

Using Ontologies for Integrated Geographic Information Systems

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Abstract

Today, there is a huge amount of data gathered about the Earth, not only from new spatial information systems, but also from new and more sophisticated data collection technologies. This scenario leads to a number of interesting research challenges, such as how to integrate geographic information of different kinds. The basic motivation of this paper is to introduce a GIS architecture that can enable geographic information integration in a seamless and flexible way based on its semantic value and regardless of its representation. The proposed solution is an ontology-driven geographic information system that acts as a system integrator. In this system, an ontology is a component, such as the database, cooperating to fulfill the system's objectives. By browsing through ontologies the users can be provided with information about the embedded knowledge of the system. Special emphasis is given to the case of remote sensing systems and geographic information systems. The levels of ontologies can be used to guide processes for the extraction of more general or more detailed information. The use of multiple ontologies allows the extraction of information in different stages of classification. The semantic integration of aerial images and GIS is a crucial step towards better geospatial modeling.

1 Introduction

Today, there is a huge amount of data gathered about the Earth, not only from new spatial information systems, but also from new and more sophisticated data collection technologies. During the last few years, data from one-meter resolution satellites have become commercially available, and unmanned aerial vehicles can provide us with aerial video over rapidly evolving focused scenes. The use of GPS devices is so common today that they are available even in wristwatches. At the same time, global networking and the continuous development of new application domains have introduced important changes to information dissemination and application processes. Contemporary information systems are becoming increasingly distributed and heterogeneous. Digital Libraries are a component of this emerging trend towards knowledge-based distributed environments. Considering geographic information systems (Longley *et al.* 1999) this scenario leads to a number of interesting research challenges. One of them is on how to integrate geographic information of different kinds at different levels of detail. It is widely

recognized that the need to integrate information is so pressing that we often accept loss of detail to achieve it.

The goal of this paper is to find a GIS architecture that can enable geographic information integration in a seamless and flexible way based on its semantic value and regardless of its representation. To this end, it is necessary to develop a conceptual model for geographic data and its computer representation. The most widely accepted common conceptualization of the geographic world is based on ideas of objects and fields (Couclelis 1992; Goodchild 1992). The *object model* represents the world as a surface occupied by discrete, identifiable entities, with a geometrical representation and descriptive attributes. These objects are not necessarily related to a specific geographic phenomenon. Human-built features, such as roads and buildings, are typically modeled as objects. The *field model* views the geographic reality as a set of spatial distributions over the geographic space. Climate, vegetation cover, and geological maps are typical examples of geographic phenomena modeled as fields. Although this simple dichotomy has been subject to objective criticism (Burrough and Frank 1996), it was proven a useful frame of reference and has been adopted, with some variations, in the design of the current generation of GIS technology (Câmara *et al.* 1996).

One important problem of field-object models is that it is only a very generic conceptual model, without support for specific semantics for the different types of spatial data. This problem has led many researchers to consider the use of ontologies as a means of knowledge sharing among different user communities to improve interoperability among different geographic databases (Smith and Mark 1998; Fonseca and Egenhofer 1999).

The proposed solution is an ontology-driven geographic information system (ODGIS) that acts as a system integrator independently of the model. Ontologies are theories that use a specific vocabulary to describe entities, classes, properties, and functions related to a certain view of the world. They can be a simple taxonomy, a lexicon or a thesaurus, or even a fully axiomatized theory. Ontologies here are seen as dynamic, object-oriented structures that can be navigated. A definition is given in Gruber (1992): an ontology is an explicit specification of a conceptualization. Guarino (1998) makes a refined distinction between an ontology and a conceptualization: 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), whereas a conceptualization is the formal structure of reality as perceived and organized by an agent, independently of the vocabulary used or the actual occurrence of a specific situation. The intended models of a logical language that use such a vocabulary are constrained by its ontological commitment. This commitment and the underlying conceptualization are reflected in the ontology by the approximation of these intended models.

To understand the role of ontologies in geographic data modeling, we build on the four-universes-paradigm for modeling a computer representation (Gomes and Velho 1995). The four universes are the *physical universe*, which comprises the objects and phenomena of the real world that will be modeled in the computer; the *logical universe*, which includes a formal definition of these objects and phenomena; the *representation universe*, where a finite symbolic description of the elements in the mathematical universe is made; and the *implementation universe* used to map the elements from the representation universe into data structures implemented in a computer language.

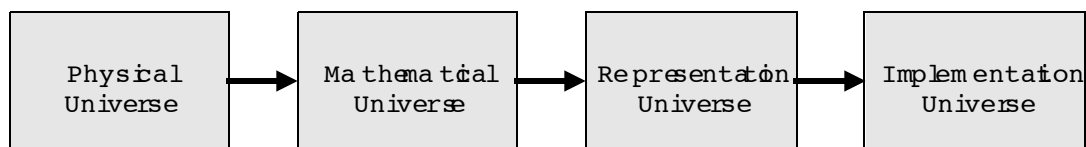


Figure 1 The four-universes paradigm extended from Gomes and Velho (1995)

We added the *cognitive universe*, which captures what people perceive about the physical universe. The physical universe is the real world, the cognitive universe has such concepts as rivers, land parcels, and soils, the logical level has the formal concept of geographic objects, the geo-ontologies, at the representation level we have the object and field concepts, and at the implementation universe are the data structures that are used to implement the concepts of the previous level, including vector and raster geometries (Câmara *et al.* 2000).

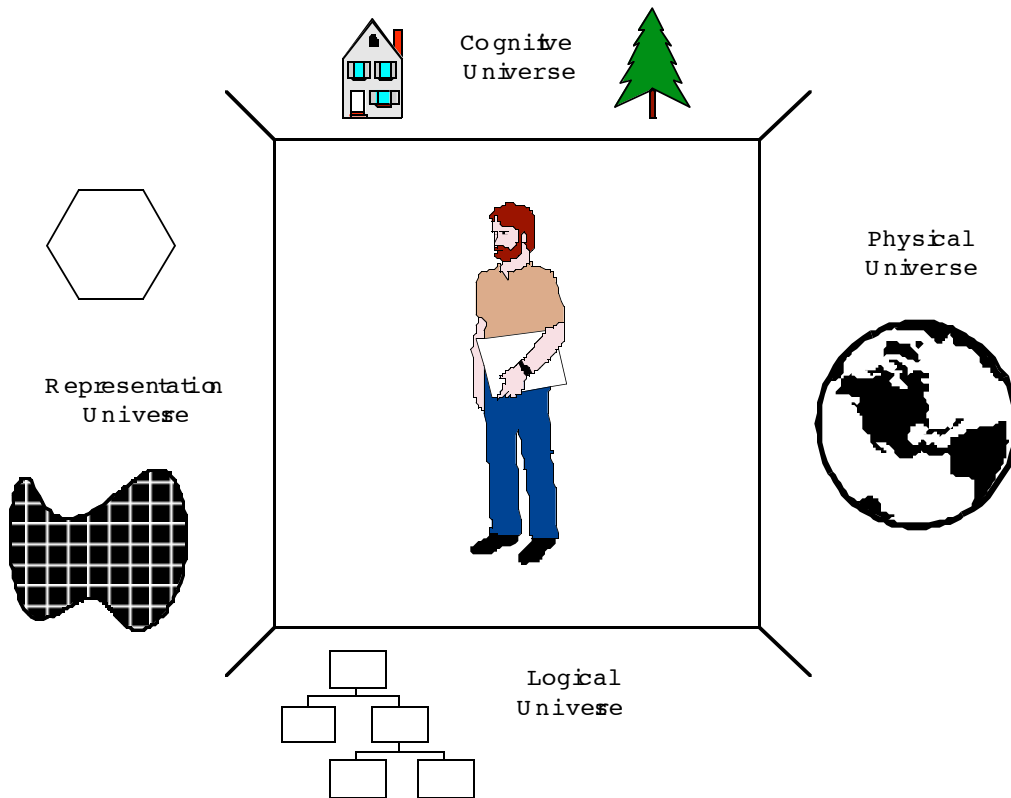


Figure 2 - The human perspective of the four-universes-paradigm

In adding the cognitive universe, we highlighted the human perspective in the four-universes-model. The point of view of an individual or a group of individuals is perceived in the cognitive universe and modeled in the logical universe. Goodchild *et al.* (1999) define GIScience as the systematic study according to scientific principles of the nature and properties of geographic information. GIScience is mainly concerned with three areas, the *Individual*, the *System*, and the *Society*. This paper addresses the intersection of *Individual* and *System*. We start in the *Individual* area using the individual perception of the geographic world formalized into geo-ontologies and go to the software components, extracted from ontologies, that can be used in the classification of images in the *System* area.

Research on geographic information integration has started with the implementation universe and later moved towards the representation universe. Our approach is reverse, working on GIS interoperability solutions that start from the physical, cognitive and logical universes. After a framework based on the physical universe has been designed to work on the logical universe, the solutions available on the representation and implementation universes can be used in a complementary form.

Therefore, we consider that geo-ontologies should be the essential components of the logical universe for geographic data modeling, which is a view that is supported by recent research in ontologies (Guarino 1998).

In ontology-driven geographic information systems (ODGIS), an ontology is a component, such as the database, cooperating to fulfill the system's objectives. The first step to build an OGDIGS is to specify the ontologies using an ontology editor. The editor stores a formal representation of the ontologies and provides a translation of the ontologies into a formal computing language (e.g., Java). By browsing through ontologies the users obtain information about the knowledge embedded in the system. After translation, the ontologies are available as classes. These classes contain the operations and attributes that constitute the system's functionality.

The expected result of this paper is an architecture for an ontology-driven geographic information system. The ontology editor and its embedded translator were developed to support the knowledge generation phase of the architecture. For the knowledge use phase, a user interface to browse ontologies was also developed and the container of objects was extended from Fonseca and Davis (1999).

In this paper, special emphasis is given to the using ontological structures for semantic information integration between geographic information systems (GIS) and remote sensing systems (RSS). By RSS in this paper we refer to large collections of remotely sensed imagery, like the ones typically produced by an aerial or satellite sensor. Despite substantial efforts, this integration is still elusive. One of the first steps of the Digital Earth project is to integrate data that is already available from diverse sources (Gore 1998). The development of new sensors and new data collection strategies is increasing the necessity for the development of new architectures to enable geographic information integration.

The environment uses different levels of ontologies to guide processes for the extraction of more general or more detailed information and to allow the extraction of information in different stages of classification.

