Representing and Reasoning over Spatial Relations in OWL: A Rule-Based Approach

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Abstract. Representing spatial information for Semantic Web applications often involves missing or imprecise information. For example the exact coordinates of the boundaries of two regions may be unknown, but it may be known that these regions overlap. This fact can be expressed using qualitative terms such as "Overlapping". Embedding such information into ontologies and Linked Data is an important practical issue. This paper presents an approach for representing qualitative spatial information and reasoning over such spatial relations. This approach is fully compliant with existing Semantic Web standards and tools. Directions of future work are presented as well.

1 Introduction and Problem Definition

Creating and using Linked Data that conform to W3C standards is a step towards materializing the Semantic Web vision. These machine readable data will enable automating tasks that are typically handled manually by users. Geospatial data in particular is an important category of Linked Data since applications involving spatial information are very common. Data are in RDF format and OWL[1], the Web Ontology Language used for formal definitions of concepts, their properties and their relations.

Reasoning rules can be embedded into the ontology using SWRL[2], these rules apply only on named individuals in the ontology ABox (i.e., on objects explicitly asserted into the knowledge base and not anonymous objects whose existence is inferred by concept definitions). Specifically, rules in the form $A \wedge B \wedge ... \Rightarrow C$ can be expressed using SWRL.

Spatial relations are mainly topological and directional relations. Topological relations in particular are very important since they are used in the GeoSPARQL query language[3]. When coordinates are available spatial relations between points and regions can be extracted using computational geometry algorithms, and this is the common approach in existing systems.

In case coordinates are not available qualitative defined relations can be used instead. For example, coordinates of a location may not be known, but the region that the location is into may be known. Using qualitative spatial relations this fact (location

[1] http://www.w3.org/TR/owl-ref/
[2] http://www.w3.org/Submission/SWRL/
[3] http://www.opengeospatial.org/standards/geosparql

A is into region B) can be asserted into the knowledge base. Asserting qualitative relations is not enough since these assertions imply facts that must be also inferred. For example by asserting that region A is into region B and region B into region C it can be inferred that A is into C. These semantics must be part of the representation as well. Ideally semantics of spatial relations will be part of a representation fully compliant with Semantic Web standards and tools. Thus, qualitative spatial information will be exchanged, modified and reused without needing specialized software. Expressing spatial semantics using SWRL rules is an efficient way of embedding these semantics into a knowledge base.

In addition to missing quantitative information, qualitative spatial relations can be used when information is not precise. The exact coordinates of a place may be unknown but it may be known that the location is into a rectangle whose endpoint coordinates are known. By combining coordinates (for defining the enclosing rectangle) and qualitative relations (for asserting that the location is into the rectangle) the existing knowledge about the location can be fully represented.

Thus, by offering support for qualitative spatial relations knowledge that cannot be represented using only quantitative representations can be asserted into a knowledge base. Developing software for reasoning over qualitative spatial relations in RDF or OWL format offer such support. Systems such as Pellet-spatial [5] and Choros [6] extract spatial relations from a knowledge base and reason over these qualitative spatial relations, both topological and directional. But reasoning using specialized software also complicates re-usability and sharing of data. Specifically, whenever the definitions of spatial relations and semantics in RDF/OWL format are modified spatial reasoners must modified as well. In addition to that the above-mentioned specialized software is needed for querying spatial information.

In the following an approach that offers reasoning support using only W3C standards (without additional specialized software software) is presented. This is achieved using SWRL rules that are embedded into OWL ontologies containing definitions of spatial relations. The application of the approach for RCC-5 topological spatial relations is presented as an example case. The method that is presented has been used for representing RCC-8 topological relations and directional relations as well [1, 3]. For specific sets of supported relations the presented method is sound, complete and tractable.

The corresponding workshop presentation will illustrate how qualitative spatial reasoning can be embedded into a W3C compliant knowledge base. The case of RCC-5 relations will be used as an example. In addition limitations of existing approaches and directions of future work will be presented as well.

2 Proposed Solution

Region Connection Calculus [4] 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.

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 1 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).

