SOWL: A Framework for Handling Spatio-Temporal Information in OWL 2.0

Sotiris Batsakis and Euripides G.M. Petrakis

Department of Electronic and Computer Engineering
Technical University of Crete (TUC)
Chania, Greece
e-mail:{batsakis, petrakis}@intelligence.tuc.gr

Abstract. We propose SOWL, an ontology for representing and reasoning over spatio-temporal information in OWL. Building upon well established standards of the semantic web (OWL 2.0, SWRL) SOWL enables representation of static as well as of dynamic information based on the 4D-fluents (or, equivalently, on the N-ary) approach. Both RCC-8 topological and cone-shaped directional relations are integrated in SOWL. Representing both qualitative temporal and spatial information (i.e., information whose temporal or spatial extents are unknown such as "left-of" for spatial and "before" for temporal relations) in addition to quantitative information (i.e., where temporal and spatial information is defined precisely) is a distinctive feature of SOWL. The SOWL reasoner is capable of inferring new relations and checking their consistency, while retaining soundness, completeness, and tractability over the supported sets of relations.

1 Introduction

Ontologies offer the means for representing high level concepts, their properties, and their interrelationships. Dynamic ontologies in addition enable representation of information evolving in time and space. Welty and Fikes [2] showed how quantitative temporal information (i.e., in the form of temporal intervals whose left and right endpoints are well defined) as well as the evolution of concepts in time can be represented effectively in OWL using the so-called "4D-fluents approach".

In our previous work [1], we extended this approach in certain ways: (a) the 4D-fluents mechanism was enchanced with qualitative (in addition to quantitative) temporal expressions allowing for the representation of temporal intervals with unknown endpoints by means of their relation (e.g., "before", "after") to other time intervals, and (b) spatial information was also supported. Accordingly, the spatial representation supports both quantitative and qualitative expressions. However, only basic (non-disjunctive) relations were supported. Neither soundness nor completeness of reasoning were guaranteed.

This work handles all these issues. The expressiveness of the model increases by introducing sets of disjunctive relations by means of SWRL rules and OWL 2.0

constructs. Both, the 4D-fluents and the N-ary relations approach are expanded to accommodate this information. Reasoning implements path consistency [4] and it is sound and complete.

Related work in the field of knowledge representation is discussed in Section 2. This includes issues related to representing and reasoning about information evolving in time and space. The SOWL representation model is presented in Section 3 and the corresponding reasoning mechanism in Section 4, followed by conclusions and issues for future work in Section 5.

2 Background and Related Work

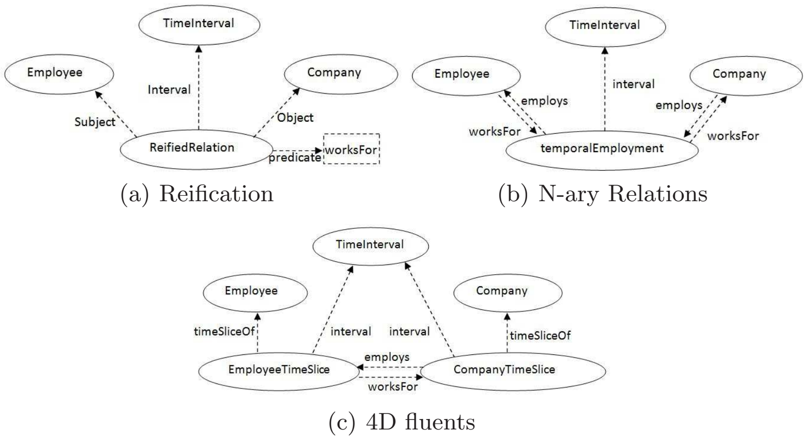
The OWL-Time temporal ontology[1] describes the temporal content of Web pages and the temporal properties of Web services. Apart from language constructs for the representation of time in ontologies, there is still a need for mechanisms for the representation of the evolution of concepts (e.g., events) in time.Representation of time in the Semantic Web can be achieved using *Reification*, *N-ary relations*[2], *temporal RDF* [3], *named graphs* [10] or *4D-fluents* [2].

