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Bridging Ontologies and Conceptual Schemas in Geographic Information Integration

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Abstract

Integration of geographic information has increased in importance because of new possibilities arising from the interconnected world and the increasing availability of geographic information. Ontologies support the creation of conceptual models and help with information integration. In this paper, we propose a way to link the formal representation of semantics (i.e., ontologies) to conceptual schemas describing information stored in databases. The main result is a formal framework that explains a mapping between a spatial ontology and a geographic conceptual schema. The mapping of ontologies to conceptual schemas is made using three different levels of abstraction: formal, domain, and application levels. At the formal level, highly abstract concepts are used to express the schema and the ontologies. At the domain level, the schema is regarded as an instance of a generic data model. At the application level, we focus on the particular case of geographic applications. We also discuss the influence of ontologies in both the traditional and geographic systems development methodologies, with an emphasis on the conceptual design phase.

Keywords: ontologies, geographic conceptual models, geographic data modeling, geographic information systems

1. Introduction

Ontologies are on the path that leads from the observation of the world to the creation of databases and the development of information systems. In the traditional systems modeling approach, the modeler is required to capture a user's view of the real world in a formal conceptual model. In doing so, the modeler follows an established paradigm, such as object-orientation or entity-relational, that is chosen in terms of the available programming environment. Such an approach forces the modeler to mentally map concepts acquired from the real world to instances of abstractions available in his paradigm of choice. This mapping is done informally and in an ad-hoc fashion, thereby introducing inconsistencies and inaccuracies that inevitably lead to conflicts between the user's concepts and the abstractions captured by the conceptual model. The basic reason for these conflicts is the lack of an initial agreement between user and modeler on the concepts of the real world. Such an agreement could be established by means of an ontology, which is a shared conceptualization of an application domain. If the ontology, based on the user's view of the world, is previously generated and formalized so that it can be used in the development process, such conflicts would be less likely to happen. On the other hand, the consolidation of concepts and knowledge represented by a conceptual schema can be useful in the initial steps of ontology construction.

This paper intends to demonstrate how mappings between ontologies conceptual schemas can be created. The possible connections between a conceptual schema and an ontology are explored, including a formal description of the mappings. The implementation of such mappings in a broader scale can accelerate the development of ontologies, since conceptual schemas are widely available as documentation components for current information systems. They can also shorten the applications development cycle by providing, from the ontology, a more precise set of concepts, from which the conceptual schema can be more accurately designed.

From the concepts presented in this paper, a software tool that will bring automation to the important area of semantic information integration can be developed. Automatic connection between concepts in an ontology and primitives in a conceptual schema will also allow the user to access information stored in databases using high-level concepts [1], [2]. Guarino [3] suggests that common conceptual schemas in data warehousing applications can be created to map heterogeneous conceptual schemas to a common top-level ontology. Hakimpour and Geppert [4] and Hakimpour and Timpf [5] use ontology integration to enhance the results of schema integration. Their reasoning system uses what it has learned in the ontology integration process to derive global schemas from local schemas. Therefore, while that approach keeps the ontologies and the schemas at different levels, we propose in this paper a direct mapping from map ontologies directly onto schemas.

But what are the specifics of the geographic world that influence the mapping of ontologies to conceptual schemas? ''What is special about spatial?'' [6], [7]. To adequately represent the geographic world, we must have computer representations capable of not only capturing descriptive attributes about its concepts, but also capable of describing the geometrical and positional components of these concepts. These representations also need to capture the spatial and temporal relationships between instances of these concepts. For example, in order to represent a public transportation system, the application ontology must contain concepts such as street, neighborhood, bus stop, and timetable. The computer representation of the transportation system has to recognize relationships such as ''this bus line crosses these neighborhoods'', ''there is a bus stop near the corner of these streets'' and ''the bus stops at this location at 1:00 pm''. Unlike the case of conventional information systems, most of these spatial and temporal relationships are not explicitly represented in a GIS, and can often be deduced using geographic functions. Therefore, there must be additional semantics in the geographic application's conceptual schema, semantic details that are part of the application's ontology and have been captured by the modeler. This paper sets out to identify and to use such concepts that are embedded in the primitives that comprise a conceptual data model for geographic applications, and to use such concepts, along with application-specific characteristics, to achieve a mapping between ontologies and conceptual schemas.

This paper is organized as follows. In Section 2 we discuss the differences between ontologies and conceptual schemas. Section 3 reviews a basic set of concepts about ontologies and conceptual data modeling, with a particular focus on geographic applications. Section 4 explores the role that ontologies can play in a methodology for the development of geographic information systems. In Section 5 we suggest mapping ontologies to conceptual schemas using three different levels of abstraction: the formal, domain, and application levels. We also introduce a formalization of the mapping. Finally, Section 6 presents our conclusions and indicates directions for future work.

2. Ontologies and conceptual schemas

The literature shows many proposals for the integration of information, ranging from federated databases with schema integration [8] and the use of object orientation [9], [10], to mediators [11] and ontologies [3], [12]. Research on integration of databases can be traced back to the mid 1980s [13], and today it is widespread among the GIS community [14]–[21]. The new generation of information systems should be able to handle semantic heterogeneity by making use of the amount of information available with the arrival of the Internet and distributed computing [22]. The semantics of information integration is getting more attention from the research community [15], [17]–[19], [21]–[25]. 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 can capture the semantics of information, can be represented in a formal language, and can also be used to store the related metadata, thus enabling a semantic approach to information integration.

