Web Semantics: Science, Services and Agents on the World Wide Web 7 (2009) 278–286

Contents lists available at ScienceDirect

Web Semantics: Science, Services and Agents on the World Wide Web

journal homepage: www.elsevier.com/locate/websem

Exploring the Geospatial Semantic Web with DBpedia Mobile

Christian Becker*, Christian Bizer

Freie Universität Berlin, Web-based Systems Group, Garystr. 21, D-14195 Berlin, Germany

ARTICLE INFO

Article history:
Received 4 May 2009
Received in revised form 27 July 2009
Accepted 16 September 2009
Available online 24 September 2009

Keywords:
Geospatial Semantic Web
Linked Data
Semantic Web
DBpedia
Location-aware applications

ABSTRACT

The Geospatial Semantic Web makes locations first-class citizens of the Web by representing them as original Web resources. This allows locations to be described in an open and distributed manner using the Resource Description Framework and provides for interlinking data about locations between data sources. In addition to using geo-coordinates to express geographical proximity, the Geospatial Semantic Web provides for relating locations as well as regions to each other using explicit semantic relationship types such as containment or shared borders. This article gives an overview of the Geospatial Semantic Web and describes DBpedia Mobile, a location-aware Semantic Web client that can be used on an iPhone and other mobile devices. Based on the current GPS position, DBpedia Mobile renders a map indicating nearby locations from the DBpedia data set. Starting from this map, the user can explore background information about his surroundings by navigating along data links into other data sources. DBpedia Mobile has been designed for the use case of a tourist exploring a city. Besides accessing Web data, DBpedia Mobile also enables users to publish their current location, pictures and reviews to the Semantic Web so that they can be used by other Semantic Web applications. Instead of simply being tagged with geographical coordinates, published content is interlinked with a nearby DBpedia resource and thus contributes to the overall richness of the Geospatial Semantic Web.

1. Introduction

Today's World Wide Web contains a wealth of geospatially referenced information: business and event listings, news article, blog posts, encyclopedia articles, transport information, photos, videos and advertisements all have locations associated with them, either explicitly or implicitly. Until recently, little effort was made to harness this geospatial component.

The introduction of mapping APIs by services such as Google Maps,[1] Yahoo! Maps,[2] and Microsoft Virtual Earth[3] led to the widespread integration of maps into web applications. It also resulted in a wide spectrum of *mapping mashups* which display data from multiple web services on a map.[4] Services such as the photo sharing site Flickr[5] and the community-authored encyclopedia Wikipedia[6] began encouraging their users to *geo-tag* content, i.e. to associate it with geographical coordinates. This allows content to be arranged by geographic location, as for instance shown by the Wikipedia overlay in Google Maps.

The term Linked Data [6,10,13] refers to a set of best practices for publishing structured data on the Web and for setting data-level links between data items published by different sources. In analogy to the classic Web, data-level links connect data from different sources into a single global data space, which can be explored by generic data browsers or can be crawled by Semantic Web search engines. Technologically, the core idea of Linked Data is to use HTTP URIs not only for the identification of Web documents, but also for the identification of arbitrary real-world entities [33]. Data about these entities is represented using the Resource Description Framework (RDF) [24]. Whenever one such URI is dereferenced, the corresponding Web server provides an RDF/XML [5] or RDFa [1] description of the identified entity. These descriptions may contain links to entities described by other data sources. Links take the form of RDF triples where the subject of the triple is a URI in the namespace of one server, while the object of the triple is a URI in the namespace of the other [10]. The predicate URI of the triple determines the type of the link. Whenever a predicate URI is dereferenced, the corresponding server responds with a RDF Vocabulary Definition Language (RDFS) or Web Ontology Language (OWL) definition of the link type [9]. These descriptions may in turn contain links pointing at other vocabularies, thereby defining mappings between related vocabularies [13].

By applying the Linked Data principles to geographic locations, the Geospatial Semantic Web is created. The Geospatial Semantic Web makes it possible to interlink data about locations between data sources and to relate locations to each other, as well as to

* Corresponding author.
E-mail addresses: chris@beckr.org (C. Becker), chris@bizer.de (C. Bizer).

1 http://code.google.com/apis/maps/.
2 http://developer.yahoo.com/maps/.
3 http://dev.live.com/virtualearth/.
4 http://www.programmableweb.com/tag/mapping.
5 http://www.flickr.com/.
6 http://www.wikipedia.org/.

1570-8268/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.websem.2009.09.004

further Web content using explicit typed links, in addition to geographic coordinates. For instance, a location could be linked to its encompassing locations in an administrative hierarchy (such as region, state, country), as well as to persons who were born, died or worked there. Semantic Web clients may then navigate across these explicit links to retrieve data describing the interlinked entities.

This article aims to show the advantages of a Linked Data approach to geospatial browsing, and to demonstrate the current state of the Geospatial Semantic Web. The Geospatial Semantic Web is described in Section 2. Section 3 introduces DBpedia Mobile, a location-aware Semantic Web client for mobile devices. Section 4 discusses related work.

2. The Geospatial Semantic Web

The World Wide Web contains a wealth of geospatially referenced information. Content is attached with geo-coordinates, which allows it to be arranged by geographic location. However, semantic links between locations are generally not provided, and data is generally not linked across different data sources.

The Geospatial Semantic Web makes locations first-class citizens of the Web by representing them as original Web resources that are addressable using URIs. These Web resources can represent single points of interest as well as areas such as administrative divisions, regions, or countries. The resources may then be described in an open and distributed manner using RDF.

This approach allows locations to be related to each other using explicit semantic relationships in addition to simple geo-coordinates. An example of such a relationship type is the GeoNames[7] `geoNames:parent-Feature` relation, which may be used to identify administrative hierarchies such as town, region and country, and thus permits to refer to resources at different levels of abstraction. For instance, this makes queries such as “all hotels in a region” easier to process than with an approach that relies only on geo-coordinates and would have to take complex regional boundaries into consideration. A second example is the `factbook:landboundary` relationship used by the Linked Data version of the CIA Factbook[8] to identify adjacent countries.

Besides relating locations to each other, the Geospatial Semantic Web also allows other types of Web resources to be related to locations. For instance, people or organizations are related to locations using the `foaf:based_near` relationship type; photos using `foaf:depiction`; web sites using `foaf:homepage`; and reviews using `rev:hasReview`.

These relationships may span Web data sources and thus function as data links connecting the sources. For instance, a data source providing information about a town may state that another data source also provides information about the same town using the `owl:sameAs` relationship type. This data source may in turn state that a third data source provides pictures or videos depicting the town and that further data sources provide listings of companies that are located in the town. By being connected through data links, all data that is published according to the Linked Data principles becomes part of a single global data space [13].

