Spatial Reasoning for the Semantic Web - Use Cases and Technological Challenges

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1 Motivation

The goal of semantic web research is to turn the World-Wide Web into a Web of Data that can be processed automatically to a much larger extend than possible with traditional web technology. Important features of the solution currently being developed is the ability to link data from from different sources and to provide formal definitions of the intended meaning of the terminology used in different sources as a basis for deriving implicit information and for conflict detection. Both requires the ability to reason about the definition of terms. With the development of OWL as the standard language for representing terminological knowledge, reasoning in description logics has been determined as the major technique for performing this reasoning [Horrocks and Patel-Schneider, 2004]. More recently, rule languages have gained more importance as well as they have been shown to be more suited for efficient reasoning about terminology and data at the same time.

So far little attention has been paid to the problem of representing and reasoning about space and time on the semantic web. In particular, existing semantic web languages are not well suited for representing these aspects as they require to operate over metric spaces that behave fundamentally different from the abstract interpretation domains description logics are based on. Nevertheless, there is a strong need to integrate reasoning about space and time into existing semantic web technologies especially because more and more data available on the web has a references to space and time. Images taken by digital cameras are a good example of such data as they come with a time stamp and geographic coordinates.

In this paper, we concentrate on spatial aspects and discuss different use case for reasoning about spatial aspects on the (semantic) web and possible technological solutions for these use cases. Based on these discussions we conclude that the actual open problem is not existing technologies for terminological or spatial reasoning, but the lack of an established mechanism for combining the two.

2 The Case for Spatial Queries

One of the most central functionality that should be supported by semantic web technology is query answering over web data. The primary language for this purpose is the evolving W3C standard SPARQL [Jorge Prez, 2006] which supports queries over labeled graphs where nodes represent objects or terminology (classes, relations) and labeled edges are relations between these elements. There is no conceptual reason, why objects should not represent locations or relations should not be spatial relations between these locations or between locations and objects located in space. Indeed there are a number of relevant use cases supporting the need for having locations and spatial relations in queries on semantic web data. Some of these cases are sketched in the following subsections.

2.1 Place Names

the most obvious occurrence of spatial information on the web is in terms of place names. The web still mostly consists of text (although this is changing as we will also argue below). Place names are the natural way, spatial references occur in these texts. News articles for instance frequently refer to countries, cities or regions by their name. In order to answer queries about certain events taking place in a certain area, it is necessary to disambiguate place names (Paris, Texas vs. Paris, France) an set these names into the geographical context: Baghdad lies in Iraq, Iraq is part of the Middle-East, etc. The description of this context requires representing and reasoning about different kinds of spatial relations, in particular partonomic, topological directional and ordinal relations [Stuckenschmidt et al., 2001]. This task is greatly complicated by the fact, that place names as well as the actual spatial extend they refer to tend to change quite a lot over time. When talking about 'Germany' it makes quite a difference if this refers to Germany in 1920, 1943, 1980 oder 2009. The same holds for historical names of regions as described in [Kauppinen et al., 2008].

Voegele and others have investigated the representation of place names based on graph-structures that support the retrieval of spatial objects based on queries containing place names [Voegele et al., 2003].

2.2 Geographic Maps

Since the advent of services like Google maps or map24.com geographic information in terms of 2D spatial models have made their way into mainstream web applications. Today spatial references are used by many applications, most often by locating information using spatial coordinates and services like Google maps for presenting this information to the user. As these services become more popular, it is a natural step to also try to make this information more accessible for machines using semantic web technologies. A typical use case is again the possibility to ask for objects or events in or near a certain geographic region. The difference to the scenario above is two-fold:

- As objects come with coordinates and are located on a digital map, it is no longer necessary to refer to possible ambiguous place names. Instead, we can rely on methods from computational geometry to determine spatial relations.
- As digital maps often come with type information for polygons is is possible to ask for objects that are in a certain spatial relation to a certain type of object rather than

a concrete object. For instance we could ask for a hotel in the mountains next to a lake.

A closely related task is the classification of objects based on terminological and spatial properties. For instance, we could be looking for ’terraced houses’ in some area. The relevant objects will normally not be annotated as ’terraced houses’ but just as buildings or houses and the membership in the concept ’terraced’houses will have to be derived based on a suitable formalization of this concept and the actual spatial configuration found on the map.

