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Representing Time and Space for the Semantic Web

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Abstract. Representation of temporal and spatial information for the Semantic Web often involves qualitative defined information (i.e., information described using natural language terms such as "before" or "overlaps") since precise dates or coordinates are not always available. This work proposes several temporal representations for time points and intervals and spatial topological representations in ontologies by means of OWL properties and reasoning rules in SWRL. All representations are fully compliant with existing Semantic Web standards and W3C recommendations. Although qualitative representations for temporal interval and point relations and spatial topological relations exist, this is the first work proposing representations combining qualitative and quantitative information for the Semantic Web. In addition to this, several existing and proposed approaches are compared using different reasoners and experimental results are presented in detail. The proposed approach is applied to topological relations (RCC5 and RCC8) supporting both qualitative and quantitative (i.e., using coordinates) spatial relations. Experimental results illustrate that reasoning performance differs greatly between different representations and reasoners. To the best of our knowledge, this is the first such experimental evaluation of both qualitative and quantitative Semantic Web temporal and spatial representations. In addition to the above, querying performance using SPARQL is evaluated. Evaluation results demonstrate that extracting qualitative relations from quantitative representations using reasoning rules and querying qualitative relations instead of directly querying quantitative representations increases performance at query time.

Keywords: Temporal Representation and Reasoning; Spatial Representation and Reasoning; Semantic Web; Rules.

1   Introduction

Understanding the meaning of Web information requires formal definitions of concepts and their properties, using the Semantic Web Ontology

definition language OWL[1]. This language provides the means for defining concepts, their properties and their relations, allowing for reasoning over the definitions and the assertions of specific individuals using reasoners such as Pellet [1] and HermiT [2]. Furthermore, reasoning rules can be embedded into the ontology using the SWRL rule language[2].

Temporal and spatial information is an important aspect of represented objects in many application areas involving change in space and time. Temporal information in turn can be defined using quantitative (e.g., using dates) and qualitative terms (i.e., using natural language expressions such as "During"). Spatial information can also be defined using coordinates or qualitative spatial relations such as "Contains". Quantitative approaches are used for example in [3,4] and in OWL-Time [5]. Qualitative temporal and spatial terms have specific semantics, which can be embedded into the ontology using reasoning rules.

In previous work [6,7] such a representation is proposed for qualitative defined temporal information in OWL, but combining qualitative and quantitative information was not supported. The current work deals exactly with the case of combined qualitative and quantitative information, which is more expressive than the representation proposed in [6]. In addition, reasoning performance using different point and temporal representations and reasoners is evaluated. Each point in time can be represented quantitatively using a date or qualitatively using relations with other points. These relations are *before, after* or *equals*. Intervals can be defined using their end-points, which in turn can be defined using dates or point relations. Alternatively intervals can be defined using qualitative interval relations. Specifically, between each pair of intervals, qualitative relations are asserted (e.g., "Before" or "During"). These relations represent the relative placement of intervals along the axis of time [8].

Reasoning can be applied for interfering point relations using either dates or qualitative relations or both. In case of dates, SWRL rules are used, combined with support for date datatypes by the reasoner. In case of qualitative point relations both OWL axioms and SWRL rules can be used. Both approaches and their combination with dates are evaluated. Intervals with specific end points can be represented by attaching two dates (start and end) directly to an interval as datatype properties or by attaching the dates to points which in turn are associated with intervals. When end-points are not defined using dates, qualitative point relations

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such as after can be used. Alternatively, interval relations can be inferred using directly reasoning over Allen relations [8] between intervals, instead of reasoning over points and then extracting the interval relations. Again all approaches are evaluated using different reasoners.

Spatial information can also be defined using quantitative (e.g., using coordinates) and qualitative terms (i.e., using natural language expressions such as "In"). Qualitative spatial terms have formal semantics which can be embedded into the ontology using reasoning rules. In [9] , such a representation, embedding semantics by means of SWRL rules, was proposed for spatial and temporal information in OWL. Specifically, topological information (based on the RCC-8 [10] set of topological relations) was represented (in [11,12] similar representations for topologic relations were proposed as well). In this work, we also support quantitative defined representations in addition to the aforementioned qualitative representations using SWRL rules. Each region is represented using the coordinates of the minimum bounding rectangle of the region. Furthermore, combined representations supporting both qualitative relations (such as "overlaps") and quantitative information are proposed and evaluated.

Although in the current work many different representations are proposed and evaluated, all of them are based on existing standards such as OWL and W3C member submissions such as SWRL. The requirement of full compliance with existing W3C standards and recommendations and compatibility with existing, widely used tools, was a strict design decision adopted in this work. Embedding reasoning rules into the ontology makes sharing of data easier since all SWRL compliant reasoners (such as Pellet and HermiT) can be used for temporal reasoning. To the best of our knowledge, this is the first work proposing combined qualitative and quantitative spatial and temporal representations for the Semantic Web, while retaining compatibility with existing standards and tools, and provides an evaluation of these approaches. In addition to the reasoning performance of various implementations, querying performance using SPARQL is evaluated. In case of quantitative representations, two querying approaches are compared: (a) converting quantitative information to qualitative using rules and then query using the inferred qualitative relations and (b) query directly using the quantitative representation. Evaluation results indicate that in general the first approach outperforms the second at query time.

The current work is organized as follows: related work in the field of temporal knowledge representation is discussed in Section 2. The proposed temporal representations are presented in Section 3 and the corresponding reasoning mechanisms in Section 4. The combined interval-point

reasoning mechanism is presented in Section 5. Spatial representation is presented in Section 6 and the corresponding reasoning mechanism in Section 7. Querying temporal and spatial information is presented in Section 8. Evaluation is presented in Section 9 and conclusions and issues for future work in Section 10.

2 Background and Related Work

Definition of ontologies for the Semantic Web is achieved using the Web Ontology Language OWL. Specifically, the current W3C standard is the OWL 2[3] language, offering increased expressiveness, while retaining decidability of basic reasoning tasks. Querying OWL and RDF data is achieved using the SPARQL query language [13]. Reasoning tasks are applied both on concept and property definitions into the ontology (TBox), and on assertions of individual objects and their relations (ABox). Reasoners include among others Pellet and HermiT. Reasoning rules can be embedded into the ontology using SWRL. To guarantee decidability, the rules are restricted to *DL-safe rules* that apply only on named individuals in the ontology ABox.

Temporal and spatial representations for the Semantic Web, based on quantitative representations, are used for example in CNTRO [4], OWL-Time [5], and stRDF [14]. Representation of temporal and spatial information for the Semantic Web often involves qualitative defined information since precise dates or coordinates are not always available. Qualitative temporal and spatial reasoning (i.e., inferring implied relations and detecting inconsistencies in a set of asserted relations) typically corresponds to Constraint Satisfaction problems which are *NP*, but tractable sets (i.e., solvable by polynomial algorithms) are known to exist [15]. These tractable sets (i.e., sets of qualitative relations between temporal points, temporal intervals and regions) form the basis of the current work. Relations between dynamic (i.e., evolving in time and having time dependent properties) entities in ontologies are typically represented using Allen temporal relations of Figure 1 and topological relations between regions are typically represented using the RCC relations defined in [10].

Embedding temporal and spatial reasoning into the ontology, by means of SWRL rules applied on temporal intervals and spatial regions forms the basis of the SOWL model proposed in [9] and the CHRONOS-Ed system [16]. CHRONOS-Ed and the underlying SOWL model were both not addressing the issue of combined qualitative and quantitative spatial and
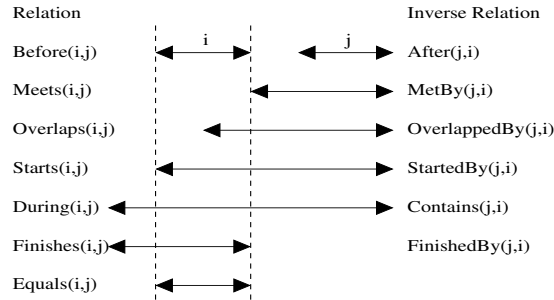

Fig. 1. Allen Temporal Relations.

temporal representation using different approaches and reasoners. Thus, the selection of the most efficient representation with respect to the type of available data remained an open issue [17] . The current work addresses, this issue and to the best of our knowledge is the first such work for temporal and spatial, qualitative and quantitative representations for the Semantic Web.

