Challenges for Qualitative Spatial Reasoning in Linked Geospatial Data

Manolis Koubarakis and **Kostis Kyzirakos** and **Manos Karpathiotakis** and
Charalampos Nikolaou and **Michael Sioutis** and **Stavros Vassos**
Dept. of Informatics and Telecommunications, National and Kapodistrian University of Athens
Dimitrios Michail
Dept. of Informatics and Telematics, Harokopio University of Athens
Themistoklis Herekakis and **Charalampos Kontoes** and **Ioannis Papoutsis**
Inst. for Space Applications and Remote Sensing, National Observatory of Athens
{koubarak,kkyzir,mk,charnik,sioutis,stavrosv}@di.uoa.gr
{therekak,kontoes,ipapoutsis}@space.noa.gr
{michail}@hua.gr

Abstract

Linked geospatial data has recently received attention, as researchers and practitioners have started tapping the wealth of geospatial information available on the Web. We discuss some core research problems that arise when querying linked geospatial data, and explain why these are relevant for the qualitative spatial reasoning community. The problems are presented in the context of our recent work on the models stRDF and stSPARQL and their extensions with indefinite geospatial information.

1 Introduction

Linked data is a new research area which studies how one can make RDF data available on the Web, and interconnect it with other data with the aim of increasing its value for everybody [Bizer *et al.*, 2009]. The resulting "Web of data" has recently started being populated with geospatial data. A representative example of such efforts is LinkedGeoData[1] where OpenStreetMap data are made available as RDF and queried using the declarative query language SPARQL [Auer *et al.*, 2009]. With the recent emphasis on open government data, some of it encoded already in RDF[2], portals such as LinkedGeoData demonstrate that the development of useful Web applications might be just a few SPARQL queries away.

We have recently developed stSPARQL, an extension of the query language SPARQL for querying linked geospatial data [Koubarakis and Kyzirakos, 2010][3]. stSPARQL has been fully implemented and it is currently being used to query linked data describing sensors in the context of project SemsorGrid4Env[4] [Kyzirakos *et al.*, 2010] and linked earth observation (EO) data in the context of project TELEIOS[5].

In the context of TELEIOS we are developing a Virtual Observatory infrastructure for EO data. One of the applications of TELEIOS is fire monitoring and management led by the National Observatory of Athens (NOA). This application focuses on the development of techniques for real time hotspot and active fire front detection, and burnt area mapping. Technological solutions to both of these cases require the integration of multiple, heterogeneous data sources, some of them available on the Web, with data of varying quality and varying temporal and spatial scales.

In this paper we show how well-known approaches to qualitative spatial representation and reasoning [Renz and Nebel, 2007] can be used to represent and query linked geospatial data using RDF and stSPARQL. Thus, we propose linked geospatial data as an interesting application area of qualitative spatial reasoning techniques, and discuss open problems that might be of interest to the qualitative spatial reasoning community. In particular, we address the problem of representing and querying *indefinite* geospatial information, and discuss the approach we adopt in TELEIOS.

The organization of the paper is as follows. Section 2 introduces the kinds of linked geospatial data that we need to represent in the NOA application of TELEIOS, shows how to represent it in stRDF, and presents some typical stSPARQL queries. Then, Section 3 shows how the introduction of qualitative spatial information in the stRDF data model enables us to deal with the NOA application more accurately. The same section introduces the new model $\mathrm{stRDF}^{\mathrm{i}}$ which allows qualitative spatial information to be expressed in RDF and gives examples of interesting queries in the new model. In Section 4 we proceed to discuss some open problems in the $\mathrm{stRDF}^{\mathrm{i}}$ framework that require new contributions by the

---

[1] `http://linkedgeodata.org/`

[2] `http://data.gov.uk/linked-data/`

[3] The paper [Koubarakis and Kyzirakos, 2010] presents the language stSPARQL that also enables the querying of *valid times* of triples. Here, we omit time and discuss only the geospatial subset of stSPARQL.