Reification is a general purpose technique for representing n-ary relations using a language such as OWL that permits only binary relations. Specifically, an n-ary relation is represented as a new object that has all the arguments of the n-ary relation as objects of properties. Fig. 1(a) illustrates the relation *Works-For(Employee, Company, TimeInterval)* representing the fact that an employee works for a company during a time interval. Reification offers limited OWL reasoning capabilities [2] since the n-ary relation is represented as the object of a property and thus OWL semantics over properties (e.g., inverse properties, are no longer applicable). Following the *N-ary relations* approach, the temporal property is represented by two properties each one related with the new object (Fig.1(b)). This approach requires only one additional object for every temporal interval, it maintains property semantics, but it suffers from data redundancy in the case of inverse and symmetric properties (e.g., the inverse of a relation is added explicitly twice instead of once as in 4D-fluents).

The *4D-fluents* (perdurantist) approach [2] suggests that concepts in time are represented as 4-dimensional objects with the 4th dimension being the time (*timeslices*). Following the approach by Welty and Fikes [2], to add a time dimension to an ontology, classes *TimeSlice* and *TimeInterval* with properties *TimeSliceOf* and *timeInterval* are introduced. Properties having a time dimension are called fluent properties and connect instances of class *TimeSlice* (see Fig.1(c)). The 4D-fluents approach still suffers from proliferation of objects, but it maintains full OWL expressiveness and reasoning support.

Representing spatio-temporal knowledge has also motivated research within the Semantic Web community. Katz et al. [5] propose representing RCC-8 topologic relations as OWL-DL class axioms (instead of object properties as in [1]), but this approach has limited scalability as shown in [11]. In our previous work

[1] http://www.w3.org/TR/owl-time
[2] http://www.w3.org/TR/swbp-n-aryRelations



(a) Reification (b) N-ary Relations (c) 4D fluents

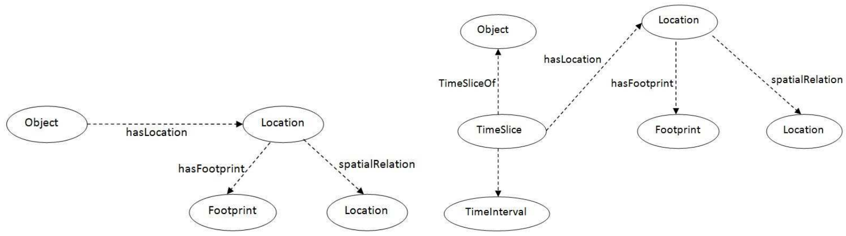
Fig. 1. Example of (a) Reification (b) N-ary Relations and (c) 4D-fluents

[1], we proposed a spatio-temporal representation model supporting both quantitative and qualitative information. The qualitative relations were restricted to basic (non disjunctive) relations.

3 SOWL ontology

In SOWL, the 4D-fluents (or the N-ary representation), is enhanced with qualitative temporal relations holding between time intervals whose left and right endpoints are not specified. This is implemented by introducing temporal relationships as object relations between time intervals. This can be one of the 13 pairwise disjoint Allen's relations [8]. In addition, SOWL supports several types of qualitative spatial relations. These can be either topologic or directional [4]. Fig. 2(a) illustrates the ontology representation of a static (non moving) object. Since the location of the object is a static property, it is a property of the object and not of a timeslice of the object (or the intermediate object introduced by the N-ary approach). Class *Location* has attribute *name* (of type string). Moreover, a *Location* object can be optionally connected with a *footprint* class with subclasses *Point, Line, Polyline, and MBR*, representing points, line segments, surrounding contours of objects (or regions) as sets of consecutive line segments, and Minimun Bounding Rectangles, respectively. In case of a moving object the location is a property of a timeslice belonging to a specific time interval (Fig. 2(b)) or the intermediate object introduced by the N-ary approach.

In an ontology, each *spatialRelation* connects two locations and has two subproperties, namely, *topologicRelation* and *directionalRelation*. The topologic spatial relations between regions can be extracted from their surrounding *MBRs* by comparing their coordinates or contours using computational geometry. In case of point-based representations, directional relations are computed using their



(a) Static Object (b) Moving Object

Fig. 2. Ontology representation of (a) Static and (b) Moving objects

formal definitions [7, 13], while, in case of regions, the directional relations are defined using their centroids. If quantitative information (i.e., location coordinates) is not given, qualitative relations can be asserted into the ontology instead. In this case, the reasoning mechanism will infer additional relations and detect inconsistencies.

