A Geo-Semantics Flyby

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Abstract. Geospatial semantics as a research field studies how to publish, retrieve, reuse, and integrate geo-data, how to describe geo-data by conceptual models, and how to develop formal specifications on top of data structures to reduce the risk of incompatibilities. Geo-data is highly heterogeneous and ranges from qualitative interviews and thematic maps to satellite imagery and complex simulations. This makes ontologies, semantic annotations, and reasoning support essential ingredients towards a Geospatial Semantic Web. In this paper, we present an overview of major research questions, recent findings, and core literature.

1 Introduction and Motivation

A flyby is a flight maneuver to celebrate an important event, to demonstrate aircraft, or to showcase flying skills. Independent of the particular purpose, the audience will see the aircraft approaching from afar, catch a more detailed glimpse of certain parts when the aircraft passes by, and then see the tail disappear in the sky. Using the flyby as a metaphor, we will give a broader overview of the general field of geo-semantics first, later highlight some selected topics in more detail, and also touch upon a few topics of emerging interest. The selection of these topics is biased, and, as with the flyby, depends on the viewer's vantage point. We will assume that the reader is familiar with the core concepts of the Semantic Web, but not with geo-semantics, the broader Geosciences, or Geographic Information Science. Consequently, we will focus on intuitive examples that do not require domain knowledge but nonetheless illustrate the research challenges. For those interested in a detailed introduction to the Semantic Web and related core technologies, we refer the reader to the recent textbook by Hitzler et al. [42].

Before we dive into the discussion, it is worth clarifying some of the terminology we will use. Much like Bioinformatics combines Computer and Information Science with Biology to improve handling and analyzing biological data, Geoinformatics is an interdisciplinary research field concerned with geo-data in their broadest definition. *Geo*, in this context, refers to the Earth Sciences, Geography, Ecology, and related research fields. Geographic Information Science (GIScience) puts more emphasis on geographic aspects and qualitative as well as quantitative data. It is closely related to geographic information systems (GIS), which are software and services to manage and analyze geographic data. These systems are used, for example, to reason about crime densities, optimize location choices, visualize land use dynamics, and so forth.[4] GIS and spatial statistics play an important role in many domains such as economics, health research, and archaeology. In fact, it is often claimed that most data has some sort of spatial reference. Sometimes the name Spatial Informatics is used to emphasize the integrative role and omnipresence of spatial

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[4] The distinction between Geoinformatics and GIScience is not crisp and mainly an artifact of their parallel evolution in Europe and United States.

aspects in many datasets and to broaden the research beyond the geo-realm. The term *geospatial* is used to explicitly restrict the scale to between 10^{-2} - 10^{7} meters. That is, everything smaller than a grain of sand and larger than the Earth is usually not considered to be part of the geo-domain. Finally, as the Geosciences are largely concerned with processes, the temporal dimension is implicit, and thus geo-data is typically *spatiotemporal*.

In order to illustrate some of the complexities and interesting challenges of geo-semantics we would like to start with what on the surface might appear to be a trivial task. That is, we want to describe the semantics of the term *mountain*. *Mountain* is one of many geographic feature types, including *river, lake, forest*, and *city*, that we are accustomed to using in everyday language and for which we have developed internal notions through our social and physical experiences. This knowledge, which has been described as *Naive Geography* by Egenhofer and Mark [25], is used by people every day to reason about the *surrounding geographic world*. Given our familiarity with these terms, we are often quick to jump to conclusions and assume a shared understanding, while, in fact, most of these terms have dozens, domain-specific, and often incompatible meanings. The fact that we want to formalize the semantics of terms for which almost everyone has common-sense understandings makes this a challenging task.

Fig. 1. Schematic map (1846) showing *principal* mountains and rivers of the world [73].

One method to formalize the notion of *mountain* is to define a minimum height for the mountain as a necessary property. This technique has been adopted in the United Kingdom and was used to humorous effect in the movie *The Englishman*

Who Went Up a Hill But Came Down a Mountain. In that movie, the members of a fictional Welsh community are dismayed to learn that their local mountain is not, in fact, a *mountain* at all but rather a *hill*, because it is a couple feet under the threshold of 1000 feet. They, however, successfully get the mountain classified as a *mountain* by adding a small pile of earth on the top. This story illustrates an important point about the semantics of geographic features. The definitions of feature types are a product of human perception, cognition, current state of knowledge, and social agreement. There is no human-independent *true* definition of *mountain* (or *forest*, *river*, *city*, etc.). Consequently, the definitions will vary between places and cultures, and it is important to represent local definitions appropriately. The importance of the local geographic context to understand the meaning of geographic terms is further illustrated by the map shown in Figure 1. This schematic map from 1846 was designed to represent the *principal* mountains and rivers of the Earth. The set of principal rivers and mountains are determined by length and height, respectively, but within context of the part of the Earth in which the feature is found. As a result, the principal mountains of England, such as Scafell Pike, the tallest mountain in England at a relative height of 912 meters, would barely be hills in the Himalayas.

