SOWL:Spatio-temporal Representation, Reasoning and Querying over the Semantic Web

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ABSTRACT

Representing dynamic information in the form of ontologies, as well as querying and reasoning over static and dynamic ontologies are the areas of interest in this work. Building upon well established standards of the semantic Web and the 4D-fluents approach for representing the evolution of temporal information in ontologies, SOWL illustrates how spatial and spatio-temporal information and evolution in space and time can be efficiently represented in OWL. It also demonstrates how qualitative temporal and spatial relations that are common in natural language expressions (i.e., relations between time intervals like “before”, “after”, etc.) are represented in the ontology. Existing approaches allow for representations of only static, spatial or temporal information, but do not support combinations on the nature of information or representation of qualitative relations. Part of the proposed representation model is the SOWL (high-level) query language, which does not require users to be familiar with peculiarities of the underlying ontology representation (which can be complex) and handles ontologies similar to relational databases. A distinct feature of SOWL is the incorporation spatio-temporal reasoning in SOWL, which is capable of inferring spatio-temporal information from representations in the underlying ontology model.

1. INTRODUCTION

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. In particular, dynamic ontologies are not only suitable for describing static scenes with static objects (e.g., objects in photographs) but also enable representation of events with objects and properties changing in time and space (e.g., moving objects in a video). Representation of both static and dynamic information by ontologies, as well as querying and reasoning over static and dynamic ontologies 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 uniform ontology [1]. Methods for achieving this goal include (among others), temporal description logics [11], temporal RDF [13], versioning [6], named graphs [28], reification, N-ary relations [2] and the 4D-fluents (perdurantist) approach [9].

In our earlier work [4] we showed how temporal information (also the evolution of temporal concepts) can be represented effectively in OWL using the 4D-fluents approach. Concepts varying in time are represented as 4-D dimensional objects, with the 4-th dimension being the time. SOWL extends this approach in certain ways: The 4-D fluents mechanism is 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. Accordingly, the spatial representation of SOWL supports both quantitative and qualitative expressions. Emphasis is 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 are supported as well [17]. Another distinctive feature of the SOWL model is spatio-temporal reasoning support which consists of a set of inference rules applying on temporal and spatial relations. Their purpose is to assert additional implied facts to the knowledge base (i.e., determine the spatial or temporal relation between two objects given their relations with a third one).

The SOWL query language is a high-level SQL-like language that handles ontologies almost like relational databases. It maintains the basic structure of an SQL language (SELECT-FROM-WHERE) enhanced by a set of temporal and spatial operators. The SOWL ontology model is not part of the query language and it is not visible to the user, so the user need not be familiar with peculiarities of the underlying mechanism for time and space representation.

Related work in the field of knowledge representation is discussed in Section 2. This includes issues related to representing and reasoning over information evolving in time and space along with a discussion on ontology query languages. The SOWL representation model is presented in Section 3 and the corresponding reasoning mechanism in Section 4. The SOWL Query Language is presented in Section 5, fol-

I-SEMANTICS 2010 September 1-3, 2010 Graz, Austria

lowed by evaluation in Section 6 and conclusions and issues for future work in Section 7.

2. 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 [7, 33] 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.

2.1 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 based on binary relations. Binary relations simply connect two instances (e.g., an employee with the company) without any temporal information. Nevertheless, representation of temporal information in OWL is feasible, although complicated [2, 9].

The OWL-Time temporal ontology [5] 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 [10] 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 the ER model semantics (e.g., OWL adopts the *Open World Assumption* while ER model adopts the *Closed World Assumption*) and (b) relations in OWL are restricted to binary ones. Existing approaches for the representation of temporal information in the Semantic Web include *Temporal Description logics (TDLs)* [11, 12], *Reification*, *temporal RDF* [13], *Versioning* [6], *named graphs* [28] and the *4D-fluents (perdurantist)* approach [9].

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 but they require extending OWL syntax and semantics with the additional constructs.

Temporal RDF [13] proposes extending RDF by allowing for 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 doesn't offer support for expressing incomplete information by means of qualitative relations.

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, this is expressed in OWL using reification as a new object with R, A, B and t being objects of properties objects. Reification suffers from two disadvantages: (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 [9] since the relation R is represented as the object of a property thus OWL semantics over properties are no longer applicable.