Luescher and others describe an approach for recognizing urban structures, in particular terraced houses based on terminological and spatial criteria using a combination of GIS and semantic web technologies [Lscher et al., 2008].

2.3 3D Models

A rather new development is the large scale provision of 3D data on the web. the available data ranges from 3D model of technical devices to complete 3D city models that have been constructed from areal images or laserscans and provide the user with a much more realistic impression of an urban scene than a 2D digital map. The availability of a complete 3D geometry also has implications for the possibilities of querying spatial configurations. While such queries and descriptions of object classes is limited to the kinds of spatial relations mentioned above, a 3D geometry also allows to involve aspects such as visibility from a certain location. Visibility is a very interesting concept with a lot of useful applications. An obvious one is navigation in a city as well as the generation of way descriptions. Another use case is site selection for services like shopping malls. Being visible from a nearby highway is an important criterion in this case as it will attract and guide customers to the location.

Similar to the case of 2D information knowledge-based object recognition is a strongly related task. Besides being close to certain kinds of spatial area objects can be identified by a characteristic 3D geometry. A good example is the detection of churches which normally have a rather characteristic 3D shape in addition to often be close to a cemetery.

The use of semantic and geometric features for annotating and querying 3D objects has for example been investigated in the AIM@SHAPE project [Falcidieno et al., 2004].

3 Different Kinds of spatial Reasoning

A crucial design decision for any spatial information system is the choice of an adequate reasoning mechanism. There exist several alternative approaches to spatial inference which all show a trade-off between generality and efficiency. In other words, the generic approaches are less efficient and the efficient ones are less generic. We briefly describe the four major classes of approaches to spatial reasoning in order of increasing specificity.

Geometric theorem proving [Kapur and Mundy, 1988] First-order logic can be used to express spatial problems which are then solved by applying a theorem prover. Several specialized proof techniques for geometrical reasoning have been proposed. From the user's point of view, a theorem-proving approach is very convenient. It allows him to simply state the problem not having to worry about how to solve it. Unfortunately, due to the computational complexity of the proof procedures, only small problem instances can be approached this way.

Constraint-based spatial reasoning [Marriott and Stuckey, 1998] Most problems studied in the field of qualitative spatial reasoning are solved with constraint solvers. Inferences consist in determining some relational terms, i.e. spatial relations holding between objects, given some other relational terms. If, for example, it is known that regions A, B, C, and D are arranged in such a way that "A inside B", "B inside C", and "C disjoint from D", we can infer that "A disjoint from D" and "B disjoint from D". Such an inference problem can be mapped onto the problem of finding an instantiation for a constraint satisfaction system. Although this type of instantiation problem cannot be solved efficiently, instantiations can be computed by means of efficient approximative algorithms. Typically, polynomial constraint propagation methods (e.g. path consistency) are used for that purpose. For GIS-related problems, the trade-off that is realized by the constraint-based approaches has turned out to be most effective.

Computational geometry [de Berg et al., 2000] For specific geometric problems (e.g. intersection of polygons) asymptotically optimal algorithmic solutions are known. Almost all efficient algorithms rely on some explicit problem representation in a dynamic data structure. Although the approaches from computational geometry are the most efficient, they are very specific. Variants of a problem may require the use of entirely different data structures, used to avoid inconsistency problems. The locations of all other spatial objects in the spatial model are represented using relations that ultimately refer to a set of landmarks. This principle of relative locations also allows an easy integration of new spatial objects. It suffices to describe the new object by spatial relations to already existing points, i.e. landmarks.

Diagrammatic reasoning [Glasgow et al., 1995] Classical theorem provers and constraint solvers do not use an explicit spatial problem representation. The advantage of such a representation consists in providing information for guiding the flow of control to make spatial inference more efficient. Diagrammatic reasoning uses map-like representations in analogy to mental images that play a prominent role in human spatial problem solving.

4 Combining Terminological and Spatial Reasoning

having acknowledged the need to be able to reason about terminological as well as spatial aspects on the semantic web, the question is how to provide the required reasoning services. We discuss this question in the following. the starting point for the discussion is a general model of queries proposed in [Visser, 2004]. This query model assumes queries of the form 'concept@location' meaning that we look for objects that have certain conceptual and certain spatial properties which are specified in the different parts of the query.