The strongly typed mapping of classes from multiple ontologies provides a high level of integration. Also, by navigating inside an ontology-derived class hierarchy, the user is provided with a guide for generalization operations. This potential to extract different levels of information inside the framework of an OGDIGS is essential for modern decision making. The use of ontologies in GIS development also enables knowledge sharing and information integration. The proposed approach provides dynamic and flexible information exchange and allows partial integration of information when completeness is impossible. Our approach is based on the commitment of communities to common ontologies. The structure used to represent the ontologies is flexible and can be opposed to standard-seeking. Standards take a long time and act as a barrier. Despite initiatives such as Spatial Data Transfer Standard (SDTS) (USGS 1998), the Spatial Archive and Interchange Format (SAIF) (Sondheim *et al.* 1999), and OpenGIS (McKee and Buehler 1996), the use of standards as the only means to achieve interoperability is not widely accepted. Since widespread heterogeneity arises naturally from a free market of ideas and products there is no way for standards to banish heterogeneity by decree (Elmagarmid and Pu 1990). The use of semantic translators in dynamic approaches is a more powerful solution for interoperability than the current approaches, which promote standards (Bishr 1997).

The OGDIGS approach leads to better integration than ad-hoc methods like the import of raster data into GISs, or the import of vector data into RSSs. OGDIGS offers a common ground in which the two models/technologies can meet each other. This solution enables the seamless integration of legacy systems that often contain valuable information. The importance of the integration of pre-existing systems is pointed out in Abel *et al.* (1994).

The remainder of this paper is organized as follows. Section 2 presents a review of related work. Section 3 describes the framework for an ontology-driven geographic information system and the basic system architecture. Section 4 presents the ODGIS perspective of image classification. Section 5 presents conclusions and future work.

2 Related Work

The use of objects and fields under the same framework is long sought for by the GIS and remote sensing communities. Some solutions have appeared, but none is satisfactory (Poulter 1996). In section 2.1 we discuss the integration of objects and fields into an integrated GIS. This integration is important, because remote sensing images can be used to correct and update information in a GIS (Ehlers *et al.* 1989; Agouris *et al.* 2000), pre-existent information can improve image interpretation (Lillesand and Kiefer 2000) and support and guide object extraction (Agouris and Stefanidis 1996). Since the classification process is fundamental for a subsequent successful integration, work related to the use of knowledge systems in the classification process is also reviewed. We review work on the use of Ontologies in Information Systems Development in section 2.2.

2.1 Integrated Geographic Information Systems

Early discussions on integrated GISs, often referred to as IGIS, can be traced to Ehlers *et al.* (1991) and Davis *et al.* (1991). For Hinton (1996), the term IGIS has a general meaning of integrating diverse GIS technologies or reflects a particular point of view of a community like the remote sensing one. We use the term IGIS here for the integration of geographic information in any representation format, including objects and fields, inside a framework that enables the user to use both in their full extent.

Davis (1991) considers that the greatest impediment to integration is more conceptual than technical in nature. Abel *et al.* (1994) consider that the view of integration as the merging of diverse technologies is one of the basic guidelines for a new generation of GIS. Research in the next-generation of GIS has been going on for some time. Couclelis (1992) and Egenhofer *et al.* (1995) ask for GIS that overcome the limitations of raster and vector representations, and of the Euclidean geometry. Pissinou *et al.* (1993) propose directions for the next generation of GIS. Among them are the use of object orientation and artificial intelligence. Worboys (1995) describes research areas where computer science plays a major role in shaping the next-generation systems and discusses 3D enabled GIS and knowledge-based GIS. Egenhofer and Mark (1995) introduce Naive Geography, a body of knowledge that captures the way people reason about geographic space and time. Future generations of GIS will incorporate formal models of naive geography. Sondheim *et al.* (1999) consider that the research of interoperability solutions is the way to migrate away from the monolithic systems that dominate the GIS market.

As we will see later on, among the requirements of a next-generation GIS that can be fulfilled by an ODGIS architecture is the ability to support representations of incomplete information, multiple representations of geographic space, and different levels of detail. ODGIS can also enhance software reuse since the architecture addresses issues such as locating, assessing and adapting software components (Borgo *et al.* 1997). Ontology-driven information systems avoid the separation of data based only on their representations. The semantic approach, based on the concept of geographic entities (Nunes 1991), enables the seamless integration of several kinds of information through the use of flexible classes. These classes are composed through the combination of other classes that can represent the richness of the geographic world. For instance, one of the common strategies for interoperation is the conversion of various formats into a common data structure. This new data structure should be defined previously and is usually based

on standards (OpenGIS 1996; Salgé 1999). Our approach defines a dynamic data structure that is derived from ontologies.

2.1.1 GIS and Remote Sensing Integration

The recent advances in remote sensing technology, with the deployment of new generation of sensors (high resolution, hyperspectral, polarimetric radar) have increased markedly the areas of application of integrated GIS, including environmental monitoring and urban management (Coulter *et al.* 1999; Jensen and Cowen 1999).

In an early paper on IGIS, Ehlers *et al.* (1989) presented a three-level integration process to be progressively achieved by GIS. These levels are:

- Level 1: includes simultaneous display of both vector and raster data and the ability to transfer pre-processed results of both kinds to the other software modules; this level is achieved using static data exchange between different systems.
- Level 2: here the software modules are still separated but can exchange data dynamically; the user interface and display are common to both modules;
- Level 3: this is called total integration as opposed to the seamless integration of level 2; at this level we are dealing with a unique system based on a single model of the world where representation would be at lower levels; this kind of system should use an object-based representation and be able to accommodate information at different levels.

Considering recent trends in theory and applications, we have to add to the above a fourth level, in which time would be also seamlessly integrated. Time has many different uses in GIS, especially in environmental applications and decision making, and has been the subject of substantial research in the GIS community. However, its integration remains an unsolved problem (Frank 1998). The system presented here can be classified as level three because it fulfills the requirements of information integration inside a unique framework using a hierarchy to represent the real world. It also enables the use of the full potential of every representation through the manipulation of classes by the end user. Time can also be integrated in an ODGIS framework through the use of an ontology of Time, but this subject is not addressed here.

2.1.2 Image Interpretation and Knowledge Systems

The development of knowledge-based systems for image interpretation has been the subject of a significant number of efforts in the literature. SPAM (McKeown *et al.* 1985), SIGMA (Matsuyama and Hwang 1990) and MESSIE (Clement *et al.* 1993) use a set of scene knowledge rules and a hierarchy to incrementally build new objects. ERNEST (Niemann *et al.* 1990), AIDA (Tonjes and Liedtke 1998) and MOSES (Quint 1997) use semantic nets to capitalize on the object structure for interpretation.

Bähr (1998) considers that any kind of image analysis requires knowledge. According to him, the most recent approaches to image understanding using knowledge representation can be summarized by the graph in Figure 3. Our ODGIS approach uses ontologies since the beginning of the process. For instance, for raw data, we can have ontologies for optical sensor images (LANDSAT) and for active sensors (RADARSAT). In the feature extraction, the features themselves are part of ontologies. In scene description, we also need ontologies as can be seen in AIDA (Tonjes and Liedtke 1998) where high-level concepts such as *landscape* are part of the system ontology. In ODGIS, the object classes are structured hierarchically and are derived from ontologies.

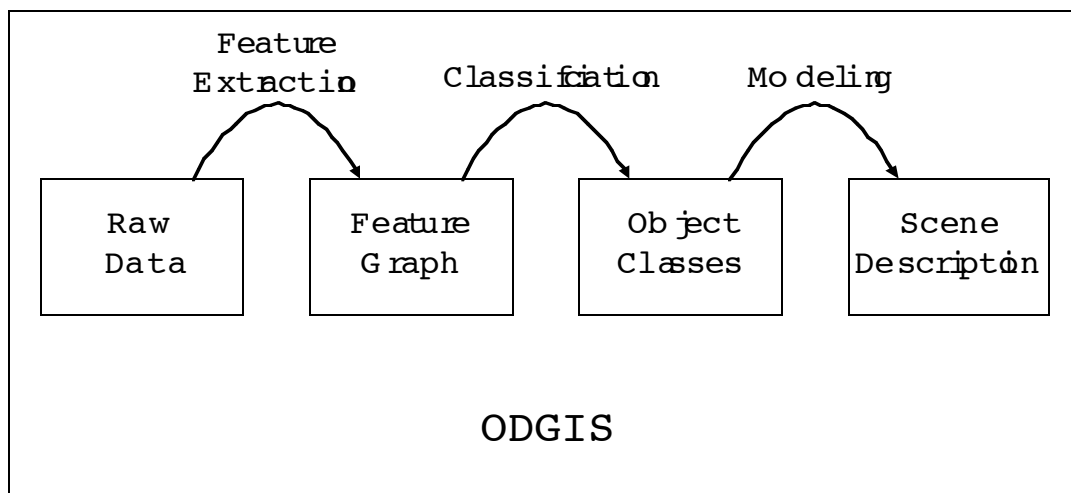


Figure 3 - ODGIS role in image interpretation extended from (Bähr 1998)

Object recognition in images and the link of extracted objects to explicit representations of the world are addressed in Pentland (1986). An overview of state-of-the-art in object extraction from aerial and satellite images may be found in Gruen *et al.* (1995; 1997). Digital image analysis typically involves modeling real world objects (or object configurations) and how these models translate into image variations. These models may be more or less general, affecting the possibility to find matches between a model and an image. In turn this can lead to minimizing misses at the risk of false positive responses and vice versa. In section 4 we address the issue of different levels of information and how objects present in an image can be assigned to these levels.

Gahegan (1996) and Gahegan and Flack (1996; 1999) present a new model for a GIS that is an extension of their previous work (Roberts *et al.* 1991; Roberts and Gahegan 1993). It is a framework for a GIS that incorporates both image interpretation methods and their use in geographic analysis and modeling. They use an approach of delaying the feature extraction process, which is performed only when the user needs it. Gahegan and Flack (1996) adapt the concept of *binding* from the database community. Here, *binding* is the process of linking the results of scene interpretation to geographic features. The system allows expert and non-expert users to choose how much they want to interfere in the image classification process. The main objective is to allow a single feature in the GIS to have more than one description.

The system has a set of pre-defined frames that contains the description of the features and the methods available to deal with these features. Gahegan (1996) and Gahegan and Flack (1996; 1999) call an image view, or view, the result of the scene understanding process. It is from the view that the spatial description of features is extracted. The features are later linked to the frames to which they belong. The system searches the knowledge base using parameters from the user query. Based on this search the appropriate image view is formed and the query is processed. The raw image is manipulated according to methods available in the frame extracted from the knowledge base. The result is a spatial representation associated with a feature instance. This instance can be a set of pixels or a set of vectors.

In our approach we address some of the considerations that appeared in Gahegan (1996) and Gahegan and Flack (1996; 1999). We also provide the ability of one geographic entity to have more than one interpretation through the use of roles and the integration of remote sensing data inside a GIS framework. We use an approach of developing the basic ontologies first and then performing the integration of systems. While Gahegan and Flack (1996; 1999) describe an

operational prototype to perform task-oriented analyses of remotely sensed data with an emphasis on the classification process, we present here an architecture for ontology-driven geographic information systems used to query and manipulate geographic information existent in either GIS or RSS. In this paper we emphasize more the use of the classification process, i.e., the resulting classes.

