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Formalization Matters: Critical GIS and Ontology Research

Nadine Schuurman

Department of Geography, Simon Fraser University

There have been several obstacles to an embrace of critical theoretical work in GIScience; chief among them is the barrier between conceptualization and formalization. Early critics of the technology were not cognizant that technological change must be implemented within the language of code. While critics expressed their concerns in a theoretical and esoteric language, increasingly GIScientists are at pains to address the same issues so that solutions can be incorporated into software technologies. Indeed an implicit recognition of the important divide between informal and formal environments has aided GIScience researchers in developing strategies to represent multiple epistemologies in GIS. The article begins with a review of early critical GIScience, examines the degree of its acceptance in the light of a content analysis of GIS journals, and then illustrates that the issue of multiple representation of the same reality is being addressed under the rubric of ontologies. New research in this area has had significant impact on GIScience because it has been articulated and addressed at both the conceptual and formal stages—a criterion for real changes to both GISystems and GIScience. The article concludes with an examination of why critical GIS remains relevant to the discipline, in spite of efforts to address issues of representation within GIScience. *Key Words: critical GIS, formalization, GIScience, ontology.*

In 2003, Jay Harman wrote a short piece in *The Professional Geographer* entitled "Whither Geography?" in which he argues that disciplines receive external funding and societal support in direct proportion to their relevance to social and technical problems in a larger arena. These criteria trump discursive debates within the discipline, in spite of what those in the discipline may imagine. In Harman's view, there are "markets" for disciplines, and they must be satisfied or the discipline will not survive. He feels strongly that geography must do a better job of connecting with needs in society than it has done in the recent past. Using an economic model, he argues that we have to earn our keep. Arguments about whether we qualify as a "science" or not are irrelevant using these criteria (Harman 2003). This logic could be extended to "critical GIS," a niche within mainstream geographic information science (GIScience) but one that has arguably not been totally integrated even in light of its remarkable impact within human geography for a period in the mid-1990s. This article examines the extent to which critical GIScience remains relevant as GIS researchers are integrating mechanisms to represent multiple ontologies.

Critical GIScience is an approach to evaluating GIS technology and principles that draws on social theory, science and technology studies, and philosophy. This article argues that critical GIScience as it has emerged over the course of the past decade has had a salutary effect on the discipline but it risks losing sway on GIScience researchers. There are two related reasons for a potential diminished influence of critical GIScience. The first is that the critiques have largely been conceptual, lacking a means of connecting them to the formal computational environment, albeit with important exceptions (e.g., Harvey et al. 1999; Kwan 1999, 2002; Cromley and McLafferty 2002; Sieber 2004). The second is that a community of research has emerged *within* GIScience with emphasis primarily on ontologies and methods of incorporating indeterminate or vague features of geospatial information and relations, but with some attention to emancipatory issues such as feminism (McLafferty 2002). This article examines (a) the extent to which critical GIScience has influenced the discipline; (b) reasons why there has been some reluctance to embrace it; (c) how research within "mainstream" GIScience has tackled some, but not all, of the issues identified by critics; and (d) why a continued and close relationship between critical GIS and mainstream GIScience is desirable. The chief contention is that GIScience scholars are working to incorporate multiple ontologies by using a formal notation to address issues of representation.

Introducing Critical GIS

Critical GIS was born as human geographers awoke in the early 1990s to the increasing importance of GIS as a subdiscipline of geography. The rapid dissemination of

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GIS began to attract attention from human geographers, some of whom were suspicious and wary of GIS researchers' claims. Geographers concerned about the direction that GIS was leading the discipline began in 1990 to publish their apprehensions of the effects of GIS on geographical knowledge and disciplinary epistemologies (Taylor 1990; Taylor and Overton 1991; Smith 1992; Lake 1993). The next five years saw a rash of publications by human geographers who were frequently skeptical about the role that GIS could productively play in the discipline (Schuurman 1999). Critical GIS was alive and kicking, especially among human geographers.

Critiques of GIS can be described as developing in three distinct waves (Schuurman 2000). The first wave, between 1990 and 1994, was characterized by the ferocity of the criticism that human geographers reaped on technical geography and spatial analysis. Though many analyses were well warranted interrogations of a GIS that had been oversold in its early days, the tone of the papers was frequently scolding and paternalistic (Smith 1992; Lake 1993; Pickles 1993). The arguments were, however, legitimate as authors called for a more reflective GIS that concerned itself with epistemological and ontological implications of spatial analysis and representation. The sum total of these and other suspicions of GIS gave the first wave of critical GIS a distinctly antagonistic flavor.

The second wave of critiques took place between 1995 and 1998. By 1995, more than forty papers had been published by human geographers worried about the implications of a pervasive GIS. Many of these publications were included in two key 1995 anthologies: *Ground Truth,* edited by John Pickles (1995), and *GIS and Society,* a special issue of *Cartography and GIS,* edited by Eric Sheppard (1995a). Concern was expressed that GIS best served large corporations and public agencies rather than the disenfranchised (Goss 1995; Sheppard 1995b). Moreover, critics were skeptical about a technology that they deemed a relic of the quantitative revolution (Taylor and Johnston 1995). Human geographers had worked hard to extricate the discipline from a mechanistic approach to geography characterized by the quantitative revolution, and many were dubious about a technology linked to it (Pickles 1997). Critics were also wary of a masculinist influence pervading GIS and its output (Roberts and Schein 1995). The second wave was thus characterized by the intertwining of substantive issues and theoretical concerns that predominated in contemporary human geography.