Apart from the notion of context based on local jurisdictions and communities, since geospatial terms like *mountain* are based on perception, their meanings can be highly situation-dependent. For example, imagine a geo-semantics informed location-based service that is designed to give wayfinding instructions. A human that gives a route description might say, "take a right and walk toward the mountain," where the mountain in question is a clearly identifiable higher-elevation landmark feature. The meaning of *mountain* in this case is not based on any canonical definition but entirely on the situated context of the given route [13,6].

How does this impact searching and integrating geo-data in the Linked Data Cloud and the Semantic Web? Let us assume you are interested in studying the role of the forest industry in rural economics. For instance, you may be interested in migration and depopulation, government policies, or the changing role of forestry in the context of ecological and amenity services. While we will use a simplified example here, this use case is real and was, for instance, addressed by Elands and Wiersum [26]. Suppose terms such as *forest*, *town*, *farm*, and *countryside* are used without making their intended meaning explicit. Suppose further that you would like to query for *towns near forests* such as in the SPARQL query shown below, and you plan to use the retrieved towns to conduct your analysis.[5]

```
[...]
SELECT distinct ?town ?forest
WHERE {
    ?town
       geo-pos:lat ?lat ;
       geo-pos:long ?long ;
       a dbp-ont:Town .
    ?forest
       omgeo:nearby(?lat ?long "25mi") ;
       a dbp-ont:Forest .
}[...]
```

No matter what the query will return and how you will process and analyze the data from those thousands of towns, your results will be misleading at best. Most likely you will have overlooked that among all those small populated places,

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[5] This query will fail as the class *Forest* (or similar classes) are not defined in DBpedia. However, querying for Mountains, for instance, would work.

your dataset will also contain Los Angeles, Stuttgart,[6] and other metropolises. The reason for this apparently odd result is that the class *city* and *town* are defined to be equivalent by Californian law. In fact, most of US states have their own legal definition of these terms. While some rely on maximum population as a criterion, others do not [47]. The situation for forests is even more complicated. Lund [66], for instance, lists over 900 different definitions for *forest*, *afforestation*, and related terms. These definitions are not without consequences but often legally binding. In the past, loop holes in these definitions have been used for massive deforestation.[7] Finally, the alert reader may be wondering why a radius of 25 miles is used in the example above to define *nearby*. First, as with many other terms, the semantics of nearby is context-dependent. Second, unfortunately, most of today's Linked Data represents geographic features by their centroids (geometric center points) instead of polygons. Thus, even if a GIS would represent a particular town and forest by two adjacent polygons, their centroids may still be miles apart; see [8] for more details on spatial queries over Linked Data.

As these examples show, understanding what the authors of a scientific study or data providers in general mean by apparently obvious terms is a difficult task. Without better geo-ontologies, semantically annotated (meta) data, and more complex ontology alignment services that can map between local ontologies, reusing and integrating data from heterogeneous sources is merely a distant dream.

Geospatial terms are often taken for granted, but they pose interesting challenges once we want to formally describe their semantics in information systems and share them in an environment such as the Linked Data. Interestingly, the problem is not that machines cannot communicate, but that humans misunderstand each other when communicating via machines [86]. It is worth noting that geo-semantics research is therefore not interested in *overcoming* or *resolving* semantic heterogeneity. Local definitions exist for good reasons. If one could just standardize meaning globally, there would be no need for Semantic Web research. Instead, geo-semantics tries to restrict the interpretation of domain-vocabulary towards their intended meanings, map and translate between local conceptualizations, and try to reduce the risk of combining incompatible data [60,44].

2 Using Geospatial Referents on the Semantic Web

Geospatial and spatiotemporal phenomena, such as places (*Florida*), geographic objects (*the Eiffel tower*), and events (*Hurricane Katrina*), serve as central referents on the Semantic Web. Spatial relations between these phenomena, like *above*, *below*, *in front*, *north of*, *overlaps*, *contains*, serve to localize them relative to each other. Geospatial information maps these phenomena to points or regions in spatial reference systems and temporal reference systems to ensure their interpretation. This makes them amenable not only for cartographic mapping, but also for locational querying and comparison. It is therefore not surprising that many linked datasets either contain spatiotemporal identifiers themselves or link out to such datasets, making them central hubs of the Linked Data cloud.