3   Temporal Representation

This work deals with qualitative relations between points in addition to interval Allen relations. Qualitative relations of two points are represented using an object property specifying their relative position on the axis of time. Specifically, between two points three relations can hold, these relations are "$<$","$>$","$=$" also referred to as *before, after* and *equals* respectively. If a date/time is available then a corresponding datatype property can be used. Qualitative and quantitative representations can be combined (Figure 2).

An interval temporal relation can be one of the 13 pairwise disjoint Allen relations [8] of Figure 1. In cases where the exact durations of temporal intervals are unknown (i.e., their starting or ending points are not specified), their temporal relations to other intervals can still be asserted qualitatively by means of temporal relations (e.g., "interval i_1 is before interval i_2" even in cases where the exact starting and ending time of either i_1, i_2, or both are unknown).

Intervals can be represented using two directly attached datatype properties, corresponding to starting and ending time of each interval (Figure 3(a)). This straightforward approach can be applied only when start and end time of intervals are known. Interval relations can be inferred using comparisons of starting/ending dates using SWRL rules. An-
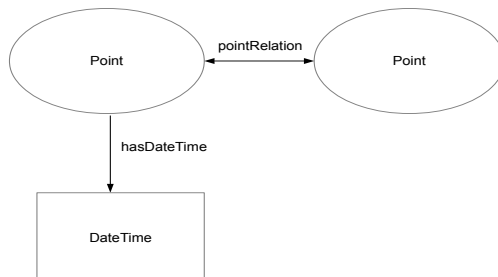
Fig. 2. Point Representations

other more flexible and more complex approach is presented in Figure 3(b). In this case intervals are related with starting and ending points, and not directly with dates. These points can be associated with dates, as in Figure 2, and/or with other points using point relations (such as *after*). Point relations can be inferred using comparisons of dates and/or reasoning rules over asserted point relations. When point relations are inferred, then Allen relations between intervals can be inferred using SWRL rules implementing the definitions of Figure 1. Finally, reasoning over qualitative defined Allen relations can be applied directly without using dates or points as in Figure 3(c).

Besides temporal property definitions, additional OWL axioms are required for the proposed representation; basic relations are pairwise disjoint i.e., "<",">" and "=" point relations are pairwise disjoint and all Allen relations of Figure 1 are pairwise disjoint as well. In addition, "<" is inverse of ">", while "=" is *symmetric* and *transitive*. Also *Before* is inverse of *After, Meets* is *inverse* of *MetBy, During* is *inverse* of *Contains, Finishes* is *inverse* of *FinishedBy, Starts* is *inverse* of *startedBy* and *Overlaps* is *inverse* of *OverlappedBy. Equals* is *symmetric* and *transitive*.

4 Temporal Reasoning

Inferring implied relations and detecting inconsistencies are handled by a reasoning mechanism. In the case of qualitative relations, assertions of relations holding between temporal entities (i.e., intervals) restrict the possible assertions holding between other temporal entities in the knowl-
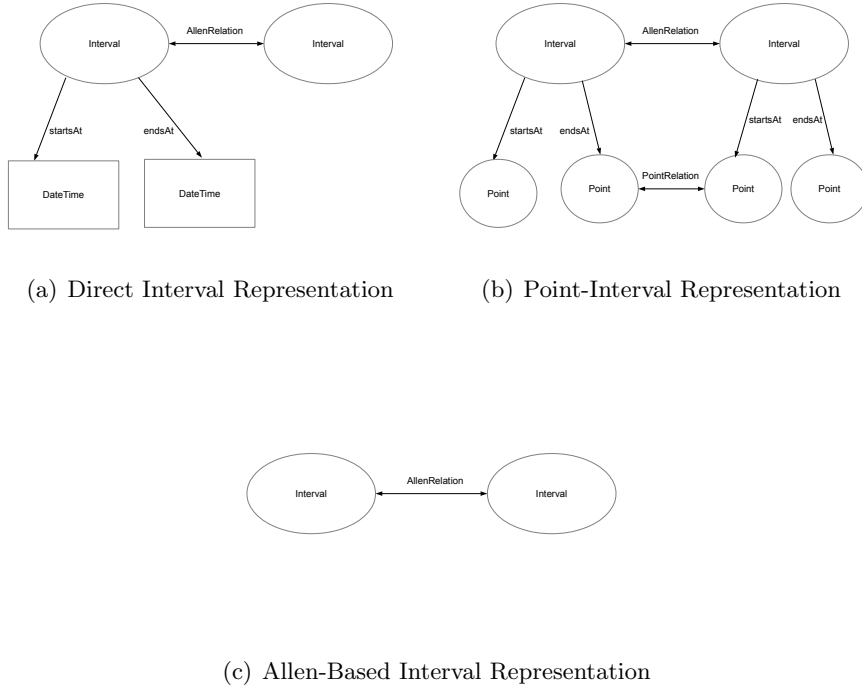
(a) Direct Interval Representation

(b) Point-Interval Representation

(c) Allen-Based Interval Representation

Fig. 3. Example of (a) Direct (b) Point Based (c) Allen Based Interval Representations

edge base. Then, reasoning on qualitative temporal relations can be transformed into a *constraint satisfaction problem*, which is known to be an *NP-hard problem* in the general case [15]. Inferring implied relations is achieved by specifying the result of *compositions* of existing relations. Specifically, when a relation (or a set of possible relations) R_1 holds between intervals i_1 and i_2 and a relation (or a set of relations) R_2 holds between intervals i_2 and i_3 then, the composition of relations R_1, R_2 (denoted as $R_1 \circ R_2$) is the set (which may contain only one relation) R_3 of relations holding between i_1 and i_3.

Qualitative relations under the intended semantics may not apply simultaneously between a pair of individuals. For example, given the time intervals i_1 and i_2, i_1 cannot be simultaneously *before* and *after* i_2. Typically, in temporal representations (e.g., using Allen relations), all basic relations (i.e., simple relations and not disjunctions of relations) are pairwise disjoint. When disjunctions of basic relations hold true simultane-

ously, then their set intersection holds true as well. For example, if i_1 is *before or equals* i_2 and simultaneously i_1 is *after or equals* i_2 then i_1 *equals* i_2. In case the intersection of two relations is empty, these relations are disjoint. Checking for consistency means, whenever asserted and implied relations are disjoint, an inconsistency is detected.

4.1 Reasoning over Interval Allen Relations

Reasoning is realized by introducing a set of SWRL rules operating on temporal relations. Reasoners, such as HermiT, supporting DL-safe rules can be used for inference and consistency checking over Allen relations. The temporal reasoning rules for Allen relations are based on the composition of pairs of the basic Allen relations of Figure 1 as defined in [8]. Specifically, if relation R_1 holds between intervals i_1 and i_2, and relation R_2 holds between intervals i_2 and i_3, then the composition table defined in [8] denotes the possible relation(s) holding between intervals i_1 and i_3. Not all compositions yield a unique relation as a result. For example, the composition of relations *During* and *Meets* yields the relation *Before* as a result, while the composition of relations *Overlaps* and *During* yields three possible relations namely *Starts, Overlaps* and *During*.

A series of compositions of relations may yield relations that are inconsistent with existing ones (e.g., if i_1 *before* i_2 is inferred using compositions, a contradiction arises if i_1 *after* i_2 has been also asserted into the knowledge base). Reasoning over temporal relations is known to be an NP-hard problem and identifying tractable cases of this problem has been in the center of many research efforts over the last few years [15]. The notion of *k-consistency* is very important in this research. Given a set of n intervals with relations asserted between them imposing certain restrictions, *k-consistency* means that every subset of the n intervals containing at most k intervals does not contain an inconsistency. Notice that, checking for all subsets of n entities for consistency is exponential on the n.

