UCGIS Emerging Research Theme:

Ontological Foundations for Geographic Information Science

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1. Introduction

The ontology of geospatial phenomena is a critical emerging research theme in geographic information science. Recently, the notion and concept of ontology has gained increased attention among researchers in geographic information science, and UCGIS should recognize its important contribution to a fundamental theory of geographic information science. The growth of interest in the topic of geospatial ontology is documented by such activities as:

- a very well attended session on ontology at the 2000 AAG meeting in Pittsburgh, organized by Nadine Schuurman and David Mark, chaired by Max Egenhofer, and featuring presentations by Michael Curry, Greg Elmes, Harvey Miller, Schuurman, and Mark, a methodologically-diverse set of authors
- a recent EURESCO conference on the topic of Geographical Domain and Geographical Information Systems—EuroConference on Ontology and Epistemology for Spatial Data Standards, organized by Stephan Winter in September 2000 (http://www.geoinfo.tuwien.ac.at/events/Euresco2000/gdgis.htm);
- a special issue of the *International Journal of Geographical Information Science* currently being edited;
- several sessions and papers on ontology at the first GIScience Conference in October 2000 (http://www.giscience.org); and
- several recent awards by the National Science Foundation and the National Imagery and Mapping Agency in this area.

The term ontology has been used in information systems and philosophy in a number of ways. Guarino and Giaretta (1995) have provided a useful discussion of the issues surrounding the use of the term, and we adopt their definitions without further discussion. “Ontology”, written with an upper case letter at the start, is defined as “that branch of philosophy which deals with the nature and the organisation of reality” (Guarino and Giaretta, 1995). An Ontology of the geospatial domain would deal with the totality of geospatial concepts, categories, relations, and processes—and with their interrelations at different resolutions. Spelled with a lower case initial letter, “an ontology” is defined as “a logical theory which gives an explicit, partial account of a conceptualization” (Guarino and Giaretta, 1995). Note that in the first, philosophical sense, Ontology is a mass noun that cannot be pluralized, whereas in the second sense—more common in information science—one can speak of “several ontologies.” In addition, we can distinguish the process of eliciting ontologies from different sorts of human subjects, which means using the standard psychological methods in order to establish the conceptual systems that people use in relation to given domains of objects. This latter aspect of the ontology research domain has implications especially for issues of usability.

2. Objectives

We propose as a UCGIS research priority the topic of "Ontological Foundations for Geographic Information." Under this umbrella we unify several interrelated research subfields, each of which deals with different perspectives on geospatial ontologies and their roles in geographic information science. While each of these subfields could be addressed separately[1], we believe it is important to address ontological research in a unitary, systematic fashion, embracing conceptual issues concerning what would be required to establish an exhaustive ontology of the geospatial domain, issues relating to the choice of appropriate methods for formalizing ontologies, and considerations regarding the design of ontology-driven information systems. This integrated approach is necessary, because there is a strong dependency between the methods used to specify an ontology, and the conceptual richness, robustness and tractability of the ontology itself. Likewise, information system implementations are needed as testbeds of the usefulness of every aspect of an exhaustive ontology of the geospatial domain. None of the current UCGIS research priorities provides such an integrative perspective, and therefore the topic of "Ontological Foundations for Geographic Information Science" is unique.

3. The UCGIS Approach

UCGIS will coordinate research in this area. Coordination is required because of the multiplicity of research communities involved. Work on geographic concepts, categories, relations, and processes from a theoretical perspective must be coordinated with geospatial data and software standards efforts on the one hand and with general ontology projects on the other. The formal approaches in ontology will augment the standards process.

Since, implicitly or explicitly, ontological theories and commitments underlie all forms of cognition, Ontology is an enterprise that cross-cuts all branches of science and information systems. However, in practice, it is much closer to the research issues dealt with by geographic information science under headings such as data modeling and representation. However, the project of ontology-building does not focus on the design of specific algorithms and data structures that would allow implementation and coding of geospatial information and processes. Rather it aims to find appropriate representations for geospatial phenomena to match the underlying phenomena. The ontology topic also has overlap with the conceptual or semantic aspects of the interoperability topic, and the scale topic.

