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Experiential and Formal Models of Geographic Space[1]

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ABSTRACT
This paper is concerned with human experience and perception of phenomena and relations in space. This focus is in contrast to previous work that has examined space and spatial relations as objective phenomena of the world. This concern leads in turn to a goal: to identify models of space that can be used both in cognitive science and in the design and implementation of geographic information systems (GISs). Experiential models of the world are based on sensorimotor and visual experiences with environments, and form in individual minds as the associated bodies and senses experience their worlds. Formal models consist of axioms expressed in a formal language, together with mathematical rules to infer conclusions from them. This paper reviews both kinds of models, considering them each to be abstractions of the same 'real world.' The review of experiential models is based primarily on recent developments in cognitive science, expounded by Rosch, Johnson, Talmy, and especially Lakoff. These models suggest that perception and cognition are driven by image-schemata and other mental models, often language-based. Cross-cultural variations are admitted and even emphasized. The ways in which people interact with small-scale ('table-top') spaces filled with everyday objects are in sharp contrast to the ways they experience geographic (large-scale) spaces during wayfinding and other spatial activities. The paper then addresses the issue of the 'objective' geometry of geographic space. If objectivity is defined by measurement, this leads to a surveyors' view, and a near-Euclidean geometry. These models then are related to issues in the design of GISs. To be implemented on digital computers, geometric concepts and models must be formalized. The idea of a formal geometry of natural language is discussed, and some aspects of it are presented. Formalizing the link between cognitive categories and models on the one hand, and geometry and computer representations on the other is a key element in the research agenda.

Key words: geographic theory, spatial relations, cognitive science, wayfinding, spatial cognition, geometry, geographic information systems, GIS

Introduction

Spatial relations do not exist in the world in any meaningful sense; rather, they exist in minds, to aid in making sense of the world, and in interacting with it. Our concern therefore is not with space and spatial relations as objective entities of the world, but rather is with human experience and perception of phenomena and relations in space, and the representation of these things in mathematics and digital computers. We admit that this is a 'non-standard' position for people involved with geographic information systems, and one that appears to be at odds with the positivist paradigm—in fact, it has almost a 'post-modern' flavor (see Harley, 1990). However, here we present an approach from cognitive science, and apply it to geographic space and spatial relations. This approach attempts to avoid some of the fundamental inconsistencies that are embedded within the positivist approach and the scientific method,

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yet avoids falling into pure solipsism[1]. We discuss relevant observations and propose formal models to account in part for how people think about their geographic worlds. More specifically, we discuss and compare two kinds of models that can be used to define space and spatial relations: experiential models and formal models.

Experiential models of the world are based on sensorimotor and visual experiences with the environment, but also include concepts developed through inference and spatial reasoning, all within a cultural and linguistic context. Experiential models form in individual minds as the associated bodies and senses experience their worlds. Due to the physiological similarities that exist between individual human beings, it appears that most people experience their environments in similar ways. Thus, we can expect that the basic features of individual experiential models of geographic space, while inherently personal, will have much in common across individuals, even if they developed in isolation. Experiential models of space can reveal themselves through spatial reference in natural language, through experiments with human subjects, through observation of spatial behavior, or through study of the artifacts of such behavior. Experiential realism, a philosophical basis for cognitive science that has recently been advanced by George Lakoff (1987) and Mark Johnson (1987), and discussed in a geographic context by Couclelis (1988, 1991), Mark and Frank (1989), Mark (1989), Frank and Mark (1991), and others, is central to the models discussed here, and is reviewed below.

Formal models consist of axioms expressed in a formal language, together with mathematical rules to infer conclusions from these axioms. We will review formal models as they are used to represent geographic space and spatial relations. Researchers typically use results from geometry, topology and algebra in our efforts to build formal models that are useful for geography. Formal models often bear strong similarities with experiential models of space and spatial objects; this is because both experiential and formal models often have been developed as abstractions of the same aspects of human observation and experience with the same world. Euclidean geometry is fully consistent with Newtonian (solid-body) physics; however, Newtonian physics itself corresponds closely with naive (experiential) physics in many every-day situations.

Most previous work on spatial cognition in geography has concentrated on studies of human behavior (for examples, see Golledge and Zannaras, 1973; Golledge, 1976, 1978; Golledge et al., 1983; Golledge, 1988). In a departure, Peuquet (1988), emphasized results from studies of human visual perception and cognition. The conceptual basis of our work is found primarily in the more linguistic parts of cognitive science. Our approach differs from most previous work on geographic theory, in that it draws primarily on concepts related to human natural language, especially the work of Eleanor Rosch (Rosch, 1973, 1978), Leonard Talmy (Talmy, 1983), George Lakoff (Lakoff and Johnson, 1980; Lakoff, 1987), Annette Herskovits (Herskovits, 1982, 1985, 1986), Mark Johnson (Johnson, 1987), and others in the cognitive sciences. Although a few articles drawing on this research have already been published in the geographic and GIS literatures (Mark, Svorou, and Zubin, 1987; Couclelis, 1988; Mark, 1989; Mark and Frank, 1989; Mark, Gould, and Nunes, 1989; Haller, 1989; Haller and Ali, 1990; Haller and Mark, 1990), this paper extends this work substantially.

GIS and Theoretical Geography

Geographers have long sought to develop a theory or theories of geographic space, or perhaps geographic theories of space in general. Recent developments in geographic information systems (GIS) have brought renewed calls for 'general' theories of spatial relations, beginning more than a decade ago (Boyle et al., 1983) and growing in urgency in the late 1980s (cf. Abler, 1987; Frank, 1987; Peuquet, 1988; NCGIA, 1989). Although theories of space and spatial relations need not have the explanatory power of the theories of a prototypical 'science' such as physics, GISs cannot be built without them. Furthermore, in a

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1 Solipsism is a philosophical position which denies the existence of the "real world", or at least insists that human minds can have no direct access to such a world, but that the mind can know only what the senses 'tell it'.

formal sense, a computer program can be considered to be a statement of some theory, and in this sense any GIS already is, or at least contains, geographic theory. If a more rigorous and explanatory definition of 'theory' is used, GIS certainly can be a test-bed for evaluating geographic theory.

One of the five high-priority topics for research by the National Center for Geographic Information and Analysis (NCGIA) was defined to be a search for "a general theory of spatial relationships" (Abler, 1987, p. 304). Abler went on to elaborate that the goal is "a coherent, mathematical theory of spatial relationships" (Abler, 1987, p. 306). On the same page, he also stated:

"Fundamental spatial concepts have not been formalized mathematically and elegantly. Cardinal directions are relative concepts, as are ideas basic to geography such as near, far, touching, adjacent, left of, right of, inside, outside, above, below, upon, and beneath."

But it is not sufficient for a "theory of spatial relationships" to be mathematically elegant. The concepts embedded in such a theory also must correspond with the concepts used by human minds during spatial cognition, spatial reasoning, and spatial behavior, for otherwise the theory will be of little if any use to geographers, spatial analysts, or GIS users. The search for "fundamental spatial concepts" must be conducted in the cognitive sciences in parallel with searches in mathematics (NCGIA, 1989).

The search for fundamental spatial concepts is not new in geography and associated disciplines. Blaut's 1961 Space and Process, Bunge's 1962 Theoretical Geography, Nystuen's 1963 Identification of Some Fundamental Spatial Concepts, and Sack's 1973 Geography, Geometry, and Explanation represent some of the more prominent of such efforts. Geographical theory has often appeared to be mathematical, and has sometimes been connected to language, but mathematical language, not human natural language. For example, geometry was discussed by Harvey (1969, pp. 191-229) as "the language of spatial form." Several papers at the October 1977 symposium on data structures for GIS, convened by Harvard University, addressed just these issues and provided a number of approaches (found most notably in the papers by Chrisman, 1979; Kuipers, 1979; Sinton, 1979; and Youngman, 1979).

The need for theory in GIS was even more clearly expressed in 1983, when, in the report of a NASA-sponsored meeting, it was recognized that:

The (present) lack of a coherent theory of spatial relations hinders the use of automated geographic information systems at nearly every point. It is difficult to design efficient databases, difficult to phrase queries of such databases in an effective way, difficult to interconnect the various subsystems in ways that enhance overall system function, and difficult to design data processing algorithms that are effective and efficient. As we begin (to) work with very large or global spatial databases the inabilities and inefficiencies that result from this lack of theory are likely to grow geometrically.

While we can continue to make some improvement in the use of automated geographic information systems without such a coherent theory on which to base our progress, it will mean that the development will rest on an inevitably shaky base and that progress is likely to be much slower than it might be if we had a theory to direct our steps. It may be that some advances will simply be impossible in the absence of a guiding theory (Boyle et al., 1983).

The needs for a sound conceptual basis for GIS, and for a mathematical basis for theories of geographic space, leads to parallel and complementary research efforts within the GIS agenda, in cognitive science, and in general geography. Some signposts along this path are presented in this paper.

Cognitive Categories & Experiential Realism

Many of the concepts and principles presented in this paper are based on a concept of human cognition initiated by Rosch (1973, 1978) and her colleagues, and recently elaborated upon by linguist George Lakoff (1987) and philosopher Mark Johnson (1987). A cornerstone of these theories is a concept of categories that departs from the classical or set-theoretic view in a number of fundamental ways, and requires some exposition here.

Categories

The classical view of categories is that they correspond mathematically to sets (Lakoff, 1987). In fact, it probably would be more correct to say that the mathematical concept of a set is a formalized version of the naive concept of a category, but the formalization into set theory produces some subtle yet fundamental effects. The set-theoretic idea of categories contains the assumption that there are necessary and sufficient observable properties of any entity, from which its membership or non-membership in some set can be deduced without ambiguity. Another principle is that all members of any set are equally related to the set, and thus would be equally good examples of the set. Thus classical set theory would predict that, when asked to give an example of a member of a set, a person would be equally likely to name any known member of that set.

Experiments in cognitive science have found that neither of these aspects is true of most of the categories that individuals use to organize their worlds (see Smith and Medin, 1981; also Lakoff, 1987, pp. 54-57). Problems with this classical theory were noted quite early by Cassirer (1923), but the work of Rosch (1973, 1978) was central to the diffusion of doubt about the cognitive validity of classical set theory. Rosch and her co-workers discovered that, in many cases, all members of a category are not 'equal'. For example, when asked to give an example of a bird, subjects tend to name robins and sparrows as examples far more often than they mention turkeys or penguins or ducks. Rosch's data are far more consistent with a model in that a category has one or more prototypes or exemplars. In addition, the set has some methods for extending the category, by analogy, metaphor, and other procedures, to attach more peripheral members to the central ones. Lakoff (1987) later discussed this in terms of a radial structure for some categories. He noted that peripheral members of different arms of a radially-organized categories may have nothing in common, except different chains of resemblance to some common prototype.

