An Ontological Approach to Unveiling Connections between Historical Events

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Abstract

Knowledge-based Information Systems have been proven to provide intelligent support in several domains. For instance, these systems can be valid tools to help people discover implicit relationships between entities and events. In particular, historical domains are complex and loosely structured, and impose a number of additional challenges (e.g. dealing with temporal information). This paper describes a formal approach for generating *Semantic Trajectories*, logically connected knowledge units, which are derived from an event ontology and refined using inference and connection rules. Such *Semantic Trajectories* would help users discover key ideas and elicit significant connections according to their information seeking goals (e.g. writing an essay). The approach is illustrated in a case study from the History of Science domain, and it also includes evaluation results.
Keywords: *Event Modelling*, *Formal Ontologies*, *History Ontologies*, *Narratives*.

1 Introduction

Seeking out information in historical domains is complex, multifaceted and requires unveiling and exploring new associations and relationships between happenings. Although several event-centred approaches [8, 11, 12, 14] and information systems for handling connections between events have been developed so far [9, 13, 16], there is a lack of formal approaches to build a framework for connecting historical events: our research focuses precisely on this key aspect and aims at combining an event ontology representation and a systematic model for constructing connections between events (*Semantic Trajectories*). Historical domains tend to be both complex and loosely structured and they involve a wide variety of different kinds of entities and relations including temporal, conceptual and physical entities. Central element of any historical investigation is the need of reconstructing a narrative, that is an articulated path, which arranges historical events in a chronological order, but also links them on the basis of deeper and more meaningful connections. Understanding historical facts embraces a journey which sheds light on their participants, temporal and spatial features, preceding and succeeding events, events which involved the same participant, so forth so on. The aim of this paper is to describe a formal approach for generating *Semantic Trajectories*, defined as logically constructed paths derived from an *Event Ontology* and semantically enriched by using a set of rules as well as connection templates definitions. Our approach employs the notion of *Semantic Trajectories* to help users discover key ideas and explore relevant connections. The remainder of this paper is organised as follows. First we will outline the modelling decisions underpinning our event-centred framework. In 3, we will define the notion of *Semantic Link* as a mean for constructing sequences of semantically-related pieces of information. In 4, the notion of *Semantic Trajectories*, that are semantically connected entities or events, will be introduced and exemplified. In 7, we will present our experimental settings and results. Finally, in 8, we will outline our future plans.

2 Representing and Reasoning upon Historical Events

Event-token reification approaches have emerged as a widely popular concept in the domain of Artificial Intelligence [10, 15]. Our approach for representing events was inspired by Davidson's theory of events [7] and 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 correspond to particular dated occurrences. The method of event-token reification, as proposed by Davidson, enables linking properties (e.g. location, scientific instrument and temporal information) to historical events, which are referred to through the use of unique identifiers (event IDs). Its 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. Furthermore, the advantage of employing an event-token reification approach is that the inference process does not require any additional logical apparatus over and above standard first-order predicate logic, thereby the logical validity is always ensured. Following [6], we were able to associate events to domain relations (e.g. invent), instead of linking time parameters to relations, being able to deal with a broad range of historical events, such as scientific events, (e.g. observations, discoveries), human and social occurrences, (e.g. births, deaths, working collaborations and conflicts). The result is a unified way by which time-place related properties are added to instantiated relations. For instance, The event of Hans Lippershey inventing the spyglass in 1608, in the Netherlands, can be represented as follows:

$$(\exists e)(Invent(HansLippershey, spyglass, e) \wedge Place(e, TheNedherlands) \wedge Time(e, 1608))$$