There are ontology integration approaches that create mappings between ontologies. Wiederhold and Jannink [26] allow composition of preexisting, independently developed ontologies using a context algebra. OBSERVER [19], [20], [27] is an architecture for query processing in global information systems that supports interoperation across ontologies. It focuses on information content and semantics, and employs a loosely-coupled approach to match different vocabularies used to describe similar information across domains.

The complexity and richness of geographic information and the difficulty of its modeling raise specific issues for GIS interoperability, such as the integration of different models of geographic entities (i.e., objects and fields) and different computer representation of these entities (i.e., raster and vector). In the past few years, since ontologies have gained the attention of the GIS research community [28]–[38], many researchers have asked themselves whether ontologies were actually the well-known conceptual data modeling techniques in disguise [39]. Guarino [3] advises against using ontology as just a fancy name denoting the result of activities like conceptual analysis and domain modeling. Fikes and Farquhar [40] consider that ontologies can be used as building block components of conceptual schemas. We agree with Cui et al. [41] in that there is a main difference between an ontology and a conceptual schema: they are built with different purposes. While an ontology describes a specific domain, a conceptual schema is created to describe the contents of a database. Bishr and Kuhn [42] consider that an ontology is external to information systems and is a specification of possible worlds, while a conceptual schema is internal to information systems and is chosen as the specification of one possible world.

Ontologies are semantically richer than database conceptual schemas, and thus closer to the user's cognitive model. Conceptual schemas are built to organize what is going to be stored in a database, and then are used to document it. An ontology represents concepts in the real world. For instance, a reservoir 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. For instance, a reservoir is a reservoir, regardless of whether it is represented, for the purposes of an information system, by an aerial photograph, a polygon, or a digital terrain model. A conceptual schema that intends to capture all the peculiarities of geographic data should specify differently each of the three representations.

We must also point out that the database community establishes a clear distinction between a conceptual data model and a conceptual schema. The former refers to the technique that is used to model any database, including its notation: Entity-relationship (ER) [43], object modeling technique (OMT) [44], and unified modeling language (UML) [45] are examples of conceptual data models. Conceptual schemas, on the other hand, refer to the result of the modeling, namely a set of diagrams that use a given data model as a language to express the specific data structures for an application that is going to be developed.

In practice, conceptual schemas are limited by the representations available on current computer technology. Additionally, a conceptual schema for spatial applications depends on the implicit assumption that its components are measurable. Therefore, conceptual schemas assign, for each of their components, one or more suitable computer representations. In this view, a conceptual schema requires a commitment to a set of computer representations, whereas an ontology does not require such a commitment.

This debate on the differences between ontologies and conceptual schemas was partially motivated by the lack of practice in the use of ontologies for real-world problem solving, along with the scarcity of consistent ontologies. In fact, the theory on the use of ontologies is being developed with the broader intention of providing a basis for knowledge consolidation and exchange, a goal that is far beyond the capabilities of current data modeling tools and techniques. Nevertheless, conceptual schemas certainly correspond to a level of knowledge formalization, in spite of leaving out of the schema a number of concepts and ideas over which the data modeler and the user have agreed upon, and which constitute background knowledge about the entire information systems development process.

In the conventional conceptual modeling activity, ontologies are either bypassed or lack a formal specification [33], but information on the data structures, classes, and domains that compose the conceptual schema can be adapted to fill in the classes of the ontologies. Sowa [46] considers that the same is true for a programmer trying to solve a problem. He or she has the knowledge to implement a solution, but the way of encoding this knowledge can vary from each individual to another. Both the programmer and the modeler have their own ontologies, and they can be either implicit or explicit. Guarino [3] coined the term ontology-driven information systems for systems that make use of formally defined ontologies. Fonseca [47] addressed the use of ontologies in the development of geographic information systems and proposed ways to integrate geographic information using ontologies.

3. From geographic facts in the real world to representations in a geographic database

The development of ontologies of the geographic world (geo-ontologies) is important to allow the sharing of geographic data among different communities of users. Nevertheless, before we share digital data it is necessary to collect and organize it. Conceptual schemas are built in order to abstract specific parts of the real world and to represent schematically what data should be collected and how it must be organized. In the next sections we review the most recent work on geo-ontologies and geographic data models, in order to gain insight on how the distance between ontologies and conceptual schemas can be shortened.

3.1. Geographic space

Spatial databases intend to be a representation of geographical space. But what exactly is geographic space composed of? The most widely accepted conceptual model for geographic information science considers that geographic reality is represented as either fully definable entities (objects) or smooth, continuous spatial variation (fields). The object model represents the world as a surface occupied by discrete, identifiable entities, with a geometrical representation and descriptive attributes. The field model views the geographical reality as a set of spatial distributions over the geographical space. As some authors have already pointed out [48], the field and object model have an underlying common notion, which is the implicit reliance on Cartesian (or absolute) space as an a priori frame of reference for locating spatial phenomena. In this view, Cartesian space is simply a neutral container within which all physical processes occur. The primitive notion on a Cartesian space is the idea of georeferenced location. Each entity of space is associated to one or more locations on Earth, and spatial relations are derived from the location. The alternative to absolute space is to consider a relative notion of space [49], constituted through the spatial relations arising among geographic entities. In the framework of relative space, the primitive notion is that of the spatial relation between entities. Spatial interaction models and location-allocation models used in transportation are examples of applications that use the relative notion of space.

