Title

Language, Cognitive Science, and Geographic Information Systems (90-10)

Permalink

https://escholarship.org/uc/item/1qh3q6n8

Authors

Mark, David M.
Frank, Andrew U.

Publication Date

1990-10-01

NCGIA

National Center for Geographic Information and Analysis

Language, Cognitive Science, and Geographic Information Systems

Preprints of two papers by

David M. Mark
State University of New York at Buffalo

Andrew U. Frank
University of Maine, Orono

Technical Report 90- 10

October 1990

Simonett Center for Spatial Analysis
University of California
35 10 Phelps Hall
Santa Barbara, CA 93106-4060
Office (805) 893-8224
Fax (805) 893-8617
ncgia@ncgia.ucsb.edu

State University of New York
301 Wilkeson Quad, Box 610023
Buffalo NY 14261-0001
Office (716) 645-2545
Fax (716) 645-5957
ncgia@ubvms.cc.buffalo.edu

University of Maine
348 Boardman Hall
Orono ME 04469-5711
Office (207) 581-2149
Fax (207) 581-2206
ncgia@spatial.maine.edu

Table of Contents

Preface and Acknowledgements

The two papers contained in this report summarize the major themes of Research Initiative #2 of the National Center for Geographic Information and Analysis, entitled "Languages of Spatial Relations". They are being published as a technical report to make them accessible before they are published and printed in permanent outlets. The first paper, entitled **"Experiential and Formal Models of Geographic Space"**, has been prepared for an audience primarily composed of geographers, and summarizes the main conceptual and cognitive issues that we believe will be of greatest interest to that community. It is hoped that it will be published in a refereed journal in geography. The second paper, **"Language Issues for Geographical Information Systems"**, was written for the GIS community, and will appear as a chapter in **"Geographical Information Systems: Principles and Applications"**, edited by David Maguire, David Rhind and Michael Goodchild, a reference volume that will be published by Longmans Publishing Co. Although there is some overlap in the topics covered in the two papers, we believe that the papers complement each other well, and together provide a good overview of Initiative #2 work toward the closing of that Initiative at the NCGIA. Clearly, there is still much work to be done on filling in the details of topics identified in these papers.

This report presents work that has been supported by a grant from the National Science Foundation (SES-88-10917); support by NSF is gratefully acknowledged.

EXPERIENTIAL AND FORMAL MODELS OF GEOGRAPHIC SPACE

David M. Mark and Andrew U. Frank
National Center for Geographic Information and Analysis

ABSTRACT

This paper is concerned not with space and spatial relations as objective entities of the world, but rather with human experience and perception of phenomena and relations in space. The goal arising from this concern is 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. The paper reviews both kinds of models, viewing them each as abstractions of the same 'real world.' The review of experiential models is grounded in recent developments in cognitive science, expounded by Rosch, Johnson, Talmy, and especially Lakoff. Among other things, these models suggest that perception and cognition are driven by schemata and other mental models, often language-based. These models form a framework for a review of models of small-scale spaces filled with everyday objects. The ways in which people interact with such spaces is in sharp contrast to the bit-by-bit experience with 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. The paper then relates these models 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 real world; 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. This is a strong statement, and one which appears to be at odds with the positivist paradigm. However, in this paper, 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, yet avoids falling into pure solipsism[1], losing the ability to discuss the relevant observations and to propose formal models. More specifically, this paper discusses and compares 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 our environments. The experiential models form in individual minds as the associated bodies and senses experience their worlds. Due to the physiological similarities that exist among 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. 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), Mark and Frank (1989), and Mark (1989), is central to the models discussed here.

Formal models consist of axioms expressed in a formal language, together with mathematical rules to infer conclusions from them. We will review the use of such models as they are used to represent geographic space and spatial relations. We will typically use results from geometry, topology and algebra in our quest 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*. For example, as we will discuss below, Euclidean geometry is said to have begun through the formalization (by Euclid and others) of rules and procedures used for land surveying in ancient Egypt. This geometry is fully consistent with Newtonian (solid-body) physics; however, Newtonian physics itself corresponds closely with naive (experiential) physics in many every-day situations.

Our approach differs from most previous work on geographic theory, in that it draws on concepts related to human natural language. 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, the recent *Annals* paper by Peuquet (1988), emphasized results from studies of human vision. In contrast, the conceptual basis of our work is found primarily in the more linguistic parts of cognitive science. Our approach draws heavily on the work of Eleanor

---

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 knows only what the senses 'tell it',

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 Cognitive Science. Although a few articles drawing on this literature 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), 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 out renewed calls for 'general' theories of spatial relations (Boyle *et al*., 1983; 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 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.

Thus, it is not surprising that one of the five high-priority topics for research by the National Center for Geographic Information and Analysis (NCGIA) is "a general theory of spatial relationships" (Abler, 1987, p. 304). Abler goes on to elaborate that the goal is "a coherent, mathematical theory of spatial relationships" (Abler, 1987, p. 306). On the same page, he also states:

> "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 as parts of spatial cognition, spatial reasoning, and spatial behavior; otherwise, it will be of little if any use to geographers, spatial analysts, or geographic information systems (GIS) users. Thus the search for "fundamental spatial concepts" must be conducted in the cognitive sciences in parallel with searches in mathematics (NCGIA, 1989).

Of course, this search for fundamental spatial concepts is not new. Blaut's (1961) *Space and Process*, Bunge's (1962) *Theoretical Geography*, and Sack's (1973) *Geography, Geometry, and Explanation* represent three of the more prominent of such efforts. Geographical theory has often appeared to be mathematical, and has sometimes been connected to language. For example, geometry was discussed by Harvey (1969, pp. 191-229) as "the language of spatial form." And, more than a decade ago, several papers at the Harvard symposium on data structures for GIS addressed just these issues, and provided a number of approaches (in particular, see Chrisman, 1979; Kuipers, 1979; Sinton, 1979; 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 which enhance overall system function, and difficult to design data processing algorithms which are effective and efficient. As we begin (to) work with very large or global spatial databases the inabilities and inefficiencies which 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, can lead to parallel and complementary research efforts within the GIS agenda, in cognitive science, and in geography in general. Some signposts along this path are presented in this paper.

COGNITIVE CATEGORIES & EXPERIENTIAL REALISM

The concepts and principles presented in this paper are based on a model of human perception and cognition initiated by Rosch (1973, 1978) and her colleagues, and recently elaborated upon by Lakoff (1987) and particularly by Johnson (1987). The model departs from the classical or set-theoretic view of categories 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 is more correct to say that the *mathematical* concept of a set is a formalized version of the *naive* concept of a category. Among the fundamental principles of this set-theoretic model of categories is that there are some necessary and sufficient observable properties of an object, from which its membership in some set can be unambiguously deduced. Another principle is that all members of the set are equally related to the set, and thus would be equally good examples of the set; this classical model thus would predict that, when asked to give an example of a member of a set, a person would be equally likely to name any member of that set as any other.

Experiments in cognitive science find that neither of these aspects is true of the categories that individuals use to characterize their worlds (see Smith and Medin, 1981; also Lakoff, 1987, pp. 54-570). 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 classical theory. Rosch and her co-workers discovered that 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 far more often than they mention turkeys or penguins. Rosch's data are far more consistent with a model in which a category has a prototype or exemplar (or a small set of these), plus some rules for extending the category, by analogy, metaphor, and other procedures, to more peripheral members. Lakoff (1987) later discussed this in terms of a radial structure for some categories; peripheral members of different arms of a radially-organized class may have nothing in common, except resemblance (in different senses) to a common prototype.

Smith and Medin (1981) reviewed the classical theory, and the problems with it, and proposed two alternative models of categories. One is a probabilistic model; this, however, fails to predict some areas in which observed category structures depart from the classical model. Another model they discuss, at much less length, is one based on exemplars. That model would represent a class by a collection of one or more actual cases which 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 rather than actual-case exemplars.

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)

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) claims that mental activities such as perception and cognition are heavily influenced by what he calls *image-schemata*. Johnson defined a schema in a way which is different from, yet consistent with, the definition provided by Neisser:

> "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. Also, the schema themselves may change with each use. 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.

Johnson (1987, p. 126) provides 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
> BLOCKAGE
> ENABLEMENT
> PATH
> CYCLE
> PART-WHOLE
> FULL-EMPTY
> ITERATION
> SURFACE
> BALANCE
> COUNTERFORCE
> ATTRACTION
> LINK
> NEAR-FAR
> MERGING
> MATCHING
> CONTACT
> OBJECT
> COMPULSION
> RESTRAINT REMOVAL
> MASS-COUNT
> CENTER-PERIPHERY
> SCALE
> SPLITTING
> SUPERIMPOSITION
> PROCESS
> 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). For example, 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 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). One should note here that this method of 'spatialization' of inherently non-spatial concepts makes results from geography, as the science investigating space and spatial relations, applicable to 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 thought, and language. In this section we will use some examples of natural-language expressions describing geographic situations which allow us to deduce which image schema was likely to have been dominant in the speakers 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.) 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. 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 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 an explanation. Furthermore, the distinction between ground objects which require "in" and those which require "on" probably is quite old, since, although there are a few exceptions, German and Dutch commonly require **auf** or **op** (respectively) for the same situations for which English uses "on". 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.

Mark (1989) provided an explanation for this, which actually changes the question, rather than answers 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 are activated for which kinds of ground objects and used 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 schemas to sheer size of the landmass is 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 normally translate to "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 these differences allows us then to deduce when people use one image schema, and when they might use another. In the above example, native speakers of German, English and Dutch appear to share an image-schematic differentiation which 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" yet "***auf*** [=on] **dem Parkplatz**") 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"). We expect that image-schemata themselves will be common across linguistic and cultural groups, but their use will differ with those factors. (Image-schemata for languages other than English, or for other cultures, have yet to be examined in detail.) Studies are needed to establish cross-linguistic differences in the way that image-schemata are applied to various geographical situations.

MODELS OF SPACE

The previous section discussed the image-schemata which appear to mitigate between mind, perception, and language. 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 *perceptual*[1] *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 focussing upon in this paper. They claimed that "the two scales of space are quite distinct" (p. 197) in the ways people 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, Benjamin 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 which are visible from a single point. (We also note that there is risk of confusion with cartographic use of the terms small-scale and large-scale; representing a small-scale space on a fixed medium would use a rather large-scale map, whereas fitting a large-scale space onto the same medium would require a small-scale map.)

Our cognitive models of small-scale space develop from direct perceptions 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, which 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

---

[1] We use the term *perception* strictly to mean mental reactions to sensory inputs in the presence of a stimulus. Perception results 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.'

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' by the age of about two years (see Rosch, 1973).

