Chapter 2

Geographic Information Systems: A Challenge to Computer Graphics[1]

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Geographic Information Systems are widely used to collect, manage and present information about the world in which we live. They are used in science, for example to collect and analyze environmental data for small areas and for 'global change' research. They are also used in administration, for example to maintain property registers or dispatch emergency vehicles. Geographic Information Systems are finding widespread use and increasing applications.

Geographic Information Systems manage data with respect to a spatial location. The most important operation is an 'overlay' function which combines data at the same location. Geographic data is modeled with respect to the spatial concepts used in the application area. Their software consists of a database to store and retrieve spatial data and a graphical presentation package to render the data beneficial to the user. Commercially available GIS can be classified according to their architecture or their range of functionality.

A list of limitations of current GIS leads to a set of research questions, some of them also pertinent to computer graphics.

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1.0 Introduction

Geographic Information Systems - usually abbreviated to GIS - are a tool to collect, manage and present information about the world in which we live. They are used in science, for example to collect, analyze and present environmental data for small areas or for 'global change' research. They are also used in administration, for example to maintain property registers or dispatch emergency vehicles. Geographic Information Systems are finding widespread use and increasing applications.

GIS were invented in the '60s when it became apparent that computers could be used to treat spatial data and produce maps. There was much excitement about the potential of computer graphics for cartographic applications, and the first map rendering packages appeared. After several years of experimentation in the '70s, when software development and application were often in the same hands, an increasing number of GIS projects were undertaken in the '80s and a commercial GIS market became established. Today GIS is booming and new applications of the base technology are discovered every day [Steinitz, 1993].

Geographic Information Systems are a special kind of information system, namely those that deal with spatial information, i.e. information relating to objects in the world with respect to their location. As with other information systems, they consist of data and the programs to manage the data. One should also never forget the organization that sets up the system and provides manpower and other resources to run it.

A number of companies sell GIS, but they only offer GIS software packages and sometimes additional services to set up a GIS which will manage a particular set of data. In this paper, I will concentrate mostly on GIS software, and consider the interaction between GIS and computer graphics. There are other treatments, which discuss the non-technical, organizational aspects [Aronoff, 1991]. These non-technical aspects are crucial today and have taken over from the hardware development as the prime movers for further development of GIS. Therefore they cannot be entirely left out here.

Despite the short history of the GIS field, there are already a number of text books available [Burrough, 1986; Laurini, and Milleret-Raffort, 1990; Antenucci, *et al.*, 1991; Huxhold, 1991; Aronoff, 1991; Star, and Estes, 1989], each having a different focus. There is a very comprehensive two Volume 'Handbook' [Maguire, Goodchild, and Rhind, 1991] of which Vol. I covers the theoretical issue and Vol. II explains a large number of applications for GIS. In addition, there are annual proceedings of URISA (Urban and Regional Information System Association), AM/FM (Automated Mapping and Facilities Management, and association of public utilities), GIS/LIS and a number of other professional meetings. Finally, there are a few scientifically and research oriented meetings [Bresnahan, Corwin, and Cowen, 1992; Abel, and Ooi, 1983; Frank, Campari, and Formentini, 1992; Frank, and Campari, 1993].

A few comments on terminology are in order in a field that has not yet found a standardized set of terms. GIS users and researchers come from many different backgrounds and each brings its own set of notions. Here I use the term Geographic Information System (GIS) as the generalized term to describe all types of system which manage spatial information. Different application areas have used particular terms, e.g. Land Information Systems for the property oriented systems of Land Surveyors, multi-purpose cadastre for municipalities [National Research Council, 1980; National Research Council, 1983], AM/FM ('automated mapping and facilities management') used by public utilities to administer their large distribution networks. I will use here what I perceive to be the common ground of today's discussion, but have to admit my roots, which are in surveying-engineering and computer science, in particular, the database world.

In this paper the first sections describe the applications of GIS technology and show the diversity of uses this technology has found. The following two sections characterize the typical operations and data. The next section then discusses the issue of modeling geometry for geographic data. From current limitations on GIS we deduce research questions, and conclude with a set of problems, where computer graphics could contribute to the development of GIS.

2.0 Typical Applications of Geographic Information Systems

Geographic Information Systems are used in all situations where data must be analyzed with respect to location in the world. Obviously many - if not most - administrative decisions affect space and society demands that they are undertaken with full consideration of the circumstances. GIS are usually used to elaborate urban and regional plans, but there are also many sciences that must analyze their subject as situated in space, and consider spatial interaction.

The different applications of GIS have very different needs - indeed one can see different historical roots of GIS, each associated with one particular use:

On the administrative side, the public utilities used CAD to draw up plans for construction of new lines and moved on to use such systems to maintain their collection of utility line maps. Property registration demanded computer assistance early on and particular systems were constructed [Andresson, 1987].

