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Representing Narratives in Digital Libraries: The Narrative Ontology

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Abstract. Digital Libraries (DLs), especially in the Cultural Heritage domain, are rich in narratives. Every digital object in a DL tells some kind of story, regardless of the medium, the genre, or the type of the object. However, DLs do not offer services about narratives, for example it is not possible to discover a narrative, to create one, or to compare two narratives. Certainly, DLs offer discovery functionalities over their contents, but these services merely address the objects that carry the narratives (*e.g.*, books, images, audiovisual objects), without regard for the narratives themselves. The present work aims at introducing narratives as first-class citizens in DLs, by providing a formal expression of what a narrative is. In particular, this paper presents a conceptualization of the domain of narratives, and its specification through the Narrative Ontology (NOnt for short), expressed in first-order logic. NOnt has been implemented as an extension of three standard vocabularies, i.e. the CIDOC CRM, FRBRoo, and OWL Time, and using the SWRL rule language to express the axioms. On the basis NOnt, we have developed the Narrative Building and Visualising (NBVT) tool, and applied it in four case studies to validate the ontology. NOnt is also being validated in the context of the Mingei European project, in which it is applied to the representation of knowledge about Craft Heritage.

Keywords: Narratives, Digital Libraries, Semantic Web, Ontology, Cultural Heritage, Craft Heritage

1. Introduction

Digital Libraries (DLs) abound with narratives, in the sense that every digital object in a DL tells some kind of story, regardless of the medium, the genre, or the type of the object. This is especially true for DLs in the Cultural Heritage domain [1]. However, there is no track of narratives in the services offered by today's DLs. It is not possible, *e.g.*, to discover a narrative, or to create one, or to compare two narratives. Of course, any DL offers a discovery service over its content; but this service addresses the objects that carry the narratives, whether books, audio-visual messages and the like; narratives *per se* are not addressed. It may be said, in short, that DLs ignore their contents.

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Yet, narratives are central to the documentation of human activity, whether in the cultural, the scientific, or the social area. An art historian willing to tell the reconstructed story surrounding the creation of a painting; a scientist wishing to describe the phases of the development and the validation of a theory; a sociologist wishing to recount the impact of a social media in time. All these knowledge operators would take great advantage of a narrative service. And so would a librarian wishing to provide an account of the process of curating a certain type of collection, or an archivist giving an historical record of the preservation of an item. The only option available to these people is to use text, or an analogous medium, to tell their story. But once so encoded, the narrative is lost to the DL.

Until machines will exhibit the human ability to interpret media contents, one way to overcome the present status is to make narratives emerge as objects of an autonomous data type, different from any other data type, and amenable to (narrative-aware) machine processing. In other words, to make narratives emerge as formal objects, much in the same way other documentation artifacts such as bibliographic records, ontologies and terminologies have emerged as formal objects in time. But to be most effective, formal narratives should not *replace* traditional, informal narratives: rather, they should *enhance* them, by adding a formal dimension to the existing one.

The study of narrative goes back to Aristotle [2] and to the fourth century BC, and has been further elaborated by many philosophers afterwards. The Russian formalists, around the 20s of the last century, have offered an account of narratives that has been used for a systematic study of narrative structure [3]. This account has finally given rise to narratology as an autonomous scientific discipline. According to the Russian formalists, a narrative consists of:

- the *fabula, i.e.*, the story itself as it happened, in reality or in fiction;
- the *narrations, i.e.*, one or more expressions, each in its own language and *medium,* that narrate the fabula. Each narration corresponds to Bal's definition of *presentation* [4];
- the *plot, i.e.*, the story as it is narrated by the narrator. The plot corresponds to the *syuzhet* of the Russian formalists and to Aristotle's *logos.*

Current DLs contain only the *narration* level of the narrative, i.e. the expression of the narrative through a media object. To enhance the representation of narratives in DLs, we propose adding a formal expression of the *fabula* and of the *plot*. The resulting representations would enter the information space of a DL as first-class citizens, enabling an entirely new set of services, able to exploit both the informal and the formal dimension of narratives, and the relation between them. Needless to say, knowledge extraction methods from media objects are central to our proposal, as it will be argued in due course.

The paper presents a research work that significantly extends a previous study [5]. We have defined a conceptualization of the domain of narratives, and we have provided its specification through the Narrative Ontology (NOnt for short), expressed in first-order logic. The ontology has been implemented as an extension of three standard vocabularies, i.e. the CIDOC CRM, FRBRoo, and OWL Time, and using the SWRL rule language to express the axioms. On the basis of the ontology, we have developed the Narrative Building and Visualising (NBVT) tool [6], and applied it in four case studies[1]. NOnt is also being validated in the context of the Mingei European project[2], in which the ontology is used for the representation of knowledge about Craft Heritage [7].

The paper is structured as follows: after describing our methodological approach (Section 2), we report a review of existing works about narrative modelling (Section 3). Section 4 presents a detailed conceptualization of narratives based on narratology, followed by a discussion of narratives in DLs (Section 5). Section 6 presents the NOnt ontology, i.e. a specification of the conceptualization in first-order logic. Section 7 discusses an implementation of NOnt using Semantic Web languages. Section 8 reports the usage of the ontology in two practical scenarios: (i) the Narrative Building and Visualising tool and (ii) the Mingei European project. Section 9 concludes and outlines further developments.

2. Methodological Approach

The methodological approach we followed to introduce narratives as a new functionality in DLs is very similar to the one that characterises a common workflow to develop an algorithm in Computer Science [8], that is:

1. Formalisation of the problem
2. Computational analysis
3. Development of a new algorithm
4. Experimentation with a case study
5. Evaluation

The phases of algorithm development were adapted to our aim. In particular, the adopted methodological approach consists of the following phases:

1. Creation of a conceptualisation of the domain, in which the issue is described and analysed in its main parts.

[1] https://dlnarratives.eu/narratives.html
[2] http://www.mingei-project.eu

2. Development of an ontology as the specification of the conceptualisation in terms of a logical theory whose axioms admit as models those licensed by the conceptualisation.
3. Development of an inference engine for reasoning on knowledge bases conforming to the ontology.
4. Implementation of the ontology using Semantic Web technologies and of the inference engine.
5. Evaluation of the ontology.

In this paper we cover all these phases. The first and second phases are described in Sections 4 and 5, respectively. We note that in most of the cases, the third phase is not necessary, as Semantic Web technologies provide inference engines for ontologies whose axioms are expressible in one of the Semantic Web languages. These engines perform two fundamental tasks: (1) they answer queries and (2) they check the consistency of a knowledge base; in carrying out both tasks, they reason over the ontology, that is they deduce implicit knowledge from the knowledge explicitly given. Now, our ontology includes predicates for representing qualitative temporal knowledge about the intervals of occurrence of events. Using these predicates, it can be stated, for instance, that an event occurred before, or during, another event. For this purpose, our ontology relies on 13 basic temporal relations (BTRs for short), proposed in the seminal work of James Allen [9] to capture all possible ways in which two intervals can relate to each other. Allen also provided transitivity rules that allow deriving implicit temporal relations from known ones. These transitivity rules can indeed be expressed in one of the Semantic Web languages, the SWRL rule language. However, the temporal relations between two intervals become exponentially many if disjunctions of BTRs are used to state temporal knowledge; and in the case of narratives these disjunctions are needed, as it will be shown in Section 6.5. Consequently, transitivity rules become exponentially many, making reasoning over narratives practically impossible. Tractable subsets of BTRs are known to exist for certain domains, but unfortunately, no-one of these known subsets can be applied to our case, as it will also be shown in Section 6.5. We had therefore to search for a tractable subset of BTRs, so as to provide a complete axiomatization of our ontology in SWRL, enabling efficient reasoning on narratives. This research is precisely the third phase of the above methodology, and the good news is that we were able to find a tractable subset of BTRs for our ontology, as reported in Section 6.5 of this paper.

We discuss the fourth phase in Section 7, providing an implementation of NOntusing Semantic Web technologies.

Concerning evaluation, the last phase of the methodology, we note that our ontology is endowed with a reasoning algorithm that is sound, complete and efficient, as just explained. We consider this as a qualitative validation of our work, and a crucial one: without such a reasoning algorithm our ontology would not be usable, given that we aim at *computable* narratives. Of course, a theoretical validation is not sufficient, it must be complemented by a pragmatic one. In this respect, it must be said that the very notion of narrative has been recognized as a complex one, and there is a whole community, that of narratologists, that still tries to understand the fundamental aspects of narrative [10]. Under these circumstances, no ontology can be validated as *the* ontology of narratives. Pragmatically, then, all it can be done is to test a tentative ontology that is promising, to see whether it responds reasonably well to the requirements at hand. This is what we have done with our ontology, by applying it in two evaluation contexts: one in the laboratory and the other on the field in the context of the Mingei project. So far, we have gathered positive feedback in both settings, as detailed in Section 8.

3. Related Works

To define a conceptualisation, we started from the study of Narratology in order to identify the fundamental concepts of narratives. Narratology is a discipline in the Humanities "dedicated to the study of the logic, principles, and practices of narrative representation" [11]. In this research field, the concept of *event* is a core element of narrative. Event is generally intended as an occurrence taking place at a certain time at a specific location. Despite its antecedents in classical theories of aesthetics [2], the theoretical principles of Narratology derive from linguistic-centred approaches to literature defined by Russian formalists in the early 20th century. Russian formalism identified two structural levels of narratives: (i) the *fabula*, i.e. the sequence of events of the narrative in chronological order; (ii) the *syuzhet* (or plot), that is the way in which these events are presented in a narrative [12]. In more recent years, Bal [4] defined a third level, called *presentation*, that constitutes the concrete representation of the content that is conveyed to the audience (*e.g.,* the text in a novel). In Narratology, characters are a fundamental constituent in a story. Aristotle [2] affirms that characters appear in every type of tale. McKee [13] claims that it is not possible to talk about the plot without the characters and vice versa. According to Chatman [14], the elements of a story can be distinguished in: (i) characters, (ii) elements in the scenario. Characters are usually humans or humanoid beings, while the elements in the scenario are places and objects. We used the structural levels of narratives as defined by Russian formalism as the base elements of our conceptualisation.