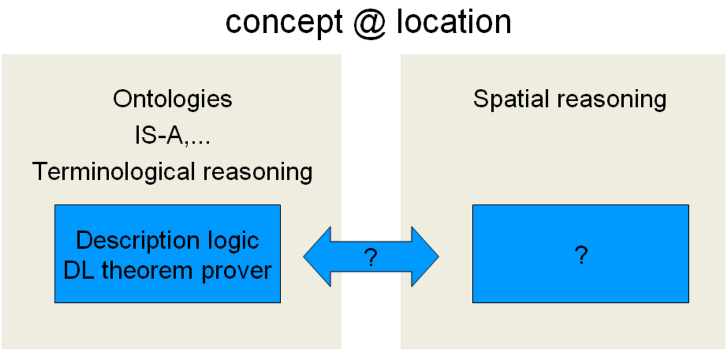

Fig. 1. A blueprint for combining terminological and spatial reasoning

From a semantic web point of view, the situation presents itself as shown in figure 1: On the conceptual side, the choice has been made to use description logics for reasoning about ontological structures represented in OWL, but there are little ideas about how to process the spatial part of the query and even less ideas about how to smoothly integrate the two. In the following, we discuss a number of possible ways for implementing and linking the spatial reasoning part to existing semantic web technology, i.e. OWL and rule languages.

4.1 Direct Encoding

A direct way to try to also cover spatial aspects is to encode them in the ontology language as well. In particular, we can try to represent locations as objects in the ontology and encode spatial relations using ObjectProperties in OWL. This makes it possible to define classes of objects not only on the basis of terminological, but also of spatial criteria. Different versions of the relation 'spatially related' as well as a number of typical topological relations can be encoded in OWL and be used for classifying spatial objects [Stuckenschmidt and van Harmelen, 2004]. The kind of reasoning supported, however is not the same as for dedicated spatial calculi like RCC-8. For instance it will not be possible to draw the conclusion that if region A is a tangential proper part of region B and B is part of C then A will also be a tangential proper part of C. Further, also inferences that can be encoded in description logics will normally suffer from a very bad performance. This is due to the fact that description logic reasoning is optimized for reasoning about concepts and usually shows a very poor performance on larger numbers of objects and relations between them which is required for any decent reasoning about spatial configurations.

4.2 Tight Integration

In order to benefit from more complete reasoning about topological relations, terminological models have to be connected to specialized reasoning services for spatial knowledge. In early approaches this was done using functional extensions of concept languages such as LOOM (compare [Haarslev et al., 1994]). A tighter integration of terminological and spatial reasoning can be achieved by defining spatial regions as special datatypes with a special set of predicates that correspond to relations between spatial regions. Using special data-type properties, class definitions can be linked to spatial regions defined by applying a predicate on a set of region names. While this approach allows us to define and reason about spatial properties of instances of a class, a tighter integration of spatial relations into the concept language requires an extension of the formal semantics that turns out to be undecidable even for much simpler languages than OWL [Haarslev et al., 1998].

4.3 Loose Coupling

The way out of this dilemma is to go for a loose integration of the terminological and the spatial part of the reasoning method and limit their mutual interactions in such a way that reasoning remains efficient. The work reported in [Lscher et al., 2008] is a good example of this kind of loose coupling. the authors use rule language for describing concepts and delegate the computation of certain predicates used in the rule bodies to a spatial database system that performs geometric reasoning on the spatial configuration to determine whether a certain spatial relation holds between objects. This approach represents a loose coupling between terminological and spatial part as spatial predicates that are computed by the spatial database may only appear in the body of rules limiting the interaction between the rule base and the spatial database to requests from the logic to the database. Further interactions would make the approach infeasible and deriving spatial relations in the rule-part would most likely make the approach incomplete for the reasons given above.

