A Logical Model of an Event Ontology for Exploring Connections in Historical Domains

Ilaria Corda, Brandon Bennett, and Vania Dimitrova

School of Computing, University of Leeds
ilaria,brandon,vania@comp.leeds.ac.uk

Abstract. Exploring connections between events is paramount to any historical investigation. In the course of human occurrences, historians have been always interested in unveiling connections between events for the purpose of establishing the significance of certain happenings and measure their impact. The paper describes a formal model for representing events and comparing temporal dimensions as the backbone for drawing connections and exploring relationships between happenings. The approach is illustrated in a case study from the Astronomical Revolution, a sub-domain of History of Science.

1 Introduction

Historical information is not just a collection of the most significant happenings, treated as distinct and unchained entities. It tells a story, forms a narrative which describes a chronological order and also suggests deeper connections. Hence, the ability to represent events and reason about their temporal relationships are paramount requirements when building a framework for exploring connections between historical occurrences. Understanding historical facts requires knowledge of many aspects of events such as: when and where an event happened, what events preceded or succeeded it, and whether its participants are involved in other events. Whereas ontological approaches are already established within subjects such as Biology and Medicine, domain ontologies for modelling historical domains, e.g. History or Philosophy, are still a relatively unexplored area. This may be attributed to a number of factors: historical domains tend to be both complex and loosely structured, they involve a wide variety of different kinds of entity and relation including temporal, conceptual and physical entities. There is clearly a need for a well-founded and general ontology applicable across historical domains which rigorously characterises the notion of events and formalises their key role within temporal information.

The remainder of this paper is organised as follows. First, we will describe the modelling decisions underpinning our model of an *Event Ontology* and temporal framework. In Section 4, we will illustrate a formal model of an *Event Ontology*, which includes vocabulary, domain, syntax and rules. Furthermore, in Section 6 the notion of semantic links will be introduced and exemplified as a means to construct sequences of semantically-related information. Finally, we will review related works and outline application domains in which our model can be employed.

2 Modelling Events

Events are situated occurrences incorporating complex and rich information which normally refers to the *5W*: *Who* (subject of the event), *What* (object), *When* (temporal dimension), *Where* (spatial dimension) and *Why* (causes and effects). We have developed a generic approach, applicable across historical domains, for modelling historical events and comparing time between them. This was inspired by Davidson's theory of events [5], which lays on the idea that each event-forming predicate is enriched with an extra argument-place to be filled with a variable ranging over event-tokens, which stands for particular dated occurrences. The main advantage is the ability to associate multiple properties to events, such as time, location, and other additional information, thereby avoiding adding extra relations to handle different event dimensions:

$$(\exists \mathrm{e})(\mathrm{born}(\mathrm{Galileo\ Galilei,\ e})\ \wedge\ \mathrm{Time}(\mathrm{e,\ 1564})\ \wedge\ \mathrm{Place}(\mathrm{e,\ 1564}))$$

Davidson's theory of events enabled us to deal with a wide range of historical events, such as scientific events, e.g. observation, discovery, human and social happening, e.g. births, deaths, cooperations and conflicts. In many cases, references to event tokens are hidden within the verbs that are used to describe them and, as in the above example, an additional event token variable is required to articulate the logical form. However, in the historical domain there are also cases where an event token is referred to directly by a naming phrase (what philosophers usually call a definite *description*). For instance wars and battles often have a specific name such as the "battle of Hastings", and historical periods are also referred to in this way, e.g. "Early Modern", and "Scientific Revolution". In such cases a term of the form named_de("Scientific Revolution") is used to refer directly to an event token.

$$\begin{aligned}
\mathrm{named_e}(\textit{``Scientific Revolution''}) \wedge \\
\mathrm{Time\text{-}start}(\mathrm{named_e}(\textit{``Scientific Revolution''}),\ 1543) \wedge \\
\mathrm{Time\text{-}end}(\mathrm{named_e}(\textit{``Scientific Revolution''}),\ 1750) \wedge \\
\mathrm{Place}(\mathrm{named_e}(\textit{``Scientific Revolution''}),\ \mathrm{Europe})
\end{aligned}$$

In the next section, we will discuss the issues of dealing with temporal information in historical domains and present our modelling decisions in that respect.