The 1990s also witnessed the nascence of a still-growing public participation GIS (PPGIS) sector. PPGIS occupies a different niche of GIScience than critical GIS. It has its own conferences, proceedings, and scholastic following. Indeed PPGIS has flourished relative to critical GIS, perhaps because practitioners and researchers are engaged in on-the-ground research with communities in many parts of the globe and over the web (Harris, Weiner, and Levin 1995; Weiner et al. 1995; Carver 2001; Ghose 2001; Warren 2004). A number of PPGIS conference papers and articles deal with issues of representation and—obliquely—ontologies (Rundstrom 1995; Brandt 1998; Sieber 2000; Elwood and Leitner 2003; Kyem 2004). PPGIS emphasis remains on better representing underprivileged groups and those with least access to the public forum. It comprises an active and growing method of influencing public policy and debate.[1]

By the late 1990s, critical GIS had also moved from an antagonistic activity to a means of positively affecting a technology that was being widely adopted in other disciplines and in the commercial sphere. A summary of issues that emerged from the more than sixty published critiques of GIS during the 1990s are in Table 1.

The content of these critiques was largely thoughtful and certainly relevant to the emergence of a new science within geography. The tactics used by critics were, however, of questionable efficacy, largely because they were

Table 1. Subject matter of critiques of GIS from 1990 to 2001

Source of critique	Complaint about GIS
Pre 1993 papers (e.g., Taylor 1990; Taylor & Overton 1991; Smith 1992; Lake 1993; Pickles 1993)	Based on data rather than information; subject to naive empiricism; a positivist technology that assumes the possibility of objectivity; complicit in warfare; based on a Cartesian framework incapable of describing human geography or natural phenomena.
1995 publications: *Ground Truth* (Pickles, ed.) Special issue of *Cartography and GIS* (Sheppard, ed.)	A masculine technology; part of a cybernetic grid of control; a marketing tool; epistemological inertia; limitations of visualization; Cartesian perspectivalism and rationalism; need to make the technology accessible.
1995–1999 (e.g., Curry 1997; Pickles 1997; Katz 2001)	Lack of attention to epistemologies and ontologies; failure to accommodate marginalized voices; a means of greater surveillance.

external to GIS. Critique in and of itself has no effect on technologies or the science on which the technologies are based. To instigate change in theory or implementation, critique must adhere to the logic of the discipline (Pratt 1996; Schuurman and Pratt 2002). At present, implementation of concerns raised by critics hinges on partnerships between critics and GIScientists precisely because critique has been external. Though such relationships are increasingly common (Harvey 1997; Miller 2003; Sheppard 2005; Warren 2004), they are not paradigmatic of the discipline as the content analysis reveals. Not surprisingly, critiques have been underrepresented in the disciplinary journals, as is illustrated by the content analysis that follows.

A Content Analysis of GIScience Journals

A recent content analysis of GIScience journals speaks to the inherent limitations of a model of scholarship in which critiques of GIS are external to the discipline. An earlier content analysis covering the period from 1995 to 2001 (Schuurman 2004) was based on analysis of four journals selected on the basis of primary commitment to GIScience: *International Journal of Geographical Information Science* (*IJGIS*); *Transactions in GIS*; *Cartography and Geographic Information Science* (*CAGIS*); and *Cartographica*. Here we present an extension to this analysis, adding the journal *GeoInformatica* and extending the analysis to mid-2004. Each paper published in the journals from 1995 to early 2004 was assessed (subjectively) to determine its principal focus. Nine categories wereused as the basis for classification:

- Algorithms
- Applications of GIS
- Cartography and visualization
- Cognitive/spatial reasoning
- Data
- Error and uncertainty
- GIS and society
- Ontology and epistemology
- Spatial analysis and modeling.

Figure 1 illustrates the distribution of subject areas in the major GIScience journals. Only 49 papers of 762 fall under the generously defined GIS and society rubric; the category included a broad range of topics including policy and educational initiatives. This is in contrast to 190 papers in the category of spatial analysis and modeling, and 159 in the algorithm category. Though not evident from the histogram, only four of the GIS and society papers were published in the past three years. Not only are there proportionally very few papers pub-

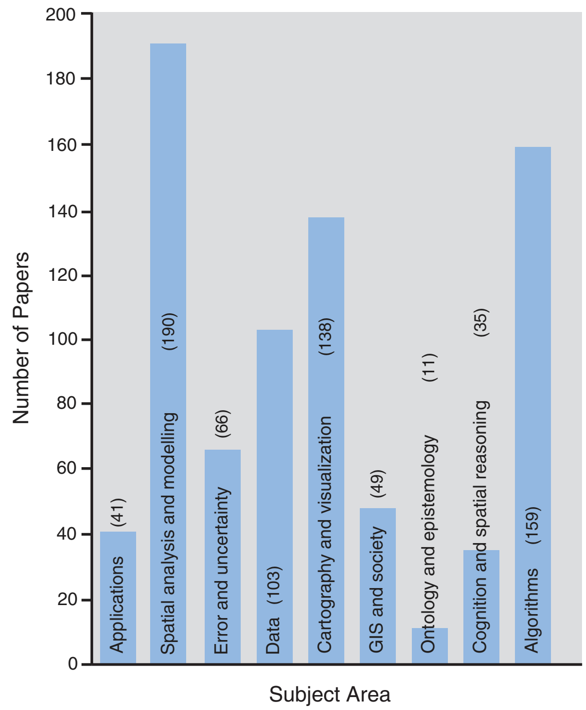

Figure 1. Content analysis of GIS journals from 1995–2004 (based on 792 papers).

lished in the GIS and society category, their representation has diminished as the waves of early critiques of GIS have retreated. The content analysis points to the preponderance of emphasis on technological problem solving in GIS.