[4] `http://www.semsorgrid4env.eu/`

[5] `http://www.earthobservatory.eu/`

qualitative spatial reasoning community. Finally, in Section 5 we discuss related work and in Section 6 we draw conclusions.

The paper is mostly informal and uses examples from the NOA application of TELEIOS. Even in the places where the paper becomes formal, we do not give any detailed technical results for which the interested reader is directed to [Koubarakis *et al.*, 2011].

2 Linked geospatial data in the NOA application

The NOA application of TELEIOS concentrates on the development of solutions for real time hotspot and active fire front detection, and burnt area mapping. Technological solutions to both of these cases require integration of multiple, heterogeneous data sources with data of varying quality and varying temporal and spatial scales. Some of the data sources are streams (e.g., streams of EO images) while others are static geo-information layers (e.g., land use/land cover maps) providing additional evidence on the underlying characteristics of the affected area.

2.1 Datasets

The following datasets are available in the NOA application:

- **Hotspot maps.** NOA operates a MSG/SEVIRI[6] acquisition station and receives raw satellite images every 15 minutes. These images are processed with image processing algorithms to detect the existence of hotspots. The information related to hotspots is stored in ESRI shapefiles and KML files. These files hold information about the date and time of image acquisition, cartographic X, Y coordinates of detected fire locations, the level of reliability in the observations, the fire radiative power assessed, and the observed fire area. NOA receives similar hotspot shapefiles covering the geographical area of Greece from the European project SAFER (Services and Applications for Emergency Response).
- **Burnt area maps.** From project SAFER, NOA also receives ready-to-use accumulated burnt area mapping products in polygon format, projected to the EGSA87 reference system[7]. These products are derived daily using the MODIS satellite and cover the entire Greek territory. The data formats are ESRI shapefiles and KML files with information relating to date and time of image acquisition, and the mapped fire area.
- **Corine Land Cover data.** The Corine Land Cover project is an activity of the European Environment Agency which is collecting data regarding land cover (e.g., farmland, forest) of European countries. The Corine Land Cover nomenclature uses a hierarchical scheme with three levels to describe land cover:

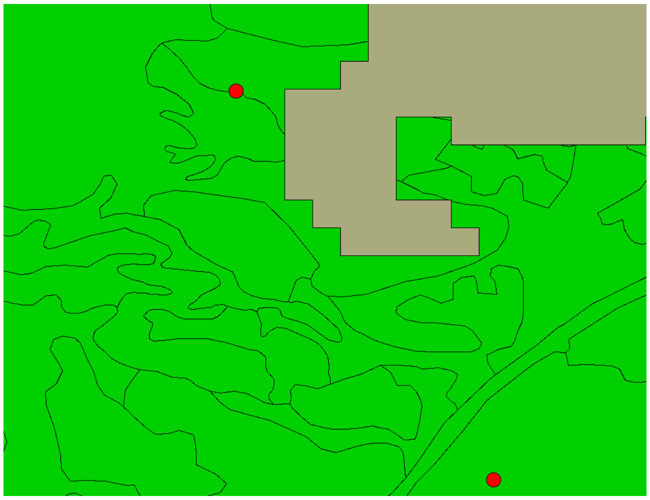

Figure 1: An example of hotspots and burnt area mapping products in the region of Attiki, Greece

  - The first level consists of five items and indicates the major categories of land cover on the planet, e.g., forests and semi-natural areas.
  - The second level consists of fifteen items and is intended for use on scales of 1:500,000 and 1:1,000,000 identifying more specific types of land cover, e.g., open spaces with little or no vegetation.
  - The third level consists of forty-four items and is intended for use on a scale of 1:100,000, narrowing down the land use to a very specific geographic characterization, e.g., burnt areas.