Versioning [6] 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. Furthermore, ontology languages such as OWL [7] are based on binary relations (relations connecting two instances) without a temporal dimension.

Named Graphs [28] represent the temporal context of a property by inclusion of a triple representing the property in a named graph (i.e., a subgraph of the RDF graph 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 [35] (i.e., there are not OWL constructs translated into named graphs) and they are not supported by OWL reasoners.

The *4D-fluent* (perdurantist) approach [9] shows how temporal information and the evolution of temporal concepts can be represented effectively in OWL. Concepts in time are represented as 4-dimensional objects with the 4-th dimension being the time. Time instances and time intervals are represented as instances of a *time interval* class which in turn is related with time concepts varying in time. Changes occur on the properties of the temporal part of the ontology keeping the entities of the static part unchanged. TOWL [34] is a temporal representation approach based on 4-D fluents that extends OWL syntax with temporal concepts and supports quantitative time intervals.

2.2 Representing Spatio-Temporal Information in Ontologies

Formal spatial, and spatio-temporal representations have been studied extensively within the Database [14] and recently, the Semantic Web community [15]. 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 [21]. Relations among 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 [16, 17].

Representing spatio-temporal knowledge has also motivated research within the Semantic Web community. Katz et.al. [19] propose representing RCC-8 relations as OWL-DL class axioms (instead of object properies as in [20]) but this approach has limited scalability as shown in [31]. Chen et.al. [29] similarly to Sotnykova et.al. [30] propose an integrated spatio-temporal representation which includes qualitative relations but without specialized spatio-temporal reasoning support. Perry et.al. [22] proposed a representation based on quantitative spatio-temporal data. Pellet Spatial [31] offers reasoning support for RCC-8 topologic relations.

2.3 Querying Spatio-Temporal Information in Ontologies

Query languages for RDF and OWL ontological representations such as SPARQL [8] and SeRQL [3] form the basis for developing languages for querying spatio-temporal information in ontologies and the semantic Web. SPARQL is a W3C recommendation query language. SPARQL and SeRQL offer support of features such as: Graph transformation, RDF and XML Schema data type support, expressive path expression syntax and optional path matching. Querying spatio-temporal information over the semantic Web using languages such as SPARQL is a tedious task. Recent work on query languages for temporal ontologies include TOQL [4] and t-SPARQL [28] using 4-D fluents and named graphs respectively for the representation of temporal information. In this work we extend TOQL [4] to handle spatial (in addition to temporal) and also qualitative spatial and temporal information.

3. SOWL ONTOLOGY MODEL

Following the approach by Welty and Fikes [9], to add the time dimension to an ontology, classes *TimeSlice* and *TimeInterval* with properties *tsTimeSliceOf* and *tsTimeInterval* 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 *tsTimeSliceOf* connects an instance of class *TimeSlice* with an entity, and property *tsTimeInterval* 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.* Fig. 1 illustrates a temporal ontology with classes *Company* with datatype property *companyName*, *Product* with datatype properties *price* and *productName*, and *Location* which represents spatial information (Fig. 3 and Fig. 4). In this example, *CompanyName* is a static property (it's value do not change in time), while properties *produces*, *productName*, *locatedAt* and *price* are dynamic (fluent) properties whose values may change in time. Because they are fluent properties, their domain (and range) is of class *TimeSlice. CompanyTimeSlice*, *LocationTimeslice* and *ProductTimeSlice* are instances of class *TimeSlice* and are provided to denote that the domain of properties *produces*, *locatedAt*, *productName* and *price* are time slices restricted to be slices of a specific class. For example, the domain of property *productName* is not class *TimeSlice* but it is restricted to instances that are time slices of class *Product.*