Representing temporal information is paramount when building a framework for modelling and exploring connections between historical occurrences. In order to reason about temporal relationships between events, we have exploited Allen's interval relationships model [1], a temporal reasoning formalism which takes the notion of interval as primitive. Following [1], the thirteen basic relationships have been formally modelled to detect possible temporal relations between pairs of historical events. Particular emphasis has been given to comparing time dimensions of different granularities in events for which the notion of refinements and incidents was introduced [3, 4]. For instance, 1610-10 refines 1610 meaning that 1610-10 is incident within 1610. Two *time* *grains* are said to be incident if they are either equal, (hence of the same granularity), or one refines another by adding temporal elements otherwise missing, i.e. the month. Hence, our semantics of incidents enabled us to employ Allen's vocabulary of interval relations to describe temporal relationships between pairs of historical events whose start and end points can be of different granularities. 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:

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

An illustration of our logical model of an *Event Ontology*, which includes formal syntax, semantics and reasoning rules can be found in [3, 4]. It is important to remark that our Event model[1] has been translated into a Prolog-based implementation which has been initially presented in [2], [5] and further expanded in [4].

3 Semantic Links

Our *Event Ontology Model* underlies the mechanism for drawing connections and exploring relationships between happenings based on the notion of *Semantic Trajectories*. *Semantic Trajectories* are sequences of links, also known as *Semantic Links* through which events are connected and relationships are made explicit on the basis of factual information and ontological structures. We define *Semantic links* using the following notation:

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

where N >= 2 and $\chi_1, \ldots, \chi_n$ are variables referring to elements in the *Event Ontology Model* (Ω); link_type denotes specific connections between those variables and $\Omega(\chi_1, \ldots, \chi_n)$ is a constraint linking at least two variables, χ_1 and χ_n, expressed in terms of a set of formulas from the ontology language. *Semantic Links* can make also reference to common elements occurring in facts, e.g. a particular scientist participating in several events, and the conceptual relations such as that between a concept and sub-concept. Tuples of ontology elements related by a semantic link of type *link_type* will be denoted 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 set membership relation:

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

For instance:

$$\delta_l(isa) = \{\langle \text{tide}, \text{physical phenomenon}\rangle, \langle \text{gravitational force},$$

[1] In [4], we have analysed and compared existing semantic approaches for modelling events and the one discussed in this paper, by presenting a benchmark table that draws and documents solutions on the basis of a set of criteria: Event and Time, Participation, Event Connections, Part-hood and Composition, Formal Model, Implementation, Reusability, Applications.

physical phenomenon⟩, ⟨precession, physical phenomenon⟩, ... }

- *Semantic Links associated with Inference Rules*. These are links that correspond to relations that can be inferred from the explicit facts in the ontology by logical inference rules. For instance:

  $$semantic\_link(indirect\_instance, \chi_1, \chi_2) \Rrightarrow \{\text{indirect\_instance}, \chi_1, \chi_2\}$$

  For instance:

  $$\delta_l(indirect\_instance) = \{\langle\text{lunar eclipse}, \text{phenomenon}\rangle, \langle\text{stellar parallax}, \text{phenomenon}\rangle, \langle\text{retrograde motion}, \text{phenomenon}\rangle, \dots\}$$

- *Semantic Links associated with a condition involving a common element*. These links correspond to relations between two elements from the ontology that depend on their relation to a third intermediate element of Ω. For instance, two events may be linked by having a common participant:

  $$semantic\_link(common\_events, \chi_1, \chi_2) \Rrightarrow \{\text{participate}(\xi, \chi_1), \text{ participate}(\xi, \chi_2)\}$$

  The following example indicates that the events of Galileo Galilei improving on the invention of the telescope and Galileo observing the phenomenon of lunar libration 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):

  $$\delta_l(common\_events) = \{\langle\text{Gal\_Improve\_Tel}, \text{Gal\_Observe\_LunarLibr}\rangle, \langle\text{Har\_Observe\_Sunsp}, \text{Gal\_Observe\_Sunsp}\rangle, \dots\}$$

Gal_Improve_Tel, Gal_Observe_LunarLibr, Har_Observe_Sunsp and Gal_Observe Sunsp are the unique identifiers for particular instances of events (event tokens), which happen over a particular interval of time. Full list of formal specifications and Prolog predicates of *Semantic Link predicates* can be found in [4]