Planners were among the first to see the advantages of computers and in particular computer mapping as a method of dealing with their data and to present the results quickly and convincingly. They used computers as fast and tireless drafting machines and mostly analyzed the results visually.

Scientists discovered the visualization capabilities of computers [McCormick, DeFanti, and Brown, 1987] and wanted to apply them to the special problems of regional or global studies. Their problems are often to organize storage for large regularly structured data sets [Ehlers, Edwards, and Bedard, 1989] and to provide access to powerful spatial analysis and effective visualization tools.

2.1 Administrative Applications

Since all human activities use space, almost all decisions affect space in one form or another. A parcel can be used for many different uses, but usually one use excludes all others. Difficult questions regularly arise from the location of undesirable land uses, e.g. waste storage facilities, sewage purification or power plants. Conflicts exist between the desire for exclusive use by a land owner and the interest of the public in responsible use of land. Examples are the management of large forest areas, where maximal yield and recreational use of the land conflict, or when citizens demand access to sea or lake shores, limiting the privacy of the owners of the shore land.

More mundane applications are the registration of property ownership, the calculation of property taxes and the enforcement of building rules. Municipalities usually maintain large collections of data related to spatial locations (addresses or parcels) and use them in their daily decisions. It has been observed, that different departments in public administrations maintain essentially the same data collections for different purposes and it is assumed that considerable effort (and thus public funds) is wasted in the duplication of maintenance tasks [National Research Council, 1983].

2.2 Public Utilities

A large set of users are the public utilities, which must maintain information about their distribution network. The spatial location of gas lines or telephone cables, and installations like transformers and switches must be known, for example, to avoid damage when digging. Traditionally this data was maintained in large scale drawings, but this becomes increasingly inadequate and in most cities computerized systems are set up. Public utilities were among the early users of GIS technology and some systems were developed specifically to respond to their needs.

2.3 Urban and Regional Planning

Urban and regional planning is one of the traditional user groups of GIS [Tomlin, 1983; Tomlin, 1989; Steinitz, 1993]. For effective planning, it is crucial to collect appropriate base data and to analyze it properly. Not only is there a need for spatial statistics and other analytical tools, but there is also a requirement for a convincing graphical presentation. The result of the planning process is usually subject to review and approval by some political authority. It then becomes crucial, to present the data that was used as well as the results in a convincing graphical manner. Graphic quality can be a decisive factor in approval of a plan - this is particularly important in the US. where plans are often prepared by the interested parties, not the government, and there are large interests at stake.

2.4 Private Corporations

The use of GIS is not restricted to public bodies, there are also private corporations that can use GIS. GIS is appropriate for managing large real estate holdings, for example forest management. GIS is widely used for marketing decisions, which can be improved if geometric presentations of the location of actual and potential clients can be studied and compared with socio-economic data. Last, but not least, a GIS can be used to plan routes for distribution vehicles.

2.5 Computer Assisted Cartography

Computerized systems for map maintenance are cost effective; map revisions that are necessary every few years (5 to 10 year intervals are typical for topographic map series) affect only small areas of the total map. A computerized system allows editing of changes and then the complete map can be redrawn for printing. In principle map scale can be changed and area of interest selected in response to user needs. In practice, such changes are extremely limited, because the map data is prepared for a specific map scale and cut in map sheets. A data set generalized for 1:100,000 can be drawn at 1:25,000, but it does not give the same information as a true 1:25,000 (and it cannot be used at 1:10,000). Names placed correctly for one map boundary are confusing if another map sheet boundary is selected. For special applications careful encoding of the map features allows plotting of maps at two different scales, but the current cartographic data sets do not permit drawing of a map on any scale on demand.

2.6 Scientific Applications

Increasingly, many sciences consider spatial location and spatial interaction. Obviously geographers have made that the central point of their endeavor, but anthropologists, archeologists, economists, historians and social scientists in general often need to investigate the spatial distribution of the phenomena in which they are interested. Physical sciences, climatology, biology etc. have always used various methods to show the spatial distribution of objects of interest.

The current push for research into changes that affect the world as a whole is putting more emphasis on spatial databases with coverage of the globe. Global coverage and analysis pose a particular problem, since analysis and presentation of results must relate to the sphere and not only to a 2 dimensional projection.

3.0 Important Operations in a GIS

Before data models or GIS architectures can be discussed, the different operations which can be performed with a GIS must be understood. There are three major types of operation:

- Rendering operations, to show the data that is stored in form of a map or a cartographic sketch on a screen;
- Analytical operations, which deduce some properties of interest from the stored data. Most important is the 'overlay' operation to combine two or more sets of attribute data for the same area;
- Access methods, which allow the user to search for a data element with given properties.

3.1 Cartographic Rendering

Early systems relied on a digitized version of an actual map, which was then updated by a cartographer and plotted. Today's systems provide quite sophisticated control of symbols, lettering, and the general layout of the map. Demands are high, as a glance at any topographic map reveals. Functions are required to place names along irregular lines, e.g. river names which follow the line of the river. Cartographic display rules have been refined over several hundred years. They are necessarily complex in order to achieve a pleasing map image that is easily read by a human. Three issues can be mentioned here: feature encoding, name placement and cartographic generalization.