Current GIS technology embodies an absolute view of space, since the most common geometric representations available in GIS—such as grids, TINs, planar vector maps—are all based on the notion of a georeferenced location. It is therefore not surprising that the notions of objects and fields—as defined in the current GIS literature—can be generalized into a single formal definition.

In a more formal view, geographical space is usually constrained to a region of interest. A geographical field is defined by a relation $f = (R, V, \lambda)$, where R is a geographical region, V a set of attributes and $\lambda{:}R \rightarrow V$ is a mapping between points in R and values in V (in OpenGIS [50], λ is called the coverage function). Geo-objects represent individual entities of the geographic realm. Given a set of geographical regions $R_1, \ldots, R_n$ and a set of attributes $A_1, \ldots, A_n$ with domains $D(A_1), \ldots, D(A_n)$, a geographical object is defined by a relation $(a_1, \ldots, a_n, S_1, \ldots, S_m)$, where a_i are its descriptive attributes $(a_i \in D(A_i))$ and S_i its geographical locations $(S_i \subseteq R_i)$.

3.2. Geo-ontologies

Nunes [51] 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 playing a software specification role was suggested by Gruber [52]. Wiederhold suggested the use of ontologies as the common point among diverse user communities [12]. 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 [29]. Frank [33] believes that the use of ontologies will contribute to better information systems by avoiding problems such as inconsistencies between ontologies implicitly embedded 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. Harvey [17] warns about the importance of bringing fundamental semantic concerns early into the design process. Bittner and Winter [36] identify the role of ontologies in modeling spatial uncertainty with the one often associated with object extraction processes. Kuhn [53] asks for spatial information theories that look toward GIS users instead of focusing on implementation issues. Another semantic approach to integrate geographic information is GeoCosm [54], a web-based prototype to integrate autonomous distributed heterogeneous geospatial data. They employ a canonical model that integrates diverse conceptual schemas. An ontology is used to help in solving conflicts among information sources.

Fonseca [47] proposed a framework for the development of geographic applications using ontologies. The framework uses ontologies as the foundation for the integration of geographic information. By integrating ontologies that are linked to sources of geographic information, Fonseca created a mechanism that allows geographic information to be integrated based primarily on its meaning. Since the integration may occur across different levels, he also created the basic mechanisms for changing the level of detail. The use of an ontology, translated into an information system component, is the basis of ontology-driven geographic information systems (ODGIS).

Ontologies are classified according to their dependence on a specific task or point of view [55]:

- 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 [56], is at this level.
- Domain ontologies describe the vocabulary related to a generic domain, such as 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. They represent the user needs regarding a specific application, such as making an assessment of lobster abundance in the Gulf of Maine using satellite images or issuing a permit for a noise-generating urban activity.

3.3. Conceptual data models for geographic information

The first data models developed for geographic applications were guided by existing GIS internal structures, forcing the user to adjust his/her interpretation of geographic phenomena to whatever structures were available. As a consequence, the modeling process did not offer mechanisms that would allow for the representation of the reality according to the user's mental model. Even well-known semantic and object-oriented data models such as the ER model [43], the OMT [44], and the IFO model [57] do not offer adequate facilities to represent geographic applications. Even though these models are highly expressive, they present limitations to the adequate modeling of such applications, because they do not include geographic primitives that would allow for a satisfactory representation of geographic data.

The difficulties in using such models in geographic applications are countless. Many geographic applications need to deal with details such as location constraints, time of observation, and accuracy [58]. Furthermore, in conventional models it is impossible to distinguish between object classes that have a geographic reference and purely alphanumeric classes. It is also difficult to represent the geometric nature of objects and the spatial relations between them. Spatial relations are abstractions that help us to understand how, in the real world, objects relate to each other [59]. Many spatial relations need to be explicitly represented in the application's schema in order to make it more understandable. Topologic relations are fundamentally important to the definition of spatial integrity rules [60], which in turn determine the geometric behavior of objects.

There are particular characteristics of geographic data that make modeling more complex than in the case of conventional applications. Modeling the spatial aspects is fundamentally important in the creation of a geographic database, mainly because it deals with an abstraction of geographic reality where the user's view of the real world varies, depending on what he needs to represent and what he expects to gain from this representation. It can be perceived that modeling geographic data requires models that are more specific and capable of capturing the semantics of geographic data offering higher abstraction mechanisms and implementation independence. Within this geographic context, concepts such as geometry and topology are important in the determination of spatial relationships between objects. These concepts are also decisive in the data entry process and in spatial analysis.

4. The role of ontologies in a methodology for systems development

The traditional approach to information systems development starts with a conceptual design phase in which, by eliminating unwanted detail and focusing on essential information about real-world objects, a conceptual schema is produced for the database. A logical design phase follows, in which the high-level conceptual schema is transformed into an internal or implementation schema, which considers the tools and functions supported by the database management system (DBMS) that is going to be used to actually store the data [61]. Finally, a physical design phase specifies the needs of the system in terms of data structures, ensuring that all concepts that have been incorporated to the conceptual schema are adequately represented and managed. Conceptual schemas are, therefore, developed to be independent from the underlying DBMS, while physical schemas are strongly coupled to the DBMS. These phases of the traditional information systems design are illustrated in figure 1.