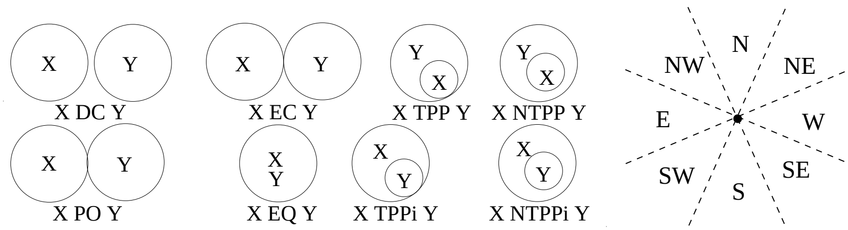


Fig. 3. Topologic relations (left) Directional relations (right) .

The topologic relations holding between two regions *x,y (DC, EC, EQ, NTPP, NTPPi, TPP, TPPi, PO)*, are referred to as RCC-8 relations [6], as shown in Fig. 3 Direction relations holding between two points are defined based on cone-shaped areas [7, 13], as shown in Fig. 3. Nine direction relations can be identified, namely, North (N), North East (NE), East (E), South East (SE), South (S), South West (SW), West (W) North West (NW), and the identical point relation (O), following the cone-shaped areas approach of Frank [7]. Directional relations apply to objects represented by points (e.g., by their centroid).

4 Reasoning in SOWL

Reasoning in SOWL is realized by introducing a set of SWRL[3] rules operating on spatial (topologic or directional) relations as well as by a set of temporal

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

Allen rules for asserting inferred temporal relations. Notice that, OWL does not support role intersection and that (in order to retain decidability[4]) transitivity of properties cannot be combined with property disjointess . In SOWL, path consistency is implemented using SWRL. Reasoners that support DL-safe rules such as Pellet[5] can be used for inference and consistency checking over spatio-temporal relations.

The temporal reasoner implements the compositions of the 13 basic Allen relations defined in [8]. These relations are: *Before, After, Meets, Metby, Overlaps, Overlappedby, During, Contains, Starts, Startedby, Ends, Endedby* and *Equals*. Not all compositions yield a unique relation as a result. For instance, the composition of relations *During* and $Meets$ yields the relation $Before$ as result, while the composition of relations *Overlaps* and *During* yields the three possible relations *Starts, Overlaps, and During.* Rules corresponding to compositions of relations *R1, R2* yielding a unique relation $R3$ can be expressed in SWRL as follows:

$$R1(x, y) \wedge R2(y, z) \rightarrow R3(x, z)$$

An example of temporal inference rule is the following:

$$During(x, y) \wedge Meets(y, z) \rightarrow Before(x, z)$$

Rules yielding a set of possible relations cannot be represented in SWRL since disjuctions of atomic formulas are not permitted as a rule head. Instead, disjunctions of relations are represented using new relations whose compositions have been defined and asserted into the knowledge base. For example, if the relation *DOS* represents the disjunction of relations *During, Overlaps* and *Starts*, then the composition of *Overlaps* and *During* is expressed as:

$$Overlaps(x, y) \wedge During(y, z) \rightarrow DOS(x, z)$$

In addition to the above, inverse axioms (relations *After, Metby, Overlappedby, Startedby, Contains* and $Finishedby$ are the inverses of *Before, Meets, Overlaps, Starts, During* and $Finishes$, respectively) and rules defining the relation holding between two intervals with known starting and ending points (e.g., if the end of $interval1$ is smaller than the start of *interval2*, then *interval1* is *before interval2*) are also asserted into the knowledge base.

Notice that, starting and ending points of intervals are represented using concrete datatypes such as *xsd:date* that support ordering relations. Axioms concerning relations that represent disjunctions of basic relations are defined using the corresponding axioms for these basic relations. Specifically, compositions of disjunctions of basic relations are defined as the disjunction of the compositions of these basic relations. Similarly, the inverse of a disjunction of basic relations is the disjunction of the inverses of these basic relations. For example,

[4] http://www.w3.org/TR/2009/REC-owl2-syntax-20091027

[5] http://clarkparsia.com/pellet

the inverse of the disjunction of relations $Before$ and $Meets$ is the disjunction of the inverse relations of $Before$ and $Meets$ ($After$ and $MetBy$, respectively).