Figure 2 depicts point-like features classified as *places* extracted from a representative fraction of the Linked Data cloud using SPARQL endpoints and their geoindexing capabilities. It is remarkable that the figure does not contain a base map, but is entirely composed of millions of extracted points. In other words, the

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[6] Stuttgart is described as the 'sixth-largest city in Germany' in DBpedia but classifieds as a town via `dbpedia:Stuttgart rdf:type dbpedia-owl:Town`; see `http://live.dbpedia.org/page/Stuttgart`.

[7] Readers interested in deforestation and in combining SPARQL with spatial statistics in R may want to check the new Linked Brazilian Amazon Rainforest Dataset[52].

coverage of *places* on the Linked Data cloud is very high. On the downside, the map also shows massive (and often systematic) errors; e.g., the huge cross in the middle of the map. For lack of space we do not discussed these errors here.[8]

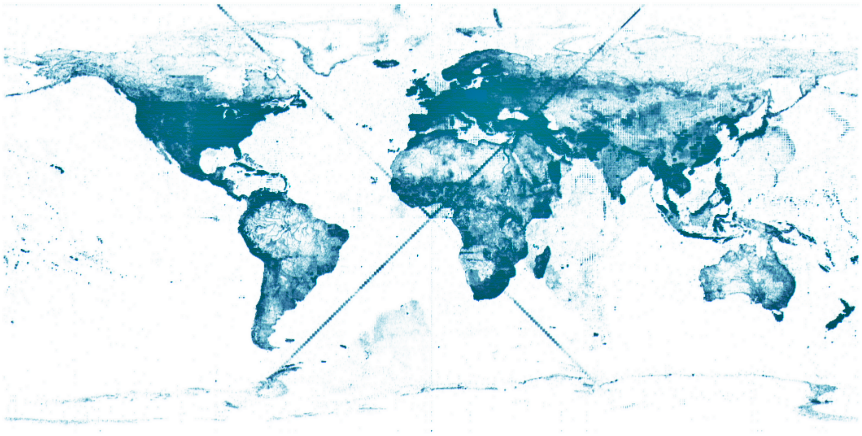

Fig. 2. A representative fraction of places in Linked Data (EPSG:4326, Plate Carrée).

Prominent examples of geo-specific, yet general purpose Linked Data include Geonames.org as well as the Linked Geo Data project, which provides a RDF serialization of Points Of Interest from Open Street Map [91] . Besides such voluntary geographic information (VGI), governments and governmental agencies started to develop geo-ontologies and publish *Linked Spatiotemporal Data* [33,48]; see Table 1. Examples include the US Geological Survey [95] and the UK Ordnance Survey [35]. Furthermore, many other Linked Data sources contain location-based references as well. To give a concrete example, data from the digital humanities may interlink information about particular exhibits to places and their historic names [69]. By following these outgoing links, researchers can explore those places and learn about events which took occurred there. The historic events data may in turn link to repositories about objects and actors that were involved in the described events [36].

Linked Data repositories	
LinkedGeoData.org	`http://linkedgeodata.org/About`
GeoLinkedData.es	`http://geo.linkeddata.es/web/`
Geo.Data.gov	`http://geo.data.gov/geoportal/catalog/main/home.page`
Ordnance Survey	`http://data.ordnancesurvey.co.uk/.html`
TaxonConcept	`http://lsd.taxonconcept.org/sparql`
USGS The National Map	`http://cegis.usgs.gov/ontology.html`
Linked Amazon Rainforest Data	`http://linkedscience.org/data/linked-brazilian-amazon-rainforest/`
Ontologies	
The Geonames Ontology	`http://www.geonames.org/ontology/documentation.html`
GAZ Ontology	`http://gensc.org/gc_wiki/index.php/GAZ_Project`
W3C Geospatial Ontologies	`http://www.w3.org/2005/Incubator/geo/XGR-geo-ont-20071023/`
TaxonConcept Ontologies	`http://www.taxonconcept.org/ontologies/`
GeoLinkedData.es Ontologies	`http://geo.linkeddata.es/web/guest/modelos`
Darwin Core	`http://rs.tdwg.org/dwc/`
GeoSPARQL Schemas	`http://www.opengeospatial.org/standards/geosparql`
U.S. Geological Survey Ontologies	`http://cegis.usgs.gov/ontology.html`
European INSPIRE Models	`http://inspire.ec.europa.eu/index.cfm/pageid/2/list/datamodels`

Table 1. Selected Linked Data repositories and ontologies for geo-data.