Smith and Medin (1981) reviewed the classical theory of categories, and the problems with it, and proposed two alternative models. One is a probabilistic model; this, however, fails to predict some areas in which observed category structures depart from the classical model. Another model is one based on exemplars. This model would represent a class by a collection of one or more actual cases that in some sense exemplify the class. Although such a model is highly consistent with observed cognitive data, complete description of all properties of class exemplars seems unlikely, and comparison of a new case with all the exemplars, which would be needed to assign that object to some category, may not be a practical model of the mind. The model proposed by Lakoff (1987) and Johnson (1987) is similar to Smith and Medin's (1981) exemplar model, but is based on idealized prototypes (idealized models) rather than actual-case exemplars. Prototypes may be obtained from exemplars by abstraction and generalization.

Perception, Cognition, and Schemata

Recent developments in cognitive science suggest that the categories that people use are not necessarily 'objective'. According to this view, perception and cognition do not involve 'direct' interaction with the world, but rather occur through cognitive models, image-schemata, etc. Neisser (1976) discussed how even apparently-direct visual experiences are influenced (biased) by what we expect to see, or what we look for:

In my view, the cognitive structures crucial for vision are the anticipatory schema that prepare the perceiver to accept certain kinds of information rather than others and thus control the activity of looking. Because we can see only what we know how to look for, it is these schema (together with the information actually available) that determine what will be perceived. (Neisser, 1976, p. 20)

Schema-driven perception is a central idea to experiential realism. Neisser presented the following definition of a schema:

A schema is that portion of the entire perceptual cycle which is internal to the perceiver, modifiable by experience, and somehow specific to what is being perceived. The schema accepts information as it becomes available at sensory surfaces and is changed by that information; it directs movements and exploratory activities that make more information available, by which it is further modified. (Neisser, 1976, p. 54)

Schemata form a central part of Neisser's model of cognition. Objects are conceptualized through "object schema" (see Neisser, pp. 67-70). He also emphasized the role of schema in wayfinding and navigation:

I will ... frequently use the term "orienting schema" as a synonym for "cognitive map" to emphasize that it is an active, information-seeking structure. Instead of defining a cognitive map as a kind of image, I will propose ... that spatial imagery itself is just such an aspect of the functioning of orienting schemata. (Neisser, 1976, p. 111).

This theme will be picked up in a later section of this paper.

Johnson (1987) claimed that mental activities such as perception and cognition are heavily influenced by what he called image-schemata. Johnson defined a schema differently from how Neisser did:

"A schema consists of a small number of parts and relations, by virtue of which it can structure indefinitely many perceptions, images, and events. In sum, image-schemata operate at a level of mental organization that falls between abstract propositional structure, on the one side, and particular concrete images on the other." (Johnson, 1987, p. 29)

For any particular domain of investigation, one conceptual schema may be more useful than others. It is more likely that the most appropriate schema will change from problem to problem, context to context. Johnson also noted that schema themselves may change each time they are used. No particular schema is "correct," but particular schema are useful for particular situations.

Johnson (1987, p. 126) provided a clear statement, with examples, of how an image-schemata-based model of cognition would operate:

"... Much of the structure, value, and purposiveness we take for granted as built into our world consists chiefly of interwoven and superimposed schemata... My chief point has been to show that these image schemata are pervasive, well-defined, and full of sufficient internal structure to constrain our understanding and reasoning. [Johnson's italics] To give some idea of the extent of the image-schematic structuring of our understanding (as our mode of being-in-the-world or our way of having-a-world), consider the following partial list of schemata, which includes those previously discussed:

Container	Balance	Compulsion
Blockage	Counterforce	Restraint Removal
Enablement	Attraction	Mass-Count
Path	Link	Center-Periphery
Cycle	Near-Far	Scale
Part-whole	Merging	Splitting
Full-empty	Matching	Superimposition
Iteration	Contact	Process
Surface	Object	Collection

This brief list is highly selective, but it includes what I take to be most of the important image-schemata. If one understands 'schema' more loosely than I do, it might be possible to extend this list at length." (Johnson, 1987, p. 126).

Many of the image-schemata that Johnson lists are inherently spatial or even geographical: Container, Blockage, Path, Surface, Link, Near-Far, Contact, Center-Periphery, Scale, perhaps others . Johnson recognizes the importance of 'near' in his discussion of how image schemata, and in particular the center-periphery schema, constrain meaning, understanding, and rationality:

"Given a center and a periphery we will experience the NEAR-FAR schema as stretching out along our perceptual or conceptual perspective. What is considered near will depend upon the context, but, once that is established, a SCALE is defined for determining relative nearness to the center." (Johnson, 1987, p. 125) .

Lakoff and Johnson point out that spatial schemata appear to be at the core of cognitive structure, and form the basis for organizing many less-concrete domains. "Spatialization metaphors are rooted in physical and cultural experiences" (Lakoff and Johnson, 1980, p. 18). A physical journey through geographic space becomes the source domain for metaphors for various kinds of work projects and even for interpersonal relationships ("We're at a crossroads"; "This relationship is a dead-end street"; etc.; Lakoff and Johnson, 1980, p. 44-45). This method of 'spatialization' of inherently non-spatial concepts makes results from geography, as the field investigating space and spatial relations, likely to be applicable in other domains.

Some Geographical Examples

Image-schemata are, in principle, not directly observable. However, if Lakoff, Johnson, and the others are correct, image-schemata have a profound and pervasive influence on cognition and language. In this section we use examples of natural-language expressions describing geographic situations that allow us to deduce which image schema was likely to have been dominant in the speaker's mind at the time the expression was uttered.

Most Indo-European languages express fundamental spatial relations through prepositions. (Some other languages used 'post-positions', cases, or other grammatical structures to indicate relative locations.) In English, spatial relations of features (figures) to areal or polygonal reference (ground) regions are expressed by the preposition "in" in some cases yet by "on" in other cases. For example, note the use of "in" and "on" in the following: "I was standing in my back yard on my property in Amherst." Each ground object ("back yard", "property", "Amherst") has a surface, and each has a boundary; thus to an objectivist, both "in" and "on" would seem to be valid in each case. Nevertheless, most ground objects do not give the English speaker a choice, but rather require one preposition or the other. Herskovits (1986, p. 147; p. 153) catalogued some cases, but did not provide explanations for why some ground objects require "in", while other very similar grounds require "on". Furthermore, the distinction between grounds that require "in" and those that require "on" probably is quite old, since, with just a few exceptions, German and Dutch commonly require auf or op (respectively) for the same situations for which English uses "on", and in for situations in which English also uses "in".

Mark (1989) provided an explanation of sorts for this, although it only changes the question, rather than answering it. Mark (1989) proposed that the choice of preposition depends on the image schema adopted. In some cases, a Platform schema is adopted; once this schema is activated, the English preposition "on" is obligatory. (We follow Mark, 1989, in using a new Platform schema rather than Johnson's Surface schema, to allow us to use distinct schemata for the German auf and an, whose distinction will be discussed below.) In other cases, a Container schema is invoked, forcing the speaker or writer of English to use "in". The question relating to the use of "in" or "on" then becomes: "Which image-schemata is activated for which ground objects in which circumstances?" Finding an answer to this question is a challenging research problem.

Mark (1989) noted that conceptualizing something as an island more-or-less forces an English speaker to select the Platform image-schema, and use the preposition "on". If the word "island" appears in the name, this almost requires the speaker to say "on". ("Who lived on Manhattan Island before the Europeans came?") On the other hand, for political units, English almost invariably invokes the Container schema and uses "in". This will be true even for regions that happen to be in 1:1 correspondence with a physical island. ("Does your uncle still live in Puerto Rico?") However, for such island units, either "in" or "on" might be used, and the preposition chosen can indicate whether one is talking about a physical island or a country by forcing the listener/reader to use a particular schema. "Did anyone live on Cuba before 1492?"-- the same sentence with "in" might sound strange, since Cuba-the-country did not exist then. (Unlike islands, continents typically take the preposition "in" in English; the relation of choice of schema to sheer size of the land mass, suggested by Grimaud, 1988, remains an open question.)

The following example of how the choice of preposition may force the reader or listener to make different interpretations, based on different image-schemata, was first presented by Mark (1989):

"Hawaii" is the name of a State of the USA; but, "Hawaii" is also the name of the largest and easternmost island in that State. Recall that in English, political units normally involve the Container image-schema, whereas islands use the Platform image-schema. Thus, if I say: "My friend Sherry lives in Hawaii", it seems that "in" forces the Container image-schema, leading to the "State-of-Hawaii" interpretation. She might live in Honolulu (on the Island of

Oahu), or anywhere else in the State. But, if I say: "My friend Sherry lives on Hawaii", then the Platform image-schema leads to the "Island-of-Hawaii" interpretation, and the residence probably is Hilo or Kona. The use of "in" or "on" forces either the Container or Platform schema, respectively, thus reducing ambiguity. (Mark, 1989, p. 554)

Natural languages differ in their potential to influence meaning in this way. For example, in Spanish, most locative expressions use more generic prepositions such as en (in, on, or at) or de (also used as a possessive). Indeed, a dictionary gives the primary meaning of en as "prep. of time or place" (Velázquez, 1973, p. 267). Thus a Spanish-speaking person would not normally use a choice of prepositions to distinguish the two Hawaiian situations discussed in the last paragraph, but would have to explicitly use either "El estado de Hawaii" or "La isla de Hawaii" as the reference (ground) object, or simply leave the expression ambiguous. On the other hand, German has two prepositions (an and auf) that both may translate to the English "on". An applies to lateral adjacency, whereas auf has a meaning closer to "on top of". A German speaker could use an or auf to force different meanings in cases where an English speaker would have to use additional words or would have to tolerate ambiguity.

Observing such differences sometimes allows us to deduce which image schemata people are using. In the example above, native speakers of German, English and Dutch appear to share an image-schematic differentiation that is manifested in their use of prepositions. In this case, the use of image-schemata becomes observable, that is, we have some observable facts that can be accounted for by the assumption that image-schemata are used in the proposed form. The occasional situations in which English and German seem to require different prepositions, such as the fact that a car is "in the parking lot" (Container) yet "auf [=on] dem Parkplatz" (Platform) apparently apply to modern situations in which different base nouns are used in compound names for ground objects. But using a different noun that forces another image-schema, a German speaker would say "der Wagen ist im Parkfeld" ("the car is in the park(ing) field", between the white markings that delimit a space) or "der Wagen ist in der Parkzone" ("in the parking zone"). Evidence suggests that image-schemata may be common across linguistic and cultural groups (universals), but their use will differ1. Studies are needed to establish cross-linguistic differences in the way that image-schemata are applied to various geographical and other spatial situations.

Models of Space

In this section, we review models of geographic and other spaces, and their relation to naive physics and to navigation and wayfinding.

Models of 'Small-Scale' Space

Downs and Stea (1977, p. 197) distinguished perceptual2 space, studied by psychologists such as Jean Piaget and his colleagues and followers (Piaget and Inhelder, 1956), from "transperceptual" space that geographers deal with, and that we are focusing on in this paper. They claimed that "the two scales3 of space are quite distinct" (p. 197) in the ways people

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1 Image-schemata for languages other than English, or for other cultures, have yet to be examined in detail, however.