Client applications can access this data space by dereferencing URIs over the HTTP protocol into RDF descriptions [10]. The retrieved descriptions may in turn contain data links pointing at resources served by other data sources. By dereferencing the URIs identifying these resources, clients can navigate between data sources [7]. Just as the traditional document Web can be crawled by following hypertext links, the Semantic Web can be crawled by following data links. Applications that work on the crawled data can provide sophisticated query capabilities, similar to those provided by conventional relational databases [20,37].

2.1. The Linking Open Data project

A practical testbed for geospatial integration using Semantic Web technologies is the W3C Linking Open Data community project.[9] The project aims to extend the Web with a data commons by publishing various open-license data sets as RDF on the Web and by setting data links between data items from different data sources [12].

As of October 2009, the resulting data space contains around 7.7 billion RDF triples (see footnote 9) describing millions of resources, including many physical locations. Data sets are often interlinked using the predicate `owl:sameAs` to indicate that two items from distinct data sets refer to the same real-world entity. Fig. 1 shows data sources that provide location information with a shaded background and illustrates their linkage relationships to other data sources. In the following, we describe these data sources in more detail.

- *DBpedia*: The DBpedia data set has been extracted from Wikipedia [14]. For currently more than 2.6 million“things”, it features labels and short abstracts in 30 different languages, 609,000 links to images and 3,150,000 links to external web pages. The DBpedia data set contains information about more than 320,000 locations. Altogether there are around 4,900,000 data links pointing from DBpedia into other Linked Data sources. Of these links, 300,000 connect locations in DBpedia with locations in Freebase, 300,000 links point at photo collections generated by the flickr ™ wrappr, 85,000 links point at data about locations provided by GeoNames, 200 links connect data about countries between DBpedia and the CIA World Factbook, and 200 links point from DBpedia to statistical data about European regions provided by EuroStat. Within DBpedia, locations are frequently interlinked with other resources using properties such as `dbpedia-owl:location`, `dbpedia-owl:city` and `dbpedia-owl:country`, which relate a resource to a location, city or country, or `dbpedia-owl:capital`, which relates a country or region to its capital city.
- *GeoNames*: The GeoNames geographical database provides data such as names in different languages, feature type and geo-coordinates for over 8 million places. The predicate `geoNames:parentFeature` is used to link to a resource's parent within GeoNames, resulting in a feature hierarchy that maps administrative subdivisions of a country (states, districts, counties, etc.), and links countries to a continent, which are linked to a single *Earth* resource. The Linked Data interface further provides pointers to retrieve a resource's children features, nearby features, and for countries, neighboring countries. GeoNames contains 85,000 cross-dataset links pointing at DBpedia.
- *US Census Data*: The RDF version of the US Census data[10] comprises population statistics at various geographic levels, on the order of 1 billion RDF triples. A feature hierarchy links the United States to its states, districts and counties. Many locations are geographically referenced.
- *Freebase*: Freebase[11] is an online database which users can edit in a similar fashion as they edit Wikipedia articles today. Freebase currently contains data about 874,000 locations which is served as Linked Data on the Web.

[7] http://www.geonames.org/.
[8] http://www4.wiwiss.fu-berlin.de/factbook/.
[9] http://esw.w3.org/topic/SweoIG/TaskForces/CommunityProjects/LinkingOpenData.
[10] http://www.rdfabout.com/demo/census/.
[11] http://www.freebase.com/.

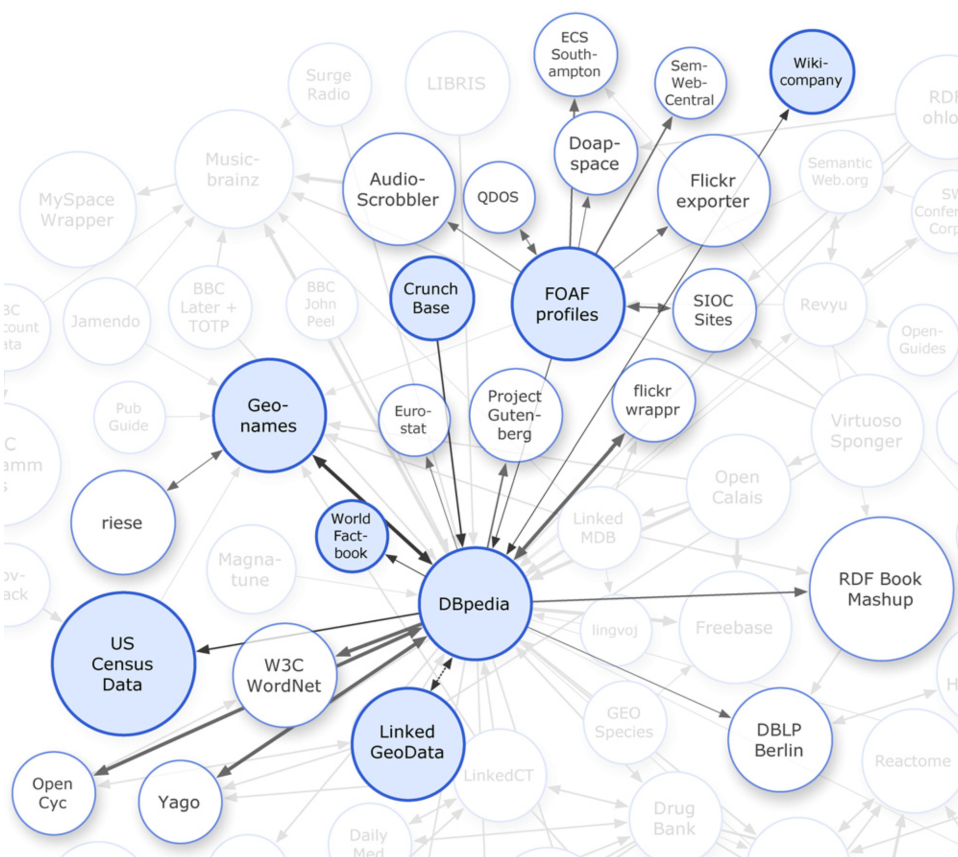

Fig. 1. Data sets that provide geospatial entry points within the Linking Open Data cloud and the data sets they directly link to, as of 04/2009 (adapted from [13]).