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[8] See `http://stko.geog.ucsb.edu/location_linked_data` for more details.

Arriving at such a network of interlinked repositories, however, is not trivial as geospatial phenomena come with a large degree of *semantic ambiguity*. This makes them challenging to use as semantic referents. Consider the problem of retrieving objects on a sports ground, such as the one depicted on the areal photograph in Figure 3, for the purpose of noise abatement planning [39]. For example, the goal may be to find objects that serve as referents for localizing sources of noise.

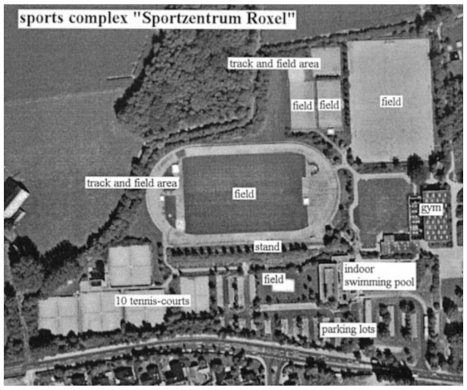

Fig. 3. Sportsground Roxel near Münster in an aereal photograph; taken from [39].

Fig. 4. The sportsground on Google maps.

There are different kinds of maps (and datasets used to render them) of the same sports ground, showing different kinds of objects (Figures 5 and 6). Starting with the *cadastral* map in Figure 5, one can see that the most prominent feature, the track and soccer field area, is not depicted on the map. Similarly, the tennis courts are left out. This can be explained if we recall that a cadastral map depicts land parcels and ownerships and that the distinction between a soccer field and its surrounding area is not one of ownership. Thus, the German cadastre does not store this information, and, consequently, they are not rendered on the map. Google maps shares a similar but slightly different perspective as shown in Figure 4 and often reduces areal features to points.

Fig. 5. Cadastral map (ALK) of the Sportsground Roxel [39].

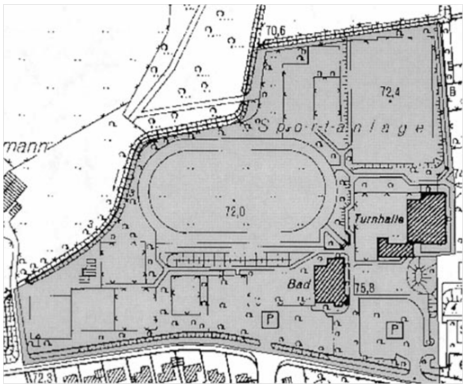

Fig. 6. Topographic map (DGK) of the Sportsground Roxel [39].

In contrast, the sports ground as such is represented in the cadastral map, since it can be distinguished from its surroundings precisely based on ownership. The *topographic map* in Figure 6 shows the track area and the tennis courts but leaves out the soccer field. This can be explained if we recall that a topographic map is a map of ground surface features. There is a distinction in surface texture between the elliptic track area or the tennis courts on one hand and the lawn on the other hand. However, since our goal is to identify sources of noise, we are interested in identifying the soccer field as well. Surface texture does not allow to distinguish it from its embedding lawn. Soccer fields are not just physical objects, they are actual dispositions to play a game, indicated by linear signs on the lawn.[9] Consequently, their identification requires yet a different perspective on the sports ground, and, thus, an additional data source. There are many different sources that could be used in addition such as yellow pages, human activity surveys, geo-social check-ins from location-based services and their semantic trajectories [98], just to name a few. Establishing identity between features from all those sources, i.e., declaring that the sports ground in dataset A is the same entity in the physical world as the sports ground in dataset B, is a major research challenges [37,38]. Once this relation is established and made explicit, e.g., by using *owl:sameAs*, the attribute spaces of the involved data sources can be conflated.

As this example illustrates, there is large variability in mapping a single area, and many geospatial concepts have an intrinsic multi-perspectival nature. They are situated, i.e., their interpretation depends on space and time, and sometimes on a group of researchers [13]. This frequently causes interoperability problems. However, if we make the inherent geospatial semantic perspectives explicit, we are able to distinguish them, understand their advantages and limitations, combine them, and to a certain degree also translate between them. Geo-semantics develops methods and tools for disambiguating and describing these spatial perspectives, and, thus, provides reliable referents for the Semantic Web, together with useful spatial relations between them. Both can be used to improve retrieval, re-usage, and interlinkage of data.

