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# A Formal Ontological Structure for Semantic Interoperability of GIS and Environmental Modeling

# Abstract

Most of the environmental problems have an obvious spatial dimension and Geographic Information System (GIS) are widely used for solving environmental problems. Service oriented architecture in 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 new layers for describing geo-services. 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 related to geo-services. An upper ontology adds new general concepts to an existing ontology in order to make 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

Natural environment includes physical processes such as surface flow, soil erosion or infiltration. Environmental degradation occurs when natural resources are being consumed faster than nature can replenish them, when pollution results in irreparable damage, or when human beings destroy or damage ecosystems. The goal of environmental protection is to minimize such degradations.

Scientists model the physical processes and impacts of human activities in natural environment for prediction and analysis of relationship between 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). Sharing geospatial data and geo-services from heterogeneous resources and multiple GISs is a basic requirement to model physical process and impacts of human activities.

Currently different approaches are used to link GIS and environmental models. Goodchild (2001) classifies these approaches in

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

The tightly coupled and full integration approaches cannot take advantage of the Web because they lack interoperability.

GIS and environmental models are linked with distributed computing architecture based on loosely coupled interoperable geo-services. However, these architectures fix mostly syntactic issues and lack to address the semantic ambiguities and implicit details; these hinder the discovery of geo-services. This paper proposes a solution for description of the semantics of geo-services.

The next section discusses research works linking 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 and the fifth section discusses semantic interoperability and ontology as means of describing semantic ambiguities and implicit details. Section 6 pays attention to the proposed layer-based structure of ontology 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. 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 Works

Most approaches for linking GIS and environmental models use one of three methods: full integration, loose coupling or tight coupling. [e.g., Sydelko et al. 2000, Fedra 1996, Djokic 1996]. An embedded system is the highest level of integration, where GIS and modeling functions are interwoven elements of a software system (also called full integration) [Goodchild 2001]. Two systems are loosely coupled if they communicate by the self-describing, text-based messages. Developer and user are confronted with tedious batch conversion tasks, import/export obstacles, and barred from using distributed resource 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.

Some research efforts focused on using open systems, object oriented method and framework to develop tools [Bernard and Krüger 2000, MDSF, Feng 2000]. In order to share GIS and models across various domains, some used distributed computing technologies such as COM (Component Object Model) or CORBA (Common Object Request Broker Architecture) in a 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 architectures [Hutchings et al. 2002].

The current researches shift to a distributed computing architecture based on loosely coupled web services [Alameh 2003, Jaakkola 2005, ArcWeb 2006]. Key to the interoperation of web services is 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 however, but "knowing the type of a data structure is not enough to understand the intent meaning behind its use" [W3C 2004].

OGC initiated standards about Web Processing Service (WPS), which provides a common view on geo-processes ranging from complex such as modeling of climate change to simple, e.g., buffering [Kiehle et al. 2006]. The *getCapabilities* interface is used for retrieving service metadata. A detailed description about input and output of one specific process is accessible through the *describeProcess* interface. The *execute* interface provides underlying functionality of the service, e.g., 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].

Semantic interoperability of web services is addresses by few researchers. For examples, 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 to develop 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. 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]. According to ISO 19119 geo-services can be defined as a collection of geo-operations, accessible through an interface [ISO 2001]. The geo-services can be categorized into two classes that are called geo-data-services and geo-operation-services [Fallahi et al. 2006]. The paper focuses on geo-operation-services that consist of a set of geo-operations. A geo-operation is defined by its inputs, outputs, and its function and uses a certain algorithm to derive new data from input data. Most environmental modelers conceptualize the world as fields [Couclelis 1992; Peuquet et al. 1999; Galton 2001; Smith and Mark 2003], i.e., a set of states, which are observable and measurable in each location, describe the conditions of the system being modeled [Casti 1989]. The field conceptualization assumes that these states have continuous nature and describe a natural system in terms of distribution of properties (attributes) such as temperature, population density, pH of the soil, or soil type.

This paper focuses on geo-operation services that use field-based geospatial data as input and produce new field-based geospatial data. These geo-operations and the collection of them useful for environmental modeling are respectively called *field-based geo-operations* and *field-based geo-services*.

Field-based geo-services may be categorized into primitive, or "atomic" services, and complex or "composite" services [OWL-S 2004]. Atomic services are those where a single Web-accessible computer program, sensor, or device is invoked by a requested message, performs its task and perhaps produces a single response to the requester. For example, a service that creates a buffer around a given polygon at a user specified distance would be classified as an atomic service. Complex or 'composite' services are composed of multiple atomic services, and may require an extended interaction or conversation between the requester and the set of services that are being utilized.

## 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 agents for discovering, publishing, and invoking field-based geo-services (Fig.1).

