoan" starts, whenever that might have been. Consequently, we introduce here a new set of "temporal relation primitives" with the following characteristics:

- It is a minimal set of properties that allows for specifying all possible relations between two time intervals given by their start and end points, either directly, or by conjunction (logical AND condition) of the latter.
- Start and end points are interpreted as "thick" fuzzy boundaries as described above.
- Conditions of equality of end points are relaxed to the condition that the fuzzy boundaries **overlap**. Therefore, knowledge of the shape of the fuzzy function is **not** needed.
- All of Allen's relationships can be expressed either directly or by conjunctions of these properties.
- In case of time intervals without or with negligibly short fuzzy boundaries, all of Allen's relationships can exactly be described by adequate conjunctions of these properties.
- No relationship is equal to the inverse of another. Inverses are specified by exchanging the roles of domain and range.

Notation

We use the following notation:

Comparing two instances of E2 Temporal Entity, we denote one with capital letter A, its (fuzzy) starting time with A^{start} and its (fuzzy) ending time with A^{end}, such that $A = [A^{start}, A^{end}]$; we denote the other with capital letter B, its (fuzzy) starting time with B^{start} and its (fuzzy) ending time with B^{end}, such that $B = [B^{start}, B^{end}]$.

We identify a temporal relation with a predicate name (label) and define it by one or more (in)equality expressions between its end points, such as:

A *starts before the end of* B if and only if (⇔) $\mathbf{A^{start} < B^{end}}$

We visualize a temporal relation symbolizing the temporal extents of two instances A and B of E2 Temporal Entity as horizontal bars, considered to be on a horizontal time-line proceeding from left to right. The fuzzy boundary areas are symbolized by an increasing/decreasing colour gradient. The different choices of relative arrangement the relationship allows for are symbolized by two extreme allowed positions of instance A with respect to instance B connected by arrows. The reader may imagine it as the relative positions of a train A approaching a station B. If the relative length of A compared to B matters, two diagrams are provided.

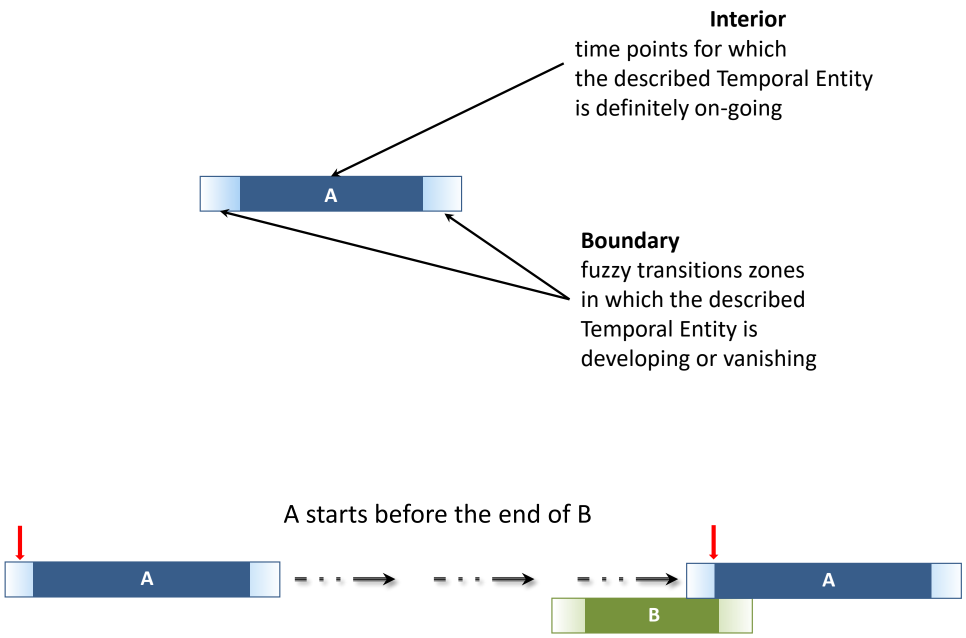

Figure 7: Explanation of Interior and Boundary and an Example of Use from P174 starts before the end of (ends after the start of).

Overview of Temporal Relation Primitives

The final set of temporal relation primitives can be separated into two groups:

1 Those based on improper inequalities, such as $A^{start} \leq B^{end}$ (odd number items in the list below- table 2).

2 Those based on proper inequalities, such as $A^{start} < B^{end}$ (even number items in the list below- table 2).

Improper inequalities with fuzzy boundaries are understood as extending into situations in which the fuzzy boundaries of the respective endpoints may overlap. In other words, they include situations in which it cannot be decided when one interval has ended and when the other started, but there is no knowledge of a definite gap between these endpoints. In a proper inequality with fuzzy boundaries, the fuzzy boundaries of the respective endpoints must not overlap, i.e., there is knowledge of a definite gap between these endpoints, for instance, a discontinuity between settlement phases based on the observation of archaeological layers.

Table 2: Temporal Relation Primitives

	Property	**Interpretation**
1	P173 starts before or with the end of	$A^{start} \leq B^{end}$
2	P174 starts before the end of	$A^{start} < B^{end}$
3	P175 starts before or with the start of	$A^{start} \leq B^{start}$
4	P176 starts before the start of	$A^{start} < B^{start}$
5	P182 ends before or with the start of	$A^{end} \leq B^{start}$
6	P183 ends before the start of	$A^{end} < B^{start}$
7	P184 ends before or with the end of	$A^{end} \leq B^{end}$
8	P185 ends before the end of	$A^{end} < B^{end}$