Encoding of a feature often varies with the context; for example on Swiss topographic maps, contour lines which are usually in a brown tint are in blue when inside a water body or on a glacier, and in black when in mountainous rock areas. This is will not confuse a competent map user, and ensures that contour lines do not overpower other elements of the map.

Names are a very important element on cartographic maps and must be placed to clearly denote their association with the feature. This is difficult along the map boundary, where only the names of features included must be shown and in areas with much detail, where more than one name should be place in a confined area. Rules for conflict resolution have been encoded in 'name placement' software [Ahn, and Freeman, 1983; Freeman, and Ahn, 1984] but they are not widely used in practice, despite the fact, that the placement of names is a very major cost element in the preparation of a map.

Cartographic generalization is the process that leads to a map that has an adequate amount of information with relation to its scale and intended use. Large scale maps (1:25,000 and larger) show minuscule detail and are often thought as 'not generalized'; small scale maps (1: 100,000 and smaller) cannot show all the details and must make an appropriate selection - based on the intended use of the map. There is an extensive literature on map generalization (see [Buttenfield, and McMaster, 1991] for a recent discussion). In general, cartographers differentiate between selection rules (what is shown?), methods to simplify features, particularly to simplify the graphical rendering (how is it shown?) and methods that slightly move features so they do not conflict with each other (where is it shown?). Different map agencies have different style sheets and instructions, but there are no formalized rules for cartographic generalization and the outcome depends on the skills of the professional.

3.2 Analytical Functions

Analytical functions combine data in the GIS and produce new data. The most important function is the combination of multiple data elements that describe different aspects of the same location in space. A GIS is often conceived as a set of layers (figure 1) which can be easily combined to show further layers. For example, one may ask for all wooded areas above 1000 m. Such operations are even possible manually, if one produces a map that shows areas above in yellow and lower areas in brown, then overlays it on a light table with a map that shows all woods as green. Light green areas are then woods above 1000 m and olive-green are woods in the lower areas. Such procedures were very common in planning practice before GIS and are still used for some simple analyses.