In the case of geographic applications, there are some basic differences. First, during a conceptual modeling phase, the developer must also decide whether each concept of the

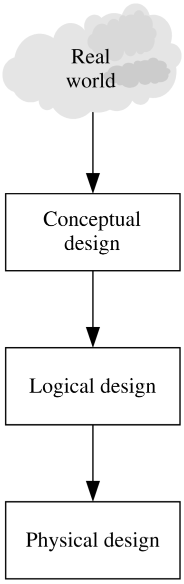


Figure 1. Information systems development methodology.

real world will be represented as either individual and fully definable entities (objects) or smooth, continuous spatially varying phenomena (fields), following the objects and fields view mentioned earlier. Then, he/she will decide which geometrical representations will be used to capture each concept, thus operating in a representation definition phase. It should be noted that the same concept can be associated to different geometrical representations; for instance, a terrain can be represented by a TIN, a regular grid, or a set of isolines, and a river can be either represented as a line, or as a polygon covering the space between its banks. However, the conceptual and the representation levels must actually be combined in the design, since usually the modeler defines the representation alternatives right after the decision on objects/fields is taken, because this decision is required before the modeling can proceed with the specification of spatial relationships. Therefore, this modeling stage is called the conceptual representation level [60].

At the conceptual representation level, any useful transformations between representations can be specified, in order to avoid redundancy. Imagine, following the previous example, that data on the terrain are primarily collected as a TIN; however, the application also needs the terrain to be represented as a set of isolines. The isolines can be derived, through the use of some interpolation algorithm, from the TIN, and this operation can also be specified at the representation level. Notice that the concepts about the terrain or its basic geographic location characteristics do not change throughout the process of selecting a representation alternative or when transformations between representations are performed.

Later on, presentation alternatives must be defined for each representation [62]. Since these presentations are fundamentally dependent on the type of representation that has been chosen, but they can still be designed to be independent from the underlying GIS, this design phase takes place in a separate level, called the presentation level. In this level, concerns about the readability or the ease of visual interpretation of the data on a given presentation medium (screen, paper) are addressed by defining graphic parameters, such as symbol shape, color, line type, or polygon fill texture.

With the representations and presentations already designed, the process moves along to an implementation level, in which spatial data structures used to store data are decided, using the tools and languages available in the GIS or in a spatially enabled DBMS. Since geographic applications generally require some basic information, such as a base map, to be of any use, there can also be the need for a data conversion stage. The overall process is illustrated in figure 2.

Both in the case of traditional and geographic applications, development efforts rely on the efficiency of the transmission of the specialist's ideas, needs, and concepts to the implementation team, as required in the conceptual modeling phase, to a data modeler or to a group of information systems experts which are in charge of the development process. Any inaccuracy or imprecision while capturing these concepts and ideas, specially in the case of the choice of a geographic representation alternative, can generate dire consequences to the final product, forcing the existence of a continuous improvement cycle between design, implementation, and testing. An inadequate selection of a representation alternative can even upset geographic data collection or conversion efforts, with potentially large economic consequences for the project.

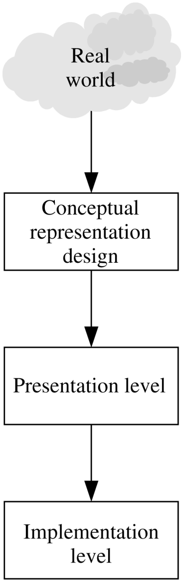


Figure 2. Geographic information systems development methodology.

The inaccuracies in the capture of the required concepts about the real world must be reduced in order to improve the process. They occur basically because it is the specialist's—and not the modeler's—view of the problem that must be captured to compose the conceptual schema. But the modeler, a human being after all, in most cases

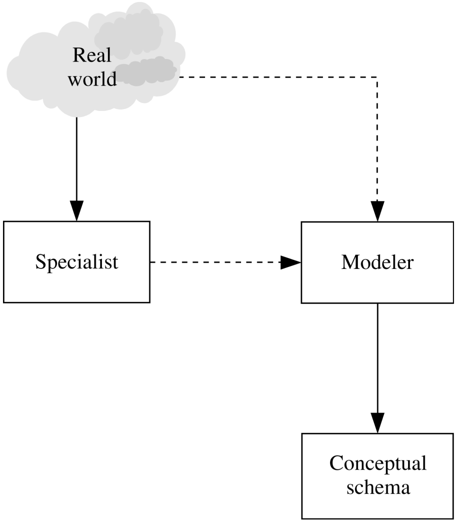


Figure 3. Traditional modeling process.

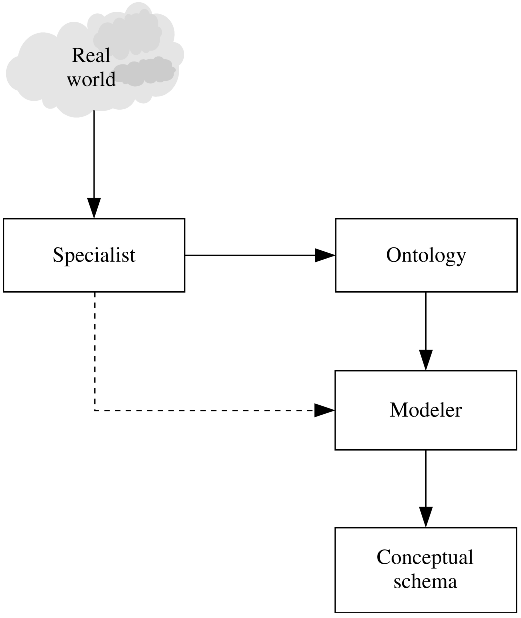


Figure 4. Ontology-driven modeling process.

cannot avoid having a personal view of the problem, a view that can be inaccurate and incomplete. This rough knowledge interferes with the modeler's perception of the specialist's view, thereby leading to confusion and wasted effort. The widespread and traditional usage of cartographic media and visual metaphors multiply this effect in the case of geographic applications development. Figure 3 illustrates this situation, showing with dashed lines the most problematic paths for the acquisition of knowledge in the conceptual modeling process.