People naturally build cognitive models based on the way they perceive familiar objects behaving (reacting to forces) in small-scale space. The field known as *naive physics* (sometimes '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). Of course, 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., which 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 because they help us to effectively reason and deal with situations which are currently not tractable with the methods of classical physics. For instance, the behavior of lettuce and salad dressing can be modelled using the principles of classical physics, but the resulting formal system is so complex that it is not useful, for example, to guide a robot (Hobbs and Moore, 1985, p. xi). Principles of 'naive' physics may be successfully and easily used in such situations, and 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 obviously 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. This salience ordering of the three dimensions of everyday space (up-down >> forward-back >> left-right), and the fact that the latter distinction is necessarily egocentric, 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 by and large to the geometry which 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, Aristotelean physics predicts that an object must expend energy to keep moving, and will stop if force is no longer applied to it, but the fact that everyday objects behave this way is due to friction, and not the fundamentals of mechanics (see Di Sessa, 1982, for a discussion of Aristotelean, Newtonian, and naive physics). The classical physics which 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 which is extremely useful in engineering and scientific applications, where it can be used to build models and to predict accurately 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. However, 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 this as "space whose structure cannot be observed from a single viewpoint." At some risk of criticism, we call this *geographic* space. Note that experience with this space is intimately intertwined with wayfinding and navigation.

Kuipers' model of spatial knowledge acquisition (Kuipers, 1978, 1983a, 1983b) begins from a sensorimotor experiential base. As we move through geographic space, we see a sequence of views (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). With some views, we associate actions; some 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 another[1]. 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 these large-scale spaces are the ones that geographers often 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 inference rules to build network models of places and connections, paths and barriers, in geographic space. Such a cognitive model of geographic space allows route-planning to novel destinations, or the planning of alternate routes when habitual paths are blocked. (Incidentally, such adaptive route-planning appears not to be restricted to human beings; Tolman (1948) discussed experiments in which laboratory rats were observed to use alternate paths when the usual ones were blocked by barriers.) Paths may have associated with them properties such as length in miles, kilometers, or blocks, or expected

---

[1] 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).

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. 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) felt 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).

Matthew McGranaghan has stated that the power of maps comes from the fact that they represent space with space[1]. In fact, maps represents use a *small-scale* space, namely a piece of paper or a computer screen, as a model of 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, as they experience objects on a desk-top or kitchen table in their everyday lives. 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 this is appropriate or not depends primarily on the use which 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 space, one can plan routes and perform other spatial inference using the familiar Euclidean model. If, however, the perceived geometric properties of geographic space is not compatible with the Euclidian geometry of the map, then the map may be an 'incorrect' model for geographic space. The map model of geographic space would be a sort of 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 which mimic it, are also very useful, and most assuredly 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

---

[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.

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 their concept of their space. However, perhaps the authorities would not have believed them otherwise:

> "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 examination 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. This is an assumption and not a 'fact', since the human mind has no 'direct' access to the real world, but only is aware of what the senses appear to report. Since the decision to adopt a particular definition of objectivity is itself subjective, 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, which has consistent properties, so that when people interact with that world, their mental experiences are very similar.

Measurement

One way to escape from this problem 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*. In that case, 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 to provide a geometry and physics (respectively) which are mathematically formal, yet consistent with measurement and observation. The fact that Euclidean geometry breaks down at certain time, space, or velocity scales, and that Einstein's theory of relativity required new geometries, thus re-orienting the cutting edge of academic geometry, is of little 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 10^6) do not observe any discrepancies between the model and their observations.

Map projections allow us to transform from one two-dimensional surface (over the spheroid) to another (a cartesian plane) in ways which 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 which 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 is often considered to be the only way to 'see' space in an objective way. However, it also is possible to define 'correct' in a way which 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 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 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 (GIS). Numerous organizations have collected data and built GISs or other similar "spatial information systems". Not all of these systems have met with success. Many of the systems constructed were either extremely limited in their capabilities to exploit spatial location, or the methods used were mathematically well-defined but not necessarily 'intuitive', i.e. they did not agree with the spatial concepts used by all their users. The slow progress in GIS development appears at least partially to be due to the 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 analysis, the concepts it embodies and the ones employed by its users must be as similar as possible. This similarity can be achieved by training the user to understand the concepts used by the system. But such a strategy requires a great deal of training, and thus may severely limit the user community and thus the applicability of the system. Alternatively, the system can be built using concepts very close to the ones that an untrained user 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 reflect these concepts, and particularly that the user interfaces for such systems should be 'natural'. In the remainder of this section, we will discuss the mathematical bases of geometry, and how such concepts could be formalized. Unless these concepts can be formalized they cannot be included in a GIS; but conversely, the inclusion of any of these concepts in a GIS implementation may constitute the required formalization.

A GIS is a fixed set of instructions embodying in a formal way a set of procedures (algorithms) to process data. To develop such programs properly, a clear, formal, theoretical base is necessary. Most GISs are based on Euclidian geometry and implemented using analytical geometry: 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. Euclidian geometry and the formulae of analytical geometry are well known and relatively easy to understand, and thus the actual writing of a GIS was expected to be an easy and straightforward task.

There are however, a number of problems related to the use of Euclidian geometry in this manner. First, the implementation of GIS concepts as a computer program is not straight forward. 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 only can represent approximations of them. These approximations are limited both in their magnitude (over- or under-flow conditions arise if results of computations become too large or too small) and in their resolution. In Euclidean geometry, one can always find an intermediate point exactly half way between any two given points; in computer coordinates, however, this is often not possible. Known GIS implementations show surprising artifacts that are due to this problem; they may even break down in unexpected situations (see Franklin, 1984). The implementation of analytical 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 Euclidian geometry do not hold (Franklin, 1984; Nievergelt and Schorn, 1988).

A GIS programmer thus faces the problem of taking 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, the software engineer designing the GIS must transform the naive geometry of the user into the (quasi-)Euclidean system that the programmer can implement (Figure 1, left side).

Naive Geometry ----> Abstract Euclidian----> Geometry of Implemented
of the User Geometry GIS

Figure 1: Using Euclidean geometry in modelling geographic information on computers involves two transformations.

The concepts applied by users of geographic information are not exactly Euclidian. This is not so much a disagreement with the concepts that Euclidian geometry proposes, but rather involves additional concepts that are not included in Euclidian geometry (for example, the direction between extended objects). GIS the are occasionally unable to answer questions which appear reasonable and well defined to the user, like 'What is the direction from New York to Canada?'. Peuquet and Zhan (1987) investigated this problem, and provided solutions for some situations.

It is unlikely that the shortcomings of the one mapping can be compensated for by the other. More likely, the problems will be compounded, and the user will be forced to learn how to transform his concepts into the Euclidian geometry, and may be surprised to see that the implementation is not following the theory that he has just learned. A more sensible solution would be to directly map the user concepts to the implementation, bypassing Euclidian geometry (see Figure 2). But such a mapping is far from trivial, and requires groundwork in cognitive science.

Naive Geometry --?-> Geometry of Implemented
of the User GIS

Figure 2: If a GIS users' naive geometry can be modelled directly on the computer, a more successful implementation should result. However, it is not yet known how to accomplish this.

A second problem in achieving working GISs is caused by the fact that geographers often work with data that are the results of measurement and processing, and contain an error component. People are accustomed to the common, small positional errors one encounters when combining data from different sources. Euclidian geometry on the other hand assumes ideal points and lines and locations without error.

Formalization of conceptual geometries

In order to implement the concepts that users may have regarding space and spatial relations, the concepts must be formalized, that is, converted into a formal mathematical theory. This presumably will lead to a new and different geometry. Constructing new geometries is not unheard of in mathematics. Until the beginning of the last century, Euclidean geometry was the only form of geometry. Efforts to show that his set of axioms was minimal, and especially to show that the axiom based on parallel lines was independent of others, 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 which 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. Despite the fact that non-Euclidean geometries have been discussed in geographic contexts by Harvey (1969, pp. 199-203), Tobler (1976), Müller (1982), and others, they have not made 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, as more that one geometric theory was designed, the problem became the determination of what made a theory of space a ***geometry***. What is the essence of 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 which remain unchanged (invariant) when the object was 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, Euclidian geometry deals with properties such as the length of a line, the sizes of angles, etc., all of which remain invariant under the transformations of rotations and translations. This definition of geometry also includes areas of mathematics such as graph theory and topology, which have a geometric component. Typically, each group of transformations defines a set of properties which remain invariant and thus creates a geometry which can be formally defined and studied.

This definition of geometry, based on groups of transformations, reflects a similar structure to that which we see in Talmy's pragmatic approach to linguistic representations of space (Talmy 1983, p. 258 - 263; see also Talmy 1988, p. B-3). It 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.

This more general framework for the definition of a geometry is well-suited to questions such as: "what is the geometry of natural language?" And perhaps this should be: "what *are* the geometr*ies* 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). Expressions of spatial relations and properties in natural language are typically invariant, in most languages, under a wide set of transformations (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 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 irrelevant);
- *closure neutral*: (the preposition is used whether the ground is completely closed [as in a box] or partially open [as in a bowl]); and
- *continuity-neutral*: ('in" is used both for continuous enclosures, discontinuous enclosures [such as a bird cage], or conceptual (e.g., 'in town', or even 'in love').

And, whereas some languages have a few examples that depart from this pattern, these independences seem to be the rule in natural language.

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. (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.) Not all terms of a natural language define the same geometry, as they may remain invariant under different sets of transformations (i.e. appropriate sets of transformations will define geometries, each of which will include some of the spatial relationships expressed in natural language). For example, all properties expressed in a reference frame which 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 which leave the reference frames invariant (for example, an expression using cardinal points would be invariant under a translation, but not for a 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 which 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 (for the example of Icelandic, see Haugen, 1957; for a partial review and discussion, see Mark, Svorou, and Zubin, 1987) and in some circular lakes.

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 which contain the same features but at, for example, different levels of resolution or different levels of generalization (Buttenfield and DeLotto, 1989). Current systems not capable of managing such collections of data as single logical units, in which changes propagate from one level to the other and 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 and is known as object-oriented specification (Guttag, Horrowitz, and Mousser, 1978; Goguen, Thatcher, and Wagner, 1978). It has already been applied to geometric problems (Goguen 1988; Mallgreen, 1982). Algebraic specifications for cell complexes have been advocated for use as the base modelling block in a vector oriented GIS (Frank and Kuhn, 1986; Bruegger and Frank, 1989).

Given such individual algebraic specifications for a specific geometry, we have then to construct relations between them. Mathematicians have studied the connections between different algebras under the topic of algebraic morphism. They establish mappings between the objects in the one algebra to the ones in the other and map operations from one algebra to the other. Then one can study the regularities in these mappings. A homomorphism between an algebraic structure with elements **A** (a1, a2, ...) and operations **f** and another structure with elements **A'** (a'1, a'2...) and operations **f'** is a mapping **G** which maps elements from **A** to **A'** and also maps the operations **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:

$$(a^b)(a^c)= a^{(b+c)}$$

and

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

Mathematicians have used this isomorphism to replace difficult multiplications by simple additions of 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 will 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 space, which can be perceived only in relatively small parts. Fundamental terms for spatial relations are often based on concepts from small-scale space, and are metaphorically extended to geographic (large-scale) space. Thus, terms and concepts for the spatial relations among the objects in a small space can form an appropriate core for spatial language. Additional spatial relations on a geographic scale can be formed by the addition of small sets of axioms or postulates (for example, letting "north" equal "up"). Finally, we set as a short-term but important goal a search for geometries of spatial language. This search will attempt to define those properties of particular instances of spatial reference in natural language which remain invariant under groups of transformations, and the development of a link between these properties and the geometry and topology of GISs. This fusion could form the basis both for geographic data structures and for the understanding and generation of spatial language itself. If properly formalized it will be an effective base for constructing GIS software which will be more 'natural' to use.