After this analysis of the Narratology literature, we reviewed the Artificial Intelligence literature and in particular the Event Calculus theory [15–17], in order to understand if the components of narratives had been formally defined in this research field. The Event Calculus (EC) is a logic language for representing actions that have duration and can overlap with each other. In the EC we found the basic elements for representing the fundamental concepts of narratives. The first is the concept of *Fluent* that identifies a function or a predicate that vary over time, used to describe the effects of actions [18]. Two other key concepts are *Events* and *Actions*. In EC the terms Actions and Events are interchangeable and represent changes performed over time. On the other hand, Davidson's theory [19] defines actions as a particular subclass of events, that is the events endowed with intentionality. The last core concept is the *Generalised event*, that is a space-time chunk which generalises concepts like actions, locations, times, and physical objects such as things, animals, agents, humans. The fundamental concepts of narrative extracted from the EC were represented as core elements of our conceptualisation.

Regarding the core concept of event, in the Semantic Web field, various models have been developed for representing events. For example, some of these models are the Event Ontology [20], the Linking Open Descriptions of Events (LODE) [21], the Event-Model-F ontology [22], and the Simple Event Model (SEM) [23]. More general models for semantic data organisation are the CRM [24], the Europeana Data Model [25], and the DOLCE upper level ontology [26]. Among the models reported above, we used the CRM as reference vocabulary for our ontology for narratives, and we took inspiration in particular from the LODE and SEM ontologies in order to represent the factual components of the events [27].

In the Digital Libraries field, narratives have been proposed as functionalities to improve the information discovery and exploration of their contents. In the following, we report several projects that introduced narratives as instruments to explore digital objects and that we took into account in the development of our ontology and software. For example, CultureSampo [28] is a portal and a publication channel for Finnish cultural heritage based on Semantic Web technologies. It uses an event-based model that allows linking events with digital objects, even if it does not define how semantic relations connect events and objects. BiographySampo [29] is a project that aims to develop a system to extract narratives from biographical dictionaries, represent them in a formal way using the CIDOC CRM and other ontologies, and publish them on the Web as Linked Data. The system has been used to build a portal containing more than 13,000 biographies of historical Finnish people. Another example is Bletchley Park Text [30], an application that helps users to explore the collections of museums. Visitors express their interests on some specific topics using SMS messages containing keywords. The semantic description of the resources is used to organise a collection into a personalised Web site based on the keywords chosen by the user. The PATHS system [31] allows creating a personalised tour guide through existing digital library collections. The system defines events linked to each other by semantic similarity relations. The Storyspace system [32] allows describing stories based on events that span museum objects. The focus of the system is the creation of curatorial narratives from an exhibition. Each digital object has a linked creation event in the story of a heritage object. The Labyrinth 3D system [33] integrates the semantic annotation of cultural objects with the interaction style of 3D games. The system immerses the user into a virtual reality, where the user can explore the collection using paths representing the semantic relations over cultural objects.

In comparison with the above systems, our idea is to develop a software that allows creating semantic networks endowed with the events that compose the narratives along with their formal components and the related digital objects. The events are linked to each other with semantic relations.

4. Conceptualisation

This Section presents our view of a computable representation of narrative, as informed by the background reported in Section 3. It introduces the relevant notions both at an informal level and more formally in set-theoretic terms. An initial version of this conceptualisation has been presented in [34]. The present version extends the initial one in several important ways.

Narrative We view a *narrative* as a story told by a narrator, which may be an individual person or a group of persons taking up the role of the narrator. The narrative reflects the point of view of its narrator. The stories in the scope of our work are generally real stories of the present or the past. Fictional stories may also be expressed in our ontology. However, since supporting science is for us more important, these stories have to be consistent with the axioms on physical reality that our ontology is able to capture. This excludes stories in which, for instance, effects precede causes, events nest circularly, and objects bilocate.

A narrative consists of three main elements:

1. the *fabula, i.e.*, the story itself as it happened, in reality or in fiction;
2. the *narrations, i.e.*, one or more expressions, each in its own language and *medium,* that narrate the fabula. Each narration correspond to Bal's definition of *presentation* [4];
3. the *reference, i.e.*, a relation that connects (fragments of) the narrations to (fragments of) the fabula, allowing to derive the *plot* (or *syuzhet*) of the narrative.

Fabula A fabula consists of events, each of which encompasses a significant fragment of the story. We define an event as a group of coherent phenomena situated in space and time. An event is contextualized in terms of the entities that participate in it. In addition to space and time, the other entities that participate in the event can be identified having persistent characteristics of structural nature. They may be physical entities (*e.g.,* people, physical objects) or conceptual entities (*e.g.,* concepts, ideas). Actions, and more generally activities, are special cases of events. In the fabula, the events are ordered chronologically, as defined by Russian formalism. Moreover, the events in a fabula participate in three main relations:

- a *mereological* relation, connecting events to other events that include them as parts, *e.g.*, the birth of a person is an event that is part of the broader event of the life of that person. The event composition relation is a strict partial order, *i.e.*, it is an irreflexive and transitive relation over the fabula's events; consequently, it is asymmetric and more generally acyclic, so that no event is a sub- or super-event of itself or of some other event.
- a *temporal occurrence* relation, associating each event with a time interval during which the event occurs. As such, the temporal occurrence relation is a total function. In turn, time intervals are connected to each other through the 13 relations of Allen's interval algebra [9]. These relations are jointly exhaustive and mutually exclusive, so each pair of events is connected by one and only one Allen relation. Each time interval has a starting and ending time point. Time points are connected to each other by *before*, *after* or *equals* relations;
- a *causal dependency* relation, relating pairs of events such that the occurrence of the former causes the occurrence of latter, *e.g.*, the eruption of the Vesuvius and the destruction of Pompeii. Clearly, a formal account of the causal dependency relation requires a complete knowledge of the laws governing reality, and is out of question. We will confine ourselves to assert that causal dependency is a *strict partial order.* Acyclicity in this case guarantees that no event is at the

same time a cause and an effect of itself or of some other event.

In addition to the features of the individual relations in a fabula stated so far, the following conditions are met by every fabula:

1. The period of occurrence of an event is included in the period of occurrence of any of its super-events.
2. The beginning of occurrence of an event precedes the beginning of occurrence of any event that causally depends on it.

The expression of the inclusion and precedence relations mentioned in the last two statements will be dealt with in Section 6.4, upon considering the representation of temporal knowledge in narratives.

Narrations In a narrative, a fabula may have any number of narrations, each of which has the obvious characteristic of being about the fabula. Intuitively, this aboutness is a notion of *representation* between fabula and narration, in the sense that any narration of the fabula must somehow represent the fabula, in whole or in part. Logically, this amounts to say that any proposition in the narration, whether explicitly or implicitly stated, must be true in the fabula.

Each *narration* has one or more narrators, the authors of the narration, and of a narration content. In general, the narration content is a message and may take any form in which a fabula can be communicated, ranging from text, to audio-visual message, to theatrical enactment *etcetera.* For obvious reasons we are interested in narrations that have at least one digital representation, whether such representation is only the carrier of a non-digital narration (*e.g.*, an audio-visual recording of a theatrical piece) or a born-digital narration (*e.g.*, a born-digital text or a video game). In our conceptualization of a narration, the content will therefore be any media object, *i.e.*, a text, an image, an audio-visual object, or any multimedia complex object that a particular narrator, or group of narrators choose to tell their version of the fabula.

Reference Reference in a narrative is a relation that connects regions of narrations, which we call *narrative fragment* (or simply *fragment*), to events of the fabula. Each fragment is maximal, in that it comprises all portions that narrate the same event.

A fragment is identified in ways that depend on the structure of the narration. For instance, a textual fragment will be a set of disjoint intervals, each giving the boundaries of texts narrating the same event. A fragment that narrates an event e necessarily narrates any super-event of e, and no other event.

Using the reference relation, it is possible to reconstruct the plot of the narrative, that is the sequence of fragments in the order established in the narration by the narrator.

Because a fabula is identified by its composing events, two narrations of the same fabula may differ for any combination of the following:

1. the set of fabula's events narrated by the narrations; each narration may pick a different subset of events, as a way of giving more emphasis to certain aspects of the story;
2. the order in which the selected events are narrated;
3. the expressions used for the narration.

Two narrations offering accounts of the same story that are incompatible, in the sense expressed above, are not narrations of the same fabula. This fact does not prevent to compare the narrations, for instance to appreciate the differences.

5. Representing narratives in DLs

In our view, a Digital Library (DL) should provide digital representations of narratives as first-class citizens. For simplicity, we will call such digital representations "narratives" whenever no ambiguity can arise.

For completeness, the narratives in a DL should encompass all aspects discussed in the previous Section, *i.e.*, narrations, fabulae and reference functions. While it is expected that a DL already possesses narrations in digital forms, our work is motivated by the target of lifting such narrations into narratives, endowing them with a formal representation of the corresponding fabulae, acting as a semantical counterpart of those narrations. Clearly, this "2-level" representation of the narrative allows supporting the union of the use cases supported by the purely syntactical (*i.e.*, based solely on narrations) and the purely semantical (*i.e.*, based solely on fabulae) representations.

From now on, when there is no ambiguity we will speak of the fabula of a narrative meaning the representation of the fabula, as we do for narratives.

A narrative can be constructed in at least two different ways:

- starting from a narration and associating it to a fabula, or
- starting from a fabula and associating it to a narration for it.

In the former case, the involved process is *formalization:* the narration is decomposed into meaningful events and each event is formally represented via statements drawn from the narration; the reference function is used to establish the proper connection between fragments of the narration and the corresponding formalizing events. In the latter case, the involved process is *documentation:* the events of the fabula are given, and the narrative is constructed by linking each of them to a narration fragment that illustrates the event, using for that purpose (the inverse of) the reference function. In either case, automatic or semi-automatic methods can be devised to support the process and make it scale.