3 Modelling Time

Temporal information in events has been embedded employing a calendar structure consisting of year, month and day in the form of YYYY-MM-DD. Temporal entities are represented as *time grains* which correspond to particular years, months, and days within the Gregorian calendar structure, also known as a Western calendar. In historical domains, temporal information can be missing due to the fact that historical sources cannot fully reconstruct when exactly a given event occurred, and because of that time dimensions are only partially provided. *Time grains* refer to temporal entities that are considered as atomic, with respect to the temporal granularity with which information can be specified within the historical knowledge base. They correspond to particular time periods embedded within a calendar structure. More specifically, they refer to particular years, months or days within the calendar structure. We have mostly dealt with years as a minimum requirement and months. Instead, the finer day granularity is unusual in our domain. For instance, we are generally aware of the date of birth and death of a scientific figure, e.g. Isaac Newton died the 20th of March 1727, whereas it is quite unusual to hold complete information for events such a conducted experiment, e.g. Galileo Galilei conducted the experiment of falling bodies during 1604. Hence, the granularity in which the temporal information is expressed can vary, and our model needed to allow representing both coarse and fine-grained time dimensions. This particular modelling challenge has been taken into account when defining the semantics of ordering relations over the domain for comparing temporal information in events holding different time granularity. For instance, the time point 1564 is potentially coincident with 1564-04 as both occurred within the temporal span of that year. Comparing time points of different granularity was possible by introducing a weaker form of time inclusion based on the idea of *incidents*. *Incidents* define events that are temporally subordinated or included within a main event and can be applied between different levels of granularity. 1610-10 refines 1610 meaning that 1610-10 is incident within 1610. Hence, the first *time grain* is temporally within the second. In [1] a theory of time which takes intervals as primitives is presented, however the interval relations can be specified in terms of ordering constraints on their end points. We have employed Allen's vocabulary of interval relations to describe temporal relation between events on the basis of their start and end points. All 13 relations, including the converses, have been represented within our model. For instance, the relation *meet*(e_1, e_2) holds when the end point of e_1 is equal to or incident within the beginning e_2, as follows:

$$\text{Meet}(e_1,\ e_2),\ \text{Time-end}(e_1, t_2) =\ \text{Time-end}(e_2, t_4) \text{ or refines}(e_1,\ e_2)$$

In the next section, we will illustrate our *Event Ontology Model*, which includes vocabulary, domain, syntax and a set of inference rules.

4 An Event Ontology Model: Vocabulary and Domain

An Event Ontology is a logical structure such that:

$$\Omega = \langle \mathcal{V}, \mathcal{D}, \Phi, \preccurlyeq, begin, end, location, \delta \rangle$$

where: $\mathcal{V}$ is a vocabulary of symbols; $\mathcal{D}$ is a domain representing all entities in the real world; Φ is the set of all asserted and inferred formulae; $\preccurlyeq$ is an order relationship over the domain $\mathcal{D}$; *begin* and *end*, *location* are functions over the domain; δ is an interpretation structure.

The **vocabulary** $\mathcal{V}$ specifies the sets of non-logical symbols:

$$\mathcal{V} = \langle \mathcal{V}_\mathsf{c}, \mathcal{V}_n, \mathcal{V}_t, \mathcal{V}_h, \mathcal{V}_r, \mathcal{V}_v \rangle$$

where $\mathcal{V}_c$ is the set of concept symbols; $\mathcal{V}_n$ is the set of name symbols; $\mathcal{V}_t$ is the set of *time grain* symbols; $\mathcal{V}_h$ is the set of symbols associated with event tokens (happenings); $\mathcal{V}_r$ is the set of binary relation symbols; $\mathcal{V}_v$ is the set of event-verb symbols.

The **domain** $\mathcal{D}$ specifies the objects from the real world and includes three distinct sub-domains

$$\mathcal{D} \;=\; I \cup E \cup T$$

where I is the set of all individuals. For instance, these can include particular people, places, physical objects and so forth; E is the set of all event tokens. These correspond to particular instances of events, which happen over a particular interval of time. Each event token has been defined following our adaptation of Davidson's theory of events. Event tokens are associated to particular event verbs which bind pairs of individuals known as subject and object of the relation; T is the set of all *time grains*. *Time grains* are particular years, months or days within the calendar structure and may be expressed in terms of any of these different levels of granularity. For example, the year 1066 is considered to be a *time grain* as is June 1965 and 1st April 2020. T consists of the union of all individuals from the three types of temporal entity:

$$T \;=\; Y \cup M \cup D$$

where Y is the set of all years; M is the set of all event months; D is the set of all days. We can define ordering relations on each of the sets of Y, M and D using the order relation $\preccurlyeq$. For instance, Y is a totally ordered set $(Y, \preccurlyeq)$ such that:

$$\forall y_1, y_2 \in Y: \; y_1 \preccurlyeq y_2 \;\vee\; y_2 \preccurlyeq y_1$$

