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An Ontological Structure for Semantic Interoperability of GIS and Environmental Modeling

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Abstract

Service oriented architecture in a distributed computing environment, with loosely coupled geo-services is a new approach for using GIS services in environmental modeling. The messages exchanged must follow a set of standard protocols which support syntactic interoperability, but do not address application semantics.

This article proposes a layer-based ontology with additional layers for describing geo-services, especially the measurement units used. The paper gives an ontology of measurements for describing the input and output of field-based geo-services and a core ontology of geo-services containing the domain concepts. An upper ontology adds new general concepts to an existing ontology in order to achieve an agreement between geo-service developers and environmental modelers. The layer-based structure is the building block for discovering geo-services that support semantic interoperability in GIS and environmental modeling.

Keywords: GIS, Geo-service, Semantic Interoperability, Ontology

1 Introduction

The natural environment includes physical processes such as surface flow, soil erosion and infiltration. Scientists model physical processes and impacts of human activities on the natural environment for prediction and analysis of relationships among phenomena affecting the environment. A model is a formal representation of the relationships between defined quantities or qualities [Jeffers 1982]. Some of the defined quantities or qualities in environmental models have a spatio-temporal nature. Thus, environmental modelers use GIS for describing the models of how the environment changes (e.g., models of erosion, flooding, vegetation growth and changes, urbanization).

Currently, different approaches are being used to link GIS and environmental models. Goodchild (2001) classifies these approaches into:

1) full integration (embedding),
2) tight coupling, and
3) loose coupling.

The tightly coupled and fully integrated approaches can not take advantage of the Web because they often lack interoperability.

GIS and environmental models are linked with distributed computing architectures based on loosely coupled geo-services. However, these architectures fix mostly syntactic issues, but lack to address the semantic ambiguities and implicit details. A requester needs detailed descriptions of the services, including the measurement units used, to discover the appropriate geo-service; thus these missing details hinder the discovery of geo-services. This paper proposes a solution for describing the semantics of geo-services. The hypothesis is that descriptions of measurement units are (1) useful in deciding between geo-services and (2) can be integrated with current methods for ontology based service discovery.

The next section discusses research that links GIS and environmental models. Section 3 explains field-based geo-services. The fourth section focuses on semantic ambiguities and implicit details in field-based geo-services. The solution proposed in this paper is based on an ontology. The fifth section discusses semantic interoperability and ontology as a means of describing semantic ambiguities and implicit details. Section 6 pays attention to the proposed layer-based structure of ontologies and the ontologies that comprise this structure. The relationships included in the ontology of "theory of measurement" and the core ontology of geo-services for describing field-based geo-services are clarified and an upper ontology is extended by adding new general concepts to describe measurements. Section 7 discusses Description Logics (DLs) and OWL as an ontology language for formalizing these ontologies. Section 8 explains the approach for building ontologies of structure and discusses their concepts, axioms and constraints for describing geo-services. Section 9 describes the implementation of a prototype for building the geo-services ontologies and gives examples of its use.

2 Previous Work

Two systems are loosely coupled if they communicate by self-describing, text-based messages [Newcomer 2002]. In this case, developer and user are confronted with tedious batch conversion tasks, import/export obstacles, and barred access to distributed resources by heterogeneous processing environments and heterogeneous data [Buehler and McKee 1996].

Tightly coupled systems require a significant amount of customized overhead to enable communication and are difficult to modify. The integration using the existing closed and monolithic GIS and simulation models is risky [Fedra 1996] because data and services are embedded inside the closed GIS. A new integration must be achieved for each model/GIS combination.

The object-oriented framework has been used to integrate GIS and environmental models [Bernard and Krüger 2000]. Feng and Sorokine (2001) identified that the component-based approach is an efficient way to integrate GIS and hydrologic models. OpenGIS or ISO/TC 211 can be used to achieve this goal. But there remains a gap between what is provided in these specifications, and what is needed for GIS hydrologic model integration.

In order to share GIS and models across various domains, some researchers used distributed computing technologies such as COM (Component Object Model) or DCOM (Distributed Component Object Model) in Client/Server architecture. These technologies can not take advantage of the existing World Wide Web [Newcomer 2002]. One of the weaknesses of existing and developing modeling systems and frameworks is parameter semantics. Transferring parameter values from one model domain to another must use a common language that is not provided in the distributed computing architectures [Hutchings et al. 2002].

Current research is shifting to a distributed computing architecture based on loosely coupled web services [Alameh 2003, ArcWeb 2006]. Key to the interoperation of web services is the adoption of a set of enabling standard protocols that consists of WSDL (Web Services Description Language), SOAP (Simple Object Access Protocol), and UDDI (Universal Description, Discovery, and Integration) [Newcomer 2002]. However these standard protocols do not include automatic service discovery, invocation and composition. For example, one of the descriptions in WSDL is data type, but “knowing the type of a data structure is not enough to understand the intended meaning behind its use” [W3C 2004].

The OGC (Open Geospatial Consortium) produces specifications for interchanging information and geo-processing services between systems. In a consensus process, OGC initiated Web Processing Service (WPS) standards, provide a common view on geo-processes, ranging from complex (such as modeling of climate change) to simple, (for instance, buffering) [Kiehle et al. 2006]. The *getCapabilities* interface is used for retrieving service metadata. A detailed description of input and output of a specific process is accessible through the *describeProcess* interface. The *execute* interface provides underlying functionality of the service, for instance, a spatial processing algorithm like intersection, union, dissolve, etc. WPS are easily accessible and flexible libraries of geo-processing algorithms in a web service environment. However, semantics of processes is missing in the WPS [Foerster and Stoter 2006].

Few researchers address semantic interoperability of web services. The Adaptive and Composable E-emergency and Geographic Information Services (ACE-GIS) Project developed an architecture for semantic interoperability in service composition, and supplied components for semantic modeling and mapping [Probst and Lutz 2004]. ARION (Advanced Lightweight Architecture for Accessing Scientific Collections) is a European Commission project in the domain of ocean and meteorology aimed at developing a digital library that allows access to data and models over the World Wide Web [AIRON 2003]. Harvey et al. (2004) used the Model Description Framework, layered on top of the Resource Description Framework (RDF) of the World Wide Web Consortium to develop an ontology of software entities that is often referred to as meta-model.

3 Field-Based Geo-services

Web services are self-contained, self-describing, modular applications that can be published, located, and invoked across the Web [IBM's tutorial, 2007]. Web services perform functions, which can be anything from simple requests to complicated business processes. Once a Web service is deployed, other applications (and other Web services) can discover and invoke the deployed service [IBM's tutorial, 2007]. According to ISO 19119, geo-services can be defined as a collection of geo-operations, accessible through an interface [ISO 2001].

Most environmental modelers conceptualize the world as fields [Couclelis 1992; Peuquet et al. 1999; Galton 2001; Smith and Mark 2003], that is, a set of states, which are observable and measurable in each location, describing the conditions of the system being modeled [Casti 1989]. The field conceptualization assumes that these states have a continuous nature and describe a natural system in terms of distribution of properties (attributes) such as temperature, population density, soil pH, or soil type. It is a generalization of Frank's first ontological tier of point observation [Frank, 1996].

This paper focuses on geo-services that consist of a set of geo-operations. These geo-operations use field-based geospatial data as input and produce new field-based geospatial data. These geo-operations and their collection, which are useful for environmental modeling are respectively called *field-based geo-operations* and *field-based geo-services*.

4 Semantic Ambiguities and Implicit Details of Field-Based Geo-services

In the distributed computing architecture based on loosely coupled interactions of geo-services, the service interaction model illustrates the interaction between different agents for discovering, publishing, and invoking field-based geo-services (Fig.1).