There are cases where, although *k-consistency* does not imply *n-consistency* in general, there are specific sets of relations R_t (which are subsets of the set of all possible disjunctions of basic relations R), with the following property: if asserted relations are restricted to this set, then *k-consistency* implies *n-consistency* and R_t is a *tractable set* of relations or a *tractable subset* of R [15]. Tractable sets of Allen interval algebra have been identified in [18] and tractable subsets for Point Algebra have been identified in [19] . Additional tractable sets for Allen relations have

been identified in [9]. Consistency checking is achieved by ensuring path consistency by applying the following formula:

$$\forall x, y, k \; R_s(x, y) \leftarrow R_i(x, y) \cap (R_j(x, k) \circ R_k(k, y)) \qquad (1)$$

representing intersection of compositions of relations with existing relations R_i, R_j, R_k, (symbol $\cap$ denotes intersection, symbol $\circ$ denotes composition and symbols R_i, R_j, R_k, R_s denote temporal relations). The formula is applied until a fixed point is reached (i.e., the application of the rules above does not yield new inferences) or until the empty set is reached, implying that the ontology is inconsistent. Implementing path-consistency formula (using SWRL in this work) requires rules for both compositions and intersections of pairs of relations.

Compositions of relations R_1 and R_2 yielding a unique relation R_3 as a result are expressed in SWRL using rules of the form:

$$R_1(x, y) \wedge R_2(y, z) \rightarrow R_3(x, z) \qquad (2)$$

The following is an example of such a composition rule:

$$During(x, y) \wedge Meets(y, z) \rightarrow Before(x, z) \qquad (3)$$

Rules yielding a set of possible relations cannot be represented directly in SWRL since, disjunctions 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, the composition of relations *Overlaps* and *During* yields the disjunction of three possible relations (*During, Overlaps* and *Starts*) as a result:

$$Overlaps(x, y) \wedge During(y, z) \rightarrow During(x, z)$$
$$\vee Starts(x, z) \vee Overlaps(x, z) \qquad (4)$$

If the relation *DOS* represents the disjunction of relations *During, Overlaps* and *Starts*, then the composition of *Overlaps* and *During* can be represented using SWRL as follows:

$$Overlaps(x, y) \wedge During(y, z) \rightarrow DOS(x, z) \qquad (5)$$

The set of possible disjunctions over all basic Allen's relations contains 2^{13} relations, and complete reasoning over all temporal Allen relations has exponential time complexity. However, tractable 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) are also known to exist [18,19].

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

$$R_1(x, y) \wedge R_2(x, y) \rightarrow R_3(x, y), \tag{6}$$

where R_3 can be the empty relation. For example, the intersection of relation DOS (representing the disjunction of $During$, $Overlaps$ and $Starts$) with relation $During$, yields relation $During$ as a result:

$$DOS(x, y) \wedge During(x, y) \rightarrow During(x, y) \tag{7}$$

The intersection of relations $During$ and $Starts$ yields the empty relation, and an inconsistency is detected:

$$Starts(x, y) \wedge During(x, y) \rightarrow \perp \tag{8}$$

Thus, path consistency is implemented by defining compositions and intersections of relations using SWRL rules and OWL axioms for inverse relations as presented in Section 3. Notice that it is impossible to apply path consistency reasoning based only on OWL axioms since compositions (property chains), disjoint properties and property intersections are required. The computational properties of these constructs have been analysed in [20]. While property chains and disjoint properties are supported in OWL 2, property intersection required for Allen reasoning (and RCC topological reasoning) are not, thus SWRL rules are required for a reasoning mechanism compliant with existing W3C standards and recommendations.

Implementing path consistency over Allen relations requires minimizing the required additional relations and rules for implementing the mechanism. Existing work (e.g., [21]) emphasizes on determining maximal tractable subsets of relations, while practical implementations call for minimizing of such relation sets (i.e., finding the minimal tractable set that contains the required relations). For example, implementing path consistency over the maximal tractable set of Allen relations [21], containing 868 relations is impractical, since defining all intersections and compositions of pairs of relations by means of SWRL rules requires millions of such rules.

In this work the closure method [15] of Table 1 is applied for computing the minimal relation sets containing a tractable set of basic relations: starting with a set of relations, intersections and compositions of relations

Table 1. Closure method

Input: Set S of tractable relations
Table C of compositions
WHILE S size changes
BEGIN
Compute C: Set of compositions of relations in S
S=S ∪ C
Compute I: Set of intersections of relations in S
S= S ∪ I
END
RETURN S

are applied iteratively until no new relations are produced. Since compositions and intersections are constant-time operations (i.e., a bounded number of table lookup operations at the corresponding composition tables) the running time of closure method is linear to the total number of relations of the identified tractable set. Applying the closure method over the set of basic Allen relations yields a tractable set containing 29 relations, presented in the following. Relations *Before, After, Meets, Metby, Overlaps, Overlappedby, During, Contains, Starts, Startedby, Finishes, Finishedby* and *Equals* are represented using symbols B, A, M, Mi, O, Oi, D, Di, S, Si, F, Fi and Eq respectively. Basic Allen relations, or disjunctions of basic relations represented as a set of relations into brackets are used. For example the disjunction of relations Before (B), Overlaps (O), and Meets (M) is represented as {B, O, M}. The tractable set of Allen relations used in this work is:

{B},{A},{A, D, Di, O, Oi, Mi, S, Si, F, Fi, Eq}, {A, D, Oi, Mi, F}, {A, Di, Oi, Mi, Si}, {A, Oi, Mi}, {B, D, Di, O, Oi, M, S, Si, F, Fi, Eq}, {B, D, O, M, S}, {B, Di, O, M, Fi}, {B, O, M}, {D}, {D, Di, O, Oi, S, Si, F, Fi, Eq}, {D, Oi, F}, {D, O, S}, {Di}, {Di, Oi, Si}, {Di, O, Fi}, {Eq}, {F}, {F, Fi, Eq}, {Fi}, {M}, {Mi}, {O}, {Oi}, {S}, {S, Si, Eq}, {Si}.

4.2 Reasoning over Point Relations

Possible relations between points are *before, after* and *equals*, denoted as "<",">","=" respectively. Table 2 illustrates the set of reasoning rules defined on the composition of existing relation pairs. The composition table is interpreted as follows: if relation R_1 holds between *Point1* and *Point2* and relation R_2 holds between *Point2* and *Point3*, then the entry of the Table 2 corresponding to row R_1 and column R_2 denotes the

possible relation(s) holding between *Point1* and *Point3*. For example, if *Point1* is *before* ($<$) *Point2* and *Point2* is *before* ($<$) *Point3* then *Point1* is *before* ($<$) *Point3*.

The three basic temporal point relations are declared as pairwise disjoint, since they cannot simultaneously hold between two points. Not all compositions yield a unique relation as a result. For example, the composition of relations *before* and *after* yields all possible relations as a result. Because such compositions do not yield new information these rules are discarded. Rules corresponding to compositions of relations R_1 and R_2 yielding a unique relation R_3 as a result are retained (7 out of the 9 entries of Table 2 are retained), and are directly expressed in SWRL. The following is an example of such a temporal inference rule:

$$before(x, y) \land equals(y, z) \rightarrow before(x, z) \qquad (9)$$

A series of compositions of relations may imply relations which are inconsistent with existing ones. In addition to rules implementing compositions of temporal relations, a set of rules defining the result of intersecting relations holding between two instances must also be defined in order to check consistency.

Table 2. Composition Table for Basic Point-Based Temporal Relations.