- *LinkedGeoData*: The LinkedGeoData project [4] publishes geo data collected by the OpenStreetMap[12] project as Linked Data on the Web. Its data structure is composed of individual *nodes* that represent individual points, and *ways* that form collections of nodes, such as roads and rivers. The Linked Data output indicates nearby features.
- *flickr ™ wrappr*: The flickr ™ wrappr[13] provides image collections depicting locations. The images are interlinked with DBpedia using the `foaf:depiction` relationship type.
- *YAGO*: The YAGO data set [35] provides type information for locations such as museums, train stations or monuments. Locations are interlinked with DBpedia.
- *CrunchBase*: Semantic CrunchBase[14] is a Linked Data interface to CrunchBase, a free directory of technology companies, people, and investors. It provides geographical coordinates for company locations. Companies are linked to their DBpedia equivalents.
- *Wikicompany*: Wikicompany[15] is a free content licensed, worldwide business directory that anyone can edit. Like Wikipedia, it allows the specification of geographical coordinates that are translated to RDF. Wikicompany entries are interlinked with DBpedia.
- *EuroStat*: EuroStat collects statistical information about the European Union. A subset of the EuroStat data about European regions is served as Linked Data by Freie Universität Berlin.[16]
- *Revyu*: The Revyu rating website [21] collects user reviews about anything, including locations. Reviews are interlinked with the corresponding DBpedia entities.
- *FOAF profiles*: The Friend of a Friend project [17] facilitates machine-readable Web homepages for people, groups and companies. FOAF profiles often include location information in the form of geographical coordinates. Other profiles use DBpedia URIs to express the location where the profile owner lives, works or was born.

2.2. Geo-coordinates and data links

Web resources that are tagged with geo-coordinates and connected to other data sources via data links can be used as entry points into the Geospatial Semantic Web. By correlating a geographic position with those of geo-tagged resources within linked data sets, nearby resources can be found. By following data links from these resources into other data sets, additional information about a location can be discovered. This allows to better understand a given resource's context, for example by determining its type using YAGO, or its parent element using GeoNames. In Fig. 1, data sets that are directly reachable from data sets that provide geo-coordinates are shown with a white background.

In a mobile scenario, this process can be applied to infer the current context based on the user's geographical coordinates. Fig. 2 illustrates this approach by correlating a user's current position with the closest DBpedia resource in the user's proximity, in this case the resource *http://dbpedia.org/resource/Brandenburg_Gate*.

When this identifier is dereferenced, DBpedia provides labels such as "Brandenburger Tor" (German) and "Porte de Brandebourg" (French) expressed using `rdfs:label` statements, and types such

[12] http://www.openstreetmap.org/.
[13] http://www4.wiwiss.fu-berlin.de/flickrwrappr/.
[14] http://cb.semsol.org/.
[15] http://wikicompany.org/.
[16] http://www4.wiwiss.fu-berlin.de/eurostat/.

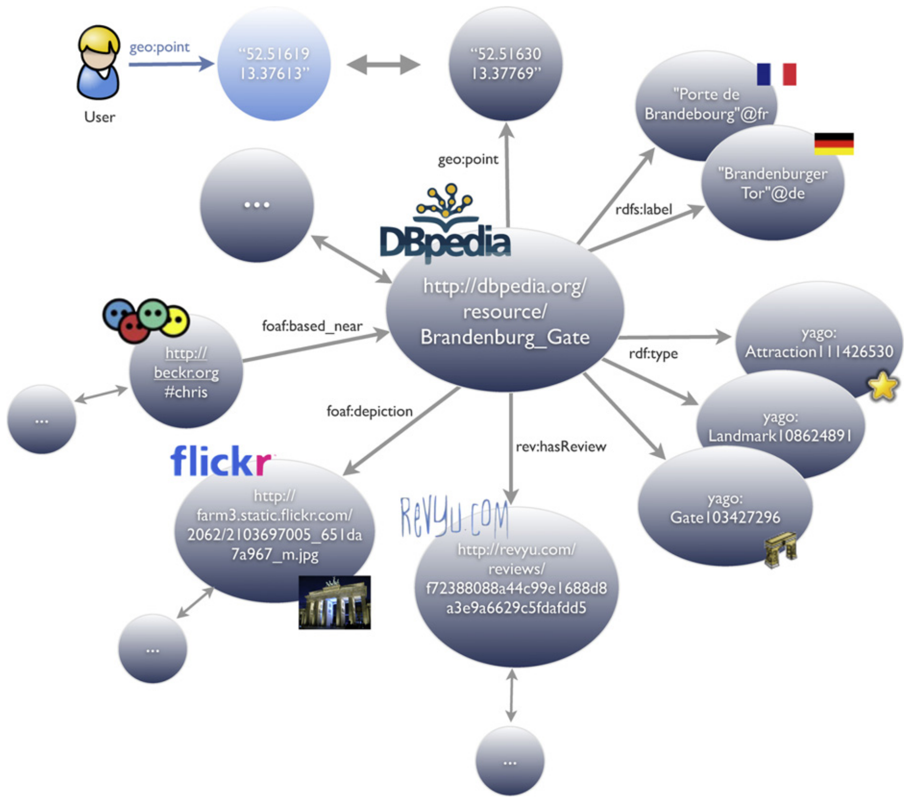

Fig. 2. A DBpedia resource in the user's vicinity serves as an entry point into the Geospatial Semantic Web.

as `yago:Attraction111426530`, `yago:Building102913152`, `yago:Gate103427296` and `yago:Landmark108624891` indicated using `rdf:type` statements. Besides inferring context, type information can also be used to find an appropriate icon to depict the resource on a map, as illustrated by the included icons. It also allows for the filtering of locations according to their type, which is especially important on mobile devices with limited screen space in order to prevent maps from overpopulating.

By following links included in DBpedia data and issuing the URI to Semantic Web search engines such as Sindice [37] and Falcons [20], additional information can be obtained. In this case, Revyu lists a review for an identical resource, the flickr ™ wrappr provides a depiction from Flickr, and a person indicates that he is `foaf:based_near` the resource in his personal FOAF profile. The aforementioned review, photo and person are themselves resources that may feature further relations, as is indicated by the "..." bubbles.

3. DBpedia Mobile

DBpedia Mobile [17] is a location-aware client for the Semantic Web. It allows users to discover, search and publish Linked Data pertaining to their current physical environment using an iPhone and other mobile devices, as well as standard web browsers. The application consists of a map view and a Fresnel-based [31] Linked Data browser. Starting from this map, users can explore background information about their surroundings by navigating along data links into other Web data sources. Besides accessing Web data, DBpedia Mobile also enables users to publish their current location, pictures and reviews to the Semantic Web. Instead of simply being tagged with geographical coordinates, published data is interlinked with a nearby DBpedia location.

3.1. Browsing the Geospatial Semantic Web

DBpedia Mobile's initial view is a map display that indicates the user's position and nearby DBpedia resources, using appropriate labels and icons. Fig. 3 shows DBpedia Mobile's initial view on an iPhone. The map can be moved by dragging it on the touch screen. It can be zoomed using a pinch gesture or the provided controls.