Our proposal is to use ontologies to match the features found in the images to classes in the ontologies. The use of ontologies early in the process of image interpretation can deliver incremental results that can be used in ontology-driven geographic information systems (ODGIS) (Fonseca and Egenhofer 1999).

2.2 Ontologies and Information Systems Development

The next generation of information systems should be able to solve semantic heterogeneity to make use of the amount of information available with the arrival of the Internet and distributed computing. An information system that aims at solving semantic interoperability should understand the user model of the world and its meanings, understand the semantics of the information sources, and use mediation to satisfy the information request regarding the above mentioned sources and users (Sheth 1999). Ontologies play a key role in enabling semantic interoperability, and it has been suggested (Sheth 1999) that research focuses on a specific domain, such as GIS, before more general architectures can be developed.

Ontology-driven information systems (Guarino 1998) are based on the explicit use of ontologies at development time or at run time. The use of ontologies in GIS development has been discussed by Frank (1997) and Smith and Mark (1998). Ontology playing a software specification role was suggested by Gruber (1991). Nunes (1991) pointed out that the first step in building a next-generation GIS would be the creation of a systematic collection and specification of geographic entities, their properties, and relations. Ontology plays an essential role in the construction of GIS, since it allows the establishment of correspondences and interrelations among the different domains of spatial entities and relations (Smith and Mark 1998). Frank (1997) believes that the use of ontologies will contribute to better information systems by avoiding problems such as inconsistencies between ontologies built in GIS, conflicts between the ontological concepts and the implementation, and conflicts between the common-sense ontology of the user and the mathematical concepts in the software. Bittner and Winter (1999) identify the role of ontologies in modeling spatial uncertainty like the one often associated with object extraction processes. Kuhn (1993) asks for spatial information theories that look toward GIS users instead of focusing on implementation issues. Ontology use can also help GIS to move beyond the map metaphor, which sees the geographic world as layers of independent information that can be overlaid. Several inadequacies of the map metaphor have been pointed out (Kuhn 1991).

There is a difference in the definition of ontology in the philosophical sense and in the way the term is used in the Artificial Intelligence (AI) field (Guarino 1998). In AI, ontology is seen as an engineering artifact that describes a certain reality with a specific vocabulary, using a set of assumptions regarding the intended meaning of the vocabulary words. Meanwhile, in the philosophical arena, ontology is characterized as a particular system of categories reflecting a specific view of the world. Smith (1998) notes that since, to the philosopher, ontology is the science of being, it is inappropriate to talk about a plurality of ontologies, as engineers do. To solve this problem Smith suggests a terminological distinction between referent or reality-based ontology (R-ontology) and elicited or epistemological ontology (E-ontology). R-ontology is a theory about how the whole universe is organized, and corresponds to the philosopher's point of view. An E-ontology, on the other hand, fits the purposes of software engineers and information scientists, and is defined as a theory about how a given individual, group, language, or science conceptualizes a given domain.

In order to build software components from ontologies, it is reasonable to assume that ontologies are available on the market. As ontology development technology evolves, the benefits of ontology use will outweigh the costs of developing them. With the success of this technology, large-scale repositories of ontologies will be available in diverse disciplines (Farquhar *et al.* 1996), and previous work has been developed based upon this availability assumption (Kashyap and Sheth 1996). As Frank (1997) assumes, we believe that there is a commercial production of ontologies, and that these ontologies are good enough to be used. This position is not shared by Guarino (1998), however, who believes that the available quantity of ontological knowledge is modest, although of good quality. Kemp and Vckovski (1998) consider that although certain types of geographic phenomena, like discrete objects, have been the object of ontology study, spatially continuous phenomena, like temperature and soil moisture, have received little attention. Guarino (1998) suggests the use very generic ontologies, although this solution has the drawback of limiting the degree of reusability of the software components and knowledge. The other option is to use an ontology library containing specialized ontologies of domains and tasks. The translation of this library into software components reduces the cost of conceptual analysis and ensures the ontological adequacy of the information system.

3 Ontology-Driven Geographic Information Systems

The use of an ontology, translated into an active information system component, leads to Ontology-Driven Information Systems (Guarino 1998) and, in the specific case of GIS, leads to Ontology-Driven Geographic Information Systems (ODGIS) (Fonseca and Egenhofer 1999). OGDIS are built using software components derived from various ontologies. These software components are classes that can be used to develop new applications. Being ontology-derived, these classes embed knowledge extracted from ontologies.

The OGDIS structure has two main aspects: *knowledge generation* and *knowledge use* (Figure 4). Knowledge generation involves the specification of the ontologies using an ontology editor, the generation of new ontologies from existing ones, and the translation of the ontologies into software components. The knowledge use phase relies on the products from the previous phase: a set of ontologies specified in a formal language and a set of classes. The ontologies are available to be browsed by the end user, and they provide metadata information about the available information. A set of classes that contains data and operations constitutes the system's functionality. These classes are linked to geographic information sources through the use of mediators.

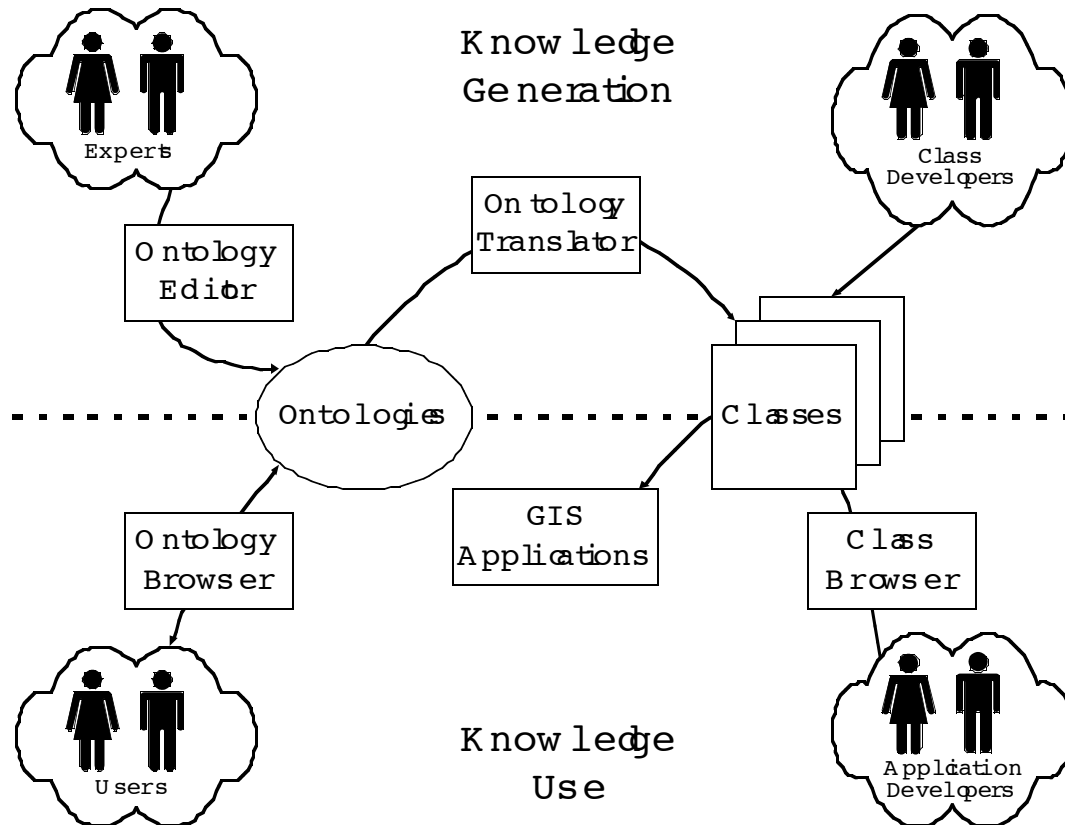


Figure 4 - ODGIS schema

3.1 Knowledge Generation

Ontology-driven geographic information systems are supported by two basic notions: making the ontologies explicit before information systems are developed, the hierarchical division of communities.

The use of explicit ontologies contribute to better information systems because, since every information system is based on an implicit ontology, making it explicit avoids conflicts between the ontological concepts and the implementation. Furthermore, top-level ontologies can be used as the foundation for interoperable systems because they represent a common vocabulary shared by a community.

It is important to stress that we are discussing here ontologies and not database schemas. Our approach is based on a group of people reaching an agreement on what are the basic geographic entities of their world. It does not matter if the entities are stored or not in a database. A database schema represents what is stored in the database. An ontology represents a view of what exists in the world. Ontologies are richer in their semantics than database schemas. The ontologies we deal with are created from the world of geographic objects. The information that exists in the databases has to be adapted to fill in the classes of the ontologies. For instance, the concept of lake can be represented differently in diverse databases, but the concept is only one, at least from one community's point of view. This point of view is expressed in the ontology that this community has specified. In the ODGIS architecture, diverse mediators have to act to gather the main aspects

of lake from diverse sources of information and assemble the instance of a lake according to the ontology.

The world is divided into different groups of people. Each of these groups has a different view of the world. In considering the different groups from the perspective of geography, McKee and Buehler (1996) named these groups *geospatial information communities* (GIC). According to them, each GIC is a group of users that shares a digital geographic information language and spatial feature definitions. Bishr *et al.* (1999) revised this concept considering a GIC as "a group of spatial data producers and users who share an ontology of real world phenomena." Guarino (1998) agrees that we should consider an ontology to be a particular knowledge base that describes facts that are always true for a community of users. This revised GIC concept is fundamental for ODGIS because it is a basic assumption of this paper that ontologies of diverse user communities can be explicitly specified and later merged if necessary. We use also hierarchies of groups to generate ontologies of different levels of detail. For instance, in a city, the mayor and his/her immediate staff view the city at a higher level. The department of transportation has a view that is more detailed than the previous one. Inside the department of transportation, the section in charge of the subway system will have an even more detailed view of the city. We should consider common ontologies as a high-level language that holds those communities together. For instance, in the department of transportation of a large city there is a software specialized in transportation modeling beyond the regular GIS package, and therefore, more than one data model. But the conceptualization of the traffic network of the city is the same among these groups, just one ontology can hold this conceptualization. So we can use the redefinition that Bishr (1997) gave for a GIC: a group of users that share an ontology. In the solution presented here, we allow the GIC to commit to several ontologies. The users have the means to share information through the use of common classes derived from ontologies. The level of detail of the information is related to the level of detail of the ontology.

In ODGIS it is necessary that GICs assemble and specify ontologies at different levels. The first ontology specified inside a community is a top-level ontology. The assumption here is that this ontology exists and that it can be specified. The question of whether this *one ontology* exists or not is a matter widely discussed without reaching a consensus. We argue that it exists inside each community, although it can be sometimes too generic. People inside each community communicate, and therefore they agree on the most basic concepts. The top-level ontology describes these basic concepts (Figure 5).

