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ABSTRACT

People use many concepts of space for different types of spatial reasoning (e.g., reasoning about empty parking spaces to move a car into, or reasoning about road networks while navigating an automobile). However, the automatic preference in Geographic Information Systems (GIS) for plane (Euclidean) geometry makes analysis of these methods of spatial reasoning more difficult.

This paper argues that different concepts of space can be abstracted from basic experience. A theory for multiple concepts of spaces is outlined which provides a method for their formalization. Examples of different types of spatial reasoning in specific situations are shown. Before the conclusions an argument for the concurrent use of multiple concepts is made, a theoretical treatment sketched and an example given.

INTRODUCTION

Human beings use different concepts to understand space, depending on the task at hand. Some of these concepts have been formalized, the most important axiomatization is certainly Euclid's set of five axioms. The Euclidean concept of geometry is so prevalent that people often assume it is the only one, and overlook its limitations. An example of another important and formalized concept is graph theory. Humans use the concept that is most appropriate for a given task, and show a surprising ability to use multiple concepts at the same time to solve complex problems. For example, standard plane geometry and reasoning about volumes and open spaces is used both to get into a car, and to drive a car out of a garage. However, to plan a route to drive, a network concept of the highway and street system is used.

Regular geometry and the corresponding Newtonian physics have been studied extensively for hundreds of years. However, recently navigation and way finding by reasoning along networks became a topic of research both in psychology and artificial intelligence (Kuipers 1978; Kuipers 1979). These and other generic models of space reduce the problem of past investigations in spatial economics (Skinner 1991), environmental psychology (Couclelis 1991; Couclelis and others 1987), etc., where observations and analysis were pushed into the Procrustean bed of analytical geometry. The same problem is evident in the implementation of GIS, primarily in the design of the user interfaces. The standard concepts of space are not always appropriate and force the user to transform tasks into an often-inappropriate form.

This paper argues that there are many concepts of space, based both on different experiences of manipulating spatial objects in "small scale space," and on navigating in geographic space. "Small scale space," refers to spaces populated by objects that are smaller than humans and can be easily manipulated. It is differentiated from geographic, or large scale space, which describes spatial situations that cannot be seen from a single point of view.

Any reasoning process that relates to objects in space and makes use of their location, position, form, etc., must be considered 'spatial reasoning.' It includes the reasoning about distances and directions between objects (Frank 1991b; Peuquet and Zhan 1987), the topological relations between object (Egenhofer and Franzosa 1991), in particular 'adjoining' and 'inclusion' and the different methods to find a way in a known or unknown territory.

Spatial reasoning is a major requirement for a comprehensive Geographic Information System (GIS) and several research efforts are underway addressing this need (Abler 1987; NCGIA 1989). A GIS must carry out spatial tasks, which include specific inferences based on spatial properties, in a manner similar to a human expert and must then explain the conclusion to users in terms they can understand (Try and Benton 1988).

SOME BACKGROUND

Most work in spatial reasoning is related to physical behavior of small objects and to expert systems which reason about the behavior of mechanical devices (Hobbs and Moore 1985). Kuipers (Kuipers 1979) and others (Mark and others 1989) have shown that geographic space is different in its conceptualization. It follows that the rules of spatial reasoning are different for different types of space.

Traditionally geodesy, cartography, and surveying sciences have dealt with measuring and describing the form and location of objects on the surface of the earth. They have extensively used the concepts of analytical geometry in 2 and 3 dimensions. Geography and cartography have realized that there are differences between the way surveyors measure the objects on the earth and how people understand and react to them. Computer science, computational geometry in particular, is similarly based on analytical geometry and is plagued by all the problems of realizing concepts of an infinitely divisible space in a finite machine.