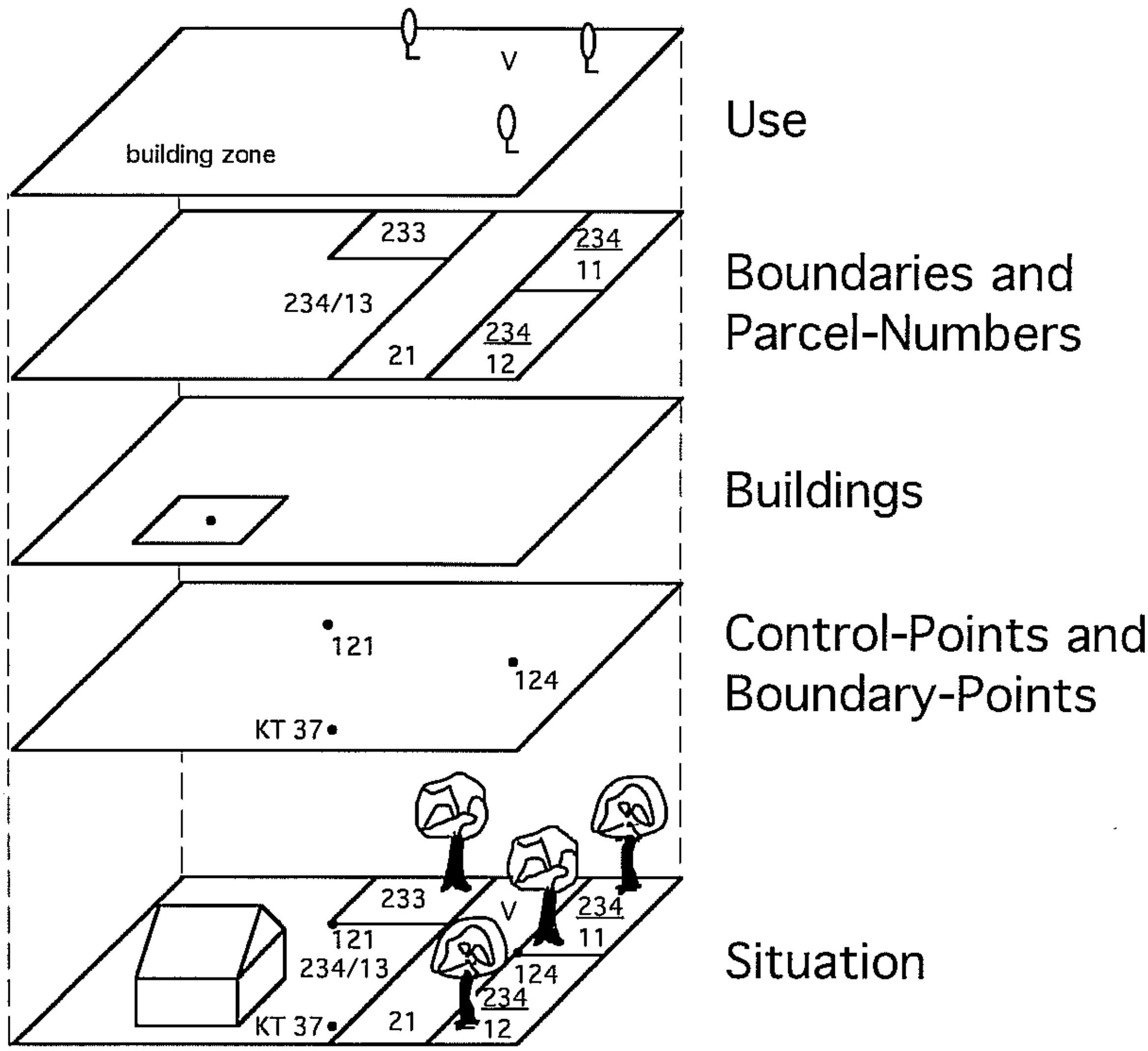

FIGURE 1. Layer Model of GIS

Computers allow the user to overcome the limitations of this manual process. The combinations of values can be more complex - indeed any computation or logical combination becomes possible - and can discern a greater number of different values than a graphical process can. Dana Tomlin designed a set of commands for generalized 'overlay' operations and extended them to problems which would have been difficult to solve with graphical methods [Tomlin, 1983;

Tomlin, 1989]. For example it is possible to compute a layer that contains distances to a point or a line. Then one can combine this with other layers to find, for example, all vineyards, which are closer than 500 m to a road.

The generalized overlay operations always result in another layer of the same area. They form a closed algebra over the type 'layer'. This not only simplifies implementation but also makes it easier for a user to learn how to use the system.

A different set of analytical operations originate in spatial analysis and spatial statistics. It is an extension of standard analysis methods applied to spatial data. There is an extensive literature and many useful methods were developed. Integration of these methods with GIS to make them available for the practitioners is lacking.

3.3 Access to Data

Finding data necessary for a task is a very important function in a GIS. In an administrative situation this may just involve finding the data for a parcel for which a building permit must be processed, but it can be more complex when a scientist wants to find small islands with limestone rock.

The first question is to decide if the data necessary for the query is available in the system. This is a logical problem, considering the data structure and the logical connections existing between the data. This problem also occurs in a regular information system, but then it is not always clear to the user what data is available to the query processor and what information is only graphically stored.

The second question concerns performance, how long will it take to find the data. Access to spatial data poses some unusual indexing problems which have been studied extensively [Samet, 1989a; Samet, 1989b]. A number of solutions are available and are built into some of the commercial GIS.

The last question is how the user communicates his data needs to the system. Query languages were developed for regular information system . SQL is widely used and a large number of proposals for its extension have been presented [Egenhofer, 1991a; Egenhofer, 1991b; Frank, 1982].

4.0 Data in a GIS

Data within a GIS are as different as the application areas which use the data. One can differentiate, not only between spatial and non-spatial data, but also between data that is widely used and data that is particular to a single application.

The fundamental concept of GIS is that all data is related to a location in space - either directly or indirectly. It therefore becomes possible to link different data, even data from very different sources, just by comparing its spatial location. Such links have enormous potential for all applications where it is important to assemble all data that is relevant for a specific location. This is particularly necessary for decisions about land use, where current use, property data etc. for the area of interest and all adjoining areas must be considered in the decision. It can be used further for comparing data that is in some form spatial and then analyzing the connections found. For example if accident data is connected to the street segments and thus localized, it becomes possible to connect it with e.g. socio-economic data and establish correlating statistics.

4.1 Spatial and Non-Spatial Data

A GIS must contain some data elements which describe the position and geometric form of objects for which the location in space is known. These objects can then be presented graphically in the form of a map. Other data describing additional (non-spatial) properties of these objects may be contained in the GIS. Non-spatial data is therefore also called attribute data. Rendering algorithms are then using these additional data to determine the graphical attributes of the objects shown or analysis methods calculate some other properties of interest (e.g. averages for an area).

Attribute data is not necessarily directly linked to the geometric object. The geometric objects may provide spatial location for widely used identifiers. This then allows the relation of (attribute) data that is stored in other databases, if the other database contains the same identifiers. This in turn allows the exploitation of data that is captured in ordinary databases, but contains some locator (e.g. street addresses or post codes), to be plotted spatially or analyzed using spatial statistics.

4.2 Base Data in GIS

Most GIS contain some base data that is used as the locational framework for the other data when it is shown graphically. One must recall that spatial data can only be interpreted by humans if shown in a context - most people do not think in terms of coordinate values and cannot understand spatial relations expressed in terms of coordinates. In order to understand the location of a point, it must be shown in the context of some surrounding features known to the user.