We argue that ontology can and should be used as a tool to formalize the concepts and ideas regarding the specialist's view of the problem. After all, the specialist is expected to hold considerable knowledge on the concepts that comprise the system's data requirements. The degree of formalization provided by ontologies can greatly improve the accuracy of the schemas that are designed by the modeler, using conceptual modeling techniques, in the applications development process. Since ontologies provide a high-level view of the problem, the modeler may need further information from the specialist in order to specify some fine details of the conceptual schema, such as cardinality and allowable attribute domains. This ontology-driven approach to conceptual modeling is illustrated in figure 4.

Going a step further, we observe that existing conceptual schemas can be useful for building ontologies, since they are formal documents that have been designed to capture the specialist's view of some aspect of the real world. Existing conceptual schemas can, therefore, be used to create rough ontologies, while existing ontologies can be used to generate conceptual schemas, with or without the aid of an expert modeler (figure 5). Specific primitives for the modeling of representation and presentation alternatives, like

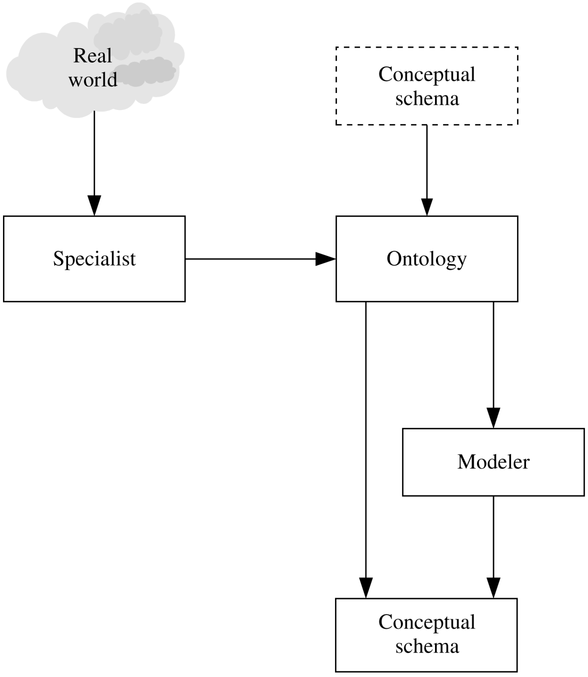


Figure 5. Ontology-based modeling process.

those that can be found in geographic application conceptual schemas when a geographic data model such as OMT-G [60] has been used, can improve the results by providing information on the spatial nature of the concepts involved in the application.

5. Mappings between ontologies and conceptual schemas

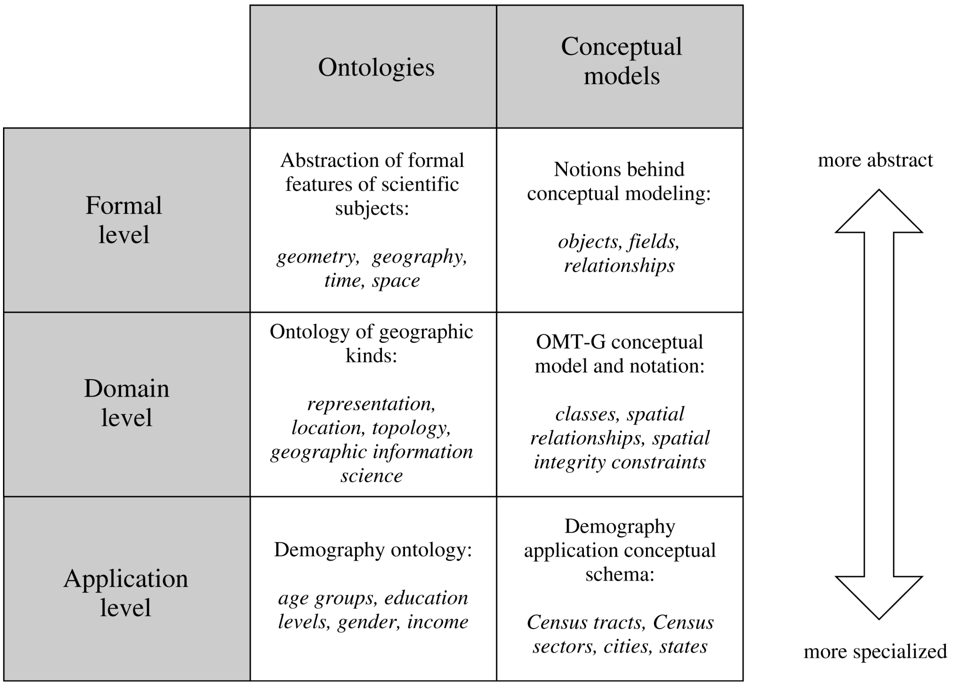
While ontologies aim at describing a set of concepts in an application domain in order to achieve a shared conceptualization, conceptual schemas are committed to formal models, which are limited by the available technology. In this view, a conceptual schema requires a commitment to a set of computer representations, whereas an ontology requires a commitment to a knowledge domain. To take a simple example, consider two spatial concepts of a possible spatial ontology: a lake and a land parcel. As shown by Smith and Mark [29], the first is an example of a bona fide object: its boundary is defined by a compromise in terms of the desired presentation scale. The second is an example of a fiat object, a product of established social conventions, whose existence depends on a legal contract. In terms of conceptual schema, both concepts would most likely be assigned to the same type of geometrical representation (a polygon or a set of polygons). This situation is caused by the fact that most GIS conceptual models do not support the concept of a fuzzy boundary, which would be required to distinguish between objects with exact boundaries (such as a parcel) from objects with inexact ones (such as a lake) [63].