In this section, we discussed how geo-spatial phenomena are important referents that enable semantic linking between datasets and addressed complexities in representing these referents and establishing identities of geographic features due to semantic ambiguity. In the next section, we give an overview on the geo-semantics research field before discussing how it serves to address the aforementioned challenges.

3 Geo-semantics from 30.000 Feet

The research field of geo-semantics builds on GIScience/geoinformatics, spatial databases, cognitive science, Artificial Intelligence (AI), the Semantic Web, and other related research areas [59]. It focuses on the meaning of digital referents at a geographic scale, such as places, locations, events, and geographic objects in digital maps, geodatabases, and earth models. Geo-semantics applies and investigates a variety of methods ranging from top-down knowledge engineering and logical deduction to bottom-up data mining and induction. It combines knowledge engineering with methods specific to GIScience, e.g., spatial reference systems, spatial reasoning, and geographic information analysis. Geo-semantics also extends work which originated in related disciplines. For example, it uses semantic similarity and analogy reasoning, which have a long research tradition in cognitive science, to enable semantics-based geographic information retrieval [45], and it combines geo-ontologies with spatial statistics, e.g., to study land cover change [4].

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[9] Similar to traffic locomotion infrastructure [85].

What are major research challenges that are addressed by the field of geo-semantics? One early challenge was to describe the semantics of Web services that provide measurements from spatially distributed sensors. For example, in order to simulate the spread of a potentially toxic gas plume, two services may be queried for wind direction observations. Both services may seem compatible as they return a string called *wind_direction* as output together with an integer ranging from 0 - 360°. However, they can have contradicting interpretations of what the returned values actually mean: *wind blows to* or *wind blows from*. Thus, sending observation values from both services to an evacuation simulation running on a Web Processing Service (WPS) will yield misleading results [78]. Besides such challenges that arise from integrating *heterogeneous data* and *combining services* [29], an important future task is to semantically describe *spatial prediction models* in order to enable data-model inter-comparison [75]. For example, spatial statistics and simulation models are an essential part of geospatial information technology, posing their own set of interoperability challenges. Another challenge for geo-semantics is *concept drift*. Most geospatial concepts are not static, they evolve over time and may even change abruptly. This leads to research challenges such as how to handle semantic aging [87]; i.e., how to preservation and maintenance of geo-data and ontologies over long periods of time to make them reusable for future generations. To give a concrete example, geo-referenced data about the distribution of species, temperature, and other ecological variables collected in the 1960s are used in recent studies as base line to study species turnover [14]. The interpretation of these datasets is difficult and time consuming as different spatial and semantic reference systems have been used and scientific workflows have evolved over the years.

Two major strands of scientific thought in geo-semantics can be differentiated, by analogy with Kuhn's [62] distinction between modeling vs. encoding on the Semantic Web. One is studying the design task of semantic modeling. How should geo-data be modeled in an information ontology? Which classes and relations are required to describe the meaning of spatiotemporal phenomena and to discover, capture, and query geospatial referents? Examples include work on geo-ontology engineering [30,54,12] and the formalization of spatial reasoning [19]. These spatial relations support localizing complex geometrical objects, such as *cities* or *forests*, relative to other referents, such as *roads* and *countries* [49]. These queries need to deal with indeterminate boundaries of geographic objects [15], a scientific strand which goes back to a tradition of research on spatial representations and operations in Geographic Information Systems [17] and on integrity constraints for spatial databases.

Another strand is interested in the retrieval, re-usage, integration, and interoperation of geo-referenced information. How can geographic referents be semantically linked to other kinds of information with related meaning? Due to the broad thematic coverage of geo-data spanning fields such as human and cognitive Geography, Transportation Research, Economics, Ecology, Climatology, Geology, and Oceanography, data integration and sharing require methods that reduce the risk of semantic incompatibilities [39]. Recent work has developed technology for enabling *spatial queries* on Linked Data. This work includes GeoSPARQL as a common query language for the Geospatial Semantic Web as well as RDF triple stores which can effectively store and index Linked Spatiotemporal Data [8]. Similar work addressed the role of semantic similarity for spatial scene queries [76,64]. Current research challenges investigate how geo-data can be represented on different *levels of abstraction, scale, and granularity* [28], and how to semantically account for its *uncertainty* [11]. Another challenge is that geospatial referents, such as places and events, are often only implicitly contained in a data set, and thus need to be *automatically discovered* in data repositories which are not yet linked or geo-referenced.