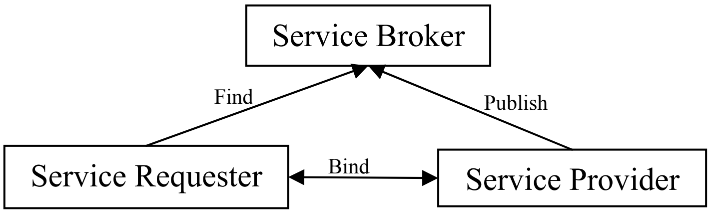


Fig. 1: The basic model of service interaction

According to the service interaction model, a modeler as 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 an area that are forested, which are owned by the state government, and which have a certain runoff rating [ArcGIS 2006].

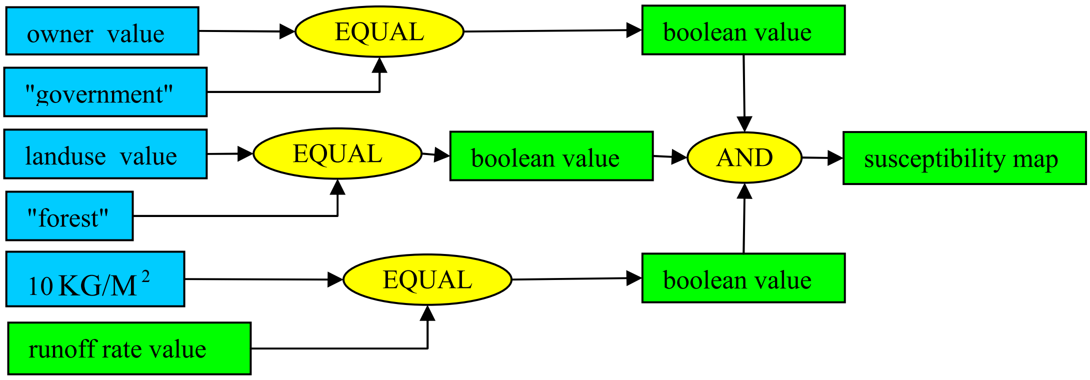


Fig. 2: The workflow of the model. The blue and green boxes show respectively primary and derived field-based geospatial data. The yellow ellipses show the field-based geo-operation.

Fig. 2 shows a solution for this problem. The workflow of the model contains geo-operations such as "EQUAL" as well as "AND" operations and geospatial data that are used as inputs and outputs of geo-operations.

To make the model, the modeler must discover appropriate geo-services. For this, the modeler must describe the desired geo-service precisely. Suppose a modeler is looking for a geo-operation that produces runoff rate value. There may be several geo-services that produce the runoff as output by using interpolation operation or according to a formula like the following [NCGIA 1998]:

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

where $S$ is the surface slope, $C$ the ground cover coefficient, $P$ the Precipitation in millimeters, and $R$ indicates runoff volume of water, (in liters per square meter).

Regarding the above example, in the model, the unit of runoff rate is $kg/m^2$ while the unit of runoff volume produced by geo-services according to 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 interpolation service, the interpolation algorithm depends on the measurement type of geospatial data used as input of the geo-service. "Numerous algorithms for point interpolation have been developed in the past. The selection of an appropriate interpolation model depends largely on the types of data, the degree of accuracy desired, and the amount of computational effort afforded" [Lam 1983]. The interpolation operation for runoff rate on a ratio scale is different from the interpolation for land use type on a nominal scale. Continuous fields of categorical data cannot be generated from points using any of the mathematical interpolation techniques since values cannot be interpolated between classes [Kemp 1993].

A modeler could confuse logical "AND" with addition and discover an addition geo-service (Fig. 3):

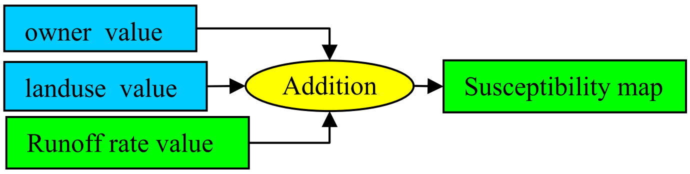


Fig. 3: The workflow of model with "Addition" operation

However, for a numerical addition operation, the measurement type and the unit for its input and output data do not fit to what is provided. Land use value and owner value have nominal type and no units. They can not be numerically added to runoff rate value with a ratio type and unit of $kg/m^2$. The result would be meaningless.

## 5 Semantic Interoperability

Semantic of geo-services promise to provide solutions to the challenges associated with automated discovery using service-based systems. Bishr (1998) lists six levels of interoperability in communication between two systems; semantic interoperability is at the highest level. Semantic description of capabilities and properties of field-based geo-services is crucial for automatic discovery of geo-services.

