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A Framework for Measuring the Interoperability of Geo-Ontologies

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Abstract

Interoperability is a crucial problem for geographic information systems. The transfer of data and models between different systems requires the ability to set up a correspondence between concepts in one system to concepts in the other. Concept matching is helped by ontologies. However, the challenge of making ontologies themselves interoperable continues. In other words, given two geo-ontologies, the basic question is: to which degree are these two geo-ontologies interoperable? In this paper, we consider that a geo-ontology describes things that can be assigned to locations on the surface of the Earth and relations between these things. A geo-ontology has concepts that correspond to physical and social phenomena in the real world. We suggest a classification of these concepts based on their use for describing geo-objects. We present a basic set of concepts for a geographical ontology, based on descriptions of the physical world and of the social reality. We also present a framework for measuring the degree of interoperability between geo-ontologies. We consider that this problem is a special case of Bernstein's model management algebra for metadata descriptions. We propose to use a matching operator for measuring interoperability between ontologies. The proposed framework provides a first basis for computational tools that allow a more precise response to problem of ontology interoperability.

Keywords: interoperability, geo-ontologies, measurement

1 Introduction

Interoperability is defined by the Open GIS consortium as the "capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units" (OpenGIS, 1996). The use of ontologies improves interoperability among different information systems in general (Mena, Kashyap, Sheth, & Illarramendi, 1996; Wiederhold, 1994) and in geographical information systems specifically (Fonseca & Egenhofer, 1999; M. Kavouras & Kokla, 2002). The subject of ontology is an important field of research in geographical information science (Y. A. Bishr & Kuhn, 2000; Bittner & Winter, 1999; Câmara, Monteiro, Paiva, & Souza, 2000; Fonseca, Egenhofer, Agouris, & Câmara, 2002; Frank, 1997; Frank, 2001; Marinos Kavouras, Kokla, & Tomai, 2005; Werner Kuhn, 2001; David Mark, 1993; Raubal & Kuhn, 2004; Rodríguez, Egenhofer, & Rugg, 1999; Smith & Mark, 1998). The use of ontologies for modeling of geographical entities aims at capturing shared conceptualizations of specific user communities and thus improve interoperability among different geographical databases (Smith & Mark, 1998). However, the quest for making ontologies themselves interoperable continue (Arumugam, Sheth, & Arpinar, 2002; Heflin & Hendler, 2000).

The general basis for ontology is the emphasis on shared vocabularies and on properties that hold in all situations. Ontologies are content theories about the sorts of objects, properties of objects, and possible relations between objects in a specified domain of knowledge (Chandrasekaran, Josephson, & Benjamins, 1999). Thus, informally defined, "ontologies are agreements about shared conceptualizations."

However, most approaches to ontological characterization focus on concrete proposals for tools and techniques for building ontologies, such as the W3C Semantic Web (Berners-Lee, Hendler, & Lassila, 2001). Frank & Raubal (1999) argue that the formalization of spatial relations in geographic space is crucial for further advances in the standardization and interoperability of GIS. They review methods for the formal description of spatial relations and create specifications and methods to formalize and describe image schemata. Here, we propose a method for computing a measurement of the degree of interoperability between two geo-ontologies. The method is illustrated by applying it to ontologies based on different land cover classification schemes. The measurement is based on the model management algebra for metadata descriptions created by Bernstein (2003). In other words, given two geo-ontologies, the basic question to be examined is to which degree are these two geo-ontologies interoperable?

This paper is an initial attempt to address this question. For the purposes of this paper only, we consider that a geo-ontology belongs to the simplest case mentioned by Guarino, namely that "an ontology describes a hierarchy of concepts related by subsumption relationships". Therefore, we opted for a hierarchical structure of geo-ontologies as shown in our examples in sections 3 and 4, although we recognize that geo-ontologies can be much more complex than that.

The rest of the paper is organized as follows. In section 2, we give an overview of the current research on the use of ontologies to implement interoperability. Section 3 discusses the special characteristics on an ontology that makes it be called a geo-ontology. In section 4, we present a framework for measuring the interoperability of geo-ontologies. In section 5 we give our conclusions and propose further work in the area.

2 Ontology-Based Interoperability

The literature shows many proposals for the integration of information, ranging from federated databases with schema integration (A. Sheth & Larson, 1990) and the use of object orientation (Kent, 1993; Papakonstantinou, Garcia-Molina, & Widom, 1995), to mediators (Wiederhold, 1991) and ontologies (Guarino, 1998; Wiederhold, 1994). Semantic heterogeneity is the disagreement about the meaning, interpretation, or intended use of data (A. Sheth & Larson, 1990). The new generation of information systems should be able to handle semantic heterogeneity in making use of the amount of information available with the arrival of the Internet and distributed computing (Amit Sheth, 1999). The semantics of information integration is getting more attention from the research geographic information science community (Y. Bishr, 1997; Câmara, Souza, Freitas, & Monteiro, 1999; Gahegan, 1999; Harvey, 1999; Kashyap & Sheth, 1996; W. Kuhn, 1994; Andrea Rodríguez & Max Egenhofer, 2003; Amit Sheth, 1999; Worboys & Deen, 1991). The support and use of multiple ontologies should be a basic feature of modern information systems if they want to support semantics in the integration of information. Ontologies that capture the semantics of information can be represented in a formal language and be used to store the related metadata enabling a semantic approach to information integration.