In this section we gave an overview of the field of geo-semantics and current research challenges, and highlighted two main threads of geo-semantics research: 1) representing geographic data models in ontologies and 2) semantically linking geographic data with information coming from other domains.

4 Research Questions and Major Findings

In the following, we will use seven research questions to introduce major areas of research and discuss findings used to provide reliable geospatial referents for the Semantic Web.

What Kinds of Geospatial Classes Should be Distinguished?

Even though geographic referents are rooted in diverse domains, they share certain common characteristics and principles that can be exploited in the design of geo-ontologies. Kuhn [61] proposed the core concepts *location*, *neighborhood*, *field*, *object*, *network*, *event* as well as the information concepts of *granularity* and *accuracy* as a common core that can be used to *spatialize* information. Geo-ontologies need to support access to phenomena on flexible resolution levels and scales in order to allow systems to query and reason on scale dependent representations [7]. For this purpose, scale dependency of representations needs to be formally expressed, as recently shown by Carral Martínez et al. [16]. Geo-ontologies also have to deal with the various natures of spatial boundaries, as distinguished in [90]. Examples for top-level geo-ontologies that incorporate the principle of spatial granularity include the work of Bittner et al. [12]. Usually, such foundational ontologies are extended by domain ontologies, such as the SWEET ontology for Earth and environmental science [80].

As we argued in Section 2, geospatial concepts are situated and context-dependent [13] and can be described from different, equally valid points of view [47,86]. This makes standard comprehensive approaches towards ontology engineering unrealistic. Semantic engineering, however, can be slightly redefined, namely as a method of communicating possible interpretations of terms by constraining them towards the intended ones [60,47], without prescribing a huge amount of abstract *ontological commitments*. Ontology design patterns can provide reusable building blocks or strategies to support knowledge engineers and scholars in defining local, data-centric, and purpose-driven ontologies [32]. Vague terms may be grounded multiple interpretations [10]. Ontologies may also be built up in a layered fashion Frank2003,Couclelis.2010. In such cases, one can start with observation procedures on the bottom level and then arrive at more abstract but reproducible ontological categories by deductive and inductive methods [2,47,21].

How to Refer to Geospatial Phenomena?

Geographic information technology relies, to large extent, on the availability of *reference systems* for the precise semantic interpretation of its spatial, temporal, and thematic components [17]. Spatial reference systems provide the formal vocabulary to calculate with precise locations, e.g., in the form of coordinates on a mathematical ellipsoid, and to perform a multitude of operations such as distance measurement. Geodetic datums, i.e., standard directions and positions of the ellipsoid, enable the interpretation of locations as results of repeatable measurements on the earth's surface. Both are required to understand spatial data. Temporal reference systems, e.g., calendars, manage the representation of time, and allow one to translate between different calendars. The thematic (sometimes also called attributive) component of geo-information requires reference systems as well [17,58]. Examples are measurement scales for qualities such as temperature or air pressure. As a consequence, Kuhn introduced the generalized notion of Semantic Reference Systems (SRS) [58]. They are supposed to enable a precise interpretation of all components of geospatial data in terms of semantic datums, which provide for their grounding in terms of measurement scales or observation procedures [86]. For example, attribute values such as the wind directions discussed before can be interpreted in terms of reference systems for cardinal wind directions and anemometers. Establishing these SRS, their standard operations, as well as their formal vocabularies, is an ongoing research area [60]. It has has been mentioned among the most pressing and challenging projects of GIScience/Geoinformatics [70]. Recent research results include methodologies and formalisms for grounding reference systems [86,79], as well as technologies for translation of attribute values based on reference systems [84].

How to Perform Geo-Reasoning & Querying over the Semantic Web?

There are several research traditions of geospatial reasoning, ranging from more computational to more conceptual approaches. One is based on *geometric operators* in a spatial database, i.e., on *explicitly represented spatial geometry.* These include point-in-polygon tests, R-tree search algorithms, quadtree compression, and geometric and set-theoretic operators for vector data. Another form is based on graph-based computational methods, which, for instance, allow reasoning about road networks [17]. *Spatial reasoning*, i.e., reasoning with qualitative spatial relations, includes topological reasoning, such as about *overlap*, *meet*, and *disjoint* relations, and reasoning with directions. Prominent spatial calculi are mereotopological calculi, Frank's cardinal direction calculus, Freksa's double cross calculus, Egenhofer and Franzosa's 4- and 9-intersection calculi, Ligozat's flip-flop calculus, Cohn's region connection calculi (RCC), and the Oriented Point Relation Algebra [82]. The latter kind of reasoning is based on deductive inference in first-order predicate logic [19], as well as on finite composition tables and constraint reasoning, in which all possible relations are enumerated exhaustively [82].