The inherent limitations of a content analysis of a subset of journals is evident by the underrepresentation of ontology articles. There are a number of publishing venues for GIScience outside these five journals, especially the Lecture Notes in Computer Science (LNCS) series that serves as an outlet for biannual GIScience and COSIT meetings as well as Interop meetings in the past. A complementary analysis of LNCS publications explains the relative paucity of ontology and epistemology papers in the leading GIScience journals. LNCS volumes from Spatial Information Theory (COSIT) proceedings (1995–2004), from GIScience 2002 and 2004, and from Interop '99 form the basis of this second content analysis. In this instance, 222 papers from eight volumes over a ten-year span were evaluated based on the same content categories as above. Figure 2 illustrates the preponderance of ontology and epistemology papers among these specialist groups. This current analysis illustrates an emphasis on cognitive and spatial reasoning that is complementary to ontology and epistemology research. The critical factor, however, is that the ontology and spatial reasoning papers are primarily concerned with

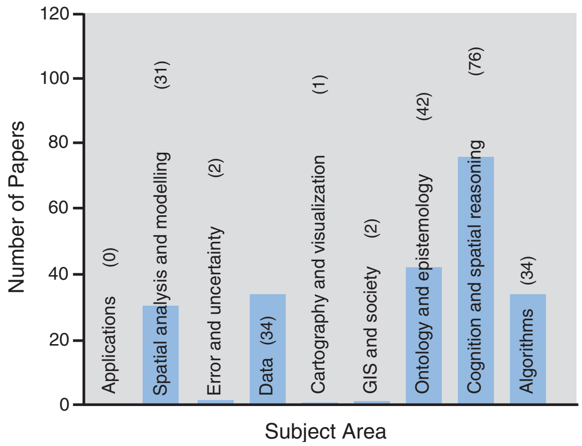

Figure 2. Content analysis of Lecture Notes in Computer Science (LNCS) GIScience publications from 1995–2004 (based on 222 papers).

implementation of complex philosophical and cognitive concepts in a computational environment.

There are a number of explanations for the relatively low numbers of critical GIS papers published during the period 1995 to 2004. One obstacle to the embrace of critical GIS is the newness of this subfield of study. GIScience is still a fledgling discipline with limited external name recognition. It was first positioned in the realm of *science* in 1992, and initially had to defend the territory (Goodchild 1992; Schuurman 1999; Sui 2004). In the decade since, leading GIS journals have changed their name to reflect the shift from systems to science, and curricula followed. Nevertheless, GIScience is still very newly established in the realm of science, and creating a new science is hard work. Those who recognize the internal logic of the new discipline are accepted; those who don't, or who question its fundamentals, are perceived as "irrational" (Barnes 2001).

Discipline-making is a boundary definition process. Researchers intent on shaping the discipline guard its perimeter. They are gatekeepers who reward certain methodologies but exclude others. This boundary patrol is accomplished through peer reviews for publication as well as control over funding. Critical papers, which may be poorly grounded from a technology perspective, are less likely to be published than are papers that address conceptual tensions within the language and equipment of GIS. Critical GIS emerged in the 1990s on the boundaries of a what was already a fresh science; not surprisingly, it was subject to the disciplinary approbation to be expected by any niche in geography and it received extra scrutiny by those who cherish a vision of GIScience as being closely related to computing sciences and information technology.

The emphasis of the majority of papers in the two content analyses on what may appear to be technical aspects of the science should not be confused with aphilosophical perspectives. Instead the emphasis reflects subscription to a common discursive regime based on computing code. Martin Dodge and Rob Kitchin make the argument that code space is a necessary influence on the production of real space in a networked society (Dodge and Kitchin 2004). They use the example of air travel to describe the ways that programming of ticketing and routing is inseparable from air space and travel; they are mutually constitutive. This is true in GIS where representations of space are expressed conceptually, programmed in code, represented graphically, and then become the basis for environmental and other decision making.

Code space acknowledges the first step of conceptualization but solidifies concepts using formal architectures that ultimately fix representation. Thrift and French (2002) extend this argument by illustrating how software has been instantiated into the geographical spaces of everyday life to the extent that it is increasingly developed in an effort to parallel human thought. Genetic algorithms and neural nets are examples of the "new artificial intelligence," which eschew linear lists of rules in favor of a more gestalt approach to logic (Schuurman 1999). Algorithmic and code-based discourses constitute a specific kind of representation and conceptualization of space that is increasingly common in all areas of modern life—and essential to GIS.

Emphasis on technical aspects of computing in GIScience journals is thus explained by (a) the importance of code as a discourse in GIScience and (b) the relationship of code space to real geographical space. The role of code-based discourse and its relationship to space explains the plethora of articles over the past nine years on spatial analysis, data, and algorithms. Likewise, though papers on ontology and epistemology appear underrepresented (11 of 792 papers in the five journals; 42 of 222 papers in the LNCS series), they are better accepted based on their presentation in the language of GIScience. Moreover, they illustrate that these issues are being explicitly tackled under the rubric of GIScience.

Technical developments expressed in code are necessary in GIS, which is based on computing, but they do not necessarily capture the diversity of GIScience or the extent to which it internally embraces critiques from critical GIS. The initial goal of critical GIS was overtly to change the technology itself by convincing researchers to rework the software to be more inclusive and better represent social issues. Mainstream GIScientists have taken up the call to address ontological and epistemological issues, as is illustrated by the emphasis on epistemology and ontology in disciplinary proceedings.