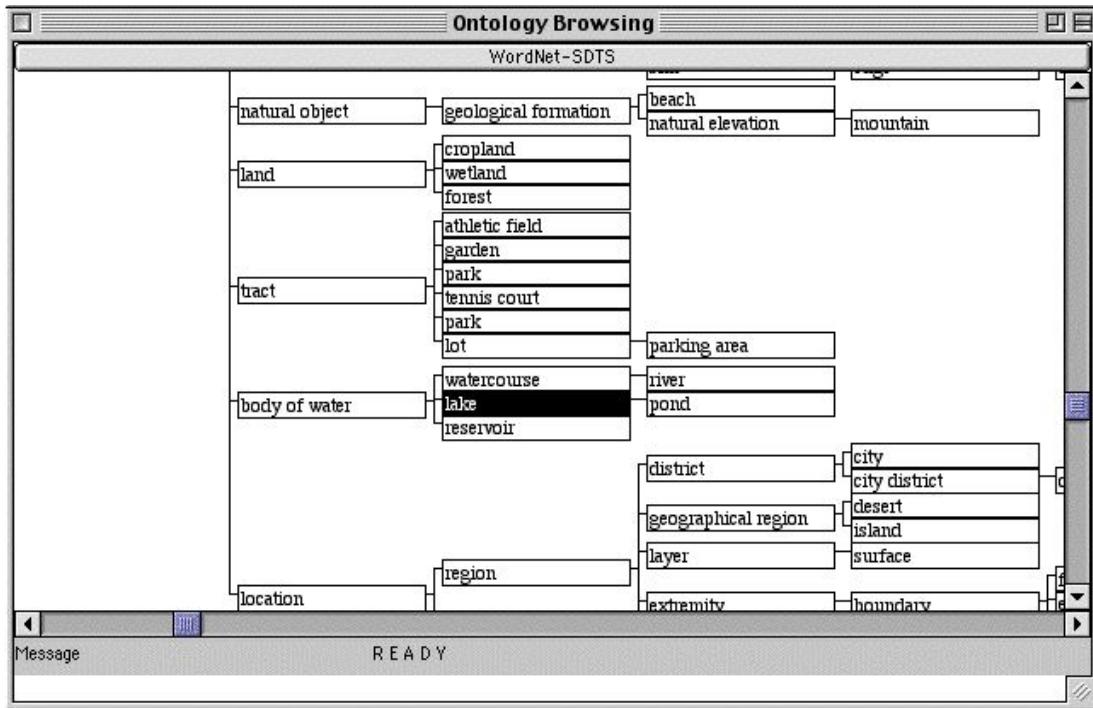


Figure 6 – The class lake in WordNet-SDTS ontology

In order to build the ontologies we have two options. First, we can consider that these small communities can assemble with other communities with the same interests and try to build from their existing ontologies a high-level ontology that encompasses their lower level ontologies. The second option is that these communities assemble before specifying their own ontologies in order to specify a high-level ontology for these groups of communities. The most important thing here is that the architecture of an ODGIS allows reusing and combination of ontologies based in the reuse of classes through the use of inheritance. The same rationale applied inside one community can be expanded to higher-level communities, or to subgroups inside a community. A good example of this is the ontology specified by the members of the Food and Agriculture Organization of the United Nations that defined a high-level ontology for the classification of different types of soil coverage to be used in the interpretation of remote sensing images. (Gregorio and Jansen 1998)

The set of ontologies is represented in a hierarchy. The components of the hierarchy are classes modeled by their distinguishing features (*parts*, *functions*, and *attributes* (Figure 7). This structure for representing ontologies is extended from Rodríguez (2000) with the addition of *roles*. Roles allow for a richer representation of geographic entities and avoid the problems of multiple inheritance.

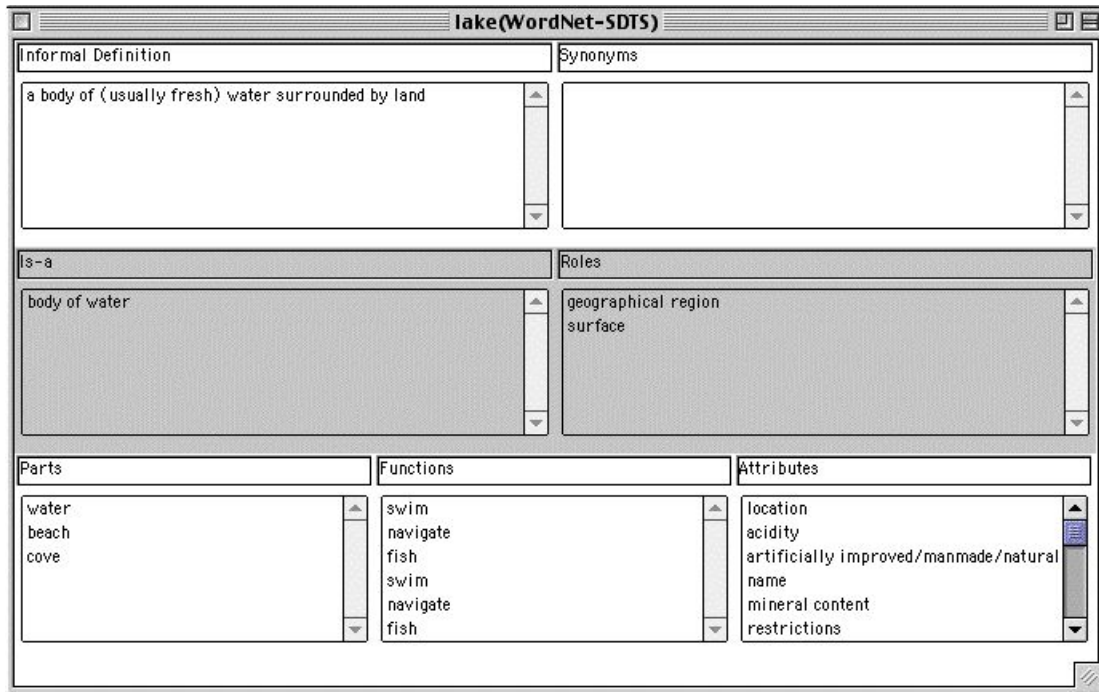


Figure 7 - Basic structure on an ontology class

The result from the work of the GICs with the ontology editor is a set of ontologies. Once the ontologies are specified we can translate them into classes. The translation is available as a function of the ontology editor. The ontologies are available to be browsed by the end user, and they provide metadata information about the available information. The set of classes contains data and operations that constitute the system's functionality. These classes contain the knowledge available to be included in the new ontology-based systems.

3.2 Knowledge Use

The result from the knowledge generation phase of an ODGIS is a set of ontologies specified in a formal language and a set of classes. The ontologies are available to be browsed by the end user and they provide metadata information about the available data. The result from the translation is a set of classes that contain data and operations that constitute the system's functionality. These classes contain the knowledge available to be included in the new ontology-based systems.

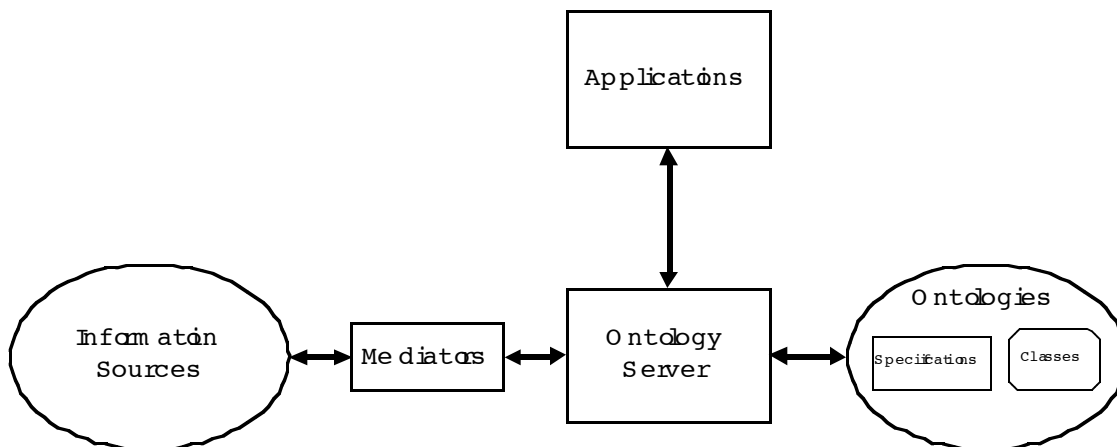


Figure 8 - Basic architecture of an ODGIS

The main components of an ODGIS architecture are (Figure 8):

- the *ontology server*: the ontology server has a central role in an ODGIS because it provides the connection among all the main components. The server is also responsible for making the ontologies available to the applications, The connection with the information sources is done through mediators. Mediators look for geographic information and translate it into a format understandable by the end user. The mediators are pieces of software with embedded knowledge. Experts build the mediators by putting their knowledge into them and keeping them up to date.
- The *ontologies*: they are represented by two kinds of structures, i.e., the specifications and the classes. The specifications are made by the experts and stored according to their distinguishing features (*parts, functions, and attributes*) and their semantic interrelations (*is-a, part-of and whole-of relations*). This structure provides information about the meaning of the available information. It can be used by the user to know what is stored and to match his conception of the world with other available conceptions stored by the ontology manager. The classes are the result of the translation of the ontologies. They are software components that can be use to develop applications and they are fully functional classes with all the operations that can be applied to that entity.
- the *information sources*: the sources of geographic information in an ODGIS can be any kind of geographic database as long as they commit themselves to a mediator. The mediator has the function of extracting the pieces of information necessary to generate an instance of an entity of an ontology. The mediator also has the function of bringing back new information in the case of an update.
- the *applications*: one of the application of an ODGIS is information retrieval. The mediators provide instances of the entities available in the ontology server. The user can browse the information at different levels of detail depending on the ontology level used. Other kind of applications can be developed, such as database update and different kind of geographic data processing, including statistical analysis and image processing.

For instance, a user wants to retrieve information about bodies of water of a determined region. First, the user browses the ontology server looking for the related classes. After that, the ontology server starts the mediators that look for the information and return a set of objects of the specified

class. The results can be displayed (Figure 9) or can undergo any valid kind of operation, such as statistical analysis.