It must be noted that either the narration or the fabula of a narrative may provide an incomplete or even an inaccurate account of the story that the narrative is about. In each of them, events may be reported by omitting or mistaking their temporal or spatial occurrence; likewise, the participation of persons in events or the causal dependencies between events may be omitted or mistaken. For this reason, the fabula of a narrative must be treated as a knowledge base (KB for short), that is as a set of statements giving the best available approximation of the fabula according to the narrator of the narrative. The relationship between the real fabula and its representation may be precisely characterized from a logical point of view as follows.

A real fabula f may be seen as a set of possible worlds, namely of the worlds that are compatible with the events in the fabula and the relationships that link these events to each other and to their factual components. Let S_f be the maximal set of formal fabula statements that are true in every world in f. A language for expressing these statements will be introduced in the next Section, but for now it suffices to assume that such language exists. Let k be a non-empty KB with the formal representation of f. Then,

- k is an *accurate* representation of f iff every statement in k is true in the fabula, formally iff $k \models S_f$, where $\models$ is the logical implication relation.
- k is a *complete* representation of f iff k says everything about f, formally iff $S_f \models k$.

Accurate and complete accounts of the fabula are therefore knowledge bases k that are equivalent to S_f, according to intuition. Needless to say, such accurate and complete accounts are idealizations that real representations can only try to approximate.

As a consequence of the inaccuracy or incompleteness of fabulae, and therefore of narratives in general, it may be the case that two narratives provide different versions of the same story, making different statements about the same events, possibly leading to contradiction. For instance, a narrative about the life of Dante Alighieri may include a travel to France as an event, while another narrative may deny the occurrence of that event, for instance by placing Dante at a different location at the same time. Needless to say, the presence of different versions of the same story is not to be seen as accidental or undesirable in a DL. To the contrary, it manifests different point of views that is important, in some cases vital, to document. On the other hand, the arising of logical contradictions in a KB is highly undesirable, because it makes the KB unusable: since everything logically follows from an inconsistent KB, the answers to queries performed against an inconsistent KB will not be reliable.

In order to enable a DL to hold incompatible narratives while at the same time avoiding the rise of inconsistencies, we view each narrative as a separate KB, and a DL as a set of narratives, possibly sharing a common set of factual components that occur in the fabulae of these narratives.

In the present study, we focus on the structure and the operation of single narratives, because they present challenging aspects in their own right, as it will be shown in the rest of the paper.

6. The NOnt ontology

This Section presents an ontology of narratives, called NOnt, which specifies the conceptualization given in the previous Section.

As already pointed out, narrations will be represented by digital media objects; each such object gives a narration of some part of, possibly all, the narrative. Our ontology will not provide machinery to deal with narrations, since they are strongly *medium*-dependent and as such outside the scope of our work. Narrations will be treated as "black boxes" each represented by a different identifier and characterized as instance of a special class. Such class will be an extension point of NOnt , in the sense that it is the part of the ontology where the classes and properties for narration can be plugged, for example they can be drawn from other standard ontologies.

The ontology is expressed in First-Order Logic [35] for maximum expressivity. Due to the fact that a DL includes a *global* KB, that is a set of statements that document the narratives encompassed in the DL, NOnt will be split in two parts: NOntNar including the classes, properties and axioms for expressing individual narratives, and NOntDL including the classes, properties and axioms for expressing the knowledge in the global KB of a DL. Before delving into the definition of the ontology, the next Section discusses some epistemic aspects at the basis of NOnt.

6.1. The $\mathcal{L}_n$ language

Our task requires the identification of a specific first-order language $\mathcal{L}_n$ that is able to capture the intended meaning of our ontology for narratives.

$\mathcal{L}_n$ is derived from the $\mathcal{L}$ presented in [36]. It includes the sentences that are required in order to axiomatise the narratives. As customary in logic, the alphabet of $\mathcal{L}_n$ includes two kinds of symbols: logical and non-logical symbols. The logical symbols are the symbols whose usage and interpretation are fixed. The logical symbols of $\mathcal{L}_n$ are:

- countably many variables $x, y, z \ldots$;
- the equality symbol $=$ naming the well known equality relation;
- the connectives $\neg$ and $\vee$ and the existential quantifier $\exists$.

The non-logical symbols are the domain-dependent symbols. The non-logical symbols of $\mathcal{L}_n$ are:

- countably many constant symbols, or simply constants: $a, b, \ldots$;
- unary and binary predicate symbols.

$\mathcal{L}_n$ includes also predicate symbols required to represent and reason about time in narratives. We defer the discussion of those symbols and of the axioms that define them until Section 6.4.

The terms of $\mathcal{L}_n$ are constants and variables. The atoms of $\mathcal{L}_n$ are expressions of the form $P(t_1, \ldots, t_k)$ where each t_i is a term. A ground atom is an atom $P(t_1, \ldots, t_k)$ where each t_i is a constant. A formula of $\mathcal{L}_n$ is one of the following:

- an atom;
- a co-reference formula of the form $(t_1 = t_2)$, where t_1 and t_2 are terms;
- the negation of a formula $\neg\alpha$;
- the disjunction of two formulas $(\alpha \vee \beta)$;
- an existential quantification of the form $\exists x.\alpha$

A sentence of $\mathcal{L}_n$ is a formula whose variables, if any, are each bound to one quantifier, *i.e.*, a formula with no free variables. As customary, we will consider sentences including the universal quantifier $\forall$ and the connectives $\wedge$ ("and") and $\rightarrow$ ("implies") as part of $\mathcal{L}_n$ obtained as abbreviations of the equivalent sentences using the previously introduced symbols. Furthermore, to simplify the notation we omit universal quantifiers in formulae. All predicate symbols denote pairwise disjoint sets, *i.e.*:

$$A(x) \rightarrow \neg B(x) \tag{1}$$

$$P(x, y) \rightarrow \neg R(x, y) \tag{2}$$

where A and B stand for any two different unary predicate symbols, and P and R stand for any two different binary predicate symbols.

The following equality axioms hold in $\mathcal{L}_n$:

$$x = x \tag{3}$$

$$(x = y) \rightarrow (y = x) \tag{4}$$

$$[(x = y) \wedge (y = z)] \rightarrow (x = z) \tag{5}$$

$$(x = y) \rightarrow [A(x) \equiv A(y)] \tag{6}$$

$$[(x_1 = y_1) \wedge (x_2 = y_2)] \rightarrow [P(x_1, y_1) \equiv P(x_2, y_2)] \tag{7}$$

where A and P are as above.

We adopt the standard first-order semantics to assign meaning to the formulas of $\mathcal{L}_n$.

Table 1
The predicate symbols of NOntNar

Unary Predicate Symbols	
Ev(e)	e is an event
Interval(t)	t is a time interval
Place(p)	p is a place
Partic(c)	c is a participant of the event (*i.e.,* a person, an object or a concept)
Fab(f)	f is a fabula
Nar(a)	a is a narration
MObj(o)	o is a media object
MOFrag(r)	r is a media object fragment
Binary Predicate Symbols	
EP(e_1,e_2)	event e_1 is part of event e_2
EC(e_1,e_2)	event e_1 is causally dependent on event e_2
ETI(e,t)	event e occurs at time interval t
EPlace(e,p)	event e occurs in place p
EPartic(e,c)	event e has participant c
FE(f,e)	fabula f has event e
Cont(n,o)	narration n has content o
OF(o,r)	media object o has fragment r
Ref(r,e)	fragment r is about event e
TINC(t_1,t_2)	interval t_1 includes interval t_2
TIP(t_1,t_2)	interval t_1 starts before interval t_2

6.2. The axioms of the NOntNar ontology

Table 1 lists the unary and binary predicates of the NOntNar ontology. A graphical representation of these predicates is provided in Figure 1. In Figure 2 we reported a view focusing on the event. In the following, we list all the axioms holding on the unary and binary predicates of NOntNar.

The following axioms provide domain and range of binary predicate symbols:

$$\mathsf{EP}(x,y) \rightarrow \mathsf{Ev}(x) \wedge \mathsf{Ev}(y) \quad (8)$$

$$\mathsf{EC}(x,y) \rightarrow \mathsf{Ev}(x) \wedge \mathsf{Ev}(y) \quad (9)$$

$$\mathsf{ETI}(x,y) \rightarrow \mathsf{Ev}(x) \wedge \mathsf{Interval}(y) \quad (10)$$

$$\mathsf{Cont}(x,y) \rightarrow \mathsf{Nar}(x) \wedge \mathsf{MObj}(y) \quad (11)$$

$$\mathsf{OF}(x,y) \rightarrow \mathsf{MObj}(x) \wedge \mathsf{MOFrag}(y) \quad (12)$$

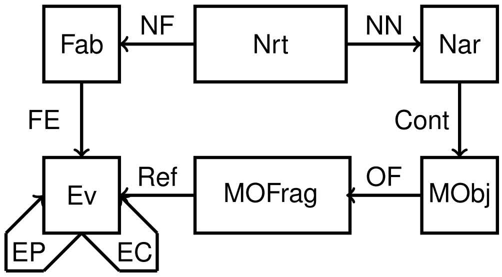

Figure 1. The NOntNar ontology, partial view to be completed by the predicated related to events, shown in Figure 2

$$\mathsf{Ref}(x,y) \rightarrow \mathsf{MOFrag}(x) \wedge \mathsf{Ev}(y) \quad (13)$$

The following cardinality restrictions apply:

– An event has exactly one time interval:

$$\mathsf{Ev}(x) \rightarrow (\exists y)\mathsf{ETI}(x,y) \quad (14)$$

$$\mathsf{ETI}(x,y_1) \wedge \mathsf{ETI}(x,y_2) \rightarrow y_1 = y_2 \quad (15)$$

– An event has exactly one place:

$$\mathsf{Ev}(x) \rightarrow (\exists y)\mathsf{EPlace}(x,y) \quad (16)$$

$$\mathsf{ETI}(x,y_1) \wedge \mathsf{EPlace}(x,y_2) \rightarrow y_1 = y_2 \quad (17)$$