2.1 Ontology and ontologies

From Gruber's (1992) definition that "an ontology is an explicit specification of a conceptualization", Guarino (1998) created a refined distinction between an ontology and a conceptualization. Guarino starts the discussion saying that a conceptualization is "a set of conceptual relations defined on a domain space" and that it is important to "focus on the meaning of these relations, independently of a state of affairs" (Guarino, 1998). He says that in a conceptualization we are interested, for instance, in the meaning of the relation 'above' instead of being concerned that in this particular state of affairs object A is above object B. After clarifying what a conceptualization is, he says that "an ontology is a logical theory accounting for the intended meaning of a formal vocabulary, i.e. its ontological commitment to a particular conceptualization of the world. The intended models of a logical language using such a vocabulary are constrained by its ontological commitment. An ontology indirectly reflects this commitment (and the underlying conceptualization) by approximating these intended models". Smith (2003) says that in the current context of research on information sharing, an ontology is seen as a dictionary of terms expressed in a canonical syntax. In this use it is implied that ontology is a common vocabulary shared by different information systems communities.

Smith gives a definition of an information system ontology: "an ontology is a formal theory within which not only definitions but also a supporting framework of axioms is included (perhaps the axioms themselves provide implicit definitions of the terms involved)" (Smith, 2003). The definition of terms for spatial relations can be studied by analyzing the entailments of statements. Frank & Raubal (1999) derive spatial relations from image schemata using language. For instance, the concept of *path* can be derived from the expression "You can drive from Baden to Vienna, and back in the evening." (p.79) and the concept of *detour* can be derived of "The way from Vienna to Budapest through Sopron is a detour. The direct route goes through Györ." (p.80).

2.2 Ontologies, Agreements, and Geographical-Information Interoperability

The interoperability of geographic information (Michael Goodchild, Egenhofer, Fegeas, & Kottman, 1999; Vckovski, 1998) has gained in importance because of the new possibilities arising from the interconnected world and the increasing availability of geographic information. New information originates from new geographical information systems and also from new and sophisticated data collection technologies. It is necessary to find innovative ways to make sense of the huge amount of information available today.

What kinds of agreement can be reached among people? Limited-scope agreements can be made within small communities. Later, these agreements can be expanded to reach larger communities. When these broad agreements occur, part of the original meaning is lost, or at least some level of detail is lost (Fonseca, Egenhofer, Davis, & Câmara, 2002). For instance, inside a community of biology scholars, a specific lake in the state of New Mexico is the habitat for a specific species and, therefore, it can have a special concept or name to refer to it such as aquatic habitat. Nonetheless, it is still a lake, and when a biologist is working at a more general level it is considered as a lake and not as an aquatic habitat only. At this higher level it is more likely that this real-world entity–lake–can find a match with a similar concept in another community. So the biologist and some member of another community can exchange information about lakes. The information will be more general than when the lake was seen as an aquatic habitat.

The agreements are represented as ontologies, one for each subject area (Wiederhold, 1994). Ontologies are crucial for information exchange and they can serve as the embodiment of a consensus reached by a professional community (Farquhar, Fikes, & Rice, 1996). Some authors (Kashyap & Sheth, 1996) consider that sharing the same ontology is a pre-condition to information sharing and integration. In this case, there should be an ontological commitment revealing the agreement between the generic user querying the database and the database administrator. Other authors suggest an alternative to an explicit ontological commitment. One common solution is the derivation of a global schema to overcome the absence of a common shared ontology. Bergamaschi *et al.* (1998) implemented this solution using description logic. Along the same lines, Rodríguez *et al.* (1999) developed a similarity assessment among ontologies using a feature-matching process and semantic distance calculations.

2.3 Model Management and Interoperability

Model Management is a new approach to metadata management that can be applied to problems such as schema integration and schema evolution. It considers models and mappings between models as objects and offers operators to compare and combine these objects (P. Bernstein, 2003; P. A. Bernstein, 2001).

In order to understand how Model Management, which was created to manage schemas, can be applied to the measurement of interoperability between Geo-Ontologies, we need to consider two points. First, we need to consider ontologies as models. Ontologies and conceptual schemas definitely belong to two different epistemic levels. Nevertheless they are part of a continuum that starts from the conceptualizations of GIS designers and users, later expressed in informal and formal languages, and goes to the creation of conceptual schemas and the subsequent representation of facts in a spatial database. Second, because Model Management is an approach to metadata, it uses only the description of data and not the data itself. Therefore, we need to consider ontologies as containing only metadata and not data. While the research in conceptual modeling argue for the creation of more generic models, the research on ontologies sometimes (wrongly in our point of view) go to specifics such as having instances of classes within ontologies. As McGuinness (2003) points out, "some classification schemes only include class names while others include ground individual content". The recording of instances or ground content should be done by the GIS itself under the guidance of the conceptual schema. The recording of facts belongs to a different epistemic level. Ontologies definitely should not include instances of its concepts.

In a traditional Model Management system, models and mappings are syntactic structures. In order to make the problem computationally tractable it is necessary to have limited expressiveness. Bernstein's Model Management opted to add semantic processing through an extension mechanism that uses an inferencing engine. This engine is able to manipulate formulas in a mathematical system (P. Bernstein, 2003; P. A. Bernstein, 2001).