Is the emerging theme a subset of one of the existing ten research priorities?

No. Ontological issues can be identified in several existing research priorities, such as Cognition of Geographic Information, Extensions to Geographic Representations, Interoperability of Geographic Information, Scale, and Uncertainty.

Is the emerging theme a superset of one of the existing ten research priorities?

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[1] This White Paper originated from two separate proposals for Emerging Themes, one on ***Geospatial Ontology*** (http://www.ucgis.org/oregon/ontology.buffalo.pdf) and one on ***Ontologies in GIS*** (http://www.ucgis.org/oregon/ontology.maine.pdf).

No. Many cognitive aspects of geographic information, such as user interface aspects, are not fundamentally ontological. Likewise, not all aspects of extensions to geographic representations relate to ontological properties.

Is the emerging theme cross-cutting of the existing ten research priorities?

Yes. While ontological issues can be identified in Cognition of Geographic Information, Extensions to Geographic Representations, Interoperability of Geographic Information, Scale, and Uncertainty, the novel focus of this research priority is on the semantics of geospatial information – or more generally still: on the relations between human minds, information systems, and the geospatial world beyond. Thus GIScience research on static and temporal models of geometries, for example, needs to be augmented with considerations about what these geometric figures stand for. None of the descriptions of the original ten UCGIS research priorities (http://www.ncgia.ucsb.edu/other/ucgis/CAGIS.html) includes the term ontology.

Is the emerging theme completely separate from existing ten research priorities?

No.

4. Importance of the Emerging Theme to National Research Needs/Benefits

It is widely recognized that semantics of geospatial information is critical for the development of interoperable geospatial data and software. It is also important that GIS software and technology be able to inter-operate with other software and databases such as those involved in wireless applications, e-commerce, logistics, environmental health, and health care delivery, to name just a few. Such interoperability requires a common or shared ontology for the phenomena under consideration—any phenomena distributed over part or all of the Earth's surface. This means also that research in the ontology of geospatial phenomena should be coordinated with efforts designed to establish ontology standards, for example the current Standard Upper Ontology project sponsored by the IEEE.

5. Priority Research Areas

As a branch of philosophy, *Ontology* studies the constituents of reality. Ontology, as applied to a given domain, seeks to describe in formal terms the constituents of reality within that domain. Ontology can serve as a valuable support for clarity in description and explanation of a sort that is conducive to building bridges between one domain and another. Information scientists have extended the philosophical meaning of Ontology. They use the term *ontology* to refer to canonical descriptions of knowledge domains, or to associated classificatory theories. In such fields as artificial intelligence and computer science, ontology typically refers to a vocabulary or classification system that describes the concepts operating in a given domain through definitions that are sufficiently detailed for capturing the semantics of that domain. GIS software engineers who rely on appropriate ontologies can build systems that are tailored to the users' needs.

Serious research on ontology of geographic phenomena has begun only recently, and thus far the work has been directed primarily toward the formal modeling of the geospatial world as this is experienced and conceptualized by non-experts. An exhaustive ontology of the geospatial domain would be vast, and might never be finalized. More reachable objectives would be to develop a complete upper level ontology for the geospatial domain, and to develop in stepwise fashion detailed ontologies for subdomains that are consistent with the upper level ontology. Subdomains of highest priority would be the principle domains of GIS application, and areas of environmental and social science where GIS has been under-utilized due to ontological mismatches between these scientific fields and GIS software.

Since the geospatial sciences deal with phenomena across a variety of scales, a common ontology for the geospatial domain will by definition provide an improved understanding not only of common-sense spatial reasoning and but also of scientific and computational models of geospatial phenomena. Above all it will provide a framework within which all of these types of representation of geospatial phenomena can be integrated.