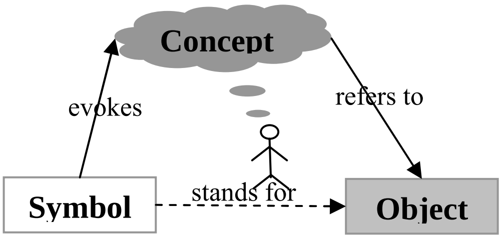


Fig.4: The Meaning Triangle [Ogden et al. 1923]

The term “semantics” here refers to the meaning of expressions in a language [Kuhn 2005]. 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.4). 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. For example, the term “jaguar” can evoke a concept of an animal, car, or jet fighter. The correct linkage is only accomplished when an agent interprets the word invoking a corresponding concept in a context picking out the intended interpretation and discarding others. The corresponding concept establishes the proper linkage between symbol and the appropriate thing in the world. Thus linkage between object, word, concept, and context can be defined as follow.

$$object = word + (concept + context)$$

The corresponding concept, which is concept plus context, is shaped by human experience with real-world entities.

## 5.1 An ontology as a Means of Describing Semantic

Describing semantics means to fix the intended meaning of vocabulary terms. Standardized vocabularies are only a partial solution for semantic heterogeneities, because they tend to be ambiguous or circular. The meaning triangle (Fig. 4) shows the linkage established between a thing in the world and its symbol through a concept. Conceptualization is a description of (a piece of) reality as perceived and organized by an agent, independently 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]. Ontology (capital “O”) is a philosophical discipline, which studies the nature and structure of possible entities. 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]. The ontologies can be used to negotiate meaning, either for enabling effective cooperation between multiple artificial agents, or for establishing consensus in a mixed society where artificial agents cooperate with humans. An ontology consists of axioms that express the meaning of terms for a particular community. Logical axioms are the means to specify a set of constraints, which declare what should necessarily hold in any possible world. They also introduce concepts, relations, and their taxonomic hierarchies. An ontology typically contains two distinct parts: names for important concepts and background knowledge/constraints in the domain [Drummond 2005].

## 5.2 The Classification of Ontologies

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

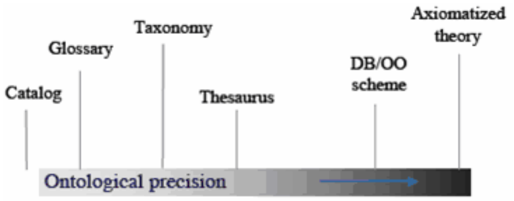


Fig.5: Levels of ontological precision from [Borgo et al. 2005].

The level of detail can be classified by the ontological precision from catalog to axiomatized theory (Fig 5). The dependence on a particular task or point of view distinguishes between top-level, domain, task, and application ontologies (Fig.6).

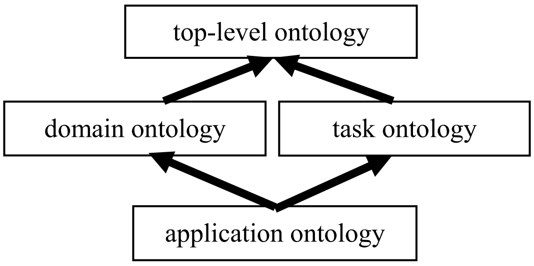


Fig.6: Kinds of ontologies. Thick arrows represent specialization relationships from [Guarino 1997]

In order to perform matching between ontologies of requested and provided geo-services at the application level, there must be an agreement between GIS and environmental modelers about basic and general concepts. In this article, this agreement is achieved by means of the proposed shared upper ontology. The contribution is to develop the ontologies of the measurement theory and 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

Four ontologies at top and domain levels including 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] are related to each other in a layer-based structure (Fig. 7).

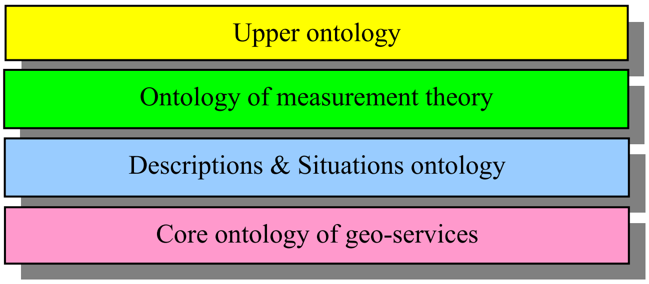


Fig. 7: Ontological structure

The (D&S) ontology is added in order 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 side. 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 like temperature, population density, or soil type which play the role of input or output for field-based geo-services. The characteristics of field including, type of measurement and unit of measurement are an important part of describing the semantic of input and output of 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 ratio, interval, ordinal, and nominal [Stevens 1946]. 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, latitude, longitude, compass directions 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, sum two values with ratio scales while it is just possible to sum or subtract two values with interval scales such as temperature in degree Fahrenheit. Attributes measured in ratio or interval scales are categorized as quantitative attributes (ratio quantity and interval quantity (Fig. 8)).

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 mathematical expressions, and are therefore classified as qualitative (ordinal quality and nominal quality (Fig. 8)).