In a similar work, Kuhn (1997) describes an algebraic mapping between data models. His main focus is information loss which is defined based on the number of operations that a *source* system can apply on data and a *target* system cannot. Goodchild (1997) considers this definition useful but counterintuitive because it misses some cases such as when a receiving system does not have an operation (information loss occurs) and later this system returns the same data to a system which has the operations (the original information is restored).

2.4 Ontology Mappings

Kalfoglou & Schorlemmer (2003), in an extensive survey, define ontology mappings as "the task of relating the vocabulary of two ontologies that share the same domain of discourse in such a way that the mathematical structure of ontological signatures and their intended interpretations, as specified by the ontological axioms, are respected." Wache et al. (2001) suggest a classification for the main approaches in inter-ontology mapping. They call *Defined Mappings* the approach in which the user creates the rules and mediators to generate specific mapping between concepts in two ontologies. While this approach provides great flexibility it does not preserve semantics. KRAFT (Preece et al., 2000) is an example for this case. The second type of approach is called *Lexical Relations*. An example is OBSERVER (Kashyap & Sheth, 1996; Mena, Kashyap, Illarramendi, & Sheth, 1998; Mena et al., 1996), an architecture for query processing in global information systems. OBSERVER focuses on information content and semantics and employs a loosely-coupled approach to match different vocabularies used to describe similar information across domains. The next approach examined by Wache et al. is called *Top-Level Grounding*. In this approach all the mappings go through a top-level ontology. The fact that the mappings go through concepts in a different ontology leads to the drawback of not having direct mappings between the ontologies of interest. Finally there is *Semantic Correspondences*, an approach favored by Wache (1999). This approach relies on a common vocabulary in the definition of concepts.

Noy has two reviews of ontology merging. In Noy & Musen (2002) an interactive ontology-merging tool called PROMPT is evaluated and criteria to group the different tools that are available for ontology merging are introduced. In Noy (2004) semantic integration is discussed in three dimensions: *Mapping Discovery* that is about how to find similarities between concepts; *Declarative Formal Representations of Mappings* which is about how to represent the mappings in order to enable reasoning between them, and finally the third dimension, Reasoning with Mappings, which is how to reason once the mappings are established.

3 Geo-Ontologies

"What is special about spatial?" (Anselin, 1989; Egenhofer, 1993) or what is special about geo-ontologies? A geo-ontology has to provide a description of geographical entities, which can be conceptualized in two different views of the world (Couclelis, 1992; M. Goodchild, 1992). The *field view* considers spatial data to be a set of continuous distributions. The *object view* conceives the world as occupied by discrete, identifiable entities. Representing geographic entities–either constructed features or natural variation on the surface of the Earth–is a complex task. As Smith & Mark (1998) put it, these entities are not merely located in space, they are tied intrinsically to space. They take from space some of its structural characteristics, such as mereological, topological, geometrical properties. A geo-ontology is different from other ontologies because topology and part-whole relations play a major role in the geographic domain. Geographic objects can be connected or contiguous, scattered or separated, closed or open. They are typically complex and have constituent parts (Smith & Mark, 1998). The topological and containment relations between objects have led to the use of *mereology* (Husserl, 1970), which describes the relation between parts and wholes. For a review of mereology see Simons (1987) and Casati & Varzi (1999). Smith (1995) introduced *mereotopology*, which extends the theory of mereology with topological methods. A theory that combines geometry and mereology using a 1st-order sublanguage is introduce by Bennet (2001). Bennet's theory of Region-Based Geometry (RBG) provides a secure ontological foundation for theories of spatial information.

3.1 What is a Geo-Ontology?

A geo-ontology has two basic types of concepts: (a) concepts that correspond to physical phenomena in the real world; (b) concepts that correspond to features of the world that we create to represent social and institutional constructs. We call the first type of concepts *physical concepts* and the second type, *social concepts* (Figure 1).

Based on John Searle's book, "*The Construction of Social Reality*" (1995), Smith and Searle (2003) have an interesting discussion on what are social objects and if they exist. Smith says that

> "*Searle tells us what social objects are by giving us an account of the way the two levels are linked together, via the formula X counts as Y in context C. His ontology of social reality thus rests on three components:*
>
> *1. certain physical objects*
>
> *2. certain cognitive acts or states in virtue of which such physical objects acquire certain special sorts of functions*
>
> *3. these functions themselves*
>
> *4. contexts in which the given cognitive acts or states are effective.*" (p. 286)

Searle does not agree with Smith's interpretation. He thinks that

> "*a social fact is simply any case of collective intentionality involving two or more animals. Institutional facts are more interesting, because they involve a deontic*

component, and with that deontic component comes the requirement of language." (p.304)

Searle is concerned with institutional reality, which is a special case of social reality.

It is important to note that both result from human conventions. As discussed in the literature (Frank & Mark, 1991; David Mark & Egenhofer, 1994; D. Mark, Smith, & Tversky, 1999; Smith & Mark, 2003) the description of physical features may vary according to cultural and social conventions but nevertheless they do not represent social conventions, they represent variations on the surface of the Earth.