– An event has one or more participants:

$$\mathsf{Ev}(x) \rightarrow (\exists y)\mathsf{EPartic}(x,y) \quad (18)$$

– A fabula has one or more events:

$$\mathsf{Fab}(x) \rightarrow (\exists y)\mathsf{FE}(x,y) \quad (19)$$

– A fabula has one or more narrations:

$$\mathsf{Fab}(x) \rightarrow (\exists y)\mathsf{FN}(x,y) \quad (20)$$

– A narration has exactly one content:

$$\mathsf{Nar}(x) \rightarrow (\exists y)\mathsf{Cont}(x,y) \quad (21)$$

$$\mathsf{Cont}(x,y_1) \wedge \mathsf{Cont}(x,y_2) \rightarrow y_1 = y_2 \quad (22)$$

– A fragment belongs to exactly one media object:

$$\mathsf{MOFrag}(x) \rightarrow (\exists y)\mathsf{OF}(x,y) \quad (23)$$

$$\mathsf{OF}(y_1,x) \wedge \mathsf{OF}(y_2,x) \rightarrow y_1 = y_2 \quad (24)$$

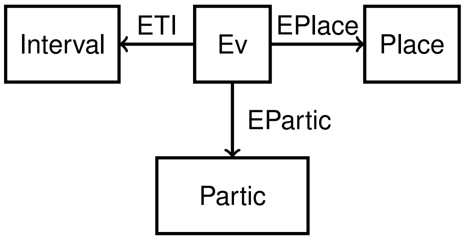

Figure 2. A view of the predicates related to events

We do not admit as consistent the ontologies in which event parthood and causal dependency are cyclic, *i.e.*, in which an event is a sub- or super-event of itself or of some other event, or in which an event is at the same time a cause and an effect of itself or of some other event. Since the relations corresponding to these symbols are transitive, by imposing irreflexivity we have acyclicity:

$$\mathsf{EC}(x,y) \rightarrow \neg(x=y) \tag{25}$$

$$\mathsf{EC}(x,y) \wedge \mathsf{EC}(y,z) \rightarrow \mathsf{EC}(x,z) \tag{26}$$

$$\mathsf{EP}(x,y) \rightarrow \neg(x=y) \tag{27}$$

$$\mathsf{EP}(x,y) \wedge \mathsf{EP}(y,z) \rightarrow \mathsf{EP}(x,z) \tag{28}$$

The next two axioms rule the interaction of event parthood and causal dependency with time. They state that the period of occurrence of an event is included in the period of occurrence of any of its super-events:

$$\mathsf{EP}(x,y) \wedge \mathsf{ETI}(x,i_x) \wedge \mathsf{ETI}(y,i_y) \rightarrow \mathsf{TINC}(i_y,i_x) \tag{29}$$

and that the period of occurrence of an event starts before the period of occurrence of any event that causally depends on it:

$$\mathsf{EC}(x,y) \wedge \mathsf{ETI}(x,i_x) \wedge \mathsf{ETI}(y,i_y) \rightarrow \mathsf{TIP}(i_y,i_x) \tag{30}$$

Finally, a fragment that narrates an event x narrates any super-event of x :

$$\mathsf{EP}(x,y) \wedge \mathsf{Ref}(z,x) \rightarrow \mathsf{Ref}(z,y) \tag{31}$$

Table 2
Unary and Binary Predicates of NOntDL

Unary Predicates	
Nrt(n)	n is a narrative
NGraph(g)	g is a narrative graph
Binary Predicates	
NG(n,g)	narrative n has graph g

Figure 3. A view of the NOntDL ontology

6.3. *The axioms of the NOntDL ontology*

Table 2 lists the unary and binary predicates of the NOntDL ontology. A graphical representation of these predicates is provided in Figure 3. In the following, we list all the axioms holding on the unary and binary predicates of NOntDL .

The two unary predicate symbols are pairwise disjoint:

$$A(x) \rightarrow \neg B(x) \tag{32}$$

Narratives and graphs are one-to-one:

$$\mathsf{NG}(n,g_1) \wedge \mathsf{NG}(n,g_2) \rightarrow g_1 = g_2 \tag{33}$$

$$\mathsf{NGraph}(g) \rightarrow (\exists n)\mathsf{NG}(n,g) \tag{34}$$

$$\mathsf{NG}(n_1,g) \wedge \mathsf{NG}(n_2,g) \rightarrow n_1 = n_2 \tag{35}$$

$$\mathsf{NGraph}(n) \rightarrow (\exists g)\mathsf{NG}(n,g) \tag{36}$$

A digital library is any ontology that includes the above axioms and a set of assertions that connect each narrative to the corresponding NGraph through the NG property. As such, these assertions link the digital library to the graphs containing the formal representations of the narratives that are part of it.

6.4. *Representing time in narratives*

As stated in Section 4, we represent time in narratives using intervals. Sometimes, the time points giving the beginning and the end of such intervals are known and the total ordering relation between time points can be used to express and reason over temporal knowledge in a narrative. However, this is not always the case: in many situations *only* the relative relation between intervals is known, such that an event occurs before, or during another event. In these cases, a relative form of representation is the only viable option. We therefore need a conceptualization of time that supports both time points and intervals, and absolute and relative relations between them.

Our conceptualization includes both time instants and time intervals, along with the following relations:

- two functions connecting a time interval to its beginning and ending time instants, respectively;
- the total ordering between instants;
- the 13 jointly exhaustive and pairwise disjoint relations in Allen's algebra [9] capturing all possible ways in which two intervals can stand to each other in relative terms. In what follows, we shall call these 13 relations as *basic temporal relations* (BTRs, for short). They are given by (see Figure 4 for a graphical illustration):

1. **Equal** (abbreviated as *e*)
2. **Before** (*b*)
3. **After** (*bi*)
4. **Meets** (*m*)
5. **MetBy** (*mi*)
6. **Overlaps** (*o*)
7. **OverlappedBy** (*oi*)
8. **During** (*d*)
9. **Include** (*di*)
10. **Starts** (*s*)
11. **StartedBy** (*si*)
12. **Finishes** (*f*)
13. **FinishedBy** (*fi*).

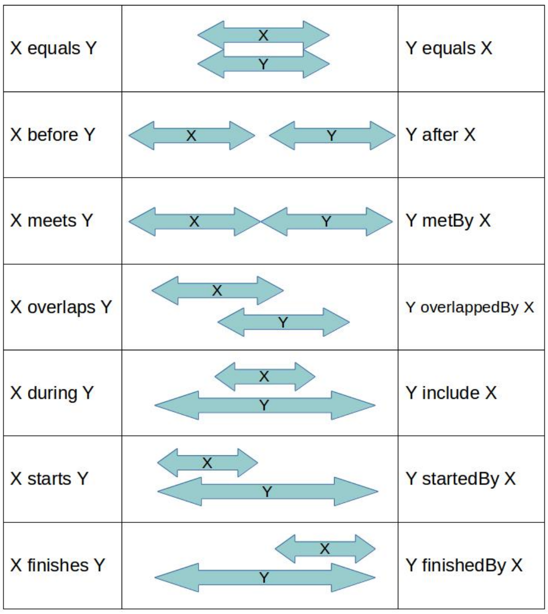

Figure 4. An illustration of Allen's relations between time intervals.

In the last Section, two more relations between time intervals have been introduced, named in $\mathcal{L}_n$ by the TINC and the TIP predicate symbols. These relations can be expressed as the union of BTRs as follows (for simplicity we abuse notation and use the predicate symbols also for the respective relation):

$$\mathsf{TINC} = \cup\,\{e, d, s, f\} \tag{37}$$

$$\mathsf{TIP} = \cup\,\{b, m, o, di, fi\} \tag{38}$$

Reasoning over Allen's temporal relations has been extensively studied in the literature. For reasons of space, we just report the results of these studies that are relevant to the present context. The interested reader may consult, *e.g.*, [37] for a general treatment and [38] for a discussion of temporal reasoning in the context of Semantic Web languages and technologies.

Following Allen's seminal work, the relationships between the time intervals in a narrative are maintained in a network, which will be called "Qualitative Temporal Knowledge" network (QN for short). The nodes of a QTK represent the time intervals in the narrative, while the arcs represent relationships between the intervals corresponding to the conjoined nodes. The arcs are labeled with non-empty sets of Allen relations. Each such set represents the union of its member relations. Specifically, an arc between nodes I and J is labelled by a set L of Allen's relations if and only if the temporal knowledge stored in the network implies that I and J are related by one of the relations in L. For example, the QTK given in Figure 5 stores knowledge about three intervals I, J and K, such that I meets or overlaps both J and K, while J starts K.

At the beginning a QTK is empty. When a set of relations R between two intervals I and J must be asserted, two nodes corresponding to I and J are created, and the arc between them is added, la-

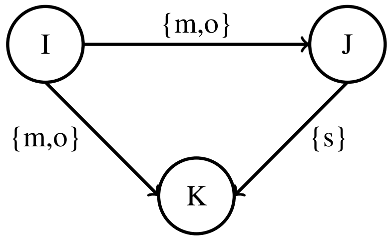

Figure 5. An example of QTK network

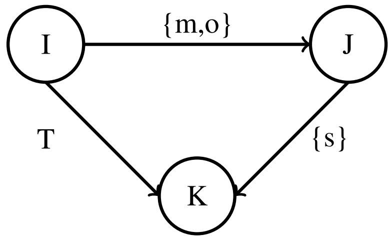

Figure 6. A QTK network including the set of all 13 Allen's relations (T)

belled by R. Now suppose relation set S between nodes J and K needs to be asserted (such as {s} in Figure 5). Correspondingly, node K is added to the network and S is used as a label of the arc connecting J and K. But node K must also be connected to all the other nodes of the network by adding the corresponding arcs, each with the appropriate label. In the example, K must be connected to node I with the appropriate label. In absence of any knowledge, the label is clearly the complete set of Allen's relations meaning that I and K can be related in *any possible way*. However, the known relations between nodes I and J and between J and K may *restrict* the possible relations between I and K. In order to compute these restrictions, *composition* rules are used. A composition rule is a statement about three intervals I, J and K. The statement has a *premise* and a *conclusion* as follows:

1. the premise gives a set of temporal relations between intervals I and J, and a set of temporal relations between intervals J and K;
2. the conclusion gives a set of temporal relations between intervals I and K.