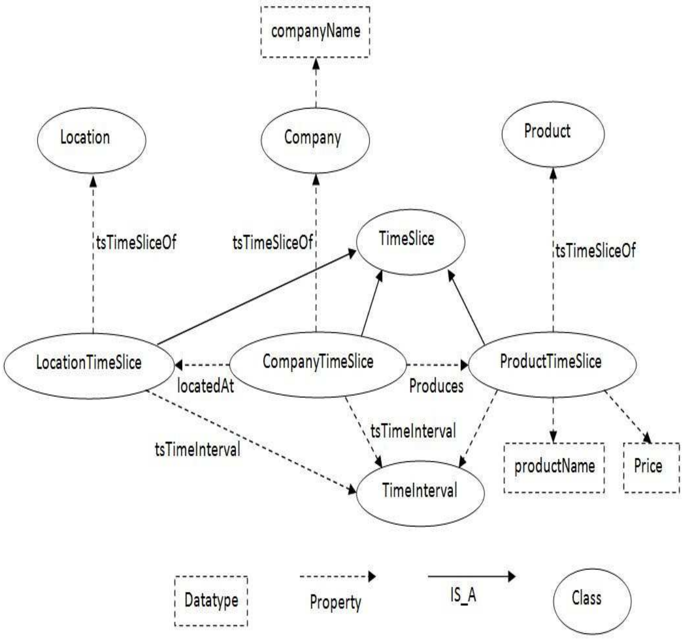


Figure 1: Dynamic Enterprise Ontology

The 4-D fluent mechanism forms the basis of the proposed spatio-temporal ontology representation. In SOWL, the 4D-fluent 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 [26] of Fig. 2.

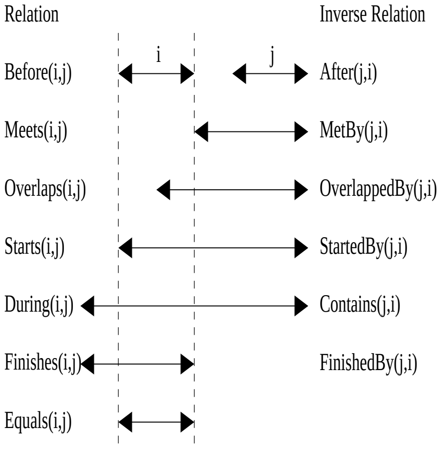


Figure 2: Allen's Temporal Relations

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. If their endoints are unkown, ad hoc approaches [28] that handle open intervals by extending their start or end point infinitely are not appropriate since lack of knowledge must not be interpreted as if a property always holds in the past or future. In SOWL, 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 [26], 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 instant 1 but it's endpoint is unknown, we assert that $t1$ is *started by* interval $t2 : [1, 1]$. Thus SOWL demonstrates enhanced expressivity compared to previous approaches [28, 30, 15, 29, 34, 22, 18] by combining 4D-fluents [9] with Allen's temporal relations and their formal semantics and composition rules as defined in [26].

The 4D-fluent mechanism is also enhanced with several types of qualitative spatial relations. These can be either topologic or directional [17]. Fig. 3 illustrates a general ontology representation model for spatial information. 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*. Class *Point* has two (or three in a three-dimensional representation) numerical attributes, namely X, Y (also Z in a three-dimensional representation). For example, *Point* will be the *footprint* of entities such as cities in a large scale map. Class *Line* has *point1* and *point2* as attributes representing the ending points of a line segment. Class *PolyLine* represents the surrounding contour of an object (or region) as a set of consecutive line segments. An object (or region) may also be represented by its *Minimum Bounding Rectangle* (MBR) specified by the four numerical attributes *Xmax, Ymax, Xmin and Ymin*. Both representations may co-exist in SOWL model (using one of them or both is a design decision).

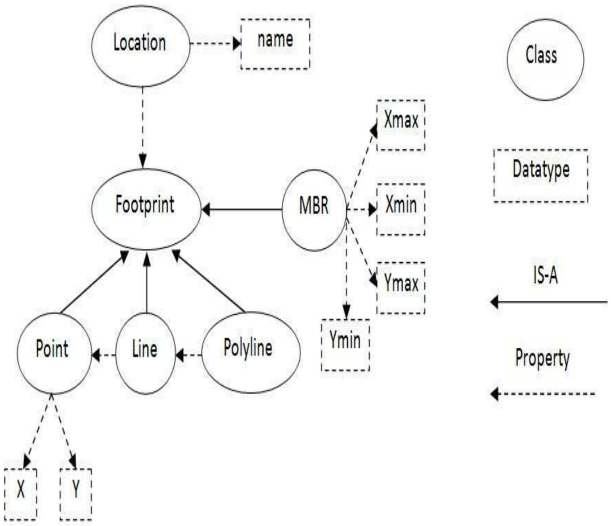


Figure 3: Ontology representation of spatial objects.