Relations	$<$	$=$	$>$
$<$	$<$	$<$	$<, =, >$
$=$	$<$	$=$	$>$
$>$	$<, =, >$	$>$	$>$

For example, the intersection of relations *before* and *after* yields the empty relation, and an inconsistency is detected (i.e., they cannot hold simultaneously between two points). As shown in Table 2, compositions of relations may yield one of the following four relations: *before, after, equals* and the disjunction of these three relations. Intersecting the disjunction of all three relations with any of these leaves existing relations unchanged. Intersecting any one of the three basic (non disjunctive) relations with itself also leaves existing relations unaffected. Only intersections of pairs of different basic relations affect the knowledge base by yielding the empty relation as a result, thus detecting an inconsistency. By declaring the three basic relations *before, after, equals* as pairwise disjoint, all intersections that can affect the ontology are defined. Thus, checking consistency of point relations is implemented by defining compositions of relations

using SWRL rules and by declaring the three basic relations as disjoint (no intersection rules are needed). In case of quantitative relations (i.e., using dates), qualitative relations are extracted by comparing dates using SWRL rules.

Compositions of relations can be also expressed using OWL *Role Inclusion Axioms* [22] instead of SWRL rules. For example, the composition of *before* and *equals* can be expressed using the following axiom:

$$before \circ equals \sqsubseteq before \qquad (10)$$

Properties involved in Role Inclusion Axioms (RIA) cannot be combined with disjointness axioms in OWL, but in case the consistency of point relations is guaranteed, then this approach can be used instead of SWRL rules. In addition to this, Role Inclusion Axioms can be used in conjunction with dates/times in a combined qualitative/quantitative approach. In total, based on the reasoning mechanism, five different representations for points have been implemented:

- Quantitative Point Representation (**P1**): Relations are extracted by comparing date/time values using SWRL.
- Qualitative Only using SWRL (**P2**): Only qualitative point relations are asserted and reasoning using Path Consistency implemented in SWRL is applied.
- Qualitative Only using Role Inclusion Axioms (**P3**): Only qualitative point relations are asserted and reasoning using Path Consistency is implemented using OWL 2 Role Inclusion Axioms.
- Combined representation using SWRL (**P4**): Both dates and qualitative relations are asserted and reasoning mechanism combines rules from representations P1 and P2.
- Combined representation using OWL Role Inclusion Axioms (**P5**): Both dates and qualitative relations are asserted and reasoning mechanism combines SWRL rules from representations P1 and OWL axioms from P3.

5 Combining Interval and Point Representation and Reasoning

In addition to the Allen based Interval representation (see Figure 3(c)) and the corresponding reasoning mechanism of Section 4.1, interval relations can be extracted using endpoint relations and/or comparisons of dates of endpoints. Using the direct representation of Figure 3(a), Allen

relations are extracted using end-point date comparisons. There are 13 SWRL rules, one for each basic Allen relation. For example, the Allen *intervalMeets* (or Meets) relation is inferred using the following rule:

$$
\begin{aligned}
&ProperInterval(a) \wedge ProperInterval(x) \wedge endValue(x, z1) \\
&\wedge startValue(a, b1) \wedge lessThanOrEqual(b1, z1) \\
&\wedge lessThanOrEqual(z1, b1) \rightarrow intervalMeets(x, a)
\end{aligned} \tag{11}
$$

In case of the representation of Figure 3(b) both date comparisons and point algebra reasoning from Section 4 are applied for inferring qualitative relations between end-points. Allen relations between intervals are then inferred using relations of end-points. There are 13 SWRL rules, one for each basic Allen relation. For example, the rule for extracting the interval *Meets* relation is:

$$
\begin{aligned}
&ProperInterval(a) \wedge ProperInterval(x) \wedge equals(z, b) \wedge \\
&hasBeginning(a, b) \wedge hasEnd(x, z) \rightarrow intervalMeets(x, a)
\end{aligned} \tag{12}
$$

Based on the above rules and the representations of Section 3 (see Figure 3), five different interval representations have been implemented (notice that different representations corresponding to Figure 3(b) are proposed, since different combinations of relations in this figure can be used):

- Allen-based Interval Representation (**I1**): Qualitative Allen relations only are asserted directly between intervals (points are not used, see Figure 3(c)) combined with the reasoning mechanism of Section 4.1.
- Quantitative Only-direct intervals (**I2**): Only dates or times are asserted attached directly to intervals (see Figure 3(a)) and Allen relations are extracted by date/time comparisons.
- Quantitative Only using Points (**I3**): Only dates or times are asserted attached to Points representing end-points of intervals (see Figure 3(b)) and Allen relations are extracted by date/time comparisons.
- Qualitative Only Point Based Interval representation (**I4**): Only qualitative relations between points (see Figure 3(b)) are asserted and reasoning mechanism is based on Point reasoning rules from Section 4.2 and Allen extraction rules from Section 5.
- Combined qualitative/quantitative Interval representation (**I5**): Both dates and qualitative relations between points are asserted (see Figure 3(b)) and date/time comparisons are combined with SWRL rules of Section 4.2 and Allen extraction rules from Section 5.

We have made all point and interval representations available on the Web at:
`https://github.com/sbatsakis/TemporalRepresentations`.

6 Spatial Representation

Region Connection Calculus [10] is one of the main ways of representing topological relations. There are several variants of the calculus corresponding to different levels of detail of the represented relations, variants such as RCC-5 and RCC-8. In the following, the representation and reasoning of RCC-5 relations is presented.
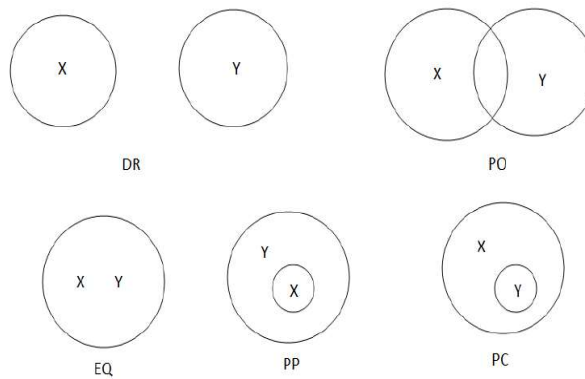

Fig. 4. Topological RCC-5 Relations

RCC-5 relations is a set of 5 topological relations namely DR (discrete), PO (partially overlapped), EQ (equals), PP (proper part) and PC (contains). Figure 4 illustrates these relations between two regions X and Y. Relations DR, PO and EQ are symmetric, and relation PP is the inverse of PC. All these 5 basic RCC-5 relations are pairwise disjoint. Also EQ, PP and PC are transitive. All the above can be represented using OWL object property axioms (i.e., symmetry, inverse, disjointness and transitivity). Topological RCC-5 relations in this work are represented as object properties between OWL objects representing regions. For example, if *Region1* is *In Region2*, the user asserts the binary relation *Region1 PP* (proper part) *Region2*, or equivalently *PP(Region1, Region2)*. This approach is similar to the approach used in [9]. The first representation proposed in this work implements reasoning rules applied on topological

relations. Following this approach for example, if a region overlaps with another region, then this is represented by asserting one relation (PO) between them. The second approach is based on coordinates of the minimum bounding rectangle of a region (see Figure 5). For example if a region r is enclosed into a minimum rectangle with coordinates of upper right point (3,5) and lower left point (1,1) then the following datatype properties are asserted: *r Xmax 3, r Ymax 5, r Xmin 1* and *r Ymin 1*. Notice that using qualitative relations can be extracted by comparing the coordinates of two regions.

(Xmax, Ymax)

(Xmin, Ymin)

Fig. 5. Minimum Bounding Rectangle (MBR) Spatial Representation

The third representation combines the qualitative and quantitative approach, so if Xmax, Ymax, Xmin and Ymin values of a region are known, then they are asserted as datatype properties. Otherwise, qualitative relations with other regions using RCC5 object properties are asserted.