Graphical base data - often from scanned maps - provides the backdrop to show other data in geographic context. Human users can navigate around them and search for particular locations as one would one a paper map. However, the graphical data does not permit specific questions. Most importantly, one can not ask where a location is, given its name (the characters visible on the screen are only raster images, not ASCII text).

An electronic gazetteer, which links toponomy, i.e. the names of locations to coordinate values, is another valuable base data set. Such a data set allows the user to ask questions like, 'show me the area around Louisville', the name 'Louisville' is looked up in the gazetteer (very much like the index in a conventional atlas, where one would find an entry "Louisville, page 217, grid A7") and the appropriate part of a scanned map can then be retrieved and displayed. Other examples of digital base data are political boundaries, that are required often.

In the past, topographic maps have provided the function of spatial base data. It is still customary to reproduce a topographic map and overlay some additional information graphically. Some mapping agencies even produce special prints (e.g. the map content printed in a light gray) that are particularly suitable for the collection and display of other data. The same functionality is provided in a GIS with a set of base data sets. They usually contain data very similar to the topographic maps, and many mapping agencies in the world provide their data in a electronic format (or plan to do so over the next few years). Most important today is probably the Digital Chart of the World, a dataset containing data from the NATO Operational Chart 1 : 1,000,000 of the whole world. It is available from several sources in the U.S.A. as a set of CD-ROM disks. The World Database II - collected by the U.S. CIA and made freely available - is another base dataset that has been used widely in the last 15 years.

4.3 Application Specific Data

Obviously, GIS must contain the data that is particular to the application. The following list is only intended to give some hints what such datasets may represent:

- property boundaries,
- public utility lines, e.g. phone, power, water, sewage, gas,
- road geometry and descriptions of surface, technical installations and road signs,
- land use, soil type,
- topography, hydrography,
- data about wind, temperature, rainfall, etc.,
- socio-economic data as collected by the national census,

  etc.

There is an enormous variation between data used by different systems. The ones used for planning of engineering work must contain a level of detail not often found on 1:100 maps. At the other extreme, are the systems used by scientists studying global phenomena, e.g. changes in climate, where data on a 1/2 by 1/2 degree grid is considered quite detailed.

Important data sets are collected by the remote sensing satellites currently in orbit. They appear as 'images' showing pictures of large areas of the world. Technically, they provide intensity value for the reflected light from the surface of the earth in a number of discrete bands. The best sensors achieve a spatial resolutions of 12 m by 12 m (the French SPOT satellite). The data is geometrically very accurate and can be used to update small scale maps (1:50,000 and smaller), for example with newly built streets that are clearly visible on remote sensing images [Welch, and Ehlers, 1988]. The use of remote sensing data in general is hindered by the need to transform the effectively measured reflectance intensities into information of interest. Classification methods based on values in the multiple band can discern land uses, vegetation types etc., with some error. As data is collected in regular intervals, longitudinal studies assessing change over time become, at least in principle, feasible. Remote sensing data collected in the past is also often the only source of reliable historic data to establish a past state.

4.4 Data Exchange

Spatial data is used often and for many applications. It is obvious that certain data are useful for many tasks. 'Topographic map' data sets, that can be used as backdrops to provide a context for a large set of applications, have already been mentioned. Also widely used are Census data. Nearly every country does a population count at regular intervals, and collects additional socio-economic data with standardized questionnaires. This data is related to census tracts and can be shown graphically. It also allows spatial analysis, to study spatial variations as well as changes over periods of time. Topographic map data and census data is usually distributed by the respective agencies in electronic format and can easily be introduced into a GIS.

Other widely used data sets include, for example, parcel data (boundary, parcel identifier and possibly ownership information), road networks with street names and address ranges. One must determine which agency is responsible for original collection and systematic updating. The data is then distributed to all other users. The major cost saving is not the cost of original data collection but in the reduction of the cost of maintaining the data.

4.5 Data Quality

A problem that gains increasing attention is data quality. Spatial data is collected by different agencies according to their particular specifications. As more precision, more detail or lower error-levels require more effort and thus lead to more expenses, agencies consider their requirements very carefully

The problem becomes more difficult when one agency collects data and makes them available to others. The agency using the data has then to decide if the data is fit for the intended usage, assess its quality and compare it with the requirements of the task. Surprisingly little is known about data quality, not only how it is described and measured, but also how it is assessed and its suitability for a task determined [Goodchild, and Gopal, 1989].

5.0 Modeling Geometry

In a GIS geometry and location of objects in real world space is treated and must be modeled. This requires a method for the formalization of geometry. Mathematics provides substantial foundations to this effect, primarily Euclidean geometry, topology and graph theory. All GIS today are based on analytical geometry and use coordinates to locate all objects. Representing analytical geometry in a computer poses serious problems, due to the finite precision of the representation of the coordinate values. Computational geometry has studied this problem extensively , but the lack of any practical solution hindered GIS development for years.