The spatial relations between regions can be easily extracted from their surrounding *MBRs* (or contours) by comparing their coordinates. In an ontology, each *spatialRelation* connects two locations and has two subproperties namely: *topologicRelation* and *directionalRelation*. Fig. 4 summarizes all types of spatial relations within a common ontology schema. Omitting either topologic or directional relations from the representation is a design decision or depends on requirements imposed by the application domain. Most frequently, only one relation type is used.

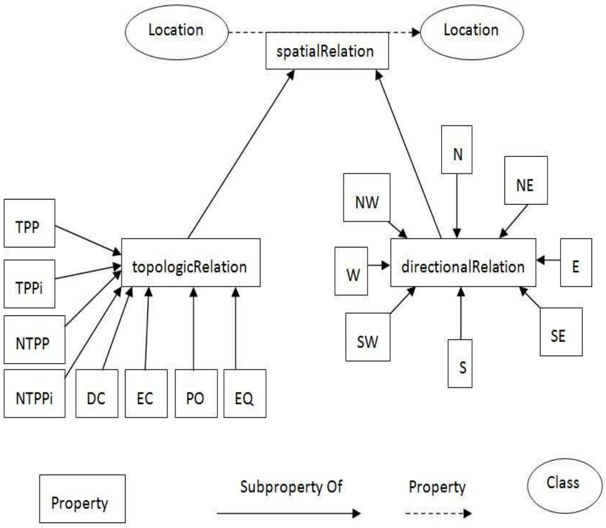


Figure 4: Ontology schema with spatial relations.

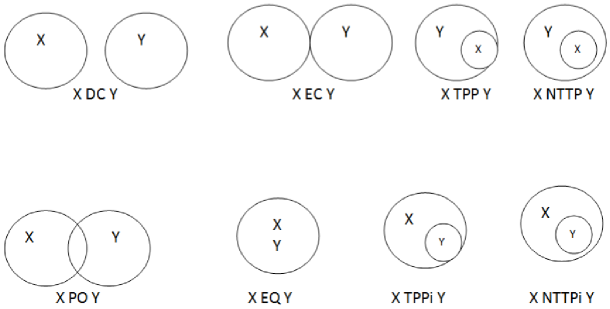


Figure 5: RCC-8 topologic relations.

The topologic relations shown in Fig. 5, *(DC, EC, EQ, NTTP, NTTPi, TPP, TPPi, PO)*, referred to as RCC-8 relations [23] are also defined in the SOWL model. Direction relations are defined based on cone-shaped areas [24]. Other alternative approaches based on 2-D projections are presented at [17, 38]. As shown in Fig. 6, eight direction relations can be identified namely, North (N), North East (NE), East (E), South East (SE), South (S), South West (SW), West (W) and North West (NW) following the cone-shaped areas approach of [24]. The cone shaped approach is typically preferred over the projection based approach because it is more suitable for objects represented by points (e.g., by their centroid).

Distance relations are also defined and can be used in SOWL in conjunction with the above relation types. Notice that, qualitative distance relations (e.g., "far" and "near") may be ambiguous especially in applications where a common scale for measuring distances is not provided. This is resolved when distance relations are expressed quantitatively (e.g., 3Km away from city A) and stored in the ontology

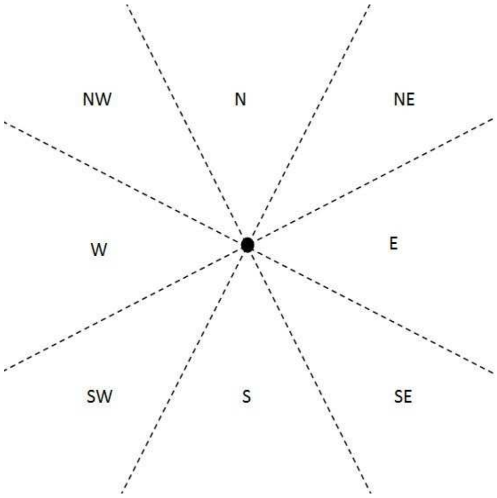


Figure 6: Cone-based direction relations.

as N-ary relations [2] (i.e., by defining an object with attributes the two related locations and a numerical attribute representing their distance). In SOWL, we opt for the later (quantitative) approach for representing distance information.

