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SPATIAL AND TEMPORAL RESOLUTION OF SENSOR OBSERVATIONS

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SPATIAL AND TEMPORAL RESOLUTION OF SENSOR OBSERVATIONS

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Abstract

OBSERVATION is a central notion to the field of Geographic Information Science. Monitoring phenomena (e.g. climate change, landslides, demographic movements) happening on the earth's surface, and developing models and simulations for those phenomena rely on observations. Observations can be produced by technical sensors (e.g. a satellite) or humans. RESOLUTION is an important aspect of observations underlying geographic information. The consequence of using observations at various resolutions is (potentially) different decisions, because the resolutions of the observations influence the patterns that can be detected during an analysis process. Despite the importance of the notion of resolution, and early attempts at its formalization, there is currently no theory of resolution of observations underlying geographic information. The goal and main contribution of this work is the provision of such a theory. The scope of the work is limited to the characterization of the SPATIAL and TEMPORAL resolution of single observations, and collections of observations. The use of ONTOLOGY as formal specification technique helps to produce, not only useful theoretical insights about the resolution of observations, but also computational artifacts relevant to the Sensor Web. At a theoretical level, the work suggests a receptor-based theory of resolution for single observations, and a theory of resolution for observation collections, based on the observed study area and observed study period. The consistency of both theories is tested through the use of the functional language HASKELL. The practical contribution of the work comes from the two ONTOLOGY DESIGN PATTERNS suggested and encoded using the Web Ontology Language. The use of the design patterns in conjunction with the query language SPARQL helps to retrieve observations at different resolution. All in all, the work brings up ideas that are of interest to research on data quality in Geographic Information Science, and in the Sensor Web.

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[1] The LaTeX template used to write this thesis is taken and extended from (Winterbottom, 2005). The responsibility for the views expressed remains entirely mine.

Publications

This thesis reuses ideas, fragments of text, and figures that appeared in the following publications:

- Degbelo, A. (2011). Estimating the spatial resolution of observation data in vector format. In A. Schwering & C. Kray (Eds.), Conference on Spatial Information Theory: COSIT'11 - Proceedings of the Doctoral Colloquium. Belfast, Maine, USA.
- Degbelo, A., & Stasch, C. (2011). Level of detail of observations in space and time. In M. J. Egenhofer, N. Giudice, R. Moratz, & M. Worboys (Eds.), Conference on Spatial Information Theory: COSIT'11 - Poster Session. Belfast, Maine, USA.
- Degbelo, A. (2012). An ontology design pattern for spatial data quality characterization in the semantic sensor web. In C. Henson, K. Taylor, & O. Corcho (Eds.), The 5th international workshop on Semantic Sensor Networks (pp. 103–108). Boston, Massachusetts, USA: CEUR-WS.org.
- Degbelo, A., & Kuhn, W. (2012). A conceptual analysis of resolution. In V. Bogorny & L. Namikawa (Eds.), XIII Brazilian Symposium on Geoinformatics (pp. 11–22). Campos do Jordão, Brazil.
- Degbelo, A. (2013). Modelling the spatial and temporal resolution of a sensor observation. In T. Jekel, A. Car, J. Strobl, & G. Griesebner (Eds.), GI_Forum 2013 - Creating the GISociety (pp. 71–80). Salzburg, Austria: Herbert Wichmann Verlag.

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List of Acronyms

BFO Basic Formal Ontology

DAML DARPA Agent Markup Language

DAML+OIL Combines both DAML and OIL

DOLCE Descriptive Ontology for Linguistic and Cognitive Engineering

FOOM Functional Ontology of Observation and Measurement

GFO General Formal Ontology

GIS Geographic Information System

GIScience Geographic Information Science

LINGO Graphical Language for Expressing Ontologies

OIL Ontology Inference Layer

OWL Web Ontology Language

RDF Resource Description Framework

RDFs Resource Description Framework Schema

SRF Spatial Receptive Field

SSW Semantic Sensor Web

SUMO Suggested Upper Merged Ontology

TRW Temporal Receptive Window

UML Unified Modelling Language

XML Extensible Markup Language

CHAPTER 1

Introduction

This introductory chapter presents relevant background work on the Sensor Web, sensor observation and resolution. The requirements of the theory to be developed within the thesis are introduced, and contents of subsequent chapters are outlined.

1.1 The Sensor Web

Sensors are nowadays used in a variety of disciplines [1] and there are plans of deploying them 'everywhere' for the benefit of the planet[2]. The huge amount of data resulting from the high number of sensors deployed has kindled the interest in mechanisms which turn data into insight, that is, turn data into something meaningful for the ultimate user. O'Reilly sees "sensors and the subsequent automated analysis of sensor data as the most important element of the next big technology and web-based movement" (Meersschaert, 2011). A prerequisite for an automatic analysis of sensor data is a standard for the description of sensors producing different types of data. The Sensor Web Enablement (SWE) initiative of Open Geospatial Consortium (OGC) addresses this issue. It focuses on "developing standards to enable the discovery, exchange, and processing of sensor observations, as well as the tasking of sensor systems" (Botts et al., 2007). The OGC defines the sensor web as "web accessible sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application program interfaces" (Botts et al., 2007). Corcho and García-Castro (2010) present the characteristics of Sensor Web applications (see the architecture in Figure 1.1). They are as follows :

- variability and heterogeneity of data, devices and networks (including unreliable

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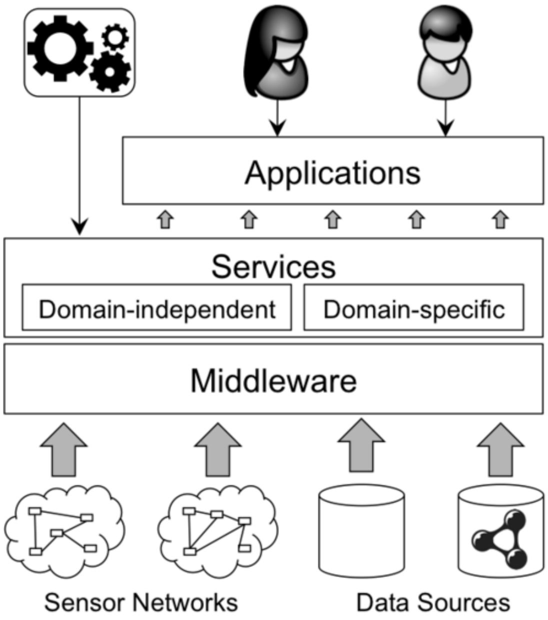
[1] See some examples of disciplines in (Sheth et al., 2008).

[2] See (MacManus, 2009; Hempel, 2010) for examples of such projects.

nodes and links, noise, uncertainty, etc.);

- use of rich data sources (sensors, images, GIS, etc.) in different settings (live, streaming, historical, and processed);
- existence of multiple administrative domains; and
- need for managing multiple, concurrent, and uncoordinated queries to sensors.

Figure 1.1: Architecture of a Sensor Web application (reprinted from [Corcho and García-Castro, 2010] with permission)



A review of the recent developments of the OGC SWE initiative was provided by Bröring et al. (2011a). As indicated by the authors, open research challenges for the OGC SWE include: (i) the improvement of interoperability; (ii) the facilitation of sensor and service integration; (iii) the advancement of sensor web eventing concepts; (iv) the realization of a Human Sensor Web; (v) the integration of the Human Sensor Web with online social networks; (vi) the assessment of the quality and uncertainty associated with the sensor outputs; and (vii) the enablement of the Semantic Sensor Web.

1.1.1 The need of semantics for the Sensor Web

Data coming from different providers can be different with respect to their syntax (i.e. file formats such as netCDF or ESRI Shapefile), their structure (i.e. different schemas[3])

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[3] An example of schema is a table in a relational database.

and their semantics (i.e. meaning associated with the terms used). Standards developed by the OGC are useful for the combination of syntactically and structurally heterogeneous data but fall short with regard to the interpretation (i.e. semantics) of the data. In that respect, Botts and Robin (2007) mention the following:

> “An important feature of the Sensor Web that has not been completely explored so far is the connections between measurement systems and their observations through semantics”.

The Sensor Web enriched with an explicit specification of the meaning of the data generated by sensors is called Semantic Sensor Web (SSW). The distinguishing feature of the SSW is that “sensor data is annotated with semantic metadata to increase interoperability as well as provide contextual information essential for situational knowledge” (Sheth et al., 2008). Table 1.1 presents some of the main technologies of the SSW and their respective purposes.

Table 1.1: Main technologies of the Semantic Sensor Web and their purposes

TECHNOLOGY	PURPOSE
OGC Standards	a common format to encode data coming from different sources
Ontologies	description of the context in which the data is produced annotation of data to answer complex queries
Rules	derive new knowledge from known instances

1.1.2 Sensor Plug and Play

> *Plug and Play, sometimes, abbreviated PnP, is a catchy phrase used to describe devices that work with a computer system as soon as they are connected. The user does not have to manually install drivers for the device or even tell the computer that a new device has been added. Instead the computer automatically recognizes the device, loads new drivers for the hardware if needed, and begins to work with the newly connected device.* (TechTerms.com, 2012)

The idea of Plug and Play for the Sensor Web was suggested in (Bröring et al., 2009, 2011b) and envisions an infrastructure where sensors can be selected, registered and their observations retrieved with *minimal human intervention*. For this vision to become reality, there is a need for mechanisms which facilitate the communication between the different components of the Sensor Web, i.e. mechanisms which make the different components of the Sensor Web semantically interoperable[4]. Semantic interoperability in turn requires a formal description of notions related to sensors and sensor outputs. The notion of 'sensor observation' (or shortly 'observation') is most important in this context. Frank (2003) asserts that "all we know about the world is based on observation". Stasch et al. (2014) point out that observations form the basis of empirical and physical sciences. Kuhn (2009a) notes that "observation is the root of information", and stresses that answering some of the deepest and most pressing questions in Geographic Information Science (GIScience), such as how to monitor change, requires progresses in the understanding of the notion of 'observation'. Adams and Janowicz (2011) indicate that the geosciences rely on observations, models, and simulations to answer complex scientific questions such as the impact of global change. Bröring et al. (2009) argue that "taking the vision of a sensor plug & play with minimal human intervention seriously [requires a modelling of] the feature of interest . . . based on the notions of observations and stimuli". The next section will review previous attempts to provide a conceptual clarification of observation.

1.2 Observation

The word 'observation', in the context of geographic information, can be used to denote both the process of observing and the outcome of this process. Observation as a process refers to "an act associated with a discrete time instant or period through which a number, term or other symbol is assigned to a phenomenon" (Percivall, 2008). Observation as a result (i.e. the outcome of the observing process) is a special case of geographic data[5] and has three components: space, time and theme. Examples of observations (as results of an observing process) are an image produced by a satellite, the value '8 decibels' returned by a mobile phone used as noise sensor to measure the level of noise at a given location, and the report 'The road before Building X is impassable' provided by a human in the aftermath of an earthquake. Throughout the current work, the terms 'sensor observation', 'sensor output', 'observation', and 'sample' are used interchangeably.

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[4] Semantic interoperability is defined here as the ability of software components to interact, despite differences in programming languages, interfaces, execution platforms, and meaning of the data they process (definition adapted and extended from [Wegner, 1996]).

[5] A map is an example of geographic data which is *not* an observation.

1.2.1 Observation vs measurement

The purpose of this subsection is to highlight the differences between the two related notions of observation and measurement. Stevens (1946) defines measurement as "the assignment of numerals to objects or events according to rules". Bittner (1999) as well as Bittner and Winter (1999) argue that measurement is a precise form of observation.

Kuhn (2009a) suggested to distinguish observation and measurement by requiring that measurements have numeric results. By doing so, the author restricted 'measurement' to quantification and used 'observation' for sensing processes with results symbolized in any form, not just numerically. Probst (2008) provided another criterion to differentiate observation and measurement, namely *communicability*. Probst states:

> "An observation process is turned into a measurement process if the observation result ... is associated with a communicable sign. We distinguish *measuring* from *observing* by requiring that a measurement process produce a communicable result, while an observation process only identifies a non-atomic quality region".

Probst's notion of observation limits itself to qualia in the observers' minds. Measurement only takes place when symbols are assigned to these qualia. The OGC (see Percivall, 2008) and Kuhn (2009a) consider the assignment of symbols as inherent in an observation process. This stand is also taken in the current work, and measurement is distinguished from observation through the type of symbol (i.e. numerical or not) resulting from the sensing process.

1.2.2 Observation ontologies

Madin et al. (2007) suggested the Extensible Observation Ontology (OBOE), an ontology which captures the process of ecological field observation and measurement. A distinguishing feature of this ontology is the consideration that "observations may have multiple measurements".

Probst et al. (2006) have analyzed the O&M[6] standard of the OGC and called for a more precise definition of central notions of the O&M model such as 'observation', 'phenomenon' and 'feature of interest'. Another analysis of O&M was done in (Probst, 2006) and a basic ontology for observations was suggested. The ontology was aligned

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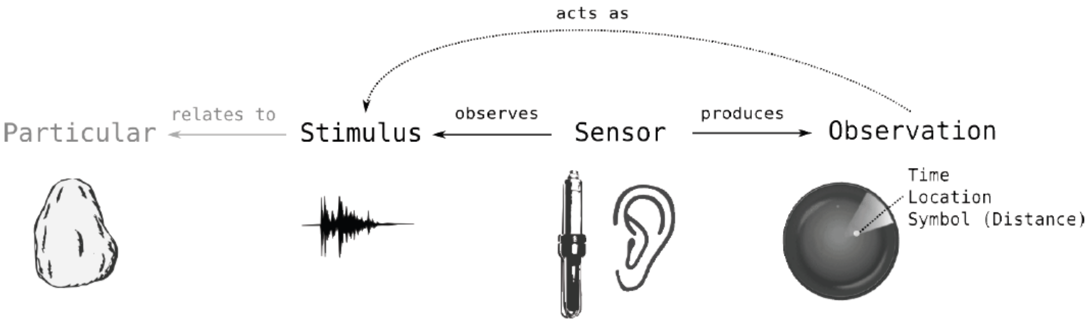
[6] O&M stands for Observations and Measurements. "The OpenGIS® Observations & Measurements (O&M) standard defines measurements and the relationships between them, mainly to improve the ability of software systems to discover and use data produced by measuring systems" (Percivall, 2008).

to the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE), a foundational ontology[7] introduced in (Gangemi et al., 2002; Masolo et al., 2003; Borgo and Masolo, 2009). Observation was identified in (Probst, 2006) as an accomplishment, i.e. something that has brought a certain state to occur. The focus of (Probst, 2006) was on the process of observing.

Another look into the process of observing was provided in (Kuhn, 2009a). His work disclosed the different entities participating in the observation process. Four entities are worth mentioning: the *particular* (i.e. entity to be observed), the *stimulus* (i.e. detectable change in the environment), the *observer or sensor* (i.e. someone or something that provides a symbol for a property of the particular) and the *observation result* (i.e. a value). The observation process is illustrated in Figure 1.2. Apropos observation as a result, Kuhn (2009a) and also Janowicz and Compton (2010); Compton et al. (2012) suggest that it is a social object[8], that is, an object that has been created in the process of social communication.

Figure 1.2: Observation process (reprinted from [Stasch et al., 2009] with permission)



1.2.3 Discussion

It was pointed out in Section 1.1.1 that standards provided by the OGC are not enough to provide interpretation (or semantics) to the data they encode. Section 1.1.2 mentioned the need for semantic interoperability if the vision of Plug and Play infrastructures for the Sensor Web is to become reality. Semantic interoperability in turn requires a formal description of concepts related to sensors and sensor outputs. Section 1.2.2 presented previous observation ontologies that are endeavors to formalize the notion

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[7] See more details on foundational ontologies in Section 3.4.1.

[8] Kuhn (2009a) states that it is an information object. An *information object* is a subclass of *social object* in the foundational ontology DOLCE Ultra Light.

of 'observation'. Some of the benefits of ontologies and semantic technologies can be found in (Hepp, 2008; Bergman, 2010; Janowicz and Hitzler, 2012).

As mentioned in Section 1.1, one of the open research challenges of the OGC SWE initiative (and consequently of the Semantic Sensor Web) is the assessment of the quality associated with sensor outputs. Bröring et al. (2011a) note:

> "Knowledge about the quality ... of sensor outputs is essential for making the right decisions based upon observations. At the moment, such information is often missing in observations and there is no unique way of how to incorporate it".

Data quality elements vary depending on the authors. For example, Chrisman (1991) mentions positional accuracy, attribute accuracy, logical consistency and completeness; Paradis and Beard (1994) include accuracy, resolution, consistency and lineage; Veregin (1998, 1999) includes accuracy, resolution, consistency and completeness; the Spatial Data Transfer Standard includes lineage, completeness, logical consistency, attribute accuracy and positional accuracy (see Goodchild and Clarke, 2002); ISO 19113 includes completeness, logical consistency, positional accuracy, temporal accuracy and attribute accuracy (see Kumi-Boateng and Yakubu, 2010).

The current work will focus on the formal specification of the resolution of sensor observations as a first step towards a solution to the problem of lack of knowledge about the quality of sensor outputs in the Sensor Web. It will limit itself to space and time. A formal account of the thematic resolution of sensor observations is left for future work. Resolution is one component of data quality as mentioned in the previous paragraph and has been identified as an important concept of spatial information (see Kuhn, 2011). The ontology developed by the W3C Semantic Sensor Network Incubator Group (see Compton et al., 2012) includes explicitly the concept 'resolution'. Degbelo and Stasch (2011) suggested a set of concepts to describe the level of detail or resolution of datasets. However both works did not tackle the *introduction of resolution* in the observation process. The current work aims at addressing this point and providing an answer to the question: *how can resolution be specified using the characteristics of the observed entity, the stimulus, and the sensor?*. The discovery of the rules governing the interplay between the resolution of the sensor observation and the characteristics of the different entities participating in the observation process will serve to set up logical inference mechanisms for the resolution of sensor observations. Inference mechanisms are in turn useful to address one of the drawbacks of adding semantic annotations to sensor nodes in sensor networks. Barnaghi et al. (2009) pointed out that adding semantics to sensor nodes in a sensor networks implies more data to be exchanged, which in turn leads to an increase of sensor nodes' power consumption. Therefore, the less the amount of semantic data to store, the better. The next section summarizes some of the previous works in GIScience dealing with the resolution of representations.

1.3 Resolution

Resolution is important to study for at least three reasons: (i) it is a critical element in determining a data set's fitness for a given use (see Goodchild and Proctor, 1997), (ii) it influences the patterns that can be observed during an analysis process (see Gibson et al., 2000), and (iii) it determines the volume of data which is generated and therefore the processing costs and storage volume (see Goodchild, 1982). Furthermore, as Goodchild and Proctor (1997); Degbelo (2011); Goodchild (2011b) indicate, resolution is necessarily present in any data collection process because the world is too complex to be studied in its full detail. Frank (2009b,c) discussed the factors from a data collection process that induce a level of detail or *resolution* in the final representation. They are as follows: (i) a sensor always measures over an extended area and time; (ii) only a finite number of observations is possible; and (iii) only a finite number of values can be used to represent an observation.

1.3.1 Related work to the thesis

This subsection touches on four topics, namely (i) the optimum resolution, (ii) the integration of multi-resolution features and multi-resolution databases, (iii) the influence of resolution on other variables, and (iv) previous formal accounts for resolution.

The optimum resolution: Lam and Quattrochi (1992) commented on the issues of scale, resolution, and fractal analysis in the mapping sciences and pointed out one important research question in this context, namely *'what is the optimum resolution for a study or does an optimum really exist?'*. On that subject, Marceau et al. (1994) proposed and tested a method to identify the optimal resolution for a study. They concluded that (i) the concept of optimal spatial resolution is relevant and meaningful for the field of remote sensing, and (ii) there is a need of selecting the appropriate resolution in any study involving the manipulation of geographical data.

Integration of multi-resolution features and multi-resolution databases: Balley et al. (2004) proposed an approach to build a unified database from source databases (i.e.

databases which contain the same feature represented at different levels of spatial and thematic detail). Du et al. (2010) suggested an approach to check directional consistency between representations of features at different resolutions. Examples of direction relations include east (of), west (of), south (of), north (of), southeast (of), southwest (of), northeast (of), northwest (of), and directional consistency is evaluated by checking whether direction relations between pairs of spatial regions at different resolutions are similar.

Influence of resolution on other variables: Gao (1997) explored the correlations between spatial resolution and root mean square error (RMSE), spatial resolution and accuracy, as well as spatial resolution and mean gradient in the context of digital elevation models (DEMs). He concluded that (1) the RMSE of a gridded DEM increases linearly with its spatial resolution from 10m to 60m, (2) the accuracy of representing a terrain with a gridded DEM decreases as the resolution decreases from 10m to 60m, and (3) resolution has a minimal impact on mean gradient. Deng et al. (2007) used correlation and regression analysis to assess the effect of DEM resolution on calculated terrain attributes such as slope, plan curvature, profile curvature, north–south slope orientation, east–west slope orientation, and topographic wetness index. Their work indicated that terrain attributes respond to resolution change in different ways. Among the different terrain attributes studied, plan and profile curvatures were found to be the most sensitive attributes, and slope was the least sensitive attribute to change in resolution[9]. The experiments reported in (Chow and Hodgson, 2009) revealed that there is a logarithmic relationship between DEM resolution and mean slope. Jantz and Goetz (2005) examined the ability of the urban land-use-change model SLEUTH (slope, land use, exclusion, urban extent, transportation, hillshade) to capture urban growth patterns across varying spatial resolutions (i.e. cell sizes). Their results suggest that the resolution of the input data impact the overall performance of an urban land-use-change model[10]. A similar conclusion was reached by Kim (2013) whose study indicated that variations in spatial and temporal resolution can generate substantial differences in the outcomes of a land-use change simulation. Pontius Jr and Cheuk (2006) have proposed a method which enables to examine the sensitivity of statistical results to changes in resolution. The method was designed to facilitate multi-resolution analysis during the comparison of maps that display a shared categorical variable. Csillag et al. (1992) have studied the impact of spatial resolution on the classification of areas into taxonomic at-

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[9] The findings are valid only for landscapes found in the Santa Monica Mountains.

[10] The authors report for example that, during their experiments, the amount of growth that could be produced through spontaneous growth at a resolution of 360m was more than five times the amount at a resolution of 45m.

tributes. 'Classification' here means that a measurement is made at a point in space, and based on the measurement value, one assigns a (predefined) class to the point at which the measurement is made. Csillag et al. (1992) used two examples during their study: (i) vegetation is sampled at given locations and classified according to species and/or associations; and (ii) soil properties are measured at given locations and soil types are assigned to the locations based on the value of the measured property. Their study led to the conclusion that there may not be a single best resolution for environmental data.

Formalisms for resolution: A formal framework for multi-resolution spatial data handling was suggested in (Stell and Worboys, 1998). The framework has five main components: *map*, *map space*, *granularity lattice*, *stratified map space*, and *sheaf of stratified map spaces*. It can be used to assess the correctness of generalization algorithms and to model the integration of geometrically and semantically heterogeneous spatial datasets. A limitation of the work presented in (Stell and Worboys, 1998) is that it only deals with datasets representing the same spatial extent at different level of details. Skogan (2001) suggested another framework to deal with multi-resolution objects and multi-resolution databases. The framework consists of four components: the *federated multi-resolution database management system*, the *resolution space*, the *multi-resolution type*, and *methods for aggregating resolution*. One limitation of the framework is that it accounts only for intra-type changes of resolution, that is changes in resolution that do not affect the geometry of the initial object[11]. Worboys (1998) dealt with multi-resolution geographic spaces and has proposed a formal account for multi-resolution geographic spaces using ideas related to fuzzy logic and rough set theory. Other formalisms for resolution, focusing on sensor observations and processes, can be found in (Frank, 2009c) and (Weiser and Frank, 2012) respectively. Frank (2009c) has suggested to model (formally) the effect of resolution on the final sensor observation using a convolution with a Gaussian kernel. Weiser and Frank (2012) proposed a formalism to represent multiple levels of detail (i.e. resolution) in discrete processes (e.g. a train ride). The last work worth mentioning in this subsection is the one of Bruegger (1995). The author suggested a theory for the integration of spatial data presenting differences in spatial resolution and representation format (i.e. raster and vector). The theory followed an object-view[12] of the world, that is, it assumed that the world is inhabited of discrete objects.

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[11] Polygons remain polygons after a generalization operation; similarly, lines remain lines and points remain points.

[12] More details on the object-view and field-view of the world can be found in (Couclelis, 1992).

1.3.2 Discussion

The formal accounts for 'resolution' presented in Section 1.3.1 are relevant to a number of research topics including geographic data handling and spatial reasoning (Stell and Worboys, 1998), the development of a fully dynamic Geographic Information System (Weiser and Frank, 2012), scale effects in information processes (Frank, 2009c), data integration (Bruegger, 1995; Stell and Worboys, 1998; Worboys, 1998; Skogan, 2001; Frank, 2009c), but they also present some limitations. Stell and Worboys (1998), Skogan (2001), Worboys (1998) and Bruegger (1995) take an object-view of the world and leave time apart. In addition, although many of the formalisms are related to the problem of data integration, none of them were implemented on actual datasets to detect inconsistencies or possibilities of merging. Bruegger (1995) acknowledged this point and commented on possible strategies of implementation of the proposed theory. Time is accounted for in the formalisms proposed in (Weiser and Frank, 2012; Frank, 2009c) but here also, the implementation on actual datasets was lacking.

1.4 Requirements of the theory to be developed

The requirements, both theoretical and practical, of the theory to be developed are the subject of this section. They are, for the most part, based on the limitations identified in Section 1.3.

From a theoretical point of view, the theory should:

R1: *remain neutral with regard to the distinction field vs object*

R2: *take into account both observation as a process and observation as a result*

R3: *explain the relationships between the characteristics of the observed entity, stimulus, sensor and the spatial and temporal resolution of the final sensor observation*

R4: *provide means to characterize the spatial and temporal resolution of collections of observations*

From a practical point of view, the theory should:

R5: *be implementable in use cases relevant for the Sensor Web*. More specifically, it should:

R5a. *support the discovery of observations at different spatial and temporal resolution*

> R5b. *be usable, both when spatial/temporal resolution is expressed quantitatively, and when spatial/temporal resolution is expressed qualitatively*[13]

The goal of the work is to provide a formal description of concepts related to the spatial and temporal resolution of sensor observations. At the theoretical level, the contribution of the work is: (i) the characterization of the spatial and temporal resolution of a single observation based solely on the physical properties of the observer participating in the observation process; (ii) the specification of the spatial and temporal resolution of a collection of observations based on the portion of the study area (or study period) that is effectively covered by the collection of observations. At the practical level, the contribution of the work is: (i) ontology modules which can be used on top of the SSN ontology from Compton et al. (2012) to characterize the resolution of observations and collections of observations; and (ii) an enhanced data discovery capability for software components in the Semantic Sensor Web. The next section presents a brief overview of the contents of subsequent chapters.

1.5 Tour of the contents

There is a variety of meanings associated with the term resolution. Chapter 2 collects some of these meanings and presents a framework to reconcile various connotations of the term. The framework consists of *definitions of resolution*, *proxy measures for resolution* and *related notions to resolution*. The chapter is a slightly modified version of (Degbelo and Kuhn, 2012).

Chapter 3 presents related work on ontologies, the 'tool' used to formalize the different concepts related to the spatial and temporal resolution of sensor observations. The ontology development method used during the work is also discussed in detail.

Chapters 4 and 5 are concerned with the design stage of the ontology development process. Chapter 4 is a revised and extended version of (Degbelo, 2013). It presents the motivating scenario for the work, and introduces a receptor-based theory for the characterization of the spatial and temporal resolution of *single* observations. Chapter 5 complements the specification of the resolution of single sensor observations with a characterization of resolution relevant to *collections of observations*. The formal specification of both fragments of theories in the functional language Haskell

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[13] Here are two equivalent ways of expressing the spatial resolution of the number of inhabitants in a given region: (a) the number of inhabitants at the **county level** is 50, and (b) the number of inhabitants over an area of '**100**km^2' is 50. In the former case, the spatial resolution is expressed qualitatively, in the latter quantitatively.

helps to test the consistency of the ideas proposed.

Chapter 6 turns the theory suggested in Chapters 4 and 5 into two ontology design patterns: one relevant to the specification of the resolution of a single observation, and one useful for the characterization of the resolution of collections of observations. These two ontology design patterns extend current work on observation ontologies (e.g. the SSN ontology from Compton et al., 2012) with concepts useful to characterize the resolution of sensor observations.

Chapter 7 demonstrates the practical usefulness of the ontology design patterns (ODPs) proposed in Chapter 6. The ODPs are encoded in the Web Ontology Language, and examples of SPARQL queries (tested on sample sets of facts from the motivating scenario) are presented. The chapter discusses also further possible applications of the ideas presented in the thesis.

Chapter 8 summarizes the findings, discusses their relevance to the field of GIScience, and comments on limitations of the work. The chapter ends with a set of additional research questions that have been raised in the course of this work[14].

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[14] A documentation of the ontology of resolution conforming to the checklist suggested in (Agarwal, 2005) is provided in Appendix F.

CHAPTER 2

Conceptual analysis of resolution

What is resolution? This question motivates the discussion presented in this chapter. The chapter looks at possible ways of defining 'resolution'[1]*, and positions the term within the landscape of related notions (e.g. scale, grain, spacing, coverage, support, pixel, accuracy, precision, discrimination). The definition of resolution adopted in this work is also introduced*[2]*.*

2.1 Introduction

The literature in GIScience has not reached a consensus on what resolution is. By way of illustration, here are some excerpts from previous work in GIScience, touching on a definition of the term:

Definition1. "Resolution: the smallest spacing between two displayed or processed elements; the smallest size of feature that can be mapped or sampled" (Burrough and McDonnell, 1998, p305).

Definition2. "Resolution refers to the amount of detail in a representation, while granularity refers to the cognitive aspects involved in selection of features" (Fonseca et al., 2002a).

Definition3. "Resolution or granularity is concerned with the level of discernibility between elements of a phenomenon that is being represented by the dataset" (Stell and Worboys, 1998).

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[1] Resolution is a polysemous word (see OxfordDictionaries.com, 2013, for various examples of meanings). The scope of the current conceptual analysis is limited to resolution, as used in geographic information science. For a discussion on the intellectual scope of GIScience, see (Mark, 2003).

[2] This chapter is an amended version of (Degbelo and Kuhn, 2012), published at GeoInfo2012.

Definition4. "The capability of making distinguishable the individual parts of an object" (a dictionary definition cited in (Tobler, 1987)).

Definition5. "Resolution refers to the smallest distinguishable parts in an object or a sequence, ... and is often determined by the capability of the instrument or the sampling interval used in a study" (Lam and Quattrochi, 1992).

Definition6. "The detail with which a map depicts the location and shape of geographic features" (a dictionary definition from (ESRI, 2012)).

Definition7. "*Resolution* is an assertion or a measure of the level of detail or the information content of an object or a database with respect to some reference frame" (Skogan, 2001).

This list shows a variety of definitions of 'resolution' and illustrates that some of them are conflicting, namely Definition2 and Definition3. The remark that resolution "seems intuitively obvious, but its technical definition and precise application ... have been complex", made by Robinson et al. (2002) during their discussion on astronaut photographs as digital remote sensing data, is pertinent to GIScience as a whole. Section 2.2 analyzes some notions closely related to resolution and arranges them based on the framework suggested in (Dungan et al., 2002). Section 2.3 suggests that resolution should be defined as the amount of detail in a representation[3], and proposes two types of proxy measures for resolution: smallest unit over which homogeneity is assumed and dispersion. Section 2.4 presents some additional comments pertaining to the conceptual analysis done in this chapter, and Section 2.5 summarizes the main ideas introduced.

2.2 Resolution and related notions

In a discussion of terms related to 'scale' in the field of ecology, Dungan et al. (2002) suggested three categories (or dimensions) to which spatial scale-related terms may be applied. The three dimensions are: (a) the phenomenon dimension, (b) the sampling dimension, and (c) the analysis dimension. The *phenomenon dimension* relates to the (spatial or temporal) unit at which a particular phenomenon operates; the *sampling dimension (or measurement dimension or observation dimension)* relates to the (spatial or temporal) units used to acquire data about the phenomenon; the *analysis dimension*

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[3] von Glasersfeld (1987) distinguishes for the English language, four principal meanings compounded in the term 'representation'. In the current work, representation denotes what von Glasersfeld has termed 'iconic representation'.

relates to the (spatial or temporal) units at which data collected about a phenomenon are summarized and used to make inferences. For instance, if one would like to study the evolution of domestic energy consumption in a city *CT*, the phenomenon of interest would be 'evolution of domestic energy consumption'. Data may be collected about the domestic energy consumption of households in *CT* every month; one month relates to the sampling dimension. The data collected may then be aggregated to yearly values which serve as a basis for trend analysis; one year refers to the analysis dimension.

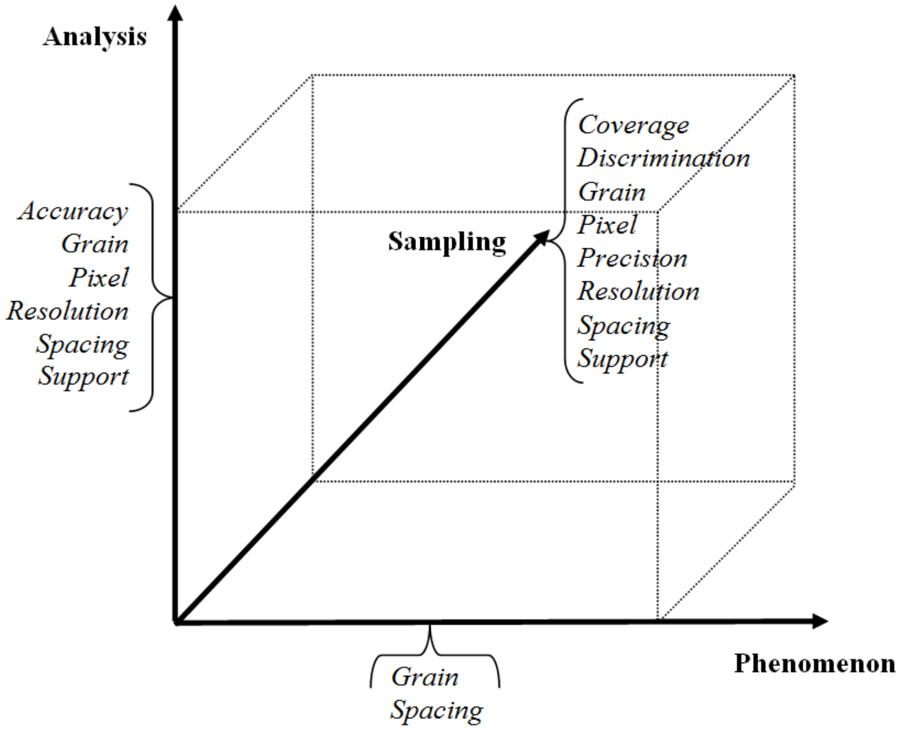
The three dimensions introduced in the previous paragraph will be used to frame the discussion on resolution and related notions. Though they were initially proposed in the field of ecology, they can be reused for the purposes of this chapter because ecology and GIScience overlap to some degree. For example:

- issues revolving around the concept of 'scale' have been identified as deserving prime attention for research by both communities (see for example (UCGIS, 1996) for GIScience, and (Wu and Hobbs, 2002) for ecology);
- both communities are interested in a 'science of scale' (see for example (Goodchild and Quattrochi, 1997) for GIScience, (Wu and Hobbs, 2002) for ecology);
- there exists overlaps in objects of studies (witness for example the research field of 'landscape ecology' introduced in (Wu, 2006, 2008, 2012), and the research field of 'ethnophysiography' presented in (Mark et al., 2007));
- there are overlaps in underlying principles (Wu (2012) mentions for example that "[s]patial heterogeneity is ubiquitous in all ecological systems" and Goodchild (2011a) proposed spatial heterogeneity as one of the empirical principles that are broadly true of all geographic information).