5 Conclusions

We conclude that there is a strong need for integrating spatial representations into semantic web approaches. There are different possible choices for implementing spatial reasoning ranging from geometric theorem proving to diagrammatic reasoning. We conclude that for the purpose of the semantic web, promising approaches are diagrammatic reasoning that provides a good bases for reasoning about simple spatial features such as place names as has been shown by Schlieder and others. When turning to 2- and 3D representations computational geometry seems to be a good choice as it comes with well established algorithms for typical problems and stable implementations that scale to realistic scenarios. We further conclude that a lose coupling of terminological and spatial reasoning is preferable, because trying to encode spatial reasoning in semantic web languages will lead to incomplete reasoning and a tight integration, although being theoretically attractive has serious limitations with respect to efficiency and decidability in the case of expressive ontology languages. Therefore investigating method for loosely coupling terminological reasoning with computational geometry is a promising topic for future research that can have significant impact both on in the area of semantic web technologies and geo-informatics.

References

[de Berg et al., 2000] de Berg, M., van Kreveld, M., Overmars, M., and Schwarzkopf, O. (2000). *Computational Geometry: Algorithms and Applications*. Springer, Berlin.

[Falcidieno et al., 2004] Falcidieno, B., Spagnuolo, M., Alliez, P., Quak, E., Vavalis, E., and Houstis, C. (2004). Towards the semantics of digital shapes: The aim@shape approach. In *Proceedings of the European Workshop on the Integration of Knowledge, Semantic and Digital Media Technology*.

[Glasgow et al., 1995] Glasgow, J., Narayanan, H., and Chandrasekaran, B. (1995). *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. MIT Press, Cambridge, MA.

[Haarslev et al., 1998] Haarslev, V., Lutz, C., and Moller, R. (1998). Foundations of spatioterminological reasoning with description logics. In *Principles of Knowledge Representation and Reasoning*, pages 112–123.

[Haarslev et al., 1994] Haarslev, V., Moeller, R., and Schroeder, C. (1994). Combining spatial and terminological reasoning. In Nebel, B. and Dreschler-Fischer, L., editors, *KI-94: Advances in Artificial Intelligence – Proceedings of the 18th German Annual Conference on Artificial Intelligence*, volume 861 of *Lecture Notes in Artificial Intelligence*, pages 142–153, Berlin. Springer Verlag.

[Horrocks and Patel-Schneider, 2004] Horrocks, I. and Patel-Schneider, P. (2004). Reducing owl entailment to description logic satisfiability. *Journal of Web Semantics*, 1(4):345–357.

[Jorge Prez, 2006] Jorge Prez, Marcelo Arenas, C. G. (2006). Semantics and complexity of sparql. In *Proceedings of the International Semantic Web Conference (ISWC'06)*, pages 30–43.

[Kapur and Mundy, 1988] Kapur, D. and Mundy, J. (1988). Geometric reasoning and artificial intelligence. *Artificial Intelligence*, 37(1-3):1–11. Introduction to the Special Volume.

[Kauppinen et al., 2008] Kauppinen, T., Henriksson, R., Sinkkil, R., Lindroos, R., Vtinen, J., and Hyvnen, E. (2008). Ontology-based disambiguation of spatiotemporal locations. In *Proceedings of the 1st IRSW2008 International Workshop on Identity and Reference on the Semantic Web*.

[Lscher et al., 2008] Lscher, P., Weibel, R., and Mackaness, W. (2008). Where is the terraced house? on the use of ontologies for recognition of urban concepts in cartographic databases. In Ruas, A. and Gold, C., editors, *Headway in Spatial Data Handling. Proceedings of the 13th International Symposium on Spatial Data Handling*, Lecture Notes in Geoinformation and Cartography, page 449466. Springer.

[Marriott and Stuckey, 1998] Marriott, K. and Stuckey, P. (1998). *Programming with Constraints*. MIT Press, Cambridge, MA.

[Stuckenschmidt et al., 2001] Stuckenschmidt, H., Schlieder, C., Visser, U., Voegele, T., and Neumann, H. (2001). Spatial reasoning for information brokering. In *Proceedings of the Conference of the Floria AI Research Society (FLAIRS'01)*, pages 568–573.

[Stuckenschmidt and van Harmelen, 2004] Stuckenschmidt, H. and van Harmelen, F. (2004). *Information Sharing on the Semantic Web*. Springer.

[Visser, 2004] Visser, U. (2004). *Intelligent Information Integration for the Semantic Web*. Springer Verlag.

[Voegele et al., 2003] Voegele, T., Schlieder, C., and Visser, U. (2003). Intuitive modelling of place name regions for spatial information retrieval. In *Proceedings of the 6th Conference On Spatial Information Theory (COSIT)*, pages 239–252.