This is not an entirely new development. The problem of linking data models to ontologies dates back to the *Harvard Papers on Geographic Information Systems*[2] (Dutton 1978). David Sinton (1978) writes in the Harvard papers that the myriad methods by which humans organize space and corresponding data are severely constrained by data models. Chrisman (1978) remarks in the same volume on the problem of reconciling cartographic data structures with different concepts of space. Data models need to include much more than data as the resultant representation must be connected to the context of everyday social life and must be interpretable in those contexts (Chrisman 1993). Even if data models were to embody such ontological nuance, there remains the problem of linking them in a meaningful way to the traditional points, lines, and areas of maps.

There is a commensurate history of wrestling with representation in cartography that is reflected in GIS literature from more than a decade ago. Our chief representational model is geometric, and one problem with Euclidean geometry is that it deals with Real numbers. The set of Real numbers assumes continuity whereas GIS data sets deal with discrete entities. Euclidean geometry captures "only limited and highly abstracted aspects of geometry and space" (Frank and Mark 1991, 149). It is appropriate for engineers but has little overlap with human experience. Only the world itself is an effective representation.

People read meanings into map symbols that transcend the literal representation of the maps. Map interpretation is recognized as a skill precisely because the map is an abstraction of reality, one that incorporates points of view. Reading maps does not include the possibility of reconstituting reality but only of extracting meaning for a particular purpose. In land-use debates and planning, for instance, it is useful to produce maps that explicitly represent different connotations of a particular scenario (Couclelis and Gottsegen 1997). There is, however, no obstacle to incorporating explicit connotations into both databases and the graphical display. There are cases where values and arguments associated with the territory are as important as the territory itself. Such "contested spaces" are categories that researchers have long recognized need to be "ontologically" permissible in GIS (Couclelis and Gottsegen 1997).

The problem to date has been that formal languages use a predicate logic that is quite removed from spatial properties. To describe space, humans use concepts that are not easy to implement in a formal structure (Frank 1992). If we think of natural language as a formal system, then we are led to the assumption that it has direct correspondence to the world, but this is a false assumption encouraged by long traditions of objectivist thinking (Deutsch 1997). Moreover, Lakoff (1987) provides much evidence that there is nothing in mathematical logic that makes it suitable to model human reasoning. The conundrum facing GIScientists is how to formalize and justify links between representational symbols on maps and the multiple ways that humans describe the world (Frank and Goodchild 1990).

This torch has been taken up again in the present emphasis on ontology research. In the past many issues of representation were considered under the rubric of cognitive science or studies of science and technology, and implementation of the software (e.g. formalization) was strictly a computing function. Current research on ontologies seeks better formal integration of such issues. In the process of pursuing better representations of diverse epistemologies, GIScience researchers have integrated some of the concerns expressed in early critiques and by GIS scholars but *within* the technological framework or discursive regime that underlies GIScience.

Cut Along the Dotted Line: Why the Boundary Between the Formal and Informal Matters

There is a powerful divide between the abstract concepts that were used to articulate critiques of GIS and the formal language (and ultimately code) that is required to implement changes to the technology. GIScientists frequently refer to *formalization* as the process of rendering concepts into a form that can ultimately be represented in a digital environment (NCGIA 1998; Duckham et al. 2001; Brodeur et al. 2003). To GIS scholars, the need to make this transition is so well-understood that it is considered implicit. Yet, to outsiders, including many early critics of GIS, this boundary was invisible and/or irrelevant.

GIS, like all information sciences, is based on a hierarchical relationship between conceptualization and formalization (Fonesca et al. 2002; Brodeur et al. 2003). If we think of conceptualization as a cognate step toward understanding spatial processes and relationships, there remains a pressing need to express these relationships in a mathematical or formal notation as a precursor to coding them. The trade-off, however, is information loss associated with formalization. There is a danger that we suppress detail in favor of abstract and formal relationships (Couclelis 1982, 1992). On the other hand, abstraction based on information loss is a powerful way of understanding structure. GIS has had such success partly because it is a relatively pared down, artificial realm that distills pattern in an abstract form (Campari 1991).

Maps, being the primary form of representation in GIS, suffer from the shortcoming of "brute representationality" (Sismondo and Chrisman 2001). Their content and representational form (e.g., projection) need be contextualized in order to be understood. Certainly the symbols that represent categories on maps cannot be directly related to the world (Lakoff 1987). As such maps can be accused of fostering ideological influence (Sismondo and Chrisman 2001), but perhaps no more than other forms of representation including text (Schuurman 1999). Moreover, these mechanistic abstractions assist us in making sense of the physical and human world; in GIS we use abstractions to model reality (Burrough and Frank 1995; Raper 1999). The process of formalization is based on abstraction of concepts into a symbolic form.

There are stages associated with formalization. Algorithms or amalgamations of graphics and text such as those used in UML (unified modeling language) are examples of semi-formalized notation. They are a precursor to code, a means of reifying concepts semantically and operationally. The actual writing of code is a stricter form of formalization that is based on flow charts or other symbolic versions of conceptualization but is subject to a greater rigor in both definition and execution of spatial entities and their relationships (Winter and Nittel 2003). These are sequential steps toward implementation of concepts in a digital environment. Semi-formal notation and coding are both based on the conversion of abstract relationships into symbols, but the former is less structured, serving more as a visual guide to the structure of relationships between entities. Implementation at the coding level requires definitional parameters. Is the field numeric or text? Integer or real? How many decimal places does it support? What is its range? Likewise, operations between entities require strict definition. Formal systems imply that we have definite answers about which properties of space should be included in a formal language and how they should be defined (Freksa 1991; Winter and Nittel 2003).