  The land cover of Greece is available as an ESRI shapefile that is based on the Corine Land Cover nomenclature.
- **Coastline geometry of Greece.** An ESRI shapefile that describes the geometry of the coastline of Greece is available.

Figure 1 presents an example of hotspots and burnt area mapping products, as viewed when layered together over a map of Greece.

2.2 Using semantic web technology

An important challenge in the context of TELEIOS is to develop advanced semantics-based querying of the available datasets along with linked data available on the web. This is a necessary step in order to unlock the full potential of the available datasets, as their correlation with the abundance of data available in the web can offer significant added value. As an introduction to Semantic Web technology, we present a simple example that shows how burnt area data is expressed in the language stRDF, and then proceed to illustrate some interesting queries using the language stSPARQL.

Similar to RDF, in stRDF we can express information using triples of URIs, literals, and blank nodes in the form *"subject predicate object"*. Figure 2 shows four stRDF triples that encode information related to the burnt area that is identified

---

[6] MSG refers to Meteosat Second Generation satellites, and SEVIRI is the instrument which is responsible for taking infrared images of the earth.

[7] EGSA87 is a 2-dimensional projected coordinate reference system that describes the area of Greece.

```
ex:BurntArea_1 rdf:type noa:BurntArea.
ex:BurntArea_1 noa:hasID "1"^^xsd:decimal.
ex:BurntArea_1 geo:geometry "POLYGON((
    38.16 23.7, 38.18 23.7,
    38.18 23.8, 38.16 23.8,
    38.16 23.7));<http://spatialreference
    .org/ref/epsg/4121/>"^^strdf:geometry.
ex:BurntArea_1 noa:hasArea
    "23.7636"^^xsd:double.
```

Figure 2: An example of a burnt area represented in stRDF

by the URI `ex:BurntArea_1`. The prefixes `noa` and `ex` correspond to appropriate namespaces for the URIs that refer to the NOA application and our running example, while `xsd` and `strdf` correspond to the XML Schema namespace and our stRDF namespace, respectively.

In stRDF the standard RDF model is extended with the ability to represent *geospatial data*. In our latest version of stRDF we opt for a practical solution that uses OGC standards to represent geospatial information. We introduce the new data type `strdf:geometry` for modeling geometric objects. The values of this datatype are typed literals that encode geometric objects using the OGC standard *Well-known Text (WKT)* or *Geographic Markup Language (GML)*. Literals of this datatype are called *spatial literals*.

The third triple in Figure 2 shows the use of spatial literals to express the geometry of the burnt area in question. This spatial literal specifies a polygon that has exactly one exterior boundary and no holes. The exterior boundary is serialized as a sequence of its vertices' coordinates. These coordinates are interpreted according to the GGRS87 geodetic coordinate reference system identified by the URI `http://spatialreference.org/ref/epsg/4121/`.

In the case of burnt area maps, these stRDF triples are created by a procedure that processes the relevant shapefiles and produces one stRDF triple for each property that refers to a particular area. Although we are currently doing this manually, in the future we plan to use automated tools as in [Blázquez *et al.*, 2010].

Figure 3 presents a query in stSPARQL that looks for all the URIs of burnt areas that are located in Greece and calculates their area. stSPARQL is an extension of SPARQL in which variables may refer to spatial literals (e.g., variable `?BAGEO` in `?BA geo:geometry ?BAGEO`[8]). stSPARQL provides functions that can be used in filter expressions to express qualitative or quantitative spatial relations. For example the function `strdf:Contains` is used in Figure 3 to encode the topological relation *non-tangential proper part inverse (NTPP*$^{-1}$*)* of RCC-8 [Cui *et al.*, 1993].