The physical concepts can be further subdivided into:

- Concepts that are associated with individual geographic objects, each of which has a clearly defined boundary such as qualitative differentiations or spatial discontinuities in the physical world. These are equivalent to the notion of *bona fide objects* (Smith & Mark, 1998). Examples: *lake, mountain*.
- Concepts that are assumed to be continuous in space (*fields*). Examples: *temperature, slope, pollution, population density.*

The social and institutional concepts that can be further subdivided into:

- Concepts describing individual objects created by institutional and legal conventions. These are equivalent to the notion of *fiat objects* of Smith and Mark (1998). Examples: *parcel, borough*.
- Concepts which are assumed to be continuous over space and represent socially agreed conventions. Examples: *social exclusion, infant mortality, homicide rate, human development*.

	Physical Reality	**Social Reality**
Bounded	Bona fide objects (e.g., mountain)	Fiat objects (e.g., parcel)
Continuous	Physical fields (e.g., temperature)	Social distributions (e.g., human development)

Figure 1 - Basic components of a geo-ontology

An alternative way of describing a geo-ontology has been proposed by Frank (2001). He proposes a coordinated set of tiers of ontology. His first tier, *Tier 0*, assumes an external reality consisting of a space-time set of continuous fields. The next tier, *Tier 1*, is composed of the measurements of this reality by humans and their instruments. *Tier 2* consists of objects which are formed by humans based on measurements. Tier 3 is the set of objects of social reality constructed by agreements and contracts, following Searle (1995). The last tier, *Tier 4*, is composed on subjective concepts about space. As an example, consider a rural geographical area. A farmer may use a GPS instrument to collect a set of coordinates. This set of coordinates may correspond to a 'closed polygon', a concept that belongs to *Tier 1*. In *Tier 2*, these set of coordinates may be assigned to a "spatial object", which distinguishes the enclosed land area. In *Tier 3*, this enclosed land area may be called a "farm", and will be assigned an owner who has certain legal rights. Finally, in *Tier 4*, this farm may be called "home" by the person who lives there.

Frank's (2001) view of tiers of ontology is similar to our distinction between physical reality and social reality. Entities of the physical reality belong to Frank's *Tier 2* ("objects with properties") and entities of the social reality belong to Frank's *Tier 3* ("social reality"). The main difference between our work and Frank's is that we are concerned with interoperability between ontologies. We consider concepts that are typically part of geographical databases. Thus, we do not consider concepts that are part of Frank's *Tier 0*, *Tier 1* and *Tier 4*. Frank's *Tier 0* (the external reality) is an implicit assumption in geo-ontologies. Measurements (Frank's *Tier 1*) are entities whose existence is required to capture different aspects of external reality. Interoperability of measurements is outside the scope of this work. The interested reader should read Kuhn (2003) and Chrisman (1999). Finally, subjective entities of *Tier 4* (such as 'home', and 'sacred area') are also outside the scope of this work. The interested reader on subjective concepts of space should see Fonseca and Martin (2004).

After Smith & Mark (1998), who wrote that "*our cognitive acts are directed towards spatial objects in the world*", we consider that concepts in a geo-ontology are directed towards spatial objects in the world. Based on this discussion, we assume that a geo-ontology is organized as a hierarchy where the root concept is termed "geo object". The root concept is specialized into two classes which correspond to the main types of geographic concepts: those related to continuous phenomena (fields) and to individual objects. The former class is further specialized into concepts associated to physical fields and those associated to socially-constructed fields. The latter class is further specialized into *bona fide* concepts and *fiat* concepts. This structure is shown in Figure 2.