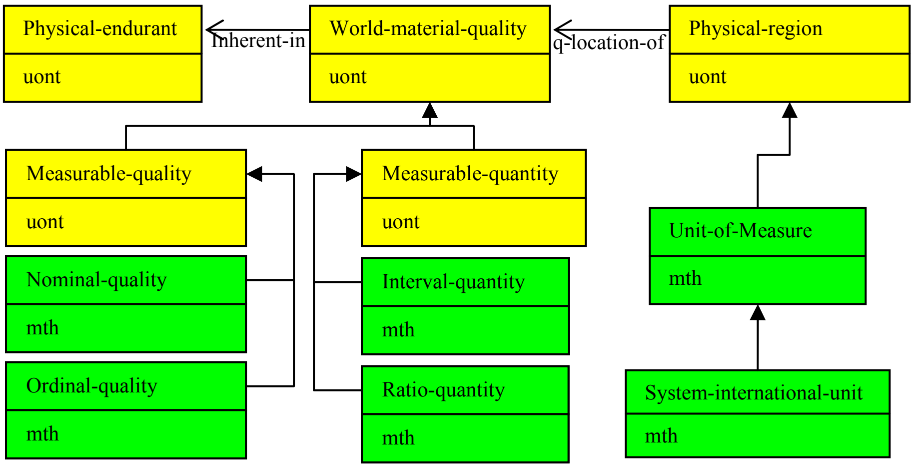


Fig. 8: The UML diagram shows the ontology of measurement theory (green boxes) and its alignment to concepts of upper ontology (yellow boxes). Filled arrows show the subsumption relationships (is-a or super-class/subclass relation).

### 6.1.2 Measurement unit

The unit of measurement is another characteristic used for describing the semantic of field's qualities. Magnitudes of quantitative attributes such as runoff rate may be compared with units of measurement such as $l/m^2$, $kg/m^2$, $pound/feet^2$. Therefore, measurement unit must be described in the ontology of measurement theory. The SI (system international) units are a subset of measurement unit. These concepts are respectively called *unit-of-measure* and *system-international-unit* as illustrated in Fig. 8. For building sample ontologies and match between them, $kg/m^2$, $l/m^2$, $m$, and $mm$ are used as individuals of unit-of-measure (*KilogramPerSquareMeter*, *LiterPerSquareMeter*, *Meter* and *Millimeter*).

## 6.2 Core Ontology of Geo-services

An ontology containing geo-service's concepts is required to describe 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 behind. Some of the missing semantics is in the text of the document [Mika et al. 2001]. 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. 2001].

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. 9). The evaluation of requested and provided geo-services can be performed by determining the degree of matching between these concepts.

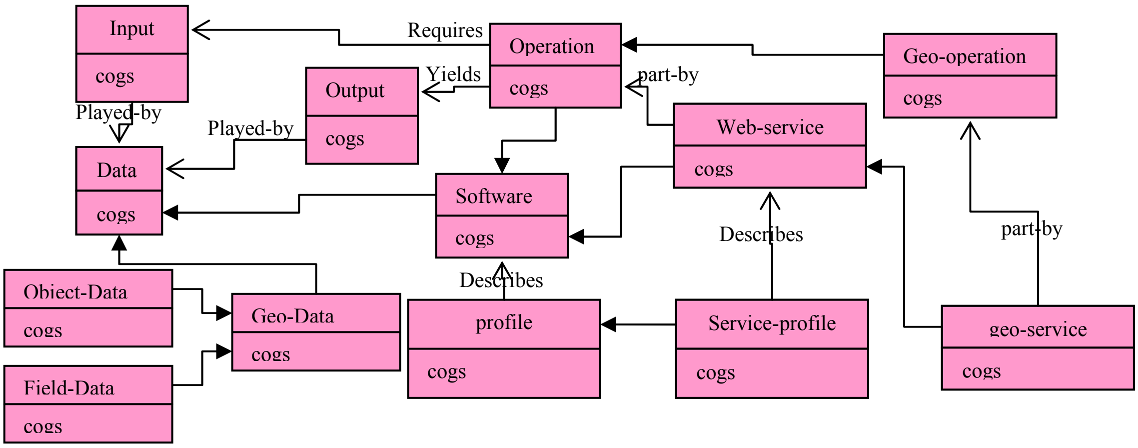


Fig. 9: This UML diagram shows the concepts and relationships for describing geo-services. Filled arrows show the subsumption relationships (is-a or super-class/subclass relation)

## 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. 8 and Fig. 10). 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 framework. In DOLCE, attributes of entities are called qualities [Masolo et al. 2003] and it is not distinguished between quantitative and qualitative aspects of attributes. 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 quality concept in the DOLCE taxonomy. Soil type, population density, precipitation-rain-fall and velocity of wind are a number of individuals of qualities that inheres in the entities such as soil, city, weather, or wind. These individuals are also member 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. 8).

### 6.4 Descriptions and Situations (D&S) Ontology

The intended meaning of non-physical objects, e.g., service descriptions emerges only in the combination of 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 gaps between core ontology of geo-services and upper ontology. For example, *operation*, *web-service*, and *service-profile* in the core ontology of geo-services are 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 UML diagram illustrated in Fig. 10 shows the alignment of core ontology of geo-service with 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 field-data concept in the core ontology of geo-service.