Besides that, ontologies are inherently richer in detail than the conceptual schemas that can be associated to or derived from them, since the modeler's objective is to create the schema from the smallest possible set of concepts that are considered important for the development of the application. Any other concepts are eliminated during the abstraction and modeling processes, since they are deemed to be either irrelevant to the solution or redundant with regard to more important or more general concepts.

Considering the above discussion, it must be recognized that any mapping between an ontology and a conceptual schema requires a simplification, through selection, of the concepts involved in the problem, while the inverse mapping requires additional information which is usually not present in the conceptual schema.

5.1. Three levels

We created a diagram relating ontologies and conceptual models to three different levels of abstraction. Note that what we are interested here in conceptual schemas that is are instances of a conceptual model. We found that there are three different abstraction levels in which both ontologies and conceptual schemas dwell: the formal, domain, and application levels (figure 6). We observe that conceptual schemas use concepts from ontologies at each of the three levels.



	Ontologies	Conceptual models
Formal level	Abstraction of formal features of scientific subjects: *geometry, geography, time, space*	Notions behind conceptual modeling: *objects, fields, relationships*
Domain level	Ontology of geographic kinds: *representation, location, topology, geographic information science*	OMT-G conceptual model and notation: *classes, spatial relationships, spatial integrity constraints*
Application level	Demography ontology: *age groups, education levels, gender, income*	Demography application conceptual schema: *Census tracts, Census sectors, cities, states*

Figure 6. Ontologies and conceptual models in formal, domain, and application abstraction levels.

The first level is the formal level, in which the more abstract concepts involved in the construction of ontologies and of conceptual schemas. In the case of ontologies, at this level we have abstractions of the formal features of standard scientific subjects [30], such as the notions of time and space. In the case of conceptual schemas, at this level we find the basic ideas behind conceptual data models, i.e., notions that are widely employed in conceptual data modeling, such as objects, fields, and relationships.

When we specialize the contents of the formal level towards the geographic applications, we compose the second level of abstraction, or the domain level. At this level, ontologies describe a vocabulary that is used to represent the reality of a specific knowledge domain, such as geography and geographic information. An ontology of geographic kinds [29] that describes the geographic space, the geographic objects, and the phenomena of the geographic space, is at this level. When a similar move towards less abstraction is made while working with conceptual models, we notice that we also need, like in the case of the ontologies, a vocabulary with which to express the abstract notions from the formal level. Conceptual data models, such as OMT-G, fulfill this need by defining a graphical notation, based on primitive concepts. These primitives correspond to semantic content from the formal level: a rectangle means an object or a field, a dashed line means a spatial relationship, a triangle denotes specialization, and so on. Therefore, the primitives that compose a conceptual data model are used as a form of language, which is then employed to specify the data that are required by a specific application, at the next abstraction level.

At the application level, ontologies are more specific, resulting from specializations from the domain level, and should be formed by concepts that are within the field (or fields) of knowledge required by the application. At this level, an ontology is what Smith [30] calls an E-ontology, a theory about how a community of users conceptualizes a given domain, a set of concepts that they must share in order to adequately interact in that domain. In the example in figure 6, the field is demography, and the concepts involve the usual notions on population groups, such as household, average age, and average income. In conceptual data modeling, at the application level the primitives from a conceptual model are combined to form readable diagrams, from which details on the needs of the application regarding data organization can be surmized. More specifically, we use primitives from the OMT-G data model to specify an application's conceptual schema, thus moving from the domain to the application level.

Notice again that the final product of conceptual data modeling, which is the conceptual schema, brings along a number of concepts from the previous levels embedded in itself, in its graphical ''language''. In the usual modeling process, the user is invited to become familiar with this language, in order to be able to verify the validity of the schema by reading and understanding it. Likewise, if we want to automatically extract an ontology from the schema, we need to formalize the translation of the model's notation into ontological concepts, and then use these concepts as a foundation to the retrieval of application-specific notions and definitions. In a sense, this is equivalent to teaching a computer program how to read and understand conceptual schemas, by providing a generic frame of reference, in the form of a set of ontological concepts from the formal and domain levels.

In this paper, we focus on the application level, in which we can work on the translation of a conceptual schema to an application ontology. In order to do that, we need to work with concepts from the previous levels, in which conceptual modeling notions and schema primitives are defined, since such concepts are implicit in the primitives, but must be made explicit for the creation of an ontology from the schema. This is addressed in the next section.

5.2. A mapping between an OMT-G schema and an ontology

In the specific case of a geographic domain, formal concepts are usually related to geometric concepts. Therefore, the first step in the path from conceptual schemas to ontologies is to create a formal ontology, by making the semantics embedded in the geographic data model's primitives explicit. Formal ontology studies the concepts that belong to the different scientific domains, in particular the wide array of mathematical concepts that support much of the work in computer science and its related fields [30], and therefore can be used to systematize the logical relations and geometric definitions usually found in geographic data models.