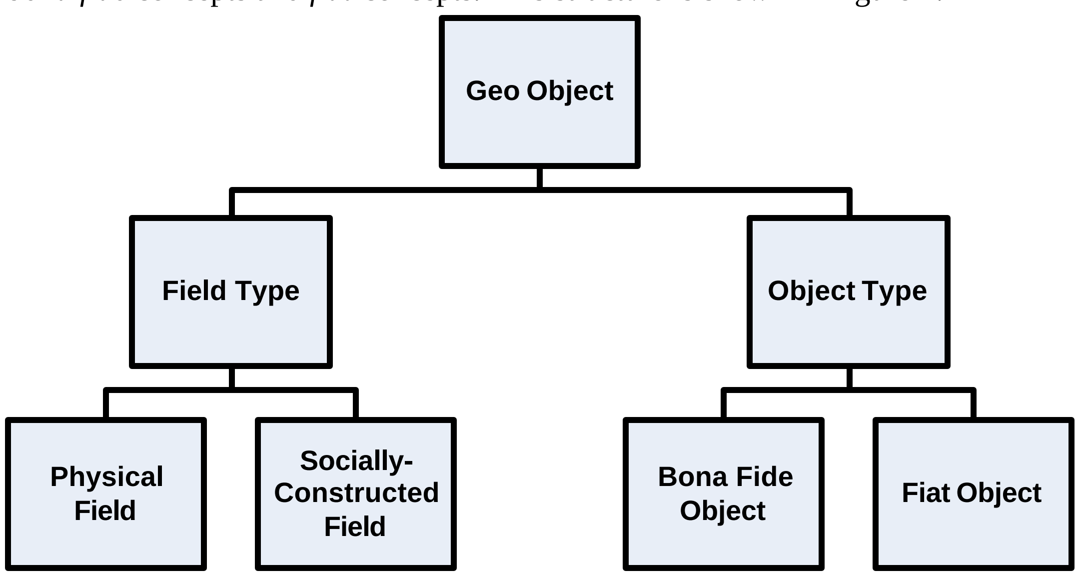

Figure 2 – Top-level hierarchy for a geo-ontology

4 Using Model Management to Measure Interoperability

This section presents a framework for measuring the interoperability between geo-ontologies. We consider that the problem of determining the interoperability between two geo-ontologies is a special case of Bernstein's (2003) *Model Management Algebra* for metadata descriptions. Bernstein proposes a generic set of operators that abstracts from the traditional *object-at-a-time* conversion techniques and treats models as abstractions that can be manipulated as single entities. For dealing with interoperability, we use the `Match` operator from the functions that Bernstein proposed in his *Model Management Algebra*. The `Match` operator takes two models and returns two sets of tuples that reflect the similarity and generalization relationships that exist between the concepts of the two ontologies.

In this paper we are not concerned either with how this function is created or with its detailed operation on particular elements in their domains. Other research deals with these matters and justifies particular choices (Bench-Capon & Malcolm, 1999; Bench-Capon, Malcolm, & Shave, 2003; A. Rodríguez & Max Egenhofer, 2003). Instead, the focus here is on how this function can be used to define the degree of interoperability between geo-ontologies. All the definitions below assume that the function `Match` exists and is applicable to geo-ontologies.

4.1 Ontologies as Models

In order to apply the concepts of model management to geo-ontologies, we must first provide a definition of ontologies such that it satisfies the technical requirements for model representation (P. Bernstein, 2003). To deal with ontologies as models, each geo-ontology should refer to a single application domain and should have the following properties:

- A geo-ontology consists of a set of concepts;
- Concepts can be related to other concepts by means of relations that include similarity, generalization, and subsumption;
- A geo-ontology consists of a single hierarchy. Starting from a root concept, concepts are placed on the hierarchy according to their specialization relation, which is assumed to be unique.

4.2 The Match Operator between Ontologies

In order to compare two ontologies, we use the `Match` operator, which compares concepts in the ontologies, following Bernstein (2003). The basic idea is to take the most specialized concepts in the first ontology (all leaf-nodes of the ontology tree) and try to find a similar concept in the second ontology. We consider that matching the leaf-nodes of both ontologies is a sufficient condition for ontology matching, since in hierarchical ontologies as those used in this paper, each geo-object is mapped to only one concept. Given a concept in the first ontology, the `Match` operator proceeds via the following steps:

(a) The SIM (similarity) algorithm tries to identify similar concepts on ontologies. Given a concept c_1 of O_1, `SIM` finds a similar concept c_2 of O_2. The conditions for this mapping may be complex (P. Bernstein, 2003). For a survey of for semantic matching proposals using ontologies see Noy (2004). In general, the retrieval operation will produce a list of possible concepts that can be ranked based on their parts, attributes and relationships (A. Rodríguez & Max Egenhofer, 2003).

(b) Should step (a) fail to produce a satisfactory result, the `GEN` algorithm tries to identify the concept in the second ontology that is most closely related to it by generalization. A possible implementation of the `GEN` algorithm would be as follows: (1) given a concept c_1 of O_1 that has no similar match on O_2, use the concept d_1 that is the generalization of c_1; (2) try to find a similar concept to d_1 in O_2. If a similar concept is found (d_2), then d_2 is a generalization of c_1 in ontology O_2.

The concept of similarity may be based on equality of names or definitions, or may be based on subjective attribution. The same assumption holds for the notions of generalization. The `Match` function produces two subsets as a result:

- $\mathtt{Sim}\ (O_1,O_2)$: The similarity subset $\mathtt{Sim}(O_1,O_2)$ of O_1 in relation to O_2 is the set of all tuples $\langle o_1, o_2 \rangle$ such that the concept o_2 in O_2 is similar to the concept o_1 in O_1.
- $\mathtt{Gen}\ (O_1,O_2)$: The generalization subset $\mathtt{Gen}(O_1,O_2)$ of O_1 in relation to O_2 is the set of all tuples $\langle o_1, o_2 \rangle$ such that the concept o_2 in O_2 is a generalization of the concept o_1 in O_1.

The properties of the geo-ontologies (as stated in Section 3) indicate that all geographical concepts can be mapped as a specialization of one of the four main concepts, shown in Figure 2. These properties indicate that any concept in a geo-ontology O_1 either has a similar concept in geo-ontology O_2 or has a generalization in O_2. In the worst case, a concept in a geo-ontology O_1 is mapped to one of the four top-level concepts of the geo-ontology O_2.

4.3 Using the Results of Matching for Assessing Interoperability

The results of the `Match` operator can be used to assess the degree of interoperability between two geo-ontologies. Intuitively, a geo-ontology O_1 is interoperable with a geo-ontology O_2 when all the information present in O_1 (i.e., all of its concepts) can be conveyed in O_2. The intuition behind this definition is the basis for the notion of fully interoperable geo-ontologies presented below. Assuming the existence of a `Match` operator between two geo-ontologies that produces as a result the sets `Sim` and `Gen` (see above), we can now define various degrees of interoperability between two geo-ontologies O_1 and O_2.

Definition 1. O_1 is *fully interoperable* with O_2 iff the similarity subset $\mathtt{Sim}(O_1,O_2)$ contains all the concepts of O_1. This definition matches the intuitive definition of interoperability given in the beginning of this section.