The meaning of a composition rule is the following: if the relations in the premise hold between nodes I and J and between nodes J and K, then only one of the relations in the conclusion may hold between nodes I and K. Every time a QTK network is updated with additional knowledge, the composition rules are applied in order to restrict the relations labelling the arcs of the network. In order to see how, let us consider the QTK in Figure 5 just after the addition of the knowledge that interval J starts (s) interval K, as shown in Figure 6. The arc connecting nodes I and K is labelled with the set of all 13 Allen's relations, indicated by T. To restrict T to only the possible relations that may hold between I and K we use a rule that has as premises the relation sets on arcs I-J and J-K, that is {m, o} and {s} respectively.

By reasoning on intervals with the Allen's relations, it is not difficult to see that the conclusion of this rule is in fact the set {m, o}, therefore the resulting QTK network is the one in Figure 5.

Given that there are $2^{13} - 1$ non-empty temporal relation sets, and that there is a different composition rule for every pair of such sets, there are millions of composition rules. However, composition rules enjoy a nice mathematical property: the conclusions of the rules having non-singleton premises can be efficiently computed from those of the rules having singleton premises. Since the latter kind of rules are of the order of dozens (they are given in [9]), we have a method to efficiently compute the label of any arc of a QTK. However, since the number of possible labels grows exponentially with the number of labelled arcs, and labels need to be re-computed at each update, it may take an exponential amount of time to compute the QTK resulting from an update. This is due to the fact that new labels may be generated for some arcs, which in turn cause new labels to propagate to other arcs of the QTK, and so on. This combinatorial explosion is one problem with QTKs.

A second problem is given by the raise of inconsistencies. To see the problem, suppose that relation *b* is asserted between intervals I and K in Figure 5. Such relation produces an inconsistent QTK due to the fact that *b* is incompatible with both the already asserted relations *m* and *o*. Likewise, an inconsistency may arise from the application of a composition rule that derives, *e.g.*, relation *b* for nodes I and K. Inconsistencies in a QTK can be detected by applying *path consistency* [37], a technique based on the application of the iterative formula for computing R(I,J)$^{n+1}$, that is the label on the arc between any two nodes I and J at step $n + 1$, given the labels between any two nodes at step n. The formula is given by ($\circ$ denotes composition of sets of BTRs):

$$R(I,J)^{n+1} = R(I,J)^n \cap (\cup_{\mathrm{K}}(R(I,K)^n \circ R(K,J)^n)) \tag{39}$$

and it is applied to a QTK until a fix-point is reached, *i.e.*, until the application of the formula does not produce any change in the QTK. If some label equals the empty set, then the QTK is inconsistent. Otherwise, the QTK resulting from path consistency contains labels that are no larger then the labels of the initial QTK and that embody the temporal knowledge currently held in the network. Path consistency can achieve its task in a polynomial amount of time, therefore the second problem does not prevent the efficient management of a QTK.

In order to address the former problem, tractable sets of temporal relations are sought, that is sets $\mathcal{T}$ including disjunctions of BTRs such that $\mathcal{T}$ is closed under intersection and composition, so that the application of path consistency always yields a relation in $\mathcal{T}$. This property clearly prevents the combinatorial explosion of the time needed to compute a QTK following an update, while guaranteeing detection of inconsistencies. In order to perform temporal reasoning over narratives, we have derived a tractable set of temporal relations including the 13 Allen's BTRs and the disjunctions TINC and TIP that we need in order to axiomatize narratives, as explained in Section 6.5. This set, which we call $\mathcal{T}_n$, only includes 81 disjunctions; in the remaining part of this Section we briefly describe its composition and the way it has been derived.

6.5. Minimal tractable set of BTRs

We started from the minimal tractable set of BTRs computed in [38]. The set consists of 28 relations, including the 13 primitive ones plus 15 disjunctions:

{*a*}, {*a, d, di, o, oi, mi, s, si, f, fi, eq*}, {*a, d, oi, mi, f*}, {*a, di, oi, mi, si*}, {*a, oi, mi*}, {*b*}, {*b, d, di, o, oi, m, s, si, f, fi, eq*}, {*b, d, o, m, s*}, {*b, di, o, m, fi*}, {*b, o, m*}, {*d*}, {*d, di, o, oi, s, si, f, fi, eq*}, {*d, o, s*}, {*d, oi, f*}, {*di*}, {*di, o, fi*}, {*di, oi, si*}, {*eq*}, {*f*}, {*fi*}, {*f, fi, eq*}, {*m*}, {*mi*}, {*o*}, {*oi*}, {*s*}, {*s, si, eq*}, {*si*}

This set includes the TINC disjunction representing the precedence relation $\{b, m, o, di, fi\}$, but it does not include the TIP disjunction $\{e, d, s, f\}$, representing the inclusion relation between time intervals. Therefore, it is not suitable for our purposes.

In order to solve this issue, we re-computed the minimal tractable set that includes TIP and TINC, using the path consistency algorithm described and implemented by [38].

In particular, given three nodes I, J and K such that I and J stand in relation $r1$ and J and K stand in relation $r2$, the relation between intervals I and K is given by a transitivity table, i.e. a 13 by 13 array whose entry $(r1, r2)$ gives the composition between the two relations.

The path consistency algorithm starts from an initial set of relations, and from the known transitivity table expressing their compositions. Each time a composition results in a new disjunction not present in the set, the algorithm adds a new row to the transitivity table and computes the composition between this disjunction and each other relation. When no new disjunctions are generated, the execution of the algorithm is stopped and the resulting set of relations is returned to the user.

In our case, the initial set given as input to the algorithm contains the 13 primitive BTRs, plus TIP and TINC. At the end of the process, the resulting set contains 81 relations:

{*a*}, {*a, d, di, o, oi, m, mi, s, si, f, fi, eq*}, {*a, d, di, o, oi, mi, s, si, f, fi, eq*}, {*a, d, oi, mi, f*}, {*a, d, oi, mi, s, si, f, eq*}, {*a, di, oi, mi, si*}, {*a, di, oi, mi, si, f, fi, eq*}, {*a, mi*}, {*a, oi, mi*}, {*a, oi, mi, f*}, {*a, oi, mi, si*}, {*a, oi, mi, si, f, eq*}, {*b*}, {*b, d, di, o, oi, m, mi, s, si, f, fi, eq*}, {*b, d, di, o, oi, m, s, si, f, fi, eq*}, {*b, d, o, m, s*}, {*b, d, o, m, s, f, fi, eq*}, {*b, di, o, m, fi*}, {*b, di, o, m, s, si, fi, eq*}, {*b, m*}, {*b, o, m*}, {*b, o, m, fi*}, {*b, o, m, s*}, {*b, o, m, s, fi, eq*}, {*d*}, {*d, di, o, oi, m, mi, s, si, f, fi, eq*}, {*d, di, o, oi, m, s, si, f, fi, eq*}, {*d, di, o, oi, mi, s, si, f, fi, eq*}, {*d, di, o, oi, s, si, f, fi, eq*}, {*d, f*}, {*d, oi, f*}, {*d, oi, mi, f*}, {*d, oi, mi, s, si, f, eq*}, {*d, oi, s, si, f, eq*}, {*d, o, m, s*}, {*d, o, m, s, f, fi, eq*}, {*d, o, s*}, {*d, o, s, f, fi, eq*}, {*d, s*}, {*d, s, f, eq*}, {*di*}, {*di, fi*}, {*di, oi, mi, si*}, {*di, oi, mi, si, f, fi, eq*}, {*di, oi, si*}, {*di, oi, si, f, fi, eq*}, {*di, o, fi*}, {*di, o, m, fi*}, {*di, o, m, s, si, fi, eq*}, {*di, o, s, si, fi, eq*}, {*di, si*}, {*di, si, fi, eq*}, {*eq*}, {*f*}, {*f, eq*}, {*f, fi, eq*}, {*fi*}, {*fi, eq*}, {*m*}, {*mi*}, {*o*}, {*o, fi*}, {*o, m*}, {*o, m, fi*}, {*o, m, s*}, {*o, m, s, fi, eq*}, {*o, s*}, {*o, s, fi, eq*}, {*oi*}, {*oi, f*}, {*oi, mi*}, {*oi, mi, f*}, {*oi, mi, si*}, {*oi, mi, si,*

Table 3

The temporal predicate symbols of NOntNar

Unary Predicate Symbols	
Ev(e)	e is an event
Interval(t)	t is a time interval
Fab(f)	f is a fabula
Nar(a)	a is a narration
MObj(o)	o is a media object
MOFrag(r)	r is a media object fragment
Binary Predicate Symbols	
IB(t,p)	interval t begins at point p
IE(t,p)	interval t ends at point p
$p_1 < p_2$	point p_1 precedes point t_2
$p_1 = p_2$	point p_1 is equal to point t_2
$p_1 > p_2$	point p_1 follows point t_2
T(t_1,t_2)	interval t_1 is in relation T with interval t_2
$\perp$	the empty relation symbol

f, eq}, {*oi, si*}, {*oi, si, f, eq*}, {*s*}, {*s, eq*}, {*s, si, eq*}, {*si*}, {*si, eq*}.

In order to reason on these 81 relations, it is necessary to explicitly express as rules all the possible compositions and intersections between each pair of relations contained in the set. In theory, this process should yield 6561 composition rules plus 6561 intersection rules, for a total of 13122 rules. In practice, however, many rules can be safely removed because they involve $\{a, b, d, di, o, oi, m, mi, s, si, f, fi, eq\}$, i.e. the disjunction of all basic relations. This disjunction always holds between two intervals, thus it does not add any new information to the graph. By removing the rules involving this disjunction, the final number of rules is reduced to 7671.

6.6. Defining and axiomatizing temporal primitives

We can now complete the expression of the narrative ontology by introducing and axiomatizing the symbols for temporal representation and reasoning.

Table 3 gives the unary and binary temporal predicate symbols. As the Table shows, $\mathcal{L}_n$ also provides time points, for usability in realistic contexts. Consequently, the symbols modelling the ordering of time points and those for linking intervals and their beginning and ending time points are added as well. T stands for each of the 81 binary predicate symbols that are one-to-one with the relations in $\mathcal{T}_n$, allowing users to exploit the full power of the temporal language in manipulating narratives. Finally, the special predicate symbol $\perp$ stands for the empty relation.