A mechanism for moving between cognitive impressions of reality and database representations of reality is required. Brodeur et al. (2003) describe five ontological stages associated with geospatial data and analysis. At the top level is reality (R), followed by cognitive models of reality (R′). The third stage consists of conceptual representations and is referred to as R″. The fourth ontological stage (R‴) converts concepts to database representations. Finally, the fifth ontological level (R⁗) is the set of spatial concepts that can be produced from the database. To human geographers, such a taxonomy might seem mechanistic, but it is essential in GIS to be able to express cognitive models in a formal language as a precursor to coding it. R″ or the set of conceptual representations marks the fuzzy dividing line between the conceptual and implementational realms. A structured vocabulary must be used to describe objects and object classes. Moreover, database representation requires a method of embedding context based on object inheritance (e.g., does "range" refer to a woodland habitat for deer or the top of a stove?). Figure 2 illustrates the divide between conceptualization and database implementation in a simplified manner that illustrates the dividing line between conceptualization and different levels of formalization.

Ontologies can exist and can be described and understood, but this does not mean that they have been formalized. Formalization is the critical step referred to by Brodeur's R‴ and R⁗ – and illustrated in Figure 3. Formalization allows us to take descriptive concepts and render them digital; it makes them real in database terms. Formalization is the critical step necessary to describe real world spatial concepts in digital terms. The divide between the descriptive world of text and graphics and the digital realm is wide. As a result, formalization is usually achieved in two steps. First, the concepts are described in a semi-formal notation often using flow chart symbols. True formalization expressed as code is the final stage. GIScientists are currently developing methods of formalizing and encoding diverse ways of looking at the spatial world—a critical component of ontology research.

Ontology Research: A GIScience Approach to Representation of Epistemological Difference

GIS researchers have a history of concern about the ontologies permitted by data models (Couclelis 1992; Burrough 1996; Kemp 1997). The emergence of critical GIS simply emphasized the need to understand and integrate issues of ontology and epistemology into GIScience research. Yet the meaning of *ontology* is multifaceted; it is interpreted differently in philosophy and the information sciences. Human geographers and social scientists have typically employed an Aristotelian philosophical understanding in which ontology is understood to signify a foundational reality, the essence of an object or phenomena. Alternatively, ontologies answer the question: What must the world be like for knowledge

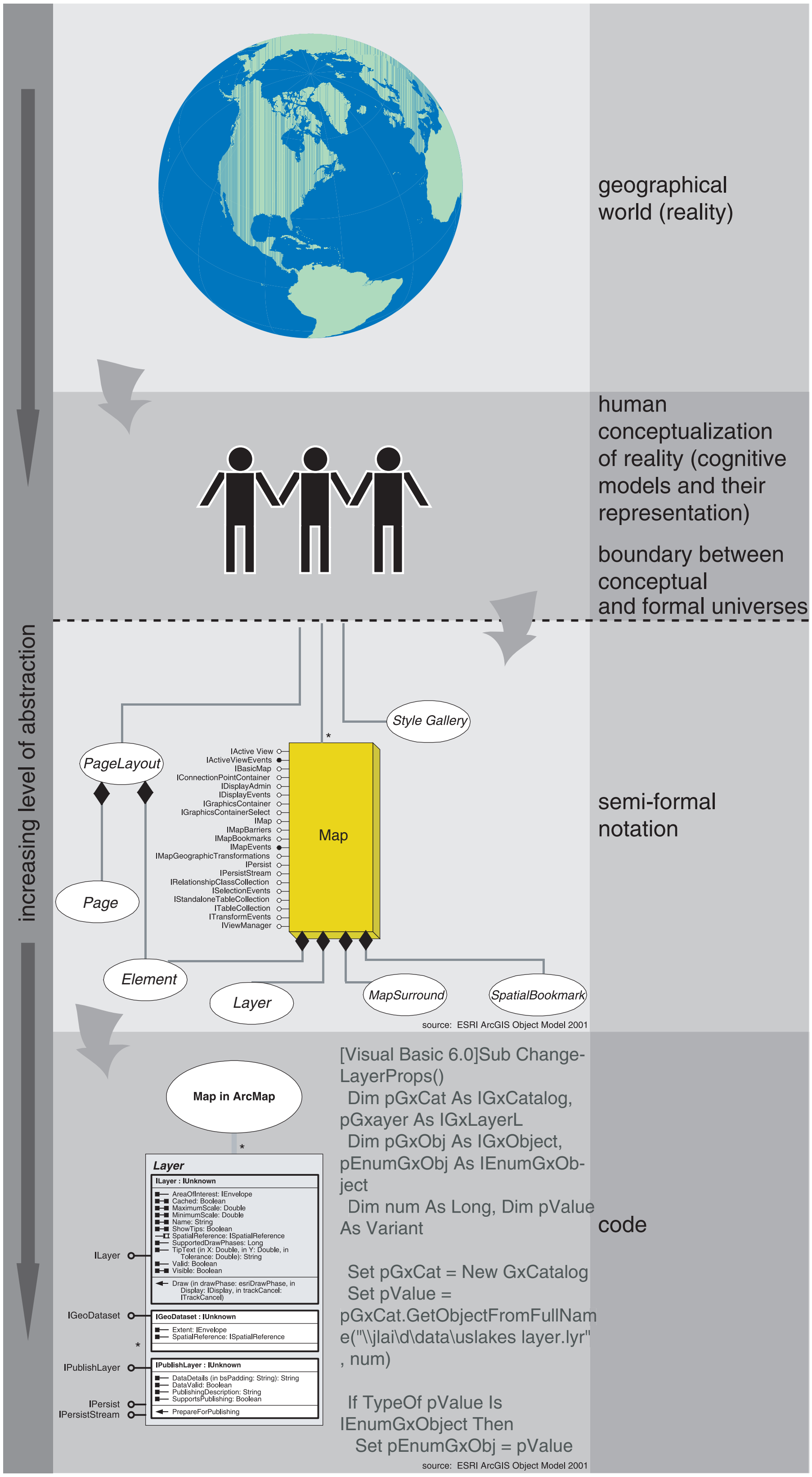

Figure 3. The boundary between conceptualization and formalization. Copyright © 2001 ESRI.

of any object or phenomenon to be possible? (Gregory 2000). Formal systems employ the ontological perspective of engineering in which an ontology is a complete and internally logical system. Ontologies, in this sense, are statements of logical theory pertaining to spatial relations (Gruber 1995; Brodaric and Hastings 2002).

