Representing and Reasoning over Spatio-Temporal Information in OWL 2.0

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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, such as objects whose position evolves in time and space. The 4D fluents mechanism forms the basis of the proposed ontology representation in SOWL. Both RCC-8 topologic relations and cone shaped directional relations are supported and integrated in SOWL. Representing both qualitative temporal and spatial information (i.e., information whose temporal or spatial extents are unknown such as "left-of", "above" for spatial and "before", "after" for temporal relations) in addition to quantitative information (i.e., where temporal and spatial information is defined precisely) is a distinctive feature of SOWL. Qualitative representations are very common in natural language expressions such in free text or speech and can be proven to be valuable in the Semantic Web. The SOWL spatio-temporal reasoner offers capabilities for inferring new relations over spatio-temporal information and is another distinctive feature of our approach. Building upon tractable sets of temporal and spatial relations the SOWL reasoner also enforces path consistency and retains soundness, completness and tractability over the supported sets of relations.

Ontologies offer the means for representing high level concepts, their properties and their interrelationships. Dynamic ontologies will in addition enable representation of information evolving in time and space. Representation of both static and dynamic information by ontologies, as well as reasoning over this information are exactly the problems this work is dealing with.

Representation of dynamic features calls for mechanisms allowing for uniform representation of the notions of time and space (and of properties varying in time and space) within a single ontology. Methods for achieving this goal include (among others), temporal description logics [5], temporal RDF [6], versioning [2], named graphs [16], reification, N-ary relations[1] and the 4D-fluents (perdurantist) approach [3].

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

Welty and Fikes [3] showed how quantitative temporal information (i.e., in the form of temporal intervals whose start and end points are defined) and the evolution of concepts in time can be represented effectively in OWL using the so called "4D-fluents approach". Concepts varying in time are represented as 4D dimensional objects, with the 4th dimension being the time. In our previous work [1] we extendend 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 starting and ending points by means of their relation (e.g., "before", "after") to other time intervals, and (b) spatial information is also supported. Accordingly, the spatial representation supports both quantitative and qualitative expressions. Emphasis was given to qualitative expressions since in natural language (the same as in many applications) spatial relations are typically expressed using qualitative (e.g. "north of") rather than by quantitative relations. Both, topologic and directional relations were supported. In [1] supported spatial and temporal relations were restricted to basic (non disjunctive) relations. Reasoning rules (expressed in SWRL) were part of the ontology as well, but the restriction to basic relations limited reasoning capabilities.

In this work we propose a reasoning mechanism operating on spatio-temporal relations based on the path-consistency method [7]. SWRL and OWL 2.0 constructs (e.g., disjoint properties) are combined, offering a sound and complete reasoning procedure by means of rules integrated into the ontology. Furthermore, by supporting sets of disjunctive relations the expressiveness of the model increases. To the best of our knowledge, such a representation over both qualitative and quantitative spatial and temporal information combined with a sound, complete and tractable reasoning mechanism in OWL, is not known to exist.

Related work in the field of knowledge representation is discussed in Section 1. This includes issues related to representing and reasoning over information evolving in time and space. The SOWL representation model is presented in Section 2 and the corresponding reasoning mechanism in Section 3, followed by evaluation in Section 4 and conclusions and issues for future work in Section 5.

1 Background and Related Work

Several representation languages are defined for the Semantic Web, the most important of them are referred to as the OWL-family[2] of languages for ontology building and knowledge representation. In the following, although interrelated, issues related to representing temporal and spatio-temporal information in ontologies are discussed separately for ease of discussion.

1.1 Representing Temporal Information in Ontologies

Representation languages such as RDF, OWL (which is based on description logics), the same as frame-based and object-oriented languages (F-logic) are all

[2] http://www.w3.org/TR/owl-features

based on binary relations. Binary relations simply connect two instances (e.g., an employee with a company) without any temporal information. Nevertheless, representation of time using OWL is feasible, although complicated [3].