Fig.7 illustrates the dynamic ontology schema representing the scenario "Product T1 was produced in City 1 between May 2006 and June 2010 and then in City 2. City 1 is west of City 2". In this example, we don't know whether the product is still produced in City 2. Also note that only the first temporal interval is defined. The second interval and both city locations are not specified exactly.

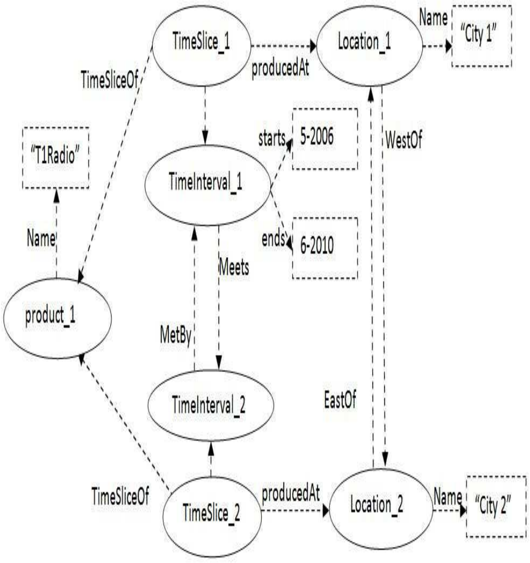


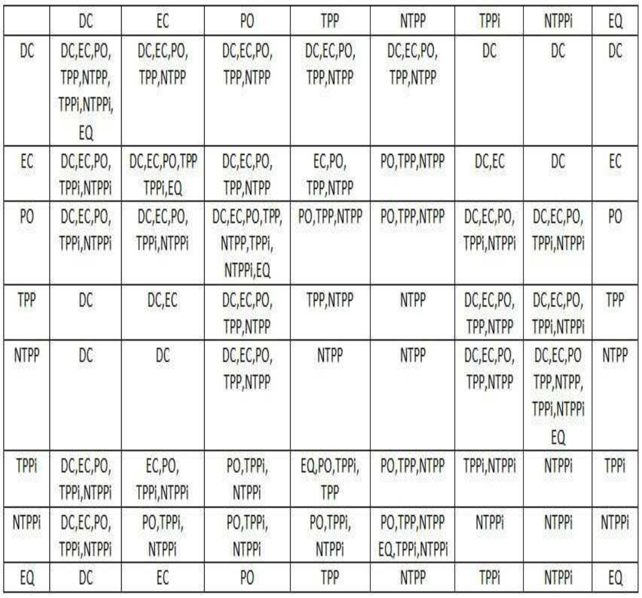
Figure 7: Instantiation example.

4. REASONING IN SOWL

Reasoning in SOWL is realized by introducing a set of SWRL [39] 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 [25] 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).

4.1 Spatial Reasoning

Additional spatial relations can be inferred from existing ones using *composition tables* which are defined for both topologic and direction spatial relations [27, 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. Table 1 illustrates a composition table using RCC-8 topologic relations. Corresponding composition tables for directional relations are defined in [24]. Spatial reasoning is then achieved by applying rules implementing the inferred relations of a composition table.



	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 1: Composition table for RCC-8 topologic relations.

As shown in Table 1, only a limited set of table entries leads to an unambiguous result. For example, the composition of the *NTPP* and *DC* topologic relations (i.e., object A is into B and object B outside of C) yields the *DC* relation as a result meaning that A is outside of C. However, the composition of *NTPP* and *PO* relations doesn't yield a unique relation as a result. Only 27 out of the 64 (RCC-8) entries of Table 1, and only 8 out of the 64 compositions of basic cone-shaped directional relations [24] can be used to infer unique relations.