One notion related to 'resolution' is 'scale'. Scale can have many meanings, as discussed for example in (Lam and Quattrochi, 1992; Quattrochi, 1993; Goodchild and Proctor, 1997; Goodchild, 2001; Montello, 2001; Förstner, 2003; Goodchild, 2011b). Like in (Dungan et al., 2002), resolution is seen as *one of many components of scale*, with other components being extent, grain, lag, support and cartographic ratio. Dungan et al. (2002) have discussed the matching up of resolution, grain, lag and support with the three dimensions of phenomenon, sampling and analysis. The next paragraph briefly summarizes their discussion. After that, another paragraph will introduce the notions of discrimination, coverage, precision, accuracy, and pixel.

According to Dungan et al. (2002), grain is a term that can be defined for the phenomenon, sampling and analysis dimensions. Sampling grain refers to the minimum spatial or temporal unit over which homogeneity is assumed for a sample[4]. Another term that applies to the three dimensions according to Dungan et al. (2002) is the term lag or spacing[5]. Sampling spacing refers to the distance between neighboring samples. Dungan et al. (2002) presented resolution as a term which applies to sampling and analysis rather than to phenomena. Regarding support, the authors argued that it is a term which belongs to the analysis dimension. Although Dungan et al. (2002) limited support to the analysis dimension, it is argued here that support applies also to the sampling or measurement dimension. This is in line with (Burrough and McDonnell, 1998, p101) who defined support as "the technical name used in geostatistics for the area or volume of the physical sample on which the measurement is made". The matching up of resolution, grain, spacing and support with the phenomenon, sampling and analysis dimensions is depicted in Figure 2.1.

Figure 2.1: Resolution and related notions matched up with the phenomenon, sampling and analysis dimensions



Lam and Quattrochi (1992) claim that "[r]esolution refers to the smallest distinguishable parts in an object or a sequence, ... and is often determined by the capability

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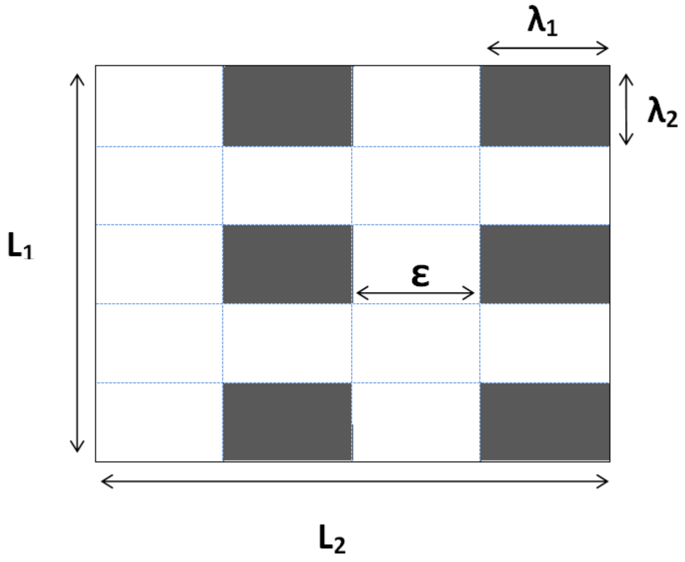
[4] The definition is in line with (Wu and Li, 2006). Unless otherwise stated, grain, as used throughout the thesis denotes sampling (or measurement or observation) grain.

[5] In the current work, the use of 'spacing' is preferred over the use of 'lag', and spacing (unless otherwise stated) refers to sampling (or measurement or observation) spacing.

of the instrument or the sampling interval used in a study". This definition points to two correlates of resolution. One of them relates to the sampling interval and was already covered in the previous paragraph under the term spacing; the second one relates to the capability of the instrument, and is called (after Sydenham, 1999) *discrimination*. 'Discrimination' is a term borrowed from the *Measurement, Instrumentation, and Sensors Handbook*. It refers to the smallest change in a quantity being measured that causes a perceptible change in the corresponding observation[6]. A synonym for discrimination is *step size* (see Burrough and McDonnell, 1998, p57). Discrimination is a property of the sensor (or measuring device) and therefore belongs to the sampling dimension.

Next to the discrimination of a sensor, coverage is another correlate of resolution. Coverage is defined after Wu and Li (2006) as the sampling intensity in space or time. Ergo, coverage is a term that applies to the sampling dimension of the framework. Synonyms for coverage are sampling density, sampling frequency or sampling rate. Figure 2.2 illustrates the difference between sampling grain, sampling coverage and sampling spacing for the spatial dimension. The grain size is $G = \lambda_1 * \lambda_2$, the spacing is $S = \epsilon$ and the coverage is $C = \frac{Number\ of\ samples\ *\ Grain\ size}{Extent} = \frac{6 * \lambda_1 * \lambda_2}{L_1 * L_2} = \frac{3}{10}$.

Figure 2.2: Illustration of sampling grain, sampling spacing and sampling coverage for the spatial dimension



Precision is defined after JCGM/WG 2 (2008) as the "closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions". Precision belongs therefore to

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[6] This definition is adapted and extended from (JCGM/WG 2, 2008) and (Sydenham, 1999).

the sampling (or observation) dimension of the framework. On the contrary, accuracy, the "closeness of agreement between a measured quantity value and a true quantity value of a measurand" (JCGM/WG 2, 2008) is a concept which belongs to the analysis dimension. In order to assign an accuracy value to a measurement, one needs not only the measurement value, but also the specification of a reference value. Because the specification of the reference value is likely to vary from task to task (or user to user), it is suggested here that accuracy is classified as a concept belonging to the analysis level. The last correlate of resolution introduced in this section is the notion of pixel. As indicated by Fisher (1997), the pixel is the elementary unit of analysis in remote sensing. The pixel is also the "smallest unit of information in a grid cell map or scanner image" (Burrough and McDonnell, 1998, p304). As a result, pixel is a term that belongs to both the sampling and analysis dimensions. Figure 2.1 shows the matching up of discrimination, coverage, precision, accuracy, and pixel with the phenomenon, sampling and analysis dimensions.

2.3 Proxy measures for resolution

The previous section has discussed various notions related to resolution and shown how these notions can be arranged according to the framework suggested in (Dungan et al., 2002). This section introduces a complementary framework which can be used to link resolution and some of its related notions. Dungan et al.'s framework is valuable in the sense that it suggests care should be taken when using terms belonging to several dimensions as synonyms. Wu and Li (2006) mention, for example, that in most cases, grain and support have quite similar meanings, and thus have often been used interchangeably in the literature. Such a use is fine in some cases because at the analysis or sampling level, the distinction between the two terms becomes blurred. On the contrary, the use of phenomenon grain and support as synonyms might not always be appropriate, since phenomenon grain might differ from analysis or sampling grain (= support).

2.3.1 A unifying framework for resolution and related notions

The framework introduced in this subsection aims at providing a basis to make compatible different views on (or definitions of) resolution in the literature. The framework has three dimensions: definitions of resolution, proxy measures for resolution, and closely related notions to resolution. *Definitions of resolution* refer to possible ways of defining the term. *Proxy measures for resolution*[7] denote different measures that can be used to characterize resolution. It is argued here that several proxy measures for resolution exist, and the choice of the appropriate measure is dependent on the task at hand[8]. This argument generalizes what Forshaw et al. (1983), after a review of different ways of describing spatial resolution in the field of remote sensing, concluded:

> "No single-figure measure of spatial resolution can sensibly or equitably be used to assess the general value of remotely sensed imagery, or even its value in any specific field".

Using the analysis from (Frank, 2009b,c) as a basis, two types of proxy measures for resolution are suggested. As mentioned in Section 1.3, resolution is introduced in the data collection process due to three factors: (a) a sensor always measures over an extended area and time, (b) only a finite number of samples is possible, and (c) only a finite number of values can be used to represent the observation. Two[9] types of proxy measures can be isolated from this: (i) proxy measures related to the limitations of the sensing device and (ii) proxy measures related to the limitations of the sampling strategy. The former type of proxy measures is concerned with the minimum unit over which homogeneity is assumed for a sample, the latter deals essentially with the dispersion of the different samples used during a data collection process. Finally, the last dimension of the framework introduced in this subsection, *closely related notions to resolution*, refers to notions closely related to resolution, but in fact different from it.

2.3.2 Using the framework suggested

Different authors have used different terms as synonyms for resolution in the literature. Resolution has been used as synonym for amount of detail in (Veregin, 1998; Fonseca et al., 2002a), level of detail in (Goodchild and Proctor, 1997; Goodchild, 2001; Skogan, 2001), degree of detail in (Goodchild, 2011b), precision in (Veregin, 1998, 1999), grain in (Reitsma and Bittner, 2003; Pontius Jr and Cheuk, 2006), granularity in (Stell and Worboys, 1998; Worboys, 1998), step size in (Burrough and McDonnell, 1998, p57) and scale in (Burrough and McDonnell, 1998, p40) and (Frank, 2009c). This list of 'synonyms' for resolution will be used as input in the next paragraph to illustrate the usefulness of the framework introduced in the previous subsection.

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[7] A short introduction to proxy measurement can be found at (Blugh, 2012).

[8] Proxy measures for resolution are also expected to vary from era to era. Goodchild (2004) points out that metrics of spatial resolution are strongly affected by the analog to digital transition.

[9] It is straightforward to see that factor (a) relates to (i) and factor (b) relates to (ii). Factor (c) relates also to (i) and is called the dynamic range of the sensor (see Frank, 2009c).

To the *definitions of resolution* belong "amount of detail in a representation", "degree of detail" and "level of detail" in a representation. Step size and grain can be seen as *proxy measures* for resolution, related to the minimum unit over which homogeneity is assumed. Precision however is a *proxy measure for resolution*, related to the dispersion of replicate measurements on the same object. Additional examples of proxy measures for resolution are the size of the minimum mapping unit[10], the instantaneous field of view of a satellite, the mean spacing and the coverage. Granularity, accuracy and scale are *closely related terms to resolution*. Stating that 'scale' is a closely related term to 'resolution' is in line with Dungan et al. (2002); Wu and Li (2006) who argued that resolution is one of many components of scale. Resolution is also different from accuracy. The former is concerned with how much detail there exists in a representation. The latter has to do with the closeness of a representation to the 'truth' (i.e. a prefect representation), and since there is no perfect representation, accuracy deals in fact with how close a representation is to a referent representation. Veregin (1999) points out that one would generally expect accuracy and resolution to be inversely related.

In line with Hornsby, cited in (Fonseca et al., 2002a), resolution and granularity are viewed as two different notions. If both notions deal with amount of detail in some sense, they are different because granularity is a property of a conceptualization and resolution is a property of a representation. The following remark on granularity was made in the field of Artificial Intelligence:

> "Our ability to conceptualize the world at different granularities and to switch among these granularities is fundamental to our intelligence and flexibility" (Hobbs, 1985).

Thus, in GIScience, granularity should be used while referring to the amount of detail in a conceptualization (e.g. field- or object-based) or a conceptual model (e.g. an ontology), whereas resolution should be used to denote the amount of detail of digital representations (e.g. raster or vector data). The definition of resolution as a property of data, and not of sensors is admittedly restrictive, but this restriction is proposed because of the following comment from the *Measurement, Instrumentation, and Sensors Handbook*:

> "Although now officially declared as wrong to use, the term *resolution* still finds its way into books and reports as meaning discrimination" (Sydenham, 1999).

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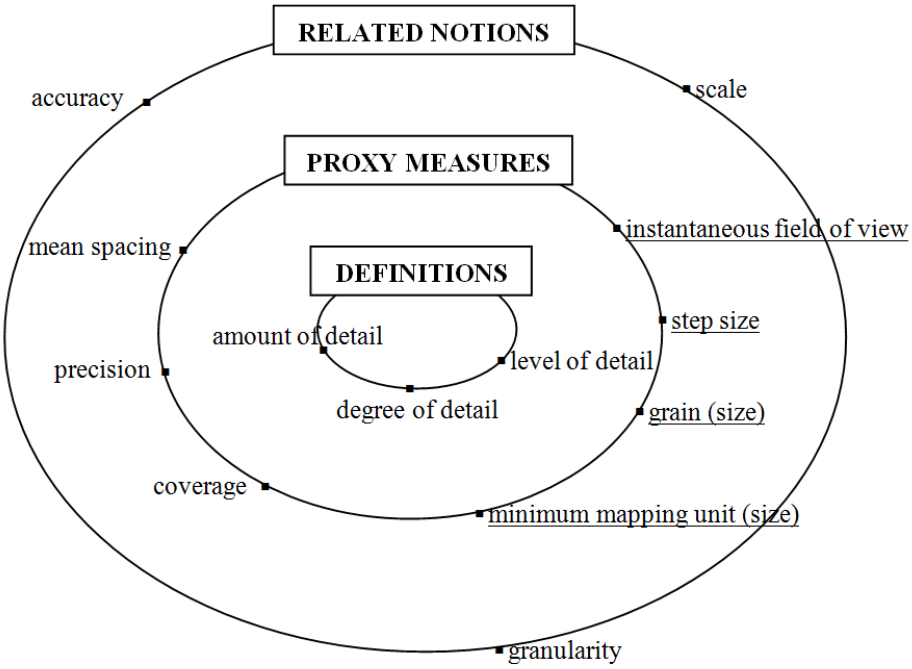
[10] "The 'minimum mapping unit' defines the smallest polygon the cartographer is willing to map (smaller polygons are forcibly merged with a neighbor)" (Goodchild and Quattrochi, 1997).

In a nutshell: resolution applies to data, discrimination to sensors, and granularity to conceptual models. The framework suggested as well as the different examples introduced in this section are summarized in Figure 2.3. Proxy measures dealing with the minimum unit over which homogeneity is assumed are underlined on the figure. Proxy measures not underlined are possible measures to characterize the dispersion of the samples used during a data collection process.

Figure 2.3: Possible definitions of, proxy measures for and notions related to resolution



2.4 Accommodating variability in word usage

Sections 2.2 and 2.3 provided a basis for conceptual clarity on resolution, discussing some of its related notions, their similarity in meaning as well as their differences. This notwithstanding, the author is aware of the unpredictability and variability inherent to the use of terms by different people and communities. This section will shed light on some ways to accommodate this issue of variability in word usage, an issue termed the 'vocabulary problem' in (Furnas et al., 1987).

Furnas et al. (1987) studied spontaneous word choice for items in a setting of human-system communication. They found that the probability that people use the same word to refer to the same item is less than 20%. As a cure, they suggested that software designers should provide many alternative words for software items. This recommendation is relevant to the current discussion, and Table 2.1 provides a list of synonyms for some of the terms mentioned in the previous sections.

Table 2.1: Table of synonyms

TERM	SYNONYM(S)
Dimensions used during the analysis	
Analysis dimension	analysis level
Observation dimension	geographic dimension, measurement dimension/level, observation level, sampling dimension/level
Phenomenon dimension	operational dimension/level, phenomenon level
Resolution and related notions	
Amount of detail	degree of detail, level of detail, quantity of detail
Analysis grain	analysis support
Coverage	sampling density, sampling frequency, sampling intensity, sampling rate
Discrimination	step size
Observation grain	observation support
Proxy measure	indirect measure, substitute measure
Spacing	lag, interval

Relevant to the current discussion also is a recommendation from (Galton, 2009). As he puts it:

> “When reading the GIScience literature, one can find varied (and sometimes idiosyncratic) usage conventions regarding the key terms ‘state’, ‘process’, and ‘event’, but it is always a good policy here to adopt the ‘principle of charity’... and seek to understand an author’s usage on the assumption that what they are saying is sensible”.

It can be seen from Section 2.1 that ‘resolution’ is not immune to the problem of variety of usage conventions in the literature. As a result, adopting Galton’s recommendation appears reasonable. The ‘principle of charity’ was introduced in (Wilson, 1959). In the context of the current discussion, its adoption implies the following: concepts which satisfy most properties of 'resolution' (as introduced in this chapter), should be read 'resolution', even if different labels are used to refer to them[11].

2.5 Summary

Kuhn (2011), in a work aiming at selecting concepts of spatial information relevant to transdisciplinary research[12], pointed out a requirement that is unavoidable, if spatial information is to become a cross-cutting enabler of knowledge and analysis. As he argued: "An effort at the conceptual level is needed [in GIScience], in order to present a coherent and intelligible view of spatial information to those who may not want to dive into the intricacies of standards and data structures". This chapter is a contribution along these lines, with a focus on resolution. The ideas presented can be summarized as follows:

I. Resolution and related notions can be applied to three dimensions: the phenomenon, observation, and analysis dimensions;

II. Resolution is a term that applies to the observation and analysis dimensions rather to phenomenon;

III. A basic distinction should be drawn between definitions of resolution, proxy measures for resolution, and notions related to resolution but different from it;

IV. There are (at least) two types of proxy measures for resolution: those which deal with the minimum unit over which homogeneity is assumed for an observation, and those which revolve around the dispersion of the observations used during an observation process;

V. Discrimination is a property of sensors, resolution is a property of representations, granularity is a property of conceptual models;

VI. Amount of detail is central to both resolution and granularity, but resolution is a more specific concept than granularity[13].

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[11] The same applies to the related notions of resolution (as they have been earlier presented).

[12] See also (Kuhn, 2012) for a subsequent work pursuing the same goal.

[13] See also (Degbelo and Kuhn, 2014) for a more detailed discussion on the difference between resolution and granularity.

CHAPTER 3

Ontology development method

How is ontology defined in this work? ... and which method of ontology development is used for the formal specification of the spatial and temporal resolution of sensor observations? Providing answers to these two questions is the central theme of the current chapter. In addition, the relevance of an ontology of resolution is stressed anew.

3.1 Definition of ontology

'Ontology' is a term associated with a variety of meanings in both philosophy and information science (i.e. computer science and related disciplines such as artificial intelligence and information systems research). This section will not review all the possible interpretations of the term. The distinction (brought up for example in Guarino, 1998; Zúñiga, 2001) between ontology as a sphere of investigation, and a particular ontology that results from an ontological investigation is also left out, and the scope of the discussion presented here is limited to particular ontologies. The section aims at touching upon the difference between **ontology**[1] and ontology, and introducing the definition of ontology adopted throughout the thesis. A collection of definitions of **ontology** (i.e. from the philosophical perspective) is available at (Corazzon, 2012a) and (Corazzon, 2012b). Fonseca et al. (2003) discuss the differences between ontology and conceptual schema. Sánchez et al. (2005) look into the relation between ontology and model. Gokhale et al. (2011) present the differences between ontology and thesaurus. A reference terminology for ontology research[2] was proposed in (Smith et al., 2006). Discussions on the different understandings of the term can be found in (Guarino and

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[1] In the remainder of this section, '**ontology**' (with change in font) is used to refer to ontology as used in philosophy; 'ontology' (without change in font) refers to ontology as used in information science.

[2] The reference terminology was initially suggested for the biomedical domain, but is relevant to the whole body of ontology research in information science.

Giaretta, 1995; Mizoguchi and Ikeda, 1997; Gómez-Pérez, 1999b; Corcho et al., 2001; Smith and Welty, 2001; Zúñiga, 2001; Corcho et al., 2003; Smith, 2003; Mark et al., 2004; Wyssusek, 2004; Agarwal, 2005; Guizzardi, 2007; Gruber, 2009). The difference between **ontology** and ontology can be summarized as follows:

> "In philosophy, . . . **ontology** is the basic description of things in the world [i.e. the description of what is said to truly exist]. In information science, an ontology refers to an engineering artifact, constituted by a specific vocabulary used to describe a certain reality" (Fonseca, 2007).

Ontology in philosophy is "a systematic explanation of Existence" (Gómez-Pérez and Benjamins, 1999). It seeks, as Smith points out, "to provide a definitive and exhaustive classification of entities in all spheres of being". 'What exists?' and 'what does *existence* means?' are questions that form the gist of **ontology**. Some examples of philosophical viewpoints on 'being' and 'not-being' can be found in (Peña, 1991) and (Quine, 1953). **Ontology** is independent of language (see Guarino, 1998; Guizzardi, 2007). On the contrary, the goal of ontology in information science is at least threefold[3]: (i) *communication* (between computers, between humans, between humans and computers), *computational inference*, and *knowledge reuse and organization*. Ontology in information science is a representational artifact, i.e. "a representation that is fixed in some medium" (Smith et al., 2006). It is also, as Fonseca observes, "a theory that explain a domain". Ontology in information science is language-dependent (see Guarino, 1998; Guizzardi, 2007). In the rest of this work, the following definition (mirroring an information-science-oriented interpretation of the term) from Guarino (1998) is adopted:

> "An ontology is a logical theory accounting for the *intended meaning* of a formal vocabulary, i.e. its *ontological commitment* to a particular *conceptualization* of the world";

where conceptualization denotes "a set of conceptual relations defined on a domain space" (Guarino, 1998).

3.2 Relevance of ontology research to GIScience

Ontology research has both a theoretical and a practical pertinence to the field of geographic information science. Two key benefits - from a theoretical perspective - appear

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[3] These three aspects were initially presented as uses of ontology in (Grüninger and Lee, 2002), but they are also valid as goals for ontology research in information science.

in (Agarwal, 2005): (i) an ontology can generate an underlying 'theory for everything' in GIScience via the determination of rules, relations and entities that can conceptualize all processes and phenomena within a minimum set of mathematical equations; and (ii) an ontological approach can pave the way for future research directions by questioning current approaches in the definition of categorization and semantic content.

From a practical point of view, Abdelmoty et al. (2005) indicate that a geo-ontology has a key role to play in the development of a spatially aware search engine. It supports in particular tasks such as query disambiguation, query term expansion, relevance ranking and web resource annotation. Furthermore, as Smith and Mark (1998) indicate, "geographic information systems need to manipulate representations of geographic entities, and ontological study of the corresponding entity types . . . will provide default characteristics for such systems". Finally, since ontologies help to make the intended meaning of vocabularies explicit, ontology research in GIScience helps to understand *why* people succeed or fail to exchange geographic information.

3.3 Research method

The method for ontology development adopted for the formal characterization of the resolution of sensor observations is expounded in this section. The philosophical basis for the method is presented first, and its steps are detailed afterwards.

3.3.1 Philosophical standpoint

The engineering view of semantics proposed in (Kuhn, 2009b) is adopted in the current work for the development of the ontology of spatial and temporal resolution of sensor observations. This view, as described in (Kuhn, 2009b), makes minimal assumptions about philosophical issues (e.g. realism vs nominalism), to the end of pragmatic solutions to semantic problems. Regarding the philosophical basis for such a view, Kuhn (2009b) suggested *radical constructivism*. A constructivistic approach, as Couclelis (2010) mentions, is philosophically "closest to instrumentalist and pragmatist philosophies of science, which tend to be neutral on the question of external reality but focus instead on seeking the most productive solutions to specific problems".

A presentation of the main epistemological tenets of radical constructivism can be found in (von Glasersfeld, 1974, 1984, 1992, 2004). At this stage, two remarks on constructivistic[4] approaches are of importance: Firstly, it should be noted that (a) "[con-

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[4] Chiari and Nuzzo (2004) point out that the vague definition of the term has led scholars to suggest

structivists] are constructing a model that should be tested in practice, not another metaphysical system to explain what the ontological world might be like" (von Glasersfeld, 2000); and secondly: (b) "constructivists never say: this is how it is! They merely suggest: this may be how it functions" (von Glasersfeld, 2000). As for the current work, the choice of a constructivistic approach has two main implications. The first one - related to remark (a) - is that the purpose of the ontology presented in Chapters 4 and 5 is not an explanation of the world (a.k.a. external reality), but the provision of a conceptual backdrop for (geographic) information systems. The second implication - from remark (b) - is that the ontology developed is *only one way* of formally specifying the spatial and temporal resolution of sensor observations. The adoption of constructivism as philosophical basis for the ontology development method is consistent with one of the fundamental rules brought up in (Noy and McGuinness, 2001), as regards the development of ontologies in information sciences. As the authors put it: "There is no one correct way to model a domain - there are always viable alternatives. The best solution almost always depends on the application that you have in mind and the extensions that you anticipate".

3.3.2 Research method: a bird's-eye view

Kuhn (2010) argues for the separation of two distinct tasks in the context of (web) ontologies: modelling semantics and encoding it. The former is a design task whereas the latter is an implementation task. These two tasks will constitute the main blocks of the method for ontology building taken in this work. For other ontology building methods, see reviews provided in (Jones et al., 1998; Fernández-López, 1999; Gómez-Pérez, 1999b; Corcho et al., 2001; Fernández-López and Gómez-Pérez, 2002; Corcho et al., 2003; Mizoguchi, 2004; Sure et al., 2009; Lavbič and Krisper, 2010; Gokhale et al., 2011; Nguyen, 2011).

The distinction between modelling task and implementation task in ontology building was already implicit in (Masolo et al., 2003) and (Bittner and Donnelly, 2007; Guizzardi, 2007). Masolo et al. stated that using the Web Ontology Language (OWL) for specifying foundational ontologies would be "non-sensical", because foundational ontologies requires an expressive language, in order to suitably characterize their intended models. For that reason, the authors resorted to a full first-order logic with modality while developing their foundational ontologies. Bittner and Donnelly argued

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different types of constructivism. In the current work, constructivism is primarily used *sensu* von Glasersfeld and refers to what von Glasersfeld calls 'radical constructivism'. For examples of other types of constructivism, see (Troelstra, 1991).

for the need to understand a computational ontology as consisting of two complementary components: (i) an expressive ontology developed in first-order logic, and (ii) an ontology developed in description logics, which is computationally efficient, and thus useful for computer implementations. The ontology developed in descriptions logics is an *approximation* of the ontology developed in first-order logic. Guizzardi advocated two classes of languages for the discipline of ontology engineering[5]: (i) "well-founded ontology representation languages" with the focus on representation adequacy, and (ii) "lightweight representation languages" with the focus on guaranteeing desirable computational properties. He pointed out that the name 'ontology representation languages' when applied to Semantic Web languages (e.g. the Web Ontology Language) is a misnomer, because these languages are motivated by epistemological and computational concerns, not ontological ones[6].

Table 3.1: Key features of the design and implementation stages of an ontology building process

	DESIGN	IMPLEMENTATION
Goal	Support human understanding	Support automated reasoning
End consumer	Humans (in tasks such as communication & domain analysis)	Machines (in tasks such as inference & reasoning)
Requirements for supporting languages	Conceptual clarity Expressiveness	Efficient automated reasoning, Decidability, Scalability[7]
Examples of supporting languages	First-order logic, Haskell, UML	OIL, DAML, DAML+OIL, RDFs, OWL, LINGO

Nota bene: an explanation of the acronyms used in this table is available at Page xvii. That some languages are classified as implementation languages in this table implies by no means that they cannot be (or have not been) used for design, but such a use might come at the expense of greater expressiveness and understanding.

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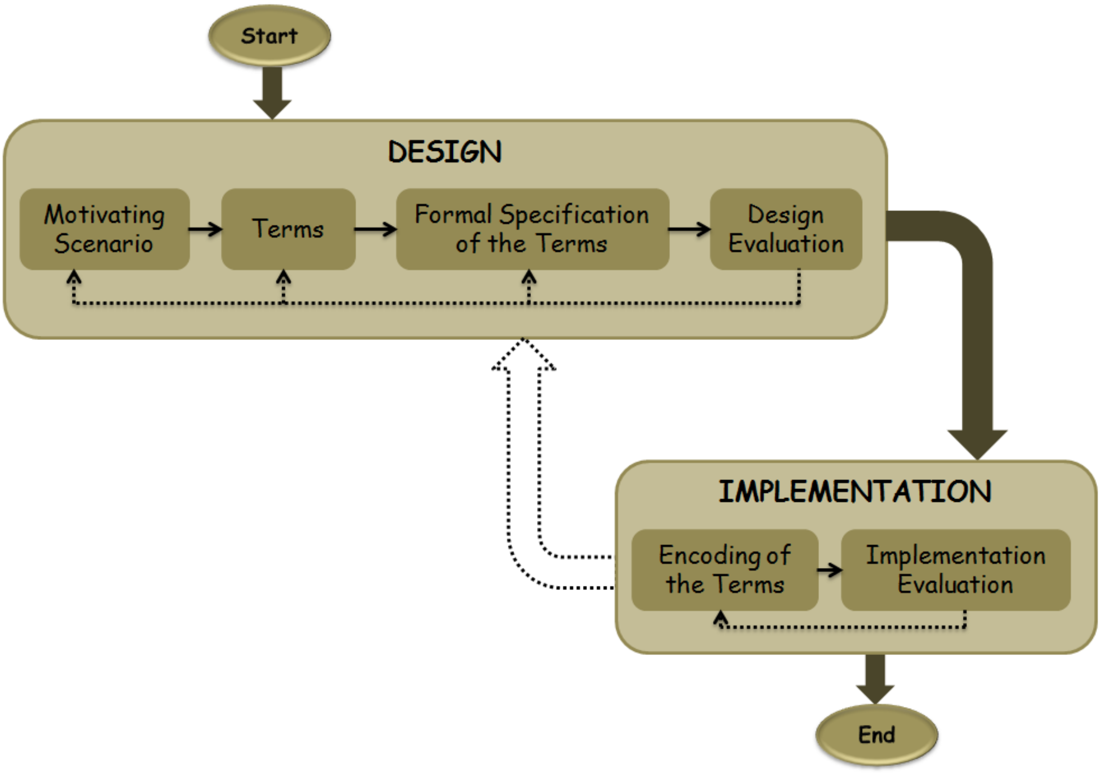
[5] After Sure et al. (2009), ontology engineering is defined in this work as the "discipline that investigates the principles, methods and tools for initiating, developing and maintaining ontologies".

[6] See (Guizzardi, 2007) for the thorough discussion.

[7] Admittedly, ontology implementation languages need also expressiveness to a certain degree. Antoniou and van Harmelen (2003, 2009) identified 'sufficient expressive power' as a requirement for ontology implementation languages, and motivated the development of OWL by the limitations of the expressive power of RDF Schema. Nonetheless, the key feature of ontology implementation languages is not expressiveness per se, rather it is *the compromise between expressiveness and efficient reasoning support*. This has been the reason for not explicitly mentioning 'expressiveness' in the column IMPLEMENTATION of the table.

Table 3.1 synthesizes the distinguishing features of the two tasks of design and implementation. The synthesis is based for the most part on the discussions provided in (Guizzardi, 2007; Kuhn, 2010). Sections 3.3.3 and 3.3.4 present in detail the tasks performed during the design stage and the implementation stage respectively. Figure 3.1 presents the main features of the research method.

Figure 3.1: Research method



Nota bene: dotted arrows indicate the possibility of iteration between different steps.

3.3.3 Design (or modelling) stage

The steps followed during this stage are partially modified from the method for design and evaluation of ontologies suggested in (Grüninger and Fox, 1995). The design stage is an iterative process consisting of three steps: (i) identification of a motivating scenario, (ii) identification of the terms of the ontology, and (iii) formal specification of the terms of the ontology.

Identification of a motivating scenario

According to Grüninger and Fox (1995); Uschold and Grüninger (1996), a motivating scenario is a story problem or example which is not adequately addressed by existing ontologies. A motivating scenario provides a set of intuitively possible solutions to the scenario problems, and helps to understand the motivation for the proposed ontology in terms of its applications.

Given the motivating scenario, a set of questions to be answered by the ontology (i.e. competency questions) is extracted. As indicated by Grüninger and Fox (1995); Uschold and Grüninger (1996), competency questions specify the (expressiveness) requirements for an ontology, and are a means to give an informal justification of the necessity of the ontology to be developed. All in all, the specification of a motivating scenario as well as competency questions helps to delineate the scope of the ontology.

Identification of the terms of the ontology

Grüninger and Fox (1995) as well as Uschold and Grüninger (1996) indicate that for every competency question, there must be objects, attributes, or relations in the proposed ontology, which are intuitively required to answer the question. This step of the design stage consists in identifying the terms (i.e. objects, attributes, relations) to be used in the ontology. Terms from existing ontologies will be considered for reuse, and new terms (i.e. terms that do not appear in previous ontologies) will be introduced if necessary, to cover the needs arising from the motivating scenario. All the terms of the ontology will be aligned to a foundational ontology. As Brodaric and Probst (2008) indicate, an alignment to a foundational ontology is realized by establishing an *is-a* relation between an ontology element and a foundational ontology element[8].

Formal specification of the terms of the ontology

At this step of the design stage, axioms are provided and the terms of the ontology are specified using an ontology design language. An axiom "contains formulas which are considered to be always true (and therefore *sharable* among multiple agents), independently of particular states of affairs" (Guarino and Giaretta, 1995). As mentioned in (Grüninger and Fox, 1995; Uschold and Grüninger, 1996), axioms are useful to specify the definitions of terms in the ontology, and constraints on their interpretation. The

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[8] See Section 3.4.1 for a detailed presentation of foundational ontologies, and the benefits of an alignment to a foundational ontology.

whole obtained by putting together terms and axioms is a *logical theory*, and this theory represents the outcome of the design stage.

3.3.4 Implementation (or encoding) stage

The terms of the ontology identified during the design stage (all or some of them) are reused at the implementation stage. A *subset of the axioms* from the design stage is isolated and implemented in an ontology implementation language. A distinguishing criterion between ontology implementation language and ontology design language is that the former *must be machine-readable*, whereas the latter *does not need to be*. There is a need to use different languages for design and implementation because, as Bittner et al. (2009) remark: "[o]nce one has developed a highly expressive theory, less expressive logics with better computational properties can be used to implement certain portions of the full theory for specific purposes". The outcome of the implementation stage is a *computational artifact* that can be used in practical tasks such as query disambiguation, query term expansion, relevance ranking and web resource annotation[9].

3.3.5 Ontology languages

Several languages have been proposed in the past for the design and implementation of ontologies. Examples already mentioned in Table 3.1 are first-order logic, Haskell, UML, OIL, DAML, DAML+OIL, RDFs, OWL and LINGO. The second edition of the *Handbook on Ontologies* points further to description logics (see Baader et al., 2009), RDFS-FA[10] (see Pan, 2009), frame logic (see Angele et al., 2009), and the semantic web rule language (see Hitzler and Parsia, 2009). Additional examples of languages that have been used to design and/or implement ontologies can be found in (Corcho and Gómez-Pérez, 1999, 2000; Corcho et al., 2001; Bechhofer, 2002; Gómez-Pérez and Corcho, 2002; Su and Ilebrekke, 2002; Kalinichenko et al., 2003; Mizoguchi, 2004; Pulido et al., 2006; Cardoso, 2007; Maniraj and Sivakumar, 2010; Kalibatiene and Vasilecas, 2011; Nguyen, 2011). The reader might ask him-/herself why the discussion on ontology languages has not been integrated with the separation of the two tasks of design and implementation. The reason lies in the fact that ontology languages should be placed along a continuum, rather than be classified as either belonging to one category (design) or to the other (implementation). At one end of the continuum, there are lan-

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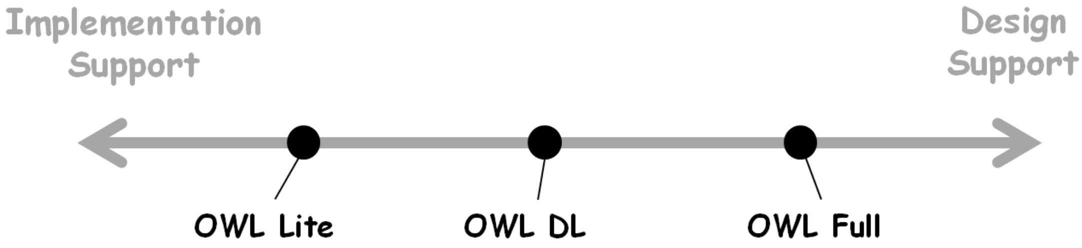
[9] At this stage, no facts (or instances) are added to the ontology. Adding facts or instances to the ontology leads (following the distinction introduced in Noy and McGuinness, 2001) to the creation of a *knowledge base*.