The OWL-Time temporal ontology[3] 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. This is related to the problem of the representation of time in temporal (relational and object oriented) databases. Existing methods are relying mostly on temporal Entity Relation (ER) models [4] taking into account valid time (i.e., time interval during which a relation holds), transaction time (i.e., time at which a database entry is updated) or both. Also time is represented by time instants, intervals or finite sets of intervals. However, representation of time in OWL differs because (a) OWL semantics are not equivalent to ER model semantics in Relational Databases (e.g., OWL adopts the *Open World Assumption* while DBs typically adopt the *Closed World Assumption*) and (b) relations in OWL syntax are restricted to binary ones in constrast to DBs. Representation of time in the Semantic Web can be achieved using *Temporal Description logics (TDLs)* [5], *Reification*, *N-ary relations*, *temporal RDF* [6], *Versioning* [2], *named graphs* [16] or *4D-fluents* [3].

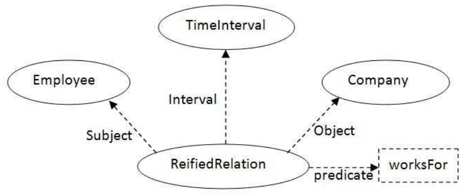
Temporal Description Logics (TDLs) extend standard description logics (DLs) that form the basis for semantic Web standards with additional constructs such as "always in the past", "sometime in the future". TDLs offer additional expressive capabilities over non temporal DLs and retain decidability (with an appropriate selection of allowable constructs) but they require extending OWL syntax and semantics with the additional temporal constructs. Representing information regarding specific time points requires support for concrete domains, resulting to the proliferation of objects [5]. Also the concrete domain approach requires extending OWL with additional datatypes.

Temporal RDF [6] proposes extending RDF by labeling properties with the time interval they hold. This approach also requires extending the syntax and semantics of the standard RDF, although representation over RDF (e.g., using reification) can be achieved. Note that Temporal-RDF cannot express incomplete information by means of qualitative relations. Temporal-RDF is combined with fuzzy logic in [25].

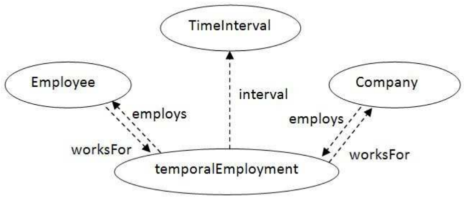
Reification is a general puprose technique for representing n-ary relations using a language such as OWL that permits only binary relations. Specifically, an n-ary relation is represented as a new object that has all the arguments of the n-ary relation as objects of properties. For example if the relation R holds between objects A and B at time t, this is expressed as *R(A,B,t)*. Furthermore, in OWL, using reification this is expressed as a new object with R, A, B and t being objects of properties. Fig. 1(a) illustrates the relation *WorksFor(Employee, Company, TimeInterval)* representing the fact that an employee works for a company during a time interval. Reification suffers mainly from two disadvantages:

[3] http://www.w3.org/TR/owl-time/

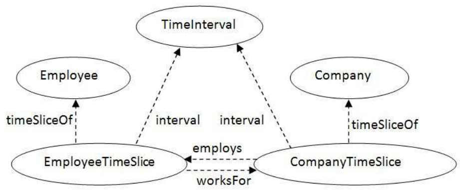
(a) data redundancy, because a new object is created whenever a temporal relation has to be represented (this problem is common to all approaches based on non temporal Description Logics such as OWL-DL) and (b) offers limited OWL reasoning capabilities [3] since relation R is represented as the object of a property thus OWL semantics over properties (e.g., inverse properties) are no longer applicable (i.e., the properties of a relation are no longer associated directly with the relation itself).



(a) Reification



(b) N-ary Relation



(c) 4D fluents

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

N-ary relations is also a general purpose technique that represents an n-ary relation using an additional object. In contrast to reification, the n-ary relation is not represented as the object of a property but as two properties each related with the new object. This is also illustrated in Fig.1(b). This approach requires only one additional object for every temporal interval, maintains property semantics but suffers from data redundancy in the case of inverse and symmetric properties (e.g., the inverse of a relation is added explicitely twice instead of once as in 4D-fluents).