The SOWL spatial representation implements reasoning rules for RCC-8 relations and cone-shaped direction relations using SWRL. Specifically, the eight 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. By defining the transitive and inverse relations, all inferences of basic cone shaped direction relations can be obtained.

Reasoning on RCC-8 relations combines transitive, symmetric, inverse and equality rules along with a set of composition rules (i.e., rules defining compositions of RCC-8 relations). Specifically, relation *NTPP* is transitive, relations *DC, EC* and *PO* are symmetric, relations *NTPPi* and *TPPi* are inverse of *NTPP* and *TPP* respectivelly and *EQ* corresponds to the equality relation for *Location* objects. In SOWL, the spatial reasoner implements the RCC-8 composition rules of Table 1. However, not all 27 rules (yielding unique relation as a result) need to be defined explicitly as most of them can be inferred from others using the following set of rules:

$$(rule\,1) TPP(x,y) \wedge DC(y,z) \rightarrow DC(x,z)$$

$$(rule\,2) NTPP(x,y) \wedge DC(y,z) \rightarrow DC(x,z)$$

$$(rule\,3) NTPP(x,y) \wedge EC(y,z) \rightarrow DC(x,z)$$

$$(rule\,4) NTPP(x,y) \wedge TPP(y,z) \rightarrow NTPP(x,z)$$

$$(rule\,5) TPP(x,y) \wedge NTPP(y,z) \rightarrow NTPP(x,z)$$

The remaining rules are derived from these rules in conjunction with a set of inverse, symmetry, transitivity and equality axioms. For example the rule:

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

can be derived as follows:

$$(a) TPPi(x,y) \rightarrow TPP(y,x) (inverse\, relations)$$

$$(b) NTPPi(y,z) \rightarrow NTPP(z,y) (inverse\, relations)$$

$$(c) NTPP(z,y) \wedge TPP(y,x) \rightarrow NTPP(z,x) (rule\,4)$$

$$(d) NTPP(z,x) \rightarrow NTPPi(x,z) (inverse\, relations)$$

Similarly to the example above, the remaining relations of Table 1 are obtained by combining already defined rules in conjunction with equality, symmetry, transitivity and inverse relation axioms.

Notice that, extracting spatial relations from the raw spatial data depends on the application and is not part of the reasoning mechanism. Also, only rules yielding basic spatial relations as a result (i.e., the eight RCC-8 and the eight directional raletions of Fig.5 and Fig.6 respectivelly) are supported. Consequently, only basic relations and not their disjunctions can be asserted into the ontology. For example, facts such as "Region 1 is *Overlapping* with Region 2" can be asserted while, "Region 1 is *Overlapping or* is *Bordering* with Region 2" can't. The model can be further extended with additional relations corresponding to disjunctions of basic relations (totaling $2^8 - 1$ relations in case of both RCC-8 and directional relations). Notice that using the full set of relations leads to intractability. However, tractable subsets of the full relations' set are known to exist [17]. Such subsets can be used in future extensions of the model for increasing its expressive power.

Future versions of the reasoning procedure (work now underway) will also support path consistency [17, 36, 42] (i.e., the concecutive application of compositions and intersections of existing relations until a fixed point is reached when no additional relations are added, or until the empty set is yielded implying an incosistency). Compositions and intersections of relations are expressed as SWRL rules, thus reasoning remains an integral part of the model. Supported relations must form a closed set under composition and intersection. Also, they must have polynomial time complexity over the number of locations into the ontology when path consistency is applied, thus avoiding the intractability problems of the full set of relations. Specifically, tractable sets of RCC-8 topologic relations are known to exist [41, 40]. Corresponding work regarding cardinal direction includes [38, 43]. Notice finally that, selecting the supported relations set is a design desicion which involves a trade-off between efficiency and expressivity.