[10] RDFS-FA stands for RDFs with fixed layered meta-modelling architecture.

guages that are more appropriate for implementation (e.g. RDF), and at the other end, languages more adequate for design (e.g. first-order logic). In-between, there are languages that might be used for both (e.g. OWL DL[11]), albeit with the risk of obtaining suboptimal results. If the three species of OWL described in (Antoniou and van Harmelen, 2003, 2008, 2009) were to be placed on this continuum, the result would be as Figure 3.2 shows[12]. Comparisons of ontology languages done in (Corcho and Gómez-Pérez, 1999, 2000; Gómez-Pérez and Corcho, 2002; Su and Ilebrekke, 2002; Ding et al., 2005; Keet and Rodriguez, 2007; Kalibatiene and Vasilecas, 2011) can be used as a starting point for a comprehensive characterization of this continuum[13], but this endeavour is out of the scope of the current work.

The requirements of the task to complete drive the choice of the ontology language. Chapters 4 and 7 will present the languages chosen in the current work for the design and implementation tasks respectively, as well as the motivations for their choice.

Figure 3.2: The three species of OWL on the implementation-design continuum



Note: languages further right provide greater support for design, languages further left provide greater support for implementation.

3.3.6 Evaluation

Ontology evaluation can be carried out for two major goals (indicated in Yu et al., 2009): *tracking progress in ontology development*, and *ontology selection*. The distinction mentioned in (Gómez-Pérez et al., 1995; Gómez-Pérez, 2001, 2003) between *technical*

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[11] OWL DL (short for: OWL Description Logic) is a variant of OWL. A presentation of OWL DL can be found in (Antoniou and van Harmelen, 2003, 2008, 2009).

[12] Interchangeable names for this continuum are 'implementation-design continuum', 'design-implementation continuum'.

[13] Nguyen's statement that "languages based on higher-order logics are more expressive than languages based on first-order logics, which, in turn, are more expressive than languages based on description logics", is a rule of thumb that may also be useful for such a task.

evaluation, and *user evaluation* fits with these two goals. Technical evaluation is carried out by ontology developers and aims at tracking progress during ontology development; user evaluation is done by end-users of the ontology, and aims at selecting an ontology for a given purpose. The next paragraphs present work done along these two different axes.

OntoClean, presented in (Welty and Guarino, 2001; Guarino and Welty, 2002), is a method useful to expose inappropriate and inconsistent modelling choices during the development of taxonomies. The method adopts several philosophical notions such as identity, essence, unity and dependence, and adapts them for use in information systems. As an alternative to OntoClean, Sleeman and Reul (2006) suggested CleanONTO, a checking system for taxonomies based on definitions extracted from WordNet. CleanONTO helps to remove inconsistent relations from a taxonomic structure and produce a consistent ontology. Relevant also to the evaluation of taxonomies is work done by Gómez-Pérez (1999a, 2001, 2003), where three main classes of errors that can arise during the development of taxonomies were identified: inconsistency errors, incompleteness errors, and redundancy errors. Another discussion on errors arising during the creation of taxonomies can be found in (Fahad and Qadir, 2008). With the view that a substantial amount of an ontology's expressive and inferential capabilities lies in the non-taxonomic relations that hold between the concepts, Porzel and Malaka (2004) proposed a method for task-based evaluation which yields a measure of how well vocabularies, taxonomies and non-taxonomic relations are modelled for a given task at hand. The method is useful to indicate superfluous (and also missing, ambiguous) concepts, isa- and semantic relations. Several authors also tried to automatize the evaluation task during ontology development. Völker et al. (2005, 2008) proposed AEON, a tool to automatize the different steps of OntoClean. Lavbič and Krisper (2010); Lavbič et al. (2011) introduced rapid ontology development (ROD). ROD (with the accompanying tool IntelliOnto) aims at decreasing the technical knowledge required for the development of ontologies, and tracks progress in the ontology development task through the ontology completeness indicator. Besides, Pammer et al. (2006) presented a method (called ontology coverage check) which helps, in the course of ontology development, to check the extent to which an ontology's concepts and axioms cover a set of (test) individuals. Baclawski et al. (2002) proposed ConsVISor, a tool for checking the consistency of ontologies encoded in languages such as RDF and DAML+OIL. Brewster et al. (2004) proposed the comparison between the terms of an ontology and a corpus of text representing a given domain as a method for ontology evaluation. Brank et al. (2006) suggested an approach for ontology evaluation based on the comparison between an ontology and a gold standard ontology. Casellas (2009) hypothesized that ontology evaluation would benefit from the inclusion of human-centred methods (e.g. expert involvement for the evaluation task) in the ontology development life-cycle. Finally, Evermann and Fang (2010) identified cognitive ontology quality as an important characteristic of ontologies and proposed a method to evaluate it.

Regarding the selection of ontologies for a given task, Lozano-Tello and Gómez-Pérez (2004) suggested a method which enables users to choose among existing ontologies. The method is called ONTOMETRIC and takes into account 160 characteristics of ontologies, spread over five dimensions: content, language, methodology, tool and costs. Supekar (2005) proposed a peer-review based approach for ontology evaluation that allows users to provide qualitative ratings on the ontology content. Lewen et al. (2006) suggested an approach for ontology evaluation based on Open Rating System[14]. Alani and Brewster (2006) presented a system (called AKTiveRank) for ranking ontologies based on the analysis of their structures. OntoQA, proposed in (Tartir and Budak, 2007), is another tool which helps to evaluate ontologies and rank them according to a set of metrics.

Examples of work covering both technical evaluation and user evaluation are (Gangemi et al., 2005a,b, 2006; Kehagias et al., 2008). Kehagias et al. (2008) proposed a set of criteria to ensure ontology validation. The authors distinguish between internal measures concerned with the ontologies themselves (e.g. density, cognitive adequacy), and external measures concerned with their take-up and use within user communities (e.g. availability, ease and effectiveness of access). Gangemi et al. (2005a,b, 2006) identified three types of measures for ontology evaluation: structural measures, functional measures, and usability-related measures. Structural and functional measures are pertinent to both *technical* and *user evaluation*, usability measures are relevant to *user evaluation*. Reviews of approaches for ontology evaluation can be found in (Staab et al., 2004; Brank et al., 2005; Hartmann et al., 2005; Sabou et al., 2006; Brank et al., 2007; Obrst et al., 2007; Yu et al., 2007; Murdock et al., 2010; Tartir et al., 2010; Murdock et al., 2013).

Since ‘evaluation’ is used in the literature in reference to both the tasks of selecting ontologies, and tracking progress during ontology development, there is a need for further precision regarding the use of this term in the current work. Ontology evaluation is defined after Gómez-Pérez et al. (1995) as a technical judgment of the ontology with respect to a frame of reference. As Gómez-Pérez et al. point out, the frame of

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[14] “The basic idea of Open Rating Systems ... is to have a democratic approach to rating where anyone can review pieces of content” (Lewen et al., 2006).

reference can be requirements specification, competency questions, and the real world. Henceforth, ontology evaluation refers to the *technical evaluation* done by the ontology developer, during an ontology development endeavour.

All the works previously cited have one point in common, namely that they have not discussed ontology evaluation in relation to the design-implementation distinction. To fill this gap, this work proposes the following repartition of previous criteria suggested in the context of ontology evaluation. The focus is on *what* should be evaluated, not *how* the evaluation should be carried out. Relevant references to the criteria introduced next include (Gruber, 1995; Grüninger and Fox, 1995; Noy and Hafner, 1997; Gómez-Pérez, 2003; Kehagias et al., 2008; Kuhn, 2009b; Vrandečić, 2009).

Evaluation of the design stage

Criteria for the evaluation of the design stage of an ontology development process include:

- *accuracy* (i.e. correct representation of aspects of the real world)
- *adaptability* (i.e. ease of performing changes)
- *clarity* (i.e. effective communication of the intended meaning of defined terms)
- *cognitive adequacy* (i.e. match between formal and cognitive semantics)
- *completeness* (i.e. appropriate coverage of the domain of interest)
- *conciseness* (i.e. absence of unnecessary or useless definitions or axioms)
- *consistency* (i.e. incapacity of getting contradictory conclusions from valid input data)
- *expressiveness* (i.e. number of competency questions that the ontology can answer)
- *grounding* (i.e. number of assumptions done by the ontology's underlying philosophical theory about reality)

Evaluation of the implementation stage

Criteria for the evaluation of the implementation stage of an ontology development process include:

- *computational efficiency* (i.e. ease and speed of processing by reasoners)

- *congruency* (i.e. fitness between ontology and corpus terms)
- *practical usefulness* (i.e. number of practical problems to which the ontology can be applied)
- *precision* (i.e. fraction of retrieved instances by the ontology that are relevant)
- *recall* (i.e. fraction of relevant instances that are retrieved by the ontology)
- *scalability* (i.e. ability of the ontology to handle a growing amount of instances)

3.3.7 Documentation

Ontology documentation is an activity done in parallel to the design and implementation stages. It is viewed (in accord with Fernández-López, 1999; Fernández-López and Gómez-Pérez, 2002) as a *support activity*, i.e. an activity happening concurrently with the development of the ontology, without which the ontology could not be built. In line with Gómez-Pérez (1995), ontology documentation is broadly defined to include *general information about the ontology*, *definition of its terms*, *studied cases in its evaluation*, *definitions of terms taken from other ontologies*, *axioms of the ontology*, *description of the software and/or ontology languages used during the ontology development process*, *frequently asked questions about the ontology and tutorials*, or any combination of these. Chapters 4, 5, 6, and 7 of this PhD thesis *play the role of documentation* for the ontology of resolution developed. A shorter documentation, conforming to Agarwal's checklist of considerations for ontologies in the geographic domain, is provided in Appendix F.

3.3.8 Discussion

Three methods[15] from the literature may be found similar to the method introduced in Sections 3.3.2 to 3.3.6: the 'skeletal methodology for building ontologies' suggested in (Uschold and King, 1995), METHONTOLOGY from (Fernández et al., 1997; Fernández-López et al., 1999), and 'rapid ontology development' introduced in (Lavbič and Krisper, 2010; Lavbič et al., 2011). The goal of this subsection is to outline both the correspondences and differences.

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[15] Worth mentioning also is the three-steps method from Bachimont et al. (2002). Contrary to this work, the authors did not mention how to give a scope to the ontology, nor did they discuss evaluation.

The skeletal methodology for building ontologies

Uschold and King (1995) suggest that a (comprehensive) method for ontology building should include the following four phases:

- Identify the purpose and scope
- Building the ontology
  - ontology capture
  - ontology coding
  - integrating existing ontologies
- Evaluation
- Documentation

The authors add that any ontology building method should also include a set of guidelines for each of the four phases, and indicate what relationships exist between the phases (e.g. recommended order, interleaving, or input/outputs).

The activities performed during the design and implementation phases were described in Sections 3.3.3 and 3.3.4 respectively. As Figure 3.1 illustrates, the method is iterative, but design precedes implementation. The *identification of the purpose and the scope* of the ontology is achieved through the specification of the motivating scenario and the competency questions. The phase of *ontology capture* and the stage called ‘identification of the terms of the ontology’ (see Section 3.3.3) are alike. *Integrating existing ontologies* is done through the reuse of terms from existing ontologies, and/or alignment to a foundational ontology. The research method used in this PhD thesis takes also *evaluation* into account, and *documentation* is done throughout. However, it is at the *ontology coding* stage that it substantially differs from Uschold and King’s method. The authors defined coding as follows:

> “By coding, we mean explicit representation of the conceptualisation captured in the above stage [i.e. ontology capture stage] in some formal language. This will involve committing to some meta-ontology, choosing a representation language, and creating the code” (Uschold and King, 1995).

In the current context in which two types of representation languages exist and support different goals, the ontology coding phase as defined originally by Uschold and King can be understood in more than one sense. It might be attached to the design phase (if the goal of the coding stage is to support human understanding), or considered to be an implementation activity (if the goal is automated machine reasoning). Based on the premise that "ontologies should be developed according to the standards proposed for software generally, which should be adapted to the special characteristics of ontologies", Fernández-López (1999) analyzed Uschold and King's method using the *IEEE Standard for Developing Software Life Cycle Processes, 1074-1995*. He concluded that Uschold and King's method does not propose a design process for ontology building.

METHONTOLOGY

Fernández-López's analysis disclosed that METHONTOLOGY proposes a separation between the design phase and implementation phase during ontology building. Other similarities between METHONTOLOGY and the research method used in this work are: (i) METHONTOLOGY also starts with the identification of the ontology's purpose (see Blázquez et al., 1998), and (ii) it identifies the need for ontology evaluation (see Fernández-López et al., 1999, page 38). There is also a correspondence between the different stages of METHONTOLOGY, and the different steps of the method previously presented: Specification, Conceptualization, and Formalization (from METHONTOLOGY) are covered by the design stage; Implementation (from METHONTOLOGY) is equivalent to the implementation stage; and Maintenance (from METHONTOLOGY) is covered by the possibility of iteration between steps (see Figure 3.1). There are however a couple of differences between METHONTOLOGY and the research method outlined in previous sections.

First, as indicated by Fernández-López and Gómez-Pérez (2002), METHONTOLOGY is an *application-independent* method for ontology development. The method introduced previously, which extends and adapts Grüninger and Fox's method, is *application-dependent*. Application-dependence has advantages and disadvantages. The advantage of an application-dependent method is that the application helps during the evaluation stage to determine the suitability of the ontology developed. The drawback, is that the generality of the (logical) theory obtained (after the design stage) is questionable. Ontology development done with an application-dependent method is nonetheless valuable. As Frank (1997) notes: "New insight can be gained from detailed investigations in particular cases; ... generalizations, if the same observations are made several times, can then lead to a better general theory"[16].

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[16] A similar view is shared by Guttag and Horning (1980) who were hoping to discover *general techniques* that govern the formulation of problem-specific questions during software design, by looking first at

Second, Fernández-López and Gómez-Pérez (2002) state: "It is important to say that formalisation is not a mandatory activity, because if you use ODE or WebODE [i.e. tools supporting METHONTOLOGY], the conceptualisation model is automatically generated into ontological specification languages". Formalization, on the contrary, is a mandatory activity of the ontology development method previously introduced. One of the important benefits of formalization is that terms "become unambiguously defined such that the danger of miscommunication and misuse is reduced" (Egenhofer et al., 1999). For this reason, it is argued here that, despite the high learning curve of formal languages, formalization should be kept in any ontology design activity.

Third, METHONTOLOGY discusses (in addition to design, implementation, evaluation, documentation, presented in this work) some additional activities such as knowledge acquisition, configuration management, scheduling, control and quality assurance. The importance of these activities is acknowledged, but their detailed discussion is postponed to future work.

The rapid ontology development (ROD) method

ROD, as presented in (Lavbič and Krisper, 2010; Lavbič et al., 2011), has three steps: pre-development, development, and post-development. The design stage introduced in this chapter is equivalent to the combination 'pre-development + development' (from ROD); implementation stage and post-development (from ROD) are alike; both methods take into consideration ontology evaluation. There are two main differences:

- the first difference concerns the goals of the methods. ROD intends to serve 'less technically knowledgeable users', and therefore tries "to minimize the need of knowing formal syntax required for codifying the ontology" (Lavbič and Krisper, 2010). The method proposed in this work does not pursue this goal. Rather, the goal is to achieve excellent ontology designs, which will support better ontology implementations. A direct consequence of this goal is that there is no need to restrain oneself to tools and techniques that can be easily and quickly learned, and used by non-experts[17].
- the second difference is that ontology evaluation is achieved in ROD through the ontology completeness indicator. On the contrary, the method introduced in this work has only (and intentionally) specified what should be evaluated, leaving room for flexibility as regards how the evaluation should be done (e.g.

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individual examples of problem-specific questions.

[17] See (Guttag and Horning, 1980) for similar arguments in the context of software design.

automatic, semi-automatic or manual evaluation, involvement of domain experts or not, etc.).

3.4 Related work

Section 3.3 has given a detailed presentation of the method for ontology building used in this work. This section touches upon foundational ontologies and ontologies for the geographic domain, and provides examples for each of these types of ontologies.

3.4.1 Foundational ontologies

According to Borgo and Masolo (2009), foundational ontologies are ontologies that: (i) have a large scope, (ii) can be highly reusable in different modeling scenarios, (iii) are philosophically and conceptually well founded, and (iv) are semantically transparent and richly axiomatized. The authors indicate further that the focus of foundational ontologies is on very general concepts (e.g. object, event, quality, role) and relations (e.g. constituency, participation, dependence, parthood), that are not specific to particular domains but can be suitably refined to match application requirements. Foundational ontologies correspond to what is termed *top-level ontologies* in (Guarino, 1997, 1998), *upper ontologies* in (Mascardi et al., 2007a,b; Nguyen, 2011), *upper-level ontologies* in (Smith, 2003) and *reference ontologies* in (Lamp and Milton, 2004). Some examples of foundational ontologies can be found in (Mascardi et al., 2007a,b). Comparisons of BFO, Cyc, DOLCE, GFO, and SUMO[18] are documented in (Mascardi et al., 2007a,b; Ahmad and Lindgren, 2010).

As mentioned in Section 3.3.3, all the terms of the ontology developed in this work will be aligned to a foundational ontology[19]. Mika et al. (2004) argue that one of the long term benefits of alignment is that it allows a comparison between several aligned ontologies. Additional benefits of alignment for ontology design are conceptual disambiguation, increased axiomatization, improved design (see Mika et al., 2004). A last benefit of alignment to a foundational ontology is that it helps the ontology designer to relate his/her work to already existing ontologies.

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[18] The explanation of the acronyms is available at Page xvii.

[19] Section 4.3.2 presents the foundational ontology used in this work as well as the motivation for its choice.

3.4.2 Geo-ontologies

Geo-ontologies can be defined after Fonseca and Câmara (2009), as ontologies which describe *entities*, *semantic relations*, and *spatial relations*: *entities* can be assigned to locations on the surface of the Earth; *semantic relations* between these entities include for example hypernymy, hyponymy, mereonomy, and synonymy; *spatial relations* between entities include for instance adjacency, spatial containment, proximity and connectedness. Significant attention has been devoted to ontology research in GIScience, and the goal of this section is to briefly present some of the previous work[20]. Examples of geo-ontologies[21], with different levels of generality and formality, can be found in (Smith and Mark, 1998, 1999; Bittner and Smith, 2003a,b; Lemmens, 2003; Raskin, 2003; Reitsma and Bittner, 2003; Grenon and Smith, 2004; Raskin and Pan, 2005; Abdelmoty et al., 2005; Arpinar et al., 2006; Perry et al., 2006; Raskin, 2006; Hess et al., 2007; Bennett et al., 2008; Kauppinen et al., 2008; Bittner et al., 2009; Lopez-Pellicer et al., 2010; Sinha and Mark, 2010; Bittner, 2011).

Relevant frameworks for ontology research in GIScience are the tiers of ontology presented in (Frank, 2001, 2003), the layered mereotopological framework suggested in (Donnelly and Smith, 2003), the framework for mapping ontologies and geographic conceptual schema from Fonseca et al. (2003), and the framework for identification and resolution of semantic heterogeneity between geographic categories presented in (Kokla and Kavouras, 2005). Further examples of frameworks include the architecture of an ontology-driven GIS outlined in (Fonseca et al., 2002b), the framework for measuring the degree of interoperability between geo-ontologies suggested in (Fonseca et al., 2006), the framework for geographic information ontologies proposed in (Couclelis, 2010), and the observation-driven framework from Janowicz (2012).

In parallel, there has also been works bringing to the fore some desiderata for geo-ontologies. Galton (2003) identified three key desiderata for a fully-temporal geo-ontology; Smith and Mark (2003) pointed out the need for both field-based and object-based ontologies; and Galton (2005) called for the development of an ontological framework which takes into account the relationship between objects and fields. Additional examples of desiderata for geo-ontologies can be found in (Klien and Probst, 2005; Henriksson et al., 2008): Klien and Probst argued in favor of the separation between concepts for data representation (e.g. point, line, polygons) and geospatial concepts (e.g. town); Henriksson et al. argued that geo-ontologies should contain classes that

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[20] The section serves illustrative purposes only and does not aim to be exhaustive.

[21] The examples that follow are a mix of ontologies developed from both a philosophical and an information science point of views, and this reflects the interdisciplinary nature of the field of GIScience.

describe four aspects, namely: spatial aspects of places (e.g. location), aspects of regional geography (e.g. administrative regions), aspects related to human interaction with nature (e.g. land use), and aspects related solely to the physical environment (e.g. landforms).

Examples of research projects devoted to the development of geo-ontologies were mentioned in (Mark et al., 2000, 2004). Cognitive categorization of geographic entities was the subject of (Mark et al., 1999; Mark and Turk, 2003), and Casati et al. (1998) proposed three key theoretical tools that can help to solve ontological problems arising in the geographic domain. Relevant reviews to ontology research in GIScience appear in (Agarwal, 2005) and (Bateman and Farrar, 2004, 2006).

3.4.3 Discussion

Section 3.4.2 provides evidence that the topic of ontology has received a significant amount of scholarly attention in GIScience. Nonetheless, apart from (Reitsma and Bittner, 2003), few authors in GIScience have touched upon the notion of resolution[22]. Reitsma and Bittner's investigation relied on the tacit assumption that the world is organized into hierarchies[23], and focused on the characterization of the relationships between objects and processes at various hierarchical levels ('granularity tree' in the authors' terminology). Their study led to a conclusion regarding the nature of processes, namely: a part of a process is contained within the spatial and temporal extent of the whole process, and has a higher spatial and temporal grain than the whole process. As mentioned in Section 1.2.3, the goal of the current work is to investigate how resolution is introduced in observation processes. A necessary assumption thereby is that there exists a world (a.k.a. reality) that can be observed through some means. More specifically, it follows from the adoption of Kuhn's semantic engineering view, that there is an assumption of the existence of *observation sentences* in the sense of Quine. According to Quine (1995)[24], observation sentences:

> "…are occasion sentences - true on some occasions, false on others …they report intersubjectively observable situations, observable outright …all members of the language community are disposed to agree on the truth or falsity of such a sentence on the spot, if they have normal perception and are witnesses to the occasion" (page 22).

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[22] See, along the same lines, an early statement from Frank (2009a).

[23] See for example the last comment of the paper in (Reitsma and Bittner, 2003, section 6).

[24] See also (Quine, 1993) for a pertinent discussion on observation sentences.

The investigation pursued here is therefore different in its goal and underlying assumption from the one done in (Reitsma and Bittner, 2003); both works however are necessary pieces of the 'science of scale' whose agenda was outlined in (Goodchild and Quattrochi, 1997).

3.5 Summary

Ontology is the 'tool' used for the formal specification of the spatial and temporal resolution of sensor observations, and this chapter situates the thesis in the current literature on ontology. There has been (implicit and explicit) calls for the separation between design task and implementation task during ontology development (in information science), and the chapter offered an in-depth discussion of ontology development along these lines. The following is an epitome of the main ideas exposed:

I. The work adopts an information science interpretation of ontology;

II. Constructivism is the philosophical basis for the ontology development method proposed;

III. The ontology development method has two main blocks: a design (or modelling) stage, and an implementation (or encoding) stage;

IV. The outcome of the design stage is a (logical) theory, the implementation stage produces a computational artifact that can serve the purposes of practical problem solving. Each of these stages should be evaluated separately, and possible evaluation criteria for each of the stages were presented;

V. Ontology languages cannot be rigorously classified as belonging to one category (i.e. design) or to the other (i.e. implementation), but should be placed along the implementation-design continuum;

VI. No work on ontology in GIScience has so far investigated how resolution is introduced in observation processes.

CHAPTER 4

Ontology design stage - resolution of single observations

The design of the ontology of resolution is spread over two chapters. This chapter - the first of the two - presents the motivating scenario for the work and selects one of the existing observation ontologies as starting point for the development of the ontology of resolution. It introduces a receptor-based theory of spatial and temporal resolution (applicable to single sensor observations) and presents the formal specification of the theory in Haskell[1].

4.1 Motivating scenario

A collection of sensors has been deployed in a city to measure the concentration of carbon monoxide (CO) in the air. The concentration of CO is taken at different moments of the day, by different carbon monoxide analyzers (COAs) placed at different locations in the city. A group of scientists is interested in analyzing the quality of the air in the city. Using the Semantic Sensor Observation Service (SemSOS)[2], the group is able to develop an application software which retrieves data generated by the COAs so that differences of sensors and observations regarding measurement procedures and measurement units are harmonized. The group is now interested in *extending the semantic capabilities* of the application so that the resolution of the observations is made explicit, and retrieval at different resolution, with minimal human intervention, is made possible. In particular, the group would like to know the spatial and temporal resolution of one observation (**Q1**), and the spatial and temporal resolution of the observation collection produced by the COAs (**Q2**). Making an application software understand what

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[1] This chapter is an extended and substantially revised version of (Degbelo, 2013), published at GI_Forum 2013.

[2] See an introduction to SemSOS in (Henson et al., 2009).

'resolution' of an observation (or an observation collection) means, is only possible through a formal characterization of the concept[3].

4.2 Viewpoint on space and time

Galton (2004) brought forward two different ways of viewing space and time[4]: the Newtonian, and the Non-Newtonian. The Newtonian view of space and time reposes on two tenets indicated in (Galton, 2004):

P1: space and time are *absolute* frameworks existing independently of any objects and events that might populate them;

P2: space and time are *separate* frameworks, i.e. given two events, their spatio-temporal separation can be cleanly resolved into a temporal component and a spatial component, and these components, for those two events, are absolute (i.e. the same for all observers).

Regarding the Non-Newtonian ways of viewing space and time, Galton (2004) draws a distinction between two doctrines: Leibniz's relationalism, and Einstein's relativistic point of view. As Galton (2004) notes, Leibniz is opposed to Newton on **P1**, that is, Leibniz argues that space and time have no absolute, independent existence but only exist by virtue of the things that exist and the events that occur. In a nutshell, Leibniz's viewpoint is that space and time are *relational*. Einstein, on the contrary, is opposed to Newton as regards **P2**. Einstein's standpoint is that space and time are not cleanly separable in the way that Newton (and common sense) supposed, rather, space and time are *relative* to one another, and to the observer[5].

Galton (2004) asserts that the Theory of Relativity (TR) is largely irrelevant to GIScience because of the scale of the earth[6]. For this reason, a *relative* view on space and time is not adopted for the theory of spatial and temporal resolution proposed in this work. Newton's tenet **P2** is adopted, i.e. space and time are viewed as *separate* frameworks. Commitment to either an absolute (Newton's tenet **P1**) or a relational

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[3] This scenario presupposes the use of in-situ COAs, but remote COAs such as the MOPITT instrument introduced in (Drummond and Mand, 1996) might be also used for data collection purposes. The theory proposed in this chapter takes into account both in-situ and remote sensors.

[4] See also, related to this, (Nunes, 1991) for an early discussion on a model of geographic space suitable for GIS, and (Couclelis, 1999) for a discussion on the conceptual roots of space and time representations.

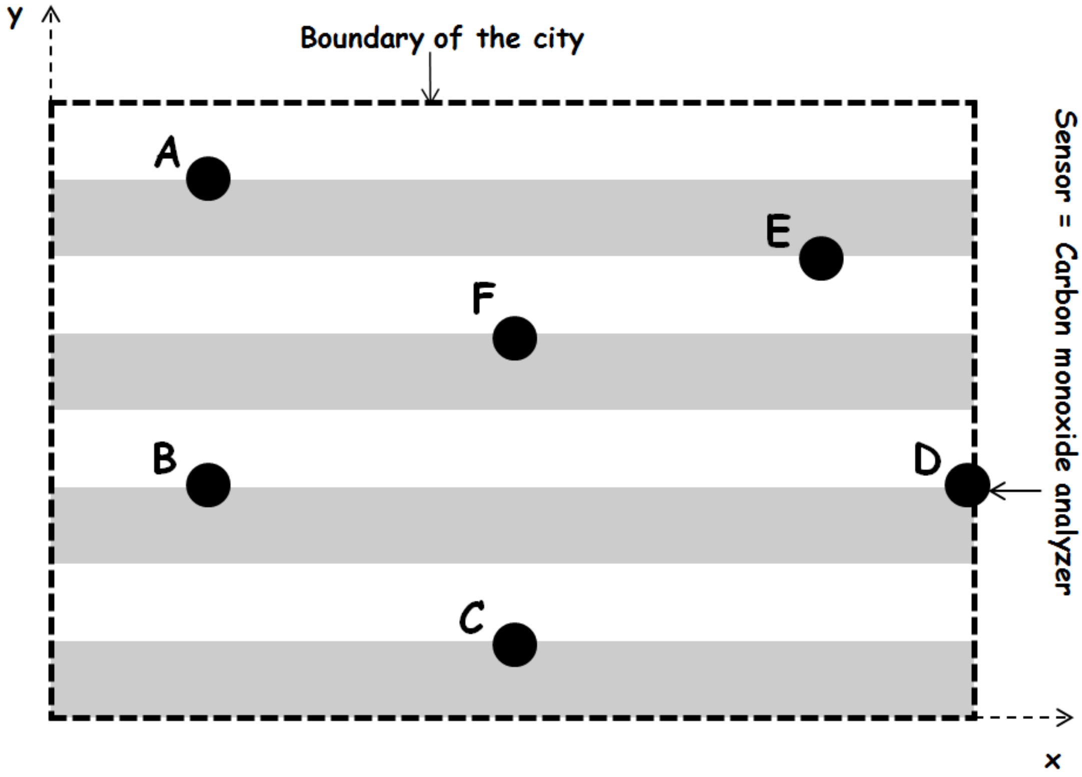
[5] See (Galton, 2004) for the detailed discussion.

[6] On the scale of the earth, TR can indeed be replaced by its Newtonian approximation, in which there is a clean separation between the time dimension and the three dimensions of space.

(Leibniz) view on space and time is not required for the theories of resolution exposed in the rest of the work. The author remains neutral as regards these two views.

The assumption that space and time are separate frameworks allows the projection of the scenario introduced in Section 4.1 onto space and onto time[7]. The projection onto space omits altitude for simplicity, and results in a plane on which points representing the sensors are distributed (see Figure 4.1)[8]. The projection onto time results in six lines as Figure 4.2 shows. Each line represents a day, and a point on a line indicates that a sensor measures the concentration of carbon monoxide at this moment of the day. For example, sensor A returns three values per day; sensor B, five values a day; sensor C, one value; sensor D, three values; sensor E, two values; and sensor F, four values.

Figure 4.1: Projection of the motivating scenario onto space



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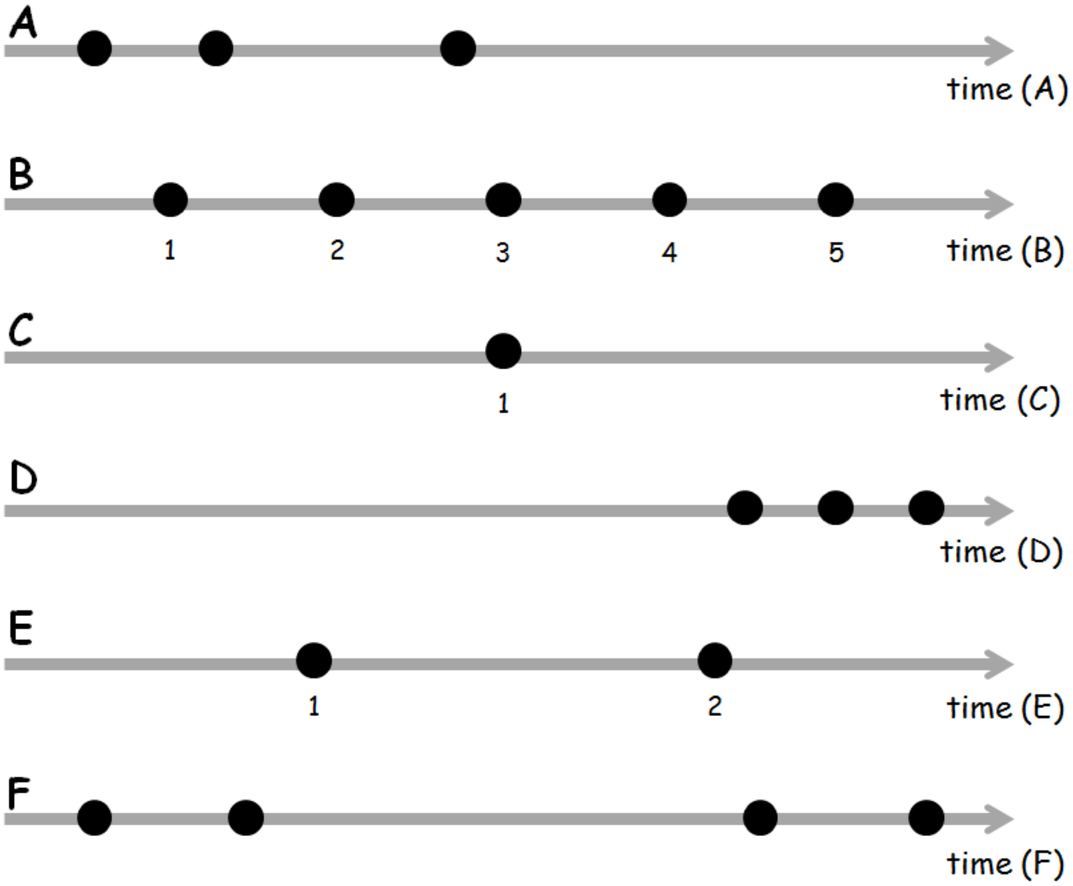
[7] If space and time were not cleanly separable, such a differentiation between a spatial component (i.e. projection onto space) and a temporal component (i.e. projection onto time) for the scenario would not have been adequate.

[8] The representation of the x-axis and y-axis on the figure reflects the possibility of ascribing a coordinate system to the plane, in order to locate the sensors.

Figure 4.2: Projection of the motivating scenario onto time



4.3 Identification of the terms of the ontology (Part I)

This section presents the terms of the ontology of resolution relevant to single observations. Existing observation ontologies are first considered for reuse. Second, the foundational ontology and the ontology design language adopted for the remainder of the work are presented. The terms of the ontology are presented third, and their alignment to DOLCE is presented at last.

4.3.1 Reuse of existing ontologies

Section 1.2 introduced previous attempts to provide a conceptual clarification of observation, and touched upon existing observation ontologies. This section aims at selecting one of these observation ontologies as starting point for the development of the ontology of resolution. Three criteria are used to guide this choice. They are as follows:

- *Remain neutral with respect to the distinction between field and object* (C1): as mentioned in (Fonseca et al., 2003), the most widely accepted conceptual model for GIScience considers that geographic reality is represented either as fully definable entities (objects) or smooth, continuous spatial variation (fields). An ontology of resolution which remains neutral to the distinction field vs object is therefore highly desirable, to ensure a wide applicability of the terms suggested in GIScience.

- *Take into account humans as sensors* (C2): Goodchild (2007) defined Volunteered Geographic Information (VGI) as the widespread engagement of private citizens in the creation of geographic information, and pointed out some valuable aspects of the information produced by volunteers: (i) the information can be timely; (ii) it is far cheaper than any alternative; and (iii) information produced by volunteers can tell about local activities in various geographic locations that go unnoticed by the world's media. Humans acting as sensors are at the heart of VGI; the ontology of resolution should therefore be developed using a notion of sensor encompassing both instruments and humans, to be usable for both observations generated by humans and technical devices. Only ontologies capable of processing both types of observations can help to take advantage of VGI's potential, namely, "the potential to be a significant source of geographers' understanding of the surface of the Earth" (Goodchild, 2007).

- *Take into account observation as a result and observation as a process* (C3): the term 'observation' is used to denote both the process of observing and the outcome of this process, and the ontology of resolution should be developed in such a way that justice is done to these two senses of observation.

Table 4.1 presents the results of the application of these 3 criteria to the observation ontologies from Section 1.2.2. An explanation of the results is provided in the next paragraphs.