Another important set of topological relations is the RCC-8 set of relations, which is a refinement of RCC-5 relations set. Specifically, the DR relation is refined into two distinct relations; *DC* (Disconnected) representing the fact that two regions do not have common points, and *EC* (Externally connected) representing the fact that two regions have common boundary points, but not common internal points. Similarly the PP (Proper part) relation is refined into two different relations *TPP* and *NTPP*. TPP is representing the fact that a region is a proper part of another region and also has common points with the boundary of the enclosing region. NTPP on the other hand, represents the fact that the
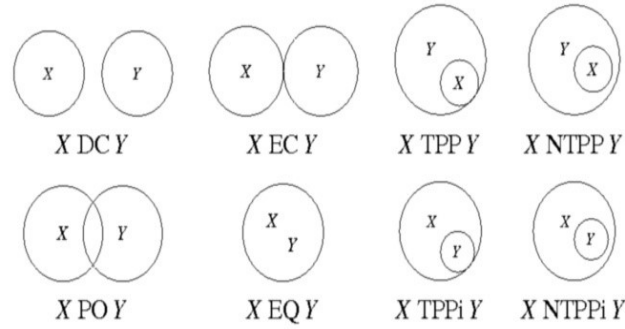
Fig. 6. Topological RCC-8 Relations

enclosed region does not have common points with the boundary of the enclosing region. *NTPPi* and *TPPi* are the inverses of NTPP and TPP respectively. RCC-8 relations are illustrated in Figure 6.

The composition table for RCC-8 relations has been defined in [10], and an implementation based on path consistency using SWRL and OWL axioms was presented in [9]. To the best of our knowledge, this is the first work dealing with combined RCC-8 qualitative and quantitative information for the Semantic Web. The quantitative approach is based on the coordinates of the minimum bounding rectangle (Xmax, Ymax, Xmin, Ymin) as in the case of RCC5 and these coordinates can be combined with qualitative relations in case of a combined representation. In total six spatial representations are presented:

- RCC5 Qualitative (**RCC5Q**): RCC5 relations are asserted between regions, while coordinates are not supported. Reasoning rules for qualitative RCC5 relations are part of the representation.
- RCC5 coordinates (**RCC5C**): Regions are represented using coordinates as in Figure 5, and rules for extracting RCC5 relations from coordinates are integral part of the representation. Qualitative reasoning support is not included.
- RCC5 combined (**RCC5**): Both qualitative relations and coordinates are supported and rules for extracting RCC5 relations from coordinates and reasoning over qualitative RCC5 relations are defined. If

coordinates are known then they can be asserted, otherwise qualitative relations can be used.

– RCC8 Qualitative (**RCC8Q**): RCC8 relations are asserted between regions, while coordinates are not supported. Reasoning rules for qualitative RCC8 relations are part of the representation.
– RCC8 coordinates (**RCC8C**): Regions are represented using coordinates as in Figure 5, and rules for extracting RCC8 relations from coordinates are integral part of the representation. Qualitative reasoning support is not included.
– RCC8 combined (**RCC8**): Both qualitative relations and coordinates are supported and rules for extracting RCC8 relations from coordinates and reasoning over qualitative RCC8 relations are defined. If coordinates are known then they can be asserted, otherwise qualitative relations can be used.

7   Spatial Reasoning

Reasoning is realized by a set of SWRL rules applied on spatial relations of Section 6. Defining compositions of relations is a basic part of the spatial reasoning mechanism. Table 3 represents the result of the composition of each pair of topological RCC-5 relations of Figure 4.

Table 3. Composition Table for RCC-5 Topological Relations.

Relations	DR	PO	EQ	PP	PC
DR	All	DR,PO,PP	DR	DR,PO,PP	DR
PO	DR,PO,PC	All	PO	PO,PP	DR,PO,PC
EQ	DR	PO	EQ	PP	PC
PP	DR	DR,PO,PP	PP	PP	All
PC	DR,PO,PC	PO,PC	PC	PO,EQ,PP,PC	PC

The composition Table is interpreted as follows: if relation R_1 holds between *Region1* and *Region2* and relation R_2 holds between *Region2* and *Region3*, then the entry of the Table 3 corresponding to line R_1 and column R_2 denotes the possible relation(s) holding between *Region1* and *Region3*. For example, if *Region1* is *Proper Part* (PP) of *Region2* and *Region2* is *Proper Part* (PP) of *Region3* then *Region1* is *Proper Part* (PP) of *Region3*. Entries in the composition table are determined using the formal semantics of Region Connection Calculus as defined in [10].

A series of compositions of relations may yield relations which are inconsistent with existing ones (e.g., inferring using compositions for ex-

ample, that *X PP Z* will yield a contradiction if *X PO Z* has been also asserted into the ontology). Consistency checking is achieved by applying the path consistency formula (Equation 1) of Section 4, consisting of compositions and intersections of asserted and inferred spatial relations as in the case of temporal reasoning. Compositions of relations are implemented using rules of the form of Equation 2.

The following is an example of such a composition rule:

$$PP(x,y) \wedge DR(y,z) \rightarrow DR(x,z) \tag{13}$$

Rules yielding a set of possible spatial relations cannot be represented directly in SWRL, since disjunctions 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, the composition of relations *PO* and *PP* yields the disjunction of two possible relations (*PP* and *PO*) as a result:

$$PO(x,y) \wedge PP(y,z) \rightarrow PO(x,z) \vee PP(x,z) \tag{14}$$

If the relation *PO_PP* represents the disjunction of relations *PO* and *PP*, then the composition of *PO* and *PP* can be represented using SWRL as follows:

$$PO(x,y) \wedge PP(y,z) \rightarrow PO\_PP(x,z) \tag{15}$$

A set of rules defining the result of intersecting relations holding between two regions must also be defined using rules of the form of Equation 6 of Section 4.

For example, the intersection of relations *DR* and *PC* yields the empty relation ($\perp$ or null), and an inconsistency is detected:

$$DR(x,y) \wedge PC(x,y) \rightarrow \perp \tag{16}$$

Intersection of relations *PO* and *PO_PP* (representing the disjunction of *Overlaps* and *Proper Part*) yields relation *PO* as a result:

$$PO(x,y) \wedge PO\_PP(x,y) \rightarrow PO(x,y) \tag{17}$$

Thus, path consistency is implemented by defining compositions and intersections of relations using the above SWRL rules, and OWL axioms for inverse spatial relations as presented in Section 6. Another important issue for implementing path consistency is the identification of the additional relations, such as the above mentioned *PO_PP* relation, that represent disjunctions. Specifically, the *minimal set* of relations required

for defining compositions and intersections of all relations that can be yielded when applying path consistency on the basic relations of Figure 4 is identified. The identification of the additional relations is required for the construction of the corresponding SWRL rules.

The *closure method* [15] of Table 1 is applied for computing the minimal tractable set of relations containing the basic spatial relations, starting with the set of basic RCC-5 relations, as in the case of temporal relations. Furthermore, tractability of the initial set of basic relations guarantees tractability of the new set as well [15].

Applying the closure method over the set of basic RCC-5 relations yields a set containing 12 relations. These are the 5 basic relations of Figure 4 and the relations *DR_PO* representing the disjunction of DR and PO, *DR_PO_PC* representing the disjunction of DR, PO and PC, *DR_PO_PP* representing the disjunction of DR, PO and PP, *PO_EQ_PP_PC* representing the disjunction of PO, EQ, PP and PC, *PO_PP* representing the disjunction of PO and PP, *PO_PC* representing the disjunction of PO and PC, and *All* denoting the disjunction of all relations.

Path consistency and the closure method are applied directly over qualitative RCC8 relations as in the case of RCC5. After applying the closure method, the identified minimal tractable set contains 49 relations. SWRL rules based on comparison of coordinates are used for supporting RCC8 representation for quantitative defined information.