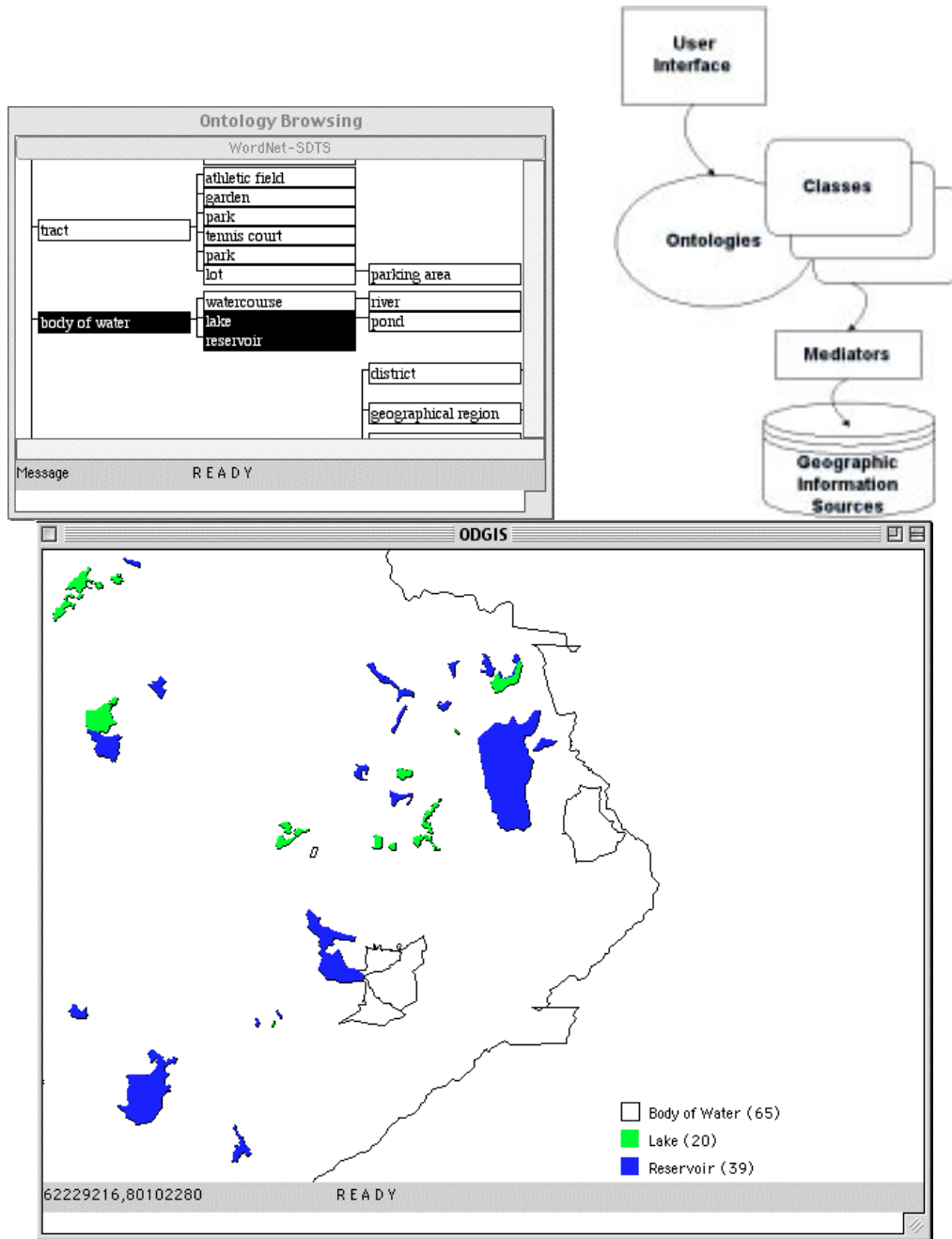


Figure 9 – Schema for a query processing with an ODGIS

In the next section we propose the use of ontologies to support digital aerial imagery classification and the integration of the results of the classification process with other information systems. The development of classes, or an ontology, specialized in image classification will enhance the classification process and will facilitate the integration of aerial images into an ODGIS

framework. This way, aerial images, will be represented by special classes extracted from geographic ontologies. These classes can integrate the classified results into an ODGIS framework and perform, for instance, digital image processing operations and then return the result back to an ODGIS.

4 Information Integration: An ODGIS Perspective

Commercial satellites in operation today record images of the Earth's surface with resolutions down to 1-meter pixels. In addition to their spatial resolution, the spectral resolution of satellites is also improving, with the development of various multispectral sensors. Temporal resolution is also improving, and it is now possible to obtain images of a place with a difference of some hours. New sensor deployment methods (e.g., unmanned aerial vehicles) even provide us with video-rate aerial imagery. Furthermore, geospatial imagery is being used in more and increasingly diverse applications, aiming at the extraction of various types of information.

The above trends provide us with more information, but at the same time introduce constraints in processing this information. We need more efficient algorithms to process these image datasets and derived information in a timely fashion. Furthermore, we are faced with an expansion of the number of object classes that are the subject of the classification process, as we pursue more specific types of information. Considering these emerging requirements, we are proposing a gradual classification process using the hierarchy of ontology classes.

4.1 Using an Ontology Hierarchy for Image Classification

In the ODGIS architecture there are different levels of ontologies. Accordingly, there are also different levels of information detail. Low-level ontologies correspond to very detailed information and high-level ontologies correspond to more general information. Thus, if a user is browsing high-level ontologies he or she should expect to find less detailed information. We propose that the creation of more detailed ontologies should be based on the high-level ontologies, such that each new ontology level incorporates the knowledge present in the higher level. These new ontologies are more detailed, because they refine general descriptions of the level from which they inherit.

Guarino (1997) classifies ontologies according to their dependence on a specific task or point of view (Figure 3).

- *Top-level ontologies* describe very general concepts. In ODGIS a top-level ontology describes a general concept of space. For instance, a theory describing parts and wholes, and their relation to topology, called mereotopology (Smith 1995), is at this level.
- *Domain ontologies* describe the vocabulary related to a generic domain, which in ODGIS can be for instance, remote sensing or the urban environment.
- *Task ontologies* describe a task or activity, such as image interpretation or noise pollution assessment.
- *Application ontologies* describe concepts depending on both a particular domain and a task, and are usually a specialization of them. In ODGIS these ontologies are created from the combination of high-level ontologies. They represent the user needs regarding a specific application such as an assessment of lobster abundance on the Gulf of Maine.

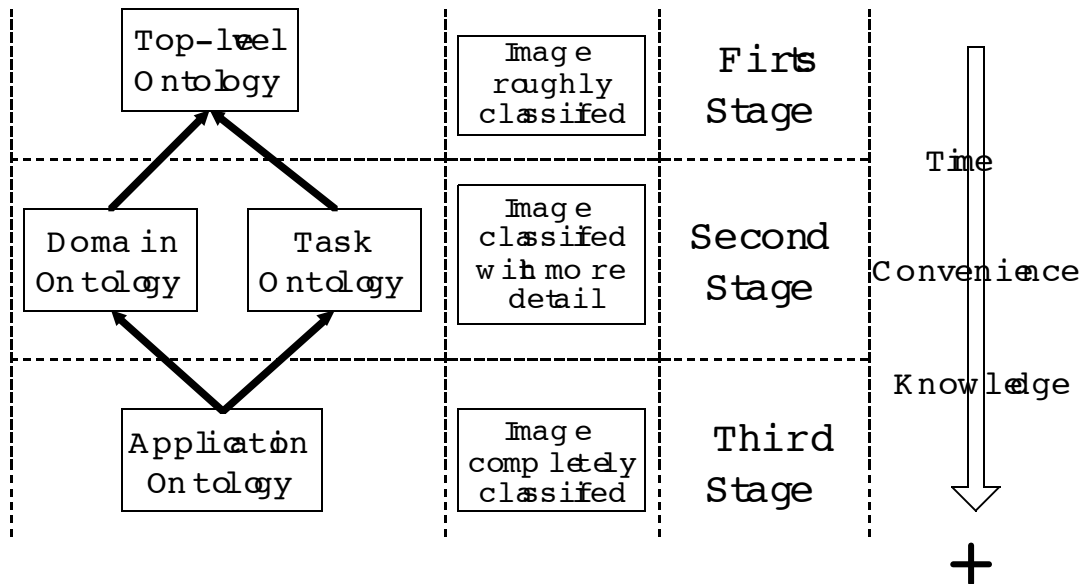


Figure 10 - Levels in ODGIS

4.2 The Classification Process

We can see the use of multispectral remotely sensed images in a GIS environment in the same light as we see the ODGIS framework: knowledge generation and knowledge use. Here, knowledge generation is the process of image classification, and knowledge use is the integration and use of aerial images in GIS.

In order to provide a better understanding of the use of ODGIS in improving the image classification process, we first discuss how the process is done currently, and then indicate the impact of using ontologies.

Currently, most applications of remote sensing image processing use two main types of semi-automated image classification procedures: supervised and unsupervised. In the supervised classification procedure, the operator makes some a priori hypotheses concerning the types of objects contained in the image and selects some representative samples. These samples are used by the classification software to obtain statistical and/or structural information about these objects. The classification software then processes the whole image, assigning each pixel to one of the predefined classes (some algorithms include a provision for non-classified pixels, that are those who fail to meet a minimum pre-specified membership criterion).

In unsupervised process classification procedures, a clustering procedure such as ISODATA (Lillesand and Kiefer 2000) is first applied to the image in order to determine sets of objects that can be statistically discriminated. These objects can then be assigned as corresponding to real-world objects by an operator.

Additionally, it has been proven efficient to precede image classification by an image segmentation procedure, whereby the image is first divided into regions (by processes such as region growing or edge detection), and these regions can then be used as an input to supervised or unsupervised classification procedures.

Image Understanding systems may include a knowledge representation procedure such as semantic nets (Tonjes and Liedtke 1998) or production rules (Matsuyama and Hwang 1990). In both cases, some *a priori* assumptions about real-world objects present in the scene are made and the knowledge base is used to drive the appropriate image classification algorithms.

In general, all these image classification procedures have some traits in common: the need for a choice of real-world types of objects that are present in the image footprint, and their association to objects in the raster image. They differ in the way this association is made: by means of training samples (supervised classification), by operator analysis of clusters (unsupervised classification) or by knowledge representation (image understanding systems).

An ODGIS can improve these classification procedures. In an ODGIS, image classification is performed through the association of image and the objects found in it to ontology entities. The hierarchical organization of ontologies allows the classification process to be done gradually, starting with very general associations and proceeding up to a final classification that can be very precise and detailed. In the classification process the operator assigns a class to a part of the image. We propose that the classification should be done first trying to find and associate objects in the image to top-level ontologies. As the classification process continues more objects can be found or the same objects previously found can be better identified and related to task and domain ontologies. These new classes are added to the previous classification. This way, one object in the image is gradually being more and more specified and the result is a more precise classification until all the objects in the image are related to application ontologies, in a very low-level classification.

The ability of performing a gradual classification is of dual importance. First, it enables progressive analysis, permitting the use and refinements of imprecise classification. Second, it allows us to revisit classified imagery, and re-interpret the results, according to newly available information. User-provided ontologies may be used to re-evaluate the classification outcome in the light of new information (e.g. re-examining a classified scene using the knowledge that an environmental crisis has been identified in a nearby area). This is a very powerful capability, enabling complex scene analysis processes.