Locations are depicted with adequate icons based on a mapping of selected YAGO categories. DBpedia Mobile allows users to switch between 14 languages to be used for labels and summary texts (English, German, French, Dutch, Polish, Italian, Spanish, Japanese, Portuguese, Swedish and Chinese).

Clicking on a resource brings up a *summary view* of the selected item. A summary view includes a short text describing the resource and optionally an image, which is often provided by DBpedia or the flickr ™ wrappr; a link to the resource's `foaf:homepage` as well as reviews of the resource from Revyu. It also shows persons who have indicated that they are `foaf:based_near` the resource in their FOAF profile or using DBpedia Mobile. At the bottom of the page, links are provided to access a *photo view* and a *full view* for the resource.

Fig. 4 shows a *summary view* for the *Brandenburg Gate* which includes a review obtained from Revyu as well as a photo obtained from the flickr ™ wrappr, and lists nearby DBpedia Mobile users. Specific site icons (such as a blue star for Revyu) are used to indicate the provenance of displayed data.

The *photo view* displays further depictions of the resource, obtained from DBpedia and the flickr ™ wrappr.

The *full view* displays all known properties of the resource. Fig. 5 shows a full view of the Brandenburg Gate's district *Tiergarten*, which incorporates Linked Data from GeoNames, the flickr™

[17] http://beckr.org/DBpediaMobile.

Fig. 3. DBpedia Mobile running on an iPhone 3G and showing a map view of resources in the user's proximity.

Fig. 4. A *summary view* of the *Brandenburg Gate* that includes a review obtained from Revyu as well as an abstract text and a photo obtained from DBpedia, and lists a nearby DBpedia Mobile user.

wrappr and DBpedia. If the displayed data contains RDF links into other data sets, the user may click them to obtain a full view of the referenced resource. In this manner, he can navigate from the DBpedia data set into other interlinked data sources. DBpedia Mobile is not limited to a fixed set of data sources but may be used to access

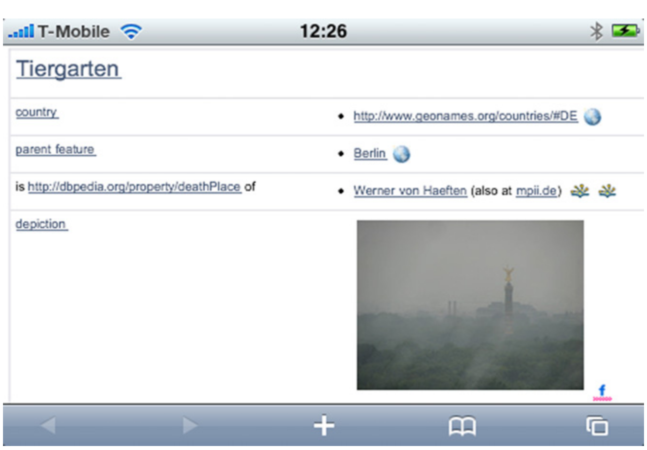

Fig. 5. A *full view* of the Brandenburg Gate's district *Tiergarten*, which incorporates Linked Data from GeoNames, the flickr ™ wrappr and DBpedia. From here, the user may navigate into other interlinked data sets.

all data sources that are or will in the future be interlinked with DBpedia or with other data sources that are reachable from DBpedia. This allows interesting navigation paths: For instance, a user may navigate into GeoNames and traverse its `parentFeature` hierarchy to find out more about the city, state and country in which a resource is located. From a location, he may navigate to a person within the DBpedia data set who was born, died or worked at the location. If the person is an author, he may then follow data links into the RDF Book Mashup [11] or the Project Gutenberg data sources and explore information about the author's books.[18] If a tourist is interested in local bands, he may navigate from DBpedia into Musicbrainz and find out more about albums of the bands.

DBpedia Mobile generates the different views using Fresnel lenses and formats on the server side. Prior to rendering a view for a resource, DBpedia Mobile performs data augmentation, whereby it retrieves interlinked data from the Web and caches retrieved data in a server-side RDF store. This involves dereferencing the resource URI and querying the Sindice and Falcons Semantic Web search engines for related information, as well as Revyu for reviews. In a similar manner as the Semantic Web Client Library,[19] specific predicates found in retrieved data such as `owl:sameAs` and `rdfs:seeAlso` are then followed for up to two levels in order to gain more information about the resource, and to obtain human-friendly resource labels. Because of this approach, there is no inherent restriction on which data sources are discovered. In fact, anyone may make statements about a DBpedia resource, and once this data link has been picked up by a Semantic Web search engine, it will be found by DBpedia Mobile and integrated into its output.

The map view is plotted based on resource coordinates expressed using the `geo:point` predicate of the W3C Geospatial Vocabulary [28]. As with the displayed data, coordinates may stem from arbitrary data sources. The W3C Geospatial Vocabulary was chosen over the more established Basic Geo (WGS84 lat/long) Vocabulary [16] because it provided for atomic storage of latitude and longitude components.

Retrieved data is stored in individual Named Graphs [18] which are identified by the URI from which the data was retrieved. A separate metadata store tracks the date of the last request as well

[18] For example, this works for the navigation paths *Bedford* → *John Bunyan* and then to his publications on Project Gutenberg, or *University of Southampton* → *Tim Berners-Lee* and then to his publications on DBLP.

[19] http://sites.wiwiss.fu-berlin.de/suhl/bizer/ng4j/semwebclient/.

as caching-related response headers for every URL, which indicate the caching recommendations of the data source. Based on this information, the application determines whether a required URL should be re-requested from its source, or whether the cached version is sufficient. Cached data is persisted across user sessions.

Different data sources may contain statements about the same resource, but may each use their own URIs to identify the resource. In order to incorporate statements that pertain to URI Aliases, an `owl:sameAs` inferencer is employed for the resource of interest before a view is rendered.

3.2. Filtering information

The user may filter the map for resources that match specific constraints. A Filter Builder supports the creation of *Simple* and *SPARQL Filters*: *Simple Filters* consist of one or multiple conditions that are applied in conjunction. Conditions can pertain to *resource types*, *ratings* that are associated with resources, and for demonstration purposes, the *population* of inhabited areas and the *number of levels* of buildings. Resource types may be chosen from pre-defined sets that encompass one or more YAGO categories, such as *Museums* or *Train Stations*, whereas ratings and numeric conditions are specified using an operator drop-drown and an associated operand input field. In Fig. 6, the Simple Filter Builder interface is used to limit the display to resources of type *Sightseeing* which have received a rating of at least three stars.