Probst (2006) includes the concept *Instrument* in his basic ontology for observations. The concept of *HumanObserver* which appeared earlier in the paper is however omitted in the ontology, and this suggests that the author accounted only for technical sensors in his ontology. The modelling of the concept *Observation* as a subcategory of the class *Accomplishment* from the foundational ontology DOLCE accounts for the fact that an observation is a process (which might have other subprocesses as parts, and in which some entities participate). The class *Observation* is related to a class *Symbol* through the relation 'has_result', and this helps to incorporate the outcome of the observation process (i.e. observation as a result) in Probst's ontology. *Observation* is also

Table 4.1: Criterias C1, C2 and C3 applied to the observation ontologies

ONTOLOGIES	C1	C2	C3
Probst (2006)	✓	x	✓
Madin et al. (2007)	x	x	x
Kuhn (2009a)	✓	✓	✓
Janowicz and Compton (2010)	✓	✓	x
Compton et al. (2012)	✓	✓	x

Legend
✓: the ontology fulfills the criterion
x: the ontology doesn't fulfill the criterion

related to the DOLCE class *Quality* by means of the relation 'observes', and this indicates neutrality with respect to the distinction field vs object, because a *Quality* can be attributed to objects or abstract positions[9].

Madin et al. (2007) did not include any concept referring explicitly to sensors in their observation ontology called OBOE[10]. The definition of observation as "a statement that an entity of a particular type was observed" implies a consideration of observation as a result, but not as a process. In OBOE, the 'Entity' is what is observed, and the notion of entity is said to be 'extremely generic', but the extensions of the 'Entity' class presented in the paper (e.g. 'Organism Entity', 'Population Entity', 'Community Entity') suggest an object-based view of the world.

The functional ontology of observation and measurement (FOOM) from Kuhn (2009a) includes humans as sensors through the introduction of the term *Observer*. The specification of the class *Observable* as a quality (in the sense of the foundational ontology DOLCE) guarantees the neutrality vis-à-vis the object-based and field-based views. The ontology discusses both observation as a process, and observation as a result.

The ontology from Janowicz and Compton (2010) is one module of the ontology presented in (Compton et al., 2012). Both ontologies have in common that they model observation as a context (i.e. one way of interpreting detectable changes in the environment) and this modelling choice connotes a move from the notion of observation as

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[9] DOLCE allows qualities to inhere in *PhysicalEndurants* and *Non-PhysicalEndurants*. Objects from an object-based view are *PhysicalEndurants*. Abstract positions from a field-based view are DOLCE *SocialObjects*, which in turn are *Non-PhysicalEndurants*.

[10] The authors link 'Observation' to 'Measurement' in OBOE, and state in the paper that "[m]easurements are taken by a Recorder (human or non-human)", but do not mention this 'Recorder' in the ontology itself.

a process[11]. The definition of 'sensor' used in both ontologies includes humans. The explicit specification of the *ObservedProperty* (a quality in the sense of the foundational ontology DOLCE) suggests that both ontologies fulfill the criterion C1.

From the foregoing discussion, FOOM is the only ontology which fulfills all the criteria C1, C2 and C3 as outlined previously, and this motivates its choice as a basis for the development of the ontology of resolution.

4.3.2 Foundational ontology and ontology design language

Two additional choices go hand in hand with the choice of Kuhn's observation ontology: the choice of the foundational ontology, and the choice of the ontology design language. At this stage, the following argument holds, namely that while extending a *base ontology*[12], using its original foundational ontology and ontology design language is more efficient than using another foundational ontology and/or ontology design language. As a result, DOLCE is used as foundational ontology, and Haskell is used as ontology design language. DOLCE is descriptive and multiplicative. Descriptive means that the foundational ontology is based on the assumption that "the *surface structure* of natural language and the so-called commonsense have ontological relevance" (Masolo et al., 2003); multiplicative signifies that DOLCE "allows for different entities to be *co-localized* in the same space-time" (Masolo et al., 2003). Furthermore, the use of DOLCE as foundational ontology is in line with the engineering view of semantics presented in Section 3.3.1, in that DOLCE "does not make claims on the intrinsic nature of the world" (Borgo and Masolo, 2009). The taxonomy of DOLCE's basic categories is depicted in Figure 4.3.

Haskell is a functional programming language[13], and examples of its use as formal specification language can be found in (Timpf and Kuhn, 2000; Kuhn, 2002; Frank, 2003; Kuhn and Raubal, 2003; Winter and Nittel, 2003; Raubal and Kuhn, 2004; Schade et al., 2004; Kuhn, 2007; Ortmann and Kuhn, 2010; Posthuma, 2010; Schade et al., 2012; Weiser and Frank, 2012; Weiser et al., 2012). In the context of the current work, the use

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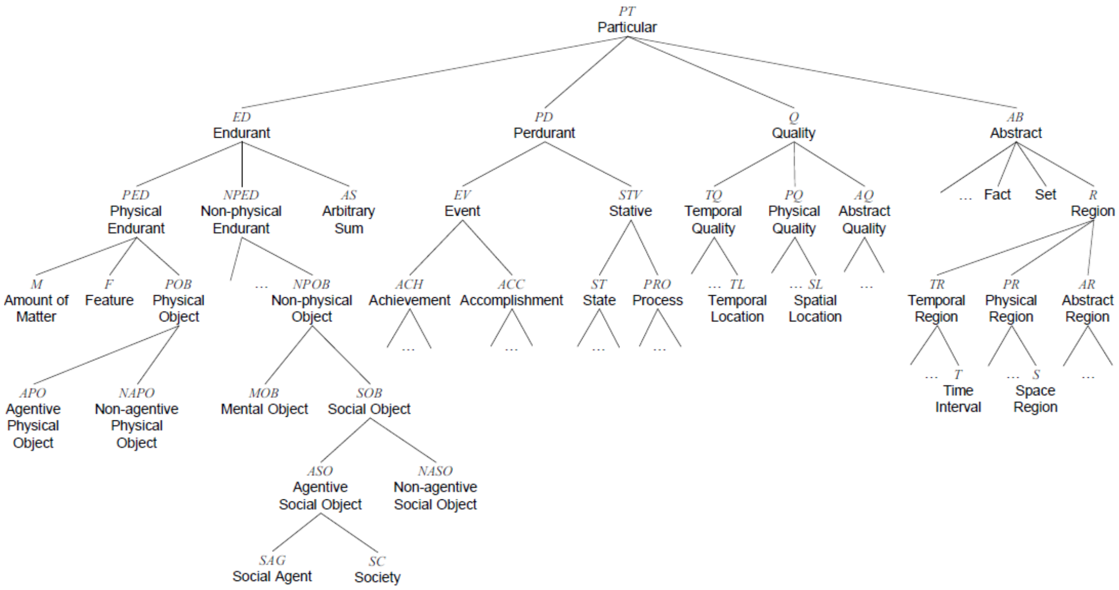
[11] Compton et al. (2012) state: "Researchers interested in the internal processes by which sensors translate stimuli into other representations may model observations as events", with 'event' being the term used in the foundational ontology DOLCE Ultra Light (DUL) to denote '[a]ny physical, social, or mental process, event, or state' (DUL was accessed from `http://www.ontologydesignpatterns.org/ont/dul/DUL.owl` on January 10, 2013).

[12] The term 'base ontology' denotes in this context an *ontology taken in its entirety*, and which is used as a starting point for another ontology development task.

[13] Or 'functional language' for short. An introduction to functional programming in Haskell can be found in (Thompson, 1999).

Figure 4.3: Taxonomy of DOLCE's basic categories (from [Masolo et al., 2003])



of Haskell as formal specification language comes with the benefit that it *guarantees an evaluation of the ontology with respect to consistency, correctness and completeness*. These three aspects (briefly discussed below) were already mentioned in (Frank and Kuhn, 1995), and have been revisited for detailed discussion in (Winter and Nittel, 2003). Definitions of consistency, correctness[14] and completeness are available in Section 3.3.6.

- *consistency*: "consistency [of an Haskell specification] is proven if a module or package is loaded successfully" (Winter and Nittel, 2003);
- *correctness*: there are two main aspects that are covered under the term 'correctness': (i) the fact that the ontology effectively represents 'aspects of the real world', and (ii) the fact that the ontology developer *said what he intended to say*. A firm and definite statement about the ontology's ability to effectively represent aspects of the real world cannot be provided (though validation by domain experts or peers is often used as means to guarantee this aspect of correctness). On the other hand, Haskell helps the ontology developer to check whether he said what he intended to say. This is possible through tests on the behaviour of the specification, and comparison of the test values with the values expected. Examples of test cases are available in the two Haskell modules accompanying the theory of resolution proposed (see `http://purl.net/ifgi/degbelo/thesisresources`);
- *completeness*: completeness of the ontology (i.e. its appropriate coverage of the do-

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[14] Correctness as defined in Winter and Nittel is covered under the term 'accuracy' in Section 3.3.6.

main of interest) has also various aspects. In the strict sense, completeness refers to the ability of the ontology to cover *all what should be said* about spatial and temporal resolution of sensor observations. Gómez-Pérez (2001, 2003) pointed out that "we cannot prove . . . the completeness of an ontology". A more manageable aspect of completeness is the appropriate coverage of competency questions. This aspect of completeness is equivalent to *expressiveness*, and "competency questions are used to evaluate the expressiveness of the ontology" (Noy and Hafner, 1997). The examples introduced later in Sections 4.3.4 and 5.2.3 show how the terms of the ontology provide the necessary information to answer questions (**Q1**) and (**Q2**) from the motivating scenario; Sections 4.4 and 5.3 present how the terms of the ontology can be formally specified.

4.3.3 Terms of the ontology: resolution of a single observation

The observation ontology, as introduced in (Kuhn, 2009a) has five core concepts: *observable*, *stimulus*, *observer*, *observation value*, and *observation process*. The *observable* is the physical or temporal quality to be observed; the *stimulus* is a detectable change in the environment; the *observer* is someone or something that assigns a symbol to the observable; the *observation value* is the outcome of the *observation process*. For the remainder of the discussion, the term *observation* will be used to denote the *observation value*, and the term *particular* will be used to refer to the observed entity[15]. The specific terms of the ontology of resolution are highlighted in this section (and in Section 5.2) using a different **font**[16].

As discussed in Chapter 2, resolution is a property of a representation. On that account, two terms are introduced: **spatial resolution**, and **temporal resolution**. The **spatial resolution** is the amount of spatial detail in an observation, and the **temporal resolution** is the amount of temporal detail in an observation. There are at least three ways of modelling the spatial and temporal resolution of an observation.

The stimulus-centric approach

Stasch et al. (2009) suggested to constrain the spatial and temporal resolution of an observation by the spatial and temporal extent of the stimulus. A drawback of this approach is that there is no one-way of defining the spatial and/or temporal extent of the stimulus involved in an observation process. For instance, in the case of a thermometer

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[15] The *observable* inheres in the *particular*.

[16] See Appendix A for a recap of all the terms of the ontology of resolution and their definitions.

placed in a room of area 20m^2 and measuring the temperature, the stimulus is the *heat flow of the amount of air in the room*. It can be stated that the spatial extent of the stimulus is equal to the spatial footprint of the amount of air in the room (e.g. 20 m^2), but there is no logical basis for preferring the value 20m^2 over smaller values of the amount of air in the room such as 15m^2, 10m^2 or 1m^2. In fact, every size of the amount of air in the room falling within the interval $]\,0, 20\,]$ has an equal right to be called the spatial extent of the stimulus participating in the observation process. Said another way, vagueness issues arise as to the determination of the spatial extent of the stimulus. As regards the temporal extent of the stimulus, its characterization is not straightforward because, as Kuhn (2009a) pointed out, a detectable change can be viewed as a process (periodic or continuous) or an event (intermittent). The duration of the stimulus is therefore *perspective-dependent*.

The property-centric approach

Frank (2009c) indicates that a sensor always measures over an extended area and time (called ϵ), and reports a point-observation (i.e. average value for an attribute) for this extended area and time. The extended area or time was termed the *support* of the sensor. Frank ascribes support to the sensor, but support has also been attributed in the literature to the observation[17]. Modelling support as an attribute of the observation rather than of the sensor is the standpoint adopted in this work[18], because ϵ needs not be related to the characteristics of the sensing device. For example, as Burrough and McDonnell (1998) pointed out, the support in demographic studies is often an irregularly shaped area determined by a census district or postcode area[19]. A general definition of support is "the largest time interval [T], area [L^2] or volume [L^3] for which the property of interest is considered homogeneous" (Finke et al., 2002). The spatial resolution of an observation can be equated with its spatial support, and its temporal resolution with its temporal support. The downside of such an approach is that no precision is given regarding the way of estimating the area, volume or time interval for which the *property of interest is considered homogeneous*. The example of demographic studies mentioned above, illustrates that the determination of the support involves in certain cases a certain degree of arbitrariness. Using support as a criterion to character-

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[17] For example, Atkinson and Tate (2000) define support as "[t]he size, geometry, and orientation of the space on which the *observation* is defined [emphasis added]".

[18] This standpoint departs from the approach taken in (Degbelo, 2013) where support was modelled as an attribute of the sensor.

[19] See page 101. The support in this case is determined independently of the sensor (i.e. the person collecting and reporting the number of people available in a district).

ize the resolution of the observation implies therefore a certain degree of arbitrariness inherent in the resolution value. The next subsection will attempt to improve this situation by proposing a method to characterize the resolution of the observation based on the physical characteristics of the observer.

The receptor-centric approach

In line with Kuhn (2009a), the observation process is conceptualized as consisting of four steps (the first two steps are required only once, to determine the observed phenomenon):

Step1: choose an observable,

Step2: find one or more stimuli that are causally linked to the observable,

Step3 (also called 'impression'): detect the stimuli producing analog signals,

Step4 (also called 'expression'): convert the signals to observation values.

The entity which produces the analog signal upon detection of the stimulus (Step 3) is termed at this point the **receptor**. **Receptors** are similar to the *threshold devices* introduced in (Braitenberg, 1984), in that the production of the output (analog signal) doesn't happen immediately upon activation of the input (stimulus), but only after a short delay. However (and contrary to Quine, 1993), **receptors** are not considered as the interface between the external world and the observer. In other words, **receptors** don't need to be located at the *surface* of the observer. It is suggested here to use the spatial region containing all the receptors stimulated during the observation process as criterion to characterize the spatial resolution of the observation. The short delay required by the receptors to produce analog signals (upon detection of the stimulus) can be used a criterion to specify the temporal resolution of the observation.

Two new terms (borrowed and adapted from Neuroscience) are introduced at this stage: the **spatial receptive field** (of the observer) and the **temporal receptive window** (of the observer). The **spatial receptive field** (SRF) is the spatial region of the observer which is *stimulated during the observation process*[20]. The **temporal receptive window** (TRW) is the smallest interval of time required by the observer's receptors in order to produce analog signals. This definition of SRF is compatible with the one of *receptive field* in Neuroscience as a "specific region of sensory space in which an appropriate

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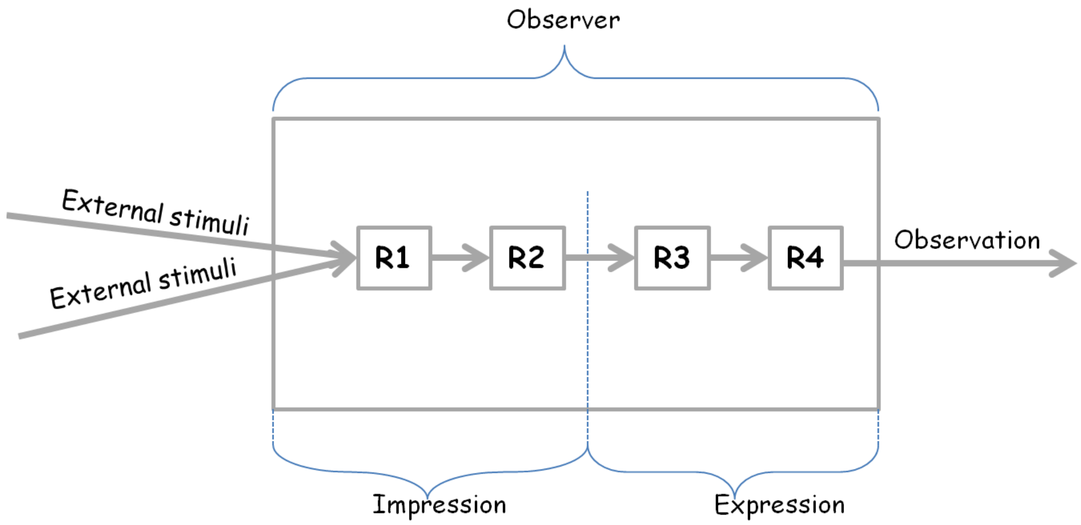
[20] This spatial region can be seen as two-dimensional (e.g. the palm of the hand) or three-dimensional (e.g. the whole hand) depending on the type of receptors participating in the observation process, and hence the word 'field' in SRF to reflect this fact.

stimulus can drive an electrical response in a sensory neuron" (Alonso and Chen, 2009). The definition of TRW paraphrases and generalizes to all sensor devices the definition proposed in (Hasson et al., 2008; Lerner et al., 2011)[21]. The **spatial resolution** of an observation can be approximated by the **spatial receptive field** of the observer, and its **temporal resolution** could be equated with the **temporal receptive window** of the observer participating in the observation process. There might be a chaining of different types of receptors in an observation process. In such cases, the relevant receptors for the computation of the spatial and temporal resolution are those that are stimulated by *external stimuli*. Figure 4.4 illustrates this point.

Figure 4.4: Observer with several receptors*



*Only receptor R1 is relevant to the estimation of the spatial and temporal resolution of the observation because it is directly stimulated by external stimuli. An example of observation process where several receptors are chained is the hearing process as described in (Society for Neuroscience, 2012). The process can be summarized as follows: *eardrums* (R1) collect sound waves and vibrate; after them, *hair cells* (R2) convert the mechanical vibrations to electrical signals. These electrical signals are then carried to the auditory cortex, i.e. the part of the brain involved in perceiving sound. In the auditory cortex, there are *specialist neurons* (R3) which specialize in different combinations of tone (e.g. some are sensitive to pure tones, such as those produced by a flute, and some to complex sounds like those made by a violin). At last, there are other neurons (R4) which can combine information from the specialist neurons to recognize a word or an instrument.

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[21] Hasson et al. (2008); Lerner et al. (2011) initially defined TRW of a neuron (or a cortical microcircuit) as "the length of time before a response during which sensory information may affect that response".

4.3.4 Examples of SRF and TRW for a single observation

With the approach introduced in Section 4.3.3, the computation of the spatial and temporal resolution of a single sensor observation involves three steps:

Step1: identify the type of receptor involved in the observation process;

Step2: find the duration needed for the production of analog signal upon detection of the stimulus (relevant to the estimation of the TRW);

Step3: find the size of the receptors and the number of receptors stimulated during the observation process (relevant to the estimation of the SRF).

The author expects the information for Steps 1-3 to be found in technical documentations (for sensor devices), and in research outcomes of the field of Neuroscience (for human observers). This section will give some examples of receptor, spatial receptive field and temporal receptive window for human and technical observers[22].

EXAMPLE 1: A Carbon Monoxide Analyzer of type GM901[23] returns the concentration of carbon monoxide (Observation) in a gas. The **receptor** of this sensing device is the *measuring probe*. The **spatial receptive field** is equal to the size of the opening of the measuring probe, and the **temporal receptive window** is equal to the response time. The value of the **temporal receptive window** lies between 5 and 360 seconds. The diameter of the opening of the measuring probe varies between 300 and 500 millimeters and this suggests a **spatial receptive field** between 707 and 1963 square centimeters. This example provides the necessary information to answer the question 'what is the spatial and temporal resolution of one observation?'[24] (i.e. **Q1**) in reference to the motivating scenario from Section 4.1.

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[22] The production of an observation involves two stages mentioned in Section 4.3.3: impression and expression. Strictly speaking, the TRW is the time interval required for the impression operation. Most information currently available is about the duration of the *whole* observation process (i.e. impression + expression). More work will be needed in the future to tease the impression's duration and the expression's duration apart. For the time being, the examples of *temporal receptive window* that follow are based on the assumption that the time needed for the expression operation is negligible compared to the time needed for the impression operation. That is, for now, TRW $\approx$ duration of the whole observation process.

[23] See `http://www.sick.com/us1/en-us/home/products/product_portfolio/analyzers_systems/Pages/gm901.aspx`; last accessed: April 19, 2014.

[24] Goodchild (2011b) points out that resolution - for the spatial dimension - can be expressed in either a linear or areal or volumetric measure. Goodchild and Proctor (1997) are more restrictive, indicating that the scientific community has traditionally defined resolution as a linear measure, and arguing that measures of spatial resolution should always have dimensions of length. Throughout the work, values of spatial resolution are expressed using areal measures. Conversions to linear measures are straightforward and are achieved by taking the square roots of areal measures.

EXAMPLE 2: A digital camera returns an image (Observation), with a **spatial receptive field** equal to the size of the aperture, and a **temporal receptive window** equal to the shutter speed. The aperture is "the size of the adjustable opening inside the lens, which determines how much light passes through the lens to strike the image sensor" (Schurman, 2013a), and the shutter speed is "the amount of time the digital camera's shutter remains open when capturing a photograph" (Schurman, 2013b). The **receptor** of the camera is the *image sensor*, but the size of the aperture determines the actual portion of the image sensor that is stimulated during the production of an image. The shutter speed determines the duration of the image sensor's exposure to light. Further examples of receptors for technical observers include *thermistors* (for medical digital thermometers), *bulbs* (for clinical mercury thermometers), *telescopes* (for laser altimeters), *aneroid capsules* (for pressure altimeters), *bulbs* (for psychrometers), to name a few.

EXAMPLE 3: A human observer reports on a scenery at a **temporal receptive window** of about 14 milliseconds (ms) using the sentence 'there is an apple here' (Observation). The value of TRW is assigned based on the results from (Keysers et al., 2001), where the authors investigated the mechanisms involved in object recognition by monkeys'- and humans' visual systems. Keysers et al. (2001) studied visual responses to very rapid image sequences composed of "color photographs of faces, everyday objects familiar and unfamiliar to the subjects, and naturalistic images taken from image archives" and reported a rate of 14 ms per image for human perception and memory.

EXAMPLE 4: The previous example is illustrative of the temporal receptive window of an *observation sentence* as defined in (Quine, 1993, 1995) in that the observer assigns unreflectively on the spot a value to external stimuli. Lederman (1997) indicates that, in the context of purposive exploration of the world, it typically takes 1 to 2 seconds to identify common objects such as spoon. Therefore, the **temporal receptive window** for the observation 'spoon' in the context of a purposive exploration task using human hands (of blind subjects) varies between 1 and 2 seconds. The **temporal receptive windows** of observations produced by human observers will depend on the observer, the type of task, and the stimulus.

EXAMPLE 5: The **spatial receptive field** of human observations is equal to the size of the surface stimulated during the observation process. This surface might be calculated using the product N * S, where N is the number of receptors which have *participated* in the observation process, and S is the size of one receptor. As starting point for the computation, the knowledge presented in Table 4.2 can be used. The *exact* knowledge of the receptors which have participated in an observation process will become available as Neuroscience evolves[25].

Table 4.2: Examples of receptors for a human observer

SENSE	RECEPTORS, NUMBER & SIZE	REFERENCES
Hearing	*eardrum* (or tympanic membrane) of the ear[26]; there is one eardrum per ear; the surface area of an eardrum is about 85 mm^2	(Society for Neuroscience, 2012; Britannica.com, 2013b; Chudler, 2013)
Sight	*photoreceptors* of the retina; photoreceptors are about 125 million in each human eye; their diameter varies roughly between 2.5 µm and 10 µm[27]	(Kolb, 2005; Society for Neuroscience, 2012; Chudler, 2013; Optipedia, 2013)
Smell	*olfactory cilia* of the olfactory neuron in the nose; there are about five million olfactory neurons in each nose, each neuron has 8-20 cilia; cilia have a length between 30 and 200 µm	(Leffingwell, 2001; Jenkins et al., 2009; Chudler, 2013; Pines, 2013)
Taste	*taste buds* of the tongue; a human has between 5,000 and 10,000 taste buds; taste stimuli interact with taste buds at a small 2-10 µm region called the taste pore	(Linden, 2001; Meyerhof, 2008; Society for Neuroscience, 2012; Britannica.com, 2013a; Chudler, 2013)
Touch	*touch receptors* of the skin; there are about 17,000 touch receptors in the human hand; the mean spatial receptive field of touch receptors of type FAI is about 12.6 mm^2	(Lederman, 1997; Society for Neuroscience, 2012; Chudler, 2013)

As this section shows, a receptor-centric approach to characterize the spatial and temporal resolution of a sensor observation is applicable to both in-situ (e.g. tongue) and remote (e.g. eye) sensors, and to both human and technical observers. Informa-

---

[25] Krulwich (2007) informs that it is only in 2002 that it became the new view that there is a fifth taste (umami), in addition to the four admitted during many centuries (bitter, salty, sour, sweet). This fifth taste is detected by a specific type of receptors (receptors for L-glutamate on the tongue).

[26] Treating eardrums as receptors (instead of the hair cells of the cochlea for example) is the direct consequence of the fact that receptors in this context *must be* directly stimulated by external stimuli.

[27] There are two major types of photoreceptors: rods and cones (see Kolb, 2005; Society for Neuroscience, 2012, for details). Diameters vary between 3 and 5.5 µm for rods, and between 2.5 and 10 µm for cones.

tion given about the Carbon Monoxide Analyzer of type GM901 (technical observer) was extracted from the technical documentation of the product[28]. Table 4.2 illustrates that the (neuroscience) literature is a useful source to gather necessary information to estimate the spatial resolution of observations produced by human observer. (Keysers et al., 2001), cited previously, is an example showing that the literature on neuroscience is also a useful source to collect information for the computation of the temporal resolution of observations generated by human observers.

4.3.5 Alignment to DOLCE: resolution of an observation

'Spatial resolution', 'temporal resolution', 'spatial receptive field', and 'temporal receptive window' as characteristics of an entity (the observation or the observer) correspond to the notion of *quality* in DOLCE. A quality can be defined as "any aspect of an entity (but not a part of it), which cannot exist without that entity"[29]. Spatial receptive field and temporal receptive window inhere in the observer, and are therefore *physical qualities*[30]. Spatial resolution and temporal resolution inhere in the observation (i.e. a social object), and hence belong to DOLCE's class *abstract quality*. Finally, DOLCE proposes a general distinction between *agentive physical objects* (i.e. endurants with unity to which we ascribe intentions, beliefs and desires), and *non-agentive physical objects* (which are endurants which constitute these agentive physical objects). The receptor, being an element of the observer, is a *non-agentive physical object*[31].

4.4 Formal specification: resolution of a sensor observation

The following example adapted from (Winter and Nittel, 2003) gives a brief introduction to the use of Haskell as formal specification language. A formal specification in Haskell consists of *data types*, *operations* (specifying behaviours pertaining to the data types), and *axioms* (i.e. equations that hold for the data types). A specification for points could include, for example, a *data type* POINTS, two *operations* (getX, getY) which return coordinates, and an *axiom* for equality between two points. Listing 4.1 presents a

---

[28] See `http://www.sick.com/us1/en-us/home/products/product_portfolio/analyzers_systems/Pages/gm901.aspx`; last accessed: April 19, 2014.

[29] The definition is taken from the foundational ontology DOLCE Ultra Light (`http://www.ontologydesignpatterns.org/ont/dul/DUL.owl`; last accessed: February 08, 2013).

[30] Spatial receptive field and temporal receptive window are also examples of *referential qualities*, i.e. "qualities of an entity taken with reference to another entities" (Ortmann and Daniel, 2011). Both SRF and TRW are qualities of the *observer* taken *with reference to the stimulus*.

[31] Put differently, the observer (which is an agentive physical object) *is constituted by* the receptor. For a more detailed discussion on constitution, see (Masolo et al., 2003).

simple formal specification for points in Haskell (comments to facilitate understanding are in italics)[32].

Listing 4.1: Haskell specification for the type 'Point'

```haskell
1  -- the keyword 'type' creates a synonym for an existing Haskell data type
2  type Name = String -- the (point's) name is of type String
3  type Value = Int -- a value in this example is of type Int
4  type Abscissa = Value -- the (point's) abscissa is of type Value
5  type Ordinate = Value -- the (point's) ordinate is of type Value
6
7  {- new data type declaration using the keyword 'data'
8     'data' is useful to define a single and new data type;
9     this type of point has a name, an abscissa, and an ordinate -}
10 data Point = Point Name Abscissa Ordinate
11
12 {- new data type declaration using the keyword 'class'
13    'class' is useful to define a collection of data types;
14    'POINTS' (below) refers to all the types of points for which it is
          possible to apply functions  to return their name, their abscissa and
          their ordinate values (the type 'Point' defined on line 10 is a
          specific example for the type 'POINTS') -}
15 class POINTS p where -- class declaration
16     -- declaration of the signature of the class
17         getName :: p -> Name
18         getX :: p -> Abscissa
19         getY :: p -> Ordinate
20
21 -- definitions of operations for the specific type 'Point'
22 instance POINTS Point where
23         getName (Point n x y) = n -- operation definition
24         getX (Point n x y) = x -- operation definition
25         getY (Point n x y) = y -- operation definition
26
27 -- definition of the equality axiom for the type Point
28 -- Haskell comes with a number of built-in classes. Classes have different
       implementations according to the type of data they are given. The Eq
       class is the generic class in Haskell to specify equality & inequality
       behaviour over data types and the Point data type is defined here as an
       instance of this class
29 instance Eq Point where
```

---

[32] More details about the Haskell class Eq introduced in the example can be found in (Thompson, 1999, page 220). The specification of the equality axiom for points is done using the instantiation of the type Eq (rather than the deriving mechanism in Haskell) as it gives more flexibility regarding the specification of the behaviour of the equality axiom.

```
        -- two Points are "equal" if they have the same name
        point1 == point2 = (getName point1 == getName point2) -- axiom definition
```

The case of a carbon monoxide analyzer (COA) of type GM901 reporting a value of the concentration of carbon monoxide (CO) at a certain location of the city (see Section 4.1) is taken as running example for the formal specification presented in this section[33]. Listing 4.2 introduces three relevant datatypes for the scenario: Magnitude (to represent the magnitude of a quality), Quale (entity evoked in a cognitive agent's mind when observing a quality), and ObsValue (to represent observation values)[34].

Listing 4.2: Definition of the datatypes Magnitude, Quale and ObsValue

```
-- A magnitude in this context is the size of a certain region in a quality space (magnitude as Double). This is in line with (Probst 2008) who views magnitudes as regions in a certain quality space and calls them atomic quality regions
type Magnitude = Double -- magnitude as Double

-- Definition of the datatype Quale
data Quale = Quale Magnitude

-- An observation value can have one of four types: numerical discrete (resulting from a counting process); numerical continuous (resulting from a measurement process - what is measured is the magnitude of a certain quality, and measurement results always come with an associated measurement unit); categorical nominal (cannot be organized in a logical sequence); categorical ordinal (can be logically ordered or ranked)
type Unit = String -- measurement unit as String
data ObsValue = Count Int | Measure Magnitude Unit | Category String | Ordinal String
```

The amount of air surrounding the COA is modelled as containing a certain amount (i.e. magnitude) of carbon monoxide, that is:

```
type Id = String -- an identifier
data AmountOfAir = AmountOfAir {carbonMonoxideMagnitude :: Magnitude}
cityAir = AmountOfAir {carbonMonoxideMagnitude = 2.8}
```

---

[33] The specification presented in this section is available for download at `http://purl.net/ifgi/degbelo/thesisresources/chapter4/ObservationResolution.hs`.

[34] See Probst (2008) for a detailed discussion about these notions.

A receptor has an id, a size, a processing time for incoming stimuli and a certain role. The receptor involved in the observation of the CO concentration in the city is the measuring probe (see Section 4.3.4). It has a size and a processing time set provisionally to 1500 cm^2 and 60 seconds respectively, and the role of detecting CO molecules[35]. The receptor's role is modelled here as a description in natural language.

```
type Area = Int -- spatial area as Int
type Duration = Int -- temporal duration as Int
type Description = String -- description in natural language as String
-- a receptor has an id, a size, a processing time for incoming stimuli, and
    a certain role
data Receptor = Receptor {receptorId :: Id, receptorSize :: Area,
    processingTime:: Duration, role :: Description}
measuringProbe = Receptor {receptorId = "re1", receptorSize = 1500,
    processingTime = 60, role = "detection of CO molecules"}
```

An observer has an id and a number of receptors of a certain type. It carries a quale and an observation value. The measurement unit used below for observation values is “ppm” standing for parts per million. For simplicity, it is assumed here that all receptors (with a similar function) have the same size[36], and there is no malfunction during the observation process (i.e. either all the receptors detecting the stimulus are stimulated or none of them). A COA has one measuring probe.

```
data Observer = Observer {observerId :: Id,  receptor :: Receptor,
    numberOfReceptors :: Int, quale :: Quale, observationValue :: ObsValue}
coAnalyzer = Observer {observerId = "ob1", receptor = measuringProbe,
    numberOfReceptors = 1, quale = Quale 0.0, observationValue = Measure 0.0
    "ppm"}
```

Listing 4.3 presents the alignment of the terms ‘observer’ and ‘receptor’ to DOLCE.

Listing 4.3: Alignment of observer and receptor to DOLCE

```
class PHYSICAL_ENDURANTS physicalEndurant
class PHYSICAL_ENDURANTS physicalObject => PHYSICAL_OBJECTS physicalObject
class PHYSICAL_OBJECTS agent => AGENTIVE_OBJECTS agent -- agentive physical
    objects
```

---

[35] The size of the receptor is set here to the size of the opening of the measuring probe; the opening of the measuring probe determines the actual portion of the measuring probe that is stimulated by external stimuli.

