Representing Qualitative Spatial Information in OWL-DL

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1 Motivation

The Web Ontology Language has not been designed for representing spatial information, which is often required for applications such as Spatial Databases and Geographical Information Systems. As a consequence, many existing OWL ontologies have little success in encoding spatial information. In this paper, we argue that the representation of spatial information is not a fundamental limitation of OWL. In fact, OWL-DL *does* provide some of the expressive power required for representation of spatial regions and their relationships. However, a direct representation is far from intuitive.

In the last decade, several languages for the representation of the relations between spatial regions have been developed. Among these formalisms for qualitative spatial reasoning, the $\mathcal{RCC}$-8 fragment of the *Region Connection Calculus*, which introduces a set of eight basic relationships between regions on the plane, has received special attention.

In this paper, we outline a translation of the $\mathcal{RCC}$-8 calculus into OWL-DL, by adapting some of the known results on the translation of qualitative spatial formalisms into Modal Logics. We argue that, in order to encode $\mathcal{RCC}$-8, it is necessary to extend the Web Ontology Language with the ability to define *reflexive roles*[1]. However, such an extension is straightforward in both syntax and semantics, and can be easily added to existing OWL reasoners. We argue that providing a reasonable encoding of $\mathcal{RCC}$ related calculi into OWL-DL is key for integrating spatial representation and reasoning features in OWL-based tools, which can be helpful for many applications.

2 The Relationship between the $\mathcal{RCC}$-8 Calculus and OWL-DL

It well-known that there is a close correspondence between Description and Modal Logics [2], and also between Modal Logics and a family of $\mathcal{RCC}$-8 related calculi [5] [6] [7] which can be exploited for our purposes. In particular, the

[1] Role in Description Logics stands for Object Property in the OWL jargon. Also note that OWL-DL already provides means for representing Symmetric and Transitive roles.

Description Logic **S** ($\mathcal{ALC}$ extended with transitive roles), augmented with a reflexive accessibility relation, yields the Modal Logic **S4**. It has also been shown that it is possible to translate the $\mathcal{RCC}$-8 calculus and some of its extensions into **S4** and its extension with the universal modality, called $\mathbf{S4_u}$. Relying on the correspondence between the two groups of formalisms, every **S4** formula can be represented in OWL-DL provided that OWL-DL is extended with the ability to define *reflexive roles*, required for accommodating the reflexive/transitive accessibility relation of **S4**. Consequently, the translation into the extension of OWL-DL involves a single role that is both reflexive and transitive. OWL-DL extended in this way is expressive enough for capturing the $\mathcal{RCC}$-8 calculus as well as some of its extensions.

The following issues immediately arise: first, is it easy to extend OWL-DL with reflexive roles? And second, will existing OWL reasoners exhibit an acceptable performance on (translated) spatial KBs?

2.1 $\mathcal{RCC}$-8 Formalism

A *region* is the set of points on the plane delimited by a continuous boundary curve. The $\mathcal{RCC}$-8 calculus provides eight binary predicates for representing relationships between two regions X, Y. The regions X, Y are disconnected, written $DC(X, Y)$, if they do not share any points; they are externally connected ($EC(X, Y)$) if they only share points in their boundary. They are equal ($EQ(X, Y)$) if they contain exactly the same points; they "partially overlap" if their interiors intersect but none is a subset of the other; the region X is a *tangential proper part* of Y ($TPP(X, Y)$) if X is a subset of Y but not of its interior. Finally, X is a *non-tangential proper part* of Y if it is contained in the interior of Y. Note that the only asymmetric relations are TPP and $NTPP$ and hence their inverses $TPP^{-1}(Y, X)$ and $NTPP^{-1}(X, Y)$ can also hold between X and Y.

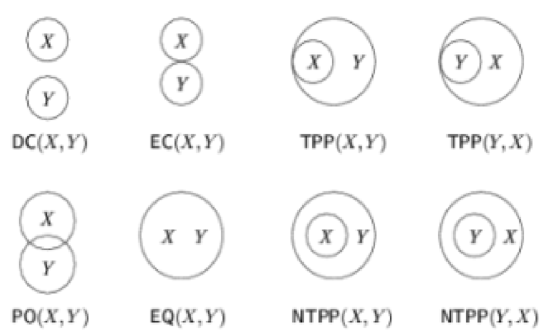

Fig. 1. $\mathcal{RCC}$-8 constructs

2.2 Extending an OWL-DL Reasoner with Reflexive Roles

A role R is reflexive if, for every model $\mathcal{I}$ of the ontology, the following condition holds: If $(x, y) \in R^{\mathcal{I}}$ then $(x, x) \in R^{\mathcal{I}}$ and $(y, y) \in R^{\mathcal{I}}$. The syntax of OWL-DL can be trivially extended with a new primitive `owl:ReflexiveProperty`, analogous to the ones already existing in OWL-DL for tagging a role as symmetric and transitive.