Initially the development of geometric models for GIS and CAD were very similar and the base structures in use today are still often the same. The winged-edge representation and other models surveyed by Requicha [Requicha, 1980; Requicha, and Voelcker, 1983] are still dominant in commercial systems and have been adapted to the specific demands.

5.1 Spatial Concepts, Geometric Model, Spatial Data Structure

The discussion on modeling geometry must be divided in three separate areas of concern, which can be treated independently and which respond to very different questions:

Spatial concepts describe how the user thinks about space and what kinds of spatial objects he uses. There are several different ways to conceptualize space. For example scientists often use a 2 dimensional plane and assume that for each point on the plane there is a data value available. Goodchild has used the term 'geographic reality' to indicate that many geographical problems can be described in these terms. Administrative problems are usually framed in a framework of individual objects, e.g. streets, utility lines or parcels [Frank, 1990; Egenhofer, and Herring, 1991]. Spatial concepts are not easy to formalize, and often cannot be implemented, but they are close to human thinking about space. The spatial concepts used in an application should be identified early and described in detail. This helps to identify situations, where more than one spatial concept is used.

Geometric model is the set of formalized and implementable concepts that can be used to describe a particular application. Geometric models are on the same abstraction level as data models in database theory, e.g. the relational data model. Geometric models are described formally and have a set of operations associated with them.

Spatial data structures are implementations of geometric models. They differ in performance, but provide the same operations. They are optimized for fast answers, for minimal storage requirements etc. Transformations from one data structure to another, where both utilize the same geometric model, can be made without loss of information.

GIS development over the past few years has been characterized by an evolution of these models. These models followed the needs and the technical possibilities of the time. The discussion was concentrated initially on the bits and bytes of the data structures and later moved more towards geometric models. Three major groups of geometric models can be differentiated:

- cartographic models, which are primarily oriented towards graphical rendering in map form;
- regular spatial models, which model space and properties of space on a regular grid, therefore often called *'raster models';*
- irregular spatial models, which model the geometry of real world objects and describe them using coordinates, therefore often called 'vector *models'*.

There has now been a considerable shift of research interest towards the spatial concepts and human cognition of space [Mark, and Frank, 1991].

5.2 Small Scale vs. Large Scale Space

Cognitively one can differentiate between:

- small scale space: The situation can be seen in a single glance, the objects are usually smaller than human beings and can be moved around. Plates and glasses on a table provide an illustrative example.
- large scale space: One cannot perceive the situation in a single glance, but has to accumulate knowledge about the environment over time, the objects are usually much larger than humans and we move among them. Mountains, forests and buildings are an illustrative example.

These two cognitive situations influence our interaction with the objects and our conceptualization of them. They have a direct bearing on the metaphors used by designers and users when interacting with a GIS [Kuhn, and Frank, 1991; Lakoff, and Johnson, 1980].

5.3 Cartographic Models

A map represents spatial objects with graphical symbols on a two dimensional surface. Green areas represent forests, black lines represent roads and blue tints represent water features. In general, lines, point symbols, areas etc. are used to represent different features. The stored model is thus not a model of geographic reality, but of the map produced by a skilled cartographer, who has encoded his understanding of the reality in graphical symbols.

Data sets encoded for map production are also of limited usability for analytical purposes. For example lines are often interrupted to allow placement of names. This does not disturb a human at all and he 'sees' the line as continuous, but it makes the algorithms that determine line length very difficult. Similarly, interrupted polygon boundaries confuse point-in-polygon algorithms or algorithms to determine area.

5.4 Regular Subdivision of Space

To subdivide space in a regular lattice (figure. 2) and to record properties of each square area is an obvious method to model space. The underlying concept of space is the (2 dimensional) coordinate space with a value of the property of interest at every location. For practical reasons the attribute values are not recorded for the infinite number of points in coordinate space, but for a representative (regular) sample and other values can be interpolated if needed.

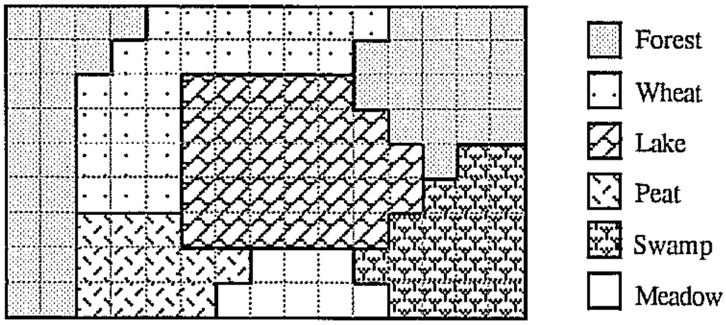

FIGURE 2. Regular Lattice

Remote sensing data collection is carried out according to this model: a sensor on a satellite or airplane collects intensity values for light reflected from the earth in specific bands in a regular square grid. Land use data collected by conventional means can be represented in this format as well and even socio-economic data can be transformed to this data model.