Each *time grain* in T is a tuple including at least an element from Y. There are three possible combinations:

$$\langle y \rangle \;\text{ or }\; \langle y - m \rangle \;\text{ or }\; \langle y - m - d \rangle \;\; where \;\; y \in Y, \;\; m \in M, \;\; d \in D$$

We define two temporal functions *begin* and *end* to map happenings from E to *time grains* from T, as follows:

$$begin : E \to T$$

$$end : E \to T$$

where for every event token $e \in E$ *begin*(**e**) is the *time grain* when e started and *end*(**e**) is the *time grain* when e ended; *begin*(**e**) always precedes *end*(**e**).

Similarly, we define the spatial function *location* to map happenings from E to individuals from I, as follows:

$$location : E \to I$$

where for every event token $e \in E$ *location*(**e**) is the place where e occurred.

The **interpretation structure**

$$\delta = \langle \delta_c, \delta_n, \delta_t, \delta_h, \delta_r, \delta_v \rangle$$

interprets the non-logical symbols from the vocabulary by mapping them to the semantics:

- $\delta_c : \mathcal{V}_c \rightarrow 2^I$ assigns to each concept symbol a subset of individuals in I;
- $\delta_n : \mathcal{V}_n \rightarrow I$ assigns to each name symbol an individual from I;
- $\delta_t : \mathcal{V}_t \rightarrow P$ assigns to each *time grain* symbol a time point from P;
- $\delta_h : \mathcal{V}_h \rightarrow E$ assigns to each event token symbol an event token from E;
- $\delta_r : \mathcal{V}_r \rightarrow 2^{I \times I}$ assigns to each binary relation a subset of pairs from I;
- $\delta_v : \mathcal{V}_v \rightarrow ((I \times I) \rightarrow 2^E)$ assigns to each event-verb symbol a mapping from the set of pairs of individuals $I \times I$ to a subset of event tokens from E.

Example
We illustrate δ_c, δ_r and δ_h:

δ_c(astronomer) = {GALILEO, PTOLEMY, BRAHE ...}

δ_r(explain) = {⟨'GALILEAN THEORY OF TIDES', TIDE⟩, ⟨'KEPLERIAN MOON THEORY', TIDE⟩ ...}

δ_v(observe) = {⟨⟨GALILEO, SUNSPOT⟩, {GAL_OBSERVE_SUNP1, GAL_OBSERVE_SUNP2}⟩,
⟨⟨BRAHE, SUPERNOVA⟩, {BRAHE_OBSERVE_SUP1, BRAHE_OBSERVE_SUNP2}⟩, ⟨⟨BRAHE, STAR SPOT⟩, {}⟩, ...}

5 An Event Ontology Model: Syntax

Our syntax consists of atomic terms and propositions. The terms include Individuals $\mathcal{V}_n = \{a, b, c, \ldots\}$; Time points $\mathcal{V}_t = \{t_1, t_2, t_3, \ldots\}$; Concepts $\mathcal{V}_c = \{C_1, C_2, C_3, \ldots\}$; and Event tokens $\mathcal{V}_h = \{e_1, e_2, e_3, \ldots\}$. The **propositions** are either atomic propositions or propositional constructs. We have defined four types of declared propositions: Concepts and Individuals Propositions, Binary Relations Propositions, Time Propositions and Event Propositions.
Concepts and Individuals Propositions. Concepts and Individuals propositions include atomic propositions which deal with concepts and individuals from the domain.

- $\mathbf{C}_1 \sqsubseteq \mathbf{C}_2$ where $\mathbf{C}_1$, $\mathbf{C}_2 \in \mathcal{V}_c$;
- $\mathbf{C}_1$ (**a**) where $\mathbf{C}_1 \in \mathcal{V}_c$ and $\mathbf{a} \in \mathcal{V}_n$;
- $\mathbf{a} = \mathbf{b}$ where $\mathbf{a}$, $\mathbf{b} \in \mathcal{V}_n$.

Binary Relations Propositions. Binary relations propositions include binary relations between individuals over the domain.