2 We use the term *perception* strictly to mean mental reactions to sensory inputs in the presence of a stimulus. Perception is what happens in our minds when we hear, see, feel, taste, or smell. This usage is consistent with the meaning of 'perception' in psychology and cognitive science. Under this usage, what some geographers call 'environmental perception' really should be called 'environmental cognition.'

3 In this paper, we use scale to be synonymous with *scope*, the characteristic lengths or extents of objects, scenes, etc. This is how the term scale is used in meteorology and other physical sciences, and in the writings of Downs, Stea, and Kuipers. In this usage, large-scale things are larger than small-scale things. This usage can be confusing for cartographers, since small-scale maps cover large areas and show large things, whereas large scale maps typically show only small areas and can depict small things. The apparent difference

perceive and think about them. Later in the book, Downs and Stea (p. 199) contrasted the terms "small-scale perceptual space" and "large-scale geographic space." At about the same time, Kuipers (1978, p. 129) defined large-scale space as "space whose structure cannot be observed from a single viewpoint," and by implication defined small-scale space as the complement of this. The large-scale vs. small-scale distinction of Kuipers does not quite correspond to a geographic vs. non-geographic contrast, since as Kuipers pointed out, a high mountain viewpoint or an aircraft permits direct visual perception of fairly large areas. Nevertheless, we will follow Kuipers, and use the term large-scale space as he defined it, and small-scale space to refer to subsets of space that are visible from a single point.

Cognitive models of small-scale space develop from direct experience of our everyday world, dominated by a combination of visual inputs and the interactions of our bodies with the objects in that space. People are very good at processing the visual field, and at interpreting observed sequences of images, that are essentially two-dimensional at the retinal level, to be views of objects in a three-dimensional space. In fact, it has been claimed that "the visual system attempts to interpret all stimulation reaching the eyes as if it were reflected from a scene in three dimensions" (Haber and Wilkinson, 1982, p. 25).

As noted above, bodily (sensorimotor) experiences with small-scale space also play a key role in the ways we build our mental models of such spaces. Lakoff and Johnson (Lakoff and Johnson, 1980; Lakoff, 1987; Johnson, 1987) claim that our spatial concepts for small-scale space largely are projected from human-body space (see also Couclelis and Gale 1986), and Svorou (1988) has shown that spatial terms themselves also often have bodily groundings. The ways in which the body interacts with objects allow us to recognize 'basic-level' objects such as 'chairs' or 'dogs' by about the age of two years (see Rosch, 1973).

People also naturally build dynamic cognitive models based on their observations of how familiar objects behave (react to forces) in small-scale space. The field known as naive physics (sometimes called 'common-sense physics') deals with the ways in which people typically think that physical objects behave. For example, many people not trained in formal physics think that, when a person drops a ball while walking, the ball will fall straight down (McClosky, 1983), when according to Newtonian or classical physics, the ball retains a forward motion component, falls in a parabola, and must be dropped before the hand is directly over a target in order to hit that target. Naive physics has associated with it concepts of distance, direction, connectivity, continuity, etc., that might be termed a 'naive geometry'.

Concepts of naive physics are of great interest not only as an aid to understanding the behavior of physical objects, but also because they help us to reason effectively and to deal with situations that are currently not tractable with the methods of classical physics. For instance, the behavior of lettuce and salad dressing can be modeled using the principles of classical physics, but the resulting formal system is so complex that it would not be useful to, for example, guide a robot (Hobbs and Moore, 1985, p. xi). In contrast, principles of 'naive' physics may be successfully and easily used in such situations, and may produce adequate results. By analogy, we expect that a formalization of some of the 'naive' geometric reasoning used in geographic space may be valuable for expert systems exploiting geographic data collections.

Perception of the physics of everyday objects, together with our own bodily structures, also influences the way we perceive and label the structure of space. Gravity is so pervasive that the up-down axis is clearly the most salient, or most important to human perception and cognition. The horizontal plane, perpendicular to this vertical axis, is less differentiated in the environment. However, for humans, the front-back contrast, while less salient than up-down, is considerably more salient than left-right. This observation, discussed by Freeman (1975) and by many others, probably arises due to the fact that humans and most other animals show bilateral symmetry for most external components; also, our eyes and ears are also arranged in side-to-side pairs. This salience ordering of the three dimensions of everyday (small-scale)

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arrives through the inverse relationship between represented size and scale when the size of the representing medium is held constant.

space (up-down >> forward-back >> left-right), and the fact that the last two distinctions are egocentric or object-centered, is important to the models discussed later in this paper.

Introduction of concepts of measurement, mathematics, and science, especially during the time of the classic Greek philosophers, made a formalization of geometry and physics desirable. School books tell us that plane geometry was first developed in Egypt to allow for land-ownership boundaries (the cadastre) to be re-established after the annual floods of the Nile. Abstraction of this practical formalization into a set of axioms is credited to Euclid. Euclidean geometry conforms well to the geometry that we observe in our everyday lives. Current school curricula instill upon the pupil the idea that Euclidean geometry is the only 'correct' geometry.

A formal theory of physics proved more elusive, and Aristotle's physics was fundamentally flawed. For example, Aristotelian physics predicts that an object must expend energy to keep moving, and will stop if force is no longer applied to it, but everyday objects appear to behave this way because of friction, and not because of the fundamentals of mechanics (see Di Sessa, 1982, for a discussion of Aristotelian, Newtonian, and naive physics). The classical physics that corresponds closely to the behavior of everyday objects in small-scale space is usually attributed to Sir Isaac Newton. Newtonian (solid-body) physics corresponds with naive physics well enough that people who 'believe in' Newtonian physics can deal with everyday objects as if the objects were governed by its 'Laws'. (For further discussions of naive physics, see McClosky, 1983, or Hobbs and Moore, 1985.) Newtonian physics conforms closely with observable reality, while at the same time is a highly abstract, formal system that is extremely useful in both engineering and scientific applications, where it can be used to build models and to predict the behavior of mechanical systems. Furthermore, Newtonian physics is completely consistent with Euclidean geometry.

Models of Geographic Space

The region of space that we can experience bodily at any moment is limited to a few cubic meters. The region we can experience visually usually is larger and much more variable, but the combined extent of all the spaces that we experience during the course of a day's activities usually is much larger again. As noted above, Kuipers (1978, p. 129) called this large-scale space, defining it as "space whose structure cannot be observed from a single viewpoint." Kuipers' model of spatial knowledge acquisition (Kuipers, 1978, 1983a, 1983b) begins from a basis in sensorimotor experience. As we move through geographic space, we see a sequence of views1. With some views, we associate actions. Some of these actions form part of the navigation or way-finding process, and other actions relate to other activities. Kuipers' TOUR model (implemented as a computer program in LISP) uses as input ordered sequences of view-action (V->A) pairs. The routes form a 'spaghetti' of familiar paths, which constitute procedures for getting from one place to another2. Note that this kind of spatial knowledge is termed 'topological' by Piaget and his followers (Piaget and Inhelder, 1956), and 'procedural' by Thorndyke and Hayes-Roth (1982) and by Mark and McGranaghan (1986). Because such large-scale spaces are the ones that geographers typically study, we consider 'geographic space' to be roughly synonymous with 'large-scale space'.

Kuipers (1978, 1983a, 1983b) noted that, as people find their way along various paths, they may recognize that the paths have some points ('places') in common. This allows them to use

1 A 'view' is defined as the sum total of all sensory inputs when at a point and oriented in a particular way, but for most people, the 'views' are dominated by visual inputs.

2 We first used the spaghetti metaphor here because of the frequent use of the term 'spaghetti files' in digital cartography. However, in his work _The Songlines,_ Bruce Chatwin explicitly used the 'spaghetti' metaphor in describing the models of geographic space that are central to Australian aboriginals' myths and traditions: "One should perhaps visualize the Songlines as a spaghetti of Iliads and Odysseys, writhing this way and that, in which every 'episode' was readable in terms of geology" (Chatwin, 1988, p. 16).

inference processes to build network models of places and connections, paths and barriers, in geographic space. Such cognitive models of geographic space allow route-planning to novel destinations, or the planning of alternate routes when habitual paths are blocked. Paths may have associated with them properties such as length in miles, kilometers, or blocks, or expected traversal times or effort, but global geometric properties, such as locations, straight line distances between points, cardinal directions, etc., often are weakly defined, inaccurate, or are absent from the model at this level. Such properties of some cognitive models of geographic (large scale) space were noted very early by Trowbridge (1913).

In Kuipers' TOUR model, spatial inference rules allow the model to be refined more and more, as more and more (V->A)-pair sequences are learned and assimilated, until a 'geometrically-correct' model of geographic space is built up. Such configurational models of space apparently are formed by at least some other organisms; for an example, see Gould's (1986) work on the 'cognitive maps' of honey bees. However, it seems that, for many people, such a two-dimensional Euclidean (Cartesian) model of geographic space is never built from experience alone, or at least that it takes a very long time. Mark and McGranaghan (1986, p. 402) proposed that "access to graphic, metrically-correct maps almost certainly plays a key role" in the development of a Cartesian cognitive model of geographic space. Such a conjecture is implicit in the findings of Thorndyke and Hayes-Roth (1982), and is supported by recent experiments by Lloyd (1989a, 1989b) and Freundschuh (1991).

Matthew McGranaghan has stated that the power of maps comes from the fact that they represent space with space[1]. In fact, maps use a small-scale space, namely a piece of paper or a computer screen, to represent a large-scale (geographic) space. This allows people to experience some aspects of the geometry of a geographic space indirectly, but in a 'familiar' way, that is, the way they experience objects in small-scale space, such as everyday objects on a desk-top or kitchen table. Thus the map allows people to extend Euclidean geometry to geographic space, to be used as a basis for spatial inference, reasoning, and decision-making.

What is the 'Objective' Geometry of Geographic Space?

There is little doubt that maps allow people to extend the geometry of small-scale space outward to geographic space. Whether or not this is appropriate depends primarily on the use that is made of the geometry, and on how different the geometry is from the 'geometry' of perceived (experiential) reality. And the difference must be judged in the context of the specific task.

If one believes that Euclidean geometry is also the 'true' or 'objective' geometry of geographic space, then the map is a very valuable tool, since it allows us to grasp this 'truth' and use it. With a map in hand, or with a map-based cognitive model of a particular geographic space, one can plan routes and perform other spatial inference using the familiar Euclidean model. If, however, the perceived geometric properties of geographic space based on experience are not compatible with the Euclidean geometry proposed by the map, then the map may be an 'incorrect' model for geographic space. The map model of geographic space would in a sense be a 'specification error'. Road maps, navigational charts, and topographic maps present Euclidean views of the world, and are very useful. But the famous schematic of the London underground (subway system), and the other subway maps that mimic it, are also very useful, and most assuredly are not Euclidean.