[36] This is in line with Quine (1993) who states: “The subject's sensory receptors are fixed in position, limited in number, and substantially alike”.

```haskell
class PHYSICAL_OBJECTS nonAgent => NON_AGENTIVE_OBJECTS nonAgent -- non-agentive physical objects

-- Qualities
-- Qualities have hosts in which they inhere
class QUALITIES quality entity where
        host :: quality entity -> entity

-- an observer is an agentive physical object
instance PHYSICAL_ENDURANTS Observer
instance PHYSICAL_OBJECTS Observer
instance AGENTIVE_OBJECTS Observer

-- a receptor is a non-agentive physical object
instance PHYSICAL_ENDURANTS Receptor
instance PHYSICAL_OBJECTS Receptor
instance NON_AGENTIVE_OBJECTS Receptor
```

During the perception of the observed quality (i.e. the carbon monoxide of the amount of air), the observer produces a quale. The perception of the observed quality involves inherently a loss of spatial and temporal detail, and this leads to a spatial and temporal resolution for the quale. The spatial resolution of the quale is modelled in the current work as being equal to the spatial receptive field of the observer involved in the perception operation. The temporal resolution of the quale is equal to the temporal receptive window of the observer which participated in the perception of the observed quality. The function magnitudeToQuale establishes a mapping from a certain magnitude to the corresponding quale, and more details about it are provided later in this formal specification.

```haskell
-- definition of the quality carbon monoxide
data PHYSICAL_ENDURANTS physicalEndurant => CarbonMonoxide physicalEndurant = CarbonMonoxide physicalEndurant
instance QUALITIES CarbonMonoxide AmountOfAir where
        -- the host of the carbon monoxide quality is the amount of air
        host (CarbonMonoxide amountOfAir) = amountOfAir

-- Stimulus as a process which involves a quality and an agent
class (QUALITIES quality entity, AGENTIVE_OBJECTS agent) => STIMULI quality entity agent where
-- perception as a behaviour, that takes as input a stimulus, and returns as output a quale that is carried by an agent
        perceive :: quality entity -> agent -> agent

```

```haskell
instance STIMULI CarbonMonoxide AmountOfAir Observer where
        perceive (CarbonMonoxide amountOfAir) observer = observer {quale =
            magnitudeToQuale(carbonMonoxideMagnitude amountOfAir)}
```

Based on the quale, the observer produces an observation value. The function qualeToMeasure introduced below establishes a mapping between a quale and an observation value (resulting from a measurement process), and is presented in detail later in this section.

```haskell
-- Observation as a process which involves a quality and an agent
class STIMULI quality entity agent => OBSERVATIONS quality entity agent where
        observe :: quality entity -> agent -> agent

instance OBSERVATIONS CarbonMonoxide AmountOfAir Observer where
observe (CarbonMonoxide amountOfAir) observer = observer{quale = quale (
    perceive (CarbonMonoxide amountOfAir) observer), observationValue =
    qualeToMeasure (quale (perceive (CarbonMonoxide amountOfAir) observer))}
```

The spatial resolution and the temporal resolution of the observation value are now equated with the spatial resolution and temporal resolution of the quale respectively[37].

```haskell
-- the specification of the resolution of an observation necessitates the
    occurrence of the observation
class OBSERVATIONS quality entity agent => OBSERVATION_RESOLUTIONS quality
    entity agent where
-- spatial resolution of an observation value (with reference to a certain
    quality) is an area. The observation value is carried by the agent
        spatialResolutionObservation :: quality entity -> agent -> Area
-- temporal resolution of an observation value (with reference to a certain
    quality) is a duration. The observation value is carried by the agent
        temporalResolutionObservation :: quality entity -> agent -> Duration

instance OBSERVATION_RESOLUTIONS CarbonMonoxide AmountOfAir Observer where
-- spatial resolution of an observation is equal to the spatial receptive
    field of the observer
```

---

[37] In fact, the following equations hold: spatialResolution(observation) <= spatialResolution(quale); temporalResolution(observation) <= temporalResolution(quale); thematicResolution(observation) <= thematicResolution(quale), since the transformation of the quale into an observation value (through the expression operation mentioned in Section 4.3.3) might involve another loss of spatial/temporal/thematic detail. The example introduced here *assumes no loss* of spatial/temporal detail during the expression operation, and equates the spatial/temporal resolution of the observation with the spatial/temporal resolution of the quale. A thorough investigation of the interplay between resolution of quale and resolution of observation value (for the spatial, temporal and thematic dimensions) is deferred to future work.

```
spatialResolutionObservation (CarbonMonoxide amountOfAir) observer =
    spatialReceptiveField (perceive (CarbonMonoxide amountOfAir) observer)
-- temporal resolution of an observation is equal to the temporal receptive
    window of the observer
temporalResolutionObservation (CarbonMonoxide amountOfAir) observer =
    temporalReceptiveWindow (perceive (CarbonMonoxide amountOfAir) observer)
```

Spatial receptive field is now specified as the size of the spatial region containing all receptors stimulated during the observation process. Temporal receptive window is the processing time of the receptors stimulated during the observation process.

```
spatialReceptiveField :: Observer -> Area
spatialReceptiveField observer = numberOfReceptors observer * receptorSize (
    receptor observer)

temporalReceptiveWindow :: Observer -> Duration
temporalReceptiveWindow observer =  processingTime (receptor observer)
```

The last stage of this formal specification is the definition of the functions magnitudeToQuale and qualeToMeasure[38]. These two functions are introduced to reflect the idea (already present in Probst, 2008) that an observation process is the approximation of the absolute magnitude of a certain quality. Probst indicated two types of approximations: qualia approximate absolute magnitude (this happens during the perception or impression process), and observation values approximate qualia (this happens during the expression process). It is argued here that - as a general requirement - the composition of magnitudeToQuale and qualeToMeasure is a monotonic increasing function[39]. This ought to be so, to ensure consistency of observation values with respect to the absolute magnitudes approximated[40]. This leaves us with two possibilities regarding magnitudeToQuale and qualeToMeasure: either both functions are monotonic increasing, or both functions are monotonic decreasing[41]. In the context of the current scenario, these two functions will be given a simple definition, assuming an approx-

---

[38] Future work should investigate the specification of a more generic function, say qualeToValue, which goes beyond qualeToMeasure and establishes the mappings from quale to all types of observation values introduced in Listing 4.2.

[39] See (Singh, 2008; Weisstein, 2014) for a short introduction to monotonic functions.

[40] That is, if magnitude1 $<$ magnitude2, then it must be the case that: observationValue1 $= f$ (magnitude1) $\leq$ observationValue2 $= f$ (magnitude2).

[41] It might appear surprising to speak about monotonic decreasing functions in this context, but an example is the process of formation of images on the human's retina. As Society for Neuroscience (2012) mentions, "the image on the retina is reversed: [...] information from the retina - in the form of electrical signals - is sent via the optic nerve to other parts of the brain, which ultimately process the image and allow us to see [upright]" (page 19).

imation factor of the magnitude amounting to 0.9 during the mapping magnitudeToQuale, and another approximation factor of 0.9 during the mapping qualeToMeasure.

```haskell
aFactor = 0.9 :: Double

-- the approximation factor is introduced to reflect the fact that qualia approximate absolute magnitudes
magnitudeToQuale :: Magnitude -> Quale
magnitudeToQuale magnitude = Quale (magnitude * aFactor)

-- the unit associated with observation values in this example is "ppm".
-- there is a further approximation of the magnitude during the expression process
qualeToMeasure :: Quale -> ObsValue
qualeToMeasure (Quale magnitude) = Measure (magnitude * aFactor) "ppm"
```

4.5 Summary

Despite different attempts to formalize resolution in the past, there is currently no formal theory of resolution of observations underlying geographic information. With a limited scope to spatial and temporal resolution, and a focus on single sensor observations, this chapter has proposed a component of such a theory as an ontology. The main ideas introduced can be recapitulated as follows:

I. The theory presupposes that space and time are *separate* frameworks;

II. The functional ontology of observation and measurement from Kuhn (2009a) is used as starting point for the development of the ontology of resolution. DOLCE is used as foundational ontology, and Haskell as ontology design language;

III. There are at least three ways of modelling the spatial and temporal resolution of a *single* sensor observation: a stimulus-centric approach, a property-centric approach, and a receptor-centric approach;

IV. A stimulus-centric approach constrains spatial/temporal resolution using the spatial/temporal extent of the stimulus participating in the observation process. It suffers from vagueness issues regarding the determination of the spatial extent of the stimulus, and is strongly dependent on one's adopted view (i.e. stimulus as process or an event) for the determination of the temporal extent of the stimulus;

V. A property-centric approach specifies resolution based on the spatial/temporal region over which the property of interest is considered homogeneous. It avoids vagueness issues, but needs to accommodate arbitrariness since there might be various reasons for which a data provider *considers* the property of interest homogeneous for his/her data collection purposes;

VI. The work opted for a receptor-centric approach where the spatial and temporal resolution of a single sensor observation are specified based on the physical properties of the observer. Spatial resolution is equated with the spatial receptive field of the observer (i.e. spatial region of the observer which is stimulated during the observation process), and temporal resolution is equated with the observer's temporal receptive window (i.e. smallest interval of time required by the observer's receptors in order to produce analog signals). The approach is workable, avoids both vagueness and arbitrariness issues, but would benefit from future work making explicit the contribution (in terms of duration) of the observer's receptors to the duration of the whole observation process.

CHAPTER 5

Ontology design stage - resolution of observation collections

This chapter builds on the theory introduced in the previous chapter and complements it with a characterization of the resolution of observation collections based on two criteria: the observed study area, and the observed study period of an observation collection. Terms suggested for the characterization of the resolution of observation collections are also formally specified in Haskell.

5.1 Introduction

Chapter 4 has proposed a theory of resolution applicable to single sensor observations. If single observations are sufficient for situation appraisal in some cases (e.g. one value produced by an altimeter is enough to get a hiker's current altitude), there are contexts where more than one observation is needed to assess a situation. A typical example is the *understanding of change* where at least two observations of the same phenomenon are required. Another example is the analysis of phenomena spread over large spatial areas but observable only at specific locations. For instance, evaluating the quality of the air in a city (i.e. the goal of the scientists from Section 4.1) requires observations at different spatial locations of the city to arrive at a sound conclusion.

The goal of this chapter is to discuss the specification of resolution when single observations are grouped (and viewed as a whole) for the purpose of analyses. Several ideas introduced in Chapter 4 are reused: the motivating scenario (presented in Section 4.1), space and time as *separate* frameworks (see Section 4.2), the choice of FOOM as base ontology (discussed in Section 4.3.1), and the use (motivated in Section 4.3.2) of DOLCE as foundational ontology and of Haskell as ontology design language. Terms specific to the ontology of resolution are also highlighted using a different **font**[1]. Before examining specifics pertaining to resolution, the chapter offers a discussion (currently missing in the literature) about the characterization of observation collections. The discussion is tailored to the needs of the Sensor Web.

5.2 Identification of the terms of the ontology (Part II)

A discussion of observation collections is presented first, before introducing additional terms of the ontology of resolution, their alignment to DOLCE, and the dependencies between the resolution of an observation collection and the resolution of the single observations belonging to the collection.

5.2.1 Observation collection

Wood and Galton (2009) recently reviewed a number of existing ontologies (including for example DOLCE and the Basic Formal Ontology) for the representation of collectives[2], and proposed a taxonomy allowing the classification of around 1800 distinct types of collectives. Following Wood and Galton and adapting their reflections to the current discussion:

- An observation collection is a *concrete particular*, not a type, nor an abstract entity;
- An observation collection is an endurant in the sense of DOLCE, that is, it is to be thought of as *wholly* present at any time it is present (by contrast to perdurants that are only *partially* present at any time);
- An observation collection has multiple observations (and only observations) as *members*[3].

The next subsections provide a more detailed analysis of the main characteristics of observation collections. The five key distinguishing features for collectives proposed

---

[1] Appendix A compiles a list of all the terms of the ontology of resolution and their definitions.

[2] The term 'collective' was used in (Wood and Galton, 2009) as the favoured general term to cover phenomena denoted by 'collection', 'collective', 'group', and 'social group'. The term 'collection' is preferred in this work because its use predominates in the Sensor Web community to refer to a group of observations viewed as a whole.

[3] The *member-collection* relationship is, following Winston et al. (1987); Chaffin et al. (1988); Wood and Galton (2009), a more specific kind of *part-of* relation. The requirement that the members of observation collections are homogeneous (i.e. only observations) suggests that they rather belong to the category COLLECTION from Gerstl and Pribbenow (1995) than MASS or COMPLEX.

in (Wood and Galton, 2009) - namely coherence, membership, spatial location, roles, and depth - are used to frame the discussion.

Coherence

According to Wood and Galton (2009), coherence refers to that in virtue of which many observations taken together form an observation collection. The coherence of an observation collection lies in the fact that all observations belonging to the collection are outcomes of observing the *same observable* (i.e. physical or temporal quality to be observed). An observation collection is an *externally caused collection* because it results from the action of a *collector* (i.e. someone who decides to group different observations and form a whole out of them).

Membership

There are two ways of viewing collections in relation to their members: (i) a collection *cannot* have different members at different times (constant membership), and (ii) a collection *can* have different members at different times (variable membership). This work takes the stance that observation collections *cannot* contain different observations at different times. The example from Figure 5.1 presents the reason for this choice. Figure 5.1a depicts the evolution of the temperature in a city during the past three days, and suggests that 'the temperature in the city has been increasing over the last three days'. In Figure 5.1b, a new observation (made say this morning) has become available, and is added to the previous three observations in the collection from Figure 5.1a. Figure 5.1b suggests a new trend for the temperature, namely that 'the temperature in the city has been increasing over the past three days, but slightly decreasing since this morning'.

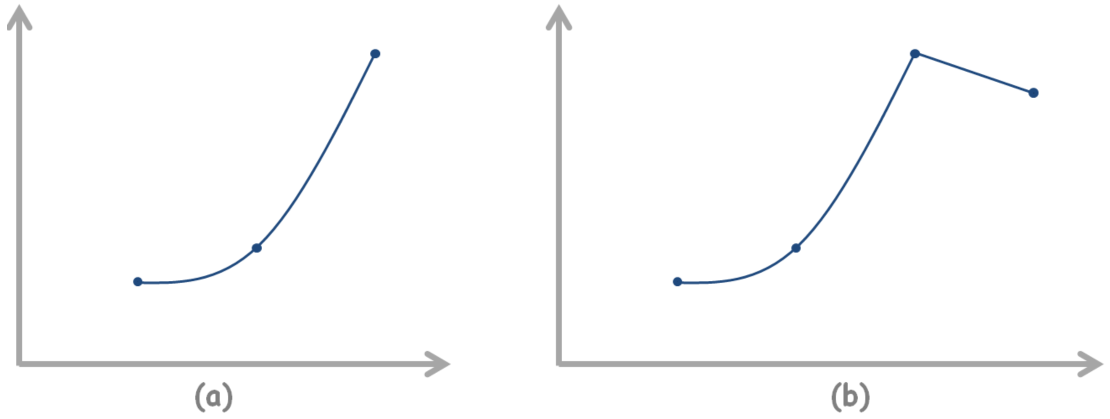
The point of the example is that the addition of a single observation to an observation collection potentially leads to different assessments of a situation[4]. Said another way, different observation collections are associated with potentially different information contents. For that reason, it is suggested that observation collections have exactly the same members at any time. Addition of an observation to (or subtraction of an observation from) an existing observation collection produces *new* and *distinct* observation collections. Furthermore, constant membership as a modelling choice connotes *constant cardinality*, i.e. an observation collection in this context has n members, where

---

[4] A logical consequence from this is that subtraction of a single observation from an observation collection leads potentially to different assessments of a situation.

n is a natural number. n must be greater than one[5]. An observation collection with only one observation is viewed in the current work as *a single observation*.

Figure 5.1: Temperature in a city - two examples of observation collections



The standpoint on membership adopted in this subsection implies that an entity, in the current context, is *either* a single observation *or* an observation collection. It cannot be both. The rationale for this is that a single observation and an observation collection are distinct. Ontologically, a single observation is a social object (in DOLCE's sense) directly derived from physical reality (i.e. an observable that inheres in an endurant or a perdurant). An observation collection is a social object as well, but derived from social objects (i.e. the single observations). With reference to Chapter 2 and the framework introduced in Section 2.2, a single observation belongs to the *measurement dimension*. An observation collection, on the contrary, belongs to the *analysis dimension*, that is, the dimension which relates to the *summarization* of data about the observed phenomenon. The standpoint adopted also suggests that observation collections are *like* mathematical sets because they are identified through their members. However, and in line with previous work in the literature (e.g. Bottazzi et al., 2006; Rector et al., 2006; Bittner et al., 2009; Wood and Galton, 2009; Guizzardi, 2010), observation collections are *not* seen as sets. The main difference between the two lies in the fact that sets are *abstract* entities, whereas collections are *concrete* entities. Finally, the view on observation collection exposed here has the derivative advantage that it preserves the principle of 'social fairness' introduced in (Frank, 2003). A proof for this is provided in Appendix B.

---

[5] That is, 'Cardinality necessarily > 1' in Wood and Galton's terminology.

Spatial location

As Wood and Galton (2009) indicate, there are various possibilities regarding the characterization of the spatial location of a collection. For example, the collection might be assigned a location (or not) and this location might be fixed or variable. It is worth mentioning three points regarding observations collections:

- *an observation can have a spatial location, and this location is fixed*: the location of the observation is the location of the sensor[6] which has produced that observation. A sensor cannot be at two locations at the same time, therefore an observation always has a fixed (or unique) location. In line with (Casati and Varzi, 1996; Bittner, 1999; Bittner and Winter, 1999; Bittner and Smith, 2003a; Grenon, 2003; Grenon and Smith, 2004), spatial location is seen as a *relation* between an entity (i.e. the observation) and a spatial region[7]. Appendix C presents the rationale for modelling the location of an observation as the location of the sensor (and not of the stimulus or the particular).

- *an observation collection can have a spatial location*: this location is the spatial region occupied by the locations of each observation. This spatial region is called (in line with Galton and Duckham, 2006) 'footprint', and methods for generating footprints for sets of points were discussed in (Galton and Duckham, 2006)[8].

- *an observation collection cannot move (i.e. change its spatial location)*: this follows from the fact that (i) observation collections always have the same members, (ii) the location of these members is fixed, and (iii) the location of the observation collection is derived from the location of its members.

Ordering and differentiation of roles

Ordering is important for observation collections because different orderings of the same observations lead potentially to different information contents for the observation collection. There are, following Ferreira et al. (2013), three possible ways of looking at a given observation collection: as *time series* (i.e. variation of a property over time

---

[6] This location might be georeferenced or not. Stasch et al. (2009) use the ability to produce an observation with georeferenced location as the distinguishing criterion between sensors and geosensors.

[7] 'Spatial region' is provisionally defined in this work as an identifiable portion of space, and a 'temporal region' is an identifiable portion of time. A thorough treatment of the ontological status of space, time, spatial regions and temporal regions, is out of the scope of this work.

[8] Galton and Duckham (2006) discussed also 'extended footprints', i.e. the case where one would also like to represent the spatial region occupied by the points themselves.

in a fixed location), as *trajectory* (i.e. evolution of locations or boundaries of an object over time) or as *coverage data type*[9] (i.e. variation of a property within a spatial extent at a time). Ordering is important in all three cases. Consider for example the observation collection mentioned in (Ferreira et al., 2013), and obtained by gathering air pollution values produced by cars equipped with GPS devices and air pollution sensors in a city. Different sequencings of air pollution values entail different trends for air pollution variation over time (*time series*); different sequencings of car locations suggest different trends for car location variation over time (*trajectory*); and different spatial orderings (i.e. the associated locations to air pollution values) imply different trends for air pollution variation within the city limits. For this reason, it is argued here that the (spatial and temporal) ordering of the observations in an observation collection should *always* be documented (or specified).

The fact that spatial and temporal orderings matter to observation collections entails that all members of an observation collection *do not play the same role*. In particular, there is always an observation that plays the role of *first*, and an observation that plays the role of *next*[10]. The choice of the *first* observation and the *next* of another one might be straightforward or involve some arbitrariness, depending on whether time or space is used as ordering scheme. Using time as ordering scheme for a time-series, the *first* observation is the one that happened first, and the *next* observation is the subsequent one. Conversely, while computing the total spacing of a coverage data type (a task that necessitates spatial ordering), one can take any location (of the irregularly spaced set of locations) as the *first*, and the *next* location as the closest one in terms of distance[11]. With reference to Wood and Galton (2009), an observation collection is a *hierarchically differentiated collection*, because the *first* observation plays the role of 'leader'.

Depth

The depth of a collection refers to the fact that members of a collection can themselves be collections or not. This work takes the stance that observations are the base-level[12]

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[9] The term used in (Ferreira et al., 2013) is 'coverage'. The use of 'coverage' is avoided here, and 'coverage data type' is preferred instead since the term 'coverage' has already been used in Chapter 2 in the sense of Wu and Li (2006) to refer to the sampling intensity in space and time.

[10] There is no need to explicitly define the last observation of a collection: the last observation is the one that has no next. It follows from the view adopted here that *List* is the suitable abstract data type for the specification of observation collections.

[11] While looking for the closest location in terms of distance, further arbitrariness creeps into when more than one location can play the role of 'next'.

[12] Most entities can be viewed as collectives at some level of granularity. Wood and Galton define base-level entities as entities which are not themselves considered as collectives in a certain context and stressed

entities of an observation collection. An observation *cannot* have other entities as *members*[13]. The depth of an observation collection is therefore 1.

Summary

This subsection has offered an analysis of possible modelling choices regarding observation collections. It complements previous treatments of observation ontologies in the literature which focused solely on single observations. The main points set out are:

- observation collections are concrete particulars, not types, nor abstract entities. They are different from single observations in that the latter belong to the measurement dimension while they belong to the analysis dimension;
- the coherence of observation collections lies in the fact that they are gatherings of observations of the same observable[14];
- observation collections should be modelled as having constant membership to reflect the fact that the addition (or subtraction) of one observation to an existing observation collection may significantly affect the information content of the existing observation collection;
- observations are the base-level entities of observation collections and observation collections have a fixed spatial location;
- spatial and temporal orderings matter to observation collections, and should therefore be documented explicitly.

The analysis helps extract five essential parameters for the characterization of observation collections in the Sensor Web, namely: *collector*, *observable*, *members*, *spatial ordering*, and *temporal ordering*. Changes in one of these parameters lead necessarily to a *new* observation collection.

5.2.2 Terms of the ontology: resolution of an observation collection

Spatial resolution and **temporal resolution** can also be specified for an **observation collection**. 'Spatial resolution' and 'temporal resolution' denote the amount of spatial detail in the observation collection, and the amount of temporal detail in the observation

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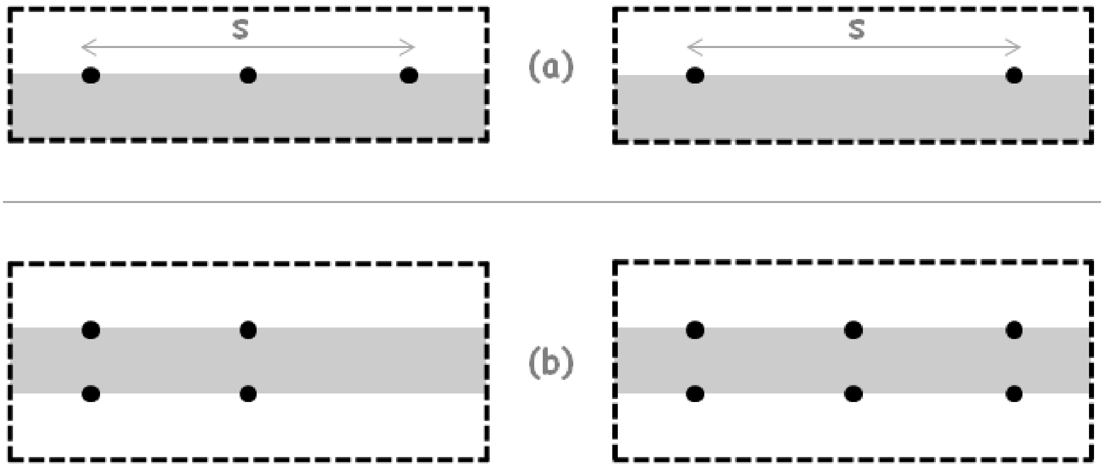
the need of specifying such base-level entities in order to avoid an infinite regress.

[13] This viewpoint is adopted because - as already indicated in Section 5.2.1 - an observation and an observation collection are different in their nature.

[14] Observation collections mixing observables (say temperature values and humidity values) should therefore be detected by software agents of the Sensor Web as incoherent (or inconsistent).

collection respectively. Figure 5.2 shows four examples of observation collections. Two criteria suggested in previous work - spacing and coverage - can be used to characterize the spatial resolution of the observation collections. These two criteria are critically discussed in the next two paragraphs[15].

Figure 5.2: Some examples of observation collections*



*Each point on the figure represents the spatial location of a single observation, the dotted box in black represents the spatial extent of the study area for which the observations have been generated.

Spacing: Goodchild and Proctor (1997) mentioned the spacing of the points (i.e. observations) as a criterion to characterize the spatial resolution of observation collections. The estimation of spacing necessitates some information about the spatial location of each observation. Spacing can be calculated in (at least) four ways: the *maximum spacing*, the *minimum spacing*, the *total spacing* and the *mean spacing*. All four have some disadvantages. For example, the *maximum spacing* and the *minimum spacing* say nothing about how the observation collection is spatially detailed. They rather tell that, within the current observation collection, the closest locations are within a distance equal to the *minimum spacing*, the farthest within a distance equal to the *maximum spacing*[16]. Regarding the *total spacing*, one disadvantage is the need to define which observation is the first, and which is the next. As mentioned in Section 5.2.1, this choice might involve

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[15] The arguments brought forward for the spatial resolution hold, *mutatis mutandis*, for the temporal resolution of the observation collections.

[16] Maximum/minimum spacing become relevant to the estimation of the spatial level of detail in the case of regularly spaced observation collections though. In this case, the distinction between maximum/minimum spacing and *mean spacing* becomes blurred, according to whether one uses maximum/minimum as criterion for the *mean spacing*. Mean spacing has its own disadvantage that is presented later in this paragraph.

some arbitrariness. The ultimate implication of the use of total spacing as criterion, is that a decision-maker will be provided with different values of spatial resolution for an observation collection, with no means to decide which one to choose for his or her purpose. In addition, there are cases such as the one from Figure 5.2a where the total spacing fails to capture the fact that two observation collections have different amounts of spatial detail. It is indeed arguable that (under the assumption that the size of the points is negligible) the two observation collections from Figure 5.2a have the same spacing S. The use of the *mean spacing* has the advantage that it is no longer necessary to define what observation is the first, and what is the next. However, a serious drawback of this criterion is that, when applied to the observation collections[17] from Figure 5.2b, it gives the same value. In other words, this criterion fails to capture the fact, as far as Figure 5.2b is concerned, the observation collection further right is spatially more detailed than the observation collection further left.

Coverage: coverage, proposed in (Degbelo and Stasch, 2011), is another criterion that can be used to characterize the spatial resolution of observation collections. The value C of this criterion for the observation collections presented in Figure 5.2 is:

$$C = \frac{number\ of\ observations\ *\ area\ covered\ by\ each\ observation}{extent\ of\ the\ study\ area}$$

This criterion will yield different values for the spatial resolutions of the observation collections from Figures 5.2a-b, capturing the fact that these observation collections have different amounts of spatial detail. There is also no need to face the arbitrariness which comes with the definition of the first and next observation. A drawback of this criterion is that it leads to a dimensionless value, and this fails to account for the intuition (reflected in expressions such as '10 meters resolution', '20 meters resolution', and so on) that resolution is a property to which humans associate a dimension of length.

From the previous paragraphs, spacing and coverage as criteria to characterize the spatial/temporal resolution of observation collections are wanting in some respects. As a general requirement for the Sensor Web (and also GIScience), proxy measures for the spatial/temporal resolution of observation collections should: (i) avoid the arbitrariness ensuant on the necessity to choose the 'first' and 'next' observation; (ii) have the dimension of length/time[18]; and (iii) mirror the fact that a perfect sampling strategy covers the whole study area/period. This motivates the introduction of the following two terms for the ontology of resolution: **observed study area** and **observed study pe-**

---

[17] These observation collections are representative of regularly spaced observation collections.

[18] Length/time is mentioned here in opposition to dimensionless values. Area/time or volume/time as dimensions are also suitable to proxy measures for resolution.

riod. The **observed study area** is the portion of the study area that has been observed. The **observed study period** is the portion of the study period that has been observed. The study area is the spatial extent of the analysis and the study period is the temporal extent of the analysis.

Observed study area and observed study period

The **observed study area** of an observation collection can be obtained by summing up the **observed area**s of each of the observations of the collection. The **observed area** of an *observation* is the spatial region of the phenomenon of interest that has been observed.

$$ObservedStudyArea = Sum_{i=1}^{n}[a_i]$$

where a_i denotes the observed area of each observation, and n is the number of observations in the observation collection. *Sum* is borrowed from (Casati and Varzi, 1996) and designates the sum of two spatial regions. *Sum* is similar to the operator *union*[19] used in set theory in that the *Sum* of two regions A and B is a region C such that all the elements belonging to C either belong to A, or B or both A and B.

Likewise, the **observed study period** of an observation collection can be obtained by summing up the **observed period**s of each of the observations in the observation collection. The **observed period** of a *single observation* is the temporal region of the phenomenon of interest that has been observed.

$$ObservedStudyPeriod = Sum_{i=1}^{n}[w_i]$$

where w_i designates the observed period of each observation, and n is the number of observations in the observation collection.

Modelling the resolution of an observation collection

The **spatial resolution** and **temporal resolution** of the observation collection can be equated with the **observed study area**, and the **observed study period** respectively. The observed study area[20] provides the decision-maker with a value which reflects how much of the study area has effectively been observed (or sampled). Its value is independent of the ordering of the observations, and also independent of the type of sampling strategy (i.e. regular vs irregular). The observed areas of the individual observations in the collection need not be alike (some might be greater or smaller than

---

[19] See (Weisstein, 2013) for a short introduction to this operator.

[20] To prevent the discussion from becoming repetitive, the remainder of this paragraph focuses on the **observed study area** but the same arguments hold, *mutatis mutandis*, for the **observed study period**.

others). The **observed study area** has a dimension of length squared, but a linear measure can be obtained by taking the square root. For a given study area, the equation $ObservedStudyArea = Sum_{i=1}^{n}[a_i]$ will approximate the study area if n tends to infinity (and under the sufficient condition that the a_i are disjoint[21]).

The **observed study area** and the **observed study period** are more suitable than spacing and coverage to characterize the spatial and temporal resolution of observation collections. Decision-makers are free to compute the proportion of the study area/study period that has effectively been observed through the ratios $\frac{ObservedStudyArea}{StudyArea}$ or $\frac{ObservedStudyPeriod}{StudyPeriod}$. A minor drawback of these two criteria is that their full significance is only unfolded when the extent of the whole study area/period is known. For example, stating that the **observed study period** of an observation collection is *one hour* says nothing about the actual quality of the observation collection, unless the whole temporal extent under consideration (e.g. one day or one month[22]) is also made explicit. The extent of the study area/period will also be required for a meaningful comparison of two observation collections with respect to their spatial and temporal resolution[23]. This drawback is not intrinsic to the criteria; it rather stems from the general fact that values need some context if their significance is to be assessed.

5.2.3 Resolution of an observation collection: illustrative example

This section applies the terms suggested for the description of the resolution of observation collections to the motivating scenario presented in Section 4.1. The *observable* which serves as coherence criterion for all the individual observations is the 'concentration of carbon monoxide (CO) in the ambient air of the city'. The *collector* who formed the observation collection is the group of scientists interested in analyzing the quality of the ambient air. The points in Figure 4.1 represent the spatial locations of the observations, and the points in Figure 4.2 stand for the temporal locations (i.e. when they happened) of the observations. A number of different *spatial orderings* can be defined while computing the mean or total spacing of the observation collection (e.g. B-F-E-D-C-A or B-C-F-E-D-A); *temporal ordering* is unambiguous: observations further right succeed observations further left.

The *observed area* and *observed period* of single observations are estimated using the spatial receptive field and the temporal receptive window of the observer which

---

[21] Disjointness is not a general constraint imposed on the a_i; they might overlap.

[22] The observation collection covers only 4% of the period under consideration if the extent of the study period is one day, only 0.14 % if the extent is one month.

[23] See Appendix D for more details on the comparison of two different observation collections.

produced the observation respectively[24]. Sensors A, B, C, D, E and F are alike in the example, and have the same spatial receptive field and temporal receptive window. Values of spatial receptive field and temporal receptive window are set provisionally to 1500 cm^2 and 60 seconds[25]. Let observationcollection1, observationcollection2, observationcollection3 be three observation collections with their *members* defined as follows: observationcollection1 = {b1, b2, b3, b4, b5}; observationcollection2 = {b3, c1}; and observationcollection3 = {e1, b2} (e1 and b2 have a temporal overlap of about 15 seconds, see Figure 4.2). Values of the *observed study area* and *observed study period* for these three observation collections are displayed in Table 5.1. The *observed study area* and *observed study period* behave as expected in that they reflect the differences in amounts of spatial and temporal detail of the observation collections. More specifically, they reflect the intuition that:

Table 5.1: Examples of observed study areas and observed study periods for observation collections

OBSERVATION COLLECTION	MEMBERS	OSA	OSP
observationcollection1	b1, b2, b3, b4, b5	1500 cm^2	300 seconds
observationcollection2	b3, c1	3000 cm^2	60 seconds
observationcollection3	e1, b2	1500 cm^2	105 seconds

OSA: observed study area
OSP: observed study period

- an observation collection which contains two observations made at different locations (observationcollection2) is spatially more detailed than an observation collection which contains many observations made at the same location (observationcollection1);
- an observation collection which contains two observations with different timestamps (observationcollection3) is temporally more detailed than an observation

---

[24] SRF and TRW pinpoint at best the spatial region or temporal region of the phenomenon of interest that has been observed, because they make explicit the spatial region of the observer which was stimulated, and the temporal duration of the exposure to the stimulus during the perception operation. Alternatives to the SRF and TRW, providing also an approximation of observed area/period of a single observation are the spatial footprint of the platform on which the observer is mounted or the whole duration of the observation process.

[25] The values are taken from the documentation of the COA analyzer of type GM901 (see `http://www.sick.com/us1/en-us/home/products/product_portfolio/analyzers_systems/Pages/gm901.aspx`; last accessed: April 19, 2014.). A spatial receptive field of 1500 cm^2 corresponds to an active aperture of the measuring probe of 437 millimeters.

collection which contains two observations with the same timestamp (observationcollection2).

The example presented in this section provides the necessary information to answer the second question (**Q2**) from the motivating scenario introduced in Section 4.1, namely: 'what is the spatial and temporal resolution of an observation collection?'.

5.2.4 Alignment to DOLCE: resolution of an observation collection

In line with Bottazzi et al. (2006), an 'observation collection' is viewed as a *social object*. A social object is an object that exists only within a process of social communication, in which at least one PhysicalObject participates[26]. For an observation collection, the physical object which participates in the process of social communication is the 'collector' (see Section 5.2.1). 'Spatial resolution', 'temporal resolution', 'observed study area', 'observed study period', 'observed area' and 'observed period' are all qualities that inhere in a social object, and therefore *abstract qualities*.

5.2.5 Dependency between the resolution of an observation collection and the resolution of its member observations

If the observed area/period is defined as spatial receptive field/temporal receptive window, there is a correlation between the resolution of the collection and the resolution of its members. This correlation is linear when (i) all the observed areas/periods of the single observations are exactly the same, and (ii) all the observed areas/periods are disjoint.

5.3 Formal specification: observation collection resolution

The running example from Section 4.4 is extended in this section for the formal specification task[27]. A new data type is first introduced to represent observation results.

```
-- an observation has an id and was produced by an observer (which carries
   the observation value)
data Observation = Observation {obsId :: Id, observer :: Observer}
-- b1 has the id "oa1" and was produced by the observer "ob1"
```

---

[26] The definition is adapted from `http://www.ontologydesignpatterns.org/ont/dul/DUL.owl` (last accessed: February 08, 2013).

[27] The formal specification presented in this section can be downloaded from `http://purl.net/ifgi/degbelo/thesisresources/chapter5/ObservationCollectionResolution.hs`.

```
b1= Observation {obsId ="oa1", observer = Observer {observerId = "ob1",
    receptor = measuringProbe, numberOfReceptors = 1, quale = Quale 2.5,
    observationValue = Measure 2.3 "ppm"} }
```

An observation collection has different observations as members, and is uniquely identified by its members (i.e. there is no need for an id); observationcollection1, observationcollection2 and observationcollection3 as presented in Section 5.2.3 are now introduced as examples of observation collections. Observation collections are specified as Haskell lists, in accordance with the modelling choice presented in Section 5.2.1.

```
type ObservationCollection = [Observation]
-- three examples of observation collections
obsCollection1 = [b1, b2, b3, b4, b5]
obsCollection2 = [b3, c1]
obsCollection3 = [e1, b2]
```

The observed area is a spatial region with a size equal to the spatial receptive field of the observer which produced the observation. The observed period is a temporal region with a size equal to the temporal receptive window of the observer which generated the observation. Observations (through the observed areas and observed periods) are associated with different spatial regions, and different temporal regions.

```
observedArea :: Observation -> SpatialRegion
observedArea Observation{obsId=oId, observer=obsSensor}
 | observerId obsSensor == "ob1" = spaceRegion1
 | observerId obsSensor == "ob2" = spaceRegion2
 | otherwise  = spaceRegion3

observedPeriod :: Observation -> TemporalRegion
observedPeriod Observation{obsId=oId, observer=obsSensor}
 | oId == "oa1" = timeRegion1
 | oId == "oa2" = timeRegion2
 | oId == "oa3" = timeRegion3
 | oId == "oa4" = timeRegion4
 | oId == "oa5" = timeRegion5
 | oId == "oa6" = timeRegion3
 | otherwise = timeRegion6
```

For simplicity, spatial regions representing the observed areas are approximated in this example using bounding boxes; temporal regions corresponding to the observed periods are time intervals[28]. Listing 5.1 presents the alignment of 'spatial region' and

---

[28] There is also the additional assumption that the center points of these spatial and temporal regions are fixed with respect to the spatial and temporal locations of the respective observers, in an uniform way

'temporal region' to DOLCE as well as some examples of spatial and temporal regions. Values for positions are provisional, and so are values for the corners of the bounding boxes, and those of the bounds of the time intervals. The model maintains its consistency in that: (i) the sizes of the spatial regions are equal to the sizes of the spatial receptive fields of the observer; and (ii) the sizes of the temporal regions are equal to the sizes of the temporal receptive windows of the observer.