Spatial data modeled as a regular raster allows a powerful set of operations. Essentially all the image processing operations can be applied. The most important operations for remote sensing data are classification methods to determine areas of similar properties. They are usually used to determine land use or vegetation. 'Overlay' operations, which combine multiple 'layers' describing the same area, are also very important. For example, from a layer with the vegetation classes and another layer with political subdivisions, the prevalent vegetation in each subdivision can be determined.

5.5 Irregular Objects with Spatial Properties

To conceptualize space as a collection of spatial objects is the alternative concept of space. Each object has spatial and attribute data and all the objects together constitute space. For technical reasons, they are embedded in coordinate space and for each point coordinate values are recorded. The points are then linked by lines, which form the boundaries between the areas. The model is therefore often called 'vector' model.

Two conceptual models are very important, namely the partition of space, where all objects together fill space without holes (figure 3), and networks or graphs, usually used for modeling of transportation and public utilities networks.

5.5.1 Topological Model

In 1975 Corbett from the U.S. Bureau of the Census pointed to the importance of topological relations, in particular to the boundary/coboundary relation between point, line and area elements [Corbett, 1979]. The data structures used in GIS are very similar to the 'winged edge' model prevalent in CAD systems [Requicha, 1980; Requicha, and Voelcker, 1983]. In the DIME (Dual Independent Map Encoding), the topological relations are used to check the encoding.

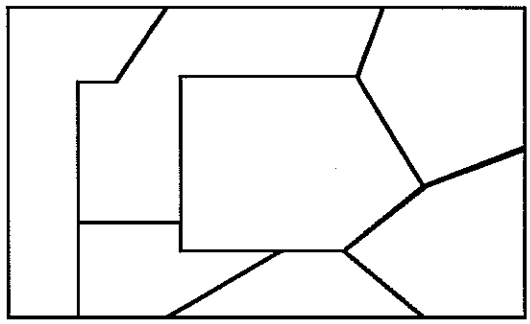

FIGURE 3. Partition of Space

The commercial GIS that are based on an irregular spatial model use topological relations for the structuring of their data. There are minor differences in the way this is implemented. Usually for each attribute a single 'layer' or 'coverage' is constructed, which partitions space in homogenous regions with a uniform value for this attribute. Layers can describe land use, building zones or political subdivisions.

5.5.2 'Spaghetti and Meatball' Model

The drawback to the cartographic model is that it is limited to lines. If one includes the areas formed by the lines into the model, it becomes suitable for analytical functions. This requires that the lines are made continuous even where cartographer interrupts them for graphical considerations. Digitizing lines in this mode is easy and leads to a dataset from which it is possible to calculate length of lines and to compute line intersections. In order to anchor area information additional points within the area are digitized and area attributes are linked to them using a point-in-polygon algorithm. Combination of two datasets as an 'overlay' operation is possible, but requires cleaning of the dataset for small errors from digitizing (lines which do not completely meet or continue slightly after the intersection with another line) and to establish the topological structure of the areas and their boundaries.

5.5.3 Cell Models

Pushing the topological conceptual model to an extreme, all the layers in a system may be integrated during data entry (not only when analysis operations are performed) and the area of uniform property used as the base building block (initially erroneously called the 'least common geographic unit'). In lieu of computing the geometrical intersection for the areas which fulfill several properties, only a simple search in the attribute data is needed [Frank, 1987].

Using combinatorial topology as the mathematical foundation, in particular cell or simplicial complexes, elegant models that lead to straight-forward implementation were designed [Herring, 1990; Frank, and Kuhn, 1986]. Computing all the intersections in a special, one-time, integration phase of layers seems attractive given the difficulty inherent in producing robust and fast 'overlay' operations for the topological data structure. The price paid for this is the large number of subdivisions that must be processed [Saalfeld, 1989]. There are several possible optimization strategies - for example to structure areas in a hierarchical fashion - but none have been developed so far [Egenhofer, and Herring, 1991].

5.6 Three Dimensional Space

Some application areas demand more than data situated in a two dimensional plane. Often a two dimensional surface embedded in 3D space is sufficient, for example when modeling the terrain (Digital Terrain Model DTM); this is sometimes called 2 1/2 D. However, in order to model geology for mineral exploration, and for modeling sea currents or for water flow in an acquifer, three dimensional models are necessary. Extension of the two dimensional raster to three dimensions is straightforward (including the extension of the quadtree data structure to three dimensions, i.e. octree [Kavouras, and Masry, 1987]) and is used for small areas with sufficient data.