In this query, linked data from DBpedia[9] are used to identify those burnt areas that are located in Greece. DBpedia is an RDF dataset consisting of the contents of Wikipedia that allows you to link other data sets on the Web to Wikipedia data. The result of this query is a list of URIs that may include `ex:BurntArea_1` of Figure 2.

```
select ?BA strdf:Area(?BA)
where {?BA rdf:type noa:BurntArea .
    ?BA geo:geometry ?BAGEO .
    ?C  rdf:type noa:GeographicBound .
    ?C  dbpedia:Country dbpedia:Greece .
    ?C  geo:geometry ?CGEO .
    filter(strdf:Contains(?CGEO,?BAGEO))}
```

Figure 3: An example of a query expressed in stSPARQL

```
select ?BA ?BAGEO
where {?R rdf:type noa:Region .
       ?R geo:geometry ?RGEO .
       ?R noa:hasCorineLandCoverUse ?F .
       ?F rdfs:subClassOf clc:Forests .
       ?CITY rdf:type dbpedia:City .
       ?CITY geo:geometry ?CGEO .
       ?BA rdf:type noa:BurntArea .
       ?BA geo:geometry ?BAGEO .
       filter(strdf:Intersect(?RGEO,?BAGEO)&&
              strdf:Distance(?BAGEO,?CGEO)<2)}
```

Figure 4: A more complex example of a query expressed in stSPARQL

Figure 4 presents a more complex query in stSPARQL that looks for all burnt areas that were classified as forests according to the Corine Land Cover dataset. These areas must also be located within 2km from a city. This query also uses linked data from DBpedia to retrieve geospatial information about cities.

3 Indefinite geospatial information in the NOA use case

This section motivates our approach towards extending the model stRDF with the ability to represent and query indefinite qualitative spatial information. The new model is named stRDF$^{\text{i}}$ where "i" stands for "indefinite".

The infrared imager SEVIRI on board of the MSG satellites has medium resolution, i.e., each image pixel representing a hotspot in the NOA shapefiles corresponds to a 3km by 3km rectangle in geographic space. Thus, a precise representation of the real world situation that corresponds to a hotspot would be to state that there is a geographic region with unknown exact coordinates where a fire is taking place, and that region is included in a known 3km by 3km rectangle. This is captured by the following triples and constraints in stRDF$^{\text{i}}$ that introduce the hotspot, the fire corresponding to it and the region corresponding to the fire. This region (`_region1`) is a new kind of literal, called an *unknown literal*, which is asserted to be inside the polygon defined by `"POLYGON((24.81 35.32, 24.84 35.33, 24.84 35.30, 24.81 35.30, 24.81 35.32))"`.

```
noa:hotspot1 rdf:type noa:Hotspot .
noa:fire1 rdf:type noa:Fire .
noa:hotspot1 noa:correspondsTo noa:fire1 .
noa:fire1 noa:occuredIn _region1 .
```

---

[8] We are assuming that DBpedia offers precise representations of country geometries as values of the predicate `geo:geometry`. This is not the case at the moment since these values are points corresponding to the bounds of a region located in the center of Greece.

[9] `http://www.dbpedia.org/`

```
_region1 strdf:NTPP "POLYGON((24.81 35.32,
  24.84 35.33, 24.84 35.30, 24.81 35.30,
  24.81 35.32));<http://spatialreference.
  org/ref/epsg/4121/>"^^strdf:geometry.
```

Unknown literals are like existentially quantified variables in first-order logic. By convention, identifiers for unknown literals in stRDF^i always start with an underscore. In the above example, `strdf:NTPP` is the *non-tangential proper part* relation of RCC-8.

The NOA fire monitoring activities include validating hotspots, i.e., making sure that they do not correspond to false alarms due to the medium resolution of the images, or fires that are not of interest since they do not take place in forested areas. Part of the validation activities of NOA include collecting information about forest fires reported in the Greek Press. Therefore, when fire `noa:fire1` is validated, NOA may want to annotate the relevant hotspot, validated fire and burnt area with information from news sources available on the Web that have reported the corresponding fire. Assuming that Greek newspapers will soon follow the example of New York Times and use tags to annotate news articles, articles reporting fire events may be tagged with the name of the administrative area in which the fire occurred and the word "fire". Then, it is easy to retrieve the geographical coordinates of the place mentioned in the tag and, using standard geometric methods, decide whether the location of the hotspot is near that place.