- $\mathbf{R}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}$, $\mathbf{b} \in \mathcal{V}_n$;

- $\mathsf{t}(\mathbf{R})(\mathbf{a}, \mathbf{b})$ where $\mathsf{t}(\mathbf{R}) \in \mathcal{V}_r$ is a transitive relation where $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
- $\mathsf{inv}(\mathbf{R})(\mathbf{a}, \mathbf{b})$ where $\mathsf{inv}(\mathbf{R}) \in \mathcal{V}_r$ is an inverse relation where $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
- $\mathsf{sym}(\mathbf{R})(\mathbf{a}, \mathbf{b})$ where $\mathsf{sym}(\mathbf{R}) \in \mathcal{V}_r$ is a symmetrical relation where $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
- Binary relations introducing a lattice order between individuals. Lattice binary relations resemble the general binary relations between individuals, although they are used to cluster individuals that stand in a hierarchy based on their conceptual generality and specificity. The complete list of lattice relations have been defined, as follows:
  - $\mathsf{sub\_field}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
  - $\mathsf{sub\_phenomenon}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
  - $\mathsf{sub\_theory}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
  - $\mathsf{sub\_law}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
  - $\mathsf{sub\_doctrine}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
  - $\mathsf{sub\_historical\_period}(\mathbf{a}, \mathbf{b})$ where $\mathbf{R} \in \mathcal{V}_r$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$.

Time Propositions. Time propositions model temporal relations between *time grains*.

- $\mathbf{t}_1 = \mathbf{t}_2$ and $\mathbf{t}_1 \approx \mathbf{t}_2$ where $\mathbf{t}_1, \mathbf{t}_2 \in \mathcal{V}_t$. They define different types of *time grains* equality;
- $\mathbf{t}_1 \leq \mathbf{t}_2$ and $\mathbf{t}_1 \lesssim \mathbf{t}_2$ where $\mathbf{t}_1, \mathbf{t}_2 \in \mathcal{V}_t$. They define different types of order relation;
- $\mathbf{t}_1 \geq \mathbf{t}_2$ and $\mathbf{t}_1 \gtrsim \mathbf{t}_2$ where $\mathbf{t}_1, \mathbf{t}_2 \in \mathcal{V}_t$. They have been defined as the converse of $\mathbf{t}_1 \leq \mathbf{t}_2$ and $\mathbf{t}_1 \lesssim \mathbf{t}_2$;
- $\mathsf{begin}(\mathbf{e}, \mathbf{t})$ and $\mathsf{end}(\mathbf{e}, \mathbf{t})$ where $\mathbf{e} \in \mathcal{V}_h$ and $\mathbf{t} \in \mathcal{V}_t$. begin and end satisfy the condition that for any $\mathbf{e}$, where $\mathsf{begin}(\mathbf{e},\mathbf{t}_1)$ and $\mathsf{end}(\mathbf{e},\mathbf{t}_2)$, $\mathbf{t}_1$ and $\mathbf{t}_2$ are of the same granularity.

Event Propositions. Event propositions include event verb relations and associated properties such as location and the equality relation between event tokens. Similar to begin and end, event properties are defined as functional properties mapping an event token $\mathbf{e}$ to an individual from the class of places, respectively.

- $\mathsf{token}(\mathbf{e}, \mathbf{V}(\mathbf{a}, \mathbf{b}))$ where $\mathbf{e} \in \mathcal{V}_h$, $\mathbf{V} \in \mathcal{V}_v$ and $\mathbf{a}, \mathbf{b} \in \mathcal{V}_n$;
- $\mathsf{location}(\mathbf{e}, \mathbf{a})$ where $\mathbf{e} \in \mathcal{V}_h$ and $\mathbf{a} \in \mathcal{V}_n$. Begin, end and location are generic functional relations across historical domains.
- $\mathbf{e}_1 = \mathbf{e}_2$ where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$.

Propositional Constructs Propositional constructs hold a newly introduced proposition name and combine one of more atomic propositions. They include the complete set of Allen's thirteen relationships which defines all possible relations that two distinct *time grain* can have. Six pairs of the event-token propositions are converses.