Listing 5.1: Alignment of spatial and temporal region to DOLCE

```haskell
-- introduction of DOLCE's classes space_region and temporal_region
class ABSTRACTS abstract
class ABSTRACTS region => REGIONS region where
      regionSize :: region -> Int   -- a region has a size
class REGIONS temporalRegion => TEMPORAL_REGIONS temporalRegion -- a DOLCE temporal region (temporal region is a region)
class REGIONS physicalRegion => PHYSICAL_REGIONS physicalRegion
class PHYSICAL_REGIONS spaceRegion => SPACE_REGIONS spaceRegion -- a DOLCE space region (space region is a region)

-- a spatial region is a (DOLCE) space region
instance ABSTRACTS SpatialRegion
instance PHYSICAL_REGIONS SpatialRegion
instance SPACE_REGIONS SpatialRegion

-- a temporal region is a (DOLCE) temporal region
instance ABSTRACTS TemporalRegion
instance TEMPORAL_REGIONS TemporalRegion

-- some examples of positions
pos1 = (1, -28)
pos2 = (51, 2)
pos3 = (52, 3)
pos4 = (102, 33)
pos5 = (103, 34)
pos6 = (153, 64)

-- spatial region as bounding box
type SpatialRegion = BoundingBox

-- examples of spatial regions
spaceRegion1= BoundingBox {srs="wgs84", minLongLat = pos1, maxLongLat = pos2}
spaceRegion2= BoundingBox {srs="wgs84", minLongLat = pos3, maxLongLat = pos4}
```

(This assumption guaranties that overlap computation of the observed areas and observed periods is done without loss of information).

```
spaceRegion3= BoundingBox {srs="wgs84", minLongLat = pos5, maxLongLat = pos6}

-- temporal region as time interval
type TemporalRegion = TimeInterval

-- examples of temporal regions
timeRegion1 = TimeInterval {minTimeStamp = 1, maxTimeStamp = 61}
timeRegion2 = TimeInterval {minTimeStamp = 122, maxTimeStamp = 182}
timeRegion3 = TimeInterval {minTimeStamp = 242, maxTimeStamp = 302}
timeRegion4 = TimeInterval {minTimeStamp = 362, maxTimeStamp = 422}
timeRegion5 = TimeInterval {minTimeStamp = 482, maxTimeStamp = 542}
timeRegion6 = TimeInterval {minTimeStamp = 77, maxTimeStamp = 137}
```

The observed study area of an observation collection is an area equal to the sum of the sizes of the distinct observed areas of the observations, minus the size of their spatial overlaps. The observed study period of an observation collection is a duration equal to the sum of the sizes of the distinct observed periods of the observations, minus the size of their temporal overlaps. The specification of observedStudyArea and observedStudyPeriod presented below ensures that the observedStudyArea is equal to the observedArea, and the observedStudyPeriod equal to the observedPeriod, when the observation collection contains only one element.

```
-- the observed study area is the sum of the sizes of the distinct observed areas of the observations minus the size of their overlaps
observedStudyArea :: ObservationCollection -> Area
observedStudyArea (x:xs) =
if observedAreas (x:xs) == overlapsOfObservedAreas (x:xs)
then sSumOfSizes (observedAreas (x:xs))
else sSumOfSizes (observedAreas (x:xs)) - sSumOfSizes (overlapsOfObservedAreas (x:xs))

-- the observed study period is the sum of the sizes of the distinct observed periods of the observations minus the size of their overlaps
observedStudyPeriod :: ObservationCollection -> Duration
observedStudyPeriod (x:xs) =
if observedPeriods (x:xs) == overlapsOfObservedPeriods (x:xs)
then tSumOfSizes (observedPeriods (x:xs))
else tSumOfSizes (observedPeriods (x:xs)) - tSumOfSizes (overlapsOfObservedPeriods (x:xs))
```

The definitions of the functions *sSumOfSizes* and *tSumOfSizes* are presented below.

```
-- sum of the sizes of a set of distinct spatial regions
sSumOfSizes :: [SpatialRegion] -> Area
```

```haskell
sSumOfSizes (x:xs) = if null xs
          then regionSize x
          else regionSize x + sSumOfSizes xs

-- sum of the sizes of a set of distinct temporal regions
tSumOfSizes :: [TemporalRegion] -> Duration
tSumOfSizes (x:xs) = if null xs
          then regionSize x
          else regionSize x + tSumOfSizes xs
```

The observedAreas of an observation collection is a list of distinct observed areas of the observation collection. The observedPeriods of an observation collection is the list of distinct observed periods of the collection.

```haskell
-- distinct observed areas of an observation collection
observedAreas :: ObservationCollection -> [SpatialRegion]
observedAreas (x:xs) = if null xs
                          then [observedArea x]
                          else nub ((observedArea x) : observedAreas xs)

-- distinct observed periods of an observation collection
observedPeriods :: ObservationCollection -> [TemporalRegion]
observedPeriods (x:xs) = if null xs
                          then [observedPeriod x]
                          else nub ((observedPeriod x) : observedPeriods xs)
```

The overlapsOfObservedAreas of an observation collection is a list of spatial regions where the observedAreas of an observation collection overlap. The overlapsOfObservedPeriods represents the temporal regions where the observedPeriods of an observation collection overlap[29].

```haskell
-- the function identifies the distinct spatial regions where the observed
    areas of observations within an observation collection overlap
overlapsOfObservedAreas :: ObservationCollection -> [SpatialRegion]
overlapsOfObservedAreas (x:xs) = if null xs
then []
else nub ((overlapsOfaSingleObservedArea x xs) ++ overlapsOfObservedAreas xs)

-- the function identifies the distinct temporal regions where the observed
    periods of different observations in an observation collection overlap
```

---

[29] The specification of overlapsOfObservedAreas and overlapsOfObservedPeriods presented below accounts only for the case where at most two observed areas/periods overlap simultaneously. The extension of overlapsOfObservedAreas and overlapsOfObservedPeriods to account for situations where n observed areas (or observed periods) overlap simultaneously (n >=3) is postponed to future work.

```
overlapsOfObservedPeriods :: ObservationCollection -> [TemporalRegion]
overlapsOfObservedPeriods (x:xs) = if null xs
        then []
        else nub ((overlapsOfaSingleObservedPeriod x xs) ++ overlapsOfObservedPeriods xs)
```

Listing 5.2 shows the alignment of 'observation' and 'observation collection' to DOLCE. Observation and observation collection are both social objects.

Listing 5.2: Alignment of observation and observation collection to DOLCE

```
-- non-physical endurants and social objects
class NON_PHYSICAL_ENDURANTS nonPhysicalEndurant
class NON_PHYSICAL_ENDURANTS nonPhysicalObject => NON_PHYSICAL_OBJECTS nonPhysicalObject
class NON_PHYSICAL_OBJECTS socialObject => SOCIAL_OBJECTS socialObject -- social object

-- an observation is a social object
instance NON_PHYSICAL_ENDURANTS Observation
instance NON_PHYSICAL_OBJECTS Observation
instance SOCIAL_OBJECTS Observation

-- an observation collection is a social object
instance NON_PHYSICAL_ENDURANTS  ObservationCollection
instance NON_PHYSICAL_OBJECTS ObservationCollection
instance SOCIAL_OBJECTS ObservationCollection
```

The spatial resolution of an observation collection is its observed study area, and its temporal resolution is its observed study period.

```
-- spatial resolution as the observed study area of the collection
spatialResolutionCollection = observedStudyArea

-- temporal resolution as the observed study period of the collection
temporalResolutionCollection = observedStudyPeriod
```

5.4 Is a high value for resolution always desirable?

Two criteria - **spatial receptive field** and **temporal receptive window** - have been suggested to characterize the spatial and temporal resolution of a single observation, and two criteria - **observed study area** and **observed study period** - have been proposed for the characterization of the spatial and temporal resolution of an observation collection. The **spatial receptive field** reflects the extent to which the observer was spatially stimulated by the stimulus, the **temporal receptive window** expresses the extent to which the observer was exposed to the stimulus before producing the observation value. The **observed study area** makes apparent how much of the study area is actually covered by the observation collection, the **observed study period** accounts for the portion of the study period which is covered by the observation collection. The question whether a high value for each of these criteria is always desirable has no straightforward answer. Csillag (1991) states: "There is an obvious assumption about objects, or processes in space, namely, *the larger the sample we have, the better* [emphasis added]". Yet, this assumption might not always be accurate, because the assessment of what 'better' means involves the consideration of other parameters. Examples of these parameters include the spatio-temporal variability of the phenomenon of interest[30], the benefit/cost ratio of producing a new observation, the cost-effectiveness ratio of adding new receptors to an observer (or acquiring a new observer with more receptors), the expectations (very short vs. moderate or quick response time), etc. The answer to the question 'what does better resolution mean?' requires the characterization of the *value* of the single observations (or observation collections). Value is a core aspect of spatial information (see Kuhn, 2011, 2012), but also of one the least understood. For this reason, no attempt is made in this work to characterize what 'better', 'best', or 'optimal' resolution of an observation/observation collection means. This task is left for future work.

5.5 Summary

Chapter 4 brought forward an observation-based theory of spatial and temporal resolution relevant to *single* sensor observations. This chapter extends and complements the theory previously introduced by suggesting a means of specifying the spatial and temporal resolution of observation collections. Here is a synthesis of the ideas exposed:

I. This chapter also presupposes space and time as *separate* frameworks, uses FOOM as base ontology, DOLCE as foundational ontology, and Haskell as ontology design language;

II. An observation collection is a collection of observations. Observation collections in this work can have a spatial location (but cannot move), *cannot* have different observations at different times, and are different (in their nature) from single observations. With reference to the framework introduced in Section 2.2, a single

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[30] Credit goes to Christoph Stasch for this example.

observation belongs to the measurement dimension but an observation collection relates to the analysis dimension;

III. There are at least five essential parameters for the specification of observation collections (the collector, the observable, the members, the spatial ordering and the temporal ordering) and changes in one of these parameters lead to new observation collections;

IV. The *observed area* of an observation is the spatial region of the phenomenon of interest that has been observed. It can be estimated using the spatial receptive field of the observer which produced the observation. The *observed period* of an observation denotes the temporal region of the phenomenon of interest that has been observed and can be computed using the temporal receptive window of the observer which generated the observation;

V. The *observed study area* is the spatial *Sum* of the *observed areas* of the individual observations in the collection, and the *observed study period* is the temporal *Sum* of the *observed periods* of the individual observations in the observation collection;

VI. Criteria brought forward earlier in the literature for the specification of resolution of observation collections (i.e. spacing and coverage) have serious drawbacks, and the chapter proposed (as alternative and improvement) to specify the spatial resolution of an observation collection using its *observed study area*, and the temporal resolution of an observation collection using its *observed study period*. The theory of observation collection resolution exposed guarantees that for n=1 (n being the number of observations in an observation collection), resolution of the observation collection equals resolution of a single observation.

CHAPTER 6

Ontology design patterns for resolution

With resolution now formally specified, the next task - according to the agenda outlined by the research method - is the implementation of the ontology of resolution. This sixth chapter allows a smooth transition between the two stages of ontology design and ontology implementation. The chapter presents two ontology design patterns: one useful to characterize the resolution of a single observation, and one for the characterization of the resolution of observation collections.

6.1 Ontology design pattern

The use of patterns for ontology design was suggested in (Svátek, 2004) and (Gangemi, 2005) as a modelling paradigm for Semantic Web content. Since then, ontology design patterns[1] have been used to model a wide variety of notions, including notions from the legal domain (see Gangemi, 2007), notions related to sensors and observations (see Janowicz and Compton, 2010), ecological notions (see Ortmann and Daniel, 2011), cartographic map scaling (see Carral et al., 2013), semantic trajectories (see Hu et al., 2013), to name but a few.

Gangemi and Presutti (2009) define an ontology design pattern (ODP) as a modeling solution to solve a recurrent design problem. A typology [2] of ontology design patterns was suggested in (Gangemi and Presutti, 2009). The authors suggested six families of ODPs, namely: structural ODPs, correspondence ODPs, content ODPs, rea-

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[1] 'Ontology design pattern', as used in this work shall not be confused with 'ontology design pattern', as used in the biological domain (e.g. in [Hoehndorf et al., 2010]), although the two notions are closely related. See Aranguren et al. (2008) for the discussion.

[2] Other classification schemes for ODPs are possible. See for example (Blomqvist and Sandkuhl, 2005), (Gangemi et al., 2007) and (Blomqvist, 2010).

soning ODPs, presentation ODPs, and lexico-syntactic ODPs. The next paragraph will give a detailed description of content ODPs (CPs) which are the focus of this work. The reader is referred to (Gangemi and Presutti, 2009) for details on other types of ODPs. Examples of ODPs can be found at ontologydesignpattern.org, a web portal dedicated to ontology design patterns[3].

A simple definition of content ODPs can be found in (Gangemi, 2005). Gangemi defines them as formal patterns that encode a generic use case, a generic use case denoting a generalization of use cases that can be provided as example for an issue of domain modeling. A more elaborated definition was suggested in (Presutti and Gangemi, 2008). According to the authors:

> “CPs are distinguished ontologies. They address a specific set of competency questions, which represent the problem they provide a solution for. Furthermore, CPs show certain characteristics i.e., they are: computational, small and autonomous, hierarchical, cognitively relevant, linguistically relevant, and best practices”.

Empirical tests conducted by Blomqvist et al. (2009) revealed several advantages of pattern-based ontology design: content ODPs were (i) perceived as useful by ontology developers; (ii) they helped to improve the clarity and understandability of the ontology; and (iii) their use led to fewer modeling ‘mistakes’. The usefulness of CPs observed by Blomqvist et al. (2009) was confirmed in follow-up experiments reported in (Blomqvist et al., 2010). In another study, Hammar (2012) reported that CPs were perceived as useful by participants, and their use was observed to increase the speed with which tasks were solved.

For these reasons, this chapter will introduce ontology design patterns[4] for resolution, based on the ontology presented in Chapters 4 and 5. It should be noted, that besides ODP’s advantages for ontology design, ontology design patterns can act as a *bridge* between the two stages of ontology design and ontology implementation. The decomposition into simple, reusable modules can help to organize knowledge during the design stage. If the ODP is additionally implemented in an ontology implementation language, it becomes usable for the various practical tasks mentioned in Section 3.3.4. The use of ODPs in this work ensures therefore a gradual, smooth transition from the theoretical investigations done in Chapters 4 and 5 to their practical complements to be presented in Chapter 7. An example template to describe ODPs is the *catalog entry*[5]

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[3] See a presentation of the portal in (Presutti et al., 2008) and (Daga et al., 2008).

[4] In the remainder of this work, ‘ontology design pattern’ (ODP) is used to refer only to content ODP.

[5] Other templates to document ODPs exist. See for example (Gangemi et al., 2007; Scharffe et al., 2008).

suggested in (Gangemi and Presutti, 2009). The catalog entry includes 12 information fields which are presented in Table 6.1. This catalog entry will be used to document the ODPs proposed in this chapter.

Table 6.1: Fields of a catalog entry for an ontology design pattern

FIELD NAME	PURPOSE
Name	gives a name for the pattern
Intent	describes a generic use case addressed by the pattern
Competency questions	contains examples of competency questions addressed by the pattern
Also known as	gives other names (if any) with which the pattern is known
Scenarios	provides examples of requirements which can be modeled using the pattern. The requirements are expressed in natural language
Diagram	shows a *conceptual map* representing the pattern[6]
Elements	describes the elements (classes and relations) included in the pattern, and their role within the pattern
Consequences	gives a description of the benefits and/or possible trade-offs when using the pattern
Known uses	gives examples of realistic ontologies where the pattern is used
Extracted from	gives the reference ontology/conceptual schema (if any), from which the pattern has been extracted
Related patterns	indicates other patterns (if any) that are either a specialization, generalization, composition, or component of the pattern being described
Building block	provides references to implementations of the pattern, e.g. a URI of an OWL file containing an implementation of the pattern

6.2 Resolution of a single observation

The ODP useful for the characterization of the spatial and temporal resolution of a sensor observation has six elements: *observer*, *spatial receptive field*, *temporal receptive window*, *spatial resolution*, *temporal resolution*, and *observation*. The definitions of these terms can be found in Section 4.3.3. The pattern along with relations between its elements are depicted in Figure 6.1. Alignment of the pattern to DOLCE is the subject of Appendix

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[6] This is a small deviation from the field 'Diagram' as originally presented in (Gangemi and Presutti, 2009) where the authors proposed a UML class diagram to represent the pattern.

E, and additional information on the pattern can be found in Table 6.2.

Table 6.2: Catalog entry for the ODP useful to characterize the resolution of a single observation

FIELD NAME	PURPOSE
Name	Ontology design pattern for the characterization of the spatial and temporal resolution of a sensor observation
Intent	to describe the spatial and temporal resolution of a *single* sensor observation
Competency questions	(i) what is the spatial resolution of a sensor observation? (ii) what is the temporal resolution of a sensor observation?
Also known as	-
Scenarios	the motivating scenario presented in Section 4.1
Diagram	see Figure 6.1
Elements	the elements of the patterns are presented in Section 6.2
Consequences	**Benefits:** annotation of sensor observations with their spatial and temporal resolution; inference of the spatial and temporal resolution of the sensor observation based on the *physical characteristics* (i.e. spatial receptive field and temporal receptive window) of the observer **Trade-offs:** the computation of the spatial receptive field, and the temporal receptive window necessitates knowledge about *relevant receptors* to the observation process; for the time being, the value of the spatial receptive field should be computed manually[7]
Known uses	see an example of use in Section 7.2.1
Extracted from	-
Related patterns	-
Building block	details on the implementation of the pattern are provided in Section 7.1

6.3 Resolution of an observation collection

The ODP for the characterization of the spatial and temporal resolution of an observation collection has eight elements: *observation*, *observed area*, *observed period*, *observation*

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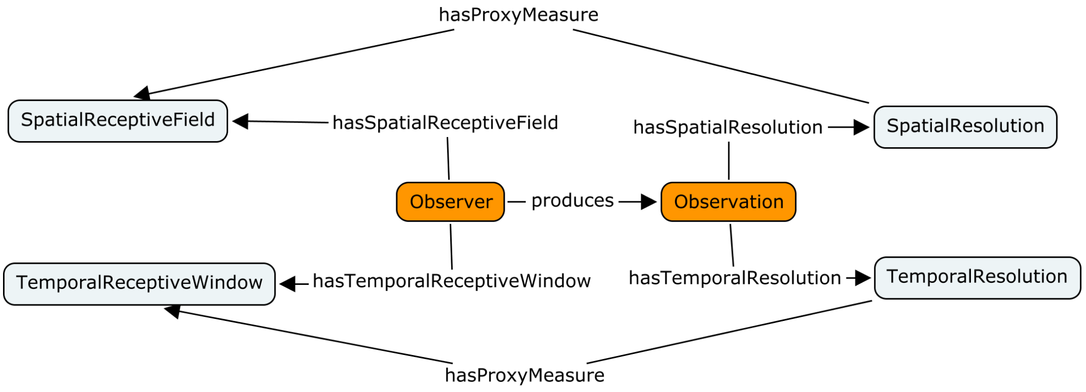
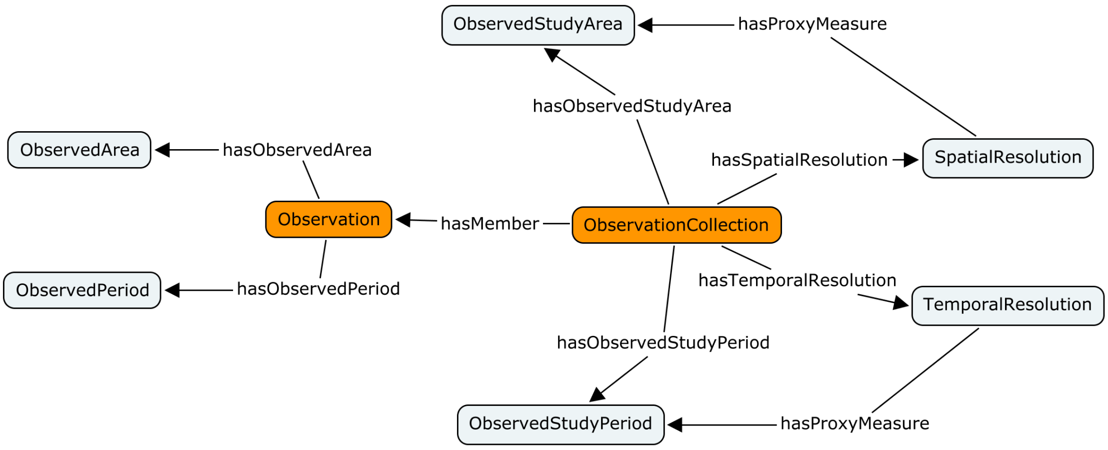
[7] The reason for this is provided in Section 7.2.3.

Figure 6.1: ODP for the resolution of a single observation



collection, *spatial resolution*, *temporal resolution*, *observed study area*, and *observed study period*. The definitions of these terms (except *observation* which is defined in Section 4.3.3) are provided in Section 5.2.2. Figure 6.2 depicts the pattern and relations between its terms, and Table 6.3 provides further description of its characteristics. The alignment of the pattern to DOLCE is presented in Appendix E.

Figure 6.2: ODP for the resolution of an observation collection



6.4 Validation of the ontology design patterns

Two types of validation mentioned in (Hammar and Sandkuhl, 2010) are relevant to the current work: *validation by example*, and *empirical validation*[9]. According to the au-

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[8] The rationale for this is provided in Section 7.2.2.

[9] The difference between *theoretical validation* and *empirical validation* suggested in (Hammar, 2011) is by and large similar to the distinction introduced in (Hammar and Sandkuhl, 2010).

Table 6.3: Catalog entry for the ODP useful to characterize the resolution of an observation collection

FIELD NAME	PURPOSE
Name	Ontology design pattern for the characterization of the spatial and temporal resolution of observation collections
Intent	to describe the spatial and temporal resolution of *observation collections*
Competency questions	(i) what is the spatial resolution of an observation collection? (ii) what is the temporal resolution of an observation collection?
Also known as	-
Scenarios	the motivating scenario from Section 4.1
Diagram	see Figure 6.2
Elements	the elements of the patterns are presented in Section 6.3
Consequences	**Benefits:** annotation of observation collections with their spatial and temporal resolution; inference of the spatial and temporal resolution of an observation collection, based on the observed study area and the observed study period of the collection **Trade-offs:** for the time being, the value of the observed study area and the observed study period should be computed manually[8]
Known uses	see an example of use in Section 7.2.2
Extracted from	-
Related patterns	-
Building block	details on the implementation of the pattern are provided in Section 7.1

thors, validation by example is performed when "one or more examples are presented in the text, validating the concepts presented in a theoretical manner" (Hammar and Sandkuhl, 2010). Empirical validation takes place when "some sort of experimental procedure or case study has been performed" (Hammar and Sandkuhl, 2010). The examples presented in Sections 4.3.4 and 5.2.3 ensure the theoretical validation of the two ODPs proposed. The implementations presented in Sections 7.2.1 and 7.2.2 (see Chapter 7) guarantee the empirical validation of the ODPs.

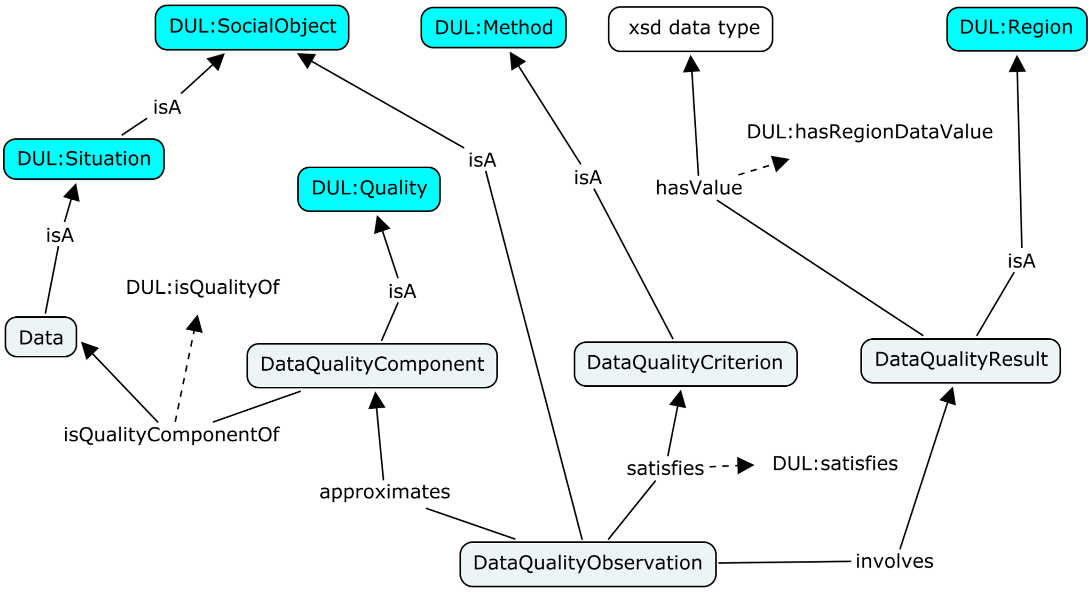
6.5 ODPs for resolution and the Semantic Sensor Web

Since resolution is an element of spatial data quality, progress towards its understanding is also useful to tackle the general problem of describing the quality of sensor outputs in the Sensor Web. This section establishes the link between the ODPs introduced previously, and the ODP proposed in (Degbelo, 2012) to characterize the quality of sensor observations in the Semantic Sensor Web.

6.5.1 Refining the ODP for spatial data quality characterization

Degbelo (2012) took a consumer-oriented perspective on data quality and suggested an ODP extracted from the SSN ontology presented in (Compton et al., 2012). The ODP has five elements: *Data*, *DataQualityCriterion*, *DataQualityComponent*, *DataQualityObservation* and *DataQualityResult*. *Data* is the output of an observation process involving a sensor, a stimulus, a sensed property and a feature. According to Degbelo, *Data* is equivalent to 'Observation' as defined in the SSN ontology. A *DataQualityComponent* is any property of the data which a consumer would like to approximate. A *DataQualityCriterion* is a criterion defined by the data consumer to get information about the quality of the data. A *DataQualityObservation* is an operation by which a data quality value is assigned to a data quality component using a data quality criterion. The outcome of a *DataQualityObservation* is a *DataQualityResult*. Figure 6.3 presents the ODP in pictorial form.

Figure 6.3: ODP for spatial data quality characterization in the Semantic Sensor Web



The ODP from Figure 6.3 does not show where to put observation collections. Actually, the concept 'observation collection' appears neither in (Degbelo, 2012), nor in the SSN ontology from which the ODP for spatial data quality characterization was extracted. In fact, Degbelo (2012) mixes *single observation* and *observation collection* under the same label 'data' in his ODP[10]. One might argue that observation collections can be viewed as *single observations* when they are aggregated (and define the aggregation procedure as a sensor). Yet, criteria such as membership, coherence, roles, depth (introduced in Wood and Galton, 2009) or spacing, extent, sampling intensity (mentioned in Degbelo and Stasch, 2011) are only relevant when talking of *collections of observations*. This suggests that observation collections deserve their own treatment in observation ontologies. For this reason, the ODP presented earlier in (Degbelo, 2012) is now refined to explicitly include observation collections. The term 'data' is removed, and replaced by the two terms 'observation' and 'observation collection' which are more precise. The definitions of *DataQualityComponent* and *DataQualityCriterion* are adjusted accordingly: a *DataQualityComponent* is any property of the observation (or observation collection) which a consumer would like to approximate; a *DataQualityCriterion* is a criterion defined by the data consumer to get information about the quality of the observation (or observation collection). Definitions of *DataQualityObservation* and *DataQualityResult* are left unchanged. Figure 6.4 shows the new version of the ODP for spatial data quality characterization in the Semantic Sensor Web. This new version of the ODP is used as basis for the remainder of the discussion.

6.5.2 Mappings between the ODPs for resolution and the ODP for spatial data quality characterization

There are some correspondences between the ODP for the characterization of the resolution of a *single* observation and the ODP for spatial data quality characterization. 'Observation' (see Figure 6.1) and *Observation* (from Figure 6.4) are alike; 'Spatial Resolution' and 'Temporal Resolution' (from Figure 6.1) are both a *DataQualityComponent*. Since 'Spatial Receptive Field' and 'Temporal Receptive Window' are identified to be proxy measures for resolution, they can be used as criteria for the assessment of the sensor observation's quality. Thus, 'Spatial Receptive Field' and 'Temporal Receptive Window' belong to the class *DataQualityCriterion*. An advantage of using spatial receptive field and temporal receptive window for quality assessment is that these two

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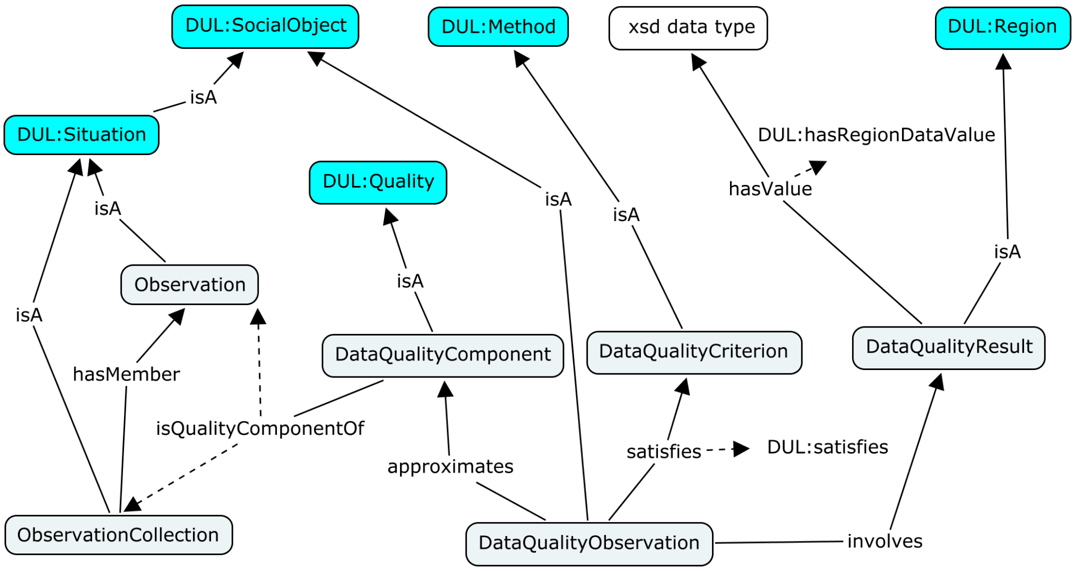
[10] For instance, Degbelo states that the term 'data' from the ODP is equivalent to 'observation', but the scenarios demonstrating the usefulness of the ODP point to assessments of the quality of observation offerings (i.e. observation collections).

Figure 6.4: Amended version of the ODP for spatial data quality characterization



criteria are based solely on the *physical properties* of the observer participating in an observing process[11], and avoid vagueness and arbitrariness issues.

Likewise, there are some correspondences between the ODP for the characterization of the resolution of an *observation collection*, and the ODP for spatial data quality characterization. 'Spatial Resolution' and 'Temporal Resolution' (from Figure 6.2) are both a *DataQualityComponent*, and the 'ObservedStudyArea' and 'ObservedStudyPeriod' are examples of *DataQualityCriterion*. The two criteria are derived from the observed area, and the observed period of the individual observations respectively. When observed area/period are computed using the spatial receptive fields/temporal receptive windows of the observers (as in Section 5.2.3), assessment of resolution based on the physical properties of the observer is the main benefit of using the 'ObservedStudyArea' and the 'ObservedStudyPeriod' to assess the quality of observation collections.

In brief, the ODPs presented in Sections 6.2 and 6.3 are *one way of specializing* the ODP for spatial data quality (with respect to the data quality components 'Spatial Resolution' and 'Temporal Resolution'). The ODP for spatial data quality was proposed by Degbelo (2012) as both extension of, and complement to the SSN ontology from Compton et al. (2012). Therefore, the ODPs for resolution also extend and complement the

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[11] This approach is very much in line with (Frank, 2009c) where the following call can be found: "Data quality research needs a quantitative, theory based approach. The theory must relate to the physical characteristics of the observation process". However, Frank did not provide an in-depth discussion on how resolution can be characterized based on the physical properties of the observer. Section 4.3.3 proposes one way of doing such a characterization.

SSN ontology, offering a set of concepts useful to characterize the resolution of observations and observation collections.

6.6 Summary

Ontology design patterns are modelling solutions to solve recurrent design problems, and previous work suggests that they are useful for ontology design. They can also act as a bridge between the stages of ontology design and ontology implementation, when they are encoded into ontology implementation languages. Yet, Janowicz (2012) reminds us that "while ontology design patterns have been successfully applied in ontology engineering, patterns specific to the needs of geographic information are largely missing and have to be developed". Janowicz adds further that "[i]t is important that such geo-patterns are closely tied to the observations and primitives levels". This chapter is an effort in that direction, with a focus on spatial and temporal resolution of sensor observations. The contributions of the chapter can be summed-up as follows:

I. ODPs are used as a *bridge* between the design stage and the implementation stage. They ensure a gradual transition between the theoretical investigations presented in Chapters 4 and 5, and their practical complements introduced in Chapter 7;

II. Two ODPs have been proposed: one for the characterization of the resolution of a single observation and one for the characterization of the resolution of observation collections. The two ODPs for resolution are extracted from the ontology presented in Chapters 4 and 5, and are documented using the catalog entry from Gangemi and Presutti (2009);

III. The ODPs for resolution extend and complement the SSN ontology from Compton et al. (2012), with a set of concepts useful to characterize the spatial and temporal resolution of observations and observation collections;

IV. The ODP for spatial data quality characterization in the Semantic Sensor Web suggested in (Degbelo, 2012) has been revisited, and one of its terms has been made more precise;

V. The ODPs for resolution are one way of specializing the ODP for spatial data quality. They can be used to assess the quality of observations and observation collections based on the physical properties of the observers which produced the observations;

VI. The two ODPs suggested are relevant both to GIScience (where resolution is an important notion), and the Semantic Sensor Web (where work is currently needed on the characterization of the quality of sensor outputs).

CHAPTER 7

Ontology of resolution - implementation stage

Implementing the ontology of resolution is the main concern of this chapter. The computational artifacts useful to characterize the resolution of sensor observations are produced at this stage. The implementation is done with the help of Semantic Web technologies such as the Web Ontology Language, the Semantic Web Rule Language, and the query language SPARQL.

7.1 Ontology implementation: language and tool

The Web Ontology Language (OWL) is the language recommended by the World Wide Web Consortium (W3C) for the encoding of ontologies. OWL as a W3C recommendation has a status of standard, and the features of its last version (OWL 2) were presented in (Cuenca Grau et al., 2008; Hitzler et al., 2012; W3C OWL Working Group, 2012). OWL is not only a *de jure* standard. It is also, as indicated by Horrocks (2008), the *de facto* standard for ontology development in fields as diverse as biology, medicine, geography, geology, agriculture, and defense. Hence, ontologies supporting implementation activities are placed in a state where reuse is most facilitated if they are encoded in OWL. As a result, the Web Ontology Language is adopted for the implementation of the ontology of resolution.

The encoding of the ontology (or ontology design patterns) in OWL is done using Protégé[1]. Some of the advantages of Protégé are mentioned in (Albrecht et al., 2008): it is free and open source; it offers many extensions for different paradigms (e.g. frames, OWL), many export formats (e.g. RDF/XML, OWL/XML, LaTeX), and has a good effort/result ratio. These features of Protégé suffice for the ontology implementation task

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[1] `http://protege.stanford.edu/`.

in the context of this PhD thesis. The reader is referred to (Gómez-Pérez, 1999b; Corcho et al., 2001; Su and Ilebrekke, 2002; Corcho et al., 2003; Mizoguchi, 2004; Ding et al., 2005; Tomai and Spanaki, 2005; Cardoso, 2007; Escórcio and Cardoso, 2007; Albrecht et al., 2008; Kalibatiene and Vasilecas, 2011) for additional examples of tools[2] which can be used to support ontology implementation.