Alternatively, using techniques from Geographic Information Retrieval and Natural Language Processing [Schockaert *et al.*, 2008; Hoffart *et al.*, 2010] one could harvest qualitative spatial information from the Web. As an example, information related to `noa:fire1` obtained from a regional Greek newspaper available on the Web might say that "there was a fire *north of* the village of Zoniana in the Prefecture of Rethymno, Crete". In this case NOA might choose to produce an annotation which mixes the qualitative spatial information discovered from the newspaper with information that corresponds to the relevant administrative regions of Greece. Of course, such techniques are not always accurate and extracted information has to be accompanied by a confidence level [Hoffart *et al.*, 2010].

The next triples introduce the burnt area corresponding to `noa:fire1` and some details related to the administrative geography of Greece as defined by the recent "Kallikratis Plan"[10]. Since there is already work in encoding the administrative geography of countries, e.g., the UK [Goodwin *et al.*, 2008], in terms of qualitative spatial constraints such as the ones we used above, we expect that such annotations can be a useful source of information for the NOA application. This is stressed by the fact that currently much of this information is or will become available as public open data in portals of the relevant European governments (e.g., see the geodata portal of the Government of Greece[11]).

```
noa:fire1 rdf:type noa:ValidatedFire .
noa:fire1 ex:hasBurntArea _region2 .

kal:Zoniana rdf:type kal:Community .
kal:Mylopotamos rdf:type kal:Municipality .
kal:Rethymno rdf:type kal:Prefecture .

kal:Zoniana kal:occupies _region3 .
kal:Mylopotamos kal:occupies _region4 .
kal:Rethymno kal:occupies _region5 .

kal:Zoniana kal:partOf kal:Mylopotamos .
kal:Mylopotamos kal:partOf kal:Rethymno .

_region3 strdf:NTPP _region4 .
_region4 strdf:NTPP _region5 .
_region1 strdf:northOf kal:Zoniana .
_region2 strdf:northOf kal:Zoniana .
```

In the following, we discuss how to evaluate stSPARQL queries over the stRDF^i data given in the beginning of this section. Let us consider the following query: "Find all fires that have occurred in a region which is a non-tangential proper part of the polygon defined by `"POLYGON((24.823 35.308, 24.827 35.308, 24.827 35.305, 24.823 35.305, 24.823 35.308))"`"[12]. In stSPARQL, this query can be expressed as shown in Figure 5. The answer to that query is the one shown in Table 1. Notice, that this answer is conditional. Because the information in the database is indefinite (the exact geometry of `_region1` is not known), we cannot say for sure whether `fire1` satisfies the requirements of the query. These requirements are satisfied under the condition given in the answer.

```
select ?F
where { ?F rdf:type noa:Fire .
   ?F noa:occuredIn ?R .
   filter (strdf:NTPP(?R, "POLYGON((24.823
     35.308, 24.827 35.308, 24.827 35.305,
     24.823 35.305, 24.823 35.308))"))}
```

Figure 5: An example of a query for the stRDF^i model expressed in stSPARQL

Table 1: A conditional answer in stRDF^i

?F	Condition
noa:fire1	_region1 strdf:NTPP "POLYGON((24.823 35.308, 24.827 35.308, 24.827 35.305, 24.823 35.305, 24.823 35.308))"

Let us consider the query of Figure 5 again. If we rephrase it to "Find fires that have *certainly* occurred in a region which is a non-tangential proper part of the polygon defined by `"POLYGON((24.823 35.308, 24.827 35.308, 24.827 35.305, 24.823 35.305, 24.823 35.308))"`", `fire1` does not satisfy the query. To be able to express such queries over stRDF^i data, in [Koubarakis *et al.*, 2011] we have extended

---

[10] http://en.wikipedia.org/wiki/Administrative_divisions_of_Greece/

[11] http://geodata.gov.gr/

[12] Notice, that this second polygon is contained in the one mentioned previously.

the semantics of query answering for stSPARQL given in [Koubarakis and Kyzirakos, 2010] using well-known techniques from the literature of incomplete information in relational databases [Imielinski and Lipski, 1984; Grahne, 1991] and constraint databases [Koubarakis, 1997].