In addition to the qualitative spatial representation based on RCC relations and the corresponding reasoning mechanism presented above, topological relations can be extracted from the coordinates of Figure 5 using comparisons. The first step is to extract the topological relation on each axis separately. Specifically in case of x-axis SWRL rules are used for detecting if the projections of regions on x-axis, are discrete (DRx), Overlap (POx), the first region contains the second (PCx), the first is part of the second (PPx) or are equal (EQx). The corresponding relations for y-axis are DRy, POy, PCy, PPy and EQy. An example SWRL rule for extracting the PPx using comparisons of coordinates:

$$Region(r1) \land Region(r2) \land Xmax(r1, X1) \land Xmax(r2, X2) \land Xmin(r1, x1)$$
$$\land Xmin(r2, x2) \land swrlb : lessThan(X1, X2) \land swrlb : lessThanOrEqual(x2, x1)$$
$$\rightarrow PPx(r1, r2)$$

$$(18)$$

After extracting relations on x and y axes, these relations are combined to extract the RCC5 relation between the 2 regions in 2D space. For example, if the projection of the first region contains the projection

of the second in x-axis (PCx) and is part of the projection of the second region on the y-axis (PPy), then the two regions partially overlap (PO) in 2D:

$$PCx(x, y) \land PPy(x, y) \rightarrow PO(x, y) \qquad (19)$$

Similar rules have been implemented for RCC8 relations. In case of combined qualitative and coordinate based representations, the above rules for extracting RCC relations from coordinates are combined with the qualitative reasoning rules implementing path consistency. When coordinates are available, qualitative relations between regions with coordinates are extracted, then using qualitative reasoning, additional relations can be inferred between regions that are defined without the use of coordinates.

8 Querying Temporal and Spatial Information

Querying information in RDF format is achieved using the SPARQL query language [13]. SPARQL 1.1 is the current W3C specification for querying RDF data[4] and there are several SPARQL implementations such as ARQ, the query engine of Apache Jena[5]. In this work we examine and evaluate alternative ways of querying temporal and spatial information using SPARQL. There are two ways to query temporal and spatial information of Sections 3 and 6:

- Applying reasoning rules for extracting qualitative spatial and temporal relations from asserted qualitative relations and/or coordinates and dates, then using SPARQL queries for retrieving inferred qualitative relations.
- Applying directly SPARQL queries over quantitative representations (i.e., representations involving dates and coordinates) based on datatype comparisons. Notice that the second approach can be applied only when dates for temporal information and coordinates of spatial information are available. Qualitative representations require reasoning for inferring relations, thus the second approach is not applicable in this case.

An example SPARQL query based on qualitative temporal relations after reasoning for retrieving all intervals that a specific interval (*i1* in this example) *meets* is the following:

---

[4] https://www.w3.org/TR/sparql11-query/
[5] https://jena.apache.org/index.html

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX time: <http://www.hud.ac.uk/temporal.owl#>
SELECT ?subject ?object
WHERE ?subject time:intervalMeets ?object .
    FILTER (regex(str(?subject),'i1$'))
```

The equivalent query using comparisons of dates over the direct quantitative interval representation (I3) is the following:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX time: <http://www.hud.ac.uk/temporal.owl#>
SELECT ?subject ?object
WHERE ?subject time:startValue ?s1. ?subject time:endValue ?e1.
    ?object time:startValue ?s2. ?object time:endValue ?e2.
    FILTER ((?e1 = ?s2) && regex(str(?subject),'i1$'))
```

In case of the quantitative interval representation involving points (I2) the equivalent query is:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX time: <http://www.hud.ac.uk/temporal.owl#>
SELECT ?subject ?object
WHERE ?subject time:hasBeginning ?ps1. ?subject time:hasEnd ?pe1.
    ?ps1 time:inXSDDateTime ?s1. ?pe1 time:inXSDDateTime ?e1.
    ?object time:hasBeginning ?ps2. ?object time:hasEnd ?pe2.
    ?ps2 time:inXSDDateTime ?s2. ?pe2 time:inXSDDateTime ?e2.
    FILTER ((?e1 = ?s2) && regex(str(?subject),'i1$'))
```

Notice that the query based on qualitative relations is simpler than those based on direct comparisons of dates over quantitative representations. This is also the case for queries retrieving RCC5 and RCC8 spatial relations. For example, the SPARQL query retrieving all regions that a specific region contains (PC) is:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX rcc5: <http://www.hud.ac.uk/RCC5#>
SELECT ?subject ?object
WHERE ?subject rcc5:PC ?object. FILTER (regex(str(?subject),'r20$'))
```