Formal ontologies emerged from artificial intelligence research and are guided by three levels of convention: representational, communication protocol, and content specification. The realm of existence is limited to that which can be represented. Domain knowledge must be formally declared and this becomes the "universe of discourse" (Gruber 1995, 908). Formal ontologies form a logical universe, and an ontology in a formal environment is equivalent to a logical theory (Kuhn 2001). Ontologies thus become the basis for communicating diverse epistemologies in GIScience.

The relationship between epistemology and ontology is pivotal to understanding the groundswell of ontology research in GIScience since 1997. Epistemologies are ways of knowing the world. In this article the word *epistemology* is used to describe ways that people describe categories: formally and informally. Traditionally, GIS has relied on an essentialist or Aristotelian approach to knowledge creation, which holds that the world is inherently divided into natural classes, the members of which shared an essence (Bryant 2000; Burrough 1996). This doctrine of essentialism is based on the premise that those classes are natural and reflect the inherent structure of shared reality (Lakoff 1987; Raper 1999). This view is a-epistemological, relying on the assumption that human observation is sufficient to devise classes. In reality, however, scientific classification uses a mixture of metaphysics and epistemology, and expert classification is just as subject to context as lay classification (Burrough 1996; Bryant 2000). Classification and epistemology are, in this view, a mixture of science and subjectivity. This is a radical departure from objectivism which is premised on one "real world" independent of the human mind and social context.

There is a growing cadre of GIScientists who acknowledge that context shapes the formation and selection of categories. Changes in context or point of view lead to a shift in perceived and/or enumerated categories (Raubal 2001; Fonesca et al. 2002). Each representation of categories leads potentially to an alternative ontology that could be implemented in a formal environment. Though there are GIScientists who would argue that categories are based on natural kinds (Smith and Mark 1998; Bittner and Edwards 2001), there is little disagreement that GIScience must be flexible enough to represent more than one system of classification (Brodaric and Gahegan 2002). Moreover, the objectivist approach to categorization is no longer applicable in a world with multiple stakeholders with divergent agenda (Harvey et al. 1999; Brodaric and Gahegan 2001; Brodeur et al. 2003; Sieber 2003).

Ontology research in GIScience arguably began in the mid-1990s, though it was preceded by two decades of cartographic inquiry into representation (as discussed earlier). Despite this tradition of investigating cartographic representation, ontology as a concept is understood very differently in different domains. Within the relatively small GIScience research community, there are multiple ways of interpreting ontology, including the following:

- Map legend (geology)
- Choice of data model for representing spatial data
- Data dictionary (WordNet)
- Classification system
- Range of spatial entities
- Computer science: fixed universe of discourse (parameterized).

Clearly this is an incomplete list of interpretations of ontologies, but it speaks to the diversity of understanding that shadows the term. Geologists, for example, limit an ontology to what can be represented in a map legend (Brodaric and Gahegan 2001). GIScientists, on the other hand, understand that the choice of data model has an explicit and often predictable effect on what can be represented (Burrough 1996; Couclelis 1996; Ferrari 1996, Schuurman 1999). For researchers who see ontologies as a means of assisting in content matching from multiple data sets, ontologies are the basis for text retrieval based on attributes or elements of a taxonomy (Guarino, Masola, and Vetere 1999). WordNet, for instance, is based on *synsets*, groups of terms with semantic equivalence, with each assigned as a noun, verb, adverb, or adjective (Raubal 2001). Substituting classification systems for "ontology" is a move similar to using WordNet as a look-up table. In this instance, the categories in the classification system represent the range of what can be represented; they are a literal interpretation of Gruber's (1995) definition of ontology as a universe of discourse. Translated into GIS terms, possible discourse is limited to the range of spatial entities that can be represented on a map or used in spatial analysis. These entities (or computable objects) must be parameterized through definitions and must constitute an ontology in computing science lingo. The nuances of meaning associated with ontologies are all linked; each understanding of ontology relates to what can be described in a computational environment.

Each of these variations in interpretation is linked, moreover, by the assumptions that (a) we need to represent multiple epistemologies and (b) formalization is a constraint in representation. There is a common understanding that concepts must be filtered through a formalization process. Some researchers argue that ontologies are separate from conceptual schemes and their implementation (e.g., data models such as vector or raster), but the irony is that all of the problems associated with semantic interoperability plague ontologies, even in their definition (Winter 2001; Fonesca, Davis, and Camara 2003). It is just as difficult to wrestle "ontology" to the ground and slap a rigid meaning on it as it is to stabilize any other concept. The process of formalization is the designated arena for fixing meaning.

Recognition of formalization as a parameter distinguishes GIScience ontology research from critical GIS. Acknowledgment of the need for formalization is both a constraint and a liberating force. It limits the types of concepts that can be implemented, while ensuring a vehicle for those concepts/epistemologies that are structured adequately. Three salient issues have been addressed in formal terms through the ontology lens since the mid 1990s: categorization, data models, and semantic interoperability. Though seemingly divergent, these research areas are closely linked by their careful attention to epistemological variation and ways of incorporating representation of difference into GIScience—overtly the ambitions of critical GIS.