In light of this question about the relation between Euclidean maps and experiential space, one must wonder about the method used by Brody (1981) in his work on land-use and occupancy patterns for the aboriginal peoples in northwestern Canada. The Athapaskan informants were asked to draw their hunting, berry-picking, fishing, and trapping areas on topographic maps of a scale of 1:250,000. It seems unlikely that this procedure captured how they experience their

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1 Paper presentation at the Eighth International Symposium on Computer-Assisted Cartography (Auto-Carto 8); the comment does not appear in the written version of his paper, which appeared in the proceedings of that meeting.

geographic spaces. However, perhaps the authorities would not have believed them otherwise, as indicated by the following quotation:

"But when they discovered a sports hunter's equipment cache and an old campsite a few miles from the bear kill, their expressions of indignation were nothing if not political. As he uncovered cans of fuel, ropes, and tarpaulins, and looked around to see if a kill had been made, Atsin declared over and over again that white men had no right to hunt there, on the Indians' land. When Joseph [an Indian elder] heard about the cache he said: 'Pretty soon we'll fix it all up. We've made maps and everyone will see where we have our land." (Brody, 1981, p. 270)

Our examinations of the concept of 'objective' or 'correct' geometry in this section have rested on an assumption that the 'real world' exists, and that it has 'objective' properties. The decision to adopt a particular definition of objectivity is itself subjective, and Hillary Putnam has shown that a paradigm of complete objectivity is internally inconsistent (see discussion in Lakoff, 1987, pp. 229-259). Nevertheless, experiential realism, discussed above, is based on the idea that there is a real world, that has consistent properties, so that when people interact with that world, their mental experiences are very similar.

Measurement

One way to escape from problem posed by individual experiential spaces is to arbitrarily adopt a definition of objectivity. An obvious candidate, common in the sciences, is to declare that objective properties are those that can be measured in a reproducible way. Then one could reasonably claim that 'the' geometry of surveying is the 'correct' and 'objective' geometry of geographic space. At scales ranging from planet Earth to the human body, Euclidean geometry and Newtonian physics seem consistent with measurement and observation, yet are mathematically formal. The fact that Euclidean geometry breaks down at certain temporal, spatial, or velocity scales, and that Einstein's theory of relativity required new geometries, thus re-orienting the cutting edge of academic geometry, seems to be of little if any relevance to geography and surveying.

It is not far wrong to view our planet as a spheroidal solid body in Euclidean three-dimensional space; geodesy has established the shape of that body, and of the geoid. The surface of the earth is essentially a two-dimensional manifold stretching over the surface of that geoid; position can be denoted as two angles (latitude and longitude), and elevation above 'sea-level' at any point may be defined as the height above that geoid. Geodesists and surveyors routinely use such a model and with the precision of the measurement techniques available today (generally better than 1 part in 106), these professionals do not observe any discrepancies between their observations and the model.

Map projections allow us to transform from one two-dimensional surface (over the spheroid) to another (a Cartesian plane) in ways that control the geometric distortions that necessarily result. For 'sufficiently-small' regions of the planet (say, up to about the size of the 48 contiguous states of the United States), the curvature of the planet can more or less be ignored; map projections exist that show almost no distortion of areas, angles, or distances over regions of that size or smaller (see Snyder, 1982).

In a scientific (positivist) view, measurement would often be considered to be the only way to 'see' space in an objective way. However, it also is possible to define 'correct' in a way that does not rely on the concept of measurement. People usually experience space not by measurements, but rather by observing results of processes that are related to or occur over or through space. An every-day example for such a process is that physical movement in space requires time. Travel time and effort are usually proportional to the distance between two points, although the relationship is seldom linear.

On a conceptual level, the difficult task is to combine the multiple, conflicting concepts that people may use in their interaction with objects in space, and to model how these concepts influence specific spatial behavior. Geography deals with many of these spatial processes, and thus geography and geographers can play a key role in discovering the spatial properties influencing these processes; this may in turn help researchers to understand human spatial cognition.

Spatial Cognition and Geographic Information Systems

Considerable effort has been spent over the last two decades to build geographic information systems (see Maguire et al., 1991). Numerous organizations have collected data and built GISs or other similar 'spatial information systems'. However, many of the systems constructed have been extremely limited in their capabilities to exploit spatial location, and many have used methods that were mathematically well-defined but not necessarily 'intuitive', i.e. they did not agree with the spatial concepts used by all their users. Progress in GIS development appears to have been impeded by a lack of formal understanding of spatial concepts as they apply to geographic space (see discussion under "GIS and Theoretical Geography", above).

In order for a GIS to be an effective information system and a useful tool for spatial representation and analysis, the concepts it embodies and the ones employed by its users must be as similar as possible. Donald Norman (1990) identified three conceptual models of a device and its use: the design model, the user's model, and the system image. Ideally, all three models would be equivalent, but this is unlikely for complex devices. The design model is what the designer or design team had in mind when designing the device. "The designer must develop a conceptual model that is appropriate for the user, that captures the important parts of the operation of the device, and that is understandable by the user" (Norman, 1990, p. 189). "The user's model is what the user develops to explain the operation of the system" (Norman, 1990, p. 189). The user's model may be influenced by training, education, manuals, and the system itself. The third component, the system image, is the way the device actually operates. The image of the system includes "its physical appearance, its operation, the way it responds, and the manuals and instruction that accompany it" (Norman, 1990, p. 190). A strategy based on training may severely limit the user community and the applicability of the system. Alternatively, systems can be built using concepts very close to the ones that untrained users would expect. Current systems are primarily designed and constructed following the first approach.

In the preceding sections, we discussed some observations regarding concepts people use to structure geographic space. A GIS should embody these concepts, and it is especially important that the user interfaces for such systems be 'natural'. In the remainder of this section, we will discuss the mathematical bases of geometry, and how such concepts could be formalized while keeping them faithful to the cognitive engineering principles outlined above. If these concepts cannot be formalized, then they cannot be included in GISs; in fact, the simple fact of inclusion of any of these concepts in a GIS implementation may constitute the required formalization.

A GIS can be regarded as a fixed set of instructions embodying a set of procedures (algorithms) to process spatially-referenced data in a formal way. Most GISs are based on Euclidean geometry and are implemented using analytical geometry. In a vector-based GIS, every point or line is situated on a coordinate plane, and the locations of the points are characterized by coordinate pairs. The assumption is that all other necessary or interesting spatial properties can be derived from these points and their coordinates, although selected spatial relationships are often explicitly encoded to improve efficiency. Euclidean geometry and the formulae of analytical geometry are well known and relatively easy to understand, and thus the actual writing of GISs was expected to be an easy and straightforward task. There are however, a number of problems related to the use of Euclidean geometry in this manner. First, the implementation of Euclidean geometry on a digital computer is not straightforward. Analytical geometry and the validity of its formulae assume a coordinate plane created from real numbers (R x R). A computer, being a finite-precision system, cannot implement real numbers exactly, but can only represent approximations to the real numbers. These approximations are limited both in their magnitude (overflow or underflow conditions arise if results of computations become too large or too small) and also in their resolution (not every point in the plane can be represented). In Euclidean geometry, one can always find an intermediate point exactly half way between any two given points; in computer coordinates, however, this is not always possible. GIS implementations may show artifacts that are due to this problem; they may even break down in unexpected situations (see Franklin, 1984). The implementation of analytical geometry on a computer is really a geometry on a discrete (though admittedly very fine) grid, where point locations are restricted to grid points. In such a situation, many of the standard laws of Euclidean geometry do not hold (Franklin, 1984; Nievergelt and Schorn, 1988).

A GIS programmer thus faces the problem of taking a conceptual framework expressed in Euclidean geometry, and expressing it as a program on a finite-precision digital computer (Figure 1, right side). But if GISs are to reflect the concepts that untrained users might employ, this approach also must bridge the gap between the naive geometry of the user and the (quasi-) Euclidean system that the programmer can implement (Figure 1, left side).

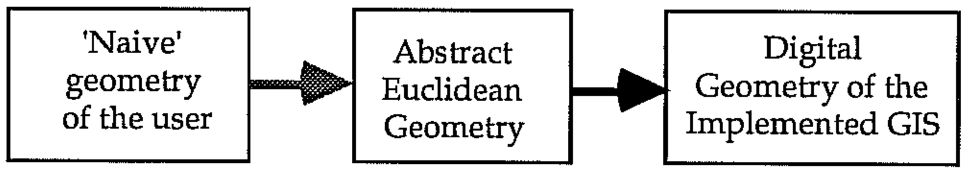

Figure 1: Using Euclidean geometry in modeling geographic information on computers involves two transformations, one (on the right) fairly well understood, the other less so.

There is much evidence to suggest that the concepts employed by users of geographic information are not exactly Euclidean, either. This is not so much a disagreement with the concepts of Euclidean geometry, but rather involves additional concepts that are not included in Euclidean geometry, such as, for example, the directions between extended objects. GISs thus may be unable to answer questions that appear reasonable and well defined to the user, such as 'What is the direction from New York to Canada?'. Peuquet and Zhan (1987) investigated this problem, and provided solutions for some situations, but they did not evaluate their solutions through user testing.

It is unlikely that shortcomings in one of the mappings in Figure 1 can be compensated for by adjustments in the other. More likely, the problems will be amplified, and even if the user has successfully learned how to transform his or her concepts into the Euclidean geometry, the implementation cannot follow that theory exactly. A more sensible solution would be to map the user concepts to the implementation directly, bypassing Euclidean geometry (see Figure 2). However, such a mapping is far from trivial, and requires groundwork and basic human-subjects research in cognitive science.

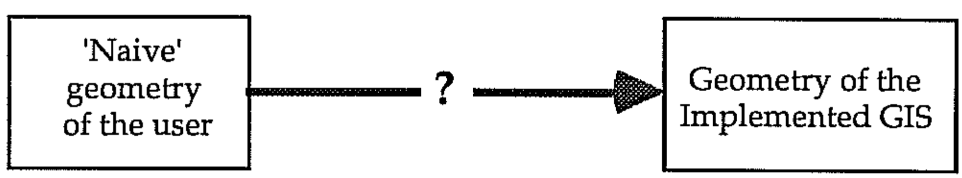

Figure 2: If a GIS users' naive geometry can be modeled directly on the computer, a more successful implementation should result.