4 Semantic Trajectories Definition

To formally define *Semantic Trajectories*, we first provide the definition of *Generic Semantic Trajectories*, that are are sequences of *Semantic Links* connected through common elements. Let us consider a pair of *Semantic Links* $\langle s_1, s_2\rangle$ where:

$$s_1 = semantic\_link(link\_type, \chi_1, \dots, \chi_2)$$

$$s_2 = semantic\_link(link\_type, \chi_2, \dots, \chi_3)$$

An example of a pair of *Connected Semantic Links* sharing the same event token, Gal_Observe_Sunsp, is:

$$\langle semantic\_link(participate\_event, \text{sunspot}, \text{Gal\_Observe\_Sunsp}),$$

$$semantic\_link(common\_events, \text{Gal\_Observe\_Sunsp}, \text{Harr\_Observe\_Sunsp})\rangle$$

A sequence of *Semantic Links* $\langle s_1, s_2, \ldots, s_n \rangle$ is connected when it consists of sequential pairs of *Connected Semantic Links*, i.e.:

$$\text{For every i } (0 < i < n), \text{ the pair of Semantic Links } \langle s_i, s_{i+1} \rangle \text{ is connected}$$

A *Semantic Trajectory* τ is defined as:

$$\tau = \langle s_1, s_2, \ldots, s_n \rangle$$

where $\langle s_1, s_2, \ldots, s_n \rangle$ is a sequence of *Connected Semantic Links*.

5 Semantic Trajectories Constraints

Semantic Trajectories can be constrained by restricting the number of *Semantic Links*, specifying the starting point (focus), or selecting certain link types.

- **Constraints on the length** of the *Semantic Trajectories*. They are defined as follows:

  $$\tau(k),\ n = k$$

  where k is a specific number of *Connected Semantic Links* which compose the *Semantic Trajectory* τ.

- **Constraints on the link type**. For instance, if we want to simply go through the hierarchy of a concept, we would employ link types associated to taxonomical relations, e.g. subclass, indirect_concept, etc. Given a sequence of link types $L = \langle link\_type_1, link\_type_2, \ldots, link\_type_n \rangle$, a *Semantic Trajectory* based on L is a sequence of *Connected Semantic Links*:

  $$\tau(L),\ L = \langle s_1, s_2, \ldots, s_n \rangle$$

  where for every $i, (1 \leq i \leq n)$

  $$s_1 = semantic\_link(link\_type_i, \chi_1, \ldots, \chi_2)$$

- **Constraints on the focus or foci**. Each *Semantic Trajectory* can have a focus which is either an argument f or a pair of arguments f_1, f_2 corresponding to individuals, concepts or event tokens from the domain. The *Semantic Trajectory* defines relevant connections about the focus argument (or pair of arguments) which can guide the user's exploration of the corresponding domain object. Given an argument f, a *Semantic Trajectory with a focus* f is a sequence of *Connected Semantic Links*:

  $$\tau(f),\ \mathrm{participate}(f, s_1)$$

  where s_1 includes the term f. We have also defined *Semantic Trajectories* with two foci that set the starting and ending arguments of the sequence of *Connected Semantic Links* by finding relational associations between them. Given two arguments f_1 and f_2, a *Semantic Trajectory connecting* f_1 *and* f_2 is a sequence of *Connected Semantic Links*:

  $$\tau(f_1, f_2),\ \mathrm{participate}(f_1, s_1),\ \mathrm{participate}(f_2, s_2)$$

  where s_1 is of the form $semantic\_link(link\_type, f_1, \ldots \chi)$ and s_2 is of the form $semantic\_link(link\_type, \chi, \ldots, f_2)$.