The equivalent SPARQL query using comparisons of coordinates is:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX rcc5: <http://www.hud.ac.uk/RCC5#>
SELECT ?subject ?object
WHERE ?subject rcc5:Xmax ?x1M.
    ?subject rcc5:Xmin ?x1m.
    ?subject rcc5:Ymax ?y1M.
    ?subject rcc5:Ymin ?y1m.
    ?object rcc5:Xmax ?x2M.
    ?object rcc5:Xmin ?x2m.
    ?object rcc5:Ymax ?y2M.
    ?object rcc5:Ymin ?y2m.
    FILTER ( (((?x1M > ?x2M) && (?x1m <= ?x2m))
    || ((?x1M >= ?x2M) && (?x1m < ?x2m))
    && (((?y1M > ?y2M) && (?y1m <= ?y2m))
    || ((?y1M >= ?y2M) && (?y1m < ?y2m))) ))
    && (regex(str(?subject),'r20$')) )
```

The above queries illustrate that in case of spatial relations, SPARQL queries involving coordinates are much more complex than queries based on qualitative relations, since they involve comparisons over two axes. As part of this work, SPARQL queries, both qualitative based and quantitative based, over all Allen, Point and RCC5/8 relations, and over all supported representations have been defined and evaluated.

9 Evaluation

The required expressiveness of the proposed representations is within the limits of OWL 2 expressiveness combined with SWRL and date/time and decimal datatypes. Thus, reasoners such as Pellet and HermiT can be

used for reasoning. Reasoning mechanism is tractable since it consists of date/time comparisons and/or path consistency using SWRL [18]. A summary of all proposed point representations is presented in Table 4.

Table 4. Comparison of Point Representations

Representation	$P1$	$P2$	$P3$	$P4$	$P5$
Qualitative	No	Yes	Yes	Yes	Yes
Quantitative	Yes	No	No	Yes	Yes
Reasoning Support: HermiT (H), Pellet (P)	P	H,P	H,P	P	P
Consistency Checking	N/A	Yes	No	Yes	No

Comparison of interval based representations is presented in Table 5.

Table 5. Comparison of Interval Representations

Representation	$I1$	$I2$	$I3$	$I4$	$I5$
Qualitative	Yes	No	No	Yes	Yes
Quantitative	No	Yes	Yes	No	Yes
Reasoning Support: HermiT (H), Pellet (P)	H,P	P	P	H,P	P
Consistency Checking	Yes	N/A	N/A	Yes	Yes

Comparison of spatial representations is presented in Table 6 (RCC5 Qualitative is abbreviated as RCC5Q, RCC5 coordinates is abbreviated as RCC5C, the combined quantitative/qualitative representation is RCC5, and the corresponding RCC8 representations are abbreviated as RCC8Q, RCC8C and RCC8 respectively).

Table 6. Comparison of Spatial Representations

Representation	$RCC5Q$	$RCC5C$	$RCC5$	$RCC8Q$	$RCC8C$	$RCC8$
Qualitative	Yes	No	Yes	Yes	No	Yes
Quantitative	No	Yes	Yes	No	Yes	Yes
Reasoning Support	H,P	P	P	H,P	P	P
Consistency Checking	Yes	N/A	Yes	Yes	N/A	Yes

Notice that quantitative only approaches do not need to perform consistency checking since date/time assertions (or coordinate assertions in case of spatial relations) represent a valid instantiation of such values, while qualitative assertions may impose restrictions that cannot be satisfied. Also to the best of our knowledge, HermiT and Pellet are the only

reasoners currently supporting SWRL, while only Pellet currently supports date/time comparisons needed for SWRL rules used by quantitative approaches. HermiT currently does not support datatypes (required for representations involving dates and coordinates) in SWRL rules, thus can be used only for qualitative representations.

9.1 Experimental Evaluation of Reasoning Performance

Measuring the efficiency of the proposed representations requires temporal intervals and points containing instances, as defined in Section 3. Thus, datasets of various sizes containing points and intervals, both qualitative (using relations) and quantitative (using dates) generated randomly were used for the experimental evaluation. Reasoning response times of the temporal reasoning rules are measured as the average over 10 runs. The same approach was followed for spatial representations. HermiT 1.3.8 and Pellet 2.3.0 running as a Java library were the reasoners used in the experiments. All experiments were run on a PC, with Intel Core CPU at 2.4 GHz, 6 GB RAM, and Windows 7.

Measurements illustrate that there are major differences in performance between various approaches, and reasoners. Interval representations can be used for reasoning over 100 intervals, while qualitative representation combined with HermiT reasoner (representation I1 with HermiT, not presented in Figure 7) can reason over 500 intervals in 133.1 seconds when using Allen relations directly (representation I1). For 100 intervals corresponding time is 2.1 seconds respectively, clearly outperforming representations of Figure 7.

Point representations can be used for reasoning over 500 points efficiently (with the exception of qualitative representations using SWRL -P2 and P4- and Pellet, which can be practically used for at most 100 points and they are not presented in Figure 8, while reasoning time for representation P2 using HermiT over 500 points is 286 seconds, thus slower than all measurements presented in Figure 8). An interesting case is the representation based on Role Inclusion Axioms (P3) that can be used for reasoning over 100K points in less than 3 seconds when using Pellet (but not when using HermiT, see Figure 8) being orders of magnitude faster than all other approaches. This illustrates that there is clearly room for optimization on SWRL implementations of current reasoners.

Comparing reasoning times over qualitative defined spatial RCC5 relations using Pellet is presented in Figure 9 and over RCC8 qualitative relations using Pellet in Figure 10.
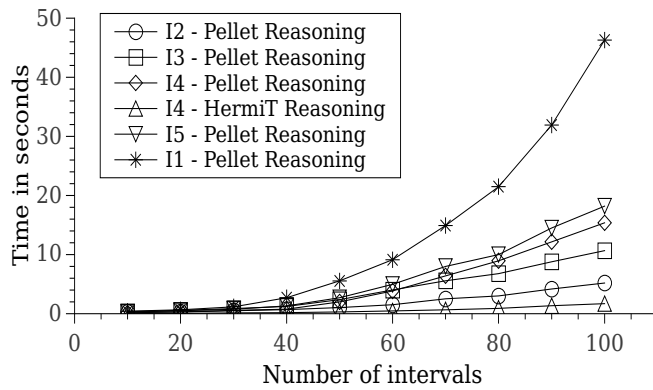
Fig. 7. Average reasoning time as a function of the number of intervals
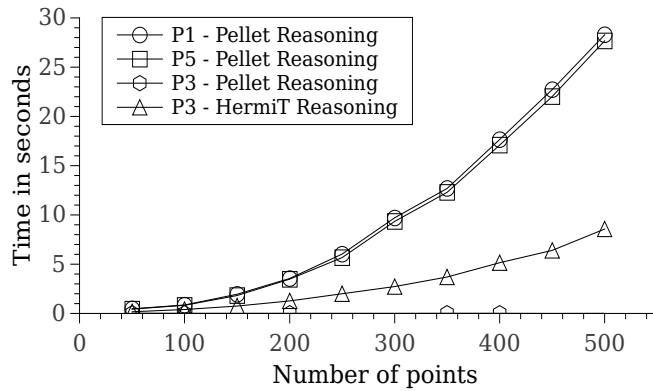

Fig. 8. Average reasoning time as a function of the number of points

The corresponding reasoning times for qualitative RCC5 and RCC8 relations using HermiT are presented in Figure 11. Notice that HermiT clearly outperforms Pellet over RCC5/8 relations (as in the case of qualitative temporal representations) and can support qualitative reasoning over 100K relations. The increased performance is due to the optimizations used in HermiT both for OWL reasoning (Hypertableau calculus) and SWRL implementation as described in [2,23].

An advantage of Pellet over HermiT is that it supports datatypes in SWRL, thus quantitative representations using coordinates are also supported by Pellet (HermiT supports only qualitative representations). Reasoning over RCC5/8 relations using coordinates are presented in Fig-