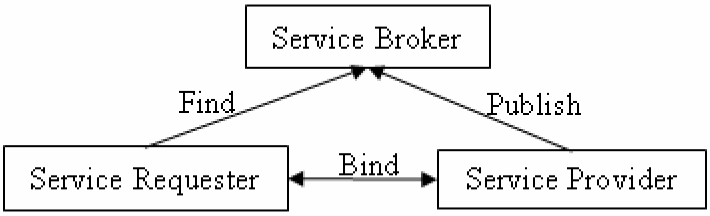


Fig. 1: The basic model of service interaction

According to the service interaction model, a modeler as the requester of field-based geo-services makes a request containing desired geo-services used in the model. Suppose an environmental modeler wants to identify all locations in a forested area that are owned by the state government, and which have a certain runoff rating [ArcGIS 2006].

In order to model the request, the modeler needs a geo-operation that produces runoff rate values in gallon per acre.

There may be several geo-services that produce the runoff as output by using an interpolation operation or according to a formula like the following [NCGIA 1998]:

$$R = \frac{S \times C \times P}{160}$$

where S is the surface slope categorized into values of 1 (0 to 3 degrees), 2 (3 to 6 degrees), 3 (6 to 9 degrees), or 4 (greater than 9 degrees), C the ground cover coefficient categorized into a value of 10 for dense, broad leaf cover, 20 for grass or mixed coniferous forest, 30 for sparse canopy forest, and 40 for bare ground, P the Precipitation in millimeters, and R indicates runoff volume of water (in liters per square meter).

The unit of runoff rate value in the modeler's request is $gallon/acre$, while the unit of runoff volume produced by geo-services according to the equation is l/m^2.

If details in the descriptions of requested and provided geo-services, such as unit of measure and type of measurement are missing, the modeler may select the wrong geo-service.

In the case of an interpolation service, the interpolation algorithm depends on the geospatial data measurement type used as input to the geo-service [Lam 1983]. For example, the interpolation operation for runoff rate on a ratio scale is different from the interpolation for land use type on a nominal scale [Kemp 1993].

5 Semantic Interoperability

Formal semantic descriptions of geo-services promise to automate service discovery. Description of input and output semantic of field-based geo-services is crucial for an automatic discovery of geo-services.

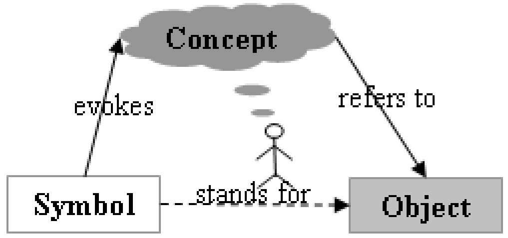


Fig.2: The Meaning Triangle [Ogden et al. 1923]

The term "semantics" here refers to the meaning of expressions in a language [Kuhn 2005, Frank 2000]. Expressions can be single symbols (the "words" of a language) or symbol combinations. The meaning triangle defines the interaction between symbols or words, concepts and things of the world (see Fig. 2). The meaning triangle illustrates the fact that the relationship between a word and a thing is indirect and words cannot completely capture the real meaning of a thing. The correct linkage is only accomplished when an agent interprets the word, invoking a corresponding concept in a context thus, picking out the intended interpretation and discarding others (we use the term agent to stress that discovery services are used either by humans or by software agents on their behalf).

Conceptualization is a description of (a piece of) reality as perceived and organized by an agent, independent of the vocabulary used and the actual occurrence of a specific situation [Borgo et al. 2005]. “An ontology is a specification of a conceptualization” [Gruber 1993]. An ontology (lowercase “o”) is a specific artifact designed with the purpose of expressing the intended meaning of a vocabulary in terms of the nature and structure of the entities it refers to [Borgo et al. 2005]. An ontology typically contains two distinct parts: names for important concepts, and background knowledge/constraints in the domain [Drummond 2005].

Ontologies can be classified according to their level of detail and their level of dependence on a particular task or point of view [Guarino 1997].

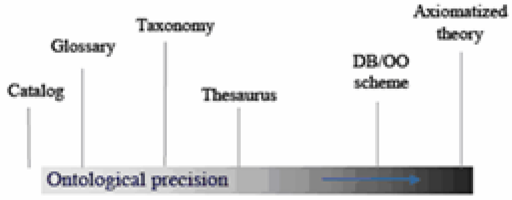


Fig.3: Levels of ontological precision from [Borgo et al. 2005].

The level of detail can be classified by the ontological precision, from catalog to axiomatized theory (Fig.3). The dependence on a particular task or point of view distinguishes between top-level, domain, task, and application ontologies (Fig.4).

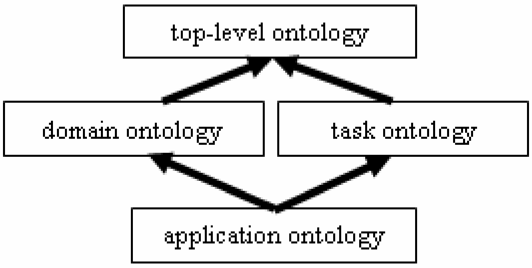


Fig.4: Kinds of ontologies. Thick arrows represent specialization relationships [after Guarino 1997]

In order to match between ontologies of requested and provided geo-services at the application level, there must be an agreement between GIS and environmental modelers on basic and general concepts. In this article, this agreement is achieved by means of the proposed shared upper ontology. The contribution of this article is to develop the ontologies of measurement theory and the core ontology of geo-services at the domain level, in order to describe concepts related to measurement scale and unit of measure that are crucial for field-based geo-service discovery.

6 Layer-Based Structure of Ontologies

The upper ontology, the ontology of measurement theory, the core ontology of geo-services and the Description and Situation (D&S) ontology [Gangemi and Mika 2003] can be structured in four layers (Fig.5).

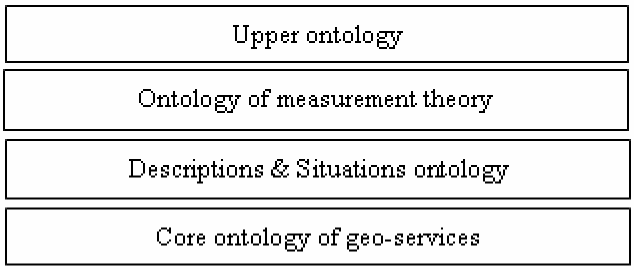


Fig.5: Ontological structure

The role of the Description and Situation (D & S) ontology is to fill the conceptual gap between the upper ontology and the ontology of measurement theory on one side, and the core ontology of geo-services on the other (details are given in subsection 6.4 and figure 8). To uniquely identify concepts and relations in these ontologies, "uont", "mth", "das", and "cogs" tags are used respectively for the upper ontology, the ontology of measurement theory, the Description and Situation ontology and the core ontology of geo-services.

The following sub-sections explain the concepts and relationships in the ontology of measurement theory.

6.1 The Ontology of Measurement Theory

Every entity comes with certain qualities, which exist as long as the entity exists [Masolo et al. 2003]. In field conceptualizations, these qualities are a set of states for modeling the natural system that can be observed in each location. Field-based geospatial data can be used to record and represent qualities such as temperature, population density, or soil type, which serve as input or output for field-based geo-services. The characteristics of a field, including type of measurement and unit of measurement, are an important part of describing the semantics of input and output in a field-based geo-service.