Acknowledgements

This paper represents part of Research Initiative #2, "Languages of Spatial Relations", of the National Center for Geographic Information and Analysis, supported by a grant from the National Science Foundation (SES-88-10917); support by NSF is gratefully acknowledged. William Mackaness, Michael Gould, Matthew McGranaghan, Helen Couclelis, Scott Freundschuh, Ronald Amundson, Sherry Amundson, and several members of the Center for Cognitive Science, University at Buffalo, provided useful comments on drafts of this paper.

REFERENCES

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

Birkhoff, Garrett, and Lipson, John D., 1970. Heterogeneous Algebras. *Journal of Combinatorial Theory*, Vol 8, pp 115-133

Blaut, J. M., 1961. Space and process. *The Professional Geographer*, v. 13, pp. 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, Hugh, 1981. *Maps and Dreams*. Hamondsworth, England: Penguin Books, Limited, 297pp.

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

Bunge, William, 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, Bruce, 1988. *The Songlines*. London: Pan Books Ltd., 327pp.

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

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

Couclelis, Helen, and Gale, Nathan, 1986. Space and spaces. *Geografiska Annaler*, 68B, 1-12.

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

Downs, Roger M., and Stea, David, 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.

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

Freeman, John, 1975. The modelling of spatial relations. *Computer Graphics and Image Processing* 4: 156-171.

Geroch, Robert, 1985. Mathematical physics. *Chicago Lectures in Physics*, University of Chicago Press, IL

Goguen, Joseph A., 1988. Modular Algebraic Specifications of Some Basic Geometrical Constructions. *In* Kapur, Deepak and Mundy, Joseph L. (eds), *Geometric Reasoning*, The MIT Press, Cambridge, MA, pp 123 - 153

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

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

Golledge, R. G., 1978. Learning about urban environments. In Carlstein, T., Parkes, D., and Thrift, N.(editors), *Timing Space and Spacing Time*, 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. *In* W. Ittleson (editor) *Environment and Cognition*, 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, John R., Horrowitz, L. L., and Mousser, David R. 1978, Abstract Data Type and Software Validation, *Communications of the ACM*, Vol. 21, Nr. 12, pp. 148-164

Haber, Ralph Norman, and Wilkinson, Leland, 1982. Perceptual components of computer displays. *IEEE Computer Graphics & Applications*, May 1982, 23-35.

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, Jerry R., and Moore, Robert C., 1985. *Formal Theories of the Commonsense World*. New Jersey: Ablex.

Johnson, Mark, 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, Benjamin,1978. Modeling spatial knowledge. *Cognitive Science* 2, 129-153.

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

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

Kuipers, Benjamin, 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, 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.

Lloyd, R., 1989a. Cognitive maps: Encoding and decoding information. *Annals of the Association fo American Geographers*, 79:1, 101-124.

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

Mallgreen, William R., 1982. Formal Specification of Graphic Data Types. *ACM Transactions on Programming Languages and Systems*. Vol. 4, Nr. 4, pp 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, v. 2, pp. 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, Michael, 1983. Intuitive physics. *Scientific American* 248 (4), 122-130, April 1983.

Müller, Jean Claude, 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, Ulric, 1976. *Cognition and Reality: Principles and Implications of Cognitive Psychology*. San Francisco: W. H. Freeman and Company.

Nievergelt, Jurg, and Schorn, P., 1988, Line Problems with Supra-Linear Growth (in German). *Informatik Spectrum*, Vol 11, pp 214-217

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, Jean, 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 T. E. Moore (editor), *Cognitive Development and the Acquisition of Language*, New York, Academic Press, pp. 111-144.

Rosch, E., 1978. Principles of categorization. *In* E. Rosch and B.B. Lloyd (editors) *Cognition and Categorization*. Hillsdale, NJ: Erlbaum, pp. 27-48.

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

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

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

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

Svorou, Soteria, 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* H.Pick and L. Acredolo (editors) *Spatial Orientation: Theory, Research and Application*. Plenum Press.

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

Thorndyke, Perry 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* R. Golledge and G. Rushton (editors), *Spatial Choice and Spatial Behavior*. Columbus: Ohio State University Press, pp. 69-91.

Tolman, 1948. Cognitive maps in rats and men. *Psychological Review* 55, 189-208.

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

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

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

Note: This paper will appear in "**Geographical Information Systems: Principles and Applications**", edited by David Maguire, David Rhind, and Michael Goodchild, and to be published by Longmans Publishing Co.

LANGUAGE ISSUES FOR GEOGRAPHICAL INFORMATION SYSTEMS

Andrew U. Frank and David M. Mark
National Center for Geographical Information and Analysis

1. Introduction; definitions of terms

Users must be able to interact with Geographical Information Systems (GIS). For this reason, it is important to study how communication between users and GISs can be made most effective. In the past, for GIS, as for other information systems, most of the effort in this area has been centred on constructing appropriate query and command languages. The approaches proposed have been to use natural language or to construct formal languages. This chapter reviews and discusses why language issues in a broad sense, including cognitive issues, are crucial for the further development of GIS. Key works are listed at the end of this Chapter; for over 500 bibliographic citations on the subject, see Mark, Gould, *et al.* [1989].

Natural languages comprise the 'everyday languages' that people use -- English, French, German, Chinese, Spanish etc.-- with all their rules, exceptions and 'idiomatic' expressions. In principle, natural languages have three components: a vocabulary (lexicon), listing words (terms) that are used; a syntax and grammar, which describe how valid sentences can be formed from these words; and semantics, indicating what the sentences mean. None of these can be fully formalized (at least not today). One should also be aware that the language that native speakers actually use is much richer and of more interest than the "prescriptive" view of the language defined by dictionaries, academies, and grammarians.

Formal languages, on the other hand, are artificially constructed languages, following formally defined rules. These too have vocabulary, syntax, and semantics, and often are modelled on natural languages, but in these cases all of the components are fully described in a rigourous format.

The use of either natural or formal language to query a GIS, may result in problems such as how to describe the information needs of a user. If we use natural language, the programme must "translate" the question into an unambiguous form which can be processed. This can be difficult, given the complex structure of natural languages. On the other hand, if we make the user express the query in a formal language format, then we force users to learn this language and to translate their information needs into this format. This has the potential to limit the user's ability to interact with the system, and also limit system access itself to specialized and trained individuals.

In the past, designers of formal query languages have not paid much direct attention to the linguistic aspects of the problem. Instead, they have selected formal structures following well-known models, probably inadvertently introducing structural elements of their own natural language. The tendency for the formal language to mimic the structure of the designer's natural language will make such systems easier to use for speakers of the same language, but perhaps more difficult for other users.

The terminology used formally has not always been based on concepts that people would use naturally; this applies to all information systems. In geographical systems, discussions on design have mostly been centred on the formulation of GIS queries, and have not considered the visualization and interaction necessary to inform the user of the result.

In this chapter, we advocate a comprehensive approach. People use a finite set of concepts to organize their perception of space, and these concepts should be respected when we design systems to communicate regarding spatial situations, both when users formulate queries and when responses are presented to them. On the other hand, computers require formal definition of terms in order to retrieve the necessary information. Thus we see the communication process as a translation between human spatial concepts and the formal spatial concepts in a computer programme.

The discussion in this chapter is on a conceptual, logical level, and does not attempt to explain how these methods should be implemented. It seems very important that the GIS literature separates the concepts involved in a programme from the mechanics of its implementation as a programme. Such a separation has been advocated in a database design standard [Tsichritzis and Klug, 1975], separating the conceptual database schema from the physical storage arrangement (internal schema). The standard also defines a third, external schema, namely 'user views', which describes subsets of the conceptual view, as appropriate for a specific task and which may be different from the 'corporate' view (Figure 1).

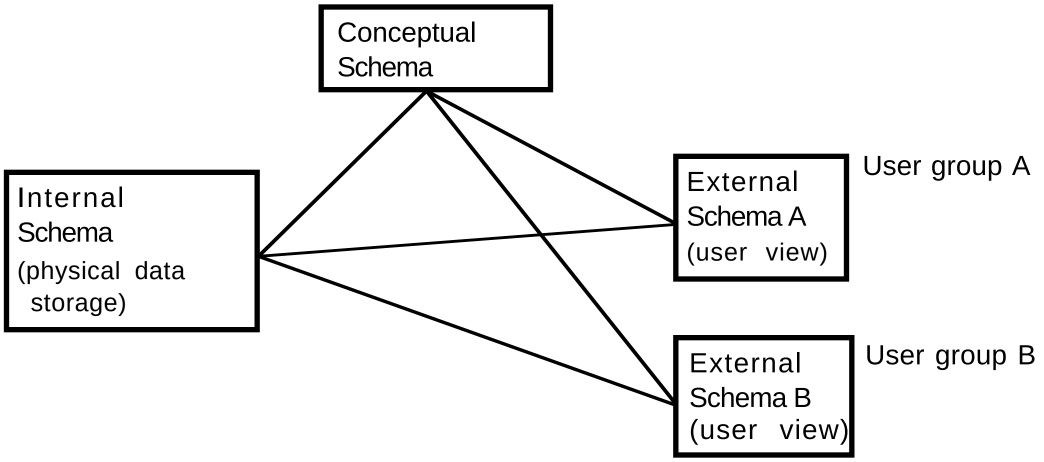

Figure 1. 3 - Level Schema

The confusion in GIS literature between concepts and implementation is a severe impediment to progress in the field. Discussion is needed to determine *what* a system does independently from *how* it is achieved, especially in light of the extremely rapid development of the computer tools, where the 'how' might change overnight. The discussion of the 'what' is intrinsically linked to cognitive and linguistic issues, and this chapter discusses the 'conceptual' and 'user view' (in terms of the standard mentioned above) and their relations.

2. Mathematical formalisms for geographical information

A computer is a machine whose chief function is to execute a set of instruction which manipulate symbols. These symbols are selected and structured to represent some situation in the real world, as it is perceived by people. The critical problem is that an individual's cognitive methods are informal and fluid, and allow ambiguities or contradictions to exist. The data processing in a computer is formal and follows strict rules of logic; even when computers are used to mimic 'fuzzy' human reasoning, a strict formalism is used to explain the fuzziness (eg. [Zadeh 1974]).