The Ontology of the geospatial domain will define geographic objects, fields, spatial relations, processes, and their categories. It will be accompanied by translation algorithms, mapping the ontology into the basic data models and representations necessary for scientific computing about geographic phenomena. The ontology will be formalized through axioms and definitions of classes, relations, and functions.

A need for formalized ontological frameworks for data integration has been recognized by many fields that specialize in the gathering and exchange of information. However, this need has received much less attention from scientists themselves. This is because, within each discipline or field of study, a shared conceptual system is normally ensured through the education and training of the scientists involved. Where cross-disciplinary communication and collaboration is required, however, ontology provides the needed common platform. Since the environmental and social sciences study phenomena that occur or act over geographic space, a formal ontology of geospatial phenomena is essential for interoperable geospatial science.

We have distinguished three types of ontology research, which must be regarded as complementary and mutually constraining:

- Research in Ontology, which attempts to establish the types of objects, processes and relations, at different levels of scale and granularity, from which the geospatial domain is constituted. The methods employed here should be maximally opportunistic, involving (1) interaction with domain scientists designed to establish the sorts of entities populating their respective domains and (2) the development of formal methods for integrating these populations of entities, for example in terms of part-whole and granularity relations. At the same time, Ontological research should be directed towards clarification of the relations between human knowledge, beliefs and representations on the one hand, the models and representations embedded in our data systems on the other hand, and the real world of objects beyond.
- Research in eliciting geo-ontologies from human subjects (both experts and non-experts) using standard psychological methods (of importance in connection with usability issues and with issues of observation, error, data-gathering and data-formulation).
- Research in method and tools for describing, accessing, comparing, and integrating geo-ontologies. This area falls into the standard information science mode, which means specifying the conceptualizations underlying different types of GISystems software and associated datasets for purposes of interoperability and cross-system translation.

The three types of ontological research are mutually constraining in virtue of the fact that we want our information systems to relate to the same real-world domain of objects as is captured in our scientific theories and in the world of everyday action and perception. The underlying complexity of this research theme is thus several orders higher than standard ontological research in information systems, which relates exclusively to the types of closed world models specified in database design and characteristically involves simplifications motivated by specific short-term pragmatic goals. Geo-ontologies take the real world as their objects, a world of constant change, of multifarious causal processes at different levels of scale and granularity, a world in which, when seen from the human perspective, uncertainty, vagueness and imprecision are paramount.

5.1 Short Term (2-3 years)

All UCGIS ontological research will involve formalization, and progress will be maximized if common formal-ontological tools and concepts are employed. A key short term priority for research in this area thus is to develop and distribute an upper level ontology for geospatial phenomena that can be used as a common framework to ensure that independently developed subdomain ontologies will be consistent and interoperable. An early agreement on a formal language for specifying the ontology will contribute substantially to the potential to achieve longer-term goals. Since consistency and interoperability with broader ontology projects is highly desirable, researchers in geospatial ontology should form links with general ontology projects such as the IEEE Standard Upper Ontology (SUO) Study Group (http://ltsc.ieee.org/suo/index.html). One medium-term project would be to study the family of formal mereotopological theories, establish their properties, and refine the best one for use in ontologies of the geospatial domain.

5.2 Medium Term (3-5 years)

Ontology-based wayfinding systems and agents (Sorrows and Hirtle, 1999; Raubal, 1997) will provide a natural bridge between the data structures of a geographic information system and the users of the system. The conceptual hierarchy of a user is in many cases only partially related to structures used by an information system, which can result in abstruse or confusing directions. An important medium term goal would be to provide a better understanding of the cognition of geographic concepts via the formalization of an ontology of naive geographical concepts (see Mark and Smith's recent work). We are close to making good progress in this area, but need additional formalizations to develop testable hypotheses.

Another important medium-term project would research on the ontology of vagueness, following up on preliminary work on geographic objects with indeterminate boundaries reported in the book edited by Burrough and Frank (1996).

Another medium-term project is the ontology of scale, and especially the issue of how to integrate spatial ontologies at different levels of granularity or resolution (Stell 2000). Scale is another of the original UCGIS research priorities or challenges.