Formalization of conceptual geometries

As we have noted many times in this paper, the concepts of space and spatial relations that users have must be formalized, that is, must be converted into a formal mathematical theory, before they can be implemented. This however will presumably lead to new and different geometries. While this may seem like a drastic step, constructing new geometries is not unheard of in mathematics. Until the beginning of the last century, Euclidean geometry was the only form of geometry that was recognized. Efforts to show that Euclid's set of axioms was minimal, and especially to show that the axiom based on parallel lines was independent of others, were unsuccessful, and this led to the discovery that other geometries were possible, and indeed that their construction is straightforward. Hyperbolic (or Lobachevskian) geometry, where two lines can fail to intersect and yet still not be parallel, was constructed by replacing Euclid's axiom for parallel lines with its negation. The elliptic (or Riemannian) geometry, in which no two lines are parallel to each other, is another geometry, and one that has a well-known application: the geometry on the sphere is (double) elliptical, and any two 'lines' (great circles) intersect in two points (Blumenthal, 1986, p. 176). Although it was difficult for some mathematicians and scientists to accept the fact that there were other geometries in addition to the widely accepted one, these new concepts of geometry became extremely important for developments in physics, especially the theory of relativity. Non-Euclidean geometries have been discussed in geographic contexts by Harvey (1969, pp. 199-203), Tobler (1976), Müller (1982), and others. However, except for geodesics on cost surfaces, non-Euclidean geometries have not made significant inroads into mainstream geographic models or (especially) into geographic information systems.

For mathematicians, however, the problem was not testing whether a particular geometry was useful or not. Instead, the problem became the determination of what made a theory of space a geometry. Felix Klein, in his famous 'Erlanger program' (Klein, 1872), which influenced the development of mathematics for several decades, defined the field of geometry by a concern for properties of objects that remain unchanged (invariant) when the object is subjected to one of a group of transformations. A transformation in this case is defined as a mapping of a space onto itself. For example, Euclidean geometry deals with properties such as lengths of lines, sizes of angles, etc., all of which remain invariant under the transformations of rotations and translations. Klein's definition of geometry also included fields of mathematics such as graph theory and topology, that have a geometric component. Typically, each group of transformations defines a set of properties that remain invariant and thus creates a geometry that can be formally defined and studied. This definition of geometry seems more appropriate for our purposes than some further refinements, which replace the group of transformations by equivalence classes (Blumenthal and Menger, 1970, p. 27). The use of groups of transformations is also part of the method used by Couclelis and Gale (1986), when they studied invariants of movements.

Leonard Talmy's pragmatic approach to linguistic representations of space also focuses on identifying invariant properties (Talmy 1983, p. 258 - 263; see also Talmy 1988, p. B-3). Expressions of spatial relations and properties in natural language are often invariant under a wide set of transformations and in most languages (Talmy, 1983; Talmy, 1988). As an example, the English-language preposition 'in', representing the Container image-schema, apparently is:

- material neutral: the use of 'in' is generally independent of the materials from which the figure and the ground are composed;
- magnitude neutral: 'in' is used without regard to the size of the figure or the ground;
- shape neutral: the shapes of the figure and the ground are normally irrelevant);
- closure neutral: the preposition is used whether the ground is completely closed (as in the case of a box) or partially open (as in the case of a bowl); and
- continuity-neutral: 'in' is used for continuous enclosures, for discontinuous enclosures such as a bird cage, or for conceptual containers (e.g., 'in town', or even 'in love').

These and similar invariances seem to be common in most natural languages.

Klein's mathematical definition of a geometry is similar to the invariance concepts encoded in natural languages: both identify properties that are invariant under transformations.[1] If we follow Klein's definition of a geometry and combine that with evidence of invariant properties of spatial language, then we can ask questions such as: "what is the geometry of natural language?" And perhaps this should be: "what are the geometries of natural language?", since there is evidence to suggest that there is more than one such geometry (see Couclelis and Gale, 1986, for a discussion based on formal properties). In fact, we expect that different geometries exists within single languages, since not all terms of a natural language remain invariant under

1 Note, however, that as we extend Klein's concept to natural language, we must relax Klein's requirement that the transformations form a mathematical group.

the same sets of transformations. For example, all properties expressed in a reference frame that is bound to the referent are invariant under translation and rotation of the object and the referent. No matter which cardinal direction a church faces, a nearby cemetery will almost always be referred to as being "behind the church" if it is near the wall of the church that is opposite the main entrance. Properties expressed in absolute reference frames are only invariant under transformations that leave the reference frames invariant (for example, an expression using cardinal points, such as "east of the church", would be invariant under translation, but not under rotation).

Comparing mathematical theory and linguistic observations raises a number of interesting questions. Reference frames have been well-studied in linguistics. Of particular interest are situations that are quite different from 'standard geometry' and do not depend on cardinal directions (astronomical reference frame) but use, for example, a radial system, as is customary on many islands and in some circular lakes (for a discussion of Icelandic, see Haugen, 1957; for a review and discussion, see Mark, Svorou, and Zubin, 1987).

The last step in the development of geometries of natural language(s) will be to bind these geometries into a comprehensive system, in which the properties of features can be from any of the different geometries. A need for such a scheme is already manifest in the efforts to combine raster and vector-based data in GIS. The same problem is also manifest in organizations that maintain multiple databases that contain the same features but at, for example, multiple levels of resolution or of generalization (Buttenfield and DeLotto, 1989). Current systems are not capable of managing such collections of data as single logical units, in which changes propagate from one level to the other and where queries are executed in the most appropriate representation of particular features.

Research has begun to address this general problem. A new, promising approach is based on the use of algebraic descriptions of each of these geometries, the traditional mathematical ones as well as formalization of the conceptual ones. There is substantial methodological knowledge of how multi-sorted algebras (Birkhoff and Lipson, 1970) can be used to describe objects and the system of operations associated with them. The method is extensively used in software engineering. It is known as object-oriented specification (Guttag, Horrowitz, and Mousser, 1978; Goguen, Thatcher, and Wagner, 1978), and has already been applied to geometric problems (Goguen 1988; Mallgreen, 1982). Algebraic specifications for cell complexes have been advocated for use as the base modeling block in a vector-based GIS (Frank and Kuhn, 1986; Bruegger and Frank, 1989).

Given such individual algebraic specifications for a specific geometry, we next must construct relations between them. Mathematicians have studied the connections between different algebras under the topic of algebraic morphism. They establish mappings from the objects in one algebra to the objects in the other, and likewise map operations from one algebra to the other. Then, one can study the regularities in these mappings. Suppose that we have an algebraic structure with elements A (a1, a2, ...) and operations f, another structure with elements A' (a'1, a'2...) and operations f', and a mapping G that maps elements from A to A' and also operations from f to f'. The mapping G is said to be a homomorphism if f(ax)' = f'(a'x), meaning we can go from A to A' first and then apply the operation f', or first apply f and then go to A'. Computation with logarithmic values provide a practical example for an application. Consider the mapping 'logarithm' from positive real numbers to real numbers. This establishes an isomorphism between (R+,*) and (R, +), mapping multiplication to addition, due to the equations:

(ab)(ac)= a(b+c)

and

log (a) + log (b) = log (ab)

Mathematicians have used this isomorphism to replace multiplications (which are difficult) by more simple addition operations on the logarithmic values. There is an extensive theory about such morphism, called category theory, which might be applicable here (Geroch 1985). This approach based on isomorphisms can and perhaps may be used to construct formal relations between the points, lines, and areas of cartographic data structures and Euclidean geometry, and the new geometries of natural language and cognition.

Summary

Development of a comprehensive model of spatial relations and properties is important for the future development of systems for geographic information and analysis, and also for cognitive science and behavioral geography. This paper first reviewed concepts of space. A critical distinction was made between small-scale spaces, whose geometry can be directly perceived through vision and other senses, and geographic spaces, that can be perceived only in relatively small parts. Fundamental terms for spatial relations are often based on concepts from small-scale space, and are extended to geographic (large-scale) space through metaphors (Mark, 1992). Thus, we believe that as a first approximation, terms and concepts for the spatial relations among the objects in small-scale space can form an appropriate core for spatial language. Additional spatial relations at a geographic scale can be formed by the addition of small sets of axioms or postulates. Finally, we set as a long-term but important goal a search for geometries of spatial language. This search should attempt to define those properties of particular instances of spatial reference in natural language that remain invariant under groups of transformations. The development of a link between these properties and the geometry and topology of GISs should advance the usability of GIS software. This fusion could form the basis both for geographic data structures and for the understanding and generation of spatial language itself.

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References

Abler, R F, 1987, "The National Science Foundation National Center for Geographic Information and Analysis" International Journal of Geographical Information Systems, 1, no. 4, 303-326.

Birkhoff, G, and Lipson, J D, 1970, "Heterogeneous Algebras" Journal of Combinatorial Theory, 8, 115-133

Blaut, J M, 1961, "Space and process" The Professional Geographer, 13, 1-7.

Blumenthal, L M, 1986 A Modern View of Geometry. New York, NY: Dover Publications.

Blumenthal, L M, and Menger, K, 1970, Studies in Geometry San Francisco, CA: W H Freeman and Company.

Boyle, A R, Dangermond, J, Marble, D F, Simonett, D S, Smith, L K, and Tomlinson, R F, 1983 Final Report of a Conference on the Review and Synthesis of Problems and Directions for Large Scale Geographic Information System Development, National Aeronautics and Space Administration, Contract NAS2-11246. (report available from ESRI, Redlands, CA)

Brody, H, 1981 Maps and Dreams. Hamondsworth, England: Penguin Books, Limited, 297 pp.

Bruegger, B and Frank, A, 1989, "Hierarchies over topological data structures", Technical Papers, ASPRS/ACSM Annual Convention, Baltimore, MD, 4, 137-145.

Bunge, W, 1962 Theoretical Geography. Lund Studies in Geography: Lund, Sweden: Gleerup.

Buttenfield, B P and DeLotto, J, 1989 Multiple Representations: Report on the Specialist Meeting. Santa Barbara, CA: National Center for Geographic Information and Analysis, Report 89-3.

Cassirer, E, 1923 Substance and Function. New York: Dover.

Chatwin, B, 1988 The Songlines. London: Pan Books Ltd., 327 pp.

Chrisman, N, 1979, "Concepts of space as a guide to cartographic data structures", in Proceedings, First International Study Symposium on Topological Data Structures for Geographic Information Systems, Ed G Dutton, Volume 7 ("Spatial Semantics: Understanding and Interacting with Map Data"), pp. CHRISMAN/1-CHRISMAN/19.

Couclelis, H, 1988, "The truth seekers: Geographers in search of the human world", in A Ground for Common Search. Eds R Golledge, H Couclelis, and P Gould, Santa Barbara, CA: The Santa Barbara Geographical Press, pp. 148-155.

Couclelis, H, 1991, "Requirements for planning-relevant GIS: A spatial perspective" Papers in Regional Science 70 (1): 9-19.

Couclelis, H, and Gale, N, 1986, "Space and spaces" Geografiska Annaler, 68B, 1-12.

Di Sessa, A, 1982, "Unlearning Aristotelian physics: A study of knowledge-based learning" Artificial Intelligence 6, 37-75.

Downs, R M, and Stea, D, 1977 Maps in Minds: Reflections on Cognitive Mapping. New York: Harper and Row.

Frank, A U, 1987, "Towards a spatial theory" Proceedings, International Symposium on Geographic Information Systems: The Research Agenda, November, 1987, Crystal City, Virginia, 2, 215-227.