The encoding of the ontology design patterns introduced in Chapter 6 results in two OWL ontologies: one relevant to the annotation of single observations with their resolution[3], and one appropriate for the annotation of observation collections with their resolution[4]. The version 4.2.0 of Protégé-OWL was used to perform the encoding task.

7.2 Implementation of the motivating scenario

The approach used at this point is adapted from the four steps suggested in (Presutti et al., 2009) to test an ontology module developed to address (a certain user story associated with) a specific competency question. The four steps are as follows:

1. encode a sample set of facts in the ontology, based on the motivating scenario;
2. define one or a set of SPARQL queries that encode the competency question;
3. associate each SPARQL query with the expected result;
4. run the SPARQL queries against the ontology, and compare obtained results with expected results.

Tables 7.1 and 5.1 present the sample sets of facts used to test the ODP characterizing the resolution of single observations, and the ODP characterizing the resolution of observation collections respectively. The values of SRF and TRW displayed in Table 7.1 are provisional examples of SRF and TRW for the carbon monoxide analyzer of type GM901 introduced in Section 4.3.4. Regarding observation collections, the example introduced in Section 5.2.3 has been reused for the implementation. The sample sets of facts were encoded (step 1 of the approach outlined above) in OWL 2.

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[2] These tools are also called 'ontology editors', 'ontology development environments', 'ontology engineering tools' in the literature.

[3] This ODP is available at `http://purl.net/ifgi/degbelo/thesisresources/chapter7/odp_resolution_oneObservation.owl`.

[4] The ODP is accessible at `http://purl.net/ifgi/degbelo/thesisresources/chapter7/odp_resolution_observationCollection.owl`.

SPARQL, as introduced in (Prud'hommeaux and Seaborne, 2008), is the query language for RDF[5] recommended by the W3C[6]. SPARQL is also, as indicated by O'Connor and Das (2009), the *de facto* standard RDF query language. O'Connor and Das (2009) point out that OWL can be serialized as RDF, and W3C OWL Working Group (2012) indicates that any OWL 2 ontology can be viewed as an RDF graph. Thus, OWL 2 ontologies can also be queried using SPARQL[7].

Table 7.1: Sample dataset for the ODP characterizing the resolution of single observations

OBSERVATION	OBSERVER	SRF	TRW
observation1	observerA	800	70
observation2	observerB	900	50
observation3	observerC	1000	30
observation4	observerD	1100	85
observation5	observerE	1200	90
observation6	observerF	900	45

7.2.1 Resolution of an observation

There are a couple of technical requirements for the successful implementation of the ODP useful to characterize the resolution of a *single observation*. There is a need for *rules*, stating explicitly that the spatial (or temporal) resolution of an observation is equal to the spatial receptive field (or temporal receptive window) of the observer which has produced the observation[8]. There is also a need for a *reasoner* to infer new information based on input ontology instances. The Semantic Web Rule Language (SWRL)

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[5] An introduction to the basic concepts of RDF is available at (Manola and Miller, 2004).

[6] An extensive discussion on the semantics of SPARQL can be found in (Pérez et al., 2009).

[7] SQWRL, presented in (O'Connor and Das, 2009), is a query language that has been specifically developed for querying OWL. Nonetheless, SQWRL is not yet supported in Protégé 4 (see `https://mailman.stanford.edu/pipermail/protege-owl/2011-September/017425.html`; last accessed: June 9, 2014).

[8] These rules are useful to implement the relation 'hasProxyMeasure' shown in Figure 6.1. In lieu of rules, one could think of implementing the 'hasProxyMeasure' relation using the OWL construct *EquivalentObjectProperties*. For instance, one can state that the properties *hasSpatialReceptiveField* and *hasSpatialResolution* from Figure 6.1 are *owl:EquivalentObjectProperties*. There are two ways of assigning meaning to ontologies in OWL 2 (see Hitzler et al., 2012): the *Direct Semantics* and the *RDF-Based Semantics*. Under OWL direct semantics, the use of *EquivalentObjectProperties* has undesirable consequences, since it entails that the properties denote the same concept. In particular, the use of *owl:EquivalentObjectProperties* would imply that '*SpatialReceptiveField* and *SpatialResolution* denote the same concept' (an inconsistent statement

presented in (Horrocks et al., 2004; Hitzler and Parsia, 2009) has been used as rule language, and Pellet (introduced in Parsia and Sirin, 2004; Sirin et al., 2007) has been used as reasoner[9]. At the moment of this writing, SPARQL queries performed using Protégé 4 only return asserted information, not inferred one. For that reason, the author used the OWL API presented in (Horridge and Bechhofer, 2009, 2011), in conjunction with the Jena Framework[10] to perform steps 2, 3 and 4 (see Section 7.2) of the implementation of the ODP. The implementation was done in Java using Eclipse[11], an open source software development environment. Listing 7.1 shows an example of SWRL rule. Listing 7.2 presents the formulation of **Q1** (see Section 4.1) in SPARQL, and Figure 7.1 depicts the results of this query. Listing 7.3 shows another possible query with the ODP (called **Q1***), and Figure 7.2 presents its results.

Listing 7.1: A SWRL rule to infer the temporal resolution of a single observation

```
Observation(?observation), Observer(?observer), produces(?observer, ?
   observation), hasTemporalReceptiveWindow(?observer, ?trw) ->
   hasTemporalResolution(?observation, ?trw)
```

Listing 7.2: Retrieve the existing sensor observations as well as their spatial and temporal resolution (query Q1)

```
prefix obsres: .....
SELECT ?observation ?spatialresolution ?temporalresolution
WHERE {
          ?observer obsres:produces ?observation.
          ?observation obsres:hasSpatialResolution ?spatialresolution.
         ?observation obsres:hasTemporalResolution ?temporalresolution
      }
```

---

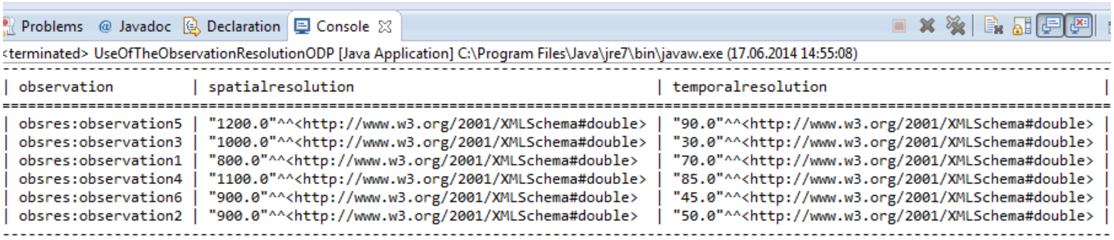
since one is a physical quality and the second an abstract quality). Under OWL rdf-based semantics, the use of *EquivalentObjectProperties* would entail that the concepts have the same extension, but may have different intensions. That is, they have the same values, but do not necessarily denote the same concept. Cuenca Grau et al. (2008) indicate that the design of an rdf-based semantics for OWL 2 is work in progress. As a result, rules are currently the only option that help implement the relation 'hasProxyMeasure'.

[9] For an overview of OWL reasoners, see (Bock et al., 2008).

[10] `http://jena.apache.org/`.

[11] `http://www.eclipse.org/downloads/`.

Figure 7.1: Results of Q1

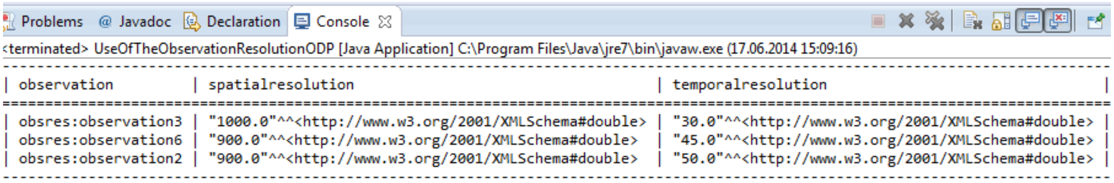


```
<terminated> UseOfTheObservationResolutionODP [Java Application] C:\Program Files\Java\jre7\bin\javaw.exe (17.06.2014 14:55:08)
---------------------------------------------------------------------------------------------------------------------------------
| observation         | spatialresolution                                   | temporalresolution                                |
=================================================================================================================================
| obsres:observation5 | "1200.0"^^<http://www.w3.org/2001/XMLSchema#double> | "90.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation3 | "1000.0"^^<http://www.w3.org/2001/XMLSchema#double> | "30.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation1 | "800.0"^^<http://www.w3.org/2001/XMLSchema#double>  | "70.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation4 | "1100.0"^^<http://www.w3.org/2001/XMLSchema#double> | "85.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation6 | "900.0"^^<http://www.w3.org/2001/XMLSchema#double>  | "45.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation2 | "900.0"^^<http://www.w3.org/2001/XMLSchema#double>  | "50.0"^^<http://www.w3.org/2001/XMLSchema#double> |
---------------------------------------------------------------------------------------------------------------------------------
```

Listing 7.3: Return existing sensor observations whose spatial resolution is greater than 800 mm^2, and temporal resolution is smaller than or equal to 80 seconds (query Q1*)

```
prefix obsres: .....
SELECT ?observation ?spatialresolution ?temporalresolution
WHERE {
        ?observer obsres:produces ?observation.
        ?observation obsres:hasSpatialResolution ?spatialresolution.
        ?observation obsres:hasTemporalResolution ?temporalresolution.
        FILTER (?spatialresolution > 800 && ?temporalresolution <= 80)
      }
```

Figure 7.2: Results of Q1*



```
<terminated> UseOfTheObservationResolutionODP [Java Application] C:\Program Files\Java\jre7\bin\javaw.exe (17.06.2014 15:09:16)
---------------------------------------------------------------------------------------------------------------------------------
| observation         | spatialresolution                                   | temporalresolution                                |
=================================================================================================================================
| obsres:observation3 | "1000.0"^^<http://www.w3.org/2001/XMLSchema#double> | "30.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation6 | "900.0"^^<http://www.w3.org/2001/XMLSchema#double>  | "45.0"^^<http://www.w3.org/2001/XMLSchema#double> |
| obsres:observation2 | "900.0"^^<http://www.w3.org/2001/XMLSchema#double>  | "50.0"^^<http://www.w3.org/2001/XMLSchema#double> |
---------------------------------------------------------------------------------------------------------------------------------
```

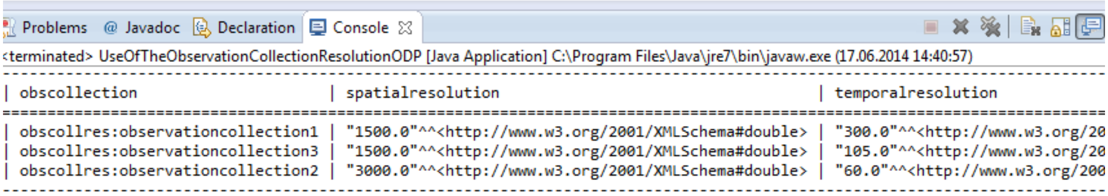
7.2.2 Resolution of an observation collection

Jena, the OWL API, SWRL, SPARQL and Pellet have also been used for the implementation of the ODP relevant to the characterization of the resolution of *observation collections*. It is worth mentioning here that the inference rule 'infer resolution to be the *Sum* of all the observed areas of the individual observations' or simpler 'infer resolution to be the product of the *observed area of one observation* times the *number of observations in the observation collection*' cannot be written in SWRL. This implies that the computation of the observed study area (or observed study period) based on the individual values of the observed areas (or periods) cannot be automatized using OWL supplemented by SWRL. The reason for this traces back to the fact that OWL offers weak support for general formulas such as the ones presented above[12]. For the time being, users have to manually enter the values of the observed study areas/periods of each observation collection in the ODP[13]. The implementation of the ODP was done using the values of the observed study areas (and study periods) from Section 5.2.3. Listing 7.4 presents **Q2** (from Section 4.1) formulated in SPARQL, and Figure 7.3 displays the results of the query.

Listing 7.4: Return the existing observation collections as well as their spatial resolution and temporal resolution

```
prefix obscollres: .....
SELECT ?obscollection ?spatialresolution ?temporalresolution
WHERE {
    ?obscollection obscollres:hasSpatialResolution ?spatialresolution.
    ?obscollection obscollres:hasTemporalResolution ?temporalresolution
     }
```

Figure 7.3: Results of Q2



```
<terminated> UseOfTheObservationCollectionResolutionODP [Java Application] C:\Program Files\Java\jre7\bin\javaw.exe (17.06.2014 14:40:57)
----------------------------------------------------------------------------------------------------------------------------
| obscollection                    | spatialresolution                                          | temporalresolution
============================================================================================================================
| obscollres:observationcollection1 | "1500.0"^^<http://www.w3.org/2001/XMLSchema#double> | "300.0"^^<http://www.w3.org/20
| obscollres:observationcollection3 | "1500.0"^^<http://www.w3.org/2001/XMLSchema#double> | "105.0"^^<http://www.w3.org/20
| obscollres:observationcollection2 | "3000.0"^^<http://www.w3.org/2001/XMLSchema#double> | "60.0"^^<http://www.w3.org/200
----------------------------------------------------------------------------------------------------------------------------
```

7.2.3 Discussion

Four main insights can be gained from the implementation presented in the previous subsections. First, the implementation of the theory presented in Chapters 4 and 5 is feasible, but to some extent. The inference of the resolution of single observations based on the spatial receptive field and the temporal receptive window is doable, and

---

[12] The general formulas referred to here follow the pattern $\sum_{i=0}^{N} X_i$, where X_i is a data property value in OWL. Iannone and Rector (2008) propose a framework to improve the situation, but there is no standard way to express in OWL that the fillers of a data property can (or should) be derived from others by means of a formula.

[13] It is still recommended, as a good documentation practice, to add the values of the observed areas/periods of each individual observation to the ontology.

so is the inference of the resolution of observation collections based on the observed study area and observed study period. In contrast, the implementation of the function *Sum* is currently not realizable because of OWL's weak support for general formulas. For the same reason, automatizing the definition of spatial receptive field as the product N*S (see Section 4.3.4) is presently not feasible. There are two ways of coping with this issue: (i) manually pre-process the values of spatial receptive field of an observer, as well as observed study area/period of an observation collection (this is the approach taken in Sections 7.2.1 and 7.2.2); or (ii) increase the expressiveness of OWL and/or SWRL (this calls for further research on the enhancement of the expressive power of the two languages). Second, the tests done previously show that despite the popularity of OWL, the language recommended by the W3C might not always be the best alternative for design purposes[14]. Third, the tests (together with the theory presented in Chapters 4 and 5) document a practical use of the method of ontology development shown in Figure 3.1. The design stage was the subject of Chapters 4 and 5; the implementation stage was presented in Section 7.2. With reference to the criteria for ontology evaluation presented in Section 3.3.6, the implementation introduced in this chapter illustrate the *practical usefulness* of the ontology of resolution. In particular, it shows how the ontology can support the retrieval of different observations (or observation collections) at different spatial and temporal resolution. Lastly, the tests (along with Chapters 4 and 5) serve as a proof of concept that the research method from Figure 3.1 is workable, and the distinction between design and implementation stages during ontology development produces valuable and distinct insights. From a researcher's point of view, *ontology design* is useful to *explore possible coherent ways of approaching an issue*; *ontology implementation* is helpful to *expose areas for future investigations regarding available technologies*. The Java code used to perform the tests is accessible at `http://purl.net/ifgi/degbelo/thesisresources/chapter7/JavaCode`. The ODPs enriched with instances can be found at `http://purl.net/ifgi/degbelo/thesisresources/chapter7`.

7.3 Further application scenarios

Section 7.2 has presented the implementation of the ontology of resolution using Semantic Web technologies. This section aims at presenting additional examples illustrating the relevance of the ideas presented in this work. The next subsections show how the ODP for the resolution of single sensor observation can be used to annotate and retrieve Flickr data with their temporal resolution, illustrate how qualitative values of

---

[14] The function *Sum* which cannot be specified using OWL was specified using Haskell in Section 5.3.

resolution can be accounted for, present an application of some of the ideas previously introduced to the Linked Brazilian Amazon Rainforest Data, and comment on the relevance of the observed study area/period for cross-comparison of average values for air quality in Europe.

7.3.1 Retrieval of Flickr data at a certain temporal resolution

The implementation presented in Section 7.2 was based on synthetic data. As a complement to this, the current subsection illustrates how the ODP useful to characterize the resolution of single observations can be used to retrieve Flickr data satisfying some (temporal) resolution constraints. Flickr[15] is an online platform for the sharing of photographs. Flickr photographs are associated with a great variety of themes but they can be organized into albums or galleries with a limited thematic scope. The Lava shots gallery[16] for example groups photos capturing "volcanic activity and areas, featuring Sicily's Mt. Etna and Hawaii's national parks". The ODP for the resolution of single observations can be used to annotate and infer the temporal resolutions of these images, based on the physical properties (i.e. the shutter speeds) of the cameras which produced them. Figure 7.4 shows the ids of the photographs from the Lava shots gallery which have a temporal resolution below 0.4 seconds. The query of the data was done on June 30, 2014 using the Flickr API[17]. The different steps followed to get the results displayed are[18]:

Step1: Retrieve the pictures contained in the Lava shots gallery using the method *flickr.galleries.getPhotos* from the Flickr API;

Step2: Get the Exif[19] data about each picture, as well as the shutter speed (if available) of the camera which produced the picture;

Step3: Populate the ODP with pictures (for which the shutter speed has been explicitly documented) using the OWL API;

---

[15] For a short presentation of Flickr, see `https://www.flickr.com/about/` (last accessed: June 30, 2014).

[16] See `https://www.flickr.com/photos/flickr/galleries/72157645265344193/` (last accessed: June 30, 2014).

[17] The documentation of the Flickr API is available at `https://www.flickr.com/services/api/` (last accessed: June 30,2014).

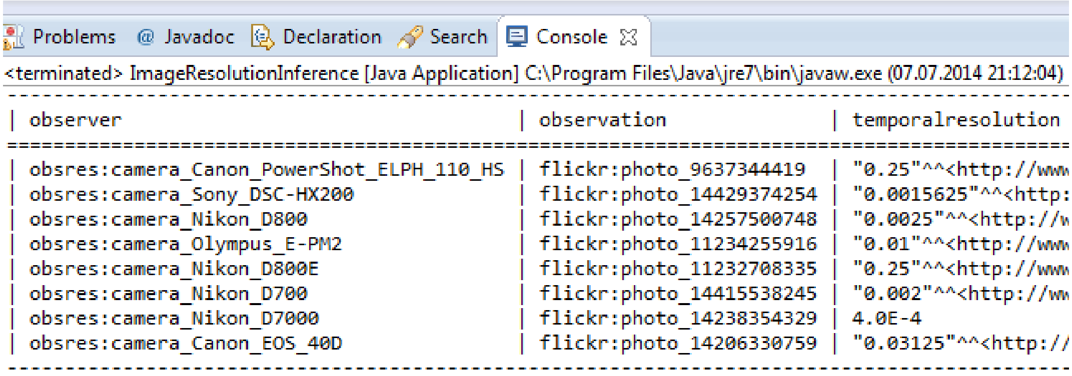
[18] The Java Code implementing these five steps is available at `http://purl.net/ifgi/degbelo/thesisresources/chapter7/JavaCode`.

[19] Exif stands for Exchangeable Image File Format. As Turner (2006) indicates, digital photographs store their metadata in Exif, and this often includes camera model, shutter speed, aperture, and date/time. Information about the cameras which produced the images is - when available - accessible through the *flickr.photos.getExif* method of the Flickr API.

Step4: Infer the temporal resolution of these pictures using the Pellet Reasoner;

Step5: Retrieve pictures at a given temporal resolution using SPARQL.

Figure 7.4: Photographs of the Lava shots gallery (Flickr) with a temporal resolution less than or equal to 0.4 seconds



```
<terminated> ImageResolutionInference [Java Application] C:\Program Files\Java\jre7\bin\javaw.exe (07.07.2014 21:12:04)
---------------------------------------------------------------------------------------------------------
| observer                                  | observation                | temporalresolution
=========================================================================================================
| obsres:camera_Canon_PowerShot_ELPH_110_HS | flickr:photo_9637344419    | "0.25"^^<http://ww
| obsres:camera_Sony_DSC-HX200              | flickr:photo_14429374254 | "0.0015625"^^<http:
| obsres:camera_Nikon_D800                  | flickr:photo_14257500748 | "0.0025"^^<http://
| obsres:camera_Olympus_E-PM2               | flickr:photo_11234255916 | "0.01"^^<http://ww
| obsres:camera_Nikon_D800E                 | flickr:photo_11232708335 | "0.25"^^<http://ww
| obsres:camera_Nikon_D700                  | flickr:photo_14415538245 | "0.002"^^<http://w
| obsres:camera_Nikon_D7000                 | flickr:photo_14238354329 | 4.0E-4
| obsres:camera_Canon_EOS_40D               | flickr:photo_14206330759 | "0.03125"^^<http://
---------------------------------------------------------------------------------------------------------
```

7.3.2 Expressing resolution qualitatively

The examples introduced so far in this work have given only quantitative values to the resolution of spatial and temporal observations (or observation collections). Even so, spatial and temporal resolution can also be expressed *qualitatively*. One could envision the following information needs where resolution is expressed qualitatively:

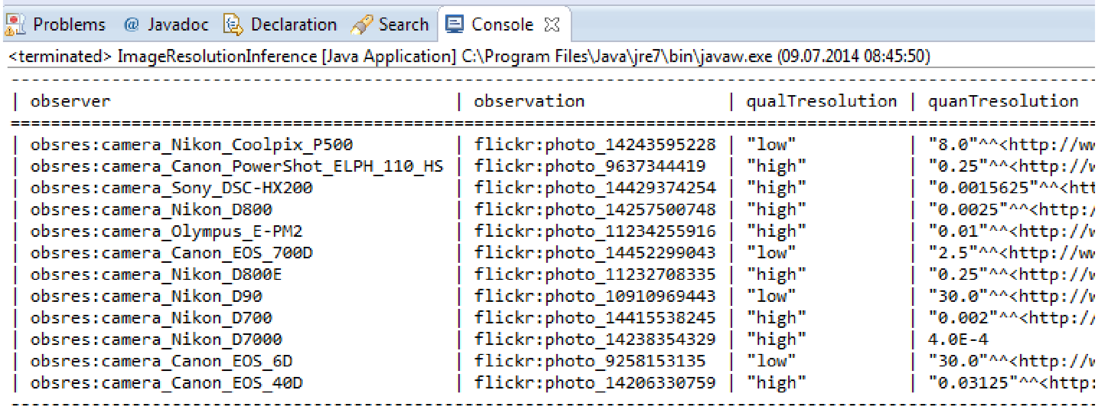
- retrieve all the remote sensing imageries (observation) in the knowledge base, which have a **high** spatial resolution
- return the census data (observation collection) from last year, at the **county level**
- provide **daily** data (observation collection) about the level of the Danube river
- retrieve the air quality observations in the database, which have a **low** temporal resolution

To account for such queries, one must specify *translation rules establishing correspondences between quantitative and qualitative values of resolution*. As an example illustrating how the translation could be done, Listing 7.5 presents a SPARQL query to retrieve the Flickr photographs from the Lava shots gallery with both their qualitative and quantitative temporal resolution. The translation rule is specified in the query through *"BIND(IF(?quantitativeTres <= 0.4 , 'high', 'low') AS ?qualitativeTres)"* which states that pictures with a temporal resolution less than or equal to 0.4 seconds have a ‘high’ temporal resolution, and those with a temporal resolution greater than 0.4 seconds have a ‘low’ temporal resolution. Figure 7.5 displays the results of the query.

Listing 7.5: Query to retrieve the Flickr photographs with their qualitative and quantitative temporal resolution (Q3)

```
SELECT ?observer ?observation ?qualitativeTres ?quantitativeTres
WHERE {
?observer obsres:produces ?observation.
 ?observation obsres:hasTemporalResolution ?quantitativeTres.
BIND(IF(?quantitativeTres <= 0.4 , ‘high’, ‘low’ ) AS ?qualitativeTres).
 }
```

Figure 7.5: Results of Q3



```
<terminated> ImageResolutionInference [Java Application] C:\Program Files\Java\jre7\bin\javaw.exe (09.07.2014 08:45:50)
----------------------------------------------------------------------------------------------------------------
| observer                                  | observation              | qualTresolution | quanTresolution
================================================================================================================
| obsres:camera_Nikon_Coolpix_P500          | flickr:photo_14243595228 | "low"           | "8.0"^^<http://ww
| obsres:camera_Canon_PowerShot_ELPH_110_HS | flickr:photo_9637344419  | "high"          | "0.25"^^<http://w
| obsres:camera_Sony_DSC-HX200              | flickr:photo_14429374254 | "high"          | "0.0015625"^^<htt
| obsres:camera_Nikon_D800                  | flickr:photo_14257500748 | "high"          | "0.0025"^^<http:/
| obsres:camera_Olympus_E-PM2               | flickr:photo_11234255916 | "high"          | "0.01"^^<http://w
| obsres:camera_Canon_EOS_700D              | flickr:photo_14452299043 | "low"           | "2.5"^^<http://ww
| obsres:camera_Nikon_D800E                 | flickr:photo_11232708335 | "high"          | "0.25"^^<http://w
| obsres:camera_Nikon_D90                   | flickr:photo_10910969443 | "low"           | "30.0"^^<http://w
| obsres:camera_Nikon_D700                  | flickr:photo_14415538245 | "high"          | "0.002"^^<http:/
| obsres:camera_Nikon_D7000                 | flickr:photo_14238354329 | "high"          | 4.0E-4
| obsres:camera_Canon_EOS_6D                | flickr:photo_9258153135  | "low"           | "30.0"^^<http://w
| obsres:camera_Canon_EOS_40D               | flickr:photo_14206330759 | "high"          | "0.03125"^^<http:
----------------------------------------------------------------------------------------------------------------
```

7.3.3 The Linked Brazilian Amazon Rainforest Data

The Linked Brazilian Amazon Rainforest Data (LBARD) described in (Kauppinen et al., 2013) is a dataset about the Brazilian Amazon rainforest. LBARD contains observations about the deforestation of the rainforest, as well as related data about things such as rivers, road networks, population, amount of cattle, and market prices of agricultural products. Kauppinen et al. (2013) indicate that all available data (representing deforestation, land uses, natural and social factors) were aggregated to grid cells of 25 km * 25 km. This suggests a spatial resolution of 625 km^2 for the dataset. The perspective taken at this point is the one of an information consumer aiming at exploring the dataset and retrieving it at a certain resolution. The information needs used as example is ‘return observations having a spatial resolution of 625 km^2, and reporting the percentage of new deforestation in 2008'. To be able to satisfy his/her information needs, the consumer needs to (a) define an observation, (b) specify the proxy measure for resolution used, and (c) choose either a quantitative or qualitative way of expressing resolution. Listing 7.6 presents a SPARQL query making the choices of the information consumer explicit. The query states that an observation is equivalent to a grid cell (from LBARD), the cell size (from LBARD) is the proxy measure for the spatial resolution of the observation, and the cell value (from LBARD) plays the role of observation value. In addition, spatial resolution is expressed quantitatively, and takes the value 625 km^2, for each observation.

Listing 7.6: Establishing correspondences between the user needs and LBARD

```
prefix amazon: <http://spatial.linkedscience.org/context/amazon/>
prefix rdf:   <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
prefix lsv: <http://linkedscience.org/lsv/ns#>
CONSTRUCT {  ?gridcell a amazon:observation.
             ?gridcell amazon:hasSpatialResolution 625.
             ?gridcell amazon:hasValue ?cellvalue }
 WHERE {
             ?gridcell amazon:DEFOR_2008 ?cellvalue }
```

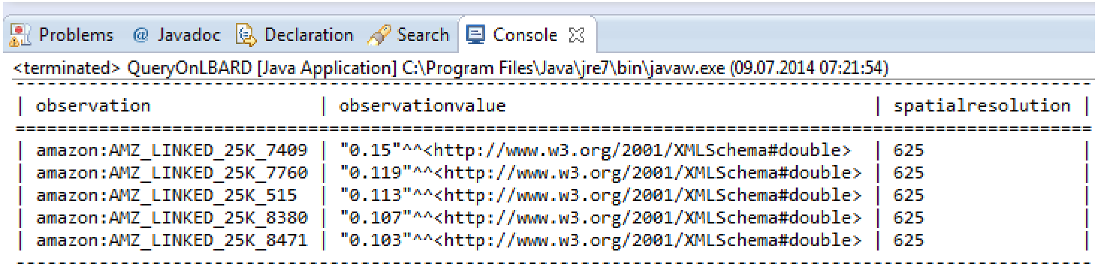
Listing 7.7 presents the SPARQL query useful to retrieve LBARD at the spatial resolution of 625 km^2 and Figure 7.6 displays the observations with the five highest percentages of new deforestation in 2008.

Listing 7.7: Query to retrieve LBARD at a certain spatial resolution (Q4)

```
SELECT ?observation ?observationvalue ?spatialresolution
WHERE {
       ?observation a amazon:observation.
       ?observation amazon:hasValue ?observationvalue.
       ?observation amazon:hasSpatialResolution ?spatialresolution
       FILTER (?spatialresolution = 625)
        }
```

Besides giving an example of use of the ideas previously introduced, this section touches indirectly on an important aspect of research on spatial data quality. In a recent review reflecting on achievements and failures of spatial data quality research,

Figure 7.6: Results of Q4



```
<terminated> QueryOnLBARD [Java Application] C:\Program Files\Java\jre7\bin\javaw.exe (09.07.2014 07:21:54)
---------------------------------------------------------------------------------------------------
| observation                | observationvalue                                   | spatialresolution |
===================================================================================================
| amazon:AMZ_LINKED_25K_7409 | "0.15"^^<http://www.w3.org/2001/XMLSchema#double>  | 625               |
| amazon:AMZ_LINKED_25K_7760 | "0.119"^^<http://www.w3.org/2001/XMLSchema#double> | 625               |
| amazon:AMZ_LINKED_25K_515  | "0.113"^^<http://www.w3.org/2001/XMLSchema#double> | 625               |
| amazon:AMZ_LINKED_25K_8380 | "0.107"^^<http://www.w3.org/2001/XMLSchema#double> | 625               |
| amazon:AMZ_LINKED_25K_8471 | "0.103"^^<http://www.w3.org/2001/XMLSchema#double> | 625               |
---------------------------------------------------------------------------------------------------
```

Devillers et al. (2010) suggested that raising users' awareness of data quality issues is an aspect that should be further explored. About 30 years ago, Openshaw (1983) pointed out that the modifiable areal unit problem is endemic to all studies of spatially aggregated data[20]. In fact, results of spatial studies invariably depend on the areal units (i.e. in this case the size of the cell) that are being studied. One way to let the user become aware of this issue is to *always* report the spatial (or temporal) resolution corresponding to an aggregated value. Listing 7.7 illustrates that this is possible at the query level, or at the result level in SPARQL. If resolution is to be always displayed at the query level, the relevant instruction in SPARQL is 'FILTER (?spatialresolution = 625)'. The user would then be required to fill in the value of spatial resolution he or she is interested in. If, on the contrary, resolution is to be always reported at a result level, adding the variable '?spatialresolution' will help to inform the data consumer of the spatial resolution associated with the aggregated value. The Java code used to test the query introduced in this subsection is available at `http://purl.net/ifgi/degbelo/thesisresources/chapter7/JavaCode`.

7.3.4 Cross-comparison of average values for air quality in Europe

In 2008, the European Commission introduced the Directive 2008/50/EC on ambient air quality and cleaner air for Europe. The following quote is taken from this directive:

> "In order to ensure that the information collected on air pollution is sufficiently representative and comparable across the Community, it is important that standardised measurement techniques and common criteria for the number and location of measuring stations are used for the assessment of ambient air quality" (European Commission, 2008).

---

[20] In this case, the aggregated value is the percentage of new deforestation in 2008.

It is argued here that the observed study area, and the observed study period of observation collections should be taken into consideration, if average values are to be "sufficiently representative and comparable across the Community" as the directive 2008/50/EC requires. To give an example, Table 7.2 shows three European Member states with their respective numbers of monitoring stations measuring ozone levels. The numbers of monitoring stations are taken from (EEA, 2013), a recent report on air pollution by ozone across Europe. It is assumed, for the purposes of the illustration, that each of the monitoring station in these countries has an observed area of 100 m^2.

Table 7.2: Number of monitoring stations for the ozone level in three European countries

COUNTRY	NUMBER OF STATIONS	OBSERVED STUDY AREA
France	375	37,500 m^2
Germany	260	26,000 m^2
United Kingdom	83	8,300 m^2

Only average values from France and Germany over an *observed study area* of 8,300 m^2 can be used for a *consistent* comparison of the average ozone levels in France, Germany and United Kingdom. Likewise, only average values from France over an *observed study area* of 26,000 m^2 are pertinent for an adequate comparison of average ozone levels in France and Germany. The report presented in (EEA, 2013) remained silent about this aspect. For instance, the occurrence of exceedances in each European country (henceforth called 'occurrences per country') was defined as "the *average* number of exceedances observed per station in a country [emphasis added]" and the report informed about the occurrences per country[21]. The occurrences per country have later been summed up and averaged, to give an average value of occurrences in Europe of 1.5 (and this without mention of the spatial areas for which the occurrences per country are valid). This approach bears the risk of producing meaningless results[22]. Observed study area and observed study period should always be documented when manipulating average values and *a similar observed study area or observed study period* is a prerequisite for an appropriate comparison of average values of observations belonging to observation collections[23]. This work has provided the basis for assessing the observed

---

[21] See page 11 of the report.

[22] Average values over 83 stations cannot be compared with average values over 260 stations, in the same way as average values over a day cannot be compared with average values over a month (observed areas and observed periods being equal).

[23] This section puts forth one prerequisite for a *meaningful comparison* of spatially and/or temporally aggregated values. Meaningful aggregation of the values themselves is another prerequisite for such a

study area and observed study period of observation collections. Both criteria are derived from the observed areas and observed periods respectively (see Section 5.2.2). The observed areas and observed periods can be estimated using the spatial receptive fields and temporal receptive windows of the observers - in this case the monitoring stations in Europe - which produced the observations.

7.4 Summary

This chapter has presented the technical requirements accompanying the implementation of the observation-based theory of resolution presented in Chapters 4 and 5. The following recapitulates the main ideas exposed:

I. The Web Ontology Language (OWL) has been used as ontology implementation language, and Protégé 4 has been used to encode the ontology design patterns from Chapter 6 in OWL;

II. The method of ontology testing from Presutti et al. (2009) has been adapted to test the ODPs presented in Chapter 6 and ensure their empirical validation;

III. The theory introduced earlier in Chapters 4 and 5 is (partially) implementable using current Semantic Web technologies;

IV. The chapter showed how *qualitative* expressions of the spatial and temporal resolution of observations (or observation collections) can be related to the equivalent *quantitative* values of resolution;

V. The chapter illustrated how ideas presented in this work can be applied to retrieve (i) Flickr data at a given temporal resolution, and (ii) the Linked Brazilian Amazon Rainforest Data at a certain spatial resolution;

VI. Similar observed study areas and observed study periods should be used while comparing average values of observations belonging to an observation collection.

---

task. For a recent and thorough discussion on meaningful spatial aggregation, see (Stasch et al., 2014).

CHAPTER 8

Conclusion

This chapter reflects on the importance of the work, touches on its limitations, and hints at future work.

8.1 Novel contributions

The main contributions of the thesis can be summarized as follows:

- a conceptual framework to reconcile various notions of resolution (Chapter 2);
- an application-dependent method of ontology development with a clear separation between a design and an implementation stage (Chapter 3);
- an observation-based and receptor-centric theory of spatial and temporal resolution applicable to a single observation (Chapter 4);
- a theory of spatial and temporal resolution of observation collections, based on the portion of the study area (or study period) that is effectively covered by the observation collection (Chapter 5);
- two ontology design patterns that can be used on top of the ontology developed by the W3C Semantic Sensor Network Incubator Group (henceforth called 'SSN-XG'), to annotate observations and observation collections with their spatial and temporal resolution (Chapter 6);
- an illustration of the practical usefulness of the ideas exposed through a variety of examples (Chapter 7).