- precede($\mathbf{e}_1$, $\mathbf{e}_2$) and preceded by($\mathbf{e}_2$, $\mathbf{e}_1$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$;
- start ($\mathbf{e}_1$, $\mathbf{e}_2$) and started by($\mathbf{e}_2$, $\mathbf{e}_1$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$;
- finish($\mathbf{e}_1$, $\mathbf{e}_2$) and finished by($\mathbf{e}_2$, $\mathbf{e}_1$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$;
- meet($\mathbf{e}_1$, $\mathbf{e}_2$) and met by($\mathbf{e}_2$, $\mathbf{e}_1$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$;
- contain($\mathbf{e}_1$, $\mathbf{e}_2$) and during($\mathbf{e}_2$, $\mathbf{e}_1$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$;
- overlap($\mathbf{e}_1$, $\mathbf{e}_2$) and overlapped by($\mathbf{e}_2$, $\mathbf{e}_1$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$;
- equal($\mathbf{e}_1$, $\mathbf{e}_2$) where $\mathbf{e}_1, \mathbf{e}_2 \in \mathcal{V}_h$.

In addition, further propositional constructs can be defined to link elements from the domain D. For example, we have included the following:

- participate($\mathbf{a}$,$\mathbf{e}$) where $\mathbf{a} \in \mathcal{V}_n$ and $\mathbf{e} \in \mathcal{V}_h$;
- instrument($\mathbf{a}$,$\mathbf{e}$) where instrument $\in \mathcal{V}_r$ and $\mathbf{a} \in \mathcal{V}_n$ and $\mathbf{e} \in \mathcal{V}_h$

The **semantic evaluation** of each proposition is defined using the interpretation structure δ and standard set theory. For instance, $C_1 \sqsubseteq C_2$, $\mathbf{t}_1 \approx \mathbf{t}_2$ and participate($\mathbf{a}, \mathbf{e}$) are evaluated as:

$[\![\mathbf{C}_1 \sqsubseteq \mathbf{C}_2]\!] = \text{true} \quad \text{if} \quad \delta_c(\mathbf{C}_1) \subseteq \delta_c(\mathbf{C}_2), \quad \text{otherwise = false}$

$[\![\mathbf{t}_1 \approx \mathbf{t}_2]\!] = \mathit{true} \;\; \mathit{if} \;\; \delta_t(\mathbf{t}_1),\ \delta_t(\mathbf{t}_2),\ (\mathbf{t}_1 = \mathbf{t}_2 \ \text{ or } \ \textit{refined-time}(\mathbf{t}_1, \mathbf{t}_2)), \ \text{otherwise = false}$

$[\![\text{participate}(\mathbf{a}, \mathbf{e})]\!] = \mathit{true} \;\; \mathit{if} \ \text{token}(\mathbf{e}, \mathbf{V}(\mathbf{a}, \mathbf{b})) \text{ or } \text{token}(\mathbf{e}, \mathbf{V}(\mathbf{b}, \mathbf{a})), \ \text{otherwise = false}$

We use a set of **rules** in the form of $\varphi_1, \varphi_2 \Rightarrow \varphi_3$ classified in three main modes:

- *Concept-based mode* includes rules that determine direct and indirect concept-individual inheritance. For instance: $\mathbf{C}_1(\mathbf{a}), (\mathbf{C}_1 \sqsubseteq \mathbf{C}_2) \Rightarrow \mathbf{C}_2(\mathbf{a})$
- *Relation-based mode* includes rules which define transitive, symmetrical inverse relationship closures as well as transitivity on lattice relations. For instance: $\text{trans(R)}(\mathbf{a}, \mathbf{b}),\ \text{trans(R)}(\mathbf{b}, \mathbf{c}) \ \Rightarrow\ \text{R}(\mathbf{a}, \mathbf{c})$ where R is a transitive relation (e.g. influence).
- *Event-based mode* includes rules which define reasoning upon events. For instance: $\text{precede}(\mathbf{e}_1, \mathbf{e}_2),\ \text{contain}(\mathbf{e}_2, \mathbf{e}_3) \ \Rightarrow\ \text{precede}(\mathbf{e}_1, \mathbf{e}_3)$

Rules can be used to derive new knowledge on the basis of established information. In our framework, we needed to derive implicit information from facts which are explicitly declared in our historical knowledge base. For example, from the lattice binary relation sub_field(classical physics, mechanics) and sub_field(mechanics, physics), we might be interested to infer that classical physics is a sub field of physics, by applying transitive closure on the sub_field relation.

6 Semantic Links

Semantic Links are the formal specifications of association patterns that we use to make explicit the links between events and entities on the basis of both factual information and structure of the ontology. Semantic Links follow the form of

$$semantic\_link(link\_type, \chi_1, \chi_2) \Rrightarrow \Omega(\chi_1, \chi_2)$$

χ_1, χ_2 are variables referring to elements in the *Event Ontology Model* Ω and link_type denotes specific connections between those variables, e.g. sub-concept relation. $\Omega(\chi_1, \chi_2)$ is a constraint linking χ_1 and χ_2 expressed in terms of a set of formulas of the Ontology language. *Semantic Links* can also make reference to common elements occurring in facts, e.g. the same person participating in two or more events.