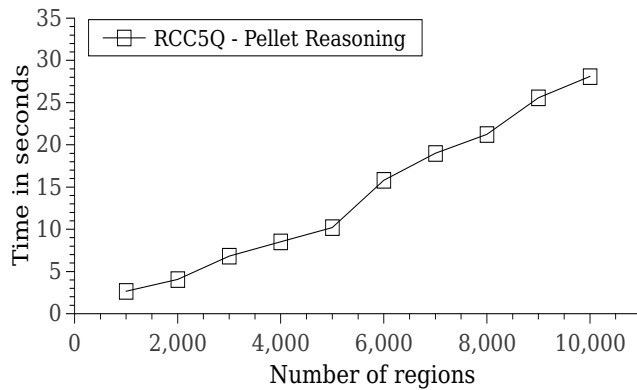
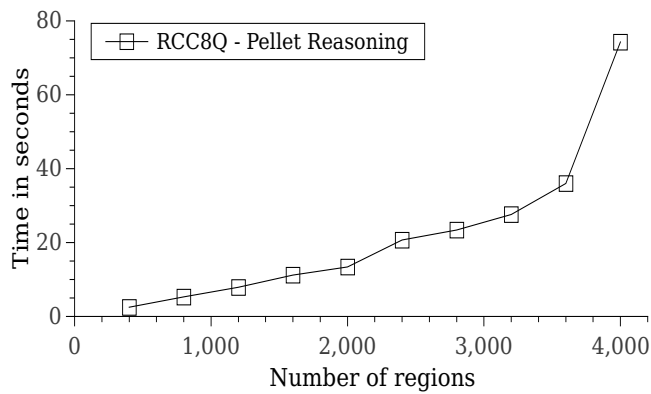**Fig. 9.** Average reasoning time as a function of the number of regions

Fig. 10. Average reasoning time as a function of the number of regions

ure 12 and reasoning over combined quantitative and qualitative RCC5/8 relations is presented in Figure 13. Notice that reasoning over quantitative spatial representations is much slower than the corresponding qualitative only representations.

In conclusion, experimental evaluation indicates that there are differences in performance between reasoners such as Pellet and HermiT and representations, which means that the proposed representations will directly benefit from future optimizations in rule engines. This is also illustrated by the fact that the OWL axiom based representation for temporal points and qualitative SWRL representation for RCC5/8 can support fast reasoning over 100K regions (see Figure 11). An alternative
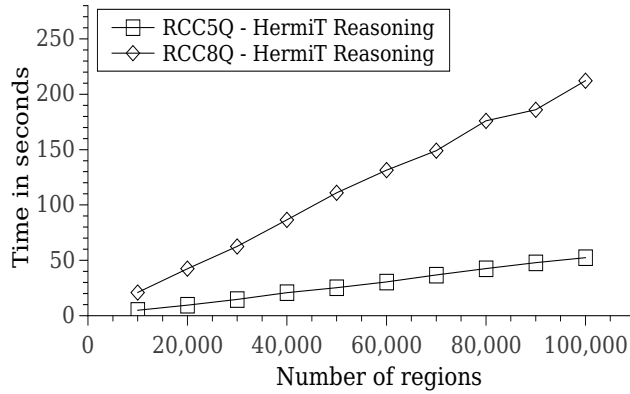
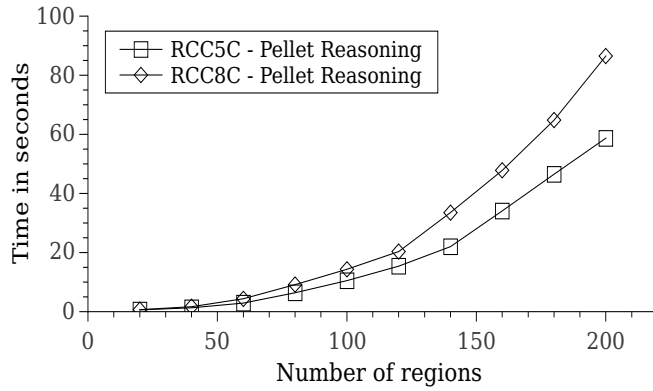**Fig. 11.** Average reasoning time as a function of the number of regions

Fig. 12. Average reasoning time as a function of the number of regions

approach instead of optimizing rule engines of reasoners such as Pellet is to build specialized standalone temporal and spatial reasoners that offer increased performance over existing SWRL based approaches for specific set of relations [24,25,26,27].

9.2 Experimental Evaluation of Querying Performance

Querying performance is evaluated using SPARQL queries of Section 8 over the set of data of Section 9.1. Randomly selected relations over randomly selected points/intervals/regions were selected for querying and average query times in milliseconds over 1000 queries are presented. ARQ, the SPARQL engine of Jena was used, and all experiments were run on
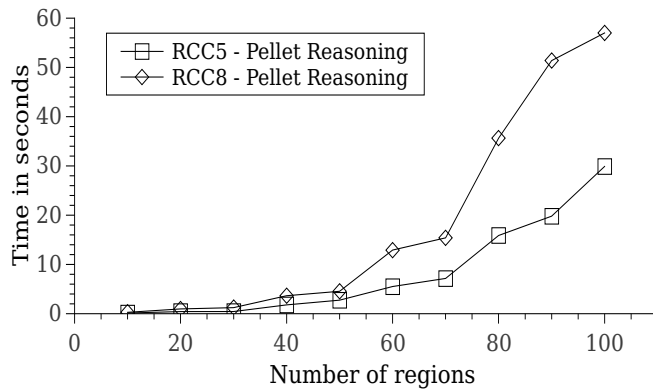
Fig. 13. Average reasoning time as a function of the number of regions

a PC, with Intel Core CPU at 2.4 GHz, 6 GB RAM, and Windows 7. Querying times over temporal points are presented in Figure 14. Since extracting point relations, if dates are available, is done by a comparison of dates, extracting relations directly is more efficient than extracting qualitative relations after reasoning. In case of qualitative representations querying performance is similar for all representations. Notice that this is not the case for reasoning performance as illustrated in Section 9.1.
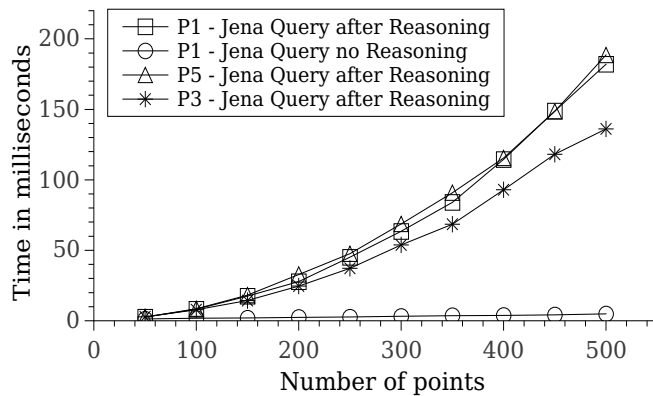

Fig. 14. Average querying time as a function of the number of points

Querying performance over intervals is presented in Figure 15. Notice that in case of quantitative representations such as I2, querying can

be applied either directly using comparisons of dates, or after reasoning involving qualitative relations (see Section 8). In this case, querying after reasoning is in most cases faster than querying directly using dates. Thus, if data do not change frequently querying can be faster if reasoning is applied off-line and then querying is performed using inferred Allen relations.
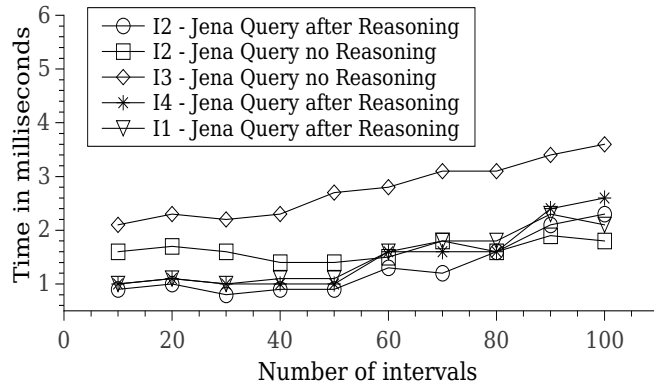

Fig. 15. Average querying time as a function of the number of intervals

Querying performance of qualitative RCC5 representation is presented in Figure 16 and over RCC8 representation in Figure 17. Notice that for qualitative representations reasoning must be applied before querying, thus queries based on comparisons of coordinates cannot be used.

In case of spatial representations based on coordinates, querying can be applied either by reasoning and then extracting qualitative relations, or by comparing coordinates directly. Querying times in milliseconds (over 1000 queries) using these two approaches for RCC5 and RCC8 relations are presented in Table 7. In case reasoning is applied before querying, querying is at least two times faster than querying directly using coordinates, which is a substantial speed-up. Reasoning is much slower than querying, thus this approach can be practically applied when data do not change frequently. Large scale reasoning over spatial data is a direction of future work, with the aim to apply off-line reasoning over Big Data and achieve faster querying time.
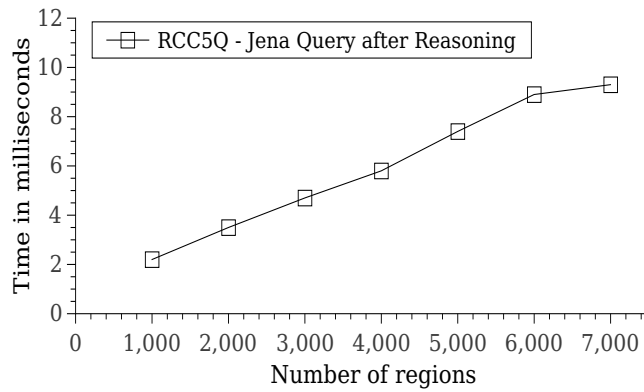
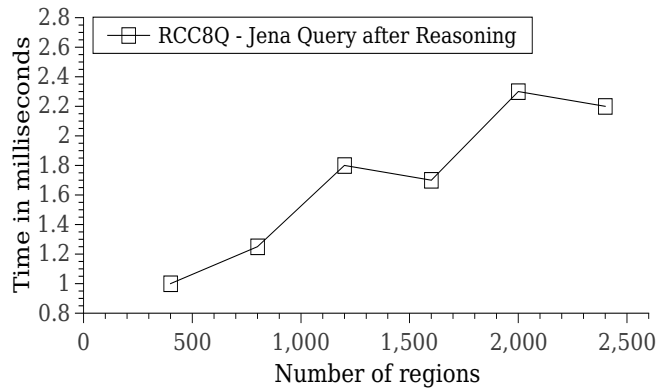**Fig. 16.** Average querying time as a function of the number of regions

Fig. 17. Average querying time as a function of the number of regions

10 Conclusions and future work

In this work, several representations for handling temporal points, temporal interval and topological spatial relations in OWL ontologies are presented. Qualitative, quantitative, and mixed qualitative and quantitative representations are proposed for temporal and spatial information. The proposed representations are fully compliant with existing Semantic Web standards specifications and member submissions, which increases their applicability. Being compatible with W3C specifications and member submissions, the proposed representations can be used in conjunction with existing editors, reasoners and querying tools such as Protégé and

Table 7. Spatial Querying Times (ms for 1K queries)

Representation	Query Method	Number of regions		
		20	40	60
RCC5C	No reasoning	2.4	3.6	5.2
	After Reasoning	0.96	1.55	2.1
RCC8C	No reasoning	2.4	3.8	5
	After Reasoning	0.9	1.2	1.6

HermiT without requiring specialized software. Therefore, information can be easily distributed, shared and modified.

Directions of future work include the development of real-world applications based on the proposed mechanisms combined with optimizations of reasoning engines. Applcations involving dynamic information such as smart cities, or applications involving natural language description of events (such as descriptions of symptoms in medical applications) can be examples of such applications. Proposing an alternative implementation using SPIN [28] in conjunction with SPARQL is an important direction of future research. Furthermore, parallelizing our rule based reasoning mechanisms and applying reasoning over Big Data and streaming data is another promising direction of future research with many practical applications.

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