The following axioms provide domain, range and cardinality of the symbols linking intervals and time points:

$$\mathsf{Interval}(x) \rightarrow (\exists b)\mathsf{IB}(x,b) \tag{40}$$

$$\mathsf{IB}(x,b) \rightarrow \mathsf{Interval}(x) \wedge \mathsf{TPoint}(b) \tag{41}$$

$$\mathsf{IB}(x,b_1) \wedge \mathsf{IB}(x,b_2) \rightarrow b_1 = b_2 \tag{42}$$

$$\mathsf{Interval}(x) \rightarrow (\exists e)\mathsf{IE}(x,e) \tag{43}$$

$$\mathsf{IE}(x,e) \rightarrow \mathsf{Interval}(x) \wedge \mathsf{TPoint}(e) \tag{44}$$

$$\mathsf{IE}(x,e_1) \wedge \mathsf{IE}(x,e_2) \rightarrow e_1 = e_2 \tag{45}$$

The axioms on the symbols for ordering time points are not given as the corresponding relations are constants and are available in any implementation.

The axioms on the symbols standing for the relations in $\mathcal{T}_n$ are given by the following sets of formulas:

- the set $\mathcal{C}_t$ containing the sentences for the composition of the temporal predicate symbols, each having the form

$$R_1(x,y) \wedge R_2(y,z) \rightarrow R_3(x,z) \tag{46}$$

where each R_i is a temporal predicate symbol;
- the set $\mathcal{I}_t$ containing the sentences for the intersection of the temporal predicate symbols, each having the form

$$R_1(x,y) \wedge R_2(x,y) \rightarrow R_3(x,y) \tag{47}$$

where each R_i is a temporal predicate symbol and R_3 can be $\perp$;
- the set $\mathcal{P}_t$ containing the sentences relating the symbols of the 13 BTRs on time intervals and those on time points. Each such sentence is an if-and-only-if statement, expressing equivalence of one of the Allen's BTRs with a conjunction of atoms on the symbols

$<$, $=$, and $>$ on time points. All these share the sub-formula

$$\mathsf{IB}(x, b_x) \wedge \mathsf{IE}(x, e_x) \wedge \mathsf{IB}(y, b_y) \wedge \mathsf{IE}(y, e_y) \tag{48}$$

which binds the six involved variables in the appropriate way. By abbreviating this formula as $\alpha(x, y)$, the sentence for the before (b) BTR is given by:

$$\alpha(x, y) \rightarrow (\mathsf{before}(x, y) \equiv e_x < b_y) \tag{49}$$

and is clearly equivalent to the two implications

$$(\alpha(x, y) \wedge \mathsf{before}(x, y)) \rightarrow e_x < b_y \tag{50}$$

$$(\alpha(x, y) \wedge e_x < b_y) \rightarrow \mathsf{before}(x, y) \tag{51}$$

Analogously, the two axioms for the overlaps BTR are given by (omitting $\alpha(x, y)$ for simplicity):

$$\mathsf{overlaps}(x, y) \rightarrow (b_x < b_y \wedge e_x < e_y \wedge e_x > b_y) \tag{52}$$

$$(b_x < b_y \wedge e_x < e_y \wedge e_x > b_y) \rightarrow \mathsf{overlaps}(x, y) \tag{53}$$

7. Implementing NOnt using Semantic Web technologies

Ontologies have long been recognized to be a crucial component of the Semantic Web [39]. The recommendation of languages for expressing ontologies is a core activity of the World Wide Web Committee, which has produced a whole family of powerful such languages, collectively known as Ontology Web Language (OWL for short) [40], directly derived from Description Logics. The OWL family has now reached the second generation, OWL 2. It is therefore natural to consider the most expressive decidable language of the OWL family, OWL 2 DL, as a candidate for implementing the narrative ontology NOnt.

In this respect, unary predicate symbols would be implemented as OWL 2 DL classes, while binary predicate symbols would be implemented as OWL 2 DL object or data properties, depending whether the range of a property is a class or a datatype. A wide array of datatypes are also available in OWL 2 DL, amongst which the XML Schema datatype `dateTime`, which would be a most natural candidate for the implementation of time points. Based on this correspondence, the axioms of NOnt would have to be translated into OWL 2 DL axioms, by relying on the rich variety of operators that OWL 2 DL offers to this end. Before considering such translation, however, there are two immediate reasons why OWL 2 DL is not sufficient for implementing NOnt:

1. Properties corresponding to the EC and EP predicate symbols would have to be declared as irreflexive and transitive, to correctly reflect axioms 25 to 28 of NOnt. However, transitive properties are composite in an OWL 2 DL ontology, and as such they cannot be declared to be irreflexive, not to violate the global restrictions on the axioms of an OWL 2 DL ontology [41].
2. Path consistency requires axioms for the composition of temporal properties (given in set $\mathcal{C}_t$). These axioms can be expressed in OWL 2 DL as complex role inclusions. Now, the properties that occur in the right-hand side of complex role inclusions are composite and this would prevent the expression of important axioms on these properties, for instance the axioms stating disjointness from other properties.

Furthermore, declaring the composition of the 81 temporal properties in $\mathcal{T}_n$ would require thousands of complex role inclusion axioms and it would most certainly be impossible to avoid circular definitions, as required by a global restriction on the axioms of an OWL 2 DL ontology. Loosely speaking, two complex role inclusion axioms form a circular definition if one of them has property P in the head and property Q in the body, while the other has property Q in the head and property P, or a property used to define P, in the body.

An alternative to OWL 2 DL, also considered in [38], is the Semantic Web Rule Language (SWRL) [3] a language of the Semantic Web family for specifying Horn clauses [42]. We recall that a Horn clause is a definite program clause (DPC) or

[3] https://www.w3.org/Submission/SWRL/

a definite goal. A DPC r is a $\mathcal{L}_n$ sentence of the form

$$r:\ B_1 \wedge \ldots \wedge B_n \rightarrow A,\ \ n \geqslant 0 \tag{54}$$

where each B_i and A are atoms. The conjunction $B_1 \wedge \ldots \wedge B_n$ is the *body* of the DPC r, while A is the *head.* A DPC clearly resembles a rule, whence the name of the language. If $n = 0$, r is given by

$$r : \rightarrow A \tag{55}$$

and is said to be a *unit* clause; a unit clause is just a notational variant for the atom A. Finally, a definite goal is a DPC with no head.

In order to implement NOnt using SWRL, the axioms of the ontology must be expressed as DPCs. In fact, most of these axioms *already* are DPCs (such as for instance the axioms in $\mathcal{C}_t$, in $\mathcal{I}_t$, or in $\mathcal{P}_t$). Some of the remaining axioms can be easily transformed into DPCs. This is the case of axioms that are implications with a conjunction in their consequent, such as axioms 8 to 13. Each such axiom is equivalent to DPCs that have as body the antecedent of the implication, and as head a different conjunct in the consequent of the implication. For instance, axiom

$$\mathsf{EP}(x,y) \rightarrow \mathsf{Ev}(x) \wedge \mathsf{Ev}(y) \tag{56}$$

is equivalent to the DPCs

$$\mathsf{EP}(x,y) \rightarrow \mathsf{Ev}(x) \tag{57}$$

$$\mathsf{EP}(x,y) \rightarrow \mathsf{Ev}(y) \tag{58}$$

Also axioms that have an equivalence in the head can be easily transformed into DPCs. These axioms are of the form

$$B_1 \wedge \ldots \wedge B_n \rightarrow (A \equiv A') \tag{59}$$

like axioms 6 and 7. Each such axiom is equivalent to the pair of DPCs

$$B_1 \wedge \ldots \wedge B_n \wedge A \rightarrow A' \tag{60}$$

$$B_1 \wedge \ldots \wedge B_n \wedge A' \rightarrow A \tag{61}$$

as it has been already argued concerning the axioms in $\mathcal{P}_t$. Finally, the reflexivity axiom for equality can be replaced by the DCP

$$\neg(x = x) \rightarrow \bot \tag{62}$$

which produces a contradiction whenever an irreflexive axiom is violated.

However, axioms containing negation (such as axiom 1) or the existential quantifier (such as axiom 14) are not trivially reduced to DPCs. The remaining part of this Section shows that these axioms can be dealt with in SWRL, which is chosen as the implementation language of NOnt.

Time points will be implemented as values of the `dateTime` datatype of XML Schema[4], thereby equating the unary predicate symbol TPoint with that datatype.

7.1. Eliminating negation

Since it does not appear in the body of any rule, negation can be handled without resorting to the techniques devised in datalog, such as stratification [43]. A much simpler approach is indeed possible [44], which consists in introducing a new set of predicate symbols, called *complements,* that are one-to-one with the predicate symbols in $\mathcal{L}_n$ and that stand for the negation of the corresponding predicate symbols. Technically, for every predicate symbol P in $\mathcal{L}_n$, we introduce a new predicate symbol called the complement of P. As customary, the complement of the equality symbol $=$ will be denoted as $\neq$, while the complement of any other predicate symbol P will be denoted as $\overline{P}$. We then modify the set of NOnt axioms as follows:

1. replace any instance of the axiom schema 1

$$A(x) \rightarrow \neg B(x) \tag{63}$$

   by the corresponding instance of the schema:

$$A(x) \rightarrow \overline{B}(x) \tag{64}$$

   and add

$$A(x) \wedge \overline{A}(x) \rightarrow \bot \tag{65}$$

2. replace any instance of the axiom schema 2

$$P(x,y) \rightarrow \neg R(x,y) \tag{66}$$

   by the corresponding instance of the schema:

$$P(x,y) \rightarrow \overline{R}(x,y) \tag{67}$$

[4] https://www.w3.org/TR/xmlschema-2/

and add

$$P(x,y) \wedge \overline{P}(x,y) \rightarrow \bot \quad (68)$$

By so doing, a new set of axioms is obtained, which is intuitively equivalent to the initial set, since the two sets state the same sentences in different ways.

7.2. Dealing with existential quantification

As it is well-known, the typical technique for eliminating existentially quantified variables from first-order formulae is Skolemization. Skolemization is performed by replacing every existentially quantified variable y in the scope of n universally quantified variables $x_1, \ldots, x_n$ with a term $f(x_1, \ldots, x_n)$ where f is a new function symbol.