6 Semantic Trajectories Event Connections

Events are situated occurrences involving complex and rich information. For instance, in the History of Science domain, we consider an event e, other events that happened at the same time as e, the scientists involved in e as well as their inventions, discoveries, observations, etc. Furthermore, we can consider how a particular invention, (e.g. the telescope), has been employed in other events, (e.g. the observation of Saturn's handles) or if pairs of events shared the same participant or the same properties, (e.g. same instrument). For validation and evaluation purposes, we have selected the task and topic of *Discuss the impact of the invention of the telescope* that has been broken down into the a number of sub-tasks. These sub-tasks can be further specified into a range of essay questions that, in turn, correspond to *Semantic Trajectories*, for example:

- **Sub-task 1: Basic information about the event - the invention of the telescope** (e.g *Who invented the telescope? When was it invented?*)
- **Sub-task 2: Additional information about of the event subject - the inventor of the telescope**. (e.g. *In which scientific fields did he work?*)
- **Sub-task 3: Additional information about of the event object - the telescope**. (e.g *What are other instruments from the same class?*)
- **Sub-task 4: Relevant events based on common participation**. (e.g. *Which scientific events used the telescope as an instrument?*)
- **Sub-task 5: Relevant events based on similar classes of inventions** (e.g. *Which scientific events happened involving other telescopes?*)
- **Sub-task 6: Temporal relationships between the invention of the telescope and other events** (e.g. *Which scientific events happened after the invention of telescope?*)
- **Sub-task 7: Possible causal connections** (e.g. *Which scientific events are contained within the temporal span of the invention of the telescope and involved its inventor?*)

6.1 Potential Causal Connections

Combining relevance based on common participation and temporal dimension allows constructing *Semantic Trajectories*, which can indicate possible causal relationships between events. We consider that there can be a chance that two events, e_1 and e_2 are causally connected when:

- e_1 and e_2 share the same participant, either subject or object, and e_1 happens before e_2. For example, the event of observing the lunar libration and that of inventing the telescope happened one after another and shared the same participant:

τ(event_verb, common_events_precede), = $\langle$*semantic_link*(event_verb, invent,
Galileo Galilei, Galilean telescope, Gal_Invent_Tel), *semantic_link*(common_events
precede, Gal_Invent_Tel, Gal_Observe_LunarLibr)$\rangle$

- e_1 and e_2 share the same participant, either subject or object, and e_1 happens at the same time as e_2. To construct *Semantic Trajectories* we use link types combining common participation and specific Allen's relations, i.e. common_event contain or common_event_overlap. The following example illustrates that the event of investigating the phenomenon of the sunspots contained that of the writing of the first *Letter on the Sunspots* and shared the same participant, Galileo Galilei:

  τ(event_verb, common_events_contain), = $\langle$*semantic_link*(event_verb, invent,
  Galileo Galilei, Galilean telescope, Gal_Invent_Tel), *semantic_link*(common_events
  contain, Gal_Invent_Tel, Gal_Write_1stLettersunp)$\rangle$

- e_1 happens before or as the same time as e_2 and they involve the same instrument. To construct *Semantic Trajectories* we use link types combining the Allen's relation event_precede and the event property instrument. For example, the Galilean telescope was used in the event of discovering the Venus Phases, which in turn happened after the invention of the telescope itself:

  τ(event_verb, instrument, event_precededby), = $\langle$*semantic_link*(event_verb, invent,
  Galileo Galilei, Galilean telescope, Gal_Invent_Tel), *semantic_link*(instrument,
  Galilean telescope, Gal_Discover_VenPhase), *semantic_link*(event_precededby,
  Gal_Discover_VenPhase, Gal_Invent_Tel)$\rangle$

7 Experimental Study

The overall goal of our study was to perform an application domain-driven assessment of our *Semantic Trajectories* mechanism by collecting and examining History of Science domain experts' ratings on its outputs. For example, an intelligent agent can act as a *domain expert helper*, which directs the student to relevant facts that can be further researched and included in an essay. The *Semantic Trajectories* mechanism can suggest possible domain links which the *domain expert helper* can bring to the student's attention. This scenario underpins the evaluation study presented here. The approach is applied to the sub-domain of the *Scientific Revolution* between the 16th and 18th centuries, with particular emphasis on the *Astronomical Revolution* between the 16th and 17th centuries.