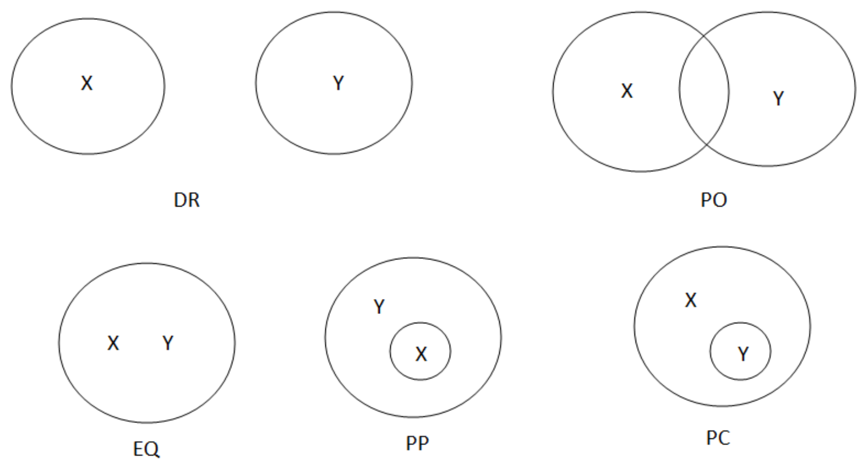

Fig. 1. Topological RCC-5 Relations

In addition to the five relations of Figure 1 additional relations are required for representing disjunctions of these five basic relations. These additional relations are required for implementing reasoning rules, specifically the reasoning rules implementing path consistency [2] that are presented in the following.

The above representation and the corresponding reasoning mechanism can be expressed and implemented using only OWL 2 axioms and SWRL rules, thus requiring only standard tools such as Protégé[4] and the Pellet reasoner[5]. No additional software is required for spatial reasoning.

Twelve object relations are required in total, 5 basic RCC-5 relations, 6 additional relations representing disjunctions and the $null$ (or $\perp$) relation representing inconsistency detection between two regions (i.e., inferred or asserted facts between two regions are incompatible). For example two regions cannot be both discrete (DR) and equal (EQ). Defining compositions of relations is a basic part of the spatial reasoning mechanism. Table 1 represents the result of the composition of two topological RCC-5 relations of Figure 1.

[4] http://protege.stanford.edu/
[5] http://clarkparsia.com/pellet/

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

Table 1. Composition Table for RCC-5 Topological Relations.

Composition Table can be 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 1 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* of $Region3$.

A series of compositions of relations may yield relations which are inconsistent with existing ones (e.g., the above example will yield a contradiction if *X overlaps Z* has been also asserted into the Knowledge base). Consistency checking is achieved by ensuring path consistency by applying formula:

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

representing intersection of compositions of relations with existing relations (symbol $\cap$ denotes intersection, symbol $\circ$ denotes composition and R_i, R_j, R_k, R_s denote spatial 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 requires rules for both compositions and intersections of pairs of relations.

Compositions and intersections of relations R_1, R_2 yielding a relation R_3 as a result are expressed in SWRL. The following is an example of a composition rule:

$$PP(x, y) \wedge DR(y, z) \rightarrow DR(x, z)$$

Another important issue for implementing path consistency is the identification of the additional relations 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 1 is identified. The identification of the additional relations is required for the construction of the corresponding SWRL rules.

This is achieved using the closure method [2] for computing the minimal relation sets containing the set of basic relations: starting with a set of relations, intersections and compositions of relations are applied iteratively until no new relations are yielded forming a set closed under composition, intersection and inverse.

The above method for representing and reasoning over RCC-5 topological relations has been applied to RCC-8 relations [1] and directional relations [3]. The method has also been used for modelling a university campus using qualitative terms [6]. The

SWRL based representation offers great flexibility and can reason over a few hundreds of points or regions in a few seconds [1, 6, 3]. Using specialized reasoners such as Choros [6] performance increases but this approach is less flexible. Nevertheless dealing with Bid Data is currently beyond the capabilities of both approaches.

3 Conclusions and future work

Representing qualitative defined spatial information for the Semantic Web is an important practical issue. Embedding spatial semantics by means of SWRL rules into the knowledge base while retaining compatibility with existing Semantic Web standards can be achieved using the presented method. Using this approach spatial information can be represented even if exact coordinates are missing (or are not accurately known). Furthermore reasoning rules can be used for inferring implied facts.

Addressing scalability issues and applying spatial reasoning for Big Data is an important direction for future work. Parallelism of spatial reasoning rules can be used in this case. Another direction of future work is the combination of qualitative and quantitative data and the development of efficient reasoning methods for this case.

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