Specification of the ontology of change and geographic process would be another medium-term priority; geographic objects such as lakes, rivers, and storm fronts have very special dynamic properties not studied in standard ontologies.

Yet another project would attempt to answer questions regarding the degree to which folk geographic concepts, such as clouds and storms, fronts and air masses, which are conceptualized as objects in folk and common-sense weather models, are useful, or even indispensable, in scientific models of atmospheric behavior.

These ontological studies will need to be complemented by the development of appropriate methods and tools to describe ontologies. Canonical languages for geo-ontologies are a medium-term project. Likewise, the development of computational methods to compare ontologies and to integrate them into web-based search engines are medium-term research projects.

5.3 Long Term (10 years and beyond)

The long term goal is to complete the description and formalization of the ontology of all phenomena at geographic scales. This needs to go hand-in-hand with the development of appropriate mechanisms that support the integration of geo-ontologies at different levels of explicitness, and the development of guidelines for the resolution of conflicts in geo-ontologies.

6. Example Research Projects

A good way to obtain examples of current research projects in geospatial ontology is to examine award abstracts from the National Science Foundation. A search of recent NSF awards relating to ontology on the NSF web site revealed 40 awards with some variant of “ontology” in the award title or abstract. The fact that half of these are from the last three years is evidence of the emergent nature of ontology as a topic in information science. Of the 40 NSF awards, four mention geographic, spatial, or geospatial themes explicitly. We also mention below some additional projects funded by other agencies.

The project directed by Kuipers (1995), entitled “An Ontological Hierarchy for Spatial Knowledge”, formalized the Spatial Semantic Hierarchy (SSH), a model for representations of spatial knowledge. This project, which ended in 1998, did not explicitly address spatial knowledge at geographic scales, and was mainly intended to support simulated and physical robots. The other three spatial ontology projects funded by NSF all began in 1999 and will extend from one to three years; all are focussed on the geospatial domain. The fact that these funded projects all were initiated in 1999 is clear evidence that the topic is in an emerging phase, at least under the name “ontology”.

Egenhofer’s (1999) ontology project, entitled “NSF-CNPq Collaborative Research on Integrating Geospatial Information” involves collaboration with the Brazilian National Institute for Space Research (INPE), and focuses on semantic interoperability of spatial and geographic databases. Under the NIMA NURI project “Similarity Assessments Based on Spatial Relations and Attributes” (http://www.spatial.maine.edu/~max/nima.html), this group is also designing computational methods to determine the similarity of different ontologies.

At the Pennsylvania State University, Mark Gahegan is working on “Enabling Collaboration and Improving Understanding: The Management of Semantics for Geospatial Information,” funded by a recent NIMA NURI award.

Findler and Malyankar (1999) were funded by NSF’s “Digital Government” program under the title “Digital Government: Representation and Distribution of Geospatial Knowledge”, a project to determine an ontology for coastal entities such as shorelines and tide tables, in partnership with the US Coast Guard and NOAA.

Mark and Smith (1999) recently began a 3-year NSF-funded project entitled “Geographic Categories: An Ontological Investigation”, designed to determine the ontology of geographic objects and associated cognitive categories; the context of Mark and Smith’s project is general common-sense or naive geography, and the project emphasizes human subjects testing in a variety of languages. The results of the project are intended to contribute to spatial data transfer and semantic interoperability of general-purpose geographic software and data.

7. Possible Showcase Demonstrations

The use of ontologies to facilitate retrieval from spatial databases can provide a visual demonstration of the richness of ontologies. The recent work of Egenhofer and his colleagues on sketched-based interfaces and the work of Sara Fabrikant on interfaces for spatial data suggest high-impact, portable demonstrations that can highlight the benefits of an ontological approach. Other demonstration projects may include the use of geospatial lexicons, for instance in intelligent web geo-services and advanced spatial similarity search engines. The application of methods for comparing computationally different ontologies will also lead to tools for comparing geospatial standards.

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