In the formal ontology, a number of concepts related to geometric representation, spatial relationships, and network relationships can be expressed and interrelated. Such concepts are shared by any geographic application, since they involve the usual alternatives for the representation of the spatial component of data and its basic characteristics, together with the usual kinds of relationships, such as spatial relationships and network relationships.

In OMT-G, just like in any other geographic data model, primitives used in the schemas correspond to a set of concepts, which are implicit in each schema but are formalized in the data model's definition. These concepts can be studied in three groups: classes, relationships, and spatial integrity constraints [60].

From the definition of OMT-G classes, information on the geometric representation alternative chosen by the designer can be obtained. Regarding geometric representation, OMT-G includes alternatives for representing point, line, polygon, network node, network arc, samples, tessellation, triangulation, isolines, and planar subdivision. By comparing with other existing geographic data models [60], it has been demonstrated that only 3-D representations other than surfaces are missing from that list, but current commercial GIS products also lack that kind of capability.

In the case of spatial relationships, it has been demonstrated for vector representations of points, lines and polygons that under certain topological constraints all possible 2-D types are reducible to a set of only five precisely defined basic relations (disjoint, in, touch, cover, overlap) [64]. Other types of spatial relations can be used in OMT-G, but the model requires that they must be accompanied by a precise definition based on a combination of the five basic spatial relation types, possibly employing well-known set operators, such as union, intersection, and difference.

Network relationships are also very well defined, provided they are based in the traditional node-arc construct. In this kind of relationship, a node can be connected to any number of arcs, but arcs can only be connected to two nodes. Arcs can also be bidirectional or unidirectional, thus being able to indicate the direction of the flow, if required by the application.

Other kinds of relationships commonly found in object-oriented conceptual schemas, such as generalization, specialization, and aggregation [44], can be mapped to semantic relationships in an ontology. Respectively, these concepts are related to the notions of hypernymy, hyponymy, and mereonymy as applied to ontologies. Hyponymy and hypernymy are semantic relations defined between words and word senses. Hyponymy (sub-name) and its inverse, hypernymy (super-name), are transitive relations between sets of synonyms [25], [27], [65].

5.3. *A formal framework for ontologies*

The preceding discussion leads to a set of definitions that can be used as a basis for algebraic formulation of the mapping between a spatial ontology and geographic conceptual schema.

Definition 1: A term is a triple $\tau = [\eta, \delta, A]$, $\tau \in T$, where η is a string of characters containing the name of the term, δ is a string of characters containing its definition and A is a set of attribute domains A_1, $A_2, \ldots,$ A_n, each associated to a value set V_i.

Definition 2: A relation $\phi : T \rightarrow T, \phi \in \Phi$ is a function from T to T such that for every term $\tau_1 \in T$, there is a term $\tau_2 = \phi(\tau_1), \tau_2 \in T$.

Definition 3: A semantic relation σ between two terms is a relation that belongs to the set of semantic relations $\Sigma = \{$`Hypernymy, Hyponymy (is-a), Mereonomy (part-of), Synonymy`$\}$, $\Sigma \subset \Phi$.

Definition 4: A spatial relation ρ between two terms is a relation that belongs to the set of spatial relations $P = \{$`adjacency, spatial containment, proximity, connectedness`$\}$, $P \subset \Phi$.

Definition 5: An explanatory relation κ between two terms is a relation that belongs to the set of explanatory relations K. K is specific for each ontology and $K \subset \Phi$.

Definition 6: An ontology is a pair $\Theta = [T, \Phi]$, where $T = \{\tau_1, \tau_2, \ldots, \tau_{n.}\}$ is a set of terms, and $\Phi = \{\phi_1, \phi_2, \ldots, \phi_{n.}\}$, and $\exists \phi_i \in (\Sigma \cup K)$.

Definition 7: A spatial ontology is a pair $\Theta_s = [T_s, \Phi_s]$, where $T_s = \{\tau_{s_1}, \tau_{s_2}, \ldots, \tau_{s_n}\}$ is a set of terms, and $\Phi_s = \{\phi_{s_1}, \phi_{s_2}, \ldots, \phi_{s_n,}\}$, $\Phi_s \supseteq (\Sigma \cup K \cup P)$, and $\exists \phi_{sj} \in P$.

5.4. A formal framework for conceptual schemas

The definitions below have been composed according to the concepts that have been introduced in the definition of the OMT-G primitives [60].

Definition 8: An entity is a tuple `e = [n, A]`, where n is a string of characters indicating the name of the entity, `A` is a set of attributes, each attribute being associated to a given domain. Every entity `e` belongs to E, the set of all entities, i.e., $\texttt{e} \in E$.

Definition 9: A geospatial entity is a triple `g = [n, A, rep]`, where n is a string of characters indicating the name of the class, `A` is a set of attributes, each associated to a given domain, and `rep` is the representation alternative chosen for the class ($\texttt{rep} \in \texttt{REP}$, where $\texttt{REP} = \{$`point, line, polygon, node, unidirectional arc, bidirectional arc, isolines, samples, TIN, planar subdivision, tessellation`$\}$). Every geospatial entity belongs to G, the set of all geospatial entities, i.e., $g \in G, G \subset E$.

Definition 10: A relation $r : E \rightarrow E, r \in R$ is a function from the set of entities, E, to itself, such that for every entity $e_1 \in E$, there is an entity $e_2 = r(e_1)$ such that $e_2 \in E$. Every relation belongs to R, the set of all relations, i.e., $r \in R$.