Frank, A U, and Kuhn, W, 1986, "Cell graphs: A provable correct method for the storage of geometry" Proceedings, Second International Symposium on Spatial Data Handling. Seattle, Washington, July 5-10, 1986, pp. 411-436.

Frank, A U and Mark, D M, 1991, "Language issues for GIS", In Geographical Information Systems: Principles and Applications, Eds D J Maguire, M F Goodchild, and D W Rhind, Longman Scientific and Technical, London, 1, 147-163.

Franklin, W R, 1984, "Cartographic errors symptomatic of underlying algebra problems" Proceedings, First International Symposium on Spatial Data Handling. Zurich, Switzerland, August 1984, 1, 190-208.

Freeman, J, 1975, "The modelling of spatial relations" Computer Graphics and Image Processing 4, 156-171.

Freundschuh, S M, 1991 Spatial Knowledge Acquisition of Urban Environments from Maps and Navigation Experience, Unpublished Doctoral dissertation, Geography, State University of New York at Buffalo.

Geroch, R, 1985, "Mathematical physics" Chicago Lectures in Physics, University of Chicago Press, IL

Goguen, J A, 1988, "Modular Algebraic Specifications of Some Basic Geometrical Constructions" in Geometric Reasoning, Eds D Kapur, and J L Mundy, The MIT Press, Cambridge, MA, pp. 123 - 153

Goguen, J A, Thatcher, J W, and Wagner, E G, 1978, "An Initial Algebraic Approach to the Specification, Correctness, and Implementation of Abstract Data Types" in Current Trends in Programming Methodology. Ed R Yeh, Englewood Cliffs, NJ: Prentice Hall. IV, pp. 80-149

Golledge, R G, 1976, "Methods and methodological issues in environmental cognition research" in Environmental Knowing: Theories, Research, and Methods, Eds G T Moore, and R G Golledge, Stroudsburg, PA: Dowden, Hutchinson & Ross.

Golledge, R G, 1978, "Learning about urban environments", in Timing Space and Spacing Time, Eds T Carlstein, D Parkes, and N Thrift, London: Edward Arnold.

Golledge, R G, 1988, "Integrating spatial knowledge" Paper Presented at International Geographical Union Conference, Sydney, Australia, August 1988.

Golledge, R G, Smith, T R, Pellegrino, J W, Doherty, S, Marshall, S P, and Lundberg, C G, 1983, "The acquisition of spatial knowledge: Empirical results and computer models of path finding processes" Proceedings XIX Interamerican Congress of Psychology, Quito, Ecuador.

Golledge, R, and G Zannaras, 1973, "Cognitive approaches to the analysis of human spatial behavior", Environment and Cognition, Ed W Ittleson, New York: Academic Press.

Gould, J L, 1986, "The locale map of honey bees: Do insects have cognitive maps?" Science, 232, 861-863.

Grimaud, M, 1988, "Toponyms, prepositions, and cognitive maps in English and French" Geolinguistics, 14, 54-76.

Guttag, J R, Horrowitz, L L, and Mousser, D R 1978, "Abstract Data Type and Software Validation" Communications of the ACM, 21, Nr. 12, 148-164

Haber, R N, and Wilkinson, L, 1982, "Perceptual components of computer displays" IEEE Computer Graphics & Applications, May 1982, 23-35.

Haller, S M, 1989, Spatial relations and locative phrase generation in a map context. Report 89-14, National Center for Geographic Information and Analysis, Santa Barbara, California.

Haller, S M and Ali, S S, 1990, "Using focus for generating felicitous locative expressions" Proceedings of the 3rd International Conference on Industrial and Engineering Applications of Artificial Intelligence & Expert Systems, ACM Charleston, SC, 472-477.

Haller, S M and Mark, D M, 1990, "Knowledge representation for understanding geographical locatives" Proceedings, Fourth International Symposium on Spatial Data Handling, Zurich, Switzerland 1, 465-477.

Harley, J B, 1990, "Deconstructing the Map" Cartographica.

Harvey, D, 1969 Explanation in Geography. New York, NY: St. Martin's Press

Haugen, E, 1957, "The semantics of Icelandic orientation" Word, 13, 447-460.

Herskovits, A, 1982 Space and the Prepositions in English: Regularities and Irregularities in a Complex Domain. Stanford University, Ph.D. Dissertation.

Herskovits, A, 1985, "Semantics and pragmatics of locative expressions" Cognitive Science, 9, 341-378.

Herskovits, A, 1986 Language and Spatial Cognition: A Interdisciplinary Study of the Prepositions in English. Cambridge, England: Cambridge University Press.

Hobbs, J R, and Moore, R C, 1985 Formal Theories of the Commonsense World. New Jersey: Ablex.

Johnson, M, 1987 The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason. Chicago: University of Chicago Press.

Klein, F, 1872 Vergleichende Betrachtungen über neuere geometrische Forschungen. Erlangen.

Kuipers, B, 1978, "Modeling spatial knowledge" Cognitive Science 2, 129-153.

Kuipers, B, 1979, "Cognitive modelling of the map user", in Proceedings, First International Study Symposium on Topological Data Structures for Geographic Information Systems, Ed G Dutton, Volume 7 ("Spatial Semantics: Understanding and Interacting with Map Data"), pp. KUIPERS/1-KUIPERS/11.

Kuipers, B, 1983a, "The cognitive map: Could it have been any other way?" in Spatial Orientation: Theory, Research, and Application. Eds H L Pick, Jr, and L P Acredolo, New York: Plenum Press, pp. 345-359.

Kuipers, B, 1983b, "Modeling human knowledge of routes: Partial knowledge and individual variation" Proceedings, AAAI 1983 Conference, The National Conference on Artificial Intelligence, pp. 1-4.

Lakoff, G, 1987 Women, Fire, and Dangerous Things: What Categories Reveal About the Mind. Chicago: University of Chicago Press.

Lakoff, G, and Johnson, M, 1980 Metaphors We Live By. Chicago: University of Chicago Press.

Lloyd, R, 1989a, "Cognitive maps: Encoding and decoding information" Annals of the Association of American Geographers, 79, 101-124.

Lloyd, R, 1989b, "The estimation of distance and direction from cognitive maps" The American Cartographer, 16, 109-122.

Maguire, D J, M F Goodchild, and D W Rhind (eds) Geographical Information Systems: Principles and Applications, Longman Scientific and Technical, London, 2 volumes.

Mallgreen, W R, 1982, "Formal Specification of Graphic Data Types" ACM Transactions on Programming Languages and Systems. 4, Nr. 4, 687-710.

Mark, D M, 1989, "Cognitive image-schemata for geographic information: Relations to user views and GIS interfaces" Proceedings, GIS/LIS'89, Orlando, Florida, 2, 551-560.

Mark, D M, and Frank, A U, 1989, "Concepts of space and spatial language" Proceedings, Ninth International Symposium on Computer-Assisted Cartography, Baltimore, Maryland, 538-556.

Mark, D M, Gould, M D, and Nunes, J, 1989, "Spatial language and geographic information systems: Cross-linguistic issues" Proceedings, II Conferencia Latinoamericana sobre el Technologia de los Sistemas de Información Geográficos (SIG), Mérida, Venezuela, 25-29 September, 1989, 105-130.

Mark, D M, and McGranaghan, M, 1986, "Effective provision of navigation assistance for drivers: A cognitive science approach" Proceedings, Auto-Carto London, London, England, September 14-19, 2, 399-408.

Mark, D M, Svorou, S, and Zubin, D, 1987, "Spatial terms and spatial concepts: Geographic, cognitive, and linguistic perspectives" Proceedings, International Symposium on Geographic Information Systems: The Research Agenda, November, 1987, Crystal City, Virginia, 2: 101-112.

McClosky, M, 1983, "Intuitive physics" Scientific American 248 (4), 122-130, April 1983.

Müller, J C, 1982, "Non-Euclidean geographic spaces: Mapping functional distances" Geographical Analysis 14, 189-203.

NCGIA (National Center for Geographic Information and Analysis). 1989, "The research plan of the National Center for Geographic Information and Analysis" International Journal of Geographical Information Systems, 3 (2), 117-136.

Neisser, U, 1976 Cognition and Reality: Principles and Implications of Cognitive Psychology. San Francisco: W H Freeman and Company.

Nievergelt, J, and Schorn, P, 1988, "Line Problems with Supra-Linear Growth" (in German). Informatik Spectrum, 11, 214-217

Norman, D A, 1990 The Design of Everyday Things. New York: Doubleday

Nystuen, J, 1963, "Identification of some fundamental spatial concepts" Papers of the Michigan Academy of Sciences, 48, 373-384. [Reprinted in B J L Berry and D F Marble, 1968 Spatial Analysis: A Reader in Statistical Geography. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.]

Peuquet, D J, 1988, "Representations of geographic space: toward a conceptual synthesis" Annals of the Association of American Geographers, 78, 375-394.

Peuquet, D J, and Zhan C-X, 1987, "An algorithm to determine the directional relationship between arbitrarily-shaped polygons in the plane" Pattern Recognition, 20, 65-74.

Piaget, J, and Inhelder, B, 1956 The Child's Conception of Space. London: Routledge & Kegan Paul.

Rosch, E, 1973, "On the internal structure of perceptual and semantic categories", in Cognitive Development and the Acquisition of Language, Ed T E Moore, New York, Academic Press, pp. 111-144.

Rosch, E, 1978, "Principles of categorization", in Cognition and Categorization. Eds E Rosch and B B Lloyd, Hillsdale, NJ: Erlbaum, pp. 27-48.

Sack, R D, 1972, "Geography, geometry, and explanation" Annals, Association of American Geographers, 62, 61-78.

Sinton, D, 1979, "The inherent structure of information as a constraint to analysis: Mapped thematic data as a case study", in Proceedings, First International Study Symposium on Topological Data Structures for Geographic Information Systems, Ed G Dutton, Volume 7 ("Spatial Semantics: Understanding and Interacting with Map Data"), pp. SINTON/1-SINTON/17.

Smith, E E, and Medin, D L, 1981 Categories and Concepts. Cambridge, Mass: Harvard University Press.

Snyder, J P, 1982, "Map projections used by the U.S. Geological Survey" Geological Survey Bulletin 1532, Second Edition, 313 pp.

Svorou, S, 1988 The Experiential Basis of the Grammar of Space: Evidence from the Languages of the World. Unpublished Ph.D. Dissertation, Department of Linguistics, State University of New York at Buffalo.

Talmy, L, 1983, "How language structures space", in Spatial Orientation: Theory, Research and Application. Eds H Pick and L Acredolo, Plenum Press.

Talmy, L, 1988, "How language structures space" [Lecture notes]. in Cognitive and Linguistic Aspects of Geographic Space: Report on a Workshop. Ed Mark, D M, Santa Barbara, CA: National Center for Geographic Information and Analysis, Appendix, pp. B-1 to B-11.