In order to show these ideas in practice, we present an example based on a case study: Brazil's National Institute for Space Research (INPE) comprehensive surveys of deforestation in the Amazon rain forest. Consider the problem of land use and land cover change over tropical forest areas we can distinguish three levels of ontologies:

- a *top-level ontology*, which is shared by different communities concerned with global change issues over tropical forest (in Amazonia and elsewhere). At this level, they may distinguish very generic types of ontologies land use and land cover, such as Forest, Non-Forest Vegetation and Deforestation objects.
- a *domain ontology*, which will consider the case of the Brazilian Amazon rain forest, and will distinguish different subtypes of Forest (e.g., TerraFirme Forest, Inundated Forest), Non-Forest Vegetation (e.g., Regrowth, Natural Savannah), and Deforested Areas (e.g., Burnings, Human Settlements, Farms). This ontology is more specific than the top-level ontology, but still is sufficiently generic to apply to the whole of Amazonia and not only to a given geographic area.
- an *application ontology*, which will consider the specific case of the geographic area which the image refers to (e.g., the northeastern part of the state of Rondonia), and in which we can identify the objects of the image in more detail (perhaps after some field

trips). For example, objects of the type *Farms*, as classified in the domain ontology can, at this level, be assigned to specific types of agricultural use (e.g., Soybeans Plantation, Cattle Farms, Abandoned Areas).

This hierarchical process also has implications in terms of complexity and time required for the analysis procedures. To obtain results at the top-level, a simpler technique such as segmentation followed by unsupervised clustering may be used. At the *domain ontology* level, a more detailed analysis procedure is needed, which might include supervised classification and ancillary information. Finally, at the *application ontology* level, image processing techniques may need to be complemented by extensive field surveys, ground truth and census data.

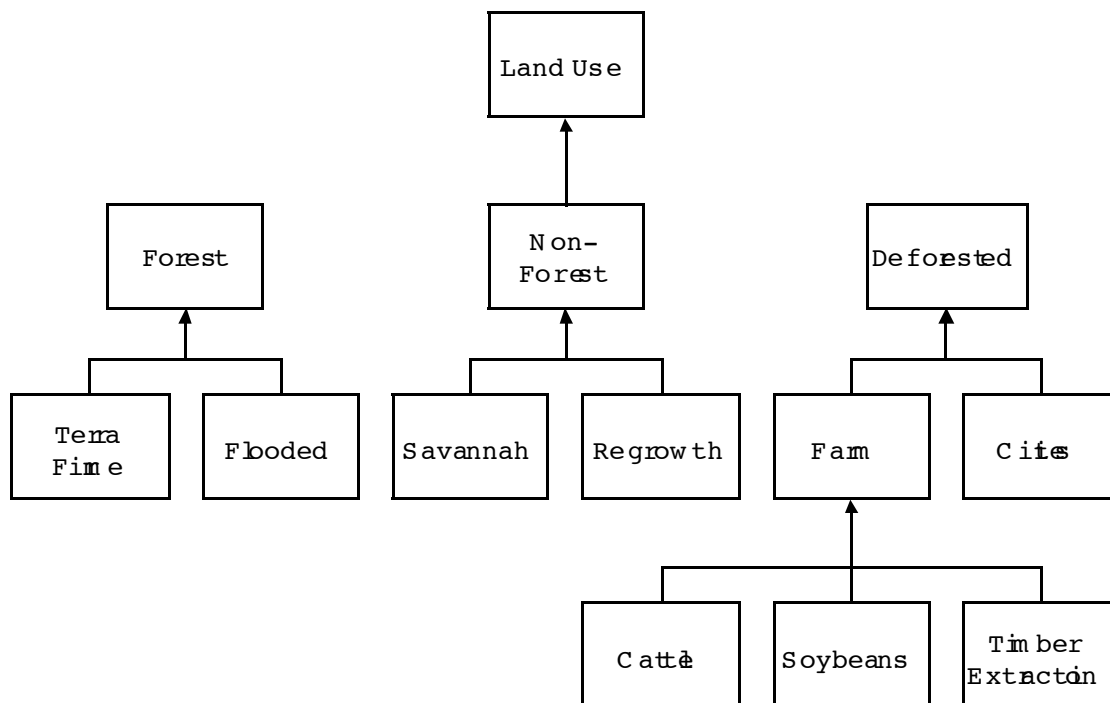


Figure 11 - Images linked to classes

4.3 Objects with Roles

One of the advantages of using an ODGIS is the ability of having multiple interpretations to the same geographic feature. Here we address the question of how the objects identified in the image can be associated with more than one class present in the ontology hierarchy.

Classes are typically defined hierarchically, taking advantage of one of the most important concept in object-oriented systems: *inheritance*. It is possible to define a more general class, containing the structure of a generic type of object, and then specialize this class by creating subclasses. The subclasses inherit all properties of the parent class and add some more of their own. For instance, within a local government you can have different views and uses for land parcels. A standardization committee can specify a land parcel definition with general characteristics. Each department that has a different view of a land parcel can specify its own land parcel class, inheriting the main characteristics from the general definition of land parcel and including the specifics of the department. In this case, we can have a land parcel definition for the whole city, and derived from it, two different specializations, one for tax assessment and the other

for building permits. When a given class inherits directly from only one class, it is called *single inheritance*, whereas when a class inherits from more than one class, it is called *multiple inheritance* (Cardelli 1984). Multiple inheritance is a controversial concept, with benefits and drawbacks. Although the implementation and use of multiple inheritance is non-trivial (Tempero and Biddle 1998), its use in geographic data modeling is essential (Egenhofer and Frank 1992).

In order to represent the diverse character of the geographic entities and avoid the problems of multiple inheritance we opted for using objects with *roles*. When defining an entity in an ontology it is important to clearly establish an identity. Here, an object is something, it has an identity, but it can play different roles. Guarino (1992) presents an ontological distinction between role and natural concepts using the concept of *foundation*. For a concept α to be founded on another concept β , any instance x of α has to be necessarily associated to an instance y of β *which is not related to x by a part-of relation*. Therefore, instances of α only exist *in a more comprehensive unity* where they are associated to some other object. A role is a concept that is founded but not semantically rigid. A natural concept is essentially independent and semantically rigid.

A role can be seen as an attribute of an object. In object orientation, and in this paper, a role is a slot, while for the database community it is a relation. Instead of using multiple inheritance, where, for instance, a downtown building is at the same time a building and a shopping center, we can say that this entity is a building that plays a *role* of a shopping center. Maybe the building was once a factory and later remodeled to be a shopping facility. In this paper, this building is seen as being always a *building* and playing during its lifetime two roles, i.e., *factory* and *shopping facility*. In ODGIS we allow an object to play many roles.

The application developer can combine classes from diverse ontologies and create new classes that represent user needs. This way, a class that represents `lake` in a Parks and Recreation department ontology can be built from `geographic region` in the Guarino and Welty (2000) ontology (Figure 12). At the same time, `lake` can be seen as a port for loading cargo, or it can be seen as a link in a transportation network. This way, `lake` can play the roles of `port` and `link`. These roles are entities in other ontologies such as WordNet-SDTS. So the real class is `lake`, but it plays many roles that together give the class its unique characteristic.

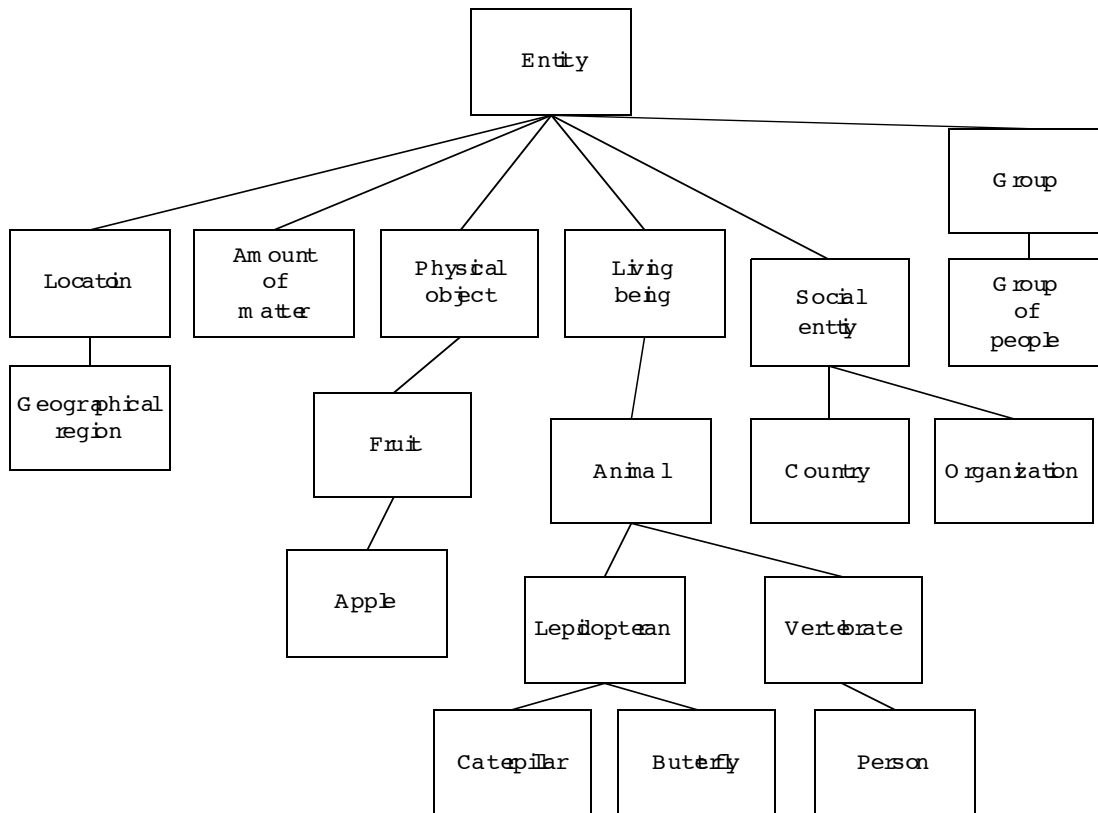


Figure 12 - A top-level ontology from Guarino and Welty (2000)

Knowledge and information sharing is achieved through the use of classes and roles that belong to common ontologies or through the conversion of instances of classes up and down in the ontology hierarchy.

4.4 Information Integration

The basic principle in this paper is to allow for the integration of what is possible instead of trying to integrate everything. It is our premise that once you achieve some kind of integration then you a complete integration can be tried out. Some kinds of information will never be completely integrated since their natures are fundamentally different. For instance, a lake from the point of view of a parks and recreation department (lake p&r) has different functions and attributes than a lake (lake w) from the point of view of a water department. The assumption in this paper is that the lake is only one entity, but seen differently by different kinds of people. Therefore, a complete integration of all information available in these two (or more) views is impossible, but the common characteristics can be shared. It is the integration of these common parts of the concepts that we are addressing here.