Versioning [2] suggests that the ontology has different versions (one per instance of time). When a change takes place, a new version is created. Versioning suffers from several disadvantages: (a) changes even on single attributes require that a new version of the ontology be created leading to information redundancy (b) searching for events occurred at time instances or during time intervals requires exhaustive searches in multiple versions of the ontology, (c) it is not clear how the relation between evolving classes is represented.

Named Graphs [16] represent the temporal context of a property by inclusion of a triple representing the property in a named graph (i.e., a subgraph into the RDF graph of the ontology specified by a distinct name). The default (i.e., main) RDF graph contains definitions of interval start and end points for each named graph, thus a property is stored in a named graph with start and end points corresponding to the time interval that the property holds. Named graphs are not part of the OWL specification[4] (i.e., there are not OWL constructs translated into named graphs) and they are not supported by OWL reasoners.

The *4D-fluent* (perdurantist) approach [3] shows how temporal information and the evolution of temporal concepts can be represented in OWL. Concepts in time are represented as 4-dimensional objects with the 4th dimension being the time (*timeslices*). Time instances and time intervals are represented as instances of a *time interval* class which in turn is related with concepts varying in time as shown in Fig.1(c). Changes occur on the properties of the temporal part of the ontology keeping the entities of the static part unchanged. The 4D-fluent approach still suffers from data redundancy but in contrast to other approaches it maintain full OWL expressiveness and reasoning support. N-ary relations is considered to be an alternative to the 4D fluents approach, although the 4-D fluents representation where the property is holding among two timeslices of objects and not between the two objects and the intermediate object representing their relation may seems more natural to users. TOWL [20] is a temporal representation approach based on 4D fluents that extends OWL syntax with temporal concepts and supports only quantitative time intervals.

1.2 Representing Spatio-Temporal Information in Ontologies

Formal spatial, and spatio-temporal representations have been studied extensively within the Database and recently, the Semantic Web community [10]. Spatial entities (e.g., objects, regions) in classic database systems are typically represented using points, lines (polygonal lines) or Minimum Bounding Rectangles *(MBRs)* enclosing objects or regions and their relationships. Relations between spatial entities can be topologic, orientation or distance relations. Furthermore, spatial relations are distinguished into qualitative (i.e., relations described using lexical terms such as “Into”, “South” etc.) and quantitative (i.e., relations described using numerical values such as “10Km away”, “45 degrees North” etc.). Accordingly, spatial ontologies are defined based upon a reference coordinate system in conjunction with a set of qualitative topologic and direction relations (e.g., RCC-8 relations). Reasoning rules for various relation sets have been proposed as well [7].

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

Representing spatio-temporal knowledge has also motivated research within the Semantic Web community. Katz et.al. [8] propose representing RCC-8 topologic relations as OWL-DL class axioms (instead of object properies as in [9]) but this approach has limited scalability as shown in [17]. Perry et.al. [10] proposed a representation based on quantitative spatio-temporal data. An representation for quantitative spatiotemporal information based on linear constrains is presented in [26]. In our previous work at [1] we proposed a spatio-temporal representation model supporting both quantitative and qualitative information. The qualitative relations were restricted to basic (non disjunctive) relations. Pellet Spatial [17] offers reasoning support for RCC-8 topologic relations.

2 SOWL ontology

Following the approach by Welty and Fikes [3], to add the time dimension to an ontology, classes *TimeSlice* and *TimeInterval* with properties *TimeSliceOf* and *TimeInterval* are introduced. Class *TimeSlice* is the domain class for entities representing temporal parts (i.e., "time slices") and class *TimeInterval* is the domain class of time intervals. A time interval holds the temporal information of a time slice. Property *TimeSliceOf* connects an instance of class *TimeSlice* with an entity, and property *TimeInterval* connects an instance of class *TimeSlice* with an instance of class *TimeInterval*. Properties having a time dimension are called fluent properties and connect instances of class *TimeSlice* (see Fig.1(c)).

The 4D fluents mechanism forms the basis of the proposed spatio-temporal ontology representation. In SOWL, the 4D-fluents representation is enhanced with qualitative temporal relations holding between time intervals whose starting and ending points 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 [14] of Fig. 2.