In a GIS one must formally define a structure to represent spatial situations (as perceived by people). Once defined, the appropriate operations and their outcome must also be defined. This is a language issue, as the objects and the operations applicable to them are defined in terms of the GIS user's chosen spatial language [Woodcock and Loomes 1989].

Despite the fact that space is a fundamental, everyday notion, its formalization is not simple. People sometimes look to the objects that fill space, thus treating space as an attribute of the objects (this follows a Kantian viewpoint). Or, one can look at space and the properties of objects that are encountered at each point, and thus attributes and objects become properties of the location (following a more Descartian viewpoint). People use both these methods interchangeably, depending on what is more suitable for the task at hand.

The well-known concepts of Euclidean geometry, which seem to be fully consistent with an appropriate concept of space, in fact helps to obscure the problem. In fact, Euclidean geometry captures only limited and highly abstracted aspects of geometry and space. One aspect of the abstraction is the concept of a continuum of possible coordinates, positions, and lengths. This may be fully consistent with the view that scientists, engineers, and many other GIS users have, but does not apply strictly to all human experience and inference. Perhaps more critical, real numbers and continuity they apply cannot formally and perfectly be implemented on finite computer systems, and this technical mis-specification may occasionally influence results. For example, in a Euclidean, real-numbered world, a precise polygon overlay procedure (no tolerances or "snapping") could combine three coverages in a way that would not be order-dependent; however, when all coordinates are represented on a computer, order-dependency may result.

The conceptual implications of these two major geometric data models (feature-based or location-based) are discussed in this chapter. Computer scientists generally use the term "data model" to describe the tools or methods that are available to describe the conceptual structure of the data, ie. the language available to describe reality or our perception of reality; this is different from some uses in the GIS literature. The consequences of the internal representation and the data structures necessary to implement these two views, often referred to as 'vector' and 'raster', are treated elsewhere in this volume. Here, we concentrate only on how people interact with the data stored in the GIS. This is parallel to the discussion regarding data models, primarily the network and the relational model [Codd 1982], in computer science. The discussion of user interfaces here is thus - in principle - on a purely conceptual level and in theory, completely independent from implementation; in practical terms, however, it is not known how to translate between the two major geometric data models without small but observable differences.

The extension of these concepts to three-dimensional GIS problems will not be trivial; because 3-D GIS is a fairly new and as yet small subfield, we will not address such problems in our discussions [Raper 1989] [Turner 1990].

2.1 Regular tessellation models

A system with a square regular tessellation geometrical data model (a raster) is built on the notion of a subdivision of space into cells of regular size and shape (Figure 2). Methods other than subdivision in squares have been studied [Diaz and Bell 1986] but are not widely used (Figure 2). For implementation in a data structure, regular subdivisions of space, which allow a hierarchical structuring of areas of varying size are very convenient (Figure 4). An example of this is the very popular quadtree structure [Samet 1984]. This, however, does not alter the conceptual data model and the behaviour of the operations at the user interface. Everything a raster system can do a quadtree system can, and vice versa - the only noticeable difference would be the execution speed and other computer resource requirements.

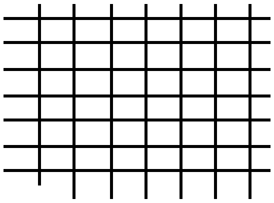

Figure 2. Raster

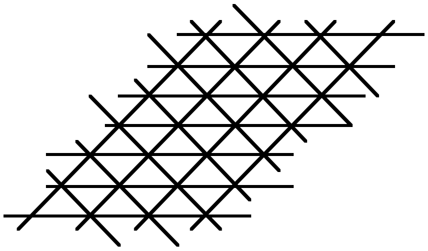

Figure 3. irregular tesselation

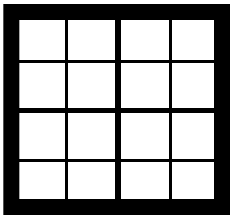

Figure 4. hierarchical square raster

For each raster cell, values for all attributes can be made available to the user. The concept can be thought of as an array with integer indices, where each array cell contains a value for each attribute of interest. This can also be visualized as a superposition of similar arrays, which each contain the attribute values for one property.

map : property x ix x iy -->> value

Based on this geometric data model, a 'map algebra' can be built [Tomlin 1983a, Tomlin 1983b, Tomlin 1989]. Operations are defined such that they have one or two maps as input and produce a new map according to a specific rule. This output map has exactly the same spatial structure (but a different content) as the input map and can thus be used as input in further operations.

2.2 Irregular tessellation model

The alternative is an irregular subdivision of space, an 'irregular tessellation' geometric data model (Figure 5). This model is based on the concept of cells as defined by algebraic topology [Alexandroff 1961, Giblin 1977, Spanier 1966]. Each cell has a specific dimension; terminology varies:

0-cell = point, node, vertex
1-cell = line, arc, edge
2-cell = area, region, cell.

Each cell is bounded by cells of lower dimension, e.g. a line is bounded by two points at each end and each cell is the boundary for some cells of higher dimension, e.g. a line is the boundary between two areas. For all points, we are given coordinate values that determine their location. Also in some systems, the lines between nodes can have arbitrary shape, in others they are restricted to straight lines. In order to simplify implementation it has been argued that only triangular cells - or generally simplices - should be allowed and other cells subdivided accordingly [Frank and Kuhn 1986] .

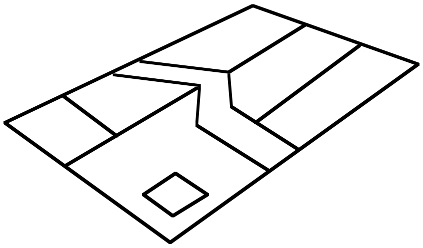

Figure 5. irregular tesselation

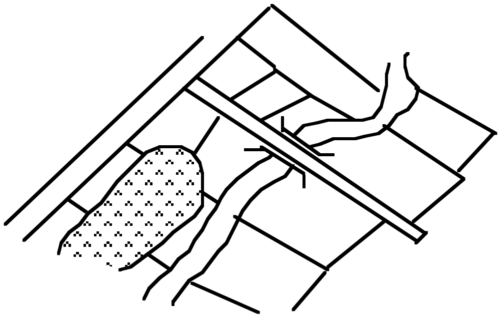

Figure 6. integrated data model

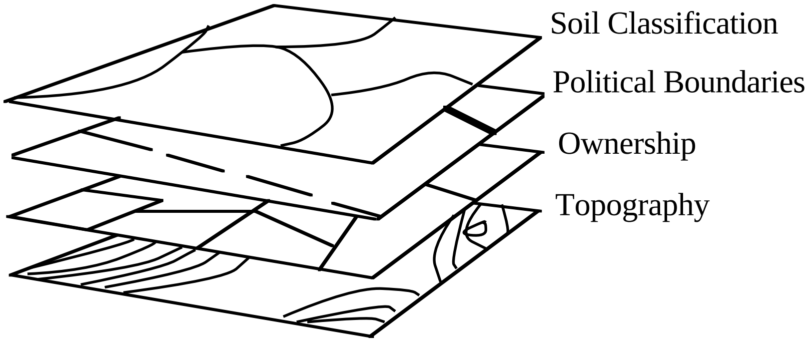

Figure 7. layered model

Using an irregular tessellation as a geometric foundation, three views are possible:

- An 'integrated geometry' concept, where all the layers are integrated at once and the cells are the largest areas for which all attribute values are homogeneous (Figure 6). Nevertheless a 'layer view' can be established as a 'user view' utilizing the operations of the map algebra.

- A 'layer' concept (Figure 7), where each layer represents a single property and the cells in this layer show the largest spatial units that have a common attribute value for this property (e.g. a layer for 'soil classification' and another one for 'ownership'). The user can then overlay, or combine, these layers and produce new layers. The operations are similar to the map algebra mentioned previously.

- An 'object' concept, where one concentrates on the individual objects, each having geometric and non-geometric properties. In this view, the fact that all objects fill the space (or even create the space) is not stressed.

Properly built software should allow these three viewpoints to coexist on top of a single data collection. Each of these viewpoints however is sufficiently different from the others to require its own language for a user to think about, to formulate queries with, and to understand the responses from the system.

Earlier, GIS were built as collections of points and lines - sometimes referred to as 'spaghetti' (Figure 8). The lines were just lines and all intersections had to be deduced from coordinates. The points represented either point features or represented areas (centroids) whose boundaries had to be sought in the collection of lines using operations from analytical geometry. Again, this is essentially an 'irregular tessellation' data model as all equivalent properties can be deduced. These deductions are not only costly in terms of computer operations, but they cannot be executed reliably (i.e. without leading to internal contradictions) on a finite computer. Thus users can observe artifacts which are due to the limitations of the specific implementation.

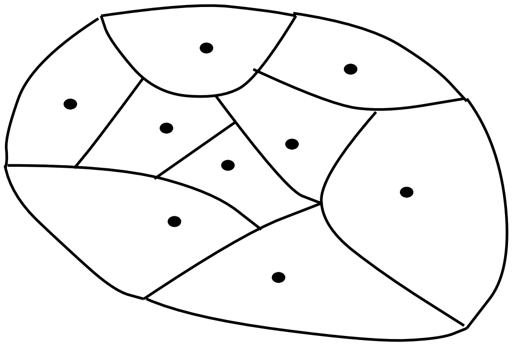

Figure 8. Spaghetti Code

In the irregular tessellation data model, topological relations are included (it is thus a 'full topology' model). For each cell, its neighbours are known. The topology in the model is very often also used to verify that the actual data are a valid representation of a topologically correct situation [Corbett 1975, Corbett 1979]. Of course, in a 'regular tessellation' model, topology is also included, although it is implicit in the tesselation pattern and tile numbering system.

The regular tesselation and earlier, line based representations should in principle be equivalent. In practice however, they are not - the limitations of computers as finite machines affect the exact behaviour of the operations. It is a reasonable assumption that the spatial resolution of a regular tessellation model (ie. how fine the grid of cells is) is much coarser than the spatial resolution of an irregular tessellation model (ie. how many bits are used for point coordinates); typical examples are 100 m cells for the one and coordinate values with cm precision, which results in a 10^4 resolution difference. This results in observable differences between corresponding operations executed in one or the other system.

2.3 Other geometric data models

The two models discussed present methods to deal with situations where space is subdivided in mutually exclusive and collectively exhaustive cells. There are phenomena for which these models are not appropriate. In this subsection we will mention briefly two additional models.

2.3.1 Feature based models

If one is only interested in isolated features, like roads, rivers, lakes or settlements, localized in space but without concern for the areas between them, using an irregular tesselation model may be inappropriate. Instead, a number of GISs have been built around a geometric data model that includes:

- point features
- linear features
- areal features

each defined by sets of coordinates. Details of individual models differ [Burton 1979, Cox et al. 1980]. A number of alternatives are discussed in the proposed U.S. cartographic data exchange standard [National Committee for the Digital Cartographic Standards, 1987] .