Definition 2. O_1 is *partially interoperable* with O_2 iff the generalization subset $\mathtt{Gen}(O_1,O_2)$ is non-empty. In this case, some concepts in O_1 are mapped into more general concepts in O_2.

Definition 3. Given a non-empty generalization subset $\mathtt{Gen}(O_1,O_2)$, the *degree of interoperability (d)* between O_1 and O_2 is given by the formula

$$d = f * \frac{\sum_{i=1}^{n} \min\,(l_2^{\,i}, l_1^{\,i})}{\sum_{i=1}^{n} l_1^{\,i}}$$

where f is the fraction of concepts of O_1 that are contained in $\mathtt{Sim}(O_1,O_2)$, and the second factor estimates the *degree of mismatch* between the ontologies. In the formula above l_1^i is the depth of the i[th.] concept of ontology O_1 and l_2^i is the depth of the corresponding concept in ontology O_2, as given by the tuples in $\mathtt{Gen}(O_1,O_2)$. The idea is that a discrepancy between the corresponding depth-levels of two related concepts in the $\mathtt{Gen}(O_1,O_2)$ relation is an additional indication of limitations of interoperability between ontologies. The degree of mismatch is obtained by comparing the depth of the tree associated to the concepts in the generalization subset $\mathtt{Gen}(O_1,O_2)$. The formula is based on the intuitive idea that the greater the difference between the depth levels of the two concepts, the smaller the degree of interoperability between the two geo-ontologies.

To allow an intuitive grasp on our argument, we will illustrate our concepts by considering the problem of *land-cover classification*. Broadly speaking, **land cover** is defined as the observed physical cover including the vegetation (natural or planted) and human constructions on the surface of the Earth. Water, ice, bare rock or sand surfaces count as land cover (Jansen & Gregorio, 2002). The rapidly changing nature of some of our environments (e.g. tropical forests) has motivated a variety of regional and global land cover products, such as the IGBP DisCover, MODIS Land Cover, and GOFC (Global Observation of Forest Cover). As an example of similarity mapping, we consider a subset of two existing land cover classification systems: the IGBP Land Cover Classification (Belward, Estes, & Kline, 1999) and the Simple Biosphere Model (SiB) (P. J. Sellers, Mintz, Sud, & Dalcher, 1986). This subset deals with forest classes. Each model has 5 forest classes, as shown in Figures 3 and 4.

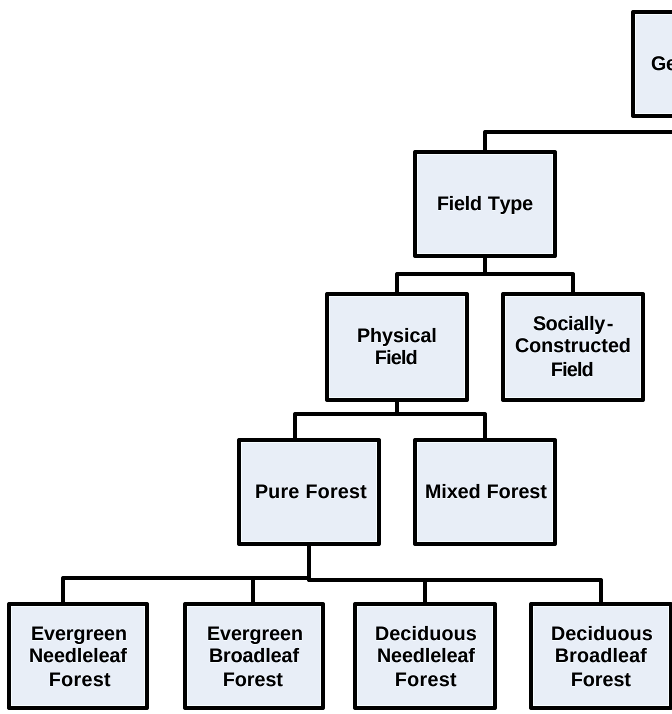

Figure 3 - Forest classification in the IGBP ontology (partial view), adapted from (Belward et al., 1999).