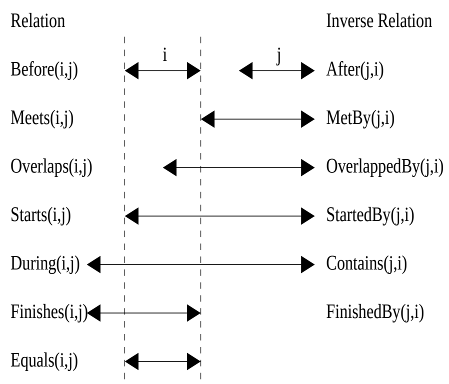
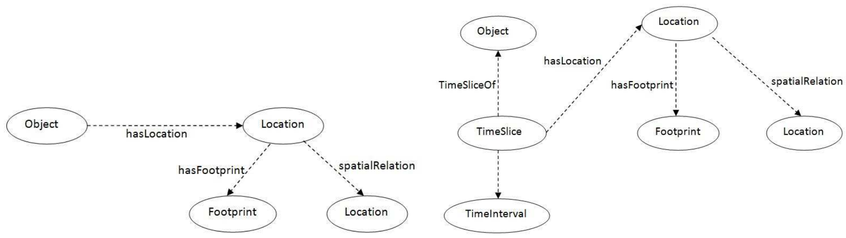


Fig. 2. Allen's Temporal Relations

By allowing for qualitative relations the expressive power of the representation increases. Temporal RDF and 4-D fluents both require closed temporal intervals for the representation of temporal information, while semiclosed and open intervals can't be represented effectively in a formal way. In this work, this is handled by Allen relations: for example, if interval $t1$ is known and $t2$ is unknown but we know that $t2$ starts when $t1$ ends, then we can assert that $t2$ is *met by* $t1$. Likewise, if an interval $t3$ with unkown endpoints is introduced and $t3$ is $before$ $t1$ then, using compositions of Allen relations [14], we infer that $t3$ is $before$ $t2$ although both interval's endpoints are unkown and their relation is not represented explicitely in the ontology. Semiclosed intervals can be handled in a similar way. For example, if $t1$ starts at time point 1, still holds at time point 2, but it's endpoint is unknown, we assert that $t1$ is *started by* interval $t2$:$[1, 2]$.

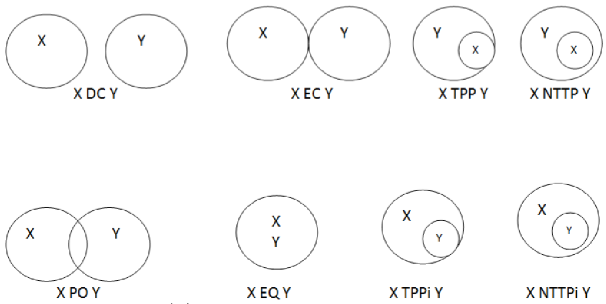
The 4D-fluent mechanism is also enhanced with several types of qualitative spatial relations. These can be either topologic or directional [7]. Fig. 3(a) illustrates the ontology representation of a static (non moving) object. Since the location of the object is a static property, it is a property of the object and not of a timeslice of the object. Class *Location* has attribute *name* (of type string). Also a *Location* object can be optionally connected with a *footprint* class with subclasses: *Point, Line, Polyline and MBR*, representing points, line segments, surrounding contour of an object (or region) as a set of consecutive line segments or Minimun Bounding Rectangles respectivelly. In case of a moving object the location is a property of a timeslice holding for a specific time interval (Fig. 3(b)).



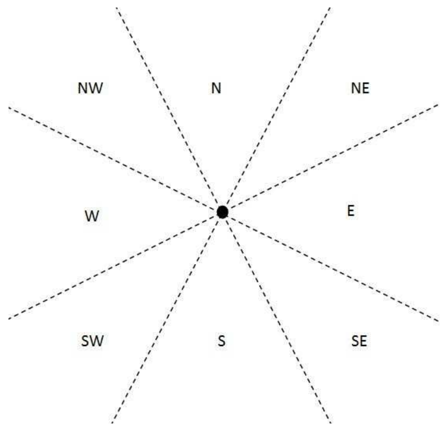
(a) Static Object (b) Moving Object

Fig. 3. Ontology representation of (a) Static and (b) Moving objects

In an ontology, each *spatialRelation* connects two locations and has two subproperties namely: *topologicRelation* and *directionalRelation* (Fig. 4). 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 representation, directional relations are computed using their formal definitions at [12, 24] while in case of areas the directional relations are defined using their centroids. If quantitative information (i.e., location coordinates) is not provided, qualitative relations can be asserted into the ontology instead. In this case the reasoning mechanism will infer additional relations and detect inconsistencies.