4 Open Problems

In Sections 2 and 3 we used the NOA application of TELEIOS as an example to demonstrate how linked geospatial data sets that typically contain geometric objects specified by exact co-ordinates can be enriched with qualitative spatial information to enable better knowledge representation and more expressive query answering.

We expect that various kinds of qualitative spatial information will soon become part of linked geospatial data sets with advances in the automatic extraction of qualitative spatial relations from textual Web sources [Schockaert *et al.*, 2008], images [Mylonas *et al.*, 2009; Hudelot *et al.*, 2008], etc., and the creation of ontologies with a geospatial component such as YAGO2 [Hoffart *et al.*, 2010].

Let us now discuss a few open problems in the $\mathrm{stRDF}^{\mathrm{i}}$ framework that require new contributions by the qualitative spatial reasoning community:

- Checking the consistency of constraint networks that involve qualitative spatial relations among regions identified by a URI and constant ones (e.g., a rectangle or a polygon in the plane $\mathbb{Q}^2$ or in a Cartesian co-ordinate system). This combination of qualitative and quantitative constraints has been studied in detail for temporal constraints [Koubarakis, 2006], but similar results do not exist for spatial constraints.
- Checking the consistency of constraint networks that involve qualitative and quantitative spatial relations among planar regions that are constrained to have certain shapes (e.g., triangles, rectangles, polygons). The case of rectangles has been studied in detail in the past (e.g., see [Balbiani *et al.*, 1999]) and there is some recent work on topological relations among convex planar regions [Li and Liu, 2010].
- Performing variable elimination in constraint networks with qualitative and quantitative spatial constraints or, equivalently, performing quantifier elimination in the associated first-order theory. As shown for the temporal case in [Koubarakis, 1997], variable elimination is needed for answering certainty queries with answer variables (i.e., "What is the region that is on fire and is certainly inside a specific area?"). This cannot be done in the general case even for topological relations [Bennet, 1997] but no detailed results beyond this are known.
- Scalable implementations of constraint network algorithms for qualitative and quantitative spatial constraints. RDF stores supporting linked geospatial data are expected to scale to *billions* of triples like their non-spatial counterparts [Neumann and Weikum, 2008] and recent work in this area is encouraging [Brodt *et al.*, 2010].

  Can this level of scalability be achieved when qualitative spatial relations come into play? A good approach here might to start with algorithms with low polynomial complexity (even if they do not cover the general case) and try to implement them as efficiently as possible. In the temporal case, this approach has been followed successfully by temporal reasoners such as TimeGraph-II and extensions [Gerevini *et al.*, 1994]. In addition, there might be cases where network structure can be exploited (e.g., hierarchical organization of geographical regions).
- There are no publicly available data sets, benchmarks and related implementations. This workshop and the associated QSTR library is an excellent way to bring together the community and make progress in this area. It is also important to liaise with similar efforts in the Semantic Web community.

5 Related Work

Enriching linked data sources with geospatial information is a recent activity. Two representative examples are [Auer *et al.*, 2009; de León *et al.*, 2010]. In [Auer *et al.*, 2009] OpenStreetMap data are made available as RDF and queried using the declarative query language SPARQL. Using similar technologies, [de León *et al.*, 2010] makes available as linked data various heterogeneous Spanish public datasets. In both of these data sources qualitative spatial relations do not appear in the triples. YAGO2 [Hoffart *et al.*, 2010] offers only a part-of relation.