However, Skolemization cannot be applied to reduce a set of axioms to SWRL rules because function symbols are not allowed in SWRL rules. As a consequence, the existentially quantified axioms of NOnt , which are:

$$\mathsf{Ev}(x) \rightarrow (\exists y)\mathsf{ETI}(x,y) \quad (69)$$

$$\mathsf{Nar}(x) \rightarrow (\exists y)\mathsf{Cont}(x,y) \quad (70)$$

$$\mathsf{MOFrag}(x) \rightarrow (\exists y)\mathsf{OF}(x,y) \quad (71)$$

$$\mathsf{Interval}(x) \rightarrow (\exists y)\mathsf{IB}(x,y) \quad (72)$$

$$\mathsf{Interval}(x) \rightarrow (\exists y)\mathsf{IE}(x,y) \quad (73)$$

cannot be transformed into SWRL rules and must therefore be expunged from the SWRL implementation of NOnt. The negative effect of this elimination can be mitigated by considering that the individuals denoted by the existential variables in the above axioms are all unique, as guaranteed by the corresponding cardinality axioms:

$$\mathsf{ETI}(x,y_1) \wedge \mathsf{ETI}(x,y_2) \rightarrow y_1 = y_2 \quad (74)$$

$$\mathsf{Cont}(x,y_1) \wedge \mathsf{Cont}(x,y_2) \rightarrow y_1 = y_2 \quad (75)$$

$$\mathsf{OF}(y_1,x) \wedge \mathsf{OF}(y_2,x) \rightarrow y_1 = y_2 \quad (76)$$

$$\mathsf{IB}(x,y_1) \wedge \mathsf{IB}(x,y_2) \rightarrow y_1 = y_2 \quad (77)$$

$$\mathsf{IE}(x,y_1) \wedge \mathsf{IB}(x,y_2) \rightarrow y_1 = y_2 \quad (78)$$

Moreover, the individuals implied by the first three axioms, *i.e.*, the time interval of an event, the content of a narration, and the media object containing a fragment, are all known at the time when the corresponding ETI, Cont, OF atoms are asserted, therefore we will design the interface of the system in a way that forces the user to specify those individuals.

The situation is different for the last two axioms: the starting and ending points of a temporal interval may not be known at the time when the interval is asserted, and this is in fact the reason why NOnt allows the representation and reasoning about qualitative temporal knowledge. In these last two cases, then, failing the user to provide a data value for each of these points, the system will force temporal constants for them, using these constants as placeholders for the corresponding values about which knowledge can be expressed or inferred by the system.

Table 4
Mapping of NOnt classes with reference ontologies

Class	Linked class
Nrt	subclass of E73 Information Object
Fab	subclass of E4 Period
Nar	subclass of F14 Individual Work
Ev	equivalent to E7 Activity
MObj	subclass of F22 Self-Contained Expression
MOFrag	subclass of F23 Expression Fragment
Interval	equivalent to Proper Interval of OWL Time and to E52 Time-Span

Table 5
Mapping of NOnt properties with reference ontologies

Property	Linked property
FN	subproperty of P148 has component
FE	subproperty of P9 consists of
Cont	subproperty of R9 is realised in
OF	subproperty of R15 has fragment
Ref	subproperty of P129 is about
EP	subproperty of P9 consists of
EC	superproperty of P15 was influenced by
ETI	equivalent to P4 has time-span

7.3. The Ontology Mapping

The first requirement we took into account to develop our ontology was its semantic interoperability. Semantic interoperability is a two-way concept: on the one hand, we aim at widening the usage of our ontology for narratives, by making it re-usable; on the other, we aim at re-using as much as possible of existing ontologies in developing our own. A natural candidate of this latter category is the CIDOC CRM ontology [45], an ISO standard largely employed in the digital library domain. The CRM includes temporal entities for capturing time-dependent concepts such as events; moreover, its harmonisation with the FRBR ontology, known as FRBRoo [46], provides fundamental notions for the modelling of text, such as expressions and expression fragments. To represent the temporal dimension, we also integrated NOnt with OWL Time [47], a domain ontology recommended by the W3C for the representation of time.

Tables 4 and 5 report the mapping between NOnt and the three reference ontologies (CIDOC CRM, FRBRoo, and OWL Time), for classes and properties respectively. In the tables, the classes starting with E and the properties starting with P are from the CIDOC CRM; the classes starting with F and the properties starting with R are from FRBRoo.

To create the mapping, we analysed the definitions of the classes and properties of the three reference ontologies. In particular, we took into account the following versions of the ontologies: (i) CIDOC CRM 6.2.7[5], (ii) FRBRoo 3.0[6], (iii) OWL Time W3C Recommendation of 19 October 2017[7].

The current implementation of the ontology is available on our website, along with the set of SWRL rules that we use for temporal reasoning[8].

In the following Section, we report two examples of applications that show how the ontology is being used in practice.

8. The Ontology in Practice

In this section, we report how the ontology is being used in practice in the context of: (i) the Narrative Building and Visualising Tool (NBVT) [6], and (ii) the Mingei European project, focused on the representation and preservation of Craft Heritage [7].

8.1. Validating the Narrative Ontology using the Narrative Building and Visualising Tool

As we explained in Section 1, in our vision, instead of lists of objects, Digital Libraries should provide narratives as answers to the users' queries, which could be useful for users in order to obtain a more complete knowledge on the subject of their searches. To reach this aim and validate NOnt, we developed the Narrative Building and Visualising Tool (NBVT)[9], a semi-automatic software based on Semantic Web technologies that allows creating narratives and visualising them in several ways [6]. We have applied NBVT to create narratives in four case studies[10]. In particular, two biographical narratives, i.e. (i) on the life of Dante Alighieri, the major Italian poet of the Middle Age; (ii) on the life of the Austrian painter Gustav Klimt. Two other narratives were developed by a researcher in Computational Biology at the CNR to narrate: (i) the history of the discoveries related to the giant squid; (ii) the history of climate change due to human activity.

We have also performed an experiment to explore the integration of our tool with the Europeana digital library, by linking the narrative about Klimt to the digital objects of Europeana [1].

The software we developed is freely available for research aims, and access to the online version of the tool is available on request.

Figure 7 shows the architecture of NBVT, whose main components are the following:

1. *Narrative building interface*. It is used for creating, modifying or visualising a narrative, possibly representing knowledge that has been derived by reading some texts. The user operates through the Graphical User Interface (GUI) of the narrative-building tool, by manually inserting the narrative components (*e.g.,* place, person, object) and, at the same time, importing resources from Wikidata[11] and images from Wikimedia Commons[12]. The created narrative is stored as an intermediate JSON[13] representation;

[5]http://www.cidoc-crm.org/Version/version-6.2.7
[6]http://www.cidoc-crm.org/frbroo/ModelVersion/frbroo-v.-3.0
[7]https://www.w3.org/TR/2017/REC-owl-time-20171019/
[8]https://dlnarratives.eu/ontology/
[9]https://dlnarratives.eu/tool.html
[10]https://dlnarratives.eu/narratives.html
[11]https://www.wikidata.org
[12]https://commons.wikimedia.org/
[13]http://json.org/

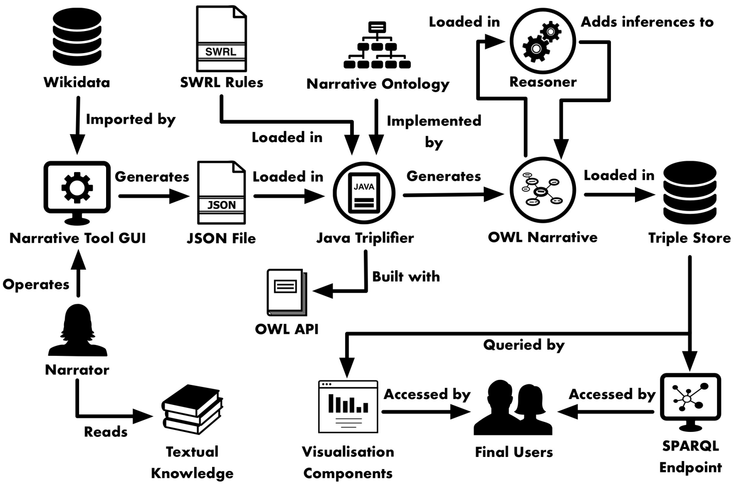

Figure 7. A view of the architecture of NBVT showing also the interactions between its components and its users.

2. *OWL triplifier*. Once the narrative is complete, the corresponding JSON representation is given as input to the Java Triplifier. The triplifier transforms the JSON data into an OWL (Web Ontology Language) ontology encoded as an RDF graph, using the OWL API library [48]. The organization of the knowledge in the graph follows the structure defined in the ontology for narratives we developed.
3. *Semantic reasoner*. It is used by the triplifier to infer new knowledge. The triplifier takes as input also a file with SWRL rules [49] that are used by the reasoner to support the temporal reasoning on the narrative.
4. *Triple store*. The triplifier stores the resulting graph, expanded with inferences produced by both the reasoner and the SWRL rules, into a Blazegraph triple store[14];
5. *Visualisation interface*. Finally, the user can access the knowledge stored in the triple store through a Web interface. The knowledge is extracted using SPARQL queries [50] and visualised in several ways, i.e. as a media-rich timeline, as a set of network graphs, and in table format.

In order to create narratives, the tool assists the user in creating the events that compose the narrative, attempting to minimize the cognitive and technical burden in the selection and identification of the involved entities. This implies support in:

– Defining the factual components that characterize the events, linking each event to persons, place, time, physical and conceptual objects through the appropriate semantic relations.
– Identifying the roles that persons played in the event.
– Defining the type of each event, choosing from a list of predefined options.

Another important set of requirements, especially for narratives created by scholars, came from the necessity of documenting the narrative creation process, allowing users to keep track of their decisions and compare them with the decisions of other users. To this end, the tool allows:

– Defining the primary sources of each event
– Storing the textual fragment, if any, providing a narration of the event in natural language.
– Relating the textual fragment with its narrator.