A server-side Query Service rewrites the Simple Filter into a SPARQL CONSTRUCT query [32]. If the checkbox *Limit to map view* is checked, a custom SPARQL `FILTER` condition will be included in order to limit results to the currently visible map area using a custom SPARQL extension function that accepts bounding box coordinates. Otherwise, the map view will be adjusted to show all returned results.

SPARQL Filters are SPARQL CONSTRUCT queries which are evaluated against the RDF store. The resulting RDF graph is then used to generate the map display. For example, the filter "Stations of Berlin's U7 train line" restricts the display to resources that have DBpedia infobox properties `system` and `line` with the values "BVG", Berlin's transportation company, and "U7", respectively. Fig. 7 shows the resulting map display.

Sample queries may be loaded from a drop-down menu. Users who are logged into the application may also contribute new queries, which then become available to all users of the application. Due to the lack of display space and comfortable editing capabilities on mobile phones, SPARQL Queries may only be created and edited on personal computers. However, they may be applied on both mobiles and PCs.

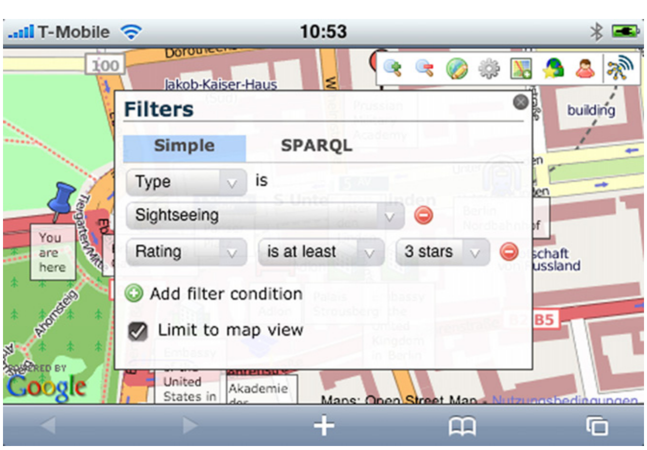

Fig. 6. The simple filter builder interface.

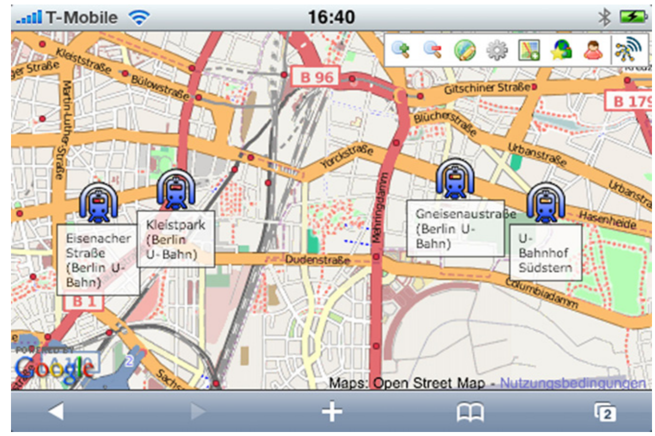

Fig. 7. Specific train lines plotted using the filter "Stations of Berlin's U7 train line".

3.3. Area-based crawling of Linked Data

DBpedia Mobile's RDF store initially includes only those DBpedia data sets that are required to generate the map display, i.e. geo-coordinates, labels and YAGO classes. To build filters that involve data from other sources, a user may request the currently visible area to be crawled using a crawling button.

The crawling process determines all DBpedia resources in the area and then queries DBpedia, Sindice and Falcons for the URIs of related resources. These URIs are then dereferenced, and links found in the data are followed as described in Section 3.1. Retrieved data is loaded into DBpedia Mobile's RDF store, where it can be used for filtering and display.

3.4. Publishing Linked Data to the Semantic Web

DBpedia Mobile facilitates the publication of content with attached location information to the Semantic Web, directly from the mobile device. A user may publish his current location as well as photos and reviews, interlinked with DBpedia resources.

When users sign up for a DBpedia Mobile account, they are provided with a *personal resource URI* in the form *http://beckr.org/DBpediaMobile/users/username*, which is associated with all content created by the respective user. When this URI is dereferenced, the client is forwarded to the associated *User Graph* which is located at *http://beckr.org/DBpediaMobile/graphs/username* using HTTP *303 See Other* redirection [10]. The User Graph contains the user's current location as well as the photos taken by him.

DBpedia Mobile wraps the triple generation process in user interface dialogs, which dramatically reduces the technical expertise required to publish content. To publish content, the user logs in and opens the Content Creation Panel (depicted in Fig. 8). He then selects the type of information to publish (i.e. position, photo or review) and chooses a DBpedia location to be used to tag the published content. Based on his location, the nearest DBpedia resource is automatically suggested, as shown in Fig. 9.

A location update is automatically reflected in his User Graph as a triple stating that he is `foaf:based_near` the selected resource. In the case of a photo, he is prompted to upload the image, which is then stored on the server and is published in his User Graph as a `foaf:depiction` of the selected resource. If the user chose to publish a review, he is presented with a review form which will be directly submitted to Revyu. The form is pre-populated with the DBpedia resource URI of the selected resource, which allows Revyu to establish equality between the reviewed resource in its own namespace and DBpedia using an `owl:sameAs` link.

Fig. 8. The content creation panel.

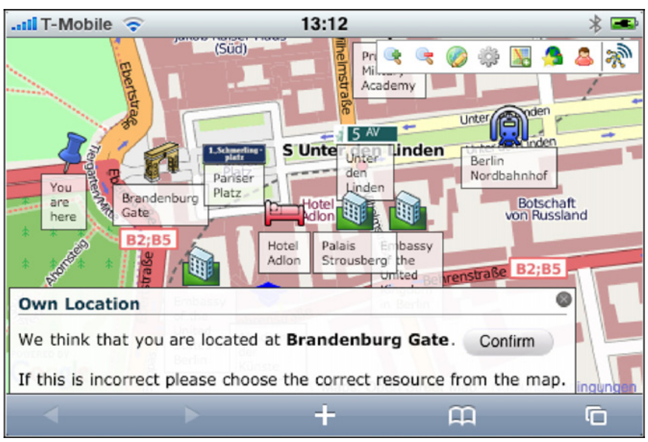

Fig. 9. The nearest DBpedia resource is suggested based on the user's position.

User-contributed content is immediately available to other users of DBpedia Mobile, as updates to the User Graph are automatically loaded into the RDF store. Reviews hosted on Revyu become available for display and filtering when the resource is browsed or the area is crawled.