6.1.1 Scale of Measurement

The result of observation is recorded as magnitudes on a measurement scale. The attribute of field data is commonly classified into four scales of measurement, namely, nominal, ordinal, interval and ratio [Stevens 1946, Chrisman 1995]. For example, attributes such as runoff rate, flow rate, wind speed, infiltration rate and physical distance are expressed on a ratio scale. Attributes such as temperature in Celsius, latitude, longitude and times of day are expressed on interval scales. These measurement scales differ in what arithmetic operators can be performed. For example, it is possible to divide, subtract or sum two values with ratio scales, while it is only possible to sum or subtract two values with interval scales. Attributes measured in ratio or interval scales are categorized as quantitative attributes (ratio quantity and interval quantity (Fig.6)).

Attributes such as drainage class or erosion potential are usually on an ordinal scale often coded by numbers (e.g., 1 = good, 2 = medium, 3 = poor). Other attributes such as land cover, soil type, soil texture and rock type are on a nominal scale (e.g., 1 = rocky, 2

= loam). The ordinal and nominal values cannot be used in arithmetic expressions, and are therefore classified as qualitative (ordinal quality and nominal quality (Fig.6)).

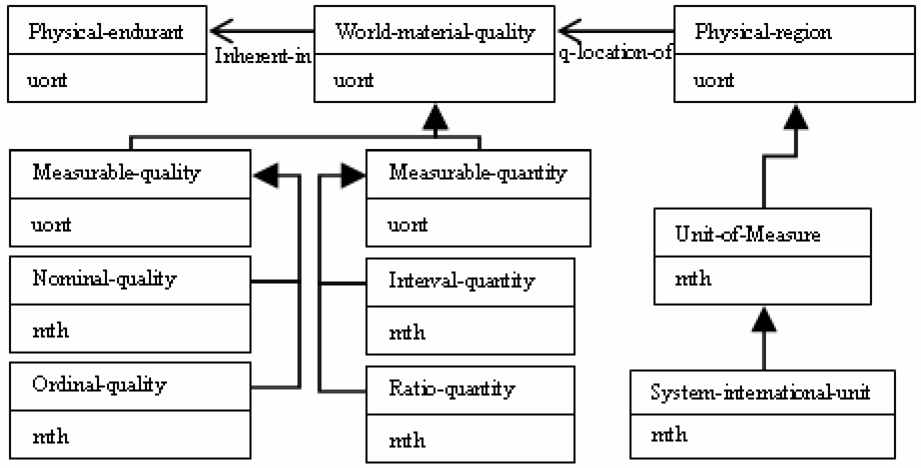


Fig.6: The diagram shows the ontology of measurement theory (boxes with 'mth' tags) and its alignment to concepts of upper ontology (boxes with 'uont' tags). Filled arrows show the subsumption relationships (is-a or super-class/subclass relation).

6.1.2 Measurement Unit

The unit of measurement is a characteristic used for describing the semantics of a field's qualities. Magnitudes of quantitative attributes, such as runoff rate, may be compared with units of measurement such as l/m^2, kg/m^2, $gallon/acre$. Measurement units are described in the ontology of a measurement theory. In this regard, the *unit-of-measure* concept is the formal description of measurement unit (Fig.6). *LiterPerSquareMeter, KilogramPerSquareMeter* and *GallonPerAcre* are individuals of the *unit-of-measure* concept which are used as measurement units for quantitative attributes.

6.2 Core Ontology of Geo-services

An ontology containing geo-service concepts describes the properties and capabilities of geo-services. The Web-Ontology Working Group at the World Wide Web Consortium has produced an ontology of service concepts that supplies a web service designer with a core set of markup language constructs for describing the properties and capabilities of a Web service [OWL-S 2004]. But, OWL-S seems to lack a formal semantic framework. Some of the missing semantics is given informally in the text of the document [Mika et al. 2004]. A specified limitation is that for each *Service*, only one *ServiceModel* is expected to hold. This makes evaluating the relationship between a *ServiceModel* required by a requester and the one underlying the provider's system impossible [Mika et al. 2004].

To overcome the limitations of OWL-S, the core ontology of geo-services must include concepts such as geo-service, geo-operation, and service profile (Fig.7). Similarity between a requested geo-service and provided geo-services can be determined by obtaining the degree of match between these concepts [Kuhn 2005].

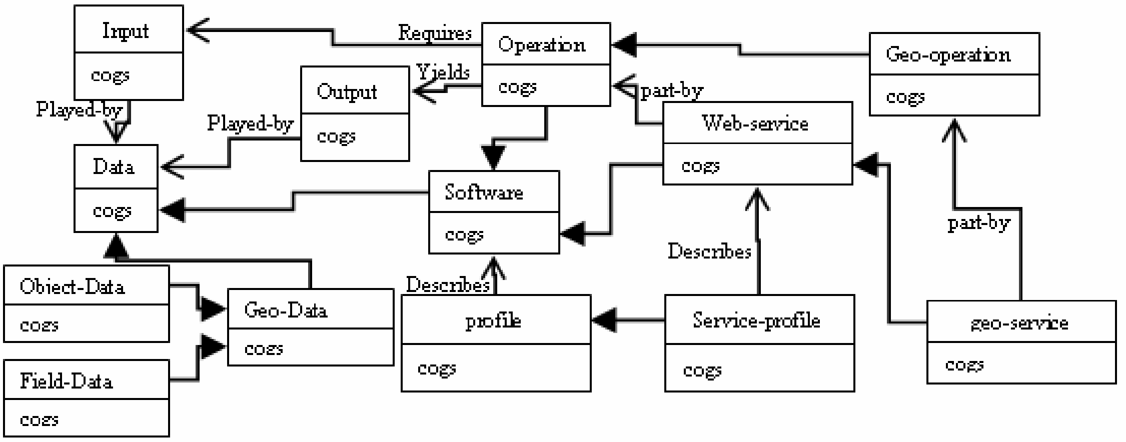


Fig.7: The diagram shows the concepts and relationships for describing geo-services. Filled arrows show the subsumption relationships (is-a or super-class/subclass relation)

6.3 The Upper Ontology

The concepts in the ontology of measurement theory and the core ontology of geo-services must be aligned with general concepts in an upper ontology (Fig. 6and Fig.8). Alignment to an upper ontology means relating the concepts and relations of an ontology to the basic categories of human cognition investigated by philosophy, linguistics, or psychology [Mika et al. 2001].

The taxonomy of Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) that belongs to the WonderWeb project Foundational Ontology Library (WFOL) [Masolo et al. 2003] has been selected as the framework for this research, because it contains a detailed ontology of qualities. In DOLCE, attributes of entities are called qualities [Masolo et al. 2003] but quantitative and qualitative aspects are not distinguished. To avoid a name conflict between quantitative and qualitative aspects of geo spatial attributes and the quality concept in DOLCE, a specialized concept called *world-material-quality* is added as subclass of the quality concept in the DOLCE taxonomy. Soil type, population density, and wind velocity are a number of individuals of qualities that inheres in the entities such as soil, city, weather, or wind. These individuals are members of the *world-material-quality*. The *world-material-quality* is categorized into measurable quantity and measurable quality according to its quantitative and qualitative aspects (Fig.6).

6.4 Descriptions and Situations (D&S) Ontology

The intended meaning of non-physical objects, e.g. service descriptions, emerge only in combination with other entities. A standard, a plan, a view, or a social role is usually represented as a set of statements that inter-relate these notions [Navratil 2002].