Figure 8 shows the main interface of NBVT. The tool takes as input resources inserted manually by the user or imported automatically from Wikidata. It also initially imports a few default events from Wikidata, such as births, deaths, marriages, and company foundations. Then, the user adds the remaining events of the narrative one by one, by inserting the following information: (i) the title of the event; (ii) the start and end dates of the event; (iii) the event type; (iv) a set of entities imported from Wikidata or defined by the user (*e.g.*,, person, location, object); (v) for each entity,

[14]https://www.blazegraph.com/

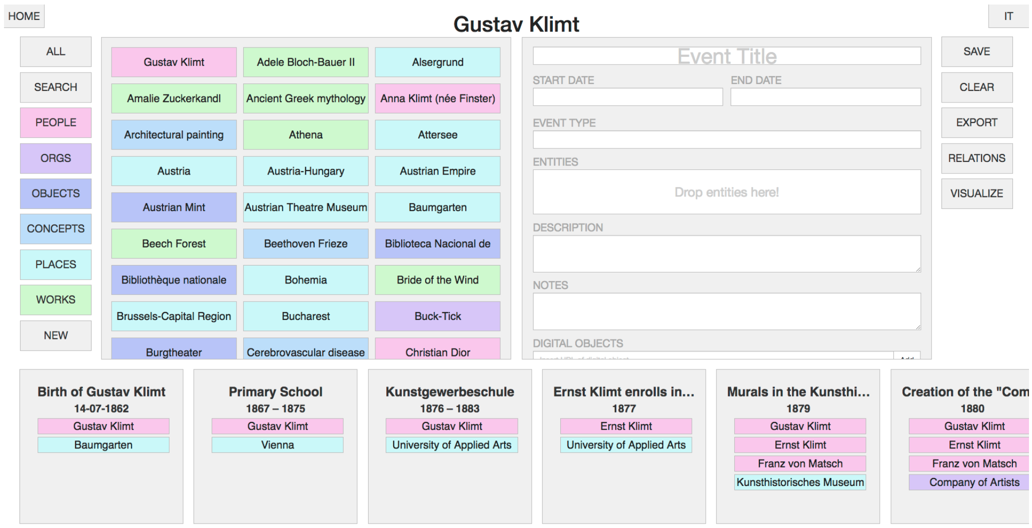

Figure 8. The main interface of NBVT.

one or more primary or secondary sources and, in the case of people, the role they played in the event; (vi) a textual description of the event; (vii) optional textual notes; (viii) one or more digital objects.

In addition to the creation of narrative, the tool supports its management as a digital object, enabling the visualisation and the storage of the narrative in a well-understood format for local download or for sharing it on the Web. Concerning visualisation, we developed predefined SPARQL queries to implement the following functionalities:

– Visualising the fabula of the narrative on a timeline, including for each event: (i) its title, (ii) its textual description, (iii) its time span, (iv) the related entities, (v) the related digital objects, (vi) an image that illustrates the event, (vii) its primary and secondary sources.
– Visualising all events in a narrative, or a subset of them defined by the user, in a tabular form, along with their primary sources. The table is exportable in CSV format.
– Visualising events that happened in a user-specified range of time, also in form of table, exportable in CSV format.
– Visualising an event and its related entities in a graph form, including the relationships that connect the event with other events.
– Visualising a particular resource and its related events in a graph form.

Figure 10 shows an event in the timeline of Klimt's biography, showing the textual description of the event, the related digital object, the primary and secondary sources, the related resources and an image from Wikimedia Commons. Figure 9 shows the graph visualisation of the event of the painting of Klimt's murals in the Burgtheater in Vienna.

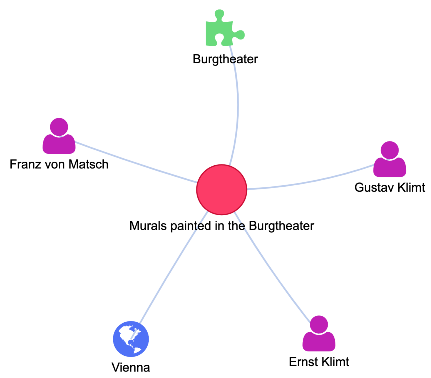

Figure 9. Graph visualisation of the painting of Klimt's murals in the Burgtheater in Vienna.

8.2. *Validating the Narrative Ontology in the Mingei European Project*

As the partner of the project expert in knowledge representation, we applied NOnt within the Mingei European project[15]. This project aims at representing and preserving knowledge about

[15]http://www.mingei-project.eu/

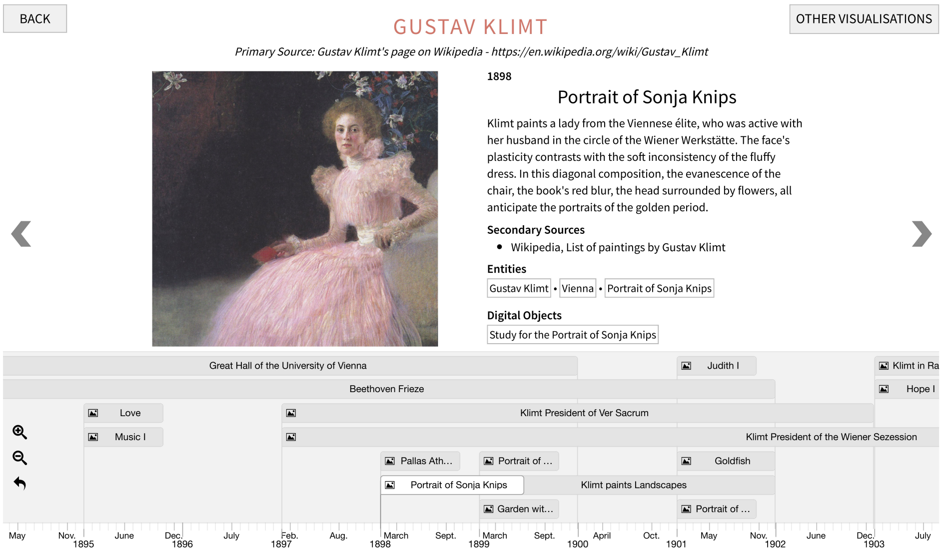

Figure 10. Timeline visualisation of the creation event of Klimt's Portrait of Sonja Knips.

both tangible and intangible aspects of craft as cultural heritage [7].

Heritage Crafts (HCs) involve craft artifacts, materials, and tools and encompass craftsmanship as a form of Intangible Cultural Heritage [51]. Intangible HC dimensions include dexterity, know-how, and skilled use of tools, as well as, tradition, and identity of the communities in which they are, or were, practiced. HCs are part of the history and have impact upon the economy of the areas in which they flourish. The project selected three pilot themes that exhibit richness in tangible and intangible dimensions and are directly related to European history: (i) glass, represented by the Conservatoire National des Arts et Métiers (CNAM) in Paris, France, (ii) silk, represented by the Haus der Seidenkultur museum of Krefeld, Germany, and (iii) mastic, represented by the Chios Mastic Museum in Greece.

In Mingei, we developed the Craft Ontology (CrO for short). CrO is an application ontology that uses NOnt as its core ontology. CrO adds to NOnt features that are useful in the context of the Mingei project, such as the notion of process and that of presentation of a narrative. Moreover, CrO has specific predicates for the chosen pilots (for instance, it specializes the Ev predicate into three Ev predicates, each relative to one of the three domains addressed by the project). The added features and predicates are not reported here because they are not crucial for modelling narratives and as such they are not part of our conceptualization. For interoperability, CrO has been integrated with the CIDOC CRM, FRBRoo and OWL Time relying on the mappings presented in Section 7.3.

The CrO ontology is currently being populated by the experts of the three pilots using the ResearchSpace platform [52].

For reasons of intellectual property rights, we cannot use any of the narratives produced in Mingei in the present paper. Some of the narratives that are being created based on our ontology are about crafts, they narrate how craft masters blow glass, weave silk and process mastic. In addition to these, there are narratives that contextualize crafts, concerning for example the history of the town of Krefeld (a center of silk production in Germany), the history of the silk cloth in the Shrine of Charlemagne and its complex motif including the figure of an elephant, the teaching of glass production at the Conservatoire des Arts et Métiers in Paris, the history of the association of mastic growers on the island of Chios in Greece. These narratives will soon be made accessible to scholars and, via special applications, also to the general public visiting the museums involved in the crafts. An overview can be found in [53].

The main outcome of the Mingei project that is relevant to the present context is that the narrative ontology presented in this paper, forming the conceptual backbone of the CrO, is adequate to support the Mingei activity. The scholars have appreciated in particular the double level of representation offered by the ontology, that is, the fabula (semantic level) and the narration. This double representation allows to overcome the main limitation of the previous projects addressing the same issue, namely the lack of a strong connection between the documents collected about the domain, which form the narration, and the role that these documents play in the general representation of the craft. In sum, Mingei proves that narratives are a powerful digitization tool.

9. Conclusions and Future Work

In the context of the Digital Humanities, and in particular of Digital Libraries focusing on the Cultural Heritage domain, the narration of major cultural or historical events is a very central point. In this article we have presented our research aiming at introducing narratives in Digital Libraries using Semantic Web technologies. In order to do so, we have adopted a methodological approach similar to the one used for developing algorithms in Computer Science. We have followed these phases: (i) conceptualisation, (ii) mathematical specification, (iii) development of an ontology using the Semantic Web languages, and (iv) experimental implementation and validation of the ontology. Before developing the conceptualisation, we have reviewed the Narratology and Artificial Intelligence literature in order to identify the formal components of narratives. First, we have expressed our conceptualisation of narrative in an informal way, then we have formalised this conceptualisation using the first-order logic. In order to represent the first-order logic specification through the technologies of the Semantic Web, we have implemented an ontology for representing narratives, that we call Narrative Ontology (NOnt), as an extension of three standard vocabularies: CIDOC CRM, FRBRoo and OWL Time.

We have reported some examples of the use of the ontology to create narratives through the Narrative Building and Visualising Tool (NBVT) we developed. Furthermore, we have described the application of the ontology within the Mingei European project, in which we use NOnt to represent the knowledge about Craft Heritage. We plan to conduct a full evaluation of the ontology as an output of the Mingei project.

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