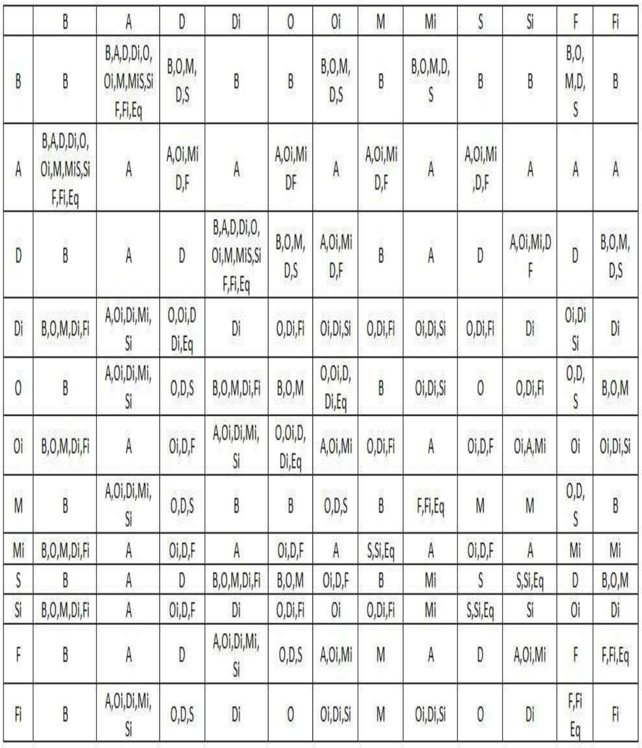
4.2 Temporal Reasoning

Temporal reasoning in SOWL relies on compositions of the basic Allen relations of Fig. 2 which are defined in [26]. Table 2 shows the respective composition table. Additional rules corresponding to compositions of more than 3 basic relations which yield a basic relation as a result, (and they can't be reduced to simpler rules), are defined as well. For example the composition of relations MEETS, METBY and MEETS (in that order) yields the relation MEETS as result, although the basic compositions of MEETS and METBY doesn't yield a simple relation as result. A rule corresponding to this composition is part of the model as well.

The composition table of basic Allen's relations is presented in Table 2. 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, and compositions with EQUALS are nor presented since these compositions keep the intitial relations unchanged. Again, not all rules need to be defined explicitly: all rules yielding unique relations as a result can be derived from a set of rules expressed using SWRL (not presented here because of space limitations) in conjunction with four transitivity axioms (for the relations BEFORE, FINISHEDBY, CONTAINS, STARTEDBY), six inverse (relations AFTER, METBY, OVERLAPPEDBY, STARTEDBY, CONTAINS and FINISHEDBY are the inverses of BEFORE, MEETS, OVERLAPS, STARTS, DURING and FINISHES respectivelly) and one equality axiom (relation EQUALS). An example of temporal inference rule is the following:

$$DURING(x,y) \wedge MEETS(y,z) \rightarrow BEFORE(x,z)$$

Again, only the 13 basic Allen relations of Fig.2 and rules yielding basic relations are supported. Notice that only 97 out of 169 relations of Table 2 can be used to infer unique relations. Other relations corresponding to disjunction of basic relations are not supported (i.e., facts such as "interval 1 *meets* or *overlaps* interval 2 can't be asserted into the ontology). Notice that, using the full set of $2^{13} - 1$ relations leads to intractability. Tractable subsets of the full set of relations do exist [36, 42] and they can form the basis of a future extension of the model (work now underway).



	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,MiS,Si F,Fi,Eq	A	A,Oi,Mi D,F	A	A,Oi,Mi DF	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,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,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,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 2: Composition Table for Allen's temporal relations.

5. QUERYING SOWL

SOWL extends our previous work on TOQL [4] for querying temporal information in OWL to handle spatial and spatio-temporal information. TOQL is a query language that treats classes and properties of an ontology almost like tables and columns of a database. In addition to the existing set of temporal operators (i.e., the AT and Allen operators) the language is enchanced with spatial operators for handling both, spatial and temporal relations, thus the IN_RANGE and all RCC-8 and directional relations are supported by corresponding operators.

Similarly to TOQL, the SOWL query language follows an SQL-like syntax (SELECT-FROM-WHERE) and supports SQL operators and constructs such as LIMIT, OFFSET, AND, OR,MINUS, UNION, UNION ALL, INTERSECT, EXISTS, ALL, ANY, IN.