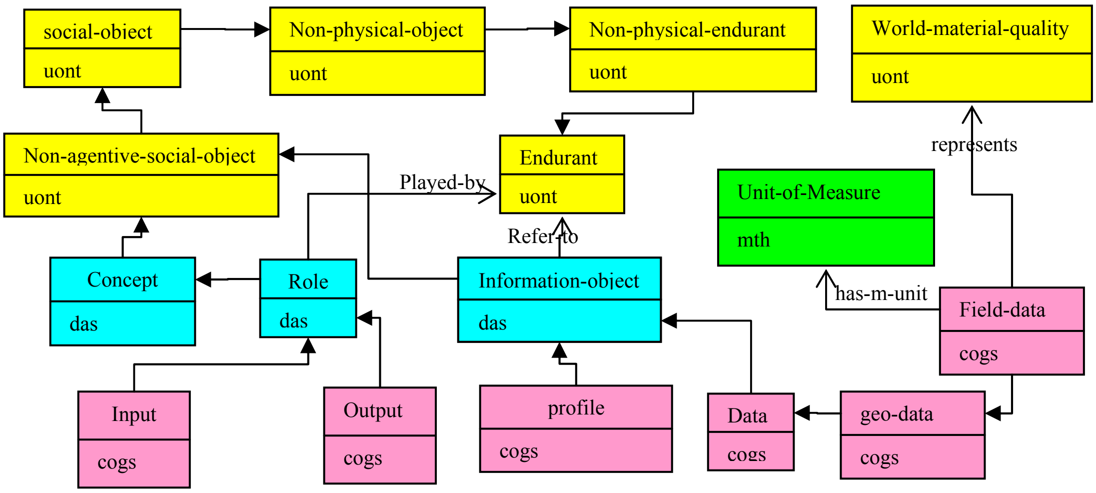


Fig. 10: The UML diagram shows alignment of core ontology of geo-services (pink boxes) to upper ontology (yellow boxes) through the D&S ontology (cyan boxes) and relation of the ontology of measurement theory (green box) with the core ontology of geo-services. "uont", "mth", "das", and "cogs" respectively denote upper ontology, ontology of measurement theory, D&S ontology and 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 (Web Ontology Language), which is a DL (Description Logic) based language is widely used and fulfills the requirement of this project [Li and Horrocks 2003].

### 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. In the following sections, expressive power and terminology of DLs are discussed.

### 7.1.1 Expressive Power of $\mathcal{AL}$

DLs are distinguished by the constructors they provide. The language $\mathcal{AL}$ (Attributive Language) is a minimal DL that is of practical interest. Elementary descriptions are atomic concepts and atomic roles. Complex descriptions can be built from them 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. Then 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 state that for an object $x$ to be instance of $\exists R.C$, there has to exist an object, say $y$, which belongs to $C$ and is related via $R$ to $x$. For instance, 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 axioms like the following axiom for *geo-operation* concept, which 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 $\mathcal{AL}$ by 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 (complement) [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 Terminology of DLs

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 of the forms:

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

where $C$, $D$ are concepts (and $R$, $S$ are roles). The 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:

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

The 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 lattice. For example *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,

$$unit - of - measure( Ki\log ramPerSquareMeter )$$

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)), and evolve from DAML+OIL (DARPA Agent Markup Language + Ontology Interface Layer)

[OWL1.1]. The OWL-DL is used to formally represent the geo-service ontologies and 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

A geo-service ontology must reason with descriptions that include cardinality restriction on properties as well as data type properties. For examples it is needed to state that a certain geo-operation requires a certain number of inputs and yields an output. A certain field data has an integer, a float or a custom object data type.

OWL-DL is an extended logical language based on $\mathcal{ALC}$ (Fig. 11). More precisely OWL-DL 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. 11) [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].

Table 2 and table 3 show that OWL-DL has a rich set of constructors in order to response the requirement 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:

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

Key:
$I$ : inverses;
$\mathcal{N}$ : number restrictions;
$\mathcal{Q}$ : qualified restrictions;
$\mathcal{H}$ : role hierarchies;
$\mathcal{R}+$ : transitivity over roles;
$\mathcal{D}$: domains of specified data types;
$O$ : enumeration;

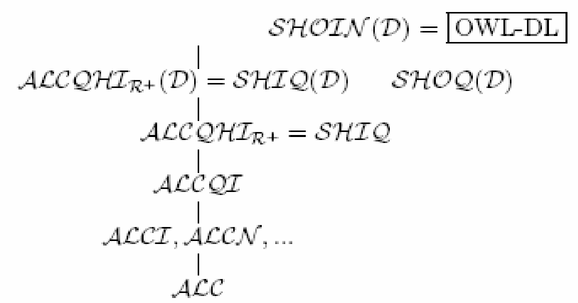


Fig. 11: Expressivity hierarchy for description logics [Farrar and Bateman, 2005]

# 8 Building Proposed Ontologies

## 8.1 Approach to Built the Proposed Ontologies

The core ontology of services, the ontological theory of measurement, the D&S ontology and the upper ontology are a collection of axioms and constraints that restrict the concepts and relationships about geo-services. Apart from subsumption (is-a) relationship, there may be other relationships between concepts such as the "*yields*" and "*requires*" relationships between "*geo-operation*", "*output*", and "*input*" concepts in order to state that every individual of geo-operation yields output and requires input.