On the other hand, extending an OWL-DL reasoner to handle reflexive roles is easy. We just have to take into consideration that every node of the completion graph with an incoming or outgoing R-edge, with R reflexive, is an R-successor of itself and apply the tableau expansion rules accordingly.

2.3 Representing $\mathcal{RCC}$-8 KBs in OWL-DL

Our translation is a variation of the one in [1] for encoding $\mathcal{RCC}$-8 in a generalized set constraints language, where regions are expressed as non-empty, closed sets. A region X in our translation must follow the *regularity* condition; that is, it must contain all of its interior points and be non-empty, which is captured by the axioms: $X \equiv \exists R.(\forall R.X)$, $X(x)$. Note that the corresponding instance assertion $X(x)$ (where x is an individual) is required to prevent a class from being unsatisfiable (i.e. empty), and the KB be consistent at the same time. The translation involves a single role R, which is defined as transitive and symmetric.

The translation proceeds in two steps: (1) we generate the concepts corresponding to every $\mathcal{RCC}$-8 constructor, some of which will be uniquely named concepts not appearing elsewhere in the KB (denoted by Z_n), and (2) we instantiate the named concepts with individuals. For brevity we show the translation of only *six* $\mathcal{RCC}$-8 constructors (omitting inverses[2]):

i. $DC(X, Y)$:- $X \sqsubseteq \neg Y$
ii. $EQ(X, Y)$:- $X \equiv Y$
iii. $EC(X, Y)$:- $\forall R.X \sqsubseteq \exists R.\neg Y$; $Z_1 \equiv X \sqcap Y$
iv. $PO(X, Y)$:- $Z_2 \equiv \forall R.X \sqcap \forall R.Y$; $Z_3 \equiv X \sqcap \neg Y$; $Z_4 \equiv \neg X \sqcap Y$
v. $TPP(X, Y)$:- $X \sqsubseteq Y$; $Z_5 \equiv X \sqcap \exists R.\neg Y$
vi. $NTPP(X, Y)$:- $X \sqsubseteq \forall R.Y$

Then, for every newly generated concept Z_n, add the ABox assertion $Z_n(z_n)$, where z_n is a new individual name, in order to make sure that Z_n cannot be empty without making the KB inconsistent.

3 Future Directions

3.1 Integration into OWL-based Tools

A translation of the $\mathcal{RCC}$-8 calculus into OWL makes it possible to adapt OWL-based tools for representing and reasoning on qualitative spatial information. In

[2] The constructors $NTPP^{-1}$ and TPP^{-1} are translated exactly as their inverses above

particular, ontology editors could be equipped with suitable user interfaces for spatial modeling and spatial KBs could be published and shared on the Semantic Web.

On the other hand, the ability to use existing OWL reasoners, such as RACER, Pellet or FaCT, directly on spatial KBs raises a number of interesting issues for future research: Will existing DL optimizations work well for our translation? If not, is it possible to find an alternative translation for which DL optimizations work better or to design new optimization techniques for OWL-encoded spatial KBs? In order to answer these questions, we are planning to provide in the near future an implementation in our OWL reasoner Pellet.

An even more relevant issue is how to combine the spatial KBs with "ordinary" OWL ontologies. Recently, it has been shown that Description Logic knowledge bases can be coupled to qualitative spatial KBs using the $\mathcal{E}$-Connections technique [3]. Using $\mathcal{E}$-Connections, it is possible to express, for example, that Spain is a Mediterranean country (in the spatial KB) and that Spain is a member of NATO (in the Description Logic KB), where "Spain" in the DL KB represents a country and in the spatial KB represents a region. The $\mathcal{E}$-Connection allows to express that the country "Spain" corresponds to the physical space occupied by Spain as a region and exploit such a correspondence to "enrich" both the DL and the Spatial KBs.

$\mathcal{E}$-Connections can also be used for coupling Description Logic KBs together in a Semantic Web context. In particular, in [4] an extension of OWL-DL for $\mathcal{E}$-Connections has been proposed and reasoning algorithms have been developed, and implemented, for $\mathcal{E}$-Connections of OWL ontologies. Our translation would make the use of the reasoning algorithms for the combinations of (only) Description Logics applicable to the combination Description Logic - Spatial Logic. Therefore it would be possible to represent spatial KBs on the Semantic Web, couple them together with an arbitrary number of "ordinary" OWL-DL ontologies and reason (hopefully effeciently) on the resulting combinations.

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