In addition to stSPARQL there have also been other works developing spatial and temporal extensions for RDF and SPARQL [Perry, 2008; Kolas, 2008]. There is also a forthcoming OGC standard [OGC, 2010] for the development of a query language for geospatial data encoded in RDF, called GeoSPARQL.

In contrast to the above works, the area of description logics has studied the representation and reasoning with qualitative spatial relations utilizing data models that are similar to RDF. Racer was the first reasoner to support qualitative spatial relations [Wessel and Moller, 2009]. More recently, [Stocker and Sirin, 2009] has developed an extension of the DL reasoner Pellet [Parsia and Sirin, 2004] that allows reasoning with RCC-8 relations. Finally, [Batsakis and Petrakis, 2010] proposes SOWL, an extension of OWL, to represent spatial qualitative and quantitative information employing the RCC-8 topological relations, cardinal direction relations, and distance relations. To reason about spatial relations a set of SWRL rules are implemented in the Pellet reasoner.

6 Conclusions

In this paper we proposed linked geospatial data on Semantic Web as an interesting application area of qualitative spatial reasoning techniques. In the context of our recent work on the models stRDF and stSPARQL and their extensions with indefinite geospatial information, we discussed some open problems that may be of interest to the qualitative spatial reasoning community. As part of our future work we intend to study the computational complexity of query processing for the languages we have developed.

Acknowledgements

This work has been funded by the FP7 project TELEIOS (257662).

References

[Auer *et al.*, 2009] S. Auer, J. Lehmann, and S. Hellmann. Linkedgeodata: Adding a spatial dimension to the web of data. In *ISWC'09*, pages 731–746, 2009.

[Balbiani *et al.*, 1999] P. Balbiani, J.-F. Condotta, and L. F. del Cerro. A new tractable subclass of the rectangle algebra. In *IJCAI*, pages 442–447, 1999.

[Batsakis and Petrakis, 2010] S. Batsakis and E. G. M. Petrakis. SOWL: spatio-temporal representation, reasoning and querying over the semantic web. In *I-SEMANTICS '10*, USA, 2010.

[Bennet, 1997] B. Bennet. *Logical Representations for Automated Reasoning about Spatial Relationships*. PhD thesis, School of Computer Studies, University of Leeds, 1997.

[Bizer *et al.*, 2009] C. Bizer, T. Heath, and T. Berners-Lee. Linked data-the story so far. *Int. J. Semantic Web Inf. Syst.*, 5(3):1–22, 2009.

[Blázquez *et al.*, 2010] L. M. Vilches Blázquez, B. Villazón-Terrazas, V. Saquicela, A. de León, Ó. Corcho, and A. Gómez-Pérez. Geolinked data and inspire through an application case. In *ACM SIGSPATIAL GIS*, pages 446–449, 2010.

[Brodt *et al.*, 2010] A. Brodt, D. Nicklas, and B. Mitschang. Deep integration of spatial query processing into native rdf triple stores. In *ACM SIGSPATIAL GIS'10*, pages 33–42, USA, 2010.

[Cui *et al.*, 1993] Z. Cui, A. G. Cohn, and D. A. Randell. Qualitative and Topological Relationships in Spatial-Databases. In *SSD'93*, 1993.

[de León *et al.*, 2010] A. de León, V. Saquicela, L. M. Vilches, B. Villazón-Terrazas, F. Priyatna, and O. Corcho. Geographical Linked Data: a Spanish Use Case. In *I-SEMANTICS*, 2010.

[Gerevini *et al.*, 1994] A. Gerevini, L. Schubert, and S. Schaeffer. The temporal reasoning tools TimeGraph I-II. In *ICTAI'94*, pages 513–520, 1994.

[Goodwin *et al.*, 2008] J. Goodwin, C. Dolbear, and G. Hart. Geographical Linked Data: The Administrative Geography of Great Britain on the Semantic Web. *TGIS*, 12:19–30, 2008.