By applying compositions of relations, the implied relations may be inconsistent. Consistency checking is achieved using path consistency [4]. Path consistency is implemented by consecutive applications of suitable instances of the following formula:

$$\forall x, y, k \, R_s(x, y) \leftarrow R_i(x, y) \cap (R_j(x, k) \circ R_k(k, y))$$

representing intersection of compositions of relations with existing relations (the symbol $\cap$ denotes intersection and the symbol $\circ$ denotes composition and symbols R_i, R_j, R_k, R_s denote Allen relations). The formula is applied until a fixed point is reached (i.e., application of rules does not yield new inferences) or until the empty set is reached, implying that the ontology is inconsistent.

An additional set of rules defining the result of intersection of relations holding between two intervals are also introduced. These rules have the form:

$$R1(x, y) \wedge R2(x, y) \rightarrow R3(x, y)$$

where $R3$ can be the empty relation. For instance, the intersection of relation *DOS* (that represents the disjunction of *During, Overlaps and Starts*), and the relation *During* yields the relation *During* as result:

$$DOS(x, y) \wedge During(x, y) \rightarrow During(x, y)$$

Intersection of relations *During* and *Starts* yields the empty relation, and an incosistency is detected:

$$Starts(x, y) \wedge During(x, y) \rightarrow \perp$$

The maximal tractable subset of Allen relations containing all basic relations when applying path consistency comprises of 868 relations [12]. Tractable subsets of Allen relations containing 83 or 188 relations [12] can be used for reasoning as well, offering reduced expessivity, but increased efficiency over the maximal subset. Notice that, the proposed temporal reasoning mechanism affects only relations of temporal intervals and can work equally well in conjunction with either the 4D-fluents or the N-ary relations approach.

The SOWL spatial reasoner implements rules for RCC-8 relations and cone-shaped direction relations using SWRL and OWL 2.0 property axioms. All basic relations are pairwise disjoint. Their inverse relations (e.g., $North$ is the inverse of *South*) are defined as well. Furthermore, the point identity relation (O) is handled using the OWL *SameAs* keyword applied on points instead of explicity asserting the relation. Path consistency is implemented by introducing rules defining compositions and intersections of supported relations until a fixed point is reached or until an incosistency is detected [9, 13].

The directional relations in SOWL (under the assumption that the line separating two 2D cone shaped areas, e.g., $North$ from $North$-$West$, is part of one of these areas, preserving the disjointness of basic relations) are a special case of the revised Star Calculus [13] and therefore are decided by path consistency when applied on basic relations. Furthermore, given a tractable set of relations and by applying compositions, intersections and inverse operations until a set of relations that is closed under these operations is yielded, the resulting set of relations is also tractable [4]. By applying this method (*closure method*) on the basic directional relations, a tractable set of relations containing the basic directional relations and all relations appearing as the result of their composition is yielded. This set of directional relations is used for directional spatial reasoning.

Reasoning on RCC-8 relations also combines OWL property axioms along with a set of composition rules (i.e., rules defining compositions of RCC-8 relations) and intersection rules. Specifically, relations *DC, EC* and *PO* are symmetrical, and relations *NTPPi* and *TPPi* are inverse of *NTPP* and *TPP*, respectively. In SOWL, the spatial reasoner implements the RCC-8 composition rules defined in [9]. Notice that, extracting spatial relations from the raw spatial data depends on the application and is not part of the reasoning mechanism. In contrast to the model presented in [1], the proposed model is extended with additional relations corresponding to disjunctions of basic relations. Notice that using the full set of relations ($2^8 - 1$ relations in case of RCC-8) leads to intractability since this set cannot be decided by path consistency. However, tractable subsets of the full set are known to exist [4, 12]. Such subsets are used in this work offering increased expressive power while retaining tractability.

The resulting OWL ontology it is decidable, since it complies with OWL 2 specifications. and does not contain role inclusion axioms with cyclic dependences or restrictions on composite (e.g., transitive) properties. Introducing the set of temporal qualitative rules of Section 4 retains decidability since rules are DL-safe rules[6] and they apply only on named individuals of the ontology Abox using Pellet (which support DL-safe rules). Furthermore, computing the rules has polynomial time complexity since tractable subsets of Allen's temporal and RCC-8 and directional spatial relations are used. The selection of these tractable subsets is a design decision representing a tradeoff between expressiveness and efficiency.