2.3.2 Continuous field

Other phenomena, like temperature, magnetic fields etc. are thought of as continuous, i.e. for every point in space there is a value and the values change gradually. The phenomenon is organized, mathematically speaking, as a function of the location in space ($f(x, y)$). If there is a single value (not a vector) associated with each point, the field may be visualized as a continuous surface. The mapping from a point in space to a value can be determined by a mathematical formula or interpolated from measured values. Current GIS are not designed to handle such phenomena directly.

3. Cognitive science, natural language, and geographical space

3.1 What is "Cognitive Science"?

The conceptual basis for our treatment of models of geographical space comes primarily from the field of cognitive science. George Lakoff offered the following definition:

> "Cognitive science is a new field that brings together what is known about the mind from many academic disciplines: psychology, linguistics, anthropology, philosophy, and computer science. It seeks answers to such questions as: What is reason? How do we make sense of our experiences? What is a conceptual system and how is it organized? Do all people use the same conceptual system? If so, what is that system? If not, exactly what is there that is common to the way all human beings think? The questions aren't new, but some recent answers are." [Lakoff 1987, p. xi]

Why do we introduce such a field here? A fundamental premise of our work is that "a main objective of GIS is to allow the user of the system to interact vicariously with actual or possible phenomena of the world" [Mark 1989]. From this, it follows that models of the human mind, and in particular how our minds deal with concepts and objects of geographical space, are a strict prerequisite to designing effective GISs. This is a bold claim, and the need for explicit cognitively-based data models as a basis for GIS data structures can be questioned. However, there is little question that effective user interfaces must be based at least in part on such models.

3.2 The Rosch-Lakoff-Johnson model of cognitive categories

The mathematical concepts that are typically used to provide data models and structures for GIS include classical set theory, and in particular the idea of geographical concepts, regions, and areal objects as sets. In the classical model, every member of a set is an equally good example of it, and further more that there is some necessary and sufficient set of properties for determining whether some object is or is not a member of a set. The first part of this model would predict, for example, that every familiar bird would be an equally good example of the class of all birds. However, it is known that, when people are asked to give an example of a bird, they tend to give 'robin' or 'sparrow' or 'canary' far more often than they give 'ostrich' or 'penguin' or 'duck'; this is the concept of prototypes. The second part of the model (necessary and sufficient observable properties to define set membership) also breaks down when applied to cognitive concepts. The repeated and largely unsatisfying attempts by quantitative and statistical geographers to use techniques such as discriminant analysis to define classic geographic regions such as the American "corn belt", or "Appalachia" is an indication that such regions are not equivalent to classical sets.

Whereas such problems with set theory were noted early, it was the research and writings of Eleanor Rosch [1973, 1978] that provided a clear statement of the problem and summary for the evidence. Several solutions have been proposed, including the "fuzzy set theory" of Zadeh [1974]. Smith and Medin [1981] also treat the problem in great detail. They propose two groups of solutions. One group is probabilistic, and is related to fuzzy set theory. While many of the problems of classical set theory are solved, solutions in this group still contain fundamental flaws, especially in the way they treat conjunctions of classes. The other approach discussed by Smith and Medin involves the concept of exemplars. Classes are defined by exemplars and by rules for establishing similarity to these exemplars. The image-schema model of cognition [Johnson 1987], and the broader philosophical position termed experiential realism [Lakoff 1987], appear to provide an even more appropriate basis for concept modelling. Rather than using actual instances as exemplars, classes have idealized or generalized prototypes. These prototypes for classes can in turn be based largely on a small number of schemata that embody properties and transmit them, through prototypes, to class members:

> "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]

Johnson [1987] follows Neisser in claiming that mental activities such as perception and cognition are heavily influenced by what Johnson calls image-schemata, which he defines as follows: "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] He goes on to add: "... Much of the structure, value, and purposiveness we take for granted as built into our world consists chiefly of interwoven and superimposed schemata... " [Johnson 1987, p. 126] Recently, Mark [1989] has discussed how an image-schematic model of geographical categories and concepts might operate, and how it could relate to concepts of 'user views' of a geographical data base.

3.3 How Language Structures Space

In the introduction to section 2 above, the term "data model" was used to describe the tools or methods that are available to describe the conceptual structure of the data, ie. the language available to describe reality or our perception of it. If we substitute "cognitive/linguistic model" for "data model", this is almost exactly the thesis of Leonard Talmy in his seminal paper, "How Language Structures Space" [1983]. The basic idea that Talmy presents in that paper is that human natural languages provide individual speakers with a set of terms that are linked to cognitive concepts. Then, consistent with the ideas of schemata discussed above, these mental concepts constrain the way people think, reason, and talk about both perceptual spaces, that can be seen from one viewpoint, and geographical spaces, that must be integrated over repeated experiences of parts of space. The somewhat-controversial Sapir-Wharf hypothesis about language and thought extends this logically to the idea that speakers of different languages may think differently, at least about some topics [Lakoff 1987, pp. 304-337].

A central issue involves the concepts of "language universals" and "language primitives". A universal would be a property that applies to all natural languages. Explicit universals may be non-existent, but we can turn to look for primitives, building blocks that may themselves be universal, and from which linguistic expressions can be built. Obviously, identifying such items would be essential to the design of a multi-lingual, natural language understanding system. Some of the primitives for the language of geographical space seem to be exactly the topological relations used in graph theory and in GIS, as discussed above. The image-schemata of Johnson [1987] form another set of primitives [Mark 1989]. The search for still more conceptual primitives for geographical space, and the study of how they combine in particular languages, is an open research question, and a critical part of the research agenda. There is little doubt that geographers and others in the GIS community will make substantial contributions to cognitive science in this area.

3.4 Fundamental Spatial Relations

Freeman [1975] produced an important and early review paper on formal representation of spatial relations. He proposed that the following form a complete set of primitive spatial relations for elements in a (2D) picture, a view of a (3D) everyday object space:

1. left of;
2. right of;
3. beside (alongside, next to);
4. above (over, higher than, on to);
5. below (under, underneath, lower than);
6. behind (in back of);
7. in front of;
8. near (close to, next to);
9. far;
10. touching;
11. between;
12. inside (within); and
13. outside.

Note that this is not a minimal set of relations, since some can be defined as combinations of some of the others.

Freeman's list is very similar to the list of terms presented by Abler [1987, p. 306] in his discussion of the research agenda for 'Geographic Information and Analysis'. The cardinal directions can be added to Freeman's list through the addition of one more axiom. If we associate 'north' with 'up', then by deduction, 'south=down', 'west=left', and 'east=right' can follow. Peuquet and Zhan [1987] extended Freeman's [1975] relation set in exactly this way, including the cardinal directions as spatial relations without comment, and substituted 'north' for 'above' and 'south' for 'below' in the example they drew from Freeman's paper [Peuquet and Zhan, 1987, p. 66]. Note that the 'north=up' axiom is quite arbitrary. Indeed, the etymology of the Indo-European root for the word 'north' is based on 'left' [Svorou 1988]; this relation results from an earlier 'east=forward' convention, and world maps in Medieval times were presented with an east up orientation (orient=east).

Some cultural and linguistic groups, including the Hawaiians, use a radial coordinate system for referencing in geographic space (see [Mark, Svorou, and Zubin 1987]). This uses the 'inside-outside' dichotomy of the CONTAINER image-schemata (see [Mark, 1989]) for one spatial dimension, and 'toward some landmark' (spatial action, rather than relation) as the other. Other island peoples use similar spatial reference frames (see [Haugen 1957] for a discussion of this for Iceland).

Herskovits [1985, 1987] has discussed formal and computational models for locative expressions in English. In particular, she discusses about 30 'use types' for the English prepositions "in", "on", and "at". Recently, Mark [1989] has proposed a link between the image-schemata model of Johnson [1987] and the models of Herskovits. For example, conceptualizing something as a CONTAINER means that an English speaker is likely to use the preposition "in". And, the use of "in" would, in turn, cause the listener or reader to use a similar CONTAINER schema in interpreting the meaning of the expression.

4. Spatial query languages and database interfaces

4.1 Requirements for a query language

A query language is the tool a user needs in order to extract data from a database and to present the result in a useful format. The query is expressed in a language understandable by the query execution programme. Thus the query processor must fulfil two important functions:

- select the subset of the data the user needs
- render the selected data in a format that is meaningful to the user.

In this section, we concentrate on the expressive power, i.e. what can be specified with a given language, and do not discuss the specific syntax or implementation issue. We also restrict our discussion to properties in which spatial query languages differ from ordinary query languages, as they are commonly used for administrative data processing. We list eight requirements for a spatial query language, which deal with the selection of data and with its representation [Egenhofer 1989c].

Spatial selection criteria: The user will need to select data to be retrieved not only based on predicates over attribute values (e.g. the standard question 'select all employees with salary > 50,000') but also based on spatial properties (e.g. 'select all parcels owned by Smith and on or within 100 metres of a lake or pond'). The query language must be extended with predicates to select data based on 'neighbour', 'connected to', 'inside' etc. Such an extension should be systematic, ie. the set of predicates covers all cases and the predicates have meaningful relations to each other. The predicates must then be given a formal meaning in terms of one of the geometric data models explained before. An arbitrary set of terms from, say, the English language is not a good starting point. For a subset of spatial relations, namely the topological ones, a systematic set has been established [Egenhofer 1989a]. From these proposed base relationships, the user can construct more complex ones, with specific meaning appropriate to the application.

Selection based on pointing: users of a GIS will naturally ask questions like 'what is this?', or 'who owns this building?'. We therefore must extend the query syntax to accept as values objects visible on the screen to which the user points. Integration of pointing gestures with queries is one of the central concepts of the CUBRICON interface [Neal and Shapiro 1990; Neal *et al.* 1989].

These requirements deal primarily with the selection of data for retrieval. The following group of requirements deal with the rendering of the result on the screen. The standard query languages as used in administrative data processing assume automatically that the result of the query can be displayed in the form of a table; this is obviously not true for a GIS, where many outputs will be in map form.

Combination of query results: the visual integration of the result from more than one query is an important feature of a GIS. It must be possible to specify that the result of a new query is added (superimposed) to the already displayed map, that it is removed from it, or that the objects selected are highlighted to make them easier to find.

Spatial context: The result of a spatial query cannot always be interpreted by itself, e.g. the query 'show the town of Orono' would result in a point with a label on an otherwise empty screen as shown in Figure 9 - this is hardly useful [Egenhofer and Frank 1988, Frank 1982].