The concepts in the core ontology of geo-services are tied to the concepts of the upper ontology through the descriptions and situations (D&S) ontology, which fills the gap between core ontology of geo-services and upper ontology. It is visible in Fig. 8 that the entities of the ontology of geo-services are not directly connected to the upper ontology. For example, *geo-operation*, *web-service*, and *service-profile* in the core ontology of geo-services are indirectly sub-concepts of *information-object* concept, which is in the D&S ontology. This concept is a sub-concept of *non-agentive-social-object*, a general concept in the upper ontology. The diagram illustrated in Fig. 8 shows the alignment of the core ontology of geo-service with the upper ontology through the D&S ontology. It also shows the *unit-of-measure* concept in the ontology of measurement theory that has a relation with the *field-data* concept in the core ontology of geo-service.

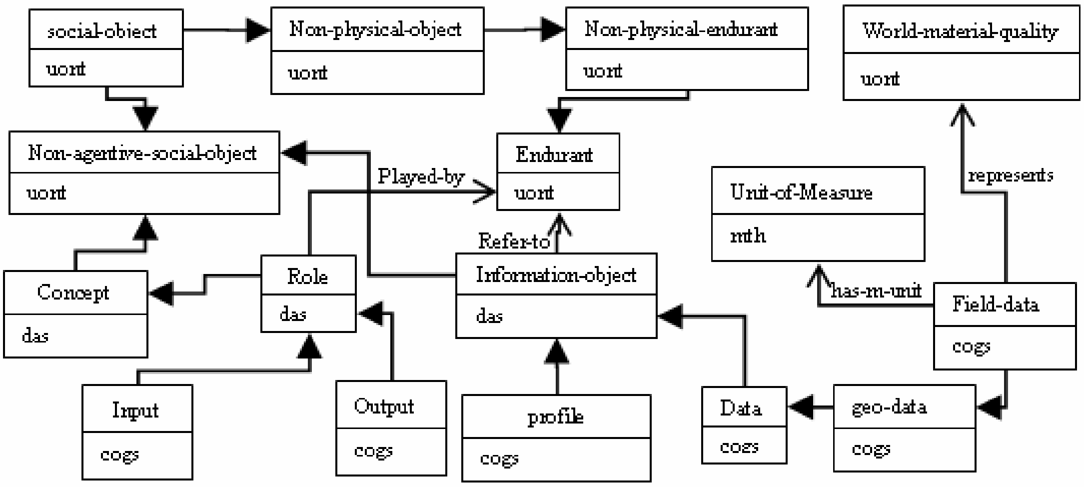


Fig. 8: The diagram shows alignment of core ontology of geo-services (boxes with 'cogs' tags) to upper ontology (boxes with 'uont' tags) through the D&S ontology (boxes with 'das' tags) and relation of the ontology of measurement theory (boxes with 'mth' tags) with the core ontology of geo-services.

7 Description Logics (DLs) and Web Ontology Language (OWL)

To describe the details of field-based geo-services by means of ontology language, needs an ontology language that introduces concepts (also known as classes, entities), properties of concepts (also known as slots, attributes, roles), relationships between concepts (also known as associations) and constraints. The ontology language OWL is a DL based language and widely used, which makes this work comparable with others [Li and Horrocks 2003, Lemmens 2006]. It is expressive enough to formalize the upper ontology, the ontology of measurement theory, the core ontology of geo-services as well as ontologies of provided and requested geo-services.

7.1 Description Logics (DLs)

DLs are subsets of First Order Logic (FOL) [Borgida 1996]. DLs are a well-known family of knowledge representation formalisms. They are based on the notion of concepts (unary predicates, classes, or types) and roles (binary relations or properties), and are mainly characterized by constructors that allow complex concepts and roles to be built from atomic ones [Baader et al. 2002]. Constructors determine the expressive power of DLs. Expressive power and terminology of DLs are discussed in the following sections.

7.1.1 Expressive Power of the minimal language $\mathcal{AL}$

DLs are distinguished by the constructors they provide. The $\mathcal{AL}$ language (Attributive Language) is a minimal DL that is of practical interest, because complex descriptions can be built from atomic concepts or roles inductively with concept constructors. Table 1 summarizes the constructors and syntax rules in $\mathcal{AL}$ [Baader et al. 2002].

For example, *female* and *person* are atomic concepts. Therefore, an $\mathcal{AL}$ concept describing that a female is a person is:

$$female \subseteq person$$

"All value restriction" states that x is an instance of $\forall R.C$ if all objects related to x via R are instances of C. For instance, if it is supposed that *hasChild* is an atomic role, then the concept denoting those persons whose children are female can be represented as follows:

$$Person \cap \forall hasChild.Female$$

Using bottom ($\perp$, means "nothing"), also those persons without a child can be described as:

$$Person \cap \forall hasChild.\perp$$

Existential quantification states that for an object x to be an instance of $\exists R.C$, there has to exist an object, say y, which belongs to C and is related via R to x. Using top concept ($\top$), those persons that have at least a child can be represented as:

$$Person \cap \exists hasChild.\top$$

7.1.2 More Expressive Description Logic

The expressive power of the $\mathcal{AL}$ language is restricted and not sufficient to characterize geo-service requirements. For example, $\mathcal{AL}$ language lacks full existential quantification and the following axiom that describes "the *geo-operation* yield an output", cannot be expressed by this language:

$$operation \cap \exists yeilds.output$$

More expressive languages are obtained with additional constructors [Baader et al. 2002]. $\mathcal{ALUE}$ is the name of an extended DL $\mathcal{AL}$ with union ($C \cup D$) and full existential quantification ($\exists R.C$) (it is equivalent to $\mathcal{ALC}$ because union and full existential quantification are equivalent to negation [Baader et al. 2002]). For example, those *geo-data* that have at least a *unit-of-measure* and represent at least a *world-material-quality* can be described as:

$$geo-data \cap (\exists has-m-unit \cdot unit-of-measure \cap \exists represents \cdot world-material-quality)$$

7.1.3 Structure of DL-Systems

Traditionally, a DL-based system is composed of two distinct parts: the TBox (Terminology Box) and the ABox (Assertion Box) [Baader et al. 2002].

The TBox describes the relation between concept and role expressions. It is a collection of definitions for role and concept, or a set of axioms that restricts the models for the ontology. Because of the nature of the subsumption relationships among the concepts that constitute the terminology, TBoxes have a lattice-like structure [Baader et al. 2002].

The TBox is composed of a set of statements in the form of:

$$C \equiv D\,(R \equiv S)\,(1)$$
$$C \subseteq D\,(R \subseteq S)\,(2)$$

where C and D are concepts (R and S are roles). Statement (1) is a concept definition and asserts that the concept expressions C and D are equivalent. It introduces a new concept in terms of other previously defined concepts. For example, a *spatio-temopral-particular* is defined as a *perdurant*, *endurant,* or *quality* by the following equivalence:

$$spatio-temporal-particular \equiv perdurant \cup endurant \cup quality$$

Statement (2) is a (general) concept inclusion axiom (GCI) and asserts that concept expression C is more specific than (or included in) expression D. It constructs a taxonomic tree. For example the statement, "*field-data* is a *geo-data*" can be declared as:

$$field-data \subseteq geo-data$$

The ABox contains assertional knowledge that is specific to the individuals of the domain of discourse, usually called membership assertions. For example,

$$unit-of-measure(KilogramPerSquareMeter)$$

is a concept assertion and states that the individual *KilogramPerSquareMeter* is a unit of measurement. Similarly,

$$has-measurement-uni(DEM,Meter)$$

is a role assertion and specifies that DEM has *Meter* as a unit [Baader et al. 2002].