As shown in [4], by restricting the supported relations set to a tractable subset of Allen's interval algebra (and the corresponding RCC-8 and directional spatial relations), path consistency has $O(n^5)$ worst time complexity (with n being the number of intervals) and is sound and complete. Also, any time interval (or location) can be related with every other interval (or location) by at most k relations, where k is the size of the set of supported relations. Therefore, for n intervals or locations, using $O(k^2)$ rules, at most $O(kn^2)$ relations can be asserted into the knowledge base. Note that, extending the model to the full set of relations would result into an intractable reasoning procedure. Applying the *closure method* over Allen, RCC-8, and directional relations, the minimal tractable sets containing the basic relations consist of 29,49, and 33 relations,

[6] http://www.w3.org/TR/rif-rdf-owl

respectively. For these sets, the required number of OWL axioms and SWRL rules are 983, 1439, and 964, respectively.

5 Conclusions and Future Work

We introduce SOWL, an ontology capable of handling spatio-temporal information in ontologies. The SOWL model extends our previous work [1] to handle both quantitative and qualitative spatial and spatio-temporal information using a sound and complete reasoning method based on path consistency. Incorporating additional forms of information (e.g., size and distance information) and addressing performance and scalability issues for large scale applications are important issues for future research.

References

1. S. Batsakis, and E.G.M. Petrakis. “SOWL: Spatio-temporal Representation, Reasoning and Querying over the Semantic Web” 6th International Conference on Semantic Systems, pp. 1-9, Graz, Austria, 1–3 September 2010.
2. C. Welty and R. Fikes. “A Reusable Ontology for Fluents in OWL”. *Frontiers in Artificial Intelligence and Applications*, 150:226–236, 2006.
3. C. Gutierrez, C. Hurtado, and A. Vaisman. “Introducing Time into RDF”. In IEEE Trans. on Knowledge and Data Engineering, 19(2) , pp. 207-218, 2007.
4. J. Renz, and B. Nebel. “Qualitative Spatial Reasoning using Constraint Calculi”. In Handbook of Spatial Logics, Springer, Netherlands , pp. 161-215, 2007.
5. Y. Katz, and B. Grau. “Representing Qualitative Spatial Information in OWL-DL”. In Proc. of Int. Workshop: OWL Experiences and Directions, Galway, Ireland, 2005.
6. D. Randell, Z. Cui, and A. Cohn. “A Spatial Logic Based on Regions and Connection”. In Proc. 3rd Int. Conf. on Knowledge Representation and Reasoning, Morgan Kaufmann, San Mateo , pp. 165-176, 1992.
7. A. Frank. “Qualitative Spatial Reasoning : Cardinal Directions as an Example”. In Int. Journal of Geographic Information Systems. 10(3), pp. 269-290, 1996.
8. J. F. Allen. “Maintaining Knowledge About Temporal Intervals”. *Communications of the ACM.* 26:832-843, 1983.
9. A. Cohn, B. Bennett, J. Goodayand and N. Gotts “Qualitative Spatial Representation and Reasoning with the Region Connection Calculus”. GeoInformatica, 1(3), pp. 275-316, 1997.
10. J. Tappolet, and A. Bernstein “Applied Temporal RDF: Efficient Temporal Querying of RDF Data with SPARQL.” In: Proceedings of the European Semantic Web Conference, LNCS 5554, 308-322, 2009.
11. M. Stocker, and E. Sirin “PelletSpatial: A Hybrid RCC-8 and RDF/OWL Reasoning and Query Engine” In: CEUR Workshop Proceedings, vol. 529-OWLED 2009, pp. 2-31, 2009.
12. J. Renz “Maximal Tractable Fragments of the Region Connection Calculus: A Complete Analysis.” Int. Joint Conference on Artificial Intelligence, vol. 16, pp. 448-455, 1999.
13. J. Renz, and D. Mitra “Qualitative Direction Calculi with Arbitrary Granularity” In PRICAI 2004: Trends in Artificial Intelligence: 8th Pacific Rim International Conference on Artificial Intelligence, Auckland, New Zealand, August 9-13, 2004.