(a) Topolologic Relations



(b) Directional Relations

Fig. 4. Spatial (a) RCC-8 Topologic and (b) Cone Shaped Directional Relations

The topologic relations holding between two areas x,y as shown in Fig. 4(a), *(DC, EC, EQ, NTTP, NTTPi, TPP, TPPi, PO)*, are referred to as RCC-8 relations [11] and they are also defined in the SOWL model. Direction relations holding between two points are defined based on cone-shaped areas [12, 24]. Other alternative approaches based on 2-D projections are presented at [7]. As shown in Fig. 4(b), 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 [12]. Directional relation apply to objects represented by points (e.g., by their centroid).

3 Reasoning in SOWL

Temporal and spatial reasoning in SOWL is realized by introducing a set of SWRL[5] rules operating on spatial (topologic or directional) relations as well as by a set of temporal Allen rules for asserting inferred temporal relations. Reasoners that support DL-safe rules such as Pellet [13] can be used for inference and consistency checking over spatio-temporal relations. In addition to reasoning applying on temporal and spatial relations, the Pellet reasoner applies to the ontology schema to infer additional facts using OWL semantics (e.g., facts due to symmetric relationships and class-subclass relationships).

3.1 Temporal Reasoning

Reasoning is realized by introducing a set of SWRL rules operating on temporal intervals. The temporal reasoning rules are based on composing pairs of basic Allen's relations of Fig. 2 as defined in [14]. The composition table of basic Allen's relations is presented in Table 1. Relations BEFORE, AFTER, MEETS, METBY, OVERLAPS, OVERLAPPEDBY, DURING, CONTAINS, STARTS, STARTEDBY, ENDS, ENDEDBY and EQUALS are represented using symbols B, A, M, Mi, O, Oi, D, Di, S, Si, F, Fi and = respecivelly. Compositions with EQUALS are not presented since these compositions keep the intitial relations unchanged. The composition table represents the result of the composition of two Allen relations. For example, if relation $R1$ holds between $interval1$ and $interval2$ and relation $R2$ holds between $interval2$ and $interval3$ then the entry of the Table 1 corresponding to line $R1$ and coloumn $R2$ denotes the possible relation(s) holding between $interval1$ and $interval3$. Not all compositions yield a unigue relation as a result. For example the composition of relations $During$ and $Meets$ yields the relation $Before$ as result while the composition of relations *Overlaps* and *During* yields three possible relations *Starts, Overlaps and During*. Rules corresponding to compositions of relations *R1, R2* yielding unique relations $R3$ as a result can be represented using SWRL as folows:

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

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 as a result can't 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 must also be 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* can be represented as follows:

$$OVERLAPS(x, y) \wedge DURING(y, z) \rightarrow DOS(x, z)$$

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

	B	A	D	Di	O	Oi	M	Mi	S	Si	F	Fi
B	B	B,A,D,Di,O,Oi M,MiS,Si,F,Fi, Eq	B,O,M, D,S	B	B	B,O,M,D,S	B	B,O,M,D, S	B	B	B,O,M, D,S	B
A	B,A,D,Di, O,Oi,M, Mi,S,Si,F, Fi,Eq	A	A,Oi,Mi D,F	A	A,Oi, Mi,D,F	A	A,Oi,Mi, D,F	A	A,Oi,Mi D,F	A	A	A
D	B	A	D	B,A,D,Di,O,Oi M,MiS,Si,F,Fi, Eq	B,O,M, D,S	A,Oi,Mi,D,F	B	A	D	A,Oi,Mi D,F	D	B,O,M, D,S
Di	B,O,M,Di, Fi	A,Oi,Di,Mi,Si	O,Oi,D, Di,S,Si, F,Fi,Eq	Di	O,Di,Fi	Oi,Di,Si	O,Di,Fi	Oi,Di,Si	O,Di,Fi	Di	Oi,Di,Si	Di
O	B	A,Oi,Di,Mi,Si	O,D,S	B,O,M,Di,Fi	B,O,M	O,Oi,D,Di,S,Si, F,Fi,Eq	B	Oi,Di,Si	O	O,Di,Fi	O,D,S	B,O,M
Oi	B,O,M,Di, Fi	A	Oi,D,F	A,Oi,Di,Mi,Si	O,Oi,D, Di,S,Si, F,Fi,Eq	A,Oi,Mi	O,Di,Fi	A	Oi,D,F	Oi,A,Mi	Oi	Oi,Di,Si
M	B	A,Oi,Di,Mi,Si	O,D,S	B	B	O,D,S	B	F,Fi,Eq	M	M	O,D,S	B
Mi	B,O,M,Di, Fi	A	Oi,D,F	A	Oi,D,F	A	S,Si,Eq	A	Oi,D,F	A	Mi	Mi
S	B	A	D	B,O,M,Di,Fi	B,O,M	Oi,D,F	B	Mi	S	S,Si,Eq	D	B,O,M
Si	B,O,M,Di, Fi	A	Oi,D,F	Di	O,Di,Fi	Oi	O,Di,Fi	Mi	S,Si,Eq	Si	Oi	Di
F	B	A	D	A,Oi,Di,Mi,Si	O,D,S	A,Oi,Mi	M	A	D	A,Oi,Mi	F	F,Fi,Eq
Fi	B	A,Oi,Di,Mi,Si	O,D,S	Di	O	Oi,Di,Si	M	Oi,Di,Si	O	Di	F,Fi,Eq	Fi

Table 1. Composition Table for Allen's temporal relations.

Note that the set of possible disjunctions over all basic Allen's relations contains 2^{13} relations, but subsets of this set that are closed under composition (i.e., compositions of relation pairs from this subset yield also a relation in this subset) do exist [21, 23]. In this work we use the subset introduced in [23].

In addition to the above, the following axioms are also asserted into the knowledge base: (a) Four transitivity axioms (for the relations BEFORE, FINISHEDBY, CONTAINS, STARTEDBY), (b) six inverse axioms (relations AFTER, METBY, OVERLAPPEDBY, STARTEDBY, CONTAINS and FINISHEDBY are the inverses of BEFORE, MEETS, OVERLAPS, STARTS, DURING and FINISHES respectivelly), (c) one equality axiom (relation EQUALS), (d) rules defining the relation holding between two intervals with known starting and ending points (e.g., if ending of *interval*1 is smaller than the start of *interval2* the *interval1* is *before interval2*).

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. For example the composition of relation DOS (representing the disjunction of *During, Overlaps and Starts*), and the relation $During$ yields the relation DOS as a result as follows:

$$DOS \circ During \rightarrow (During \vee Overlaps \vee Starts) \circ During \rightarrow$$

$$(During \circ During) \vee (Overlaps \circ During) \vee (Starts \circ During)$$

$$\rightarrow (During) \vee (During \vee Overlaps \vee Starts) \vee (During)$$

$$\rightarrow During \vee Starts \vee Overlaps \rightarrow DOS$$

The symbol $\circ$ denotes composition of relations, and compositions of basic (non-disjunctive) relations are defined using Table 1. Similarly, the inverse of a disjunction of basic relations is the disjunction of the inverses of these basic relations as presented in Fig. 2. For example 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. Concistency checking is achieved using path consistency [7, 21, 23]. Path consistency is implemented by consecutive applications of the folowing 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 doesn't 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 inervals 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 example the intersection of relation DOS (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:

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

The maximal tractable subset of Allen relations containing all basic relations when applying the path consistency method comprises of 868 relations [21]. Tractable subsets of Allen relations containing 83 or 188 relations [23] can be used for reasoning as well, offering reduced expessivity but increased efficiency over the maximal subset of [21]. Furthermore, since the proposed temporal reasoning mechanism affects only relations of temporal intervals, it can be also applied to other temporal representation methods (besides 4D fluents) such as N-ary relations. Also note that in [23] reasoning regarding time instants in addition to intervals is presented as well. Specifically qualitative relations regarding instants form a tractable set if the relation $\neq$ (i.e., a temporal instant is before *or* after another instant) is excluded. Reasoning regarding relations between interval and instants is achieved by translating interval relations to relations regarding their endpoints as specified in [14].