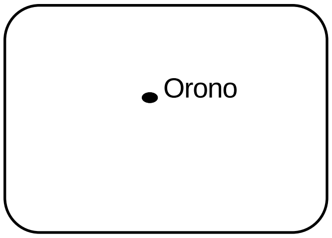

Figure 9. town of Orono, no context

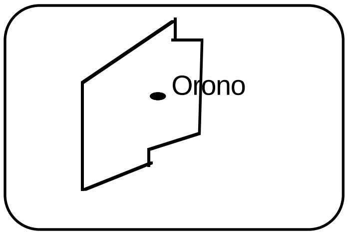

figure 10. same with some context (state)

The query language must, therefore, include means for the users, to specify the necessary context they need to understand the result as in Figure 10 (e.g. 'show AS TOPO SHEET ....', directing the system to use the standard content of a topographic map). It should also include default rules, such as how a query is expanded to include a minimal context, if the user opted not to specify one. This is necessary, because although context is ubiquitous in human interaction, people are not used to thinking about the context explicitly, and thus it is especially onerous for users to deal with context explicitly.

Selection of query window: access to data in a spatial database is usually explicitly or implicitly restricted by an 'area of interest', e.g. 'show all school buildings' means 'show all school buildings in the Orono school administration district'. Again, the query language must include methods to describe the area of interest and contain rules for how a default is selected if the user does not specify one (e.g. use the value of the previous query).

Description of scale: in some instances a display must have a certain scale to be specified by the user.

Description of map legend: the map legend describes a mapping between the data objects in the database and their graphical rendering. The user must be able to select a map legend and change it when necessary.

Differentiate representation based on attribute values: Users need often observe how an attribute value is spatially distributed (e.g. which houses in a city were built in which year). It is customary in manual cartography to build classes for objects with similar values and assign specific graphical values to them (e.g. colour, raster) [Bertin 1983]. Thus the query language for a GIS must essentially include everything that is necessary to specify choropleth and similar maps.

4.2 SQL extensions

A number of research projects [Egenhofer 1984, Egenhofer 1989b, Egenhofer and Frank 1988, Frank 1982] and some GIS manufacturers [Herring, Larsen, and Shivakumar 1988; Ingram and Phillips, 1987] have addressed the problem of constructing a GIS query language by selecting a standard database query language and exploring what extensions would be necessary . Most often the SQL language, based on the relational data model, is used as a starting point [ANSI X3H2 1985, Chamberlin and Boyce, 1974, Chamberlin et al. 1976]. It is very obvious that a language that contains commands to deal with all these problems must be quite extensive and hence may become difficult to learn. Most of the extensions which have been studied fulfil only some of the requirements, and are limited to the most important extensions using default methods for other parameters (for an overview see [Egenhofer 1989c]).

The conclusions drawn from these efforts to extend SQL are:

- Extending SQL with spatial relations and operators is straightforward once the semantics of the relations are formally defined [Pullar and Egenhofer 1988].

- SQL is not as easy to use for complex queries as is often claimed (it is much better than the previous proposals [Reisner et al. 1975], but it was designed in the early 1970's and considered dated). GIS queries tend to include complex conditions, which require careful planning for translation into SQL .

- Extending SQL to include pointing as input is feasible, but no syntax or flow of actions that have been found are compatible with natural language/human cognitive patterns (we and others have created a new keyword PICK [Frank 1982] or MOUSE [Ingram and Phillips, 1987] which can be used anyplace an object is required. During query execution the user is then asked to point to the appropriate object)

- It is advisable to build a separate SQL styled command language to deal with the graphical output issues, and not include these commands into the SQL select-from-where clause. This language will become quite complex.

4.3 GIS query languages based on direct manipulation

The SQL language that is most often extended for GIS query languages is a typed language with traditional syntax and keywords. Since its design, a new paradigm for constructing user interfaces, based on direct manipulation, has been developed and applied successfully (e.g. the Apple Macintosh personal computer) [Shneiderman 1983, Shneiderman 1987, Smith et al. 1983]. Some attempts to apply these concepts to query languages in general [Kuhn and Jackson, in press] and to GIS in particular have been studied [Egenhofer and Frank, 1988].

It has been found that the construction of a direct manipulation based interface for a raster based system is feasible and a number of implementations are known [Intergraph, 1989; Kuhn and Jackson, in press; Pazner, Kirby, and Thies, 1989]. The regular conceptual structure of the data model can be translated to visual objects and their manipulations. This could be extended to an 'irregular tessellation' data model, when the 'layer' structure is stressed. This type of interface is based on processes which combine or otherwise manipulate the 'layers'. It is procedural and the user is responsible for combining the processes in the correct order to achieve the desired result.

On the other hand, constructing non-procedural, purely descriptive spatial query languages for GIS with an object-oriented user view is more difficult. Translating a keyword-based language more or less literally to a screen based input reduces some of the complexity of the interface - the user need not remember the keywords and is prompted for the parameters - and thus makes the interface more versatile and usable. However, it does not reduce the cognitive complexity of the object and operations.

More promising is the selection of appropriate metaphors and their correct visualization for a GIS query facility. We have explored metaphors for the 'pan' and 'zoom' operation which is very powerful in selecting the area of interest and it will be expanded it to other suitable tasks, e.g. the selection of content [Kuhn and Jackson in press].

5. Natural language processing for GIS

Beyond being a basis for design of formal languages and associated data structures, natural language studies are themselves important issues for the designers of GIS for several distinct reasons. The most difficult problem in dealing with natural language in a computational sense is to understand its meaning. People understand each other, based on both the formal and conventional structure of their language, and on a large collection of perceptual and cognitive experiences discussed in section 3, above. For a computer, we take the "understanding" of natural language to mean that the computer acts on commands, queries, and other linguistic input with a response similar to the one that would be given by a person in a similar situation. Similarly, ideal natural language output by a computer will evoke in a human reader reactions that are similar to those which would be given to words and sentences generated by a person. Of course, this is more or less a restatement of the "Turing test" of artificial intelligence fame, and we do not expect a general solution immediately. However, for a limited domain such as GIS, or particularly for some GIS application area, success, or at least substantial progress, seems to be a reasonable expectation.

One important application of natural language processing in GIS involves the potential for the input of queries and commands in natural language; whereas natural language queries in typed form may be of only limited utility, natural-language commands and queries will become a common form of system interaction when real-time interpretation of normal speech becomes practical. Next, we foresee increasing need for input of geographical data and information in text form, ranging from text on biological specimen labels to interpretation of newspaper articles, explorer's journals, or tape- recorded field notes. Natural language production for limited domains, such as generation of verbal descriptions of routes for drivers already is possible, and currently is being extended to other, relatively simple cases and domains, such as the production of legal boundary descriptions for parcels of land. More general natural language text generation is further away, but production of grammatically-correct descriptive paragraphs for direct inclusion in reports would be a desirable feature of future GISs.

5.1 Natural Language Input for Queries and Commands to the GIS

In general terms, natural language understanding is still very difficult to do. The problem of "understanding" natural language in this sense can be restated as a problem of "translating" between natural languages and formal languages within a very limited domain. For such a translation, we need, among other things, a better, more formal understanding of spatial terms in natural language, as well as more complete, formal geometric data models, and, last but not least, translation methods between them. It is apparent that people may use several concepts of geometry and of geographical space, depending on the task, and we have not yet found a single, unified geometric data model that satisfies all expectations. Therefore, translations between partial formal systems of geometric reasoning may be necessary. Such translations are, mathematically speaking, mappings between algebraic systems (ie. morphism) [Egenhofer and Herring, in preparation].

There are generally three advantages seen in natural languages query and command input:

- the system user needs less training ('everybody knows natural language')
- the user can better represent demands ('natural language is the best representation of human thought')
- commands can be issued faster ('we speak faster than we type')

It is not clear whether the argument that natural language reduces training requirements applies to the GIS situation: it is based on the assumption that the user is conversing with the system about objects of his daily experience for which he possesses an adequate vocabulary. This is not necessarily the case. The current systems are still quite restricted in their representation of space and spatial situations. Thus users have to learn how to translate their concepts into the concepts of the system; therefore, training is required to convey to the user the concepts the system uses. One can argue that training the user in the systems' formal command language is an effective method to convey to the user the concepts that are utilized in the system. However, these arguments are not yet based on experience, given the lack of natural language systems. Thus the examples in training sessions do not only show how commands are used but also what they achieve and when they can be used-- this is in the best of all possible worlds, where training is effectively organized and delivered.

It is further doubtful that the second argument, that natural language is the best expression for ideas, holds. It is not evident that there is a natural language expression, for all spatial concepts that well-versed professionals use (e.g. experienced planners). Professional jargon is rife with artificially constructed words or ordinary words that are used with a different meaning. Again training in a formal language would establish a coherent vocabulary. Finally, understanding the natural language input is not sufficient for a system to be usable - if a user has to detail every explanation in the most intricate manner and cannot rely on the 'common sense' and general understanding of his goals, the circumstances etc. of his task, he will not experience the natural language dialogue as natural.

Thus, natural language may become a very important input in the future for certain GIS application. Natural language in itself does not solve many of the problems of GIS query languages and most of the problems we discussed in the section on formal query languages above apply at least in part to natural language interfaces.

5.1.1 Natural Language Queries and Commands

The process of natural language understanding should deal with the understanding of spoken language. At present, (1990) equipment is available to understand a limited vocabulary of spoken natural language as issued by arbitrary speakers, or to understand a larger (but still limited) vocabulary by a speaker for whom the system has been trained. Typically, such equipment can only recognize words spoken with clean breaks between them (so called discrete speech), and cannot cope with the continuous speech that people usually utter. Systems should also understand unrestricted vocabulary. Programs to analyze typed natural language sentences with a limited domain vocabulary and somewhat limited syntactical structure are available; users of these systems must either rephrase statements or be able to train the system to understand new terms.

For effective natural language interaction with GIS, systems will need to understand dialog and not just isolated sentences. Research in dialogue understanding is underway, and has been applied to GIS situations. Such research should lead to usable systems within a few years. It also will be necessary to understand gestures and other non-verbal input, integrated with speech, since discussion of spatial situations between people typically involves substantial amounts of non-verbal gestures, sketches, etc. [Neal and Shapiro, in press]. Despite some interesting results in advanced research the routine use of such tools is still a few years away.

5.1.2 Input of textual geographical data to GIS

Considerable amounts of geographical data are collected not in the form of maps and diagrams but in textual form. In perhaps the most prominent current example, there are many millions of biological specimens in museums and herbaria; current efforts to computerize such collections are similar to the production of computerized catalogues for libraries, but also includes a desire to geocode the data to allow for mapping and for entry into GISs [McGranaghan and Wester 1988]. But, although these specimens have labels on which the locality data and collecting date are indicated, the location is hardly ever in the form of coordinates or a map-- rather, it is in the form of natural language [McGranaghan 1989]. For the small labels on birds and insects, the location may be just a place-name. For plant specimens, which usually are mounted on paper, providing more room for description, the place-name often is supplemented by a verbal description, roughly equivalent to instructions for relocating the site [McGranaghan 1989]. If such data can be automatically analyzed and translated to spatial locations in a GIS, they could be subject to both mapping and advanced forms of spatial analysis, and thus become far more valuable, especially for endangered species, which are often more common as museum specimens than as living examples.