7.1 Objectives

The evaluation study design consists of 4 main objectives:

- **Validation** *Can we generate trajectories that correspond to specific questions and provide knowledge pointers that direct the user to corresponding factual knowledge?*
- **Appropriate Trajectories** *Do the trajectories provide significant clues that can direct a student towards the right content?*
- **Missing Trajectories** *Are there any trajectories that could have been generated, but were not constructed by our mechanism?*
- **Trajectories Combination and Ordering** *Which trajectories can be combined, and what strategies can be used to generate useful sequences of trajectories?*

7.2 Steps

Our evaluation study consists of the following ordered steps:

- **Task Segmentation** - the selected task *Discuss the impact of the invention of the telescope* has been broken down into sub-tasks and are, in turn, linked to essay questions, which correspond to *Semantic Trajectories*;
- **Formulation of a Scenario and Semantic Trajectory Evaluation Criteria** - using the specified task and topic, an evaluation scenario has been formulated. Furthermore, two criteria for evaluating *Semantic Trajectories* have been identified: *Relevance* and *Fitness for purpose*. *Relevance* describes how significant and central a trajectory is with regard to a context it is associated with. On the other hand, the criterion of *Fitness for purpose* describes how useful a trajectory is, that is, it measures its practical use for addressing the essay title;
- **Trajectories Generation** - the *Semantic Trajectories* mechanism has been initially validated by exhausting all permitted combinations of *Connected Semantic Links* up to a certain length. Then, we have generated all possible *Semantic Trajectories* related to the task by focusing them with a specific instance (in our case 'galilean telescope');
- **Trajectories Selection** - The large dataset of focused *Semantic Trajectories* for validation purposes (**404**) has been rated by the author of this work (who has a History of Science background), according to the evaluation criteria. A smaller set of *Semantic Trajectories* (**44**) has been selected for detailed inspection by 2 external domain experts who are the participants of this evaluation study. Author's ratings on the 44 selected trajectories were not analysed because potentially biased;
- **Selected Trajectories Inspection** - The selected 44 trajectories were inspected by 2 History of Science domain experts who provided ratings and comments. The 44 trajectories were presented in form of natural language sentences. For instance, *Galileo Galilei invented the galilean telescope before he observed the phenomenon of lunar libration* translates the first example presented in 6.1.

7.3 Evaluation Criteria

To rate the *Semantic Trajectories* the following questions and scales have been used:

- *Q1 - How relevant is this pointer in order to direct the student while conducting his research and collecting content for the essay type: "Discuss the impact of the invention of the telescope"*? **Scale rating**: 0 = I do not know; 1 = Not relevant for the task at all; 2 = Partially relevant (some parts are relevant, others not); 3 = Relevant, but not essential for the task; 4 = Very relevant for the task.
- *Q2 - Would you give this pointer to the student?* **Scale rating**: 0 = I do not know; 1 = No, I would not give this to the student; 2 = Yes, but I would combine it with other pointer(s), (if possible - use either pointers in the given list or any additional pointers you may suggest); 3 = Yes, given as it is.

7.4 Analysis and Results

We wanted to find out:

- How often the two domain experts agreed upon upper and lower bound trajectories. For example: Relevance = Very Relevant (4) and Fitness for purpose = Yes, I would give it as it is (3);
- How strongly pairs of *Relevance-Fitness for purpose* ratings are related and derive patterns of correlations to be further investigated at the trajectory level (Relevance - Fitness for Purpose Correlation)

We have calculated the Cohen's Kappa measure in order to establish the degree of consensus between the two experts in terms of *Relevance* and *Fitness for purpose*:

		Expert B Relevance					
		I do not know	Not relevant	Partially Relevant	Relevant, not essential	Very Relevant	TOTAL
Expert A Relevance	I do not know	0	0	0	0	0	0
	Not relevant	0	1	0	0	0	1
	Partially Relevant	0	0	5	3	0	8
	Relevant, not essential	1	0	0	11	1	13
	Very Relevant	0	0	0	2	20	22
	TOTAL	1	1	5	16	21	44
	K = 0.78						
	CI = 0.61 – 0.94						