A user may wish to interlink the location updates and photos he publishes using DBpedia Mobile with his FOAF profile. To do so, he states that the resource URI he uses to refer to himself in his FOAF profile is identical (`owl:sameAs`) to his personal resource URI with DBpedia Mobile. This enables Semantic Web crawlers and Linked Data browsers to find and merge information from both sources.

3.5. Technical background

DBpedia Mobile is realized as a client–server application. Queries, data retrieval and storage, as well as formatting activities are performed by the server-side Marbles engine,[20] which was developed in conjunction. This provides the application with high bandwidth, processing and storage resources and allows search requests as well as the Fresnel-based view generation to touch on large amounts of data. A small set of PHP scripts provide query rewriting, login and user graph services.

The client application is written in JavaScript and can be accessed with web browsers that feature adequate Document Object Model (DOM) support to host the underlying Google Maps API, such as Safari on the iPhone or Opera Mobile 8 on Windows Mobile, and all major desktop browsers. DBpedia Mobile may be initialized with the user's GPS position using a supplemental launcher application, or via the Yahoo! FireEagle[21] web service. Alternatively, the user's position may be estimated based on his IP address location.

Marbles is implemented as a Java Servlet and uses the Sesame RDF framework.[22] The triple storage is realized in conjunction with a MySQL database, whereby Sesame's RDBMS storage capabilities were enhanced to support inference, as well as storage and filtering of geospatial points using MySQL Spatial Extensions.[23] The filtering of geospatial points is realized through a custom SPARQL extension function that allows to test point values for their location within a bounding rectangle. The SIMILE Fresnel Engine[24] and the Saxon XSLT processor[25] are used for the generation of resource views. The JavaScript client and the PHP scripts interface with Marbles via its SPARQL endpoint and a lightweight API[26] that allows to obtain XHTML views and to selectively populate and update the cache for specific URIs or URLs.

Marbles has three RDF stores. The *cache* store holds data retrieved from the Semantic Web. Using Named Graphs [18], retrieved data is stored in a graph that is named after its origin URL. The cache store is pre-populated with DBpedia data sets, which are stored under designated read-only graphs. A separate *metadata store* caches request time and HTTP response headers, and an *ontology store* is used to provide human-readable labels for common ontologies in the XHTML views.

Marbles may also be used outside of DBpedia Mobile as a generic Linked Data browser. For instance, it is suitable for the display of FOAF profiles. Fig. 10 shows the FOAF profile of Tim Berners-Lee viewed using Marbles. Colored dots allow to identify facts that are mentioned in several data sources, such as his name. Furthermore, an URI Alias at *http://www4.wiwiss.fu-berlin.de* is indicated.

4. Related work

4.1. Semantic Web Browsers

Several Semantic Web browsers support the plotting of geographical coordinates in map views. Examples include Tabulator [7,8], Piggy Bank [23] and the OpenLink Data Explorer.[27] Compared to these systems, DBpedia Mobile especially targets mobile devices by having an user interface that is optimized for limited screen space.

Both Tabulator and DBpedia Mobile support the publication of Linked Data by users. Specifically, Tabulator creates graphs that anyone may edit [8], while DBpedia Mobile assigns each user an individual RDF graph that only he can update and which is Web-accessible via the URI *http://beckr.org/DBpediaMobile/graphs/username*.

A related work in the area of city exploration is mSpace Mobile [38], a faceted RDF browser for local information. Our work mainly differs in that it provides resource-centric views of a single global data space, while mSpace Mobile follows a dataset-centric approach where a priori configured data sets are browsed in their individual dimensions.

[20] http://marbles.sourceforge.net/.

[21] http://fireeagle.yahoo.net/.
[22] http://www.openrdf.org/.
[23] http://dev.mysql.com/doc/refman/5.1/en/spatial-extensions.html.
[24] http://simile.mit.edu/wiki/Fresnel.
[25] http://saxon.sourceforge.net/.
[26] http://marbles.sourceforge.net/#services.
[27] http://demo.openlinksw.com/rdfbrowser2/.

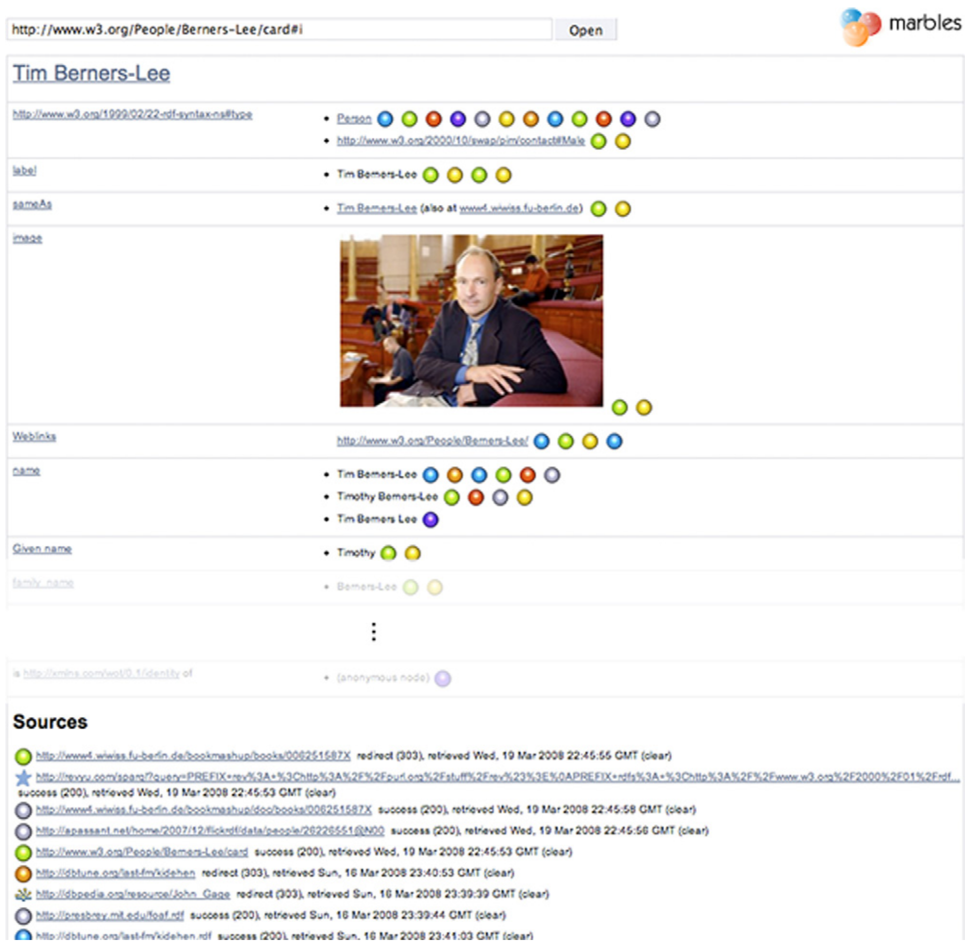

Fig. 10. A full view of a FOAF profile rendered by Marbles, containing data from a multitude of sources. Colored dots are used to indicate source origins for duplicate facts.