Another current, practical problem is understanding boundary descriptions of properties in deeds, and the translations among coordinate, graphic, and verbal representations. In most jurisdictions, the contract for selling (or otherwise conveying) a parcel of land must include a description of the land, i.e. its boundary. This description is often in verbal form, and in many parts of the world, the verbal description is the chief legal document. Most counties in the U.S. collect large amounts of such data, which is legally relevant, in their registry of deeds, but such data not easily accessible for GIS. These data are needed in map form, such as the maps used by tax assessors. Descriptions of the boundaries of the ranges of biological populations are similar, and often are found in reference volumes and check-lists.

The input of other forms of geographical information in verbal form becomes more speculative and futuristic. It is conceivable that systems of the future might be able to assimilate and analyze explorer's journals such as Columbus' logs or the journals of Lewis and Clark, check them for consistency, and perhaps reach new inferences about the itineraries of their travels. Or, that field workers of the future might speak their notes into tape-recorders, and later have the tapes not only transcribed but also analyzed and integrated directly into GISs. A number of agencies and companies would be interested in devices which would accept spoken descriptions by of locations from their field personnel and integrate their observations with map data. As appealing as these ideas may be, the development of such applications may be many years away.

5.2 Natural language production for GIS

Generation of verbal descriptions of routes for drivers already is possible, and indeed is an option of at least one current commercial GIS: the ARC/INFO "Directions" command produces a verbal description of a route through a street network (ESRI, 1989, Chapter 4, p. 9). Also, there are commercially-available real-time, computer-based navigation aid systems for vehicles [ETAK 1988, Zavoli 1989], which produce in-car maps for use in route planning. There is considerable evidence, however, that suggests that driving instructions in verbal form may be more effective than maps (see [McGranaghan, Mark, and Gould 1987] for a review). Davis [Davis 1986; Davis and Schmandt, 1989] has described a system to provide driving directions over cellular phone systems. Experimental work also has investigated the idea of using complexity of verbal description as a cost heuristic for route selection itself, finding 'simplest-to-describe' paths rather than 'shortest' paths [Ma 1987, Mark 1985]. This is a fertile area for further research.

Again drawing on with futuristic speculation, the GIS of the future might produce grammatically-correct paragraphs for direct inclusion in reports. One example is to go from a discrete set of observation points for some species of animal or plant, to a polygon representing the range of that organism, to a clear verbal description of where the organism can (or could) be found. Verbal descriptions of patterns, shapes, and spatial relations are important parts of environmental impact reports, and again their generation by GIS would probably be desirable.

6. Cross-linguistic Issues for GIS

In designing the GIS user interface, the GIS community should also pay attention to differences among various natural languages as to how they represent and express concepts, relations, and objects of geographical space. It is most likely that currently-favoured query languages are influenced by the natural language of their designers, commonly English or occasionally German. Without conscious choice, designers tend to select not only terminology and concepts based on their own everyday use of natural language, but also on word order and other major structural elements of that language.

Unless underlying concepts are explicitly and conscientiously used, compared, and translated, the use of GIS in non-English-speaking areas may be severely impeded. Any user/computer interface bridges the users' cognitive structure and the representation in the computer system. Obviously, constructing an interface must take in to account both components. If a GIS is moved from one linguistic culture (say North American English) to another (say South American Spanish), some form of "translation" of the interface is highly desirable, if not essential. In fact, many professionals and technicians in the non-English-speaking world have some working knowledge of English, and thus are able to use English-language software; but this is far from desirable, and restricts access to the technology to a very small subset of the population.

The "translation" of an interface would include the actual translation of the words used in the interface, including commands, menus and help texts, but such translations are not always straightforward, since the concepts underlying the interface may not match those of the target language. Cross-linguistic transfer of computer technology certainly calls for more than the translation of the manuals. Customarily that is the most that is done, but the GIS industry has not yet touched on the deeper issues. Computer Science and the computer industry have studied systems supporting languages which are not based on the roman alphabet, and how such differences affect database query language (see [King 1989] and other papers in the same volume).

Observations of adaptations of cultures to new languages often show a facility to adopt a new vocabulary, but to persist in using elements of the underlying structures of previous language. By analogy, we suggest that the translation of a user interface's "surface" vocabulary addresses the less urgent part of the problem, since using new words for old concepts may be fairly easy for users to adapt to in any case.

The first reaction to issues such as these is, almost invariably, to build more 'flexibility' into the GIS, and to make the interface more adaptable by the user. If this flexibility is well designed, it can indeed be used to adapt to individual differences. Ideally, the base structure of the programmes-- the geometric data model and its operations-- is available, and furthermore completely devoid of artifacts of the cognitive structure and linguistic traditions of the designer(s). However, in practice it is doubtful that this is ever the case. Otherwise, the construction of the interface has to translate the data model into a structure akin to the cognitive structure of the class of users. This is clearly no simple task and it will be desirable to identify parts which are useful everywhere, and others which depend on certain categories and which vary between target languages. The exploration of 'language universals', discussed briefly in Section 3 (above), thus becomes very important, as it would allow one to separate what is generally applicable from what needs to be adapted to a local language, culture, or subculture. These cross-linguistic issues for GIS have been addressed in more detail by Mark, Gould, and Nunes [1989].

7. Summary

Observing natural language usage to describe spatial situations is very important for the designers of GIS to achieve a system which is compatible with the way users conceptualize their problem domains. Since current GIS structures are based largely on maps and mathematics, and since maps and mathematics represent previously formalized representations of naive concepts of geographical space, adoption of a cognitively-based concept structure for GIS will not necessarily involve radical changes.

The most important issue is to understand the separation between the conceptual view of GIS, which explains how the system operates to the user community, and the implementation, which should be of interest only to programmers and systems maintenance personnel. The GIS literature continues to mix the two sets of issues, beginning even before the famous "First International Study Symposium on Topological Data Structures for Geographical Information Systems" [Dutton 1979] hosted by Harvard University in 1977, and continuing to the present. The conceptual design, the geometric and attribute data models, the user interface style-- all of these have fundamental ties to cognitive and linguistic research, whereas the implementation of the GIS software connects to computer science.

To the extent that they have been recognized at all, linguistic issues in GIS have in the past been seen primarily as issues for user interface design, especially in spatial query languages. However, recent research in these areas has shown that a GIS needs an approach based on a 'dialogue' model, and that the standard 'question and answer' model is insufficient [Mark, Frank, *et al.* 1989a, Neal *et al.* 1989]. The debate concerning whether natural language interfaces are more appropriate than formal system interaction "languages" is on-going [Shneiderman 1981] and definite results cannot be expected before some of the technical limitations of understanding naturally spoken language (continuous speech) have been removed.

The cognitive and linguistic issues in the GIS span a much wider set of issues, and touch on the general problem of how to translate users' concepts into executable operations. The current model, which is to train users in translating their task into a procedural, formal geometric problem (which is then submitted to the GIS) severely limits GIS technology to trained users. The relative merits of the tendency of technology designed in this way to promote and maintain a specialized class of 'gurus' to act as 'gate-keepers' to the technology is beyond the scope of this chapter, and has been discussed in detail by Winograd and Flores [Winograd and Flores 1986]. To go beyond this approach needs a more profound understanding of how people in general think and reason about space and things spatial.

Last, but not least, the structure of GIS interfaces, as available today, is, essentially, the product of an Anglo-Saxon (or at least, Germanic) cognitive and linguistic culture. In order to make GIS useful in other language groups and cultures, it may not be sufficient to translate the "surface structure" of the systems, such as the command language, or menu contents, or manuals. Instead, attention must be given to the deeper syntactic and cognitive structures that underlie other languages. It is clearly desirable to build alternatives to the "verb-oriented" languages currently used for commands and queries (see [Sukaviriya and Moran in press] for a discussion of word-order and system interaction). A metaphor-based, direct manipulation interface is clearly an attractive alternative, but such interfaces have their own problems. Unfortunately, we do not know the most appropriate metaphors, and associated, visualizable image-schemata, for geographical information for any natural language, let alone across many languages. Also, building such a visual interface will not resolve the cross-linguistic problems of GIS technology transfer and use, since the use of visual symbols often is as much culturally and linguistically determined as are the languages themselves.

It can be expected that these issues will increase greatly in importance and recognition within the GIS community world-wide.

Acknowledgements

This Chapter represents part of Research Initiative #2, "Languages of Spatial Relations", of the National Center for Geographic Information and Analysis, supported by a grant from the National Science Foundation (SES-88-10917); support by NSF is gratefully acknowledged. Valuable comments an earlier draft were provided by Max Egenhofer, Michael Gould, Werner Kuhn, and Michael Goodchild.

References

Abler, R. 1987. The National Science Foundation National Center for Geographic Information and Analysis. International Journal of Geographical Information Systems 1 (4) : 303-326.

Alexandroff, P. 1961. Elementary Concepts of Topology. New York, NY: Dover Publications, Inc.

ANSI X3H2. 1985. American National Standard Database Language SQL. American National Standards Database Committee. Washington, D.C.: American National Standards Institute.

Bertin, J. 1983. Semiology of Graphics. Madison, WI: The University of Wisconsin Press.

Burton, W. 1979. Logical and Physical Data Types in Geographic Information Systems. Geo-Processing 1 (4) : 167-181.

Chamberlin, D.D., M. M. Astrahan, K. P. Eswaran, R. A. Lorie, J. W. Mehl, P. Reisner, and B. W. Wade. 1976. SEQUEL 2: A Unified Approach to Data Definition, Manipulation, and Control. IBM Journal of Research and Development 20 : 560-575.

Chamberlain, Donald D., and Boyce, Raymond F., 1974, Sequel: A Structured English Query Language, in: Rustin, Randall (ed): Workshop on Data Description, Access and Control, Ann Arbor, MI, ACM SIGMOD, pp. 249 - 264

Codd, E.F. 1982. Relational Data Base: A Practical Foundation For Productivity. Communications of the ACM 25 (2) : 109-117.

Corbett, J., 1975, Topological Principles in Cartography, Proceedings, International Symposium on Computer-Assisted Cartography, Auto-Carto II, Reston, VA: U.S. Department of Commerce.

Corbett, J. P., 1979. Topological Principles of Cartography. Technical Report 48, Bureau of the Census, US Department of Commerce.

Cox, N.J., Rhind, D., and Aldred, B. K., 1980. A relational database system and a proposal for a geographic data type. Geo-Processing 1, 217.

Davis, J. R., 1986. Giving directions: A voice interface to a direction giving program. Proceedings, 1986 Conference, American Voice I/O Society, September 1986, 77-84.

Davis, J. R., and Schmandt, C. M., 1989. The Back Seat Driver: Real Time Spoken Driving Directions. Proceedings, First Vehicle Navigation & Information Systems Conference (VNIS '89), IEEE Vehicular Technology Section. New York, NY: The IEEE Society, pp. 146-150.

Diaz, Bernard M., and Sarah B.M. Bell, (Editors). 1986. Spatial Data Processing using Tesseral Methods (collected papers from Tesseral Workshops 1 and 2). NERC Unit for Thematic Information Systems, Natural Environment Research Council, Swindon, Great Britain.