3.2 Spatial Reasoning

Additional spatial relations can be inferred from existing ones using *composition tables* which are defined for both topologic and direction spatial relations [15, 12, 24]. A composition table defines the possible spatial relations holding between two spatial entities (e.g., objects or regions), given their spatial relations with a third one.

In the following, reasoning over both topologic and directional relations is discussed. Choosing either representation is a design decision that depends mainly on the application. However, both represenations may co-exist in the SOWL model (both are common in natural language expressions and may co-exist e.g., in text descriptions over the Web). Table 3 illustrates a composition table using RCC-8 topologic relations. The corresponding composition table for directional relations is illustrated in Table 2.

The SOWL spatial representation implements reasoning rules for RCC-8 relations and cone-shaped direction relations using SWRL and OWL 2.0 property axioms. Specifically, the nine direction relations have been declared as transitive OWL relations (i.e., a relation such as *South* is transitive meaning that if the relation holds between locations A and B, and between locations B and C, it also holds between locations A and C). Their inverse relations (e.g., North is the inverse of South) are defined as well. Furthermore the identity relation (O) is symmetric. All basic relations are pairwise disjoint. 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. Supported directional relations are the 9 basic relations and their disjunctions appearing in Table. 2. Compositions and intersections of disjunctive relations are defined using the compositions and intersections of basic relations as in the case of temporal reasoning.

The directional relations supported 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 [24] that is dicided by path consistency when applied to basic relations. Furthermore given a tractable set of relations, by applying compositions, intersections and inverse operations until a set of relations that is closed under these operations is yielded the resulting set is also tractable [7]. By applying this method (*closure method*) to the basic relations

	N	NE	E	SE	S	SW	W	NW	O
N	N	N,NE	N,NE,E	N,NE,E,SE	N,NE,E,SE S, SW,W NW,O	W,NW, SW,N	NW,N,W	NW,N	N
NE	NE,N	NE	NE,E	E,NE,SE	E,NE, SE,S	N,NE,E,SE S, SW, W,NW,O	N,NE, NW,W	N,NE,NW	NE
E	NE,E,N	NE,E	E	SE,E	SE,E,S	S,SW,SE E,	N,NE,E, SE,S, SW W,NW,O	N,NW, NE,E	E
SE	E,SE, NE,N	E,SE,NE	SE,E	SE	SE,S	S,SE,SW	S,SE,SW	N,NE,E,SE,S, SW,W,NW,O	SE
S	N,NE,E,SE,S SW,W NW,O	E,S,NE,SE	SE,E,S	SE,S	S	S,SW	S,W,SW	W,S,NW, SW	S
SW	W,SW N,NW	N,NE,E,SE,S SW,W NW,O	S,SW SE,E	S,SW,SE	SW,S	SW	SW,W	W,NW,SW	SW
W	N,W,NW	N,NW,NE W	N,NE,E,SE, S ,SW,W NW,O	S,SE,SW W	W,S,SW	W,SW	W	W,NW	W
NW	N,NW	N,NW,NE	N,NW,NE,E	N,NE,E,SE S,SW,W, NW,O	W,NW,SW, S	W,NW, SW	NW,W	NW	NW
O	N	NE	E	SE	S	SW	W	NW	O

Table 2. Composition table for directional relations.

of Fig.4(b) a tractable set of relations containing the basic directional relations and all relations appearing in Table 2 is yielded. This set of directional relations is used in this work for directional spatial reasoning.