The constraints are on relationships that the individuals participate in for a given property. For example the following are constraints on the "yields" and "requires" relationships:

$cogs : yields = 1$,

$cogs : requires \geq 1$.

These statements restrict the relationships and state that each individual of geo-operation concept yields an output and requires at least one input. The following statement describes the primary concept of *geo-operation*:

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

where "cogs" is a tag for uniquely identifying the core ontology of geo-services concepts. Primitive concepts are concepts that only have necessary conditions.

The following axiom states a definition for *world-material-quality*, and 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.

## 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 before 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:

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

$$\exists cogs : represents \cdot uont : world - material - quality \text{ .}$$

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

## 9 Implementation of Prototype

The prototype environment consists of the ontology editor with capabilities of building ontology in OWL language and visualizing taxonomy of OWL ontologies. The following sections describe these tools and how to build the geo-service ontologies within this environment.

### 9.1 Tools for Building and Visualizing Ontologies

Protégé is an open source ontology editor like OntoEdit, Rice, and OilEd [Sure et al. 2002; Protégé 2003; Cornet 2003; Bechhofer et al. 2001] 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 Relation of OWL Files

The ontologies in the ontological structure are modular; the ontology of each layer is in a separate OWL file connected by the <owl:imports> statement. The Fig. 12 shows the relations between these ontologies. The line connecting two ontologies implies that the one above is imported by the one underneath. For example, the upper ontology is imported to the ontology of measurement theory and the D&S ontology imports the ontology of measurement theory.

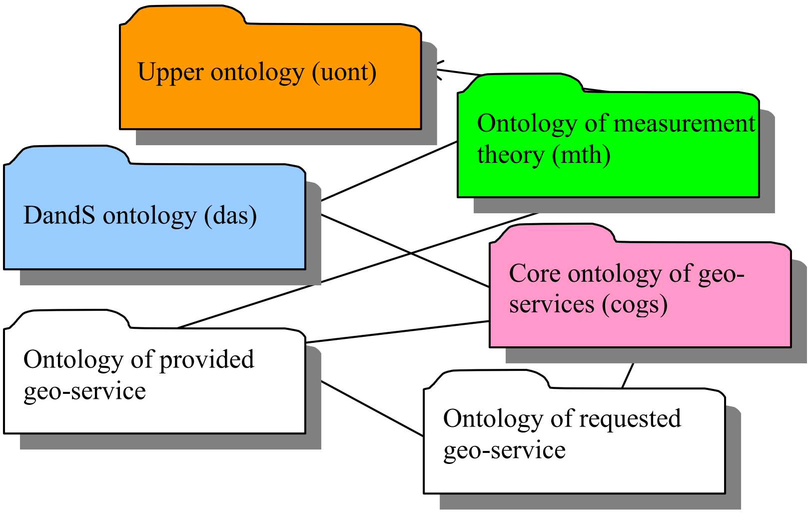
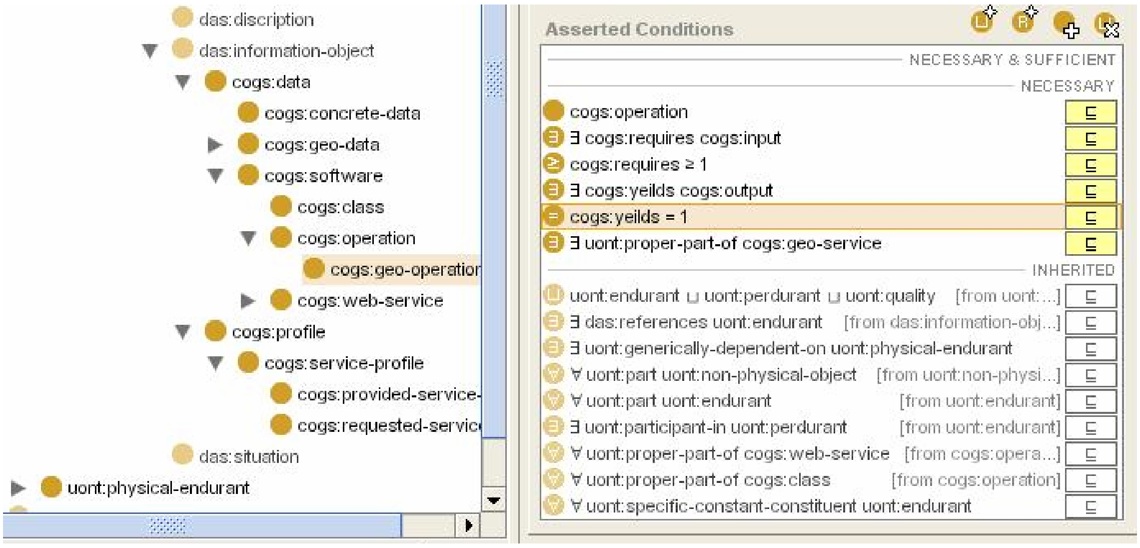