7.2 OWL-DL

OWL is a standard for ontologies on the Semantic Web from the World Wide Web Consortium (W3C). It is built on top of RDF (Resource Description Frame) (OWL semantically extends RDF(S) (Resource Description Frame Scheme)), with its predecessor language DAML+OIL (DARPA Agent Markup Language + Ontology Interface Layer) [OWL1.1]. The OWL-DL is used to formally represent the geo-service ontologies. Some aspects of the OWL-DL formalism is needed to understand the remainder of the paper.

7.2.1 Syntax and Semantics of OWL-DL

In order to discover appropriate geo-services, the ontology of the requested geo-service must be compared with ontologies of provided geo-services. This requires a reasoning engine to reason with descriptions of concept in these ontologies. Descriptions must include cardinality restrictions on properties as well as data type properties.

OWL-Lite has simple constraint features and does not support cardinality restriction. On the other hand, OWL-full has maximum expressiveness and the syntactic freedom of RDF with no computational guarantees. Unfortunately, no reasoning software will be able to support every feature of OWL-Full [W3 2007].

While OWL-DL supports those users who want the maximum expressiveness without losing computational completeness (all entailments are guaranteed to be computed) and decidability (all computations will finish in finite time) of reasoning systems. Technically, OWL-DL is an extended logical language based on $\mathcal{ALC}$ (Fig.9) and is equivalent to $\mathcal{SHOIN}(\mathcal{D})$ [Farrar and Bateman 2005] which is an $\mathcal{ALC}$ extended with transitive roles [Horrocks et al. 1999], role hierarchies (equivalently, inclusion axioms between roles), nominals (classes whose extension is a single individual) [Blackburn and Seligman 1995], unqualified number restrictions, inverses and datatypes (Fig.9) [Horrocks and Sattler 2001]. A detailed discussion of OWL is, however, beyond the scope of this research. For further details refer to [OWL 2004, OWL1.1].

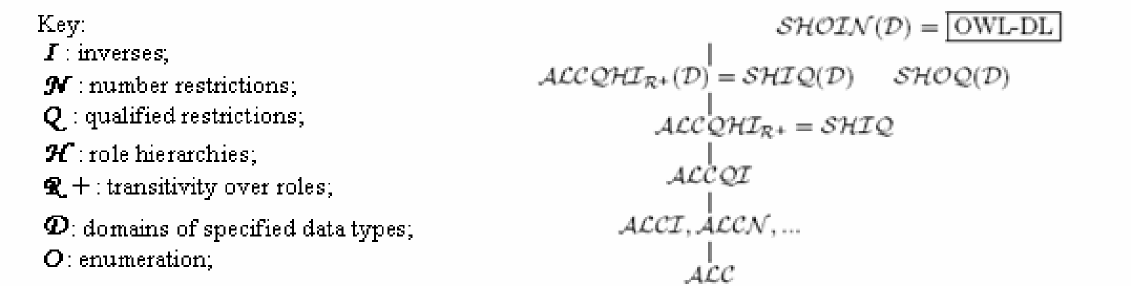


Fig.9: Expressivity hierarchy for description logics [Farrar and Bateman, 2005]

Tables 2 and 3 show that OWL-DL has a rich set of constructors to response the requirements of this research. For instance, OWL-DL with number or cardinality restrictions is able to formalize statements like "a geo-operation is an operation that requires at least one input and yields exactly one output" as:

$$operation \cap (requires \cdot input \geq 1 \cap yields \cdot output = 1).$$

8 Building Proposed Ontologies

8.1 Approach to Build the Proposed Ontologies

Well-defined ontologies are needed to successfully practice the geo-service discovery. These ontologies are the core ontology of geo-services, the ontology of measurement theory, the D&S ontology and the upper ontology. The approach to build these ontologies includes several steps.

The scope of application is the first step. It should be considered that an ontology does not contain all the possible information about the domain. There is also no need to specialize or generalize more than the application requires. Regarding this research, the scope is to discover field-based geo-services.

The second step is to specify concept hierarchy. Names for important concepts in the domain are typically one of the distinct components of ontologies. A set of formal concepts relevant to describing domain have been identified. These concepts have been represented simply by class names or unary predicates in Description Logic. For example, *measurable-quality* is a *world-material-quality*. In this regard, the taxonomies of the upper ontology, the D&S ontology, the ontology of measurement theory and the core ontology of geo-services have been formed.

Identification of relations or properties is the third step. Apart from subsumption (is-a) relationship, there are other relationships between concepts. For example, "*yields*" and "*requires*" relationships between "*geo-operation*", "*output*", and "*input*" concepts state that every individual of geo-operation, yields output and requires input. These relationships are those that the application requires.

The fourth step is to specify a set of axioms or constraints, which declare what should necessarily hold in any possible world or domain of discourse. An ontology is a set of axioms and constraints which describe the meaning of a concept in terms of a logical combination of other concepts. In this regard the axioms and constraints needed to describe the meaning of concepts and relationships have been specified. For example, *geo-operation* concept has been described as follows:

$$\begin{aligned} cogs : geo - operation \subseteq\ & cogs : operation \cap \\ & \exists cogs : requires \cdot cogs : input \cap \\ & (\forall cogs : yields.output \cap \exists cogs : yields.output) \cap \\ & \geq 1 cogs : requires \cap \\ & = 1 cogs : yields \end{aligned}$$

where "cogs" is a tag for uniquely identifying the core ontology of geo-service concepts. This is a primitive concept which only has necessary condition. It states that each individual of *geo-operation* concepts yields an output and requires at least one input.

In contrast, axioms may state a definition for concept. For example the following axiom states that any individual that satisfies this definition will belong to the *world-material-quality* concept:

$$uont : world - material - quality \equiv uont : measurable - quality \cup$$

$$uont : measurable-quantity$$

Concepts that have at least one set of necessary and sufficient conditions are known as defined concepts [Bergamaschi and Nebel 1994]. These conditions are used to check for class subsumption by the DL reasoner to automatically compute a classification hierarchy.

Finally axioms and constraints of concepts and properties have been formalized in OWL language that can be processed by reasoning systems and computers.

8.2 Concepts, Axioms, and Constraints

The *service-profile*, the *geo-service* and the *geo-operation* concepts in the ontologies of requested and provided geo-services must be evaluated to discover a geo-service. Therefore, in this section, the axioms and the constraints, which are used to describe and restrict these concepts, are discussed. The following statement describes a necessary condition for the *service-profile* concept:

$$cogs : service-profile \subseteq cogs : profile \cap \exists cogs : describes \cdot cogs : geo-service$$

The *geo-service* concept is described by the following condition:

$$\begin{aligned} cogs : geo-service \subseteq\ & cogs : web-service \cap \\ & (\forall cogs : part-by \cdot cogs : geo-operation \cap \\ & \exists cogs : part-by \cdot cogs : geo-operation) \cap cogs : part-by \geq 1 \end{aligned}$$

The *geo-operation* concept was given in the pervious section as an example of primary concepts. The *input* and *output* of a *geo-operation* can be stated as:

$$\begin{aligned} &cogs : input \subseteq das : role \cap \exists das : played-by \cdot cogs : field-data \\ &cogs : output \subseteq das : role \cap \exists das : played-by \cdot cogs : field-data\ . \end{aligned}$$

The *field-data* concept is described as:

$$\begin{aligned} cogs : field-data \subseteq\ & cogs : geo-data \cap \\ & \exists cogs : has-m-unit \cdot mth : unit-of-measure \cap \\ & \exists cogs : represents \cdot uont : world-material-quality\ . \end{aligned}$$

Each individual of *field-data* is described by its measurement unit and its scale of measurement.