Ontology research in GIScience has increasingly focused on the problems with categories and their failure to travel well across the boundary between conceptualization and computation. For example, the European Union has developed a vegetation classification system based on biotypes identified by the acronym CORINE. Many conservationists note that this classification does not match U.K. or Irish vegetation types well. Indeed, some Irish vegetation types are unclassifiable using the system (Wateron 2002). Irish conservationists do not share Russian ecologists' epistemology of vegetation types. The two classification systems reflect not only different frames of reference, but were developed under different vegetative and climatic regimes. Neither reflects a universal reality but local settings and their institutional cultures. Ontology research must develop a mapping from multiple spatial ontologies represented in database models with minimum loss of meaning (Shariff, Egenhofer, and Mark 1998; Fonesca, Davis, and Camara 2003).

This mapping between ontologies is complicated by different semantic terms used for the same phenomena as well as the same semantic terms used differently in different contexts. Harvey and Chrisman (1998) use the concept of *boundary objects* to describe spatial phenomena that stabilize dialogue but are understood and negotiated differently by different groups. In their example, "wetlands" operate as boundary objects that allow different interest groups to talk about a vaguely defined geographical phenomena. Each group understands and constructs the attributes of *wetlands* differently such that the wetland status of a contentious geographical area can be classified entirely differently. Ola Ahlqvist (2004) has posited that measures of relatedness between conceptual spaces provide a means to negotiate between different ontologies, or category systems. He uses *uncertain conceptual spaces* as primitives that are defined by a number of attributes that relate to a geographical phenomenon. *Properties* of the uncertain conceptual space are a measure of the attributes that comprise the space. The uncertain space is thus constituted by a set of property definitions that can be weighted according to their importance (Ahlqvist 2005). Semantic similarity between such conceptual spaces is measured using fuzzy arithmetic; it measures overlap and distance between conceptual spaces (Ahlqvist 2003, 2004). In this model, rough and fuzzy sets are a means of translating across different data models (e.g., field and object) or semantic terms in different datasets. Ahlqvist's uncertain conceptual spaces are in essence boundary objects as their definition varies depending on who defines the properties of the spaces.

Many other models for achieving the goal of accommodating multiple spatial ontologies have been published. Brodeur et al. (2003) suggest the use of semantic networks that draw on node-arc structures from graph theory to achieve this goal. In such a scenario, nodes are equated with conceptual elements (intrinsic properties) and arcs with relationships (extrinsic properties). Close concepts are physically close on the graph structure. This approach is reminiscent of other approaches to documenting "semantic proximity." The goal of the semantic proximity approach is to identify close or near concepts and tag database elements so that proximate concepts and entities can be linked. Methods of addressing this problem include restructuring schematics of similar semantic entities in order to develop links between semantic objects based on context (Kashyap and Sheth 1996), and the development of a set of inclusion rules that must be included during classification of entities (Stock and Pullar 1999). Each of these methods is linked by emphasis on including context in the final database implementation as a means of ensuring that the terms of classifications can be recognized in different settings.

The goal of maintaining ontological context is consistent with one of the chief objectives of present-day GIScience: interoperability. There is a trend toward distributed digital knowledge, but institutions need ways to integrate spatial information even when it is described at multiple levels of abstraction using multiple schematics. Semantic data sharing is perhaps the most elusive of interoperability objectives (Bishr 1997, 1998; Cuthbert 1999; Sheth 1999; Vckovski 1999). Sharing spatial data and attributes requires stability of language across culture and geography—assumptions that are seldom true (Baehr 2001). Instead, researchers are forced to develop methods of porting intended meaning along with field names in order to allow "intelligent" semantic sharing. Like the challenge of preserving ontologies across the formalization border, semantic interoperability must translate concepts into code and back again. Brodeur et al. (2003) and Fonesca et al. (2002) agree that mapping human cognition or categories to ontologies is the most rational basis for data integration.

Another trend in semantic interoperability research is to defer to automated mediators that will, in principle, handle decision making about which semantic terms are commensurate (Abel et al. 1998; Devogele, Parent, and Spaccapietra 1998). Alternatively, Fabrikant and Buttenfield (2001) developed a formal environment for visualization of spatial information based on three axes: geographic space, cognitive space, and semantic space, with the proviso that no two objects can occupy the same space. Brodaric and Hastings (2002) propose a meta-model that provides for ontologies. Their model recognizes the philosophical implications of geological models, and amplifies feature-based representation with an ontological context that takes into account syntax, schematics, and semantics for representing multiple geoscientific perspectives on natural phenomena. Though the tactics vary, each of these efforts is consistent with the goal of maximizing the number of possible perspectives that can be integrated into spatial analysis. They are designed to integrate epistemological diversity into a formal environment.

Critical GIS has attempted to demonstrate the need for multiple stakeholders to have access to data and their representation (Pickles 1997; Ghose 2001; Katz 2001; Warren 2004). Indeed, acknowledging and understanding alternate perspectives on the same geographical phenomena or spatial framework is a means of preserving heterogeneity of perspective with implications for democratic policy and governance (Sieber 2003). This article has illustrated that the spirit of these objectives is being achieved within the field of GIScience under the rubric of ontology research.