Figure 1: Cohen's Kappa for Relevance

Kappa results can be accepted as significant: *Relevance* 95% CI: [0.61 0.94] and *Fitness for purpose* 95% CI: [0.73 0.99]. Furthermore, the highest number of full Strong Agreements (the two experts agreed on both Relevance and Fitness for purpose) was

		Expert B Fitness for purpose				
		I do not know	No	Yes, but combined	Yes, as it is	TOTAL
Expert A Fitness for purpose	I do not know	9	0	0	0	9
	No	0	1	0	0	1
	Yes, but combined	2	0	18	1	21
	Yes, as it is	0	0	1	12	13
	TOTAL	11	1	19	13	44
	K = 0.86					
	CI = 0.73 - 0.99					

Figure 2: Cohen's Kappa for Fitness

recorded on fully relevant and useful trajectories (**12**), whereas no strong disagreements (Very relevant - No, I would not give it to the student) occurred. In [4], a more qualitative analysis has been conducted at the trajectory level by looking into comments that were written by the two experts.

The correlation coefficient ρ shows a weak positive correlation [0.68 for Expert A and 0.65 for Expert B] for Relevance - Fitness for purpose correlation and was further informed by identifying the common association patterns between the two experts. They were sorted into three types: Strong Association Patterns (4-3 and 1-1); Weak Association Patterns (3-2 or 2-2) and Association Patterns with zeros (0-0), as follows:

Table 1: Experts' Association Patterns by Types

	Expert A Association Patterns	**Expert B Association Patterns**
Strong Association Patterns	**14**	**14**
Weak Association Patterns	**12**	**11**
Association Patterns with zeros	**0**	**1**

7.5 Discussion

The findings of our evaluation study can be discussed in relation to the four main objectives.

Validity The trajectory generation output demonstrates that our mechanism is indeed able to construct sequences of *Semantic Links* that correspond to essay questions associated to each sub-task. The role of the focus has been proven crucial for targeting relevant information.
Appropriateness The objective has been positively evaluated with a significant number of agreements and with the experts' comments which often point at the same issues and/or include similar content.

Missing Trajectories The reason for missing trajectories is twofold: the factual information was not encoded in our ontology or the *Semantic Trajectories* mechanism could not make the connections which would be required because corresponding *Semantic Links* were not specified.

Trajectories Combination Experts' comments on trajectories combinations usually aim at strengthening existing causal relationships between events by unveiling hidden intermediate passages that were left implicit. For a more in-depth analysis on the similarities and as well as differences in the experts' comments, please refer to [4]

8 Conclusion and Future Work

We have developed a formal framework for modelling and exploring historical events and entities. Our approach has been then evaluated in one of the possible application domains where *Semantic Trajectories* can facilitate the process of knowledge discovery for supporting essay writing in the History of Science domain. Future directions can involve the following aspects or research areas:

- **Linking Semantic Trajectories Mechanisms to Existing Digital Collections**. This future improvement requires linking metadata descriptions of cultural heritage objects to elements from the ontology. The linking between metadata descriptions and ontological structures would allow constructing narrative paths on particular information objects.
- **Making Causality Explicit**. Event connections can point at possible cause-effects relations that might be, however, inexplicit or implied. Additional explanatory predicates can be associated with the event connection for pointing at evidence supporting the existence of causal dependencies. For instance, in parallel to generating *Semantic Trajectories*, a list of the facts used the derive the causal connections can be stored. *Semantic Trajectories*).
- **Enabling Flexible Semantic Trajectories Mechanism**
  Semantic Trajectories address specific questions which correspond to sub-tasks of a given task. However, the *Semantic Trajectory* mechanism does not construct trajectories which can depart from a particular link type and explore all possible derivative combinations. A given link type would serve as condition point to exhaust all instantiation entitled by the ontology.

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