9 Prototype Implementation

The prototype environment consists of the ontology editor with capabilities to build an ontology in the OWL language and visualize taxonomies of OWL ontologies. The following sections describe these tools.

9.1 Tools for Building and Visualizing Ontologies

Protégé is an open source ontology editor [Protégé 2003] for OWL-based ontology development and inference; it is extensible via plug-ins [Knublauch et al. 2004]. Protégé has its own internal representation mechanism for ontologies and knowledge bases, based on a meta-model, which is comparable to object-oriented and frame-based systems [Knublauch et al. 2004]. The prototype environment used here consists of Protégé version 3.2.1 Build 365, with the OWL plug-in [Horridge et al. 2004, Knublauch et al. 2004, CO-ODE-R]. OWLViz [OWLViz 2004] are used for ontology inspection and documentation.

9.2 Examples of Provided and Requested Geo-service

Suppose a modeler requests a geo-service in order to compute runoff rate and there is a runoff rate geo-service for calculating runoff rate. The profile for the provided and requested runoff rate geo-services can be described as follows:

$$\begin{aligned} pr: calculate-runoff-profile \equiv\ & cogs: service-profile \cap \\ & \exists cogs: describes \cdot pr: calculate-runoff-service \end{aligned}$$

$$\begin{aligned} requested-runoff-profile \equiv\ & cogs: service-profile \cap \\ & \exists cogs: describes \cdot requested-runoff-service\,. \end{aligned}$$

"pr" is a tag for identifying concepts in the ontology of the provided runoff geo-service.

The geo-services concepts for the provided and requested runoff rate geo-services are described as:

$$
\begin{aligned}
pr: calculate-runoff-service \equiv{} & cogs: geo-service \cap \\
& \exists cogs: part-by \cdot pr: calculate-runoff-operation \cap \\
& \forall cogs: part-by \cdot pr: calculate-runoff-operation
\end{aligned}
$$

$$
\begin{aligned}
requested-runoff-service \equiv{} & cogs: geo-service \cap \\
& \exists cogs: part-by \cdot requested-runoff-operation \cap \\
& \forall cogs: part-by \cdot requested-runoff-operation .
\end{aligned}
$$

In these cases the intersection of universal $\forall$ and existential $\exists$ restrictions for a given relationship state that "the calculate-runoff-service consists of only one calculate-runoff-operation".

The following statements describe the geo-operation concept for the provided and requested runoff rate geo-services:

$$
\begin{aligned}
pr: calculate-runoff-operation \equiv{} & cogs: geo-operation \cap \\
& \exists cogs: requires \cdot pr: calculate-runoff-input \cap \\
& \exists cogs: yields \cdot pr: calculate-runoff-output
\end{aligned}
$$

$$
\begin{aligned}
requested-runoff-operation \equiv{} & cogs: geo-operation \cap \\
& \exists cogs: requires \cdot requested-runoff-input \cap \\
& \exists cogs: yields \cdot requested-runoff-output .
\end{aligned}
$$

The following statements describe input, output, and field data used for the provided runoff rate geo-service:

$$
\begin{aligned}
pr: calculate-runoff-input \equiv{} & cogs: input \cap \exists das: played-by \cdot pr: DEM \cap \\
& \exists das: played-by \cdot pr: land-cover-value \cap \\
& \exists das: played-by \cdot pr: precipitation-rain-fall-value
\end{aligned}
$$

$$
\begin{aligned}
pr: calculate-runoff-output \equiv{} & cogs: output \cap \\
& \exists das: played-by \cdot pr: runoff-volume \cap \\
& \forall das: played-by \cdot pr: runoff-volume .
\end{aligned}
$$

The following statements formalize input, output, and field data used for the requested runoff rate geo-service:

$$
\begin{aligned}
requested-runoff-input \equiv{} & cogs: input \cap \exists das: played-by \cdot DEM \cap \\
& \exists das: played-by \cdot land-cover-value \cap
\end{aligned}
$$

$$\begin{aligned}&\exists das : played-by \cdot precipitation-rain-fall-value \cap\\&\forall das : played-by \cdot (precipitation-rain-fall-value \cup\\&land-cover-value \cup DEM)\end{aligned}$$

$$\begin{aligned}requested-runoff-output \equiv {}& cogs : output \cap\\&\exists das : played-by \cdot runoff-volume \cap \forall das : played-by \cdot runoff-volume\end{aligned}$$

where *pr:DEM*, *pr:land-cover-value*, and *pr:precipitation-rain-fall-value* are input field data sets and *pr:runoff-volume* is output field data set of the calculated-runoff-operation. The following formulas show the relation between these field data sets and their unit of measures and their measurement scales.

$$\begin{aligned}pr : DEM \equiv {}& cogs : field-data \cap \ni cogs : has-m-uni.mth : Meter \cap\\&\exists cogs : represents.mth : height\end{aligned}$$

$$\begin{aligned}pr : precipitation-rain-fall-value \equiv {}& cogs : field-data \cap\\&\ni cogs : has-m-uni.mth : Millimeter\\&\cap \exists cogs : represents.mth : precipitation-rain-fall\end{aligned}$$

$$\begin{aligned}pr : land-cover-value \equiv {}& cogs : field-data \cap\\&\exists cogs : represents.mth : land-cover\end{aligned}$$

$$\begin{aligned}pr : runoff-volume \equiv {}& cogs : field-data \cap\\&\ni cogs : has-m-uni.mth : LiterPerSquareMeter\\&\cap \exists cogs : represents.mth : runoff\end{aligned}$$

DEM, *land-cover-value* and *precipitation-rain-fall-value* are input field data sets and *runoff-volume* is the output field data set of the *requested-runoff-operation*. The following statements also show the relation between these field data sets and their unit of measures and their measurement scales.

$$\begin{aligned}DEM \equiv {}& cogs : field-data \cap \ni cogs : has-m-uni.mth : Meter \cap\\&\exists cogs : represents.mth : height\end{aligned}$$

$$\begin{aligned}precipitation-rain-fall-value \equiv {}& cogs : field-data \cap\\&\ni cogs : has-m-uni.mth : Millimeter\\&\cap \exists cogs : represents.mth : precipitation-rain-fall\end{aligned}$$

$$\begin{aligned}land-cover-value \equiv {}& cogs : field-data \cap\\&\exists cogs : represents.mth : land-cover\end{aligned}$$

$$\begin{aligned}runoff-volume \equiv {}& cogs : field-data \cap\\&\ni cogs : has-m-uni.mth : LiterPerSquareMeter\end{aligned}$$

$$\cap \exists cogs:represents.mth:runoff$$

Notice that concepts in the ontologies of the provided and requested runoff rate geo-services are precisely described.

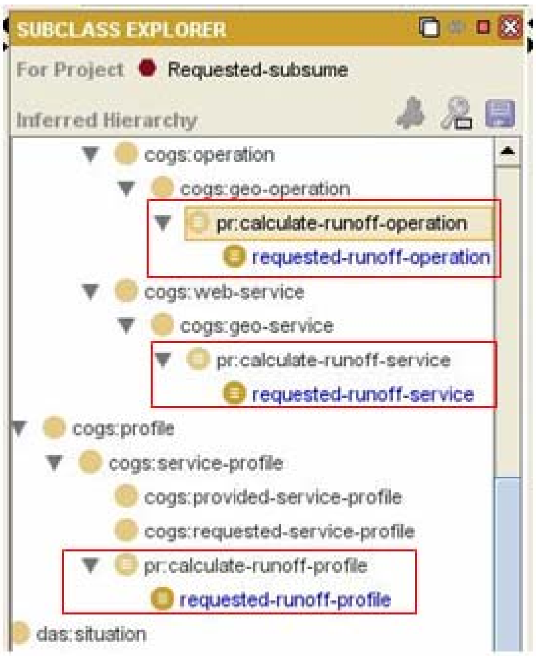


Fig. 10: Boxes show the result of matchmaking between concepts in ontologies of sample requested and provided runoff geo-services.