Dutton, Geoffrey, (Editor). 1979. First International Study Symposium on Topological Data Structures for Geographic Information Systems (1977). Cambridge, MA: Harvard University.

Egenhofer, Max J. 1984. Implementation of MAPQUERY, a Query Language for Land Information Systems (in German). Institute for Geodesy and Photogrammetry, Swiss Federal Institute of Technology, (ETH), Zurich, Switzerland Report # 79.

Egenhofer, M. 1989a. A Formal Definition of Binary Topological Relationships. In Third International Conference on Foundations of Data Organization and Algorithms (FODO), Paris, France. Edited by W. L. a. H.-J. Schek. 457-472. New York, NY: Springer-Verlag.

Egenhofer, Max J. 1989b. Spatial Query Languages. Ph.D., University of Maine.

Egenhofer, Max J. 1989c. Spatial SQL: A Spatial Query Language. Department of Surveying Engineering, University of Maine, Orono, Report # 103.

Egenhofer, Max J., and Andrew U. Frank, 1988, Towards a Spatial Query Language: User Interface Considerations, 14th International Conference on Very Large Data Bases: Los Angeles, California. Los Altos, California: Morgan Kaufmann, Inc., pp 124 - 133

Egenhofer, Max J., and John R Herring, in preparation. High Level Data Structures. In Geographic Information Systems: Principles and Applications. Edited by Maguire, D. Rhind and M. Goodchild. Longman Co.

ESRI. 1989. Network Users Guide. Redlands, California: Environmental Systems Research Institute.

ETAK, 1988. ETAK MapEngine, Programmers Guide ETAK Navigational and Digital Systems, Menlo Park, California: Etak, Inc.

Frank, Andrew U. 1982. MAPQUERY --- Database Query Language for Retrieval of Geometric Data and its Graphical Representation. ACM SIGGRAPH 16 (3) : 199 - 207.

Frank, Andrew U., and Werner Kuhn, 1986, Cell Graph: A Provable Correct Method for the Storage of Geometry, Proceedings, Second International Symposium on Spatial Data Handling, Seattle, Washington. Williamsville, New York: International Geographical Union,

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

Giblin, P. 1977. Graphs, Surfaces and Homology. London: Chapman and Hall.

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

Herring, J., R. Larsen, and J. Shivakumar, 1988, Extensions to the SQL language to support spatial analysis in a topological data base. Proceedings, GIS/LIS '88. Falls Church, Virginia: ASPRS-ACSM-AAG-URISA, pp. 551-560.

Herskovits, Annette. 1985. Semantics and Pragmatics of Locative Expressions. Cognitive Science 9 : 341-378.

Herskovits, A. 1987. Spatial Prepositions in English. Cambridge, Massachusetts: Cambridge University Press.

Ingram, Kevin J., and Phillips, William W., 1987: Geographic Information Processing using a SQL-Based Query Language. Proceedings, Eighth International Symposium on Computer-Assisted Cartography, Baltimore, MD. Falls Church, VA: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, pp 326 - 335

Intergraph, 1989. Tigris Imager Reference Manual, Intergraph Corporation, Huntsville, Alabama.

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

King, R. 1989. Introduction to the special issue on non-English interfaces to databases. IEEE Transactions on Database Engineering, Vol 12, Nr.4, pp 1-7.

Jackson, J., 1990. Developing an effective interface for geographical information systems using metaphors. Proceedings, ACSM/ASPRS Annual Conference: Denver, CO, in press.

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

Ma, P. 1987. An algorithm to generate verbal instructions for vehicle navigation using a geographic database. East Lakes Geographer 22 : 44-60.

Mark, D. M., 1985, Finding simple routes: 'Ease of description' as an objective function in automated route selection, Proceedings, Second Symposium on Artificial Intelligence Applications: Miami Beach, pp. 577-581.

Mark, D. M., 1989, Cognitive image-schemata for geographic information: Relations to user views and GIS interfaces, Proceedings, GIS/LIS '89. Falls Church, Virginia: ASPRS-ACSM-AAG-URISA-AM/FM, v. 2, pp. 551-560.

Mark, David M., Andrew U. Frank, Max J. Egenhofer, Scott M. Freundschuh, Matthew McGranaghan, and R. Michael White. 1989a. Languages of Spatial Relations: Initiative Two Specialist Meeting Report. Santa Barbara, California: National Center for Geographic Information and Analysis, Report 89-2.

Mark, D. M., Gould, M. D., Freundschuh, S. M., Egenhofer, M. J., Kuhn, W., McGranaghan, M., and Svorou, S. 1989b. Working Bibliography on "Languages of Spatial Relations." Santa Barbara, California: National Center for Geographic Information and Analysis, Report 89-10.

Mark, D. M., M. D. Gould, and J. Nunes, 1989. Spatial language and geographic information systems: Cross-linguistic issues (El Lenguaje Espacial y Los Sistemas de Informacion Geograficos: Temas Interlinguisticos), Proceedings, II Conferencia Latinoamericana sobre el Technologia de los Sistemas de Información Geográficos (SIG). Merida, Venezuela: Universidad de Los Andes, pp. 105-130.

Mark, D. M., S. Svorou, and D. Zubin, 1987, Spatial terms and spatial concepts: Geographic, cognitive, and linguistic perspectives, Proceedings, International Symposium on Geographic Information Systems: The Research Agenda. Washington, DC: National Aeronautics and Space Administration, v. II, pp. 101-112.

McGranaghan, M., 1989, Context-free recursive-descent parsing of location-description text, Proceedings, Ninth International Symposium on Computer-Assisted Cartography. Falls Church, Virginia: ACSM-ASPRS, pp. 580-587.

McGranaghan, M., D. M. Mark, and M. Gould. 1987. Automated provision of navigation assistance to drivers. The American Cartographer 14 : 121-138.

McGranaghan, M., and L. Wester, 1988, Prototyping an herbarium collection mapping system, Proceedings 1988 ACSM-ASPRS Annual Convention. Falls Church, Virginia: ACSM-ASPRS, pp. 232-238.

National Committee for the Digital Cartographic Standards, 1988: The Proposed Standard for Digital Cartographic Data, in: The American Cartographer, 15 (1), 9-140.

Neal, J. G., and S. C. Shapiro, in press. Intelligent Multi-Media Interface Technology. In Architectures for Intelligent Interfaces: Elements and Prototypes. Edited by J. W. Sullivan and S. W. Tyler. Reading, MA: Addison-Wesley.

Neal, J.G., C.Y. Thielman, Z. Dobes, S. M. Haller, and S. C Shapiro, 1989, Natural Language with Integrated Deictic and Graphic Gestures, Proceedings, DARPA Speech and Natural Language Workshop. Los Altos, California: Morgan Kaufmann, Inc., in press.

Neisser, Ulrich. 1976. Cognition and Reality: Principles and Implications of Cognitive Psychology. San Francisco: W. H. Freeman & Co.

Pazner, M., K.C. Kirby, and N. Thies. 1989. MAP II: Map Processor. New York: John Wiley & Sons.

Peuquet, D, and Zhan Ci-Xiang. 1987. An algorithm to determine the directional relationship between arbitrarily- shaped polygons in a plane. Pattern Recognition 20 : 65-74.

Pullar, Dave , and Max J. Egenhofer, 1988, Towards Formal Definitions of Topological Relations Among Spatial Objects, Proceedings, Third International Symposium on Spatial Data Handling: Sydney, Australia. Columbus, Ohio: International Geographical Union, pp. 225-241.

Raper, Jonathan. 1989. GIS: Three Dimensional Applications in Geographic Information Systems. London: Taylor and Francis.

Reisner, Phyllis, Boyce, Raymond F., and Chamberlin, D. D., 1975, Human Factors evaluation of Two Data Base Query Languages-Square and Sequel, National Computer Conference (AFIPS), pp. 447 - 452

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

Rosch, E. 1978. Principles of categorization . In Cognition and Categorization. Edited by E. Rosch and B. B. Lloyd. Hillsdale, NJ: Erlbaum, pp. 27-48.

Samet, H. 1984. The Quadtree and Related Hierarchical Data Structures. ACM Computing Surveys 16 (June) : 187-260.

Shneiderman, Ben. 1981. A Note on Human Factors Issues of Natural Language Interaction with Database Systems. Information Systems 6 (2) : 125-129.

Shneiderman, B. 1983. Direct Manipulation: A Step Beyond Programming Languages. Computer 16 (Aug.) : 57-69.

Shneiderman, B. 1987. Designing the User Interface: Strategies for Effective Human-Computer Interaction. Reading, MA: Addison-Wesley.

Smith, D.C., Eric Harslem, Charles Irby, Ralph Kimball, and Bill Verplank, 1983, Designing the Star User Interface, Proceedings, European Conference on Integrated Interactive Computing Systems: Stresa, Italy. Amsterdam, Netherlands: North-Holland.

Smith, Edward E., and Douglas L. Medin. 1981. Categories and Concepts. Cambridge, Massachusetts: Harvard University Press.

Spanier, E. 1966. Algebraic Topology. New York, NY: McGraw-Hill Book Company.

Sukaviriya, P., and L. Moran. in press. User interfaces for Asian countries. In Designing Interfaces for International Use. Edited by J. Nielson. Elsevier Science Publishers.

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

Talmy, L. 1983. How Language Structures Space. In Spatial Orientation: Theory, Research, and Application. Edited by H.Pick and L. Acredolo. New York, NY: Plenum Press, pp. 225-282.

Tomlin, C.D. 1983a. Digital Cartographic Modeling Techniques in Environmental Planning. Ph.D., Yale University.

Tomlin, D., 1983b, A Map Algebra, Harvard Computer Graphics Conference: Cambridge, MA

Tomlin, Dana C. 1989. Geographic Information System & Cartographic Modeling. Prentice Hall.

Tsichritzis, Dennis, and Klug, Anthony (eds.), 1975: The ANSI/X3/SPARC DBMS Framework Report of the Study Group on Database Management Systems, AFIPS Press, Montvale, NJ

Turner, Keith A. 1990. Three-Dimensional Modeling with Geoscientific Information Systems. NATO Advanced Research Workshop, in press.

Winograd, T., and F. Flores. 1986. Understanding Computers and Cognition: A New Foundation for Design. Reading, Massachusetts: Addison-Wesley.

Woodcock, Jim, and Martin Loomes. 1989. Software Engineering Mathematics. SEI Series in Software Engineering. Addison-Wesley.

Zadeh, L. A., 1974, Fuzzy Logic and Its Application to Approximate Reasoning, Information Processing. Amsterdam, Netherlands: North-Holland.

Zavoli, W. B. 1989. Navigation and digital maps interface for fleet management and driver information systems. Proceedings, First Vehicle Navigation & Information Systems Conference (VNIS '89), IEEE Vehicular Technology Section. New York, NY: The IEEE Society, pp. A-9 - A-14.