The requirements R1 to R5 presented at the outset of the work (see Section 1.4) are now re-examined, before discussing the importance of the thesis in the next section.

According to **R1**, the theory developed should remain neutral with respect to the distinction of field and object. Field-based and object-based views are two ways of conceptualizing *geographic reality*. The theory of resolution developed in Chapters 4 and 5 has taken FOOM - the observation ontology proposed in (Kuhn, 2009a) - as starting point. FOOM is neutral vis-a-vis the distinction field vs object. Its adoption entails that the first entity required for an observation process is an *observable*, i.e. a physical or temporal quality to be observed. The observable can (as one desires) be attributed to locations (leading to a field-based view) or to objects (leading to an object-based view). FOOM offered also some facilities for the fulfillment of requirement **R2**, because the ontology accounted for both observation as a process, and observation as a result. Regarding requirement **R3**, this work has proposed a theory that is applicable to both in-situ and remote sensors, as well as human and technical observers. For a proper characterization of the spatial and temporal resolution of a single observation, the following information is required: (i) the type of receptors participating in an observation process; (ii) their size (i.e. spatial extent); (iii) the number of receptors triggered during the observation process; (iv) the time needed by receptors to transform incoming stimuli into analog signals; and (v) receptors directly stimulated by external stimuli (in case there are several receptors). Only an indirect relationship holds between the spatial/temporal resolution of the observation, and the extents of the stimulus and the particular. The surface (or region) of the observer that is stimulated during an observation process and the duration of the perception process are always smaller than (or equal to) the spatial/temporal extent of the stimulus to which the observer is exposed. Likewise, the extent of the stimulus cannot be greater than the extent of the particular observed.

The following axioms recapitulate the main ideas of the theory of resolution applicable to a single observation. They can be used as starting point for the development of (geographic) information systems, and will be useful to check the consistency of the information stored in the system[1]. No particular syntax is used here, as the aim is to communicate the outcomes of the work in a format that is as easy as possible to grasp.

A1: temporalResolution (observation) = temporalReceptiveWindow (observer)

A2: temporalReceptiveWindow (observer) = processingTime (receptor)

A3: temporalReceptiveWindow (observer) <= temporalExtent (stimulus) <= temporalExtent (particular)

A4: spatialResolution (observation) = spatialReceptiveField (observer)

A5: spatialReceptiveField (observer) = size (Receptor) * NumberOfReceptors (observer)

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[1] See a similar comment on the usefulness of axioms in (Bittner et al., 2009).

A6: spatialReceptiveField (observer) <= spatialExtent (stimulus) <= spatialExtent (particular)

Requirement **R4** called for a means to characterize the spatial and temporal resolution of observation collections. This requirement has been fulfilled with the introduction of the observed study area and observed study period as proxy measures for the spatial resolution and the temporal resolution of observation collections respectively. Observed study area/period has been defined as the *Sum* of the observed areas/periods of the individual observations constituting an observation collection. Details on the function *Sum* are provided in Section 5.2.2. Observed areas and observed periods of the observations can be estimated using the spatial receptive fields and temporal receptive windows of the observers which produced the observations respectively. The main axioms of the theory of resolution for observation collections are summarized below.

A7: temporalResolution (observationcollection) = observedStudyPeriod (observationcollection)

A8: observedStudyPeriod (observationcollection) = *Sum* (observedPeriods)

A9: observedPeriod (observation) = temporalReceptiveWindow (observer)

A10: spatialResolution (observationcollection) = observedStudyArea (observationcollection)

A11: observedStudyArea (observationcollection) = *Sum* (observedAreas)

A12: observedArea (observation) = spatialReceptiveField (observer)

Finally, requirement **R5** imposed that the theory should be implementable on use cases relevant to the Sensor Web (a point that was missing in previous formalisms for resolution in GIScience). Chapter 7 showed that a partial implementation of the theory using current Semantic Web technologies is feasible. The examples presented in Section 7.2 illustrate that requirement **R5a** has been met. Section 7.3.2 provided the necessary basis for the fulfillment of requirement **R5b**. With regard to previous work, the investigation presented in (Frank, 2009c) is most closely related to the work presented here. The main difference is in the nature of the investigation: Frank (2009c) essentially discussed the effects of observations' limited resolution on the size of the objects that could be formed based on these observations; this thesis analyzed the relationship between the characteristics of entities participating in an observation process, and the resolution of the final observations. Table 8.1 recapitulates the similarities and differences between the two works ('previous work' denotes the work done in (Frank, 2009c) and 'current work' refers to this thesis).

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[2] See (Frank, 2001, 2003) for a presentation of the tiers of ontology.

Table 8.1: Comparison with previous work

	PREVIOUS WORK	CURRENT WORK
Goal	Influence of observation resolution on the size of derived objects	Influence of stimulus, particular, observer on observation resolution
Field vs Object	field-based view required	neutral
Formalism for resolution	convolution-based	receptor-based
Spatial resolution	discussed	discussed
Temporal resolution	mentioned	discussed
Tiers involved[2]	0, 1 & 2	0 & 1
Observation collections	not discussed	discussed
Sensor Web	applicability not discussed	applicable

8.2 Importance of the work

Previous sections have alluded to the relevance of ideas exposed in this work to transdisciplinary research (see Section 2.5), the science of scale (see Section 3.4.3), ontology design patterns tailored to the needs of geographic information (see Section 6.6), spatial data quality characterization in the SSW (see Section 6.5), spatial data quality research in general (see Section 7.3.3), and the Directive 2008/50/EC of the European Commission (see Section 7.3.4). The next subsections establish the connection between the current work, and the topics of observation ontologies, ontology development and evaluation, and semantic interoperability.

8.2.1 Observation ontologies

The outcome of the ontology design stage presented in Chapters 4 and 5 extends FOOM with a specification of the resolution of observations. The extension put forward in this work follows a slightly different approach from Kuhn's early suggestion. The author of FOOM initially proposed "specifying the resolution of observations in space, time, and theme, based on the granularity of the sensed endurants and perdurants". On the contrary, the specification of resolution done in this work is primarily based on the properties of the observer, not those of the sensed endurant or perdurant. The two OWL ontologies referred to in Section 7.1 are the main outcomes of the ontology implementation stage. They can be used as complements to the ontology (hereafter called 'SSN ontology') developed by the W3C Sensor Network Incubator Group for the description of sensors and observations. Such complements to the SSN ontology are needed because, as Compton (2011) reports:

> "In developing the ontology, the group worked to include only the sensor specific concepts and properties, thus the need to include domain and other concerns when using the ontology".

Further examples of modules extending the SSN ontology include (Stasch et al., 2011), where the authors proposed a set of concepts to describe aggregated observations, and (Bendadouche et al., 2012) where the authors suggested a pattern to describe communication in Wireless Sensor Networks. To sum up the ideas presented in this subsection, this thesis takes previous work on observation ontologies one step further, both at the theoretical and the practical level.

8.2.2 Ontology development and evaluation

As Yu et al. (2007) pointed out: "Ontology evaluation techniques are improving as more measures and methodologies are proposed. However, few specific examples of these evaluations have been found in literature. That is, specific examples of ontologies, applications and their requirements, measures and methodologies to link these together in one cohesive evaluation". The method of ontology development presented in Chapter 3 offers a possible solution to the issue of lack of cohesive examples of ontology evaluation mentioned above. Besides the neat distinction between the design stage and the implementation stage, the work has separated what should be done (discussed in Chapter 3) from how this should be done (presented in subsequent chapters). Chapters 4 and 5 are cases in point for an ontology design endeavour, Chapter 7 presents how a specific ontology implementation activity could be conducted. The method has been kept as general as possible (to facilitate reuse), and has (as Figure 3.1 depicts) foreseen an evaluation for each of its stages.

8.2.3 Semantic interoperability

The interoperability of geographic information was identified by the University Consortium for Geographic Science as one the topics deserving prime attention for research, in its agenda presented in (UCGIS, 1996). Three classes of semantic interoperability problems were differentiated in (Kuhn, 2005), namely: (i) interoperability problems related to data discovery and evaluation, (ii) those related to service discovery and evaluation, and (iii) those related to service composition. Kuhn argued further that a methodological approach which goes beyond the construction of ontologies and involve their use for discovery, evaluation and combination of geospatial information is required to solve these semantic interoperability problems. The method for ontology development presented in this work fulfills this desideratum. In a first stage, competency questions were extracted from a motivating scenario (see Chapter 4); in a second stage, a theory was proposed as an ontology (see Chapters 4 and 5); in a third stage, the ontology has been implemented over sample datasets, to answer the initial competency questions (see Chapter 7). As a result, this method is relevant to GIScience as a whole, not only for ontology research, but also for progress on the topic of semantic interoperability[3].

Another contribution of this work to semantic interoperability lies in the fact, that it provides a basis for the (detection and) handling of semantic heterogeneity as regards the use of the term 'resolution' by different information communities. The conceptual analysis in Chapter 2 is relevant to understand why semantic heterogeneity (might) occur, when different communities are using the term. The high number of *proxy measures* for resolution (see Figure 2.3) suggests that heterogeneity is likely to occur because different information communities have used different proxy measures to assess the resolution of their data. Data consumers should therefore take a closer look at the measure used to assess the resolution of the data, before adopting it for reuse.

8.3 Limitations

Ludlow (2012) rightly remarked that word meanings are dynamic, but they are also *underdetermined*. As the author further states: "What this means is that there is no complete answer to what does and doesn't fall within the range of a term like 'red' or 'city' or 'hexagonal'. We may sharpen the meaning and we may get clearer on what falls in the range of these terms, but we never completely sharpen the meaning". The word 'resolution', which has been the focus of this work is by no means an exception. Additional formal specifications of the resolution of sensor observations, might complement this work which attempted to provide a better understanding of the resolution

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[3] It is worth noting that semantic interoperability is not only of interest to GIScience. As mentioned in Section 1.1.2, semantic interoperability is required if the vision of Plug and Play for the Sensor Web is to become reality. Progress on semantic interoperability is also of importance for other visions (or long-term research goals) such as the Semantic Web (introduced in Berners-Lee et al., 2001), the Semantic Geospatial Web (suggested in Egenhofer, 2002), the Geospatial Semantic Web (presented in Fonseca and Sheth, 2002), Digital Earth (proposed by Gore, 1998), Next Generation Digital Earth (mentioned in Craglia et al., 2008).

of observations underlying geographic information.

Besides underdeterminacy, Ludlow (2012) alluded also to another unavoidable limitation of ontology development undertakings. This limitation stems from the fact that word meanings are dynamic, or more generally, from the fact that domains modelled using ontologies (might) evolve. Hepp (2007) used the terms *ontology engineering lag*, and *ontology maintenance lag* to refer to this issue. The idea is that ontology building involves a phase of *domain capture* where knowledge about the domain of interest is gathered, and a phase of *development* where knowledge about the domain is effectively turned into an ontology. Because development takes time, it might occur that new conceptual elements, which meanwhile have become relevant in the domain of discourse, are not included in the final ontology. If this happens when one is developing a new ontology, there is an *ontology engineering lag*; if on the contrary, it happens when one is updating an existing ontology, there is an *ontology maintenance lag*. The argument against these two issues is a pragmatic one (adapted from Buckner et al., 2011), i.e. given the real and pressing information management needs, and for the stake of meeting those needs, having an imperfect formal representation of a domain is better than having none at all[4].

Finally, Studer et al. (1998) proposed the definition of ontology as a "formal, explicit specification of a shared conceptualisation" as the one that characterizes best the essence of an ontology (defined from an information scientist's point of view). In comparison to Guarino's definition introduced in Section 3.1 and adopted for the whole work, the definition above stresses the fact that an ontology should convey a 'shared conceptualization'. According to the authors, the keyword 'shared' in the definition "reflects the notion that an ontology captures consensual knowledge, that is, it is not private to some individual, but accepted by a group" (Studer et al., 1998). Modulo the fact that consensus-based ontologies have their own limitations[5], they are desirable because they have better chances of adoption by the research community (and beyond). There is little evidence supporting the claim that the ontology of resolution proposed in this work mirrors consensual knowledge in GIScience, since the work has primarily been conducted by the author[6]. Nonetheless, it is argued here that ontologies proposed by individuals, and ontologies reflecting consensual knowledge are *not mutually exclusive*. This work should be seen as a first step towards an ontology of resolution

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[4] Additional examples of works that adopt the same view are (Murdock et al., 2010, 2013).

[5] For example, as Di Donato (2010) notes, the original community that committed to a certain conceptualization of a domain may evolve as new members enter or old members leave it. This can ultimately result in a new consensus, invalidating the original ontology.

[6] Of course, the ideas presented have been shaped through discussions with many people.

reflecting consensus of the whole community of GIScience. Future working groups in GIScience might reuse the ideas exposed in this work[7], and if necessary refine them while developing such an ontology. Past experience with the development of the SSN ontology suggests that this expectation is realistic[8].

8.4 Future work

An extension of the current work could provide an elaborated discussion of activities such as *knowledge acquisition*, *configuration management*, *scheduling*, *control* and *quality assurance*, with respect to the distinction between design stage and implementation stage during ontology development. This task was left out during the work, and could be the focus of future research. Further investigation areas worth mentioning include (i) incorporating complex arithmetic operations in OWL/SWRL, (ii) exploring the behaviour of the theory as regards spatio-temporal aggregation, (iii) specifying the thematic resolution of sensor observations, (iv) working on quality characterization in the Semantic Sensor Web, and (v) shedding light on the implementation-design continuum.

8.4.1 Incorporation of complex arithmetic operations in OWL/SWRL

Section 7.2.2 pointed out that the computation of the observed study area (or observed study period) based on the observed areas (or periods) cannot be automatized using OWL supplemented by SWRL. Enabling this computation requires improvements of OWL or SWRL or both. OWL offers weak support for mathematical formulas, and this calls for future research to incorporate complex arithmetic operations in the language. The incorporation of such complex operations necessitates the discovery of more expressive description logics than $\mathcal{SROIQ}$[9] which still guarantee efficient computational properties. Whether such description logics exist is an open question, since Baader and Sattler (1998) showed that extending description logics by simple aggregation functions (such as min, max, count, sum) may lead to undecidability. That being said, Iannone and Rector (2008) point out that the issue of incorporating complex arithmetic

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[7] Preliminary versions of these ideas were documented in (Degbelo and Stasch, 2011; Degbelo and Kuhn, 2012; Degbelo, 2013).

[8] In 2009, Kuhn (2009a) proposed FOOM as an extensible backbone for emerging standards in the Semantic Sensor Web. Some of the ideas conveyed in FOOM (e.g. the notion of stimulus) were later adopted by the SSN-XG while developing its ontology to describe sensors and observations. Compton et al. (2012) indicate that the SSN ontology "was developed by group consensus over a period of one year", and some 41 people from 16 organizations joined the group.

[9] $\mathcal{SROIQ}$ is the name of the description logics underlying OWL 2.

operations in OWL 2 has been raised and discussed during the drafting phase of the language, and will be resumed in the preparation of following versions of OWL. SWRL presented in (Horrocks et al., 2004) comes with some simple mathematical built-ins[10], and Horrocks et al. (2004) indicated that the set of built-ins for SWRL is motivated by a modular approach that will allow further extensions in future releases. It appears therefore promising to examine the specification of more sophisticated mathematical functions in SWRL.

8.4.2 Spatio-temporal aggregation

The need to change the spatial, temporal and thematic resolution of observation data can arise in a context of data reuse. Observation collections may be spatially or temporally aggregated to fit the purposes of a decision-maker. Pebesma et al. (2011) give a good example of a situation where spatially aggregated observations are needed. As the authors note, in case of emergency evacuation, "we cannot evacuate single points, but decide whether neighbourhoods, regions, villages, towns, or flood plain sections will be evacuated"[11]. Extending the theory of resolution proposed so that it incorporates spatio-temporal aggregation is, for the moment, an open issue. The theory is based on observed study areas and observed study periods of observation collections, which in turn, relate to physical (i.e. observable) properties of the observers which produced the observations in the collection. Spatio-temporal aggregation, on the contrary, brings in a mix between observed properties at a point (in space or time), and non-observed (or observable) ones. Future work can look at the provision of ways to inform about the original observed study areas and observed study periods *after* observation collections have been spatially or temporally aggregated. For instance, in the motivating scenario from Section 4.1 the concentration of carbon monoxide in the air is only observed at specific spatial locations of the city. With information about the carbon monoxide analyzers (COA), and the theory presented in this work, the observed study areas of the observation collection can be determined, and inform about the amount of spatial detail in the observation collections. If, for the sake of decision-making, the observation collections is spatially aggregated to a city or national or European level, *how to keep the data consumer informed about the original observed study areas and observed study periods*?

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[10] For example, built-ins for addition, subtraction, multiplication and division.

[11] This example implies that, in an emergency evacuation situation, all point observation data available must be aggregated to area observation data in order to be used for decision-making.

8.4.3 Thematic resolution

The work has focused on a formal specification of the spatial and temporal resolution of sensor observations. The ideas proposed can be used as a starting point for a formal specification of the thematic resolution of observations underlying geographic information. Veregin (1998) proposed a distinction between two types of thematic resolution: *thematic resolution for quantitative data* and *thematic resolution for categorical data*. The former refers to the degree to which small differences in the quantitative attribute can be discerned (e.g. 10.03mA and 10.0251mA[12] indicate two different thematic resolutions for an observation reporting about the amount of electric current in an electrical circuit); the latter denotes the fineness of category definition (e.g. a classification of entities as being either 'anthropogenic' or 'natural' as opposed to a classification of the same entities as belonging to the classes 'Agriculture', 'Grass and Riparian and Dense Urban vegetation' 'Desert' or 'Urban'[13]). The best setting for reuse of the ideas presented in this work is a theory of thematic resolution of quantitative data. In particular, interesting questions to investigate are *whether a receptor-based approach is applicable to the thematic resolution of sensor observations* and *what the interplay between the thematic resolution of an observation (say an image), and the discrimination of the sensor (e.g. satellite) which has produced the observation is*. These questions have not been discussed in this work and could be taken up by future studies.

8.4.4 Ontology design patterns for quality characterization in the SSW

This work has proposed two ontology design patterns (ODPs) for the description of the resolution of sensor observations, and refined the ontology design pattern proposed in Degbelo (2012), for spatial data quality characterization in the Semantic Sensor Web. More work is needed along the same lines in the future, to address other aspects of data quality such as accuracy, completeness, consistency and lineage. Since some of these terms (e.g. completeness, consistency, accuracy) are also used in the literature to denote certain aspects of ontologies, ODPs useful for their description should separate aspects pertaining to data from aspects relevant to ontologies. For example, the ODPs should help to distinguish completeness applied to data from completeness applied to ontologies. Besides the quality of observations and observation collections, additional ODPs are needed to describe the quality of: (i) web services, and (ii) ontologies themselves. The description of the quality of all components (i.e. data, web services and

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[12] mA is an abbreviation for milliampere.

[13] This second example is based on the illustration of map reclassification rules from (Buyantuyev and Wu, 2007).

ontologies) of the Semantic Sensor Web is a long-term research goal. In the medium term, efforts could address two questions, namely: *how can accuracy, completeness, consistency and lineage be formally specified for observation and observation collections*? and *how to make these formal specifications applicable to use cases relevant to the Semantic Sensor Web*? The approach taken in this work - involving a conceptual analysis of the notion studied, an ontology design phase where a theory is proposed that relates to the physical characteristics of the observation process, and an ontology implementation phase which illustrates the practical usefulness of the theory - can be reused and adapted for accuracy, consistency, completeness and lineage.

8.4.5 The implementation-design continuum

Section 3.3.5 presented some examples of languages that have been proposed for the design and implementation of ontologies, and touched on the implementation-design continuum. An important question remains, namely: *what are the languages most adequate for design, and what are the languages most appropriate for implementation*? The answer to this question requires a systematic comparison of existing languages across a number of dimensions which include expressiveness, decidability and scalability. This comparison in turn necessitates one or several frameworks/use cases where the behaviours of these different languages can simultaneously be tested and objectively evaluated with reference to the others. To the nontriviality of such a task should be added the fact that languages *evolve*. Said another way, any result of the comparison will ultimately be subject to change, and potentially quickly outdated. Accordingly, there is not only a need for comparison, but for a *periodic comparison* of languages for ontology design and implementation. There is, for example, a valuable discussion in (Frank and Kuhn, 1999) where the authors presented some of the shortcomings of logic-based formalisms for the specification of semantics, and suggested as an alternative the use of functional languages. An ontology engineer can ask him-/herself: are these shortcomings still present 15 years later? Or have logic-based formalisms caught up? Besides, Haskell was proposed in the paper as being "currently the language with the least semantic ambiguities in their typing systems and execution procedures". Is this still the case, given that other functional languages such as Isabelle[14] have recently been used as formal specification language[15]? A characterization of the implementation-design continuum that can be used as *reference* for the practice of ontology design and implementation in GIScience and the Semantic Web is currently needed and missing.

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[14] See a brief introduction to Isabelle as well as the relationship between Isabelle and Haskell in (Haftmann, 2010).

[15] See an example of such a use in (Bittner et al., 2009).

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APPENDIX A

Terms of the ontology

The goal of this appendix is to draw up a list of all the terms of the ontology of resolution and their definitions. The terms are presented in alphabetical order.

Observation collection: a collection of observations

Observed area: spatial region of the phenomenon of interest that has been observed (the term applies to a single observation)

Observed period: temporal region of the phenomenon of interest that has been observed (the term applies to a single observation)

Observed study area: portion of the study area that has been observed (the term applies to an observation collection)

Observed study period: portion of the study period that has been observed (the term applies to an observation collection)

Receptor: the entity of the observer which produces analog signals upon detection of a(n external) stimulus

Spatial receptive field: spatial region of the observer which is stimulated during the observation process

Spatial resolution: amount of spatial detail in a representation (i.e. observation or observation collection)

Temporal receptive window: smallest interval of time required by the observer's receptors in order to produce analog signals

Temporal resolution: amount of temporal detail in a representation (i.e. observation or observation collection)

APPENDIX B

Proof

The goal of this appendix is to demonstrate that the statement 'observation collections cannot have different members at different times' (hereafter called S), has the additional advantage that it preserves the principle of 'social fairness' introduced in (Frank, 2003). This is achieved through a proof by contradiction.

A short introduction to the proof by contradiction can be found in (Cusick, 2006; Cole, 2012). The basics of this type of proof are as follows:

> "In a proof by contradiction we assume, along with the hypotheses, the **logical negation** of the result we wish to prove, and then reach some kind of contradiction" (Cusick, 2006).

Regarding social fairness, Frank (2003) states:

> "Agents use their knowledge to make decisions about actions . . . Social fairness dictates that decisions of agents are judged with respect to what they could have known, not the perfect knowledge available later".

Proof: an agent has at his/her disposal an observation collection $\{obs_1, ..., obs_n\}$ when taking a decision at time T_0. It follows that *decision knowledge* $= \{obs_1, ..., obs_n\}$. Later, at $T_1 > T_0$, the 'perfect knowledge' becomes available: *perfect knowledge* $= \{obs_1, ..., obs_n, obs_{n+1}\}$[1].

In case of 'social fairness', the following equality relation holds: *judgment basis* = *decision knowledge*; and nothing is done with the perfect knowledge except learning

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[1] obs_{n+1} might be a single observation, or an observation collection (with a *finite* number of observations as members). The fact that the perfect knowledge contains more observations than the decision knowledge echoes an early intuition from (Frank, 2001), namely: "[t]he knowledge possessed by a person or an organization increases over time".

from eventual mistakes. Along similar lines, Frank (2003) points to the popular saying: “Hindsight is 20/20” or “afterwards, everybody is wiser”.

Let’s now assume that S **holds** and the principle of ‘social fairness’ as presented above **no longer holds**. The perfect knowledge is now on a par with the decision knowledge and the following equality relation holds in that case: *judgment basis = perfect knowledge = decision knowledge*. It follows that:

$\{obs_1, ..., obs_n, obs_{n+1}\} = \{obs_1, ..., obs_n\}$ (contradiction with S)

In conclusion, modelling observation collections as having exactly the same members at any time preserves the intuitive principle of social fairness[2].

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[2] The inverse of this (i.e. modelling observation collections as having *different* members at different times *does not* preserve the intuitive principle of social fairness) is not necessarily true.

APPENDIX C

Location of an observation

This appendix discusses the characterization of the *spatial* location of a sensor observation. Location, as mentioned in Section 5.2.1, is viewed in this work as a relation between the observation and a spatial region. The location of an observation can be equated with one of the locations of the entities participating in the observation process[1]. That is, the location of the observation can be equated with either (i) the location of the stimulus, or (ii) the location of the particular, or (iii) the location of the sensor.

Section 4.3.3 pointed out that vagueness issues arise as to the determination of the spatial extent of the stimulus which participates in an observation process. As a result, modelling the observation's spatial location based on the location of the stimulus would also suffer from vagueness issues. Modelling location of the observation as the location of the particular (i.e. observed phenomenon) would perform better as regards vagueness issues, but would lead to a significant loss in spatial detail regarding the site where the observation happened. For example, using this approach, observations produced by two different weather stations located in a city, would have as location 'the city'[2]. Modelling location of the observation as the location of the sensor is therefore the approach which pinpoints at best the spatial region where the observation happened. This approach implies basically that the location of the observation is equated with the spatial region *occupied* by the sensor[3].

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[1] These entities were introduced in Section 1.2.2.

[2] The observed phenomenon here is the amount of air in the city (which occupies the whole city).

[3] The area (or volume) of this spatial region is approximately equal to the size of the sensor.

APPENDIX D

Comparing resolutions

The goal of this appendix is to briefly present the steps involved in the comparison of the spatial and temporal resolution of two observation collections. There are three steps required for such a comparison:

Step1: define the 'area of interest' or 'period of interest' for the analysis task;

Step2: determine the *relevant observed area* (or *relevant observed period*) for each of the observation collections. The *relevant observed area* is the intersection of the 'observed study area' and the 'area of interest'; the *relevant observed period* is the intersection of the 'observed study period' and the 'period of interest'. The *intersection* of two regions A and B, is the region C such that all the elements of C belong to both A and B. If the 'relevant observed area' (or 'relevant observed period') of an observation collection is *empty*, the observation collection is *not relevant* for the purposes of the analysis. If the 'relevant observed area' (or 'relevant observed period') of an observation collection is *non-empty*, the observation collection is *relevant* for the purposes of the analysis. *Empty* and *non-empty* as values for the intersection of two regions are adopted from Egenhofer and Franzosa (1991)[1].

Step3: if both 'relevant observed areas' (or 'relevant observed periods') are non-empty, the observation collection with the greater 'relevant observed area' (or 'relevant observed period') is spatially (or temporally) more detailed with reference to the area (or period) of interest. If only one of the two observation collections has an empty 'relevant observed area' (or 'relevant observed period'), the second observation collection is spatially (or temporally) more detailed with respect to the

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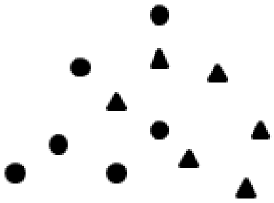
[1] It is worth mentioning that Egenhofer and Franzosa's definition of 'spatial region' is more restrictive than the definition of spatial region adopted in this work. In this work, no constraint is imposed on a spatial region except being an identifiable portion of space. Likewise, no additional constraint is put on a temporal region other than being an identifiable portion of time.

area (or period) of interest. If both observation collections have empty 'relevant observed areas' (or 'relevant observed periods'), none of them is relevant for the purposes of the analysis.

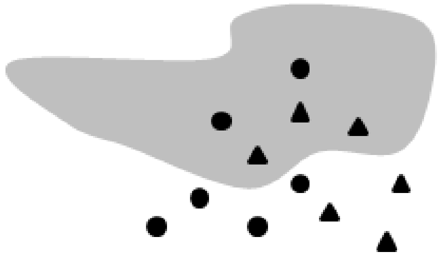
ILLUSTRATIVE EXAMPLE: Let A, B, be two observation collections with the *observed areas* of their members as depicted in Figure D.1 (the *observed areas* of A's observations are depicted as circles, those of B's observations as triangles). Let α be the *observed area* of each observation from A, and β be the *observed area* of each observation from B.

Figure D.1: Two observation collections A and B



Step1 of the comparison consists in the definition of the area of interest for the analysis task as Figure D.2 shows. The area of interest is depicted in gray in the figure.

Figure D.2: Comparison of two observation collections: Step1



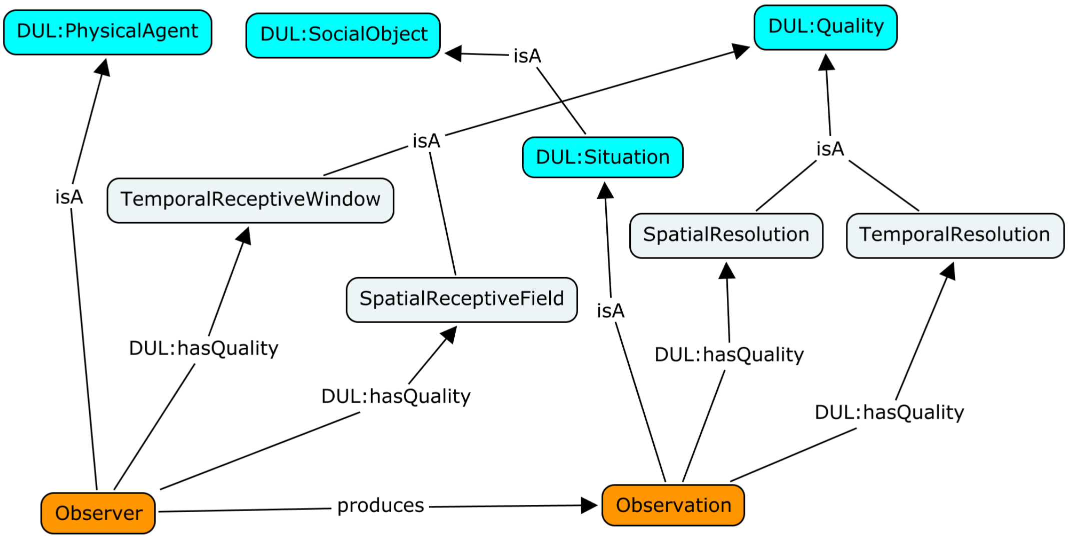
Step2 of the comparison consists in the determination of the relevant observed area (= 2α for A, and 3β for B) for each of the observation collections. Step3 boils down to the comparison of 2α and 3β to determine the observation collection which is spatially more detailed for the analysis. The example illustrates one of the advantages of the use of *observed study area/period* as criteria to characterize the resolution of observation collections, namely that it is possible to *compare* two observation collections with respect to their resolution, without (i) ordering their individual members, and (ii) knowing explicitly their (spatial or temporal) extent. Having both constraints fulfilled simultaneously wouldn't have been possible if spacing or coverage was used as criterion to characterize the resolution of observation collections.

APPENDIX E

ODPs aligned to DOLCE

This appendix presents the alignment of the ontology design patterns (ODPs) for resolution to the foundational ontology DOLCE. There are many versions of DOLCE[1], and the version used for the alignment of the ontology design patterns is DOLCE Ultra Light (DUL)[2]. DUL (in its version 3.27) has been proposed as a simplified version of DOLCE+ (i.e. DOLCE with its basic extensions such as 'Descriptions and Situations' and the 'Ontology of Plans')[3]. Motivations for using DUL at this stage are: (i) the fact that names of classes and relations have been made more intuitive, and (ii) the fact that the architecture of DUL is pattern-based (which fits with the objective of Chapter 6 to provide the ontology of resolution as reusable modules). Figure E.1 presents the align-

Figure E.1: Resolution of a single observation: ODP aligned to DUL



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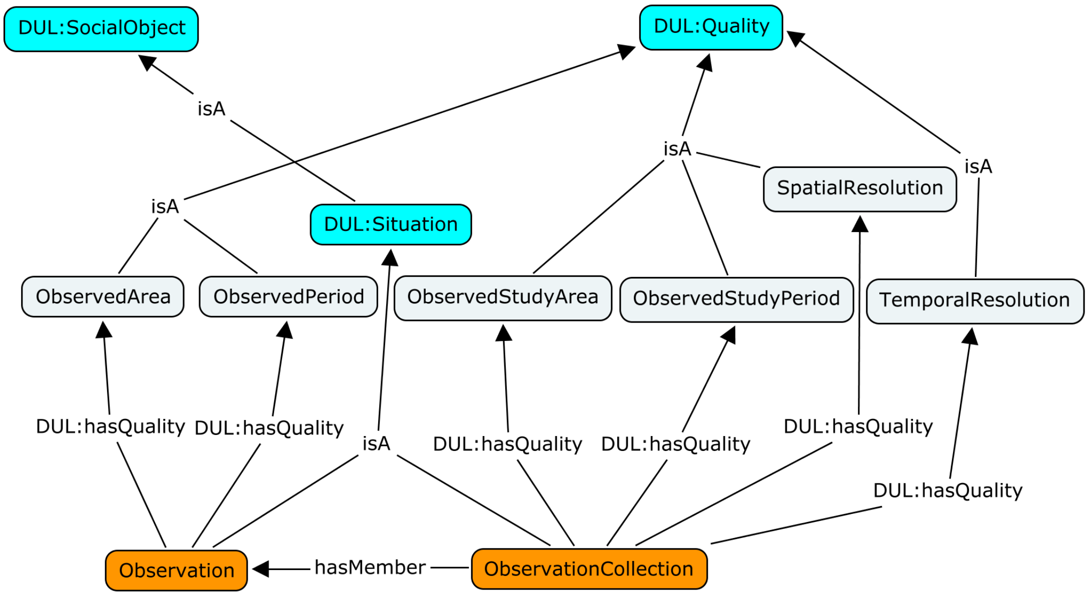
[1] See a list at `http://www.loa.istc.cnr.it/DOLCE.html`; last accessed: February 26, 2013.

[2] See `http://www.loa-cnr.it/ontologies/DUL.owl`; last accessed: February 26, 2013.

[3] The term 'DOLCE+' was coined in (Mika et al., 2004).

ment of the ontology design pattern (ODP) useful to characterize the resolution of one observation to DUL, and Figure E.2 depicts the alignment of the ODP useful to characterize the resolution of observation collections to the same foundational ontology. To avoid overloading, the relation 'hasProxyMeasure' is omitted on both figures. Details on the alignments can be found in Sections 4.3.5 and 5.2.4. Benefits of alignment to a foundational ontology were presented in Section 3.4.1.

Figure E.2: Resolution of an observation collection: ODP aligned to DUL



APPENDIX F

Ontology's summary

> *To decide whether to buy a book, we read the blurb on the book jacket; to decide whether a paper is relevant to our work, we read its abstract.* (Staab et al., 2004)

Natalya Noy used the words above-quoted to introduce ontology summarization as a means of helping potential ontology consumers to find suitable ontologies for their tasks. In line with her, this appendix provides a succinct overview of the main characteristics of the ontology of resolution proposed. Agarwal's checklist which "offers the possibility of a common basis for ontology development in the geographic discipline" is, for the purposes of this appendix, an appropriate means to an end.

Framework

i. Terms of the ontology: spatial resolution, temporal resolution, receptor, spatial receptive field, temporal receptive window, observation collection, observed area, observed period, observed study area, observed study period

Domain and intended role of the ontology

i. Type of the ontology: domain ontology
ii. Paradigm: knowledge engineering
iii. Purpose of the ontology: descriptive

Specification of the ontology and ontological commitments

i. Assumption: observation sentences (in the sense of Quine) exist
ii. Standpoint on space and time: space and time are separate frameworks

Validation

i. Linked to a foundational ontology?: Yes, DOLCE
ii. Applicability: implementable to use cases relevant for the Sensor Web

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