Since the pioneering work by Piaget (Piaget and Inhelder 1967; Siegel and White 1975), different types of spaces or space perception have been recognized (Couclelis and Gale 1986; Kuipers and Levit 1990). It is assumed that spatial reasoning is strongly influenced by the type of space it is applied to. Kuipers introduced the notion of large-scale space, which is mostly equivalent to the type of space geographers and Geographic Information Systems deal with, as

> "a space whose structure is at a significantly larger scale than the observations available at an instant. Thus, to learn the large-scale structure of the space, the traveler must necessarily build a cognitive map of the environment by integrating observations over extended periods of time, inferring spatial structure from perceptions and the effects of actions" (Kuipers and Levit 1990, p. 208).

Zubin differentiates four different spaces using the same criteria of how knowledge is gained (Mark and others 1989).

Similarly, the important field of geographic reference frames in natural language (Mark and others 1987) has mostly been treated using an analytical geometry approach. Typically, spatial positions are expressed relative to positions of other objects. Examples occur in everyday speech in forms like "the church is west of the restaurant." In the past these descriptions were translated into Cartesian coordinate space and the mathematical formulations were analyzed. A special problem is posed by the inherent uncertainties in these descriptions and the translation of uncertainty into an analytical format. McDermott (McDermott and Davis 1984) introduced a method using 'fuzz' and in (Dutta 1988; Dutta 1990) fuzzy logic (Zadeh 1974) is used to compose such approximately metric data.

The traditional methods are based on analytical geometry and thus are quantitative. Most human reasoning, including many aspects of spatial reasoning, however, are qualitative. It is therefore necessary to find qualitative approaches to the investigation of spatial reasoning. One approach that is entirely qualitative is the work on symbolic projections by Chang. It translates exact metric information (primarily about objects in pictures) in a qualitative form (Chang 1990; Chang and others 1990).

Hernández (Hernández 1990) discusses qualitative reasoning between extended objects, based on (Allen 1983), and uses topological relations (adjacent, overlap, etc.) between objects but not distances - thus avoiding the problem of defining distance relations between extended objects. His approach also includes the composition of reference frames. A similar approach is taken by (Guesgen 1989; Mukerjee 1989; Mukerjee 1990).

SPACE AND SPATIAL REASONING

The multitude of methods of spatial reasoning are each related to a specific spatial situation and it is therefore appropriate to identify the specific concept of space with the respective rules of spatial reasoning. This is a particular application of an object-oriented viewpoint, where objects and operations are tightly linked; in this case the typical objects in a conceptualization of space are linked to the spatial relations (considered as operations). It is then possible to talk about a specific 'space' (for example the street network of a town) and imply the relevant conceptualization and inference rules (for example the rules necessary for navigation in a town). The term 'space' is thus used in the sense of a conceptualization of a view of space for a specific purpose. It is expected that a given situation is conceptualized using different 'spaces' depending on the situation.

HIGH SCHOOL GEOMETRY

The geometry you learned in high school is well known, indeed so well know, that many think this is the only geometry possible. It is based on the abstractions introduced by Euclid in his famous "Elements." It models quite adequately many geometric aspects of handling small objects (i.e., objects of a size much smaller than persons and which can be moved easily), but it does not completely agree with our experiences when applied to large scale spaces. Everybody recalls the difficulties of high-school teachers, explaining the problem of parallel lines not intersecting ever.

Analytical geometry is a model of this geometry. Every geometric operation has its equivalent algebraic operation. It is then used as the foundation of computational geometry (Preparata 1985) but also for computations in surveying and cartography. Very similar methods are used for calculations on the surface of the globe, when the curvature of the earth must be taken into account.

Typically spatial properties are derived from the metric (coordinate) representation of spatial objects. For example the question if a point is inside an area is determined by comparing the point coordinates with the vectors that define the boundary of the area using one of the known 'point-in-polygon' algorithms. Similarly, other topological relations are derived from exact coordinate based geometry representations.

High-school geometry and analytical geometry in particular are very good models for spatial properties, often the only ones known. They are widely used in GIS, even if their conceptual roots are in small scale space rather than geographic space. However, it is clear, that they are not adequate models of human reasoning and are not appropriate to model human performance. There are well documented 'errors' in human spatial reasoning, where persons consistently err in comparison with the results obtained using analytical geometry (Stevens and Coupe 1978) and such human 'misconceptions' must be taken into account, for example, when explaining expert reasoning in a GIS.