Since the input and output of the requested and provided runoff rate geo-services seem the same, it may be assumed that these geo-services are the same. However, when using an inference engine (in this case RacerPro 1.8.1 [Racer 2005]) to identify the match between these geo-services, the result of matching is:

$$\begin{aligned}
&requested-runoff-operation \subseteq pr:calculate-runoff-operation \\
&requested-runoff-service \subseteq pr:calculate-runoff-service \\
&requested-runoff-profile \subseteq pr:calculate-runoff-profile\ .
\end{aligned}$$

Fig. 10 illustrates the result of matchmaking in the inferred window of the Protégé ontology editor: the requested runoff geo-service is a subclass of the calculated runoff geo-service. This result is caused by a subtle detail: the statement for describing *calculate-runoff-input* states that the provided runoff geo-services needs at least three inputs, while the statement of *requested-runoff-input* state that the requested runoff geo-service must exactly have three inputs. Therefore the input for the provided geo-service is more general than the input for the requested geo-service.

For modelers it means that the provided runoff geo-service may be an appropriate runoff geo-service in order to calculate desired runoff rate for his model.

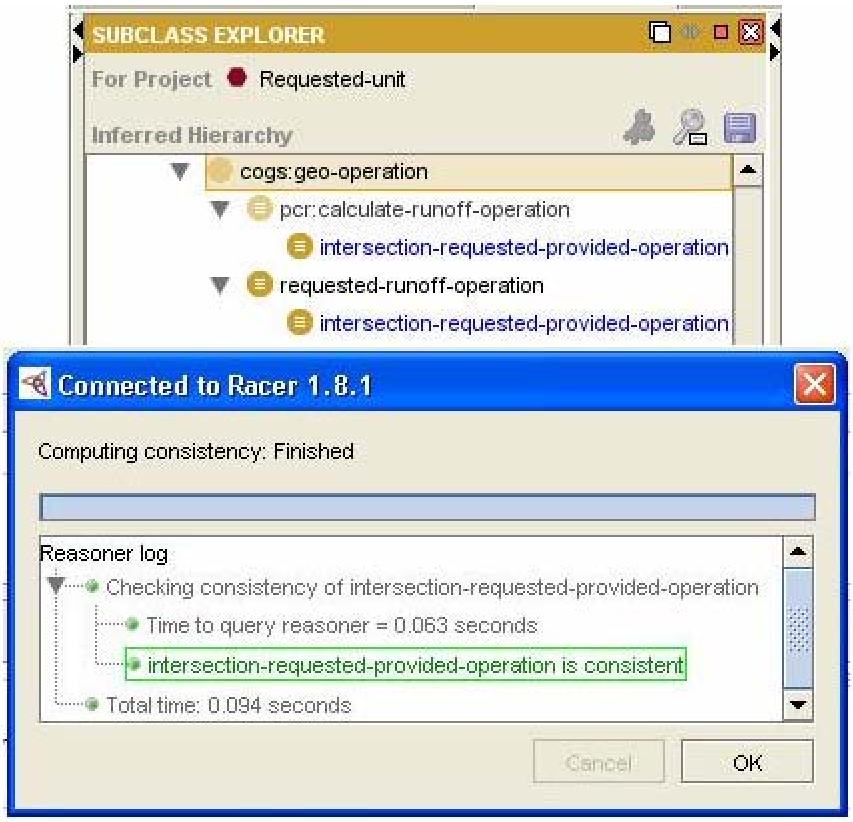
In the other example, suppose that a requester needs a geo-service that yields runoff volume in *GallonPerAcre*, but the provided geo-service yields runoff volume in *LiterPerSquareMeter*. The runoff volume output for the provided geo-service has been described in advance and the following statement describes the runoff volume output for the new requested geo-service:

$$runoff-volume \equiv cogs: field-data \cap \\ \ni cogs: has-m-uni.mth: GallonPerAcre \cap \exists cogs: represents.mth: runoff$$

The result of matching between the ontologies of the requested and provided geo-services shows that there is no inclusion (subclass) or defined relation between *requested-runoff-operation* and *calculated-runoff-operation*, *requested-runoff-service* and *calculated- runoff-service* and *requested-runoff-profile* and *calculated-runoff-profile* concepts. In order to obtain the relation between these concepts, their intersection can be calculated. The intersection of requested-*runoff-operation* and *calculated-runoff-operation* can be stated by the following formulae:

$$intersection-requested-provided-operation \equiv cogs: geo-operation \cap \\ requested-runoff-operation \cap calculate-runoff-operation$$

Fig 11 shows that the intersection-requested-provided-operation is a subclass of both calculate-runoff-operation and requested-runoff-operation and it is consistent. It means that the intersection of these two concepts is not empty. Therefore, the provided geo-service may be probably useful in order to satisfy the needs of the requester.



Computing consistency: Finished

```
Reasoner log
Checking consistency of intersection-requested-provided-operation
    Time to query reasoner = 0.063 seconds
    intersection-requested-provided-operation is consistent
Total time: 0.094 seconds
```

Fig 11: the result of classify taxonomy and consistency of *intersection-requested-provided-operation* concept

In spite of the fact that the requested and the provided geo-services are almost the same, but this result is caused by the subtle difference in measurement unit of the output of these geo-services which have been described in their ontologies.

10 Conclusion and Future Works

This article discussed that semantic ambiguities and implicit details are obstacles when discovering appropriate geo-services. Describing semantic ambiguities are crucial to the precise discovery of an appropriate geo-service. In the Ontology Web Language for Services (OWL-S), input and output data are related to a certain data type [Li and Horrocks 2003] but this is not sufficient to understand the meaning [W3C 2004]. In this regard, the ontology of measurement theory is proposed in this article to describe the semantics of input and output of geo-operations by formalizing their unit of measurement and measurement scale.

In order to discover geo-services automatically the properties of geo-services must be described in a formal language. Descriptions of geo-services offered are compared with descriptions of requested geo-services. Geo-services which are similar to the requested ones are candidates for use.

The article proposes main ontologies to form an ontological structure. The ontological structure supports a semantic framework for discovering geo-services that is missing in OWL-S [Mika et al, 2004].

The article also proposes to characterize geo-services by the measurement units and the measurement types used to express the input and output quantities. It discusses in detail the expressive power of a Description Logic to represent these properties and shows how this can be realized with correct looks for ontology construction. The simplified example performed in protégé demonstrates the capability of the approach.

In future works, a methodology is proposed for discovering geo-services. The architecture of this methodology consists of several components. The proposed ontological structure in this article will be a main component of the methodology, which supports semantic framework for this methodology.

The approach is crucial for interoperability with geographic information, where data is often collected by professionals with very different scientific backgrounds using the measurement units customary in their discipline, but it could be applied beyond geographic applications.