Reasoning on RCC-8 relations combines transitive, symmetric, inverse and equality property axioms along with a set of composition rules (i.e., rules defining compositions of RCC-8 relations) and intersection rules. Specifically, relation *NTPP* is transitive, relations *DC, EC* and *PO* are symmetric, relations *NTPPi* and *TPPi* are inverse of *NTPP* and *TPP* respectively and *EQ* corresponds to the equality relation for *Location* objects. In SOWL, the spatial reasoner implements the RCC-8 composition rules of Table 3. For example the rule defining the composition of relations $TPPi$ and $NTPPi$ for locations x, y, z is the following:

$$TPPi(x, y) \land NTPPi(y, z) \rightarrow NTPPi(x, z)$$

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 (totaling $2^8 - 1$ relations in case of RCC-8) leads to intractability since this set is not decided by path consistency. However, tractable subsets of the full set are known to exist [7, 22]. Such subsets are used in this work offering increased expressive power while retaining tractability. Specifically, in case of RCC-8 topologic relations the subset presented in [22] is used.

	DC	EC	PO	TPP	NTPP	TPPi	NTPPi	EQ
DC	DC,EC,PO,TPP,NTPP,TPPi,NTPPi,EQ	DC,EC,PO,TPP,NTPP	DC,EC,PO,TPP,NTPP	DC,EC,PO,TPP,NTPP	DC,EC,PO,TPP,NTPP	DC	DC	DC
EC	DC,EC,PO,TPPi,NTPPi	DC,EC,PO,TPP TPPi,EQ	DC,EC,PO,TPP,NTPP	EC,PO,TPP,NTPP	PO,TPP,NTPP	DC,EC	DC	EC
PO	DC,EC,PO,TPPi,NTPPi	DC,EC,PO,TPPi,NTPPi	DC,EC,PO,TPP,NTPP,TPPi,NTPPi,EQ	PO,TPP,NTPP	PO,TPP,NTPP	DC,EC,PO,TPPi,NTPPi	DC,EC,PO,TPPi,NTPPi	PO
TPP	DC	DC,EC	DC,EC,PO,TPP,NTPP	TPP,NTPP	NTPP	DC,EC,PO,TPP,NTPP	DC,EC,PO,TPPi,NTPPi	TPP
NTPP	DC	DC	DC,EC,PO,TPP,NTPP	NTPP	NTPP	DC,EC,PO,TPP,NTPP	DC,EC,PO TPP,NTPP,TPPi,NTPPi EQ	NTPP
TPPi	DC,EC,PO,TPPi,NTPPi	EC,PO,TPPi,NTPPi	PO,TPPi,NTPPi	EQ,PO,TPPi,TPP	PO,TPP,NTPP	TPPi,NTPPi	NTPPi	TPPi
NTPPi	DC,EC,PO,TPPi,NTPPi	PO,TPPi,NTPPi	PO,TPPi,NTPPi	PO,TPPi,NTPPi	PO,TPP,NTPP EQ,TPPi,NTPPi	NTPPi	NTPPi	NTPPi
EQ	DC	EC	PO	TPP	NTPP	TPPi	NTPPi	EQ

Table 3. Composition table for RCC-8 topologic relations.

4 Evaluation

The resulting OWL ontology is characterized by *SHRIF(D)* DL expressivity and it is decidable since it doesn't contain role inclusion axioms with cyclic dependences [18] (role axioms in the ontology are restricted to disjointness, transitivity, symmetry and inverse axioms). Adding the set of temporal qualitative rules of Sec. 3 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 [7, 21, 23], 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 $O(n^5)$ 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 for the full set of relations would result into an intractable reasoning procedure.

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

An alternative approach towards implementing a spatio-temporal reasoner would be to extend Pellet to handle a (tractable) relations set, along with the supported axioms and path consistency checking, similarly to the way PelletSpatial [17] implements reasoning over RCC-8 topologic relations. This approach has the following advantages: (a) The underlying representation is more simple since disjunctions of basic relations are represented without introducing additional relations and (b) certain improvements regarding efficiency and scalability can be added. On the other hand, this approach requires additional software to handle the ontology, while our approach requires only standard Semantic Web tools such as Pellet and SWRL. Because reasoning is part of the ontology model, maintenance of the ontology requires that changes are applied to the ontology only and not to the reasoner (other approaches such as [17] require modifying both the ontology and the reasoner).

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.

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