DISTANCE AND DIRECTIONS IN GEOGRAPHIC SPACE

Distances and directions are well defined between points in geographic space. In a GIS this is always done, using quantitative measures of distance and directions. In human discourse distances are typically expressed with qualitative terms like 'far,' 'near' and these terms cannot be directly translated into quantitative expressions (Robinson and Thongs 1984). Indeed, a distance characterized by 'near' may be significantly larger than another one, described as 'near' (for example, it is perfectly reasonable to say that Starnberg is close to Munich, but also to say that the zoo is far from the city center. In fact, the zoo is much closer to the city center than Starnberg). Similarly, Peuquet has indicated that the meaning of the cardinal directions, for example 'North,' can be defined in more than one way; if it is appropriate to say that Vienna is north of Munich depends on the concept applied (the geographic latitude of Vienna is slightly more north than the one of Munich). A definition of 'north' can include all points in the half-plane north of the reference object, or north includes only the points that are more north than east or west (45° cone).

It is possible to formalize qualitative inference rules for distances and directions in geographic space. In (Frank 1991) independent formalizations for distance and direction systems are given. It is evident, that there is interaction between the inference with distances and with directions. Such systems are particularly important for spatial query languages, where expressions in terms of human qualitative concepts must be treated (it is not possible to translate them to coordinate geometry without distorting the meaning). It must also be noted that qualitative reasoning is very often computationally much simpler and faster than computations from analytical geometry - an aspect relevant for the processing of spatial queries in GIS with large data collections.

BLOCK WORLD

A number of spatial concepts are based on the aggregation of spatial objects. The simplest conceptualization of space is as regular tiles of equal size, well known for floor tiling, but is also the way the Romans and the U.S. public land survey system divides land in parcel. It is so important for human conceptualization of space, that it is the base for a number of games, which need to model space in an abstract and simplified way, e.g., chess and checkers.

Regular Raster

Regular sized blocks form a very simple kind of physical world. The behavior of this world is clearly understood, because it is an abstraction from our daily experience with physical objects. However, it is simple (abstract) enough, so it can be formalized. The study of the properties of this simple world reveals that, despite its simplicity, it retains a number of interesting spatial properties, which are worthwhile to be formally studied. This is not a surprise as blocks have been given to children to play, sometimes with explicit remarks to their value for learning about the physical world and space. In the GIS world, all raster based data collection and analysis uses this spatial model.

A simple form of the block world, namely one made of regular square blocks of equal size laid out in a plane, has been completed; it does not yet include the third dimension, but this could be added. This is a very strict abstraction from the myriad of details of physical reality. It is useful, because it contains still many basic spatial properties. These include: adjacency, neighborhood, global and local reference frame. Equal sized, square blocks provide an experiential foundation for coordinates. This variant of the block world relates to blocks placed on a fixed grid (real world examples provided by Lego blocks or by most U.S. towns, where the street layout fixes the grid). In this 'world' spatial properties cannot only be expressed as local properties, depending of relations between adjacent blocks, but alternative formulations with a global viewpoint are equally valid. The resulting integer based coordinate geometry is worth investigation, because it forms the base for the effective treatment of analytical geometry in a finite precision computer.

City blocks

A formalization of a system of blocks of unequal size - for example the different sizes and shapes Lego blocks come in - placed on a regular grid has not been studied extensively so far. It seems to have immediate application if one assumes that the blocks are much larger than the grid subdivision. A city situation can be modeled as large blocks on a fine grid, where the blocks represent the buildings, which are of at least 100 m^2, placed on a grid of 1 m resolution (i.e., the smallest block is 100 grid cells). In such a model, buildings and different types of open space are differentiated: a street is an open space not big enough for another building to be place and quite different from a vacant lot, which must be big enough for a building. Such a system separates the different kinds of street neighborhood that have to be included in a GIS query language. It becomes meaningful to speak about a 'back yard neighbor,' a 'next door neighbor,' and a 'neighbor across the street' and appropriate queries can be formulated and executed.