In comparison, most Semantic Web reasoning is rather narrowly defined. It is concerned with particular decidable subsets of first-order predicate logic, namely description logics and Horn rules, which often lack the expressivity needed to reason with spatial relations [92]. Furthermore, other forms of geospatial reasoning, such as geometrical computation or approximate reasoning, are only rudimentary supported by the Semantic Web [41]. The integration of such reasoning paradigms into the Semantic Web requires further consideration of their RDF representation and computability, as well as a broadening of the existing reasoning paradigm itself. It has been argued that in the past, the reasoning paradigm of the Semantic Web might have been too narrowly occupied by soundness, completeness, and decidability constraints. Thus, in the context of geo-semantics, it might be useful to loosen soundness and completeness demands of proof procedures in order to allow for scalable approximate reasoning [41].

How can geospatial reasoning be integrated with Semantic Web technologies in a tractable way? Many spatial qualitative decision problems are NP-hard, however, tractable subsets can be identified [82]. There are several recent efforts to integrate qualitative spatial reasoning into RDF reasoners, such as Racer [97] and Pellet [92]. A promising direction of research is to combine qualitative reasoners with geometric computation. In the Semantic Web, this may be realized in terms of spatial extensions to RDF and SPARQL, such as stSPARQL or GeoSPARQL [57,8].

How to Discover Events and how to Account for Geographic Change?

Geographic assertions, such as partonomic relations between administrative regions, trajectories of moving objects and their relations to the places they cross, and membership in organizations, are valid only over a certain period of time [53]. Consequently, research investigates how this temporal dimension can be accounted for. There is a multitude of research on spatiotemporal modeling, temporal GIS [18], and simple temporal gazetteer models [40]. There is also related ontological work on the formal relationship between objects, processes, and events [31]. Research also addressed event ontology design patterns [36]. However, a particular challenge remains the automated detection of events from observation data on a geographic scale [9], such as blizzards, rainstorms, or floods [23]. Examples of research on the detection of geographic event as well as identification algorithms include the work by Agouris and Stefanidis [3]. Nevertheless, many questions regarding general formal and computational procedures of geographic event detection remain unsolved. This is especially the case for work concerning the tight coupling of geospatial ontologies with detected events, as well as the triggering of data and ontology updates by automatically detected events [65].

How to Handle Places and Moving Object Trajectories?

Humans communicate using *places* in order to refer to space. These references to places go well beyond geographic coordinates. Locations as simple coordinates are point-like, ubiquitous, and precise. Contrarily, places are not point-like and have fuzzy boundaries determined by physical, cultural, and cognitive processes [94,74]. Additionally, places, e.g., *downtown*, can change their locations over time, just like physical objects do [53]. Therefore, mere positioning data insufficiently captures the identity and meaning of places.

GIScience and geo-semantics has generated useful results in handling places in a number of different ways, for example, by the specification of place data models [40] and place ontologies [1], which can be used to improve geographic information retrieval [68,50,45]. A interesting direction for future work along these lines are affordance-based approaches toward place [51] as they allow one to associate places with the activities that can be performed at them. Another important development are technologies that can be used to handle place by automated discovery, in order to enrich data with geo-references. A typical direction of work is *geoparsing*, the discovery of places in texts by natural language processing techniques. Such research can also be applied which to identify place-related activities [5]. Recently, research has started to address the discovery of places and user activities by mining (semantic) trajectories [98]. Researchers also investigated how to reconstruct spatial footprints of places based on *geotags* in social media, e.g., Flickr [43]. Future research may address the design of place-based information systems [34], in which traditional operations of GIS have to be redesigned to handle places as referents. Geo-ontologies are considered a central part of this vision.

How to Compare, Align, and Translate Geospatial Classes?