Fig. 12: Inter-relation between the proposed ontologies

When an OWL file is opened in an ontology editor the concepts and relationships in the main ontology and the imported ontologies become available. The Fig. 13 illustrates a part of the core ontology of geo-services in Protégé ontology editor.



cogs:operation ⊑
∃ cogs:requires cogs:input ⊑
cogs:requires ≥ 1 ⊑
∃ cogs:yeilds cogs:output ⊑
cogs:yeilds = 1 ⊑
∃ uont:proper-part-of cogs:geo-service ⊑
uont:endurant ⊔ uont:perdurant ⊔ uont:quality [from uont:...] ⊑
∃ das:references uont:endurant [from das:information-obj...] ⊑
∃ uont:generically-dependent-on uont:physical-endurant ⊑
∀ uont:part uont:non-physical-object [from uont:non-physi...] ⊑
∀ uont:part uont:endurant [from uont:endurant] ⊑
∃ uont:participant-in uont:perdurant [from uont:endurant] ⊑
∀ uont:proper-part-of cogs:web-service [from cogs:opera...] ⊑
∀ uont:proper-part-of cogs:class [from cogs:operation] ⊑
∀ uont:specific-constant-constituent uont:endurant ⊑

Fig. 13: Part of the core ontology of geo-services in Protégé with OWL plug-in

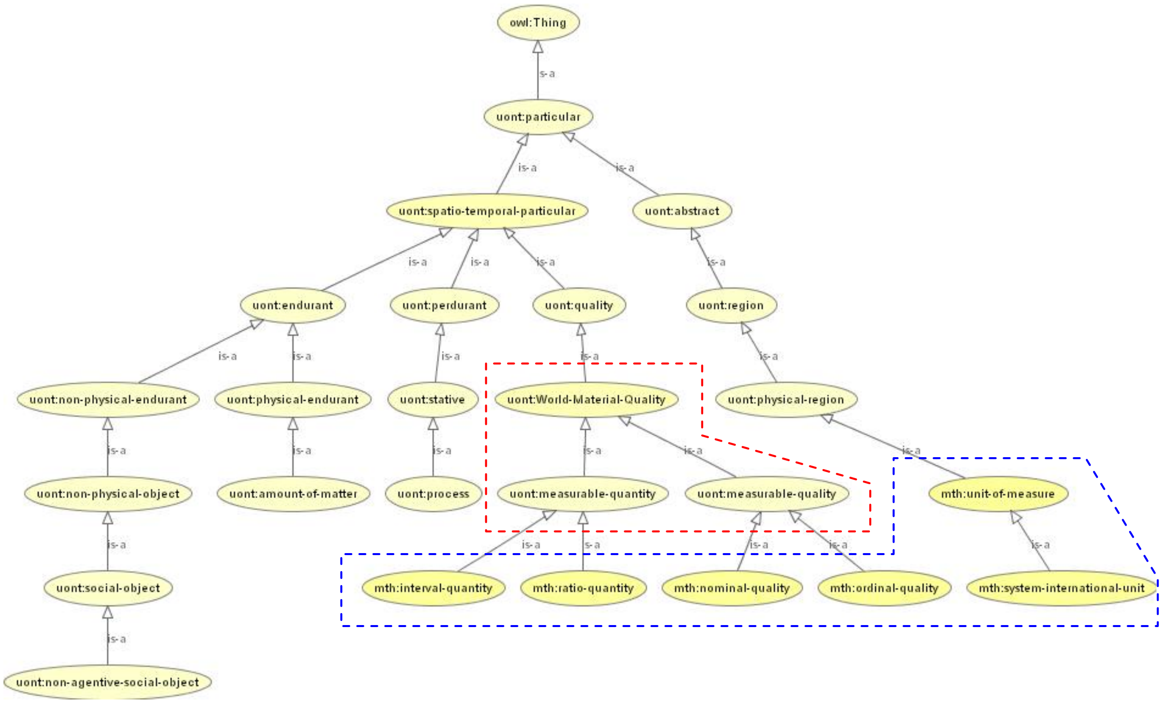


Fig 14: Taxonomy of proposed upper ontology (red dashed box show the new added concepts) and taxonomy of the measurement theory ontology (blue dashed box)

The taxonomy illustrates the "is-a" relationships between concepts. Fig 14 shows the taxonomies of the ontology of measurement theory and the upper ontology extracted by OWLViz plug-in. In this case the ontology of measurement theory was opened and the upper ontology was imported.