The set of pairs of ontology elements related by a semantic link of type *link_type* will be referred to by $\delta_l(link\_type)$.

Semantic Links are classified in three main modes:

- *Semantic Links associated with Atomic Propositions*. These are links that correspond directly to atomic propositions asserted in the ontology. For instance, we define a link corresponding to the primitive sub-concept relation:

  $$semantic\_link(subclass, \chi_1, \chi_2) \Rrightarrow \{\chi_1 \sqsubseteq \chi_2\}$$

- *Semantic Links associated with Inference Rules*. These are links that correspond to relations that can be inferred from the explicit facts in Ω by logical inference rules. For instance:
  $semantic\_link(indirect\_sub\_concept, \chi_1, \chi_2) \Rrightarrow \{\mathsf{indirect\_sub\_concept}(\chi_1, \chi_2)\}$
- *Semantic Links associated with a condition involving a common element*. These are links that correspond to relations between two elements from Ω depending on their relation to a third intermediate element of Ω. For instance, two events may be linked by having a common participant:

  $$semantic\_link(common\_participant, \chi_1, \chi_2), \Rrightarrow \{\mathsf{participate}(\xi, \chi_1),\ \mathsf{participate}(\xi, \chi_2)\}$$

  For instance:
  $\delta_l(common\_participant) = \{\langle \mathsf{Gal\_Improve\_Tel}, \mathsf{Gal\_Publish\_Sidereus}\rangle, \langle \mathsf{Har\_Observe\_Sunsp}, \mathsf{Gal\_Observe\_Sunsp}\rangle, \ldots\}$

  This indicates that the events of Galileo improving on the invention of the telescope and Galileo publishing Sidereus Nuncius have a common participant, namely Galileo; and the events of Harriot observing the sunspots and Galileo observing the sunspots also have a common participant (the phenomenon of sunspots).

Sequences of *Semantic Links* form our notion of *Semantic Trajectories*, semantically significant paths, which are derived from the *Event Ontology Model* by applying rules to construct paths constituted from relational links among entities and events. *Semantic Trajectories* support exploratory navigation of historical information, as introduced in [2].

7 Related Work

Modelling of events is increasingly gaining widespread attention in the knowledge representation community [15, 17]. There are mainly two kinds of event models: those which facilitate interoperability in distributed event-based systems [12] or enhance accessibility to museum-related information [6], and those developed for specific applications [9] or domains [10]. In particular, there is a lack of event-centred approaches, which provide formal syntax and semantics for modelling domain ontologies [7]. On the other hand, domain-independent formal models of events [14] [12] are not often adequate when modelling specific domains or families of domains, e.g. historical domains. Event-centred approaches in historical domains are often associated with enhancing access to Cultural Heritage collections [8, 16] and representing the underlying semantics of bibliographic records [6]. In [13], events are extracted from various textual data and an event model (SEM) is employed to interlink collection objects along the event dimensions. In [11] and [6] event-based models are employed for describing resources across domains and facilitate semantic interoperability of metadata. Our logical model is based on the event-token reification method as presented by [5], but also provides a formal syntax and semantics for representing relationships between entities and events which integrates our temporal representation. The resulting formal model of an Event Ontology has the ability to make explicit connections between events and entities.

8 Conclusion and Application Domains

We have illustrated a logical model of an Event Ontology, which includes formal syntax, semantics and reasoning rules for defining a generic approach applicable across historical domains. Our approach for representing events was inspired by Davidson's theory of events [5], an event-token reification method which enables linking properties (e.g. location, scientific instrument, and temporal information) to historical events. The logical model of an *Event Ontology* enables one to make explicit links between events and entities on the basis of both factual information and structure of the ontology. We have envisioned that our logical model can be employed in a number of application domains:

– Support search and browsing activities. The event ontology model would serve as a resource gateway for retrieving information associated to each semantic link. A prototypical implementation of the model has been presented in [3].

– Support essay writing. The event ontology model would help students discover key ideas and elicit their connections to support essay writing.

– Construct narratives for museum collections. The event ontology model would assist exploration in collections by generating historical narratives which describe the *contextual reference space* [4] associated to each artefact.

We are currently using our event ontology model to facilitate knowledge discovery for supporting essay writing in the History of Science domain.

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