Comparing geographic feature types across heterogeneous resources requires methods to compute conceptual similarity. Geo-semantics provides unique approaches to do this based on reference systems or conceptual spaces. Thus, over the past years, semantic translation [39,59,24,77], semantic similarity measurement [83,81,64,88,76,45], and geo-ontology alignment [22] have been major research directions. While semantic translation maps between geo-ontologies and can be thought of as the analogy to datum transformation, similarity measures the proximity between classes in a semantic space as an analogy to distance in space (and time). Geo-ontology alignment is concerned with the combination of multiple ontologies to foster data reuse and integration. The fact that most types of geographic information analysis, e.g. kernel methods, interpolation, or point pattern analysis, are based on spatial auto-correlation and distance in space, shows why semantic similarity is regarded crucial for making ontologies and geo-semantics first class citizens of geographic information systems. The notion of similarity also plays a key role in many cognitive approaches. Semantic similarity and analogy reasoning also enable new types of interaction paradigms and user interfaces which may ease browsing and navigating through (unfamiliar) geo-data and ontologies [45]. On the downside, similarity is highly sensitive to context. Therefore, researchers have analyzed the influence of contextual information and proposed different techniques to account for such effects [55].

How to Process, Publish and Retrieve Geodata?

Standardized means for publishing, querying, retrieving, and accessing geodata via Web services are provided by Spatial Data Infrastructures (SDI) as part of the framework developed by the Open Geospatial Consortium (OGC). These SDIs also support a variety of notification and processing services and, thereby, go beyond simple data stores. Data and processing services can be combined to model complex scientific workflows and be integrated as core elements in cyberinfrastructures. To ensure a meaningful combination of services, however, relies on formal specifications of the service inputs, outputs, side effects, and parameters. Therefore, semantic markups for Web services have been actively researched for years [71,27,93]. Examples of SDI specific proposals include the work of Lemmens et al. [63], Vaccari et al. [96], and Lutz [67].

What Kinds of Geospatial Classes Should be Distinguished?
How to Refer to Geospatial Phenomena?
How to Perform Geo-Reasoning & Querying over the Semantic Web?
How to Discover Events and how to Account for Geographic Change?
How to Handle Places and Moving Object Trajectories?
How to Compare, Align, and Translate Geospatial Classes?
How to Process, Publish and Retrieve Geodata?

Table 2. Seven exemplary research questions in the field of geo-semantics.

SDI services use their own markup languages (e.g., the Geographic Markup language GML) and protocols, which differ considerably from the Semantic Web technology stack. This prevents interoperability and makes a combination of the Semantic Web and the Geo-Web challenging. Consequently, researchers have proposed and implemented different approaches for a semantic enablement of the Geo-Web. Janowicz et al. [46], for instance, specified transparent and bi-directional proxies which enable users of both infrastructures to share data and combine services. Semantic annotations have been proposed to lift existing geo-data to a semantic level [56,72]. In context of digital humanities research, annotations have been applied to create Linked Spatiotemporal Data, e.g., to enrich old maps with interlinked information from the global graph [89]. With respect to OGC's family of Sensor Web Enablement standards (SWE), researchers have developed sensor and observation ontologies, semantically-enabled versions of OGC services such as the Sensor Observation Service (SOS), or RESTful transparent proxies that serve Linked Sensor Data [20].

In this section, we identified and described seven important research questions being asked in the field of geo-semantics (listed in Table 2).

5 Conclusion

We have argued that the relevance of geospatial information lies in the usefulness of geospatial referents, such as places, events, and geographic objects, and their spatiotemporal relations, which allow systems to indirectly localize and interlink numerous other resources in the Semantic Web. In part, this importance of geospatial information is reflected by the fact that the few already existing geo-data repositories, e.g., Geonames, have become central hubs on the Web of Linked Data. In addition, other key repositories, such as DBpedia, Freebase, and so forth, contain substantial collections of geo-data. However, we have also illustrated that even though geospatial information has reference systems, which allow one to precisely map and index the extent of geospatial referents, conceptualizing and formalizing these referents is an unsolved challenge. This challenge is mainly due to the situated and multi-perspectival nature of geospatial phenomena. It calls for semantic strategies that allow highlighting, distinguishing, and linking of the different perspectives to the localities that are inherent in geo-data.

Geospatial semantics addresses this need with semantic modeling of geospatial classes as well as semantic technology for access, comparison, and interlinking of geo-data. Specific semantic modeling challenges include the notions of resolution and scale in geo-ontologies, ontological perspectivity, semantic reference systems, place reference, trajectories, event discovery, the formalization of spatial relations, and the computation of spatial reasoning. Semantic technology for access and retrieval include semantically enabled spatial data infrastructures and Linked Spatiotemporal Data, as well as cognitively plausible similarity measures, analogy-based reasoning, and translation tools for geo-ontologies.

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