## 9.3 Examples of Provided and Requested Geo-service

Suppose a modeler needs a 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 services can be described as follows:

$$pr : calculate - runoff - profile \equiv cogs : service - profile \cap \exists cogs : describes \cdot pr : calculate - runoff - service$$

$$requested - runoff - profile \equiv cogs : service - profile \cap \exists cogs : describes \cdot requested - runoff - service .$$

"pr" is a tag for identifying concepts in the ontology of 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 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:

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

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

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.

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

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

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

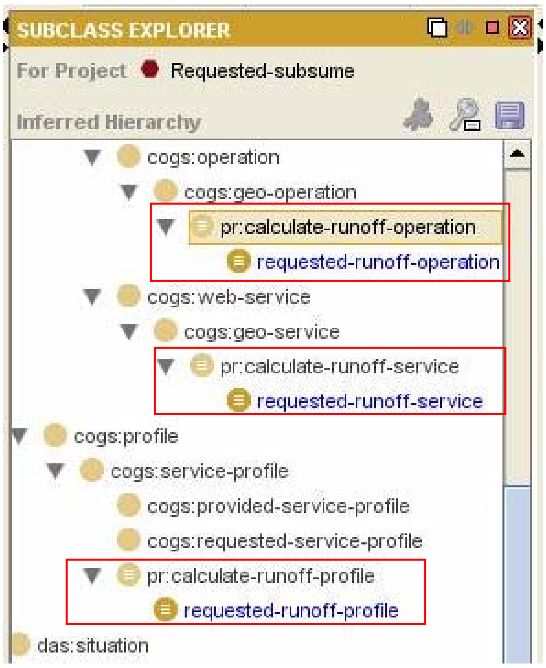
$$
\begin{aligned}
runoff-volume \equiv {} & cogs:field-data \cap \\
& \ni cogs:has-m-uni.mth:LiterPerSquareMeter \\
& \cap \exists cogs:represents.mth:runoff
\end{aligned}
$$

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

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. 15 illustrates the result of matchmaking in the inferred window of the Protégé ontology editor. This shows that the requested runoff geo-service is subclass of the calculated runoff geo-service. For modelers that means: the input and output of the requested geo-service is covered with the input and output of calculate runoff geo-service. Therefore, the calculate runoff geo-service can satisfy the need of modeler. In this case the degree of matching is called "Plugin". Details about approach and degrees of matching are out of scope of this article.



SUBCLASS EXPLORER

For Project ● Requested-subsume

Inferred Hierarchy

- cogs:operation
  - cogs:geo-operation
    - pr:calculate-runoff-operation
      - requested-runoff-operation
- cogs:web-service
  - cogs:geo-service
    - pr:calculate-runoff-service
      - requested-runoff-service
- cogs:profile
  - cogs:service-profile
    - cogs:provided-service-profile
    - cogs:requested-service-profile
    - pr:calculate-runoff-profile
      - requested-runoff-profile
- das:situation

Fig. 15: Red boxes show the result of matchmaking between concepts in ontologies of sample requested and provided runoff geo-services.

The example shows that the ontologies of the structure help with discovery of geo-services. The proposed ontologies facilitate the agreement between provider and requester of geo-services by tying the concepts at the application level to the concepts at the top and domain levels. This provides a semantic framework that is missing in the Ontology Web Language for Services (OWL-S).

Further, in 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]. The ontology of measurement theory showed here describes the semantic of input and output of geo-operations by formalizing their unit of measurement and measurement scale. This is crucial to compare provided and requested geo-services during discovery of geo-services.

## 10 Conclusion and Discussion

Many environmental modelers use a field-based conceptualization of the natural environment. Therefore they are interested in discovering appropriate field-based geo-services that are useful for their environmental models. Semantic ambiguities and implicit details are obstacles when discovering appropriate geo-services. The described extension of the OWL language gives ontological description of geo-service to overcome these impediments.

The geo-service description is based on an ontology of measurement theory for describing the semantic of input and output of field-based geo-services, and an ontology for describing the concepts related to software, web service, and geo-service. In order to achieve agreement between geo-service developers and environment modelers about the geo-service concepts the upper ontology of DOLCE was selected. The Descriptions and Situations (D&S) ontology fills the conceptual gaps between the core ontology of geo-services and upper ontology.

OWL is a DL based ontology that is expressive enough to formalize and implement concepts and relationships.

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| DL Syntax | Constructor |
|---|---|
| $C_1$ | Atomic Concept |
| $\top$ | Universal Concept |
| $\perp$ | 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

Fig. 12: Inter-relation between the proposed ontologies

Fig. 13: Part of the core ontology of geo-services in Protégé with OWL plug-in

Fig 14: Taxonomy of proposed upper ontology (red dashed box show the new added concepts) and taxonomy of the measurement theory ontology (blue dashed box)

Fig. 15: Red boxes show the result of matchmaking between concepts in ontologies of sample requested and provided runoff geo-services