Thorndyke, P W, and Hayes-Roth, B, 1982, "Differences in spatial knowledge acquired from maps and navigation" Cognitive Psychology 14, 560-589.

Tobler, W, 1976, "The geometry of mental maps", in Spatial Choice and Spatial Behavior. Eds R Golledge and G Rushton, Columbus: Ohio State University Press, pp. 69-91.

Trowbridge, C C, 1913, "On fundamental methods of orientation and imaginary maps" Science 38, 888-897.

Velázquez de la Cadena, M, 1973 A New Pronouncing Dictionary of the Spanish and English Languages (compiled with E Gray and J L Iribas). Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Youngman, C, 1979, "A linguistic approach to map description", in Proceedings, First International Study Symposium on Topological Data Structures for Geographic Information Systems, Ed G Dutton, Volume 7 ("Spatial Semantics: Understanding and Interacting with Map Data"), pp. YOUNGMAN/1- YOUNGMAN/19.

Cognitive Image-Schemata for Geographic Information: Relations to User Views and GIS Interfaces

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Abstract. Image-schemata are idealized conceptual models for human perception and cognition. Many such schemata are spatial, and some are geographic. Users interact with Geographic Information Systems (GISs) in order to learn about, or make decisions about the world. This paper contends that optimal user interfaces for GIS will be based on image-schemata for geographic and other spatial phenomena. The concept of user views also relates to this schema-based approach. An early focus on users and interfaces is important in system design, especially for systems to be used by people from different disciplines, cultures, and languages.

Introduction

A main objective of GIS is to allow the user of the system to interact vicariously with actual or possible phenomena of the world. If this is so, then the system which mediates between the user and the world should be as unobtrusive as possible. Studies of human spatial cognition and perception, of geographic phenomena, and of the relations between these, thus should be central to the design of GIS interfaces and of GISs in general. This leads to the following assertion:

> Optimal GIS interfaces will be based on the same image-schemata that are used when the person involved interacts directly with the real-world phenomena represented in the GIS.

This paper expands on this simple yet potentially powerful idea. First, the image-schemata concept, and associated cognitive models, is discussed and illustrated using geographic examples. Then, GIS "user views" are discussed. Lastly, since such user views, as discussed in the database and GIS literatures, may form a first approximation to the relevant image-schemata for GIS, the potential link between these and the cognitive models is discussed.

Image-Schemata and Cognitive Categories

The concepts and principles presented in this paper are based on a model of human perception and cognition initiated by Lakoff and Johnson (1980), and elaborated by Lakoff (1987) and particularly by Johnson (1987). Johnson claims that mental activities such as perception and cognition are heavily influenced by our cognitive image-schemata. Johnson (1987, p. 29) has defined an image-schema in the following way:

> "A schema consists of a small number of parts and relations, by virtue of which it can structure indefinitely many perceptions, images, and events. In sum, image-schemata operate at a level of mental organization that falls between abstract propositional structure, on the one side, and particular concrete images on the other."

Recent developments in cognitive science, which may be referred to as the experiential revolution in concept formation, suggest that the categories that people use are not necessarily "objective". Perception and cognition do not involve "direct" interaction with the world, but rather occur through cognitive models, image-schemata, etc. Thus even apparently-direct visual experiences are influenced (biased) by what we expect to see, or what we look for. For any particular domain of investigation, one conceptual schema may be more useful than others. It is more likely that the most appropriate schema will change from problem to problem. It is not an issue of whether one particular schema is "correct" or not, but rather is an issue of how useful some particular schema is for some particular situation.

Mark Johnson (1987, p. 126) provides a clear statement of how an image-schemata-based model of cognition would operate:

> "... Much of the structure, value, and purposiveness we take for granted as built into our world consists chiefly of interwoven and superimposed schemata... My chief point has been to show that these image schemata are pervasive, well-defined, and full of sufficient internal structure to constrain our understanding and reasoning. [Johnson's italics] To give some idea of the extent of the image-schematic structuring of our understanding (as our mode of being-in-the-world or our way of having-a world), consider the following partial list of schemata, which includes those previously discussed:

Container	Balance	Compulsion
Blockage	Counterforce	Restraint Removal
Enablement	Attraction	Mass-Count
Path	Link	Center-Periphery
Cycle	Near-Far	Scale
Part-whole	Merging	Splitting
Full-empty	Matching	Superimposition
Iteration	Contact	Process
Surface	Object	Collection

> This brief list is highly selective, but it includes what I take to be most of the important image-schemata. If one understands 'schema' more loosely than I do, it might be possible to extend this list at length." (Johnson, 1987, p. 126).

Note that many of the image-schemata that Johnson lists are inherently spatial or even geographical: Container, Blockage, Path, Surface, Link, Near-Far, Contact, Center-Periphery, Scale. Others have implications for spatial language and concepts, spatial interaction modelling, etc. (for example, Part-Whole and Attraction). Lakoff and Johnson point out that in fact, spatial schemata are at the core of cognitive structure, and form the basis for organizing many less-concrete domains. "Spatialization metaphors are rooted in physical and cultural experiences" (Lakoff and Johnson, 1980, p. 18). For example, a physical journey through geographic space becomes a metaphor for various kinds of work projects, and even for interpersonal relationships ("We're at a crossroads"; "This relationship is a dead-end street"; etc.; Lakoff and Johnson, 1980, p. 44-45).

This approach to cognitive categories has recently been discussed in a geocartographic context (Mark, Svorou, and Zubin, 1987; Couclelis, 1988; Mark, 1988, 1989; Mark and Frank, 1989; Mark and others, 1989). It is a central theme within Research Initiative #2, "Languages of Spatial Relations", of the National Center for Geographic Information and Analysis.

Some Geographical Examples

Most Indo-European languages express fundamental spatial relations through prepositions. One seemingly-unusual fact about English is that the relations of features (figures) to areal or polygonal reference (ground) regions is expressed by the preposition "in" in some cases yet by "on" in other cases. "I was standing in my back yard on my property in Amherst." Each ground object has a surface, and each has a boundary; thus both "in" and "on" would seem to be valid in each case. Nevertheless, most ground objects do not give the speaker a choice, but rather require one preposition or the other. Furthermore, although there are a few exceptions, German commonly requires auf for the same situations for which English uses "on", and likewise for the Dutch use of op. And, both German and Dutch use in for situations in which English also uses "in". Grimaud (1988) has discussed these cases for both English and French.

According to the conceptual framework adopted in this paper, the choice of preposition depends on the image schema adopted. In some cases, a Platform schema is adopted--once this schema is activated, the preposition "on" is obligatory. In other cases, a Container schema is invoked, forcing the speaker/writer to use "in". The question (as yet unanswered in the general case) then becomes: "Which image-schemata are activated for which kinds of ground objects and used in which circumstances?"

Conceptualizing something as an island more-or-less forces an English speaker to select the Platform image-schema, and use the preposition "on". If the word "island" appears in the name, this almost requires the speaker to say "on". ("Who lived on Manhattan Island before the Europeans came?") On the other hand, for political units, English almost invariably invokes the Container schema and uses "in". This will be true even for regions that happen to be in 1:1 correspondence with a physical island. ("Does your uncle still live in Puerto Rico?") However, for such island units, either "in" or "on" might be used, to indicate whether we are talking about a physical island or a country by forcing the listener/reader to use a particular schema. "Did anyone live on Cuba before 1492?"--the same sentence with "in" might sound strange, since Cuba-the-country did not exist then.

The following is an example of how the choice of preposition may force the reader or listener to make different interpretations based on different image-schemata. "Hawaii" is the name of a State of the USA; but, "Hawaii" is also the name of the largest and easternmost island in that State. Recall that in English, political units normally involve the Container image-schema, whereas islands use the Platform image-schema. Thus, if I say: "My friend Sherry lives in Hawaii", it seems that "in" forces the Container image-schema, leading to the "State-of-Hawaii" interpretation. She might live in Honolulu (on the Island of Oahu), or anywhere else in the State. But, if I say: "My friend Sherry lives on Hawaii", then the Platform image-schema leads to the "Island-of-Hawaii" interpretation, and the residence probably is Hilo or Kona. The use of "in" or "on" forces either the Container or Platform schema, respectively, thus reducing ambiguity.

Natural languages differ in their potential to influence meaning in this way. For example, in Spanish, most locative expressions use more generic prepositions such as en (in, on, or at) or de (also used as a posessive). A Spanish speaker could not use a choice of prepositions to distinguish the two Hawaiian situations discussed in the last paragraph, but would have to explictly use either "El estado de Hawaii" or "La isla de Hawaii" as the reference (ground) object, or simply leave the expression ambiguous. On the other hand, German has two prepositions (an and auf) that both normally translate to "on". An applies to lateral adjacency, wheras auf has a meaning closer to "on top of". A German speaker could use an or auf to force different meanings in cases where an English speaker would have to use additional words or would have to tolerate ambiguity.

User Views

A user view of a database or of any computer system is the conceptual model that a user has of the system and its contents. Clearly, tpeople can use the computer system most effectively if the user interface, including command and query languages, is fully compatible with the their view(s) of the system. This could be achieved by training the user to view the system in an appropriate way, or by designing the system to anticipate user views. In principle, it is possible to support many user views while keeping a single version of the information in the database. The conceptual basis of user views is important in the database literature, but has received surprisingly little attention in the GIS context. Dangermond (1987) discussed some related aspects in his presentation on "Trends in Geographic Information Systems Software" at the

IGIS'87 Meeting. However, the only mention of user views in the transcript of his talk is in the following sentence within the subsection on "GIS Data Management Trends":

> "GIS databases are now being designed for transactional updating, for the storage of data with minimum redundancy, and to permit the generation of views-on-the-fly without requiring much previous application programming." (Dangermond, 1987, p. I-78)

In another paper, Dangermond (1989) does not include the word "view" in the text, but in his first diagram, to illustrate the advantages of departments within an organization sharing geographic information, he has a "Common Data Base" connected to three boxes, each marked "view". Similarly, Guevara (1989) includes a diagram with several "views" within a box labelled "Applications", with each such view connected to one or more elements of the database, but does not discuss views in his text. The concept of supporting simultaneously a variety of user views of the same geographic database can be seen as a special kind of "multiple representation" (see Buttenfield and Delotto, 1989, for a discussion of related concepts).

An Example from Cartography

If the above conceptual model is applied to GIS and digital cartography, the relevant question becomes "Which image-schema should a GIS user or database apply in the current situation?" rather than "Which is the correct model for a certain type of data?", or "What are the correct or best feature codes for a given digital cartographic data file?"