Conclusion: Ontology and Epistemology Matter to Us All

Matt Sparke (2000) differentiated between "realworlders" (those people who do and create things in the world), and critical geographers (those who focus on how the production of knowledge reveals and reinforces certain relations of power). This article argues that no such distinction is necessary in GIScience, that GIScience recognizes the contingent nature of categories, ontologies, and spatial extent, and has also developed a body of research that attends to their implementation. Research in ontologies and epistemology in GIScience bridges a false divide between doers and thinkers. Critical GIS in the 1990s conveyed a dissatisfaction that GIS could not represent multiple versions of the same phenomena from different viewpoints (Haraway 1991; Pickles 1991, 1993, 1997; Smith 1992). Constrained by a geometric emphasis, critics argued that GIS also failed to illustrate uncertainty or vagueness associated with spatial entities and their relationships through space and across time (Katz 2001). In the interim between these criticisms and the present, GIScience has come a long way toward addressing these problems in a manner consistent with digital representation and analysis.

The ability to work across the unnatural divide of pure empiricism and conceptualization is the hallmark of this research. It speaks to recognition of the invisible barrier between conceptualization and formalization. There is a greater need for an understanding of the role of formalization in framing and implementing critique. Moreover, there is ample room for implementation with off-the-shelf software of many of the ideas that entered GIS under the mantle of ontologies.

A reexamination of Table 1, however, reveals that despite a decade of ontology research, a number of the issues raised by early critics of GIS remain unresolved, at either a conceptual or a representational level. These include possible complicity in warfare (Smith 1992), use of a Cartesian framework that is inadequate to describe many natural phenomena, and more nuanced issues such as power relations and influences of masculinity on social relations (see Roberts and Schein 1995). Complaints that GIS is part of a cybernetic grid of control (Pickles 1991, 1993) remain unresolved, at the same time there is no doubt that GIS *is* a well-established marketing tool (Goss 1995). Making geographic technologies accessible and able to accommodate marginalized voices is a triumph of a well-established PPGIS movement (Carver 2001; Ghose 2001; Elwood and Leitner 2003; Sieber 2004). What has been achieved is a distinct and concerted movement toward recognizing and incorporating multiple epistemologies and ontologies within geographic information technologies—the subject of this article.

Although ontology research has been instantiated in mainstream GIScience, there remains a need for computing to reflect a range of human expression and diversity of ideas (Montello 2002). Ontology research is fundamental to incorporation of different epistemologies. As such, this stream of research is poised to benefit from philosophical and ontological research in social and physical sciences, as well as from critical GIS. Biodiversity research, for example, has a recent tradition of focusing on diverse epistemologies associated with diverse scientific understandings of biomes, phyla, flora, and fauna (Bisby 2000; Bowker 2000a, 2000b). Geologists have also examined the issue of how they divide the world into parts (Frodeman 2000). Human geography follows the social sciences in a long tradition of questioning perspective and its relationship to representations of reality (Gregory 1978, 1994, 2000). The confluence of critical GIS in the 1990s and independent ontology research in GIScience provides an opening to broader recognition of the function that ontology and epistemology can play in representing the spatial world in GIS.

There is a lead role for critical GIS in bridging the divide between GIScience ontology research and social theory perspectives on spatial relations, events, and processes. Spatial objects have dynamic and complex ontologies and recognition of this dimensionality needs to be incorporated into GIScience thinking and ultimately operationalized. Dean Bavington, a resource ecologist, explains that there is a difference between ontological complexity and epistemological complexity (Bavington 2002). The latter views complex processes as ultimately knowable; our understanding is limited only by our epistemological lense. In this view, spatial processes are merely complicated in the way that a jet airplane or automobile is complex. Ontological complexity, on the other hand, presupposes that we cannot understand the system in its entirety; there will always be an element of unpredictability (Bavington 2002). These two approaches to understanding geography have repercussion in resource management and other domains. Moreover, such distinctions are ultimately important for GIScientists. Their theoretical recognition and practical (e.g., formal) implementation could well be developed in tandem with scholars in critical GIS. At present, however, such partnerships are too scarce, with the result that ontology research to date has been initiated and implemented by GIScientists working within traditional circles.

This article does not suggest that GIScience should rest on its laurels. Emphasis on the success of GIScientists in incorporating problems associated with multiple epistemologies in a formal environment does not suggest that there is no need for critical GIS. Quite the opposite. Attention to key concepts from critical GIS is a method of avoiding a linear history of accomplishment in GIS in which each achievement is retrospectively viewed as an inevitable outcome of a march of progress (Barnes 2002). Discussion of the genesis of recent work on ontologies reinforces the axiom that time has multiple threads and cannot be represented as a single dimension. The history of GIS is not and has never been linear (Chrisman 1993). An open historicity in which there is constant reevaluation of the technology and the power relations it reinforces will better serve both the GIS and geography communities. Ultimately, representation of the spatial realm must take the next step of representing social concerns including power relations, gender inequities, social control through numerical representation, and social marginalization. Although the PPGIS movement, for example, has been successful in addressing some of these social problems, it is ultimately restricted by the formal limitations of GIScience technologies. To realize this broad range of social objectives, GIScientists working across the boundary between conceptualization and formalization, stand to benefit from an engaged critical GIS.

Notes

1. The success of PPGIS might lead to the conclusion that, contrary to the claim of this article, formalization does *not* matter because GIS can be made to represent multiple perspectives in its present guise. The counterargument is that nonhegemonic claims promoted by PPGIS must be engineered to fit the current representational limits of GIS. In the process of being articulated to work with GIS, political claims are fashioned to look like the policies they oppose.
2. It is worth noting that the familiar chestnuts of semantics and epistemology were explicitly tackled almost thirty years ago in the *Harvard Papers*. *Plus ça change* . . .

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Correspondence: Department of Geography, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6, e-mail: nadine@sfu.ca.