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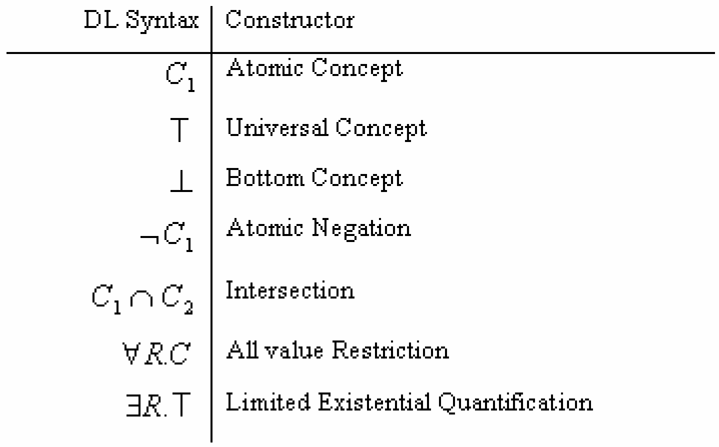
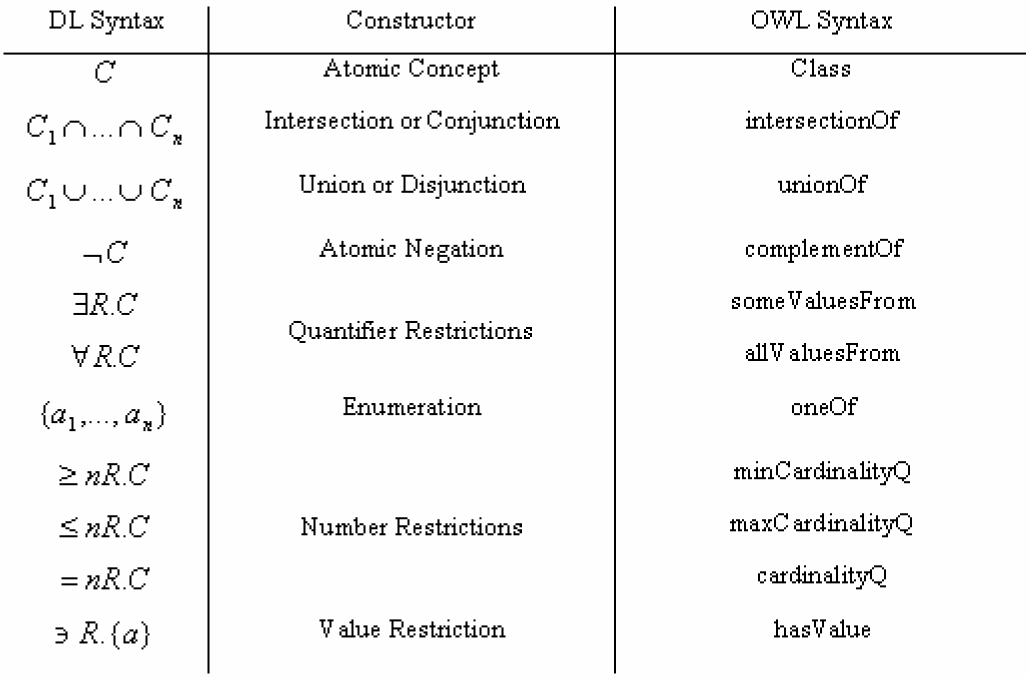


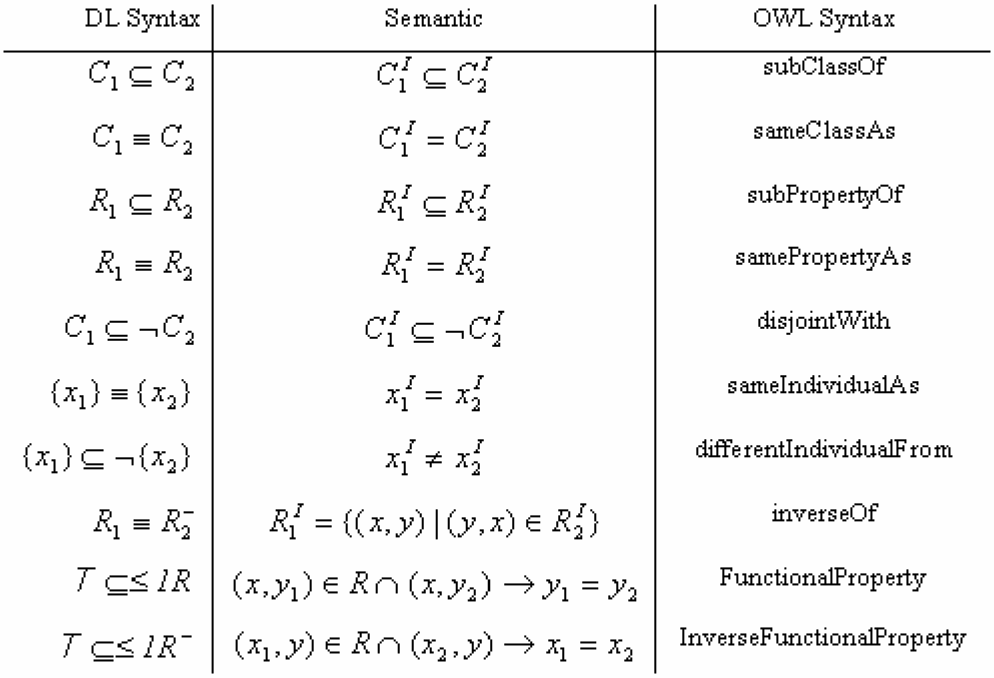
DL Syntax	Constructor
C_1	Atomic Concept
$\top$	Universal Concept
$\bot$	Bottom Concept
$\neg C_1$	Atomic Negation
$C_1 \cap C_2$	Intersection
$\forall R.C$	All value Restriction
$\exists R.\top$	Limited Existential Quantification

Table 1: DL syntax of $\mathcal{AL}$ language's constructors



DL Syntax	Constructor	OWL Syntax
C	Atomic Concept	Class
$C_1 \cap \ldots \cap C_n$	Intersection or Conjunction	intersectionOf
$C_1 \cup \ldots \cup C_n$	Union or Disjunction	unionOf
$\neg C$	Atomic Negation	complementOf
$\exists R.C$	Quantifier Restrictions	someValuesFrom
$\forall R.C$		allValuesFrom
$\{a_1, \ldots, a_n\}$	Enumeration	oneOf
$\geq nR.C$	Number Restrictions	minCardinalityQ
$\leq nR.C$		maxCardinalityQ
$= nR.C$		cardinalityQ
$\ni R.\{a\}$	Value Restriction	hasValue

Table 2: DL and OWL syntax of OWL's constructors



DL Syntax	Semantic	OWL Syntax
$C_1 \subseteq C_2$	$C_1^I \subseteq C_2^I$	subClassOf
$C_1 \equiv C_2$	$C_1^I = C_2^I$	sameClassAs
$R_1 \subseteq R_2$	$R_1^I \subseteq R_2^I$	subPropertyOf
$R_1 \equiv R_2$	$R_1^I = R_2^I$	samePropertyAs
$C_1 \subseteq \neg C_2$	$C_1^I \subseteq \neg C_2^I$	disjointWith
$\{x_1\} \equiv \{x_2\}$	$x_1^I = x_2^I$	sameIndividualAs
$\{x_1\} \subseteq \neg\{x_2\}$	$x_1^I \neq x_2^I$	differentIndividualFrom
$R_1 \equiv R_2^-$	$R_1^I = \{(x,y) \mid (y,x) \in R_2^I\}$	inverseOf
$T \subseteq \leq 1R$	$(x,y_1) \in R \cap (x,y_2) \rightarrow y_1 = y_2$	FunctionalProperty
$T \subseteq \leq 1R^-$	$(x_1,y) \in R \cap (x_2,y) \rightarrow x_1 = x_2$	InverseFunctionalProperty

Table 3: DL syntax, semantic and OWL syntax of OWL-DL's axioms

List of Figures