Definition 11: A semantic relation m between two entities is a relation that belongs to the set of spatial relations $M = \{$`generalization, specialization, aggregation`$\}$, and $M \subset R$.

Definition 12: A spatial relation s between two entities is a relation that belongs to the set of spatial relations $S = \{$*`spatial relationship`*, *spatial aggregation*, *network*$\}$, and $S \subset R$.

Definition 13: An explanatory relation x between two terms is a relation that belongs to the set of spatial relations $X = \{$*`simple association`*$\}$, and $X \subset R$.

Definition 14: A conceptual schema is a pair $C = [E, R]$, and $R \supseteq (M \cup X)$.

Definition 15: A conceptual schema for geographic information is a pair $C_g = [E_g, R_g]$, where $E_g \subset E$ and $\exists e_{gi} \in G$, $R_g \subset R$, and $\exists r_{gi} \in (M \cup X)$, and $\exists r_{gj} \in S$.

5.5. A formal framework for mappings between ontologies and conceptual schemas

From the definitions in Sections 5.3 and 5.4, a mapping between ontologies and conceptual models can now be formally expressed.

Definition 16: A mapping $\psi_{\tau - e}(\tau, e)$ between a term τ in a spatial ontology Θ_s and a entity e in a conceptual schema for geographic information C_g is such that $\forall (\tau_i) \in \Theta_s, \exists (e_j) \in C_g | \psi_{\tau - e}(\tau_i, e_j) \in \Psi_{\tau - e}$.

A mapping $\psi_{\tau-e}(\tau, e)$ is defined by the mappings between the elements of a term in an ontology and the elements of an entity in a conceptual schema: $\psi_{\tau-e}(\tau, e) = \psi_1(\eta, n) + \psi_2(\delta, \varnothing) + \psi_3(A, A) + \psi_4(\varnothing, rep)$ in which $\varnothing$ represents the impossibility of mapping.

Definition 17: A mapping $\psi_{\phi-r}(\phi, r)$ between a relation in a spatial ontology Θ_s and a relation in a conceptual schema for geographic information C_g is such that $\forall \phi_i \in \Theta_s, \exists (r_j) \in C_g | \psi_{\phi-r}(\phi_i, r_j) \in \Psi_{\phi-r}$.

A mapping $\psi_{\phi-r}(\phi, r)$ is defined by the mappings between the three kinds of relations in an ontology (semantic, spatial, and explanatory) and the corresponding relations in a conceptual schema: $\psi_{\phi-r}(\phi, r) = \psi_5(\sigma, m) + \psi_6(\rho, s) + \psi_7(\kappa, x)$.

Definition 18: A mapping $\psi(\Theta_s, C_g)$ between a spatial ontology Θ_s and a conceptual schema for geographic information C_g is such that $\forall (\tau_i, \phi_i) \in \Theta_s, \exists (e_j, r_j) \in C_g | \psi_{\tau-e}(\tau_i, e_j) \in \Psi_{\tau-e} \wedge \psi_{\phi-r}(\phi_i, r_j) \in \Psi_{\phi-r} \wedge \psi_{\phi\tau-re}(\phi_i(\tau_i), r_j(e_j)) \in \Psi_{\phi\tau-re}$.

6. Conclusions

In this paper we investigated ways to map formal representations of semantics, ontologies, to computer models describing information stored in databases, conceptual schemas. We introduced a formal framework that shows the mappings between spatial ontologies and geographic conceptual schemas. Such a framework can improve the solution of interoperability issues across heterogeneous databases as suggested in Moulton et al. [1]. Another use of the framework is for information integration as the solution proposed by Guarino [3] in which a common conceptual schema in a data warehousing application can be created to map heterogeneous conceptual schemas to a common top-level ontology.

We suggested mapping ontologies to conceptual schemas using three different levels of abstraction in which both ontologies and conceptual schemas can exist: the formal, domain, and application levels. We consider that, in all the three levels, conceptual schemas use concepts from ontologies. The first level is the formal level, in which highly abstract concepts are used to express the model and the ontologies. The second level is the domain level in which the model is an instance of a generic data model. The third level is the application level in which both the ontology and the conceptual schema are very specific, resulting from specializations from the previous level. We focused on the particular case of geographic applications. Geographic data models were represented by the OMT-G model [60]. Current ontology construction techniques [66]–[69] were also considered to establish the mappings. We introduced a set of definitions to be used as a basis for the algebraic formulation of the mapping between spatial ontologies and geographic conceptual schemas.

We also discussed the role of ontologies in a methodology for systems development. The traditional system development process is often deficient in creating formal ontologies

[33]. Sowa [46] considers that programmers have different ways of encoding the knowledge to solve a problem and that many times this knowledge is never formalized. We have shown how systems can be developed with formal ontologies specified before the system implementation. We also discussed the case in which no formal ontologies are created during system development. The lack of formal ontologies leads to many problems, such as inconsistencies between the ontologies that are built into the 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 [33].

The need of semantics in order to build better information systems is a very important research subject today [70]. Ontologies can participate in every step of the way, from the modeling phase of a system [71]–[73] to user interfaces and querying [27], [74]–[76] and information integration [12], [19], [77]. The investigation carried in this paper allows the association of concepts in our mental models to the intended meaning of information stored in databases, thus enhancing our ability to better integrate geographic information.

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