TOQL also introduces clause "AT" which compares a fluent property (i.e., the time interval in which the property is true) with a time period (time interval) or time point and returns fluents holding true at the specified time interval, thus enabling temporal queries without requiring familiarity with the underlying representation mechanism for the end user. Queries regarding static properties (properties not changing in time) are issued as normal queries applied on the static part of the ontology. A detailed description of the TOQL query language is presented at [4]. For example the following TOQL query retrieves the name of the company employee "x" was working for, from time=3 to time=5:

SELECT Company.companyName
FROM Company, Employee
WHERE Company.hasEmployee:Employee AT(3,5)
AND Employee.employeeName LIKE "x"

The following Allen operators are also supported: BEFORE, AFTER, MEETS, METBY, OVERLAPS, OVERLAPPEDBY, DURING, CONTAINS, STARTS, STARTEDBY, ENDS, ENDEDBY and EQUALS, representing the corresponding relations holding between two time intervals specified either using quantitative (i.e., interval with specified end points) desrciption or qualitative Allen relations.

Spatial operators refer to topologic or directional spatial relations represented in the underlying ontology. The result of applying spatial operators are locations qualifying the expressions specified by the query. Locations are assessed using their names (although the user can issue queries addressing the underlying quantitative representation using coordinates, but formulating such queries requires requires that the user be familiar with the underlying spatio-temporal representation). The following spatial operators are supported: NORTH_OF, NORTHEAST_OF, EAST_OF, SOUTH_OF, WEST_OF, SOUTHWEST_OF, SOUTHEAST_OF, INTO, OUTSIDE_OF, SAME_LOCATION_AS, BORDERING, OVERLAPPING, CONTAINS, INTERNALLY_BORDERING, CONTAINS_AND_BORDERING, FARTHEST_OF, NEAREST_TO, IN_RANGE. They correspond to the eight directional relations in Fig. 6, the RCC-8 relations in Fig. 5 and three operators (nearest, farthest and range) involving distance information. Spatial operators are issued in WHERE, followed by a string denoting the location name according to the pattern <SPATIAL OPERATOR> <STRING>. For example the following query retrieves the name of the company located north of a given location at a specific instant of time:

SELECT Company.companyName
FROM Company
WHERE Company NORTH_OF "Attica" AT(5)

Queries involving the IN_RANGE operator have the following syntax: IN_RANGE <Comparison operator> <Number> OFF <String> where the string denotes location name. The following query retrieves the names of employees working for companies located in distance greater than 100Km away from "Athens" in time interval between 5 and 10:

SELECT Employee.employeeName
FROM Company, Employee
WHERE Company IN_RANGE >100 OFF "Athens" AND
Company.hasEmployee:Employee AT(5,10)

6. 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 [32] (role axioms in SOWL are restricted to disjointness, transitivity and inverse axioms). Adding the set of spatio-temporal qualitative rules of Sec. 4.1 and Sec. 4.2 retains decidability since rules are DL-safe rules as defined at [37]. Notice that, if the spatial and temporal relations are used in concept restrictions and definitions that introduce anonymous individuals rules doesn't apply on these individuals, otherwise the resulting representation will become undecidable. Furthermore, computing the rules has polynomial time complexity since only basic relations are supported: by restricting representation and reasoning support to the basic Allen, RCC-8 and directional relations tractability is retained as shown in [17, 36]. Because any time interval can be related with every other interval with one basic Allen relation (basic Allen relations are mutually exclusive), between n intervals at most $(n-1)^2$ relations can be asserted. This also holds for spatial relations. Extending the model for the full set of relations will yield an intractable reasoning procedure. This is resolved by restricting the supported relations to tractable subsets of the full sets of relations.

7. CONCLUSIONS AND FUTURE WORK

We introduce SOWL, an ontology model capable of handling spatio-temporal information in ontologies. The SOWL model extends the 4-D fluent representation of [4] to handle both quantitative and qualitative spatial and spatio-temporal information. The SOWL query language supports a powerful set of operations including spatial and temporal Allen operators. SOWL incorporates reasoning rules for inferring certain spatio-temporal relations from existing ones. Query optimization, providing indexing support over both, spatial and temporal information in main memory and secondary storage, extending the query language syntax to handle queries on ontology structure (i.e., sub-classes and super-classes) and, most important, extending SOWL reasoning to handle tractable sets of spatial and temporal relations (in addition to the basic ones) using path consistency are issues for further research and need to be investigated.

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