PATH

The path and link image schemata (Lakoff and Johnson 1980) are extremely important methods to organize and conceptualize space, but are often overlooked in the GIS context. Mathematical graph theory provides the relevant abstractions, operations and algorithm (at least for problems of limited size). However, GIS software sometimes lacks graph operations and cannot deal with connectivity, street networks, etc. When applied to a particular situation, general graph theory must be specialized and extended.

Telecommunication

Telecommunication networks are an example where bi-directional connectivity is dominant and distance is related to economical considerations but not necessarily to spatial distance. This is obvious in modern computer based communication networks, e.g., internet.

Highways

Navigation along paths is a basic human experience. The rules depend on the means used for transportation. Measures of distance in such a network are most often not based on Euclidean distance in the embedding space - as can be seen from expression used to describe distances. It is very common to use time based measures, already documented in Roman times in the Tabula Peutingeriana, where distances are marked as days of travel. These concepts must be integrated in a GIS such that the zone of influence of a shopping center can be expressed as a radius of travel time, etc.

Navigation rules for street networks transform a standard graph in a specialized structure. There are differences between rules valid for inner city navigation and rules applicable to highway travel. We have also observed national differences, i.e., a modelization appropriate for the U.S. interstate network is not applicable to the German Autobahn or the Italian autostrade.

Airlines

Air travel by scheduled airlines has become an important form of travel and at least in the U.S. A. starts to influence the conceptualization of space. It originates and ends in airport and must follow the route networks of the carriers. Originally the relevant distance measure was spatial distance because it translated directly to time necessary to travel. Then the network became 'hub' oriented and travel time became independent of Euclidean distance. With the increased economical competition, the most important distance measure becomes cost, with enormous differences between Euclidean distance and fare (in the U.S. travel from New York to San Francisco costs less and is faster then a trip from Albany, NY to Providence, Rhode Island).

COMBINATIONS

The individual spatial concepts described so far each has a specific, very limited range of applications. They have their special rules and define usually a distance function that is quite different from Euclidean distance. They must be included in a GIS to understand query expressions using these concepts and modeling of situations appropriately. In most actual situations of human behavior, more than one concept must be used concurrently.

Rooms and Doors

As an example to understand the concept and explore its formalization, the following problem seems to contain the essential elements: In a building, find a path from a room to the room on it's left.

The building can be modeled as a collection of blocks, in the simplest case, as blocks of uniform size arranged in a regular grid. Such a collection of blocks standing for a building has an outside and for each (outside) room a reference frame with respect to the direction to the outside is established. Using this reference frame, relations of left and right neighbor are defined, and the next room to the left is determined. The determination of a path from the present room to the one to its left requires a concept of doors (and hallways, which are a kind of interior room), which can be modeled in the abstract as a graph. It is then necessary to connect the two sets of abstract concepts to make them available for the solution of the single problem.

CONCLUSIONS

A GIS must contain multiple concepts of space to model adequately the different ways humans think about space. In current GIS, the high-school geometry dominates and implementations use extensively analytical geometry. This is certainly not an adequate model of human spatial reasoning.

The base hypothesis here is that the complex spatial reasoning patterns that humans use can be understood as the combination of a few base patterns. The interaction of these base patterns, each of them relatively simple, then exposes the complex inferences one observes. We assume that the base patterns are linked to small, experience based, prototypical situations. For example graphs are linked to movement and navigation in (geographic) space. The block world is linked to the experience with solid physical bodies, from small objects on our desk to building blocks in a city, or in the 2-D projection, of land use tracks, countries, etc.

The paper has listed a number of different spatial concepts that are relevant for applications that use GIS technology. It is necessary to include such conceptualizations into the user interfaces, including GIS query languages, to allow users to express directly their requirements and to avoid the need for translations from user concepts to system concepts.

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