In order to integrate the common parts of shared concepts we are proposing a hierarchical representation of ontologies. Along with this structure, we are proposing also the use of roles that these objects can play. The integration is always made at the first possible intersection going upward in the ontology tree. For instance, if both views of lake mentioned before are derived from the same lake entity in WordNet-SDTS ontology, the possible integration is made at this level (Figure 13).

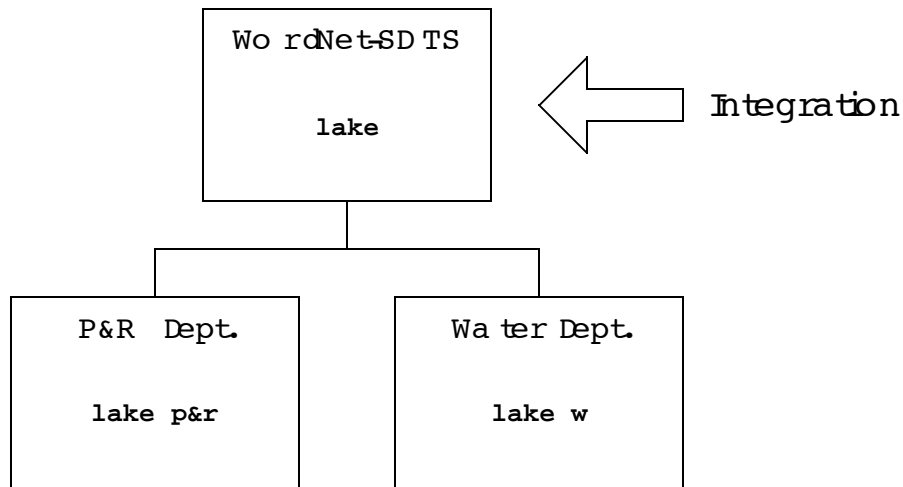


Figure 13 - Integration of lake

The integration includes all the methods and attributes of the class, i.e., the common methods and attributes of the class `lake` are all available for the user that is using the integrated information. In order for this to happen, it is necessary that the instances of `lake p&r` and `lake w` are converted to instances of the class `lake`.

In the same way, roles can also be used to integrate information. A role in one object can be matched to another class or role. For instance, the role of a `wildlife habitat` that a lake plays in the water department ontology can be extracted and converted in a instance of `wildlife habitat` from the Environmental Protection Agency (EPA) ontology and then integrated with other instances of `wildlife habitat` coming from other sources of information.

The conversion of instances from one class to another is governed by a navigation method. In ODGIS every class inherits from a basic class called `Object`. This specific class has two basic methods to be used in changes of class. One method is used to generalize new classes and it is called `Up()`, and the other is used to specialize classes and it is called `Create_From()`. These two methods provide the means to navigate through the whole ontology tree. Since each class in the ontology tree is derived from the basic class, each interface inherits the necessary navigation tools. So if the navigation methods are applied to `lake p&r`, the class returned is the next class in the upper hierarchy, the class `lake`.

4.5 Conclusions

The result of the classification process is a set of images indexed not only by its contents but also by its attribute values. The image is not only seen as a static polygon with pixel values but as a set of semantic features and its corresponding values. This approach will enable a broad field for queries when the images will be queried as seen in the next section.

The gradual classification process that was introduced here has two major advantages. First, it allows a partial classification and for classification revisions. This can be useful when there are not enough elements to positively identify an object. Later on, as more information becomes available the identification can be improved. This means that the classification process can be always incremented using new techniques or new data. Second, it allows faster results. This is because of time constraints. The time frame from when the image is acquired to when it is available to be used was shortened. For instance, the first classification that can be made is that to associate the image

to a very general class belonging to top-level ontologies. This allows the image to be immediately available in an ODGIS framework. Later on, the image can be associated with ontologies of the intermediate and low levels.

5 Conclusions and Future Work

The use of software components extracted from ontologies is a way to share knowledge and integrate different kinds of information. These software components are derived from ontologies using an object-oriented mapping. The mapping of multiple ontologies to the system classes is achieved through object-oriented techniques using inheritance. This kind of mapping allows partial integration of information when completeness is not possible.

The use of ontologies during the image classification process enhances the results and the flexibility of the classified image leading to a broader use of aerial images into a GIS framework. Matching image features to ontology-generated classes leads to flexible and dynamic pieces of information that can be loaded into a GIS and also used for integration with other systems. Furthermore, it allows us to incorporate information that may arrive from non-image sources (e.g., various sensors) into the image classification process through subsequent classification revisions.

The ODGIS approach leads to a better integration than vector-based GIS that imports raster data or than raster-based GIS that imports vector data. ODGIS was presented as a common ground into which the two models can meet each other. The result of the classification process was a set of images indexed not only by its semantics but also by its attribute values. The classified image is not seen as a static polygon with pixel values but as a set of semantic features and its corresponding values. This approach enabled a broad field for queries. In general, the ODGIS framework lets images be integrated with other kind of geographic information in a smooth and flexible way.

Future work should include the use of ontologies in the improvement of the classification process during object identification. Using the ontology browser coupled with the image display can help the operator to have more information available at the time that she/he has to make a decision. The issues of dealing with imprecise information were just introduced here. ODGIS offers a good foundation to deal with this kind of information. The decision to develop an ontology specialized in dealing with imprecision is one of the most immediate alternatives for this kind of problem and should be addressed in the future. We have shown here the potential of ODGIS to integrate geographic information of different kinds. Further study should extend the use of ODGIS to integrate other kind of information such as multimedia.

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References

- Abel D, Kilby P, and Davis J 1994 The Systems Integration Problem. *International Journal of Geographical information Science* 8: 1-12
- Agouris P, Gyftakis S, and Stefanidis A 2000 Uncertainty in Image-Based Change Detection. in: *Accuracy 2000*, Amsterdam, The Netherlands, pp. 1-8
- Agouris P, and Stefanidis A 1996 Integration of Photogrammetric and Geographic Databases. in: *International Archives of Photogrammetry and Remote Sensing, ISPRS XVIIIth Congress*, Vienna, pp. 24-29
- Bähr H-P 1998 From Data to Inference: Examples for Knowledge Representation in Image Understanding. in: *Object Recognition and Scene Classification from Multispectral and Multisensor Pixels*, Columbus, OH, pp. 301-306
- Bishr Y 1997 *Semantic Aspects of Interoperable GIS*. Ph.D. Thesis, Wageningen Agricultural University, The Netherlands
- Bishr Y A, Pundt H, Kuhn W, and Rdwan M 1999 Probing the Concepts of Information Communities - A First Step Toward Semantic Interoperability. in: Goodchild M, Egenhofer M, Fegeas R, and Kottman C, (Eds.) *Interoperating Geographic Information Systems*. pp. 55-70, Kluwer, Norwell, MA
- Bittner T, and Winter S 1999 On Ontology in Image Analysis in Integrated Spatial Databases. in: Agouris P and Stefanidis A, (Eds.) *Lecture Notes in Computer Science*. 1737, pp. 168-191, Springer Verlag, Berlin
- Borgo S, Guarino N, Masolo C, and Vetere G 1997 Using a Large Linguistic Ontology for Internet-Based Retrieval of Object-Oriented Components. in: *The Ninth International Conference on Software Engineering and Knowledge Engineering*, Madrid, Spain, pp. 528-534
- Burrough P, and Frank A, (Eds.) 1996 *Spatial Conceptual Models for Geographic Objects with Undetermined Boundaries*. Taylor & Francis, London
- Câmara G, Monteiro A, Paiva J, Gomes J, and Velho L 2000 Towards a Unified Framework for Geographical Data Models. in: Figueiredo L, (Ed.) *Geoinfo 2000—II Workshop Brasileiro de Geoinformatica*, São Paulo, Brazil, pp. 37-44
- Câmara G, Souza R C M, Freitas U M, and Garrido J C P 1996 SPRING: Integrating Remote Sensing and GIS with Object-Oriented Data Modelling. *Computers and Graphics* 20: 395-403
- Cardelli L 1984 A Semantics of Multiple Inheritance. in: Kahn G, McQueen D, and Plotkin G, (Eds.) *Semantics of Data Types. Lecture Notes in Computer Science* 173, pp. 51-67, Springer-Verlag, New York
- Clement V, Giraudon G, Houzelle S, and Sadakly F 1993 Interpretation of Remotely Sensed Images in a Context of Multisensor Fusion Using a Multispecialist Architecture. *IEEE Transactions on Geoscience and Remote Sensing* 31: 779-791
- Couclelis H 1992 People Manipulate Objects (but Cultivate Fields): Beyond the Raster-Vector Debate in GIS. in: Frank A U, Campari I, and Formentini U, (Eds.) *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space. Lecture Notes in Computer Science* 639, pp. 65-77, Springer-Verlag, New York
- Coulter L, Stow D, Kiracofe B, Langevin C, Chen D, Daeschner S, Service D, and Kaiser J 1999 Deriving Current Land Use Information for Metropolitan Transportation Planning through Integration of Remotely Sensed Data and GIS. *Photogrammetric Engineering & Remote Sensing* 65: 1293-1300