4.2. Geospatial Mashups

Google Maps was one of the first mapping services to provide an API, allowing developers to build custom map displays that combine data from different data sources. Google Maps' own overlay layers, such as the Wikipedia layer, can be considered a mashup as well. In any case, current geospatial mashups are built against a fixed, limited set of data sources. Conversely, DBpedia Mobile is able to browse content from arbitrary sources and to discover new data sources at run-time by following data links. In addition, DBpedia Mobile actively queries Semantic Web search engines to discover further content from other data sources. Its use of semantic links means that more meaningful relations between locations can be supported than simple geographic proximity based on geographical coordinates.

4.3. Geospatial Semantic Web

The idea of a Geospatial Semantic Web was first introduced in [19], whose contributions included generic requirements for a geospatial query syntax. Our SPARQL-based filter mechanism can be seen as a realization of such a query language. [15] and [26] discuss current standardization and organizational efforts for a Geospatial Web infrastructure that is based on an integrated, discoverable collection of geographically related Web services and data that spans multiple jurisdictions and geographic regions. Contrarily, our work is based on already openly available, interlinked RDF data.

The Geospatial Semantic Web was a topic of the Terra Cognita 2006 workshop[28] at the International Semantic Web Conference 2006, the W3C Ubiquitous Web Workshop[29] and the First and Second International Conference on Geospatial Semantics.[30] The research field is largely dedicated to ontology design and reconciliation (e.g. [2,22,25,30]) and the use of Semantic Web Services for geospatial data integration (e.g. [3,29,34,36]).

Semantic Web and Geographic Information System communities have recognized the complementary relation of their work: The Open Geospatial Consortium, Inc. (OGC),[31] a GIS industry consortium, has performed a Geospatial Semantic Web Interoperability Experiment that sought to "address several important steps towards the development of a Geospatial Semantic Web (GSW), where discovery, query, and consumption of geospatial content are based on formal semantic specification" [27]. The difference to our work can be seen in that the experiment aimed at introducing Semantic Web standards to existing GIS systems with limited public access, while our work is based on the idea of the Semantic Web being an open, decentralized data space.

Conversely, the W3C Geospatial Incubator Group built upon work by the OGC in the course of developing the W3C Geospatial Vocabulary [28].

[28] http://www.ordnancesurvey.co.uk/oswebsite/partnerships/research/research/terracognita.html.
[29] http://www.w3.org/2006/02/ubiwebws-agenda.html.
[30] http://geosco.org/.
[31] http://www.opengeospatial.org/.

5. Conclusions

This article gave an overview of the Geospatial Semantic Web and described the geo-related data sets that have been published and interlinked in the context of the W3C Linking Open Data community effort. Afterwards, we introduced DBpedia Mobile, an application that allows users to discover, search and publish Linked Data on the Semantic Web using mobile devices. The application is not restricted to a fixed set of data sources but may retrieve and display data from arbitrary Linked Data sources. This enables DBpedia Mobile to be employed within unforeseen use cases. Realized and proposed use cases include tourism,[32] nearby events[33] and personal recommendations.[34] DBpedia Mobile publishes user-generated content to the Semantic Web and interlinks it with nearby DBpedia resources. This advances "geo-tagging" to "resource-tagging" and allows users to contribute to the overall richness of the Geospatial Semantic Web.

More information about DBpedia Mobile is available at http://wiki.dbpedia.org/DBpediaMobile.