For an example of the need to support multiple views of a database within a single data base, one can examine the US Geological Survey (USGS). The National Digital Cartographic Data Base (NDCDB) has dual and somewhat conflicting goals. On the one hand, diagrams of the Mark II conceptual scheme (see Starr, 1987, p. 4) show data from the data base feeding into Geographic Information Systems and being supplied to "users". Furthermore, increasing demand for GIS data was listed by Guptill and others (1988, p. 252) as a factor in the program to revise and enhance the DLG model. On the other hand, the mandate for the NDCDB clearly relates to mapping, and the objective is to define a set of features that are found on USGS National Mapping Division (NMD) source materials and reflect the requirements of the NMD. It is unlikely that the features and feature classes shown on topographic maps correspond exactly with the concepts of topographic features held in the minds of GIS users of geocartographic data.

The DLG-E (Digital Line Graph, Extended) provides a model of topographic maps, and not of the world directly. This is an appropriate view of the data if one is in the business of making topographic maps, and thus is appropriate to the primary mission of the NMD (see Callahan and Olsen, 1987). However, geologists within USGS, as well as GIS users in other federal agencies, to say nothing of other geographic data users, might have quite different ideas on what geographic entities to represent, and how to represent them and their relations.

Levels of Abstraction for Geographic Data

Guptill and others (1988, p. 254) present a model of levels of abstraction. Their top level is:

Reality is the total phenomena as they actually exist.

This is followed in the hierarchy by:

Data reality is an abstraction of reality which includes only those entities thought to be relevant to anticipated needs.

The category theory of cognition, discussed above, seems to require a level between these, which might be called "Experiential Reality":

An Experiential Reality is the total of all the idealized cognitive models, image-schemata, perceptions, and memories of some particular human mind, to be referred to as 'the user'.

Although technically the human mind may have no 'direct' access to the real world, but only can know what the senses report, nevertheless the commonality of human experience means that the experiential realities of the set of all users does not grow combinatorially as individual Experiential Realities are combined. The Experiential Realities of some class of GIS users would be expected to be even more concordant, and even closer to a traditional, objectivist view.

Features, Entities, and Objects

Expanding somewhat on terms proposed by National Committee for Digital Cartographic Data Standards (Moellering 1987), Guptill and others (1988, p. 255) provided the following definitions:

"Feature: A set of phenomena with common attributes and relationships. The concept of feature encompasses both Entity and Object.

Entity: A real-world phenomenon that is not subdivided into phenomena of the same type.

Object: A digital representation of all or part of an Entity."

The phrase "phenomena of the same type", used in the definition of an entity, implies that definitions of types can be agreed upon. The Rosch-Lakoff-Johnson model of categories is central here (Rosch, 1973, 1978; Lakoff and johnson, 1980; Lakoff, 1987; Johnson, 1987). Among its key concerns is an attempt to define basic-level objects, which often act as prototypes for broader classes of related objects. Categories are not sets, but rather some members of a category are better examples than are others.

For the GNIS and DLG-E files of the NDCDB, feature codes have been included to give users of the data base an indication of the "kind" (or "type") of feature which a particular data element represents. Although these data elements are intended to represent phenomena from the "real world", in fact they are more closely based on map elements. Since maps themselves are abstractions of reality, representing large-scale (geographic) space in small-scale (everyday object) space, the NDCDB data, and their feature codes, represent in some sense models of models.

It should be obvious that the utility of the data in NDCDB will depend to a great extent on the degree to which the models of geographic phenomena used in the feature and entity definitions within the NDCDB correspond with the cognitive models of the same phenomena held in the minds of users of the data. As noted above, there are two major subcategories of NDCDB users. Whereas the data models in NDCDB probably correspond well with the views of one very important group of users, namely cartographers within and outside of USGS; however, it is less clear how well the model fits the views of another major class of users, namely the builders and users of GISs.

To what extent, or for what classes of users, to the GNIS and/or DLG-E feature class codes represent 'natural kinds'? Research to evaluate these feature codes in light of a Rosch-Lakoff-Johnson model of cognitive categories would be of value, and should be undertaken.

Definitions of DLG-E Features

There are two aspects to the definition of features in DLG-E or similar systems. One involves the determination of an appropriate set of feature classes or categories; the other is the delimitation of individuals, and their assignment to the most appropriate class. In order to focus discussion, this section will review the degree to which the DLG-E feature classes might provide a basis for a category-prototype-based approach to the generalization of cartographic lines. In particular, attention will be restricted to shorelines, streams, and other water features.

First, in the DLG-E, geographic reality is divided into five "views": cover, division, ecosystem, geoposition, and morphology. These "views" are somewhat similar to the user views discussed above, but are more like subsets of features, with each kind of features occurring in only one view. Cover reflects land use and land cover information: water is one subclass within this, and is subdivided only into classes such as "bay/estuary/inlet", "gut", "shoreline" and "stream/river", plus point features such as "ford", "rapids", or "waterfall". The category "stream/river" has several possible attributes, but only two are related to morphology: streams are classified according to"hydrographic form" (braided or not), and "hydrographic category" (intermittent, perennial, or unknown).

Division reflects cadastral, administrative, political, and similar demarcations and boundaries, and has little relation to shorelines or streams, except where they happen to form boundaries. Ecosystem is a largely undeveloped view which again does not relate to water features. Geoposition is a surveyor's or geodesist's view. Only the morphology view seems to relate to phenomenon-based cartographic generalization.

The following feature classes apply to shorelines, and may be useful in guiding cartographic generalization:

bar, beach, cape, foreshore, island, isthmus, reef

Some of these (especially beach and reef) have a limited range of possible forms; such knowledge of the feature category should prove useful. However, many other potentially-important shore features, such as fjord, spit, etc., are not included in the classification, and bay/estuary/inlet are lumped together, in the water category of the cover view. A set of feature classes to support a phenomenon-based approach to generalization of shorelines and streams would almost certainly require a different set of feature classes.

The DLG-E scheme has the flexibility to represent a wide range of feature classifications. Also, the approach already includes multiple views of (possibly) a single set of real-world entities; such multiple views would be essential to a cognitively-based model of the world. However, the particular kinds of features included in the draft description do not appear to have much potential to be useful as a guide to cartographic generalization procedures. Research investigating categorizations of features by actual or potential GIS users would presumably aid the choice of extensions to the system; utility as a guide to generalization would also be of fairly high priority.

Summary

Since the "user view" exists in its most fundamental way in the mind of the user, it seems obvious that cognitive science is a key to research progress in this area. The "applied" fields of human-computer interaction and human factors also are important (see Gould, 1989). A model of the user's mind, or at least of the user's conceptualization of the GIS domain within that mind, should be considered to be a strict prerequisite to the development of good user interface. This is especially important for systems that are intended to be employed by many users, particularly if those users come from different disciplines, professions, cultures, or linguistic groups (see Mark, Gould, and Nunes, 1989). The main contention of this paper is that general-purpose cognitive image-schemata should form the core or foundation upon which cognitively-sensible interfaces to support "user views" can be built.

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References

Buttenfield, B. P. and Delotto, J., 1989. Multiple Representations: Report on the Specialist Meeting. Santa Barbara, CA: National Center for Geographic Information and Analysis, Report 89-3.

Callahan, George M., and Olsen, Randle W., 1987. Digital Systems Development at the U.S. Geological Survey. Proceedings, 13th International Cartographic Association Conference, Morelia, Mexico, October 1987, Vol. 4, pp. 205-214.

Couclelis, Helen, 1988. The truth seekers: Geographers in search of the human world, in Golledge, R., Couclelis, H., and Gould, P. (eds.), A Ground for Common Search. Santa Barbara, CA: The Santa Barbara Geographical Press, 148-155.

Dangermond, Jack, 1987. Trends in geographic information systems software. International Conference on Geographic Information Systems (IGIS'87), Volume 1, pp. 75-85.

Dangermond, Jack, 1989. The organizational impact of GIS technology. ARC News, Summer 1989, p. 25-26.

Gould, Michael D., 1989. Human factors research and its value to GIS user interface design. Proceedings, GIS/LIS'89, Orlando, Florida, in press.

Grimaud, M, 1988. Toponyms, prepositions, and cognitive maps in English and French. Geolinguistics, 14, 54-76.

Guevara, J. Armando 1989. Toward an adaptable spatial processing architecture. ARC News, Summer 1989, p. 12-13.

Guptill, Stephen C., Fegeas, Robin G., and Domaratz, Michael A., 1988. Designing and Enhanced Digital Line Graph. Technical Papers, 1988 ACSM-ASPRS Annual Convention, Vol. 2, pp. 252-261.

Johnson, Mark, 1987. The Body in the Mind: The Bodily Basis of Meaning, Imagination, and Reason. Chicago: University of Chicago Press, 233 pp.

Lakoff, George, 1987. Women, Fire, and Dangerous Things: What Categories Reveal About the Mind. Chicago: University of Chicago Press.

Lakoff, George, and Johnson, Mark, 1980. Metaphors We Live By. Chicago: University of Chicago Press.

Mark, D. M., (editor), 1988. Cognitive and Linguistic Aspects of Geographic Space: Report on a Workshop. Santa Barbara, CA: National Center for Geographic Information and Analysis.

Mark, D. M., 1989. Languages of Spatial Relations: Researchable Questions and NCGIA Research Agenda. Santa Barbara, CA: National Center for Geographic Information and Analysis, Report 89-2A.

Mark, D. M. and A. U. Frank, 1989. Concepts of space and spatial language. Proceedings, Ninth International Symposium on Computer-Assisted Cartography, Baltimore, Maryland, 538-556.

Mark, D. M., Frank, A. U., Egenhofer, M. J., Freundschuh, S. M., McGranaghan, M., and White, R. M., 1989. Languages of Spatial Relations: Initiative Two Specialist Meeting Report. Santa Barbara, CA: National Center for Geographic Information and Analysis, Report 89-2.

Mark, D. M., Gould, M. D., and Nunes, J., 1989. Spatial language and geographic information systems: Cross-linguistic issues (El Lenguaje Espacial y Los Sistemas de Información Geograficos: Temas Interlinguisticos). Proceedings, II Conferencia Latinoamericana sobre el Technologia de los Sistemas de Información Geográficos (SIG), Mérida, Venezuela, 25-29 September, 1989, in press.

Mark, D. M., Svorou, S., and Zubin, D., 1987. Spatial terms and spatial concepts: Geographic, cognitive, and linguistic perspectives. Proceedings, International Symposium on Geographic Information Systems: The Research Agenda, November, 1987, Crystal City, Virginia, 2: 101-112.

Moellering, Harold (editor), 1987. Issues in Digital Cartographic Data Standards. Report #8 "A Draft Proposed Standard for Digital Cartographic Data." U.S. Geological Survey Open-File Report 87-308, 176 pp.

Rosch, E., 1973. On the internal structure of perceptual and semantic categories. in T. E. Moore (ed.), Cognitive Development and the Acquisition of Language, New York, Academic Press.

Rosch, E., 1978. Principles of categorization, in E. Rosch and B. B. Lloyd (eds.) Cognition and Categorization. Hillsdale, NJ: Erlbaum.

Starr, Lowell E., 1987. National Mapping Division Transition into the 1990's. Proceedings, Conference of Commonwealth Surveyors, Southhampton, England, July 1987.