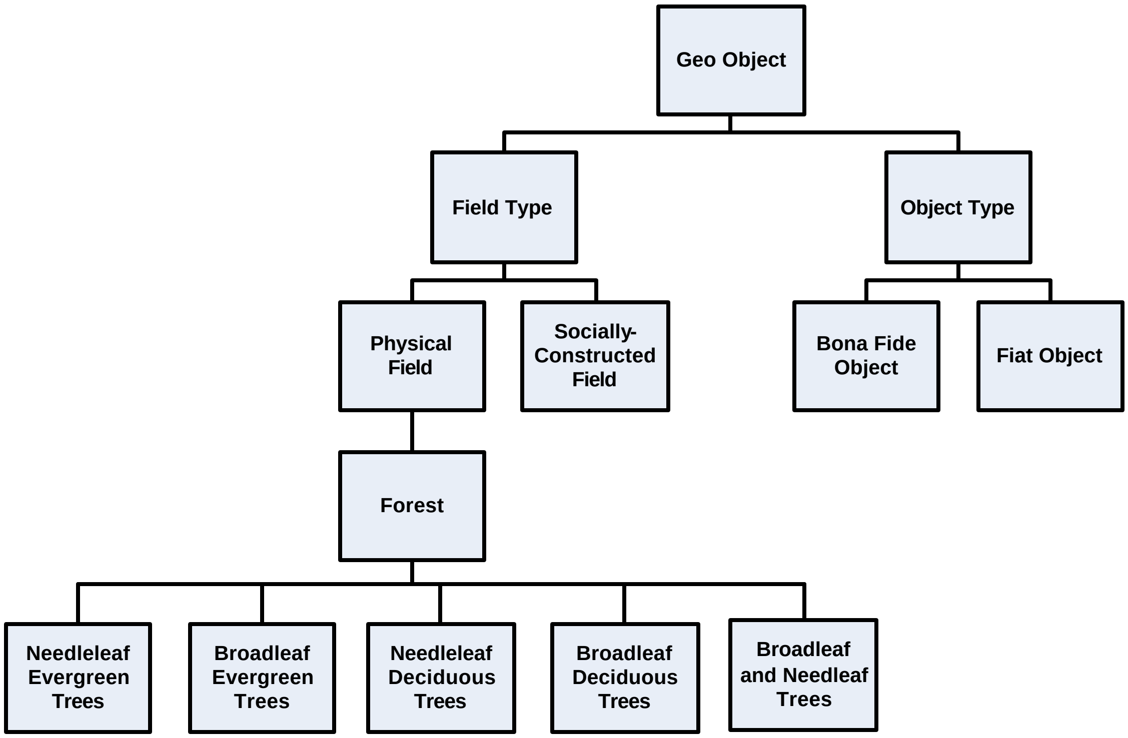

Figure 4 - Forest classification in SiB ontology (partial view), adapted from (P. J. Sellers et al., 1986).

A comparison of the IGBP and SiB forest classification reveals that the two ontologies are equivalent on their classification of pure forest types. However, they differ when dealing with mixed forest. The IGBP ontology has the concept of "mixed forest" and the SiB ontology has the concept of "broadleaf and needleleaf trees". Therefore, these two concepts are considered to be similar.

The similarity subset obtained by the `Match` operator for the IBGP and SiB ontologies for forest is shown in Table 1. All of the concepts associated to forest in the ontology O_2 (the IBGP ontology) could be mapped into similar concepts of ontology O_1 (the SiB ontology). This implies that the subsets of these two land-cover ontologies that deal with forest are fully interoperable.

Table 1 - Similarity mapping between IGBP and SiB geo-ontologies for forest land-cover

IGBP	SiB
Evergreen Needleleaf Forest	Needleleaf Evergreen Trees
Evergreen Broadleaf Forest	Broadleaf Evergreen Trees
Deciduous Needleleaf Forest	Needleleaf Deciduous Trees
Deciduous Broadleaf Forest	Broadleaf Deciduous Trees
Mixed Forest	Broadleaf and Needleleaf Trees

To take a second example, consider the case of the IBGP ontology for forests and the ontology of International Satellite Land Surface Climatology Project (ISLSCP) (P.J. Sellers et al., 1995). The ISLSCP ontology for forests is shown in Figure 5.

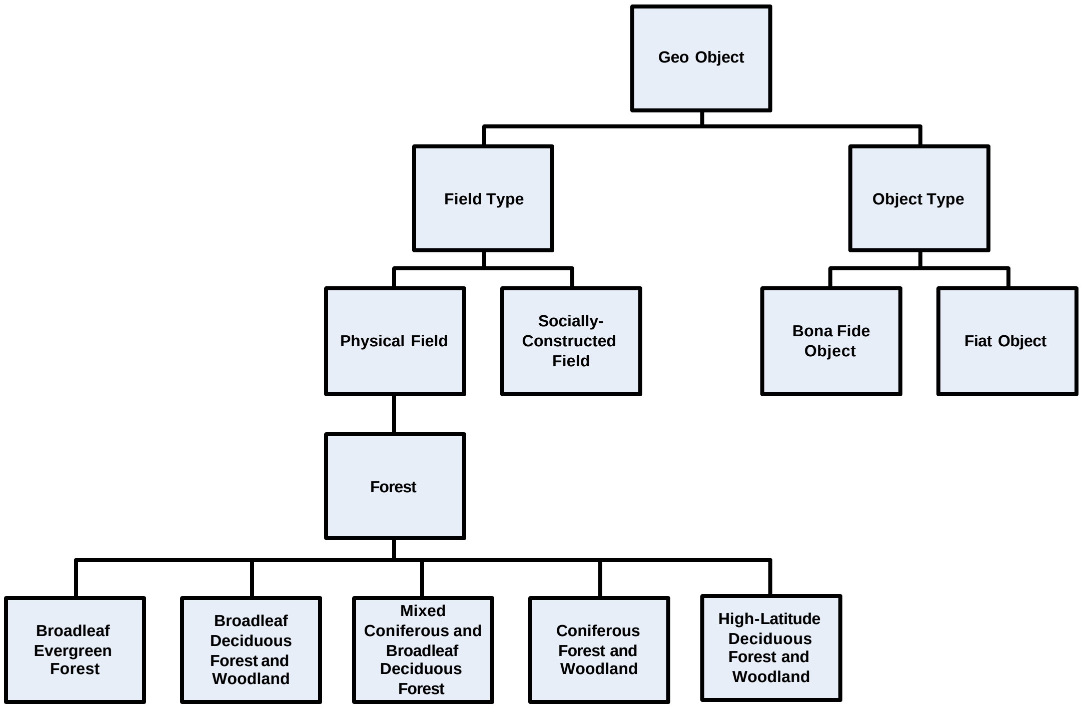

Figure 5 - Forest classification in the ISLSCP ontology (partial view), adapted from (P.J. Sellers et al., 1995).