[Grahne, 1991] G. Grahne. *The Problem of Incomplete Information in Relational Databases*, volume 554 of *LNCS*. Springer Verlag, 1991.

[Hoffart *et al.*, 2010] J. Hoffart, F. M. Suchanek, K. Berberich, and G. Weikum. YAGO2: a spatially and temporally enhanced knowledge base from Wikipedia. Technical report, Max Planck Institut Informatik, 2010.

[Hudelot *et al.*, 2008] C. Hudelot, J. Atif, and I. Bloch. Fuzzy spatial relation ontology for image interpretation. *Fuzzy Sets and Systems*, 159(15):1929–1951, 2008.

[Imielinski and Lipski, 1984] T. Imielinski and W. Lipski. Incomplete Information in Relational Databases. *JACM*, 31(4):761–791, 1984.

[Kolas, 2008] D. Kolas. Supporting Spatial Semantics with SPARQL. In *Terra Cognita Workshop*, Germany, 2008.

[Koubarakis and Kyzirakos, 2010] M. Koubarakis and K. Kyzirakos. Modeling and Querying Metadata in the Semantic Sensor Web: The Model stRDF and the Query Language stSPARQL. In *ESWC'10*, pages 425–439, 2010.

[Koubarakis *et al.*, 2011] M. Koubarakis, K. Kyzirakos, B. Nikolaou, M. Sioutis, and S. Vassos. A data model and query language for an extension of rdf with time and space. Deliverable D2.1, TELEIOS project, 2011.

[Koubarakis, 1997] M. Koubarakis. The Complexity of Query Evaluation in Indefinite Temporal Constraint Databases. *TCS*, 171:25–60, January 1997.

[Koubarakis, 2006] M. Koubarakis. Temporal CSPs. In *Handbook of Constraint Programming*. Elsevier, 2006.

[Kyzirakos *et al.*, 2010] K. Kyzirakos, M. Karpathiotakis, and M. Koubarakis. Developing Registries for the Semantic Sensor Web using stRDF and stSPARQL. In *SSN'10*, volume 668, 2010.

[Li and Liu, 2010] S. Li and W. Liu. Topological relations between convex regions. In *AAAI*, 2010.

[Mylonas *et al.*, 2009] P. Mylonas, E. Spyrou, Y. Avrithis, and S. Kollias. Using visual context and region semantics for high-level concept detection. *IEEE Trans. Multi.*, 11:229–243, 2009.

[Neumann and Weikum, 2008] T. Neumann and G. Weikum. RDF-3X: a RISC-style engine for RDF. *VLDB*, 1(1), 2008.

[OGC, 2010] Open Geospatial Consortium Inc OGC. GeoSPARQL - A geographic query language for RDF data, November 2010.

[Parsia and Sirin, 2004] B. Parsia and E. Sirin. Pellet: An OWL DL Reasoner. In *ISWC'04*, 2004.

[Perry, 2008] M. Perry. *A Framework to Support Spatial, Temporal and Thematic Analytics over Semantic Web Data*. PhD thesis, Wright State University, 2008.

[Renz and Nebel, 2007] J. Renz and B. Nebel. Qualitative spatial reasoning using constraint calculi. In *Handbook of Spatial Logics*, pages 161–215. Springer, 2007.

[Schockaert *et al.*, 2008] S. Schockaert, P. D. Smart, A. I. Abdelmoty, and C. B. Jones. Mining topological relations from the web. In *DEXA*, pages 652–656, 2008.

[Stocker and Sirin, 2009] M. Stocker and E. Sirin. Pelletspatial: A hybrid rcc-8 and rdf/owl reasoning and query engine, 2009.

[Wessel and Moller, 2009] M. Wessel and R. Moller. Flexible software architectures for ontology-based information systems. *JAL*, 7(1):75–99, March 2009.