References

[1] B. Adida, M. Birbeck, S. McCarron, S. Pemberton (Eds.), RDFa in XHTML: Syntax and Processing—W3C Recommendation. URL: http://www.w3.org/TR/rdfa-syntax/, W3C, 2008.
[2] P. Agarwal, Y.V. Huang, V. Dimitrova, Formal approach to reconciliation of individual ontologies for personalisation of Geospatial Semantic Web, in: Proceedings of the First International Conference on GeoSpatial Semantics (GeoS 2005), Springer, 2005, pp. 195–210.
[3] A. Alam, G. Subbiah, L. Khan, B. Thuraisingham, DAGIS: A Geospatial Semantic Web services discovery and selection framework, in: Proceedings of the Second International Conference on GeoSpatial Semantics (GeoS 2007), Springer, 2007, pp. 268–277.
[4] S. Auer, J. Lehmann, S. Hellmann, LinkedGeoData – Adding a Spatial Dimension to the Web of Data. To appear in: Proceedings of the 8th International Semantic Web Conference, 2009.
[5] D. Beckett (Ed.), RDF/XML Syntax Specification (Revised)—W3C Recommendation. URL: http://www.w3.org/TR/rdf-syntax-grammar/, W3C, 2004.
[6] T. Berners-Lee, Linked Data, http://www.w3.org/DesignIssues/LinkedData.html, 2009.
[7] T. Berners-Lee, Y. Chen, L. Chilton, D. Connolly, R. Dhanaraj, J. Hollenbach, A. Lerer, D. Sheets, Tabulator: exploring and analyzing linked data on the Semantic Web, in: Proceedings of the 3rd International Semantic Web User Interaction Workshop, 2006. URL: http://swui.semanticweb.org/swui06/papers/Berners-Lee/Berners-Lee.pdf.
[8] T. Berners-Lee, J. Hollenbach, K. Lu, J. Presbrey, E. Prud'ommeaux, M. Schraefel, Tabulator redux: browsing and writing linked data, in: Proceedings of the 1st Workshop about Linked Data on the Web (LDOW 2008), April 2008. URL: http://events.linkeddata.org/ldow2008/papers/11-berners-lee-hollenbach-tabulator-redux.pdf.
[9] D. Berrueta, J. Phipps (Eds.), Best Practice Recipes for Publishing RDF Vocabularies—W3C Working Group Note. URL: http://www.w3.org/TR/swbp-vocab-pub/, W3C, 2008.
[10] C. Bizer, R. Cyganiak, How to Publish Linked Data on the Web, http://sites.wiwiss.fu-berlin.de/suhl/bizer/pub/LinkedDataTutorial/, 2007.
[11] C. Bizer, R. Cyganiak, T. Gauß, The RDF book Mashup: from Web APIs to a Web of data, in: Proceedings of the 3rd Workshop on Scripting for the Semantic Web (SFSW2007), Innsbruck, Austria, May 2007. URL: http://sunsite.informatik.rwth-aachen.de/Publications/CEUR-WS/Vol-248/paper4.pdf.
[12] C. Bizer, T. Heath, D. Ayers, Y. Raimond, Interlinking Open Data on the Web, in: Poster at the 4th European Semantic Web Conference (ESWC2007), Innsbruck, Austria, June 2007. URL: http://www.eswc2007.org/pdf/demo-pdf/LinkingOpenData.pdf.
[13] C. Bizer, T. Heath, T. Berners-Lee, Linked Data—the story so far, International Journal on Semantic Web & Information Systems 5 (3) (2009) 1–22.
[14] C. Bizer, J. Lehmann, G. Kobilarov, S. Auer, C. Becker, R. Cyganiak, S. Hellmann, DBpedia—a crystallization point for the Web of data, Journal of Web Semantics 7 (3) (2009) 154–165.
[15] K. Breitman, M. Casanova, W. Truszkowski, Geospatial Semantic Web, in: Semantic Web: Concepts, Technologies and Applications, Springer, 2007, pp. 265–312.
[16] D. Brickley (Ed.): Basic Geo (WGS84 lat/long) Vocabulary. URL: http://www.w3.org/2003/01/geo/, W3C Semantic Web Interest Group, 2006.
[17] D. Brickley, L. Miller, FOAF Vocabulary Specification 0.91. URL: http://xmlns.com/foaf/spec/, 2007.
[18] J. Carroll, C. Bizer, P. Hayes, P. Stickler, Named graphs, Journal of Web Semantics 3 (4) (2005) 247–267.
[19] M.J. Egenhofer, Toward the semantic geospatial web, in: GIS 2002: Proceedings of the 10th ACM International Symposium on Advances in Geographic Information Systems, ACM Press, New York, NY, USA, 2002, pp. 1–4.
[20] H.W. Gong Cheng, W. Ge, Y. Qu. Searching Semantic Web objects based on class hierarchies, in: 1st Workshop about Linked Data on the Web (LDOW 2008), April 2008. URL: http://events.linkeddata.org/ldow2008/papers/12-cheng-ge-searching-semantic-web-objects.pdf.
[21] T. Heath, E. Motta, Revyu: linking reviews and ratings into the Web of data, Journal of Web Semantics 6 (4) (2008) 266–273.
[22] H. Hochmair, Ontology matching for spatial data retrieval from internet portals, in: Proceedings of the First International Conference on GeoSpatial Semantics (GeoS 2005), Springer, 2005, pp. 166–182.
[23] D. Huynh, S. Mazzocchi, D. Karger, Piggy bank: experience the semantic web inside your web browser, in: Proceedings of the 4th International Semantic Web Conference (ISWC2005), LNCS, vol. 3729, Springer, 2005, pp. 413–430.
[24] G. Klyne, J. Carroll (Eds.), Resource Description Framework (RDF): Concepts and Abstract Syntax—W3C Recommendation. URL: http://www.w3.org/TR/rdf-concepts/, W3C, 2004.
[25] D. Kolas, J. Hebeler, M. Dean, Geospatial Semantic Web: architecture of ontologies, in: Proceedings of the First International Conference on GeoSpatial Semantics (GeoS 2005), Springer, 2005, pp. 183–194.
[26] R. Lake, J. Farley, Infrastructure for the Geospatial Web, in: The Geospatial Web, Springer, 2007, pp. 15–26.
[27] J. Lieberman (Ed.), Geospatial Semantic Web Interoperability Experiment Report—OGC Discussion Paper. URL: http://portal.myogc.org/files/?artifact_id=15198, Open Geospatial Consortium Inc., 2006.
[28] J. Lieberman, R. Singh, C. Goad, W3C Geospatial Vocabulary—W3C Incubator Group Report. URL: http://www.w3.org/2005/Incubator/geo/XGR-geo/, W3C Geospatial Incubator Group, 2007.
[29] M. Lutz, R. Lucchi, A. Friis-Christensen, N. Ostländer, A rule-based description framework for the composition of geographic information services, in: Proceedings of the Second International Conference on GeoSpatial Semantics (GeoS 2007), Springer, 2007, pp. 114–127.
[30] H. Mizen, C. Dolbear, G. Hart, Ontology ontogeny: understanding how an ontology is created and developed, in: Proceedings of the First International Conference on GeoSpatial Semantics (GeoS 2005), Springer, 2005, pp. 15–29.
[31] E. Pietriga, C. Bizer, D. Karger, R. Lee, Fresnel: a browser-independent presentation vocabulary for RDF, in: International Semantic Web Conference (ISWC2006), LNCS, vol. 4273, Springer, 2006, pp. 158–171.
[32] E. Prud'hommeaux, A. Seaborne (Eds.), SPARQL Query Language for RDF—W3C Recommendation. URL: http://www.w3.org/TR/rdf-sparql-query/, W3C, 2008.
[33] L. Sauermann, R. Cyganiak (Eds.), Cool URIs for the Semantic Web—W3C Interest Group Note. URL: http://www.w3.org/TR/cooluris/, W3C, 2008.
[34] D. Roman, E. Klien, SWING—a semantic framework for geospatial services, in: The Geospatial Web, Springer, 2007, pp. 229–234.
[35] F. Suchanek, G. Kasneci, G. Weikum, YAGO: a core of semantic knowledge, in: WWW 2007: Proceedings of the 16th International Conference on World Wide Web, ACM, 2007, pp. 697–706.
[36] V. Tanasescu, A. Gugliotta, J. Domingue, L. Villarías, R. Davies, M. Rowlatt, M. Richardson, S. Stincic, Geospatial data integration with semantic web services: the eMerges approach, in: The Geospatial Web, Springer, 2007, pp. 247–256.
[37] G. Tummarello, R. Delbru, E. Oren, Sindice.com: weaving the Open Linked Data, in: Proceedings of the 6th International Semantic Web Conference and 2nd Asian Semantic Web Conference (ISWC/ASWC2007), LNCS, vol. 4825, Springer, 2007, pp. 552–565.
[38] M. Wilson, A. Russell, D. Smith, A. Owens, A.M. Schraefel, mSpace mobile: a mobile application for the semantic web, in: Proceedings of the End User Semantic Web Workshop at ISWC2005, Galway, Ireland, 2005.

[32] http://tomheath.com/slides/2008-09-graz-triplei.pdf.
[33] http://blog.dbtune.org/post/2008/07/30/Lastfm-events-and-DBpedia-mobile.
[34] http://apassant.net/blog/2008/04/24/social-mobile-semantic/.