The ISLSCP ontology is based on a different classification of forest types. This classification includes both pure types ("broadleaf coniferous forest") and mixed specialized types ("mixed coniferous and broadleaf deciduous forest" and "high-latitude deciduous forest and woodland"). This allows the distinction between different types of temperate forests. Thus, the IGBP and ISLSCP ontologies have different objectives, and the latter is more detailed than the former. When matching the concepts of the two ontologies, there is a similarity match between the concepts of "broadleaf evergreen forest" and "broadleaf deciduous forest" of the two ontologies. However, given the differences between the specialized types of temperate forests, there is no similarity match in the IGBP ontology to the three other concepts of the ISLSCP ontology. The two types of pure temperate forests of ISLSCP ontology ("coniferous forest and woodland" and "high-latitude decidous forest and woodland") are mapped into the more generic type "pure forest" of the IGBP ontology. The specialized mixed type of the ISLSCP ontology ("mixed coniferous and broadleaf deciduous forest") is mapped to the more generic type "mixed forest" of the IGBP ontology. Thus, the two geo-ontologies of the IGBP and the ISLSCP are not fully interoperable and the result of the `Match` operator is shown in Table 2.

Table 2 – Matching between the ISLCP and IGBP geo-ontologies for forest land-cover.

ISLSCP	IGBP	Relation
Broadleaf evergreen forest	Evergreen Broadleaf Forest	Similarity
Broadleaf deciduous forest and woodland	Deciduous Broadleaf Forest	Similarity
Mixed coniferous and broadleaf deciduous forest	Mixed Forest	Similarity
Coniferous forest and woodland	Pure Forest	Generalization
High latitude deciduous forest and woodland	Pure Forest	Generalization

Given that there is only a partial relation of interoperability between the ISLSCP and the IGBP geo-ontologies for forests, we can compute the degree of interoperability between them. The similarity subset comprises 60% of the ontology. The three concepts of ISLSCP that are generalized in the IGBP ontology are placed in level 4 of the ISLSCP tree hierarchy and are mapped to a single concept in level 3 of the IGBP tree hierarchy. This mismatch produces a further decrease on the degree of interoperability of 75%. The degree of interoperability between ISLSCP and IGBP is the product of the fraction of similarity (60%) by the degree of mismatch between hierarchies (75%) thereby obtaining an estimate of 45%. This example is an illustration of the expressive power of the proposed methodology for assessing the degree of interoperability between two geo-ontologies.

5 Conclusions and Future Work

In this paper we studied the problem of interoperability between geo-ontologies. A geo-ontology describes: (a) things that can be assigned to locations on the surface of the Earth; and (b) semantic and spatial relations between these things. We argued that a geo-ontology has concepts that correspond to physical and social phenomena in the real world. We called the first type of concepts physical concepts and the second type, social concepts. We suggested a classification of these concepts based on their type of boundary and based on their physical or social characteristics.

We presented a framework for measuring interoperability between geo-ontologies. We considered that this problem is a special case of Bernstein's (2003) model management algebra for metadata descriptions. We proposed using the `Match` operator for dealing with interoperability. The `Match` operator takes two models and returns two sets of tuples that reflect the similarity and generalization relationships that exist between the concepts of the two ontologies.

Based on the `Match` operator, we defined various degrees of interoperability between two geo-ontologies O_1 and O_2. Two ontologies can be fully or partially interoperable. We also provided a way to measure to what degree two ontologies are interoperable.

Since we consider that concepts in an ontology are separated from instances in a database, we limited ourselves to discuss only concepts in ontologies. Nonetheless it is important to extend this discussion to the data itself, i.e., the measurements that are linked to the concepts in an ontology. Once we have a measurement of how interoperable two ontologies are, how this will reflect on the interoperability of the datasets that are represented by these ontologies?

Another aspect to be considered is what Goodchild (1997) correctly highlights: what is the information used for? Algebraic approaches as ours and Kuhn's (1997), still have to incorporate a further semantic dimension to information integration and interoperability problems. The philosophical approaches on ontology integration based on hermeneutics (Fonseca & Martin, 2005) may be a direction to be explored. The concept of the pre-understanding that a user makes of information and its extension to the pre-understanding of a whole community (and its ontology) is very close to the central role of presuppositions, or prejudices, in framing and guiding the emergence of experience in the work of Heideger (1962) and Gadamer (1975). Hence, attempts to develop interoperation frameworks that will satisfy both the formalism proposed by us and Kunh, and the practical and intuitive issues raised by Goodchild will have to deal with a hermeneutic approach to ontologies – one compatible with the orientation introduced into information science by Winograd and Flores (1986). Recent work emphasizing the importance of interpretation as one of the basic constituents of the information process (Capurro & Hjørland, 2003) and stressing the importance of hermeneutics in the construction of ontologies (Fonseca & Martin, 2005) point in a direction that may give some answers to Goodchild's questions.

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