- Davis F, Quattrochi D, Ridd M, Lam N, Walsh S, Michaelsen J, Franklin J, Stow D, Johannsen C, and Johnston C 1991 Environmental Analysis Using Integrated GIS and Remotely Sensed Data: Some Research Needs and Priorities. *Photogrammetric Engineering & Remote Sensing* 57: 689-697
- Egenhofer M, and Frank A 1992 Object-Oriented Modeling for GIS. *Journal of the Urban and Regional Information Systems Association* 4: 3-19
- Egenhofer M, and Mark D 1995 Naive Geography. in: Frank A and Kuhn W, (Eds.) *Spatial Information Theory—A Theoretical Basis for GIS*, International Conference COSIT '95. *Lecture Notes in Computer Science* 988, pp. 1-15, Springer-Verlag, Berlin
- Ehlers M, Edwards G, and Bedard Y 1989 Integration of Remote Sensing with Geographic Information Systems: A Necessary Evolution. *Photogrammetric Engineering & Remote Sensing* 55: 1619-1627
- Ehlers M, Greenlee D, Smith T, and Star J 1991 Integration of Remote Sensing and GIS: Data and Data Access. *Photogrammetric Engineering & Remote Sensing* 57: 669-675
- Elmagarmid A, and Pu C 1990 Guest Editors' Introduction to the Special Issue on Heterogeneous Databases. *ACM Computing Surveys* 22: 175-178
- Farquhar A, Fikes R, and Rice J 1996 *The Ontolingua Server: A Tool for Collaborative Ontology Construction*. Knowledge Systems Laboratory, Stanford University, Stanford, CA, Technical Report KSL 96-26
- Fonseca F, and Davis C 1999 Using the Internet to Access Geographic Information: An OpenGis Prototype. in: Goodchild M, Egenhofer M, Fegeas R, and Kottman C, (Eds.) *Interoperating Geographic Information Systems*. pp. 313-324, Kluwer Academic Publishers, Norwell, MA
- Fonseca F, and Egenhofer M 1999 Ontology-Driven Geographic Information Systems. in: Medeiros C B, (Ed.) *7th ACM Symposium on Advances in Geographic Information Systems*, Kansas City, MO, pp. 14-19
- Fonseca F, Egenhofer M, and Davis C 2000 Ontology-Driven Information Integration. in: Bettini C and Montanari A, (Eds.) *The AAAI—2000 Workshop on Spatial and Temporal Granularity*, Austin, TX, pp. 61-64
- Frank A 1997 Spatial Ontology. in: Stock O, (Ed.) *Spatial and Temporal Reasoning*. pp. 135-153, Kluwer Academic Publishers, Dordrecht, The Netherlands
- Frank A 1998 Different Types of 'times'. in: Egenhofer M and Golledge R, (Eds.) *Spatial and Temporal Reasoning in Geographic Information Systems*. pp. 40-62, Oxford University Press, New York
- Gahegan M 1996 Specifying the Transformations Within and Between Geographic Data Models. *Transactions in GIS* 1: 137-152
- Gahegan M, and Flack J 1996 A Model to Support the Integration of Image Understanding Techniques within a GIS. *Photogrammetric Engineering & Remote Sensing* 62: 483-490
- Gahegan M, and Flack J 1999 The Integration of Scene Understanding within a Geographic Information System: A Prototype Approach for Agricultural Applications. *Transactions in GIS* 3: 31-49
- Gomes J, and Velho L 1995 Abstraction Paradigms for Computer Graphics. *The Visual Computer* 11: 227-239
- Goodchild M 1992 Geographical Data Modeling. *Computers and Geosciences* 18: 401-408
- Goodchild M, Egenhofer M, Kemp K, Mark D, and Sheppard E 1999 Introduction to the Varenius Project. *International Journal of Geographical Information Science* 13: 731-745

- Gore A 1998 The Digital Earth: Understanding our Planet in the 21st Century, <http://www.digitalearth.gov/VP19980131.html>
- Gregorio A D, and Jansen L J M 1998 *Land Cover Classification System: Classification Concepts and User Manual*, Food and Agriculture Organization of the United Nations, <http://www.fao.org/WAICENT/FAOINFO/SUSTDEV/EIdirect/EIre0062.htm>
- Gruber T 1991 The Role of Common Ontology in Achieving Sharable, Reusable Knowledge Bases. in: *Principles of Knowledge Representation and Reasoning*, Cambridge, MA, pp. 601-602
- Gruber T 1992 *A Translation Approach to Portable Ontology Specifications*. Knowledge Systems Laboratory, Stanford University, Stanford, CA, Technical Report KSL 92-71
- Gruen A, Kuebler O, and Agouris P, (Eds.) 1995 *Automatic Extraction of Man-Made Objects from Aerial and Space Images*. I. Birkhäuser Verlag, Basel
- Gruen A, Kuebler O, and Henricsson O, (Eds.) 1997 *Automatic Extraction of Man-Made Objects from Aerial and Space Images*. II. Birkhäuser Verlag, Basel
- Guarino N 1992 Concepts, Attributes and Arbitrary Relations. *Data and Knowledge Engineering* 8: 249-261
- Guarino N 1997 Semantic Matching: Formal Ontological Distinctions for Information Organization, Extraction, and Integration. in: Pazienza M, (Ed.) *Information Extraction: A Multidisciplinary Approach to an Emerging Information Technology, International Summer School, SCIE-97*, Frascati, Italy, pp. 139-170
- Guarino N 1998 Formal Ontology and Information Systems. in: Guarino N, (Ed.) *Formal Ontology in Information Systems*. pp. 3-15, IOS Press, Amsterdam, Netherlands
- Guarino N, and Welty C 2000 Ontological Analysis of Taxonomic Relationships. in: Laender A and Storey V, (Eds.) *Proceedings of ER-2000: The 19th International Conference on Conceptual Modeling. Lecture Notes in Computer Science* 1920, pp. 210-224,
- Hinton J 1996 GIS and Remote Sensing Integration for Environmental Applications. *International Journal of Geographical information Systems* 10: 877-890
- Jensen J, and Cowen D 1999 Remote Sensing of Urban/Suburban Infrastructure and Socio-Economic Attributes. *Photogrammetric Engineering & Remote Sensing* 65: 611-622
- Kashyap V, and Sheth A 1996 Semantic Heterogeneity in Global Information System: The Role of Metadata, Context and Ontologies. in: Papazoglou M and Schlageter G, (Eds.) *Cooperative Information Systems: Current Trends and Directions*. pp. 139-178, Academic Press, London
- Kemp K, and Vekovski A 1998 Towards an Ontology of Fields. in: *Third International Conference on GeoComputation*, Bristol, UK
- Kuhn W 1991 Are Displays Maps or Views? in: Mark D and White D, (Eds.) *AUTO-CARTO 10, Tenth International Symposium on Computer-Assisted Cartography*, Baltimore, MD, pp. 261-274
- Kuhn W 1993 Metaphors Create Theories for Users. in: Frank A and Campari I, (Eds.) *Spatial Information Theory. Lectures Notes in Computer Science* 716, pp. 366-376, Springer-Verlag, Berlin
- Lillesand T, and Kiefer R 2000 *Remote Sensing and Image Interpretation*. John Wiley & Sons, New York
- Longley P, Goodchild M, Maguire D, and Rhind D, (Eds.) 1999 *Geographical Information Systems*. John Wiley & Sons, New York

- Mark D 1993 Toward a Theoretical Framework for Geographic Entity Types. in: Frank A and Campari I, (Eds.) *Spatial Information Theory. Lectures Notes in Computer Science* 716, pp. 270-283, Springer-Verlag, Berlin
- Matsuyama T, and Hwang V S 1990 *A Knowledge-based Aerial Image Understanding System*. Plenum Press, New York
- McKee L, and Buehler K, (Eds.) 1996 *The Open GIS Guide*. Open GIS Consortium, Inc, Wayland, MA
- McKeown D M, Harvey W A, and McDermott J 1985 Rule Based Interpretation of Aerial Imagery. *IEEE Transactions on Pattern Analysis and Machine Intelligence-PAMI* 7: 570-585
- Miller G A 1995 WordNet: A Lexical Database for English. *Communications of the ACM* 38: 39-41
- Niemann H, Sagerer G, Schroder S, and Kummert F 1990 ERNEST: A Semantic Network System for Pattern Understanding. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 12: 883-905
- Nunes J 1991 Geographic Space as a Set of Concrete Geographical Entities. in: Mark D and Frank A, (Eds.) *Cognitive and Linguistic Aspects of Geographic Space*. pp. 9-33, Kluwer Academic Publishers, Norwell, MA
- OpenGIS 1996 *The OpenGIS® Guide-Introduction to Interoperable Geoprocessing and the OpenGIS Specification*. Open GIS Consortium, Inc, Wayland, MA
- Pentland A 1986 From Pixels to Predicates. in: Pentland A, (Ed.) *From Pixels to Predicates*. Ablex Publishing Corporation, Norwood, NJ
- Pissinou N, Makki K, and Park E 1993 Towards the Design and Development of a New Architecture for Geographic Information Systems. in: Bhargava B K, Finin T W, and Yesha Y, (Eds.) *Second International Conference on Information and Knowledge Management*, Washington, DC, pp. 565-573
- Poulter M 1996 On the Integration of Earth Observation Data: Defining Landscape Boundaries to a GIS. in: Burrough P and Frank A, (Eds.) *Geographic Objects with Indeterminate Boundaries*. pp. 287-298, Taylor & Francis, London
- Quint F 1997 MOSES: A Structural Approach to Aerial Image Understanding. in: Gruen A, Baltasvias E P, and Birkhäuser O H, (Eds.) *Automatic Extraction of Man-Made Objects from Aerial and Space Images*, Ascona, Switzerland
- Roberts S, and Gahegan M 1993 An Object-Oriented Geographic Information System Shell. *Information and Software Technology* 35: 561-572
- Roberts S, Gahegan M, Hogg J, and Hoyle B 1991 Application of Object-Oriented Databases to Geographic Information Systems. *Information and Software Technology* 33: 38-46
- Rodríguez A 2000 *Assessing Semantic Similarity among Spatial Entity Classes*. Ph.D. Thesis, University of Maine, Orono, ME
- Salgé F 1999 National and International Data Standards. in: Longley P, Goodchild M, Maguire D, and Rhind D, (Eds.) *Geographical Information Systems 1 Principles and Technical Issues*. pp. 693-706, John Wiley & Sons, New York
- Sheth A 1999 Changing Focus on Interoperability in Information Systems: from System, Syntax, structure to Semantics. in: Goodchild M, Egenhofer M, Fegeas R, and Kottman C, (Eds.) *Interoperating Geographic Information Systems*. pp. 5-29, Kluwer Academic Publishers, Norwell, MA

- Smith B 1995 On Drawing Lines on a Map. in: Frank A and Kuhn W, (Eds.) *Spatial Information Theory—A Theoretical Basis for GIS*, International Conference COSIT '95. Lecture Notes in Computer Science 988, pp. 475-484, Springer Verlag, Berlin
- Smith B 1998 An Introduction to Ontology. in: Peuquet D, Smith B, and Brogaard B, (Eds.) *The Ontology of Fields*. pp. 10-14, National Center for Geographic Information and Analysis, Santa Barbara, CA
- Smith B, and Mark D 1998 Ontology and Geographic Kinds. in: *International Symposium on Spatial Data Handling*, Vancouver, Canada, pp. 308-320
- Sondheim M, Gardels K, and Buehler K 1999 GIS Interoperability. in: Longley P, Goodchild M, Maguire D, and Rhind D, (Eds.) *Geographical Information Systems 1 Principles and Technical Issues*. John Wiley & Sons, New York
- Tempero E, and Biddle R 1998 *Simulating Multiple Inheritance in Java*. Victoria University of Wellington, School of Mathematical and Computing Sciences, Wellington, New Zealand, Technical Report CS-TR-98/1
- Tonjes R, and Liedtke C-E 1998 Knowledge-based Interpretation of Aerial Images Using Multiple Sensors. in: *EUSIPCO-98 IX European Signal Processing Conference*, Island of Rhodes, Greece
- USGS 1998 View of the Spatial Data Transfer Standard (SDTS) Document, <http://mcmcweb.er.usgs.gov/sdts/standard.html>
- Worboys M F 1995 *GIS—A Computing Perspective*. Taylor & Francis, London