5.7 Cognitive Aspects of Space

GIS mostly use a concept of regular Euclidean space, measured with surveying instruments and projected onto a 2 D plane. This does not correspond to the experience of people in geographic space, e.g. in a town or a valley. The topography and morphology of the terrain, the land use, trees, forests etc. change the conceptualization of space. Esthetic, cultural, social and emotional effects further transform space from an objective reality to a subjective experience. These subjective experiences however, determine people's decisions and it is therefore desirable to model not only physical space but also the cognitive space in order to understand human decisions.

6.0 Architectures of GIS Software

Two major GIS architectures can be recognized - one oriented towards projects of limited duration, and the other towards long-term use of data. The current trend is towards a unification of the two, and commercial systems are often presented as capable of using both these forms.

6.1 Database Oriented

Since a GIS is an information system, and the most important - and also most expensive - asset of such systems is the data, it can be considered a particular kind of database application. This leads to an architecture that is database oriented (figure 4); all data are put - possibly through some application programs - into the database and all output is retrieved from the database and processed by the application programs.

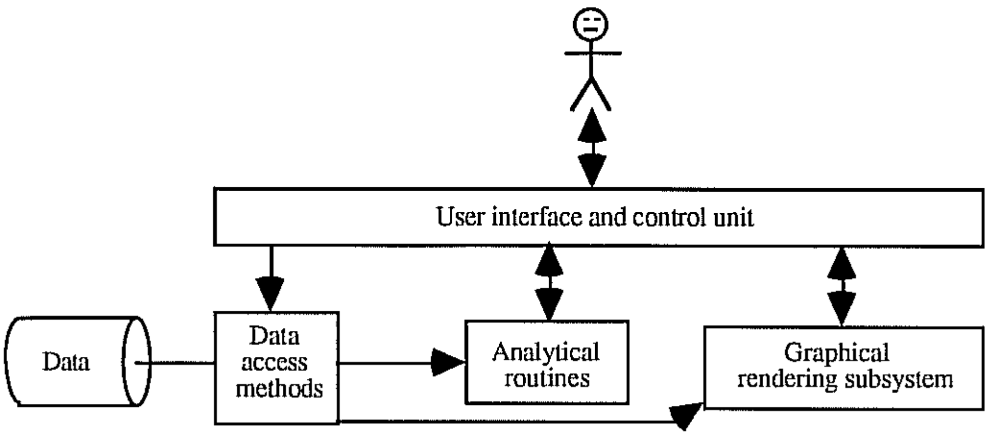

FIGURE 4. Architecture of Database-oriented GIS

This basic set-up was the starting point for today's GIS, which mostly use networks to connect the server containing the data store with the workstations where users do the work. There are several ways of distributing services over the network and of controlling access and concurrency of users.

6.2 Project Oriented

If spatial data from a project is organized in layers, operations like overlay, and display functions can be applied to the layers. The layers are then mapped to files of the operating system and output from overlay operations creates new layers as files [Tomlin, 1983; Tomlin, 1989].

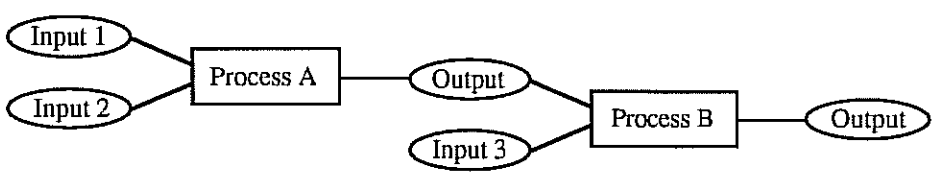

FIGURE 5. Project-oriented GIS Architecture

This leads to a well-structured, user-friendly conceptual model and a general structure similar to the UNIX processes: apply an operation to an input file and produce an output file which can be operated on again by the same or a similar process (figure 5). The file system is used for storage of the data and it remains the user's concern, to recall which file contains which data. As the data are not protected by a database management system, data corruption is more likely and therefore the design is most appropriate for projects of limited duration where flexibility is an asset.

6.3 Assessment

Both architectures lead to viable GIS, but they have different application areas:

- planning projects are often carried out in such a way that all the relevant data is initially collected and transformed in the format used for the project. Different input datasets are then combined, analyzed and rendered to produce a final solution. After the solution is finalized only the product remains and the input datasets are archived and hardly ever used again.
- administrative procedures require a large dataset that is kept up to date, and which is used again and again, for individual decisions on a single property or for town-wide tax assessment. Similar examples can be constructed for public utilities, where a database with all information about the utility lines must be maintained and is used for long periods of time.

It is obvious that administrative procedures demand the database oriented approach, whereas many short-lived engineering or planning projects can be done with the project oriented architecture. Fortunately, most commercial GIS now offer facilities to support both forms of work.

7.0 Commercial Software Packages for GIS

GIS is a rapidly expanding market and a large number of packages are now available. There are a few large vendors - mostly U.S. based companies - who have been marketing GIS several years, and there are a large number of newcomers, often with only a national market base. There are also a number of 'public domain' GIS software packages, i.e. software produced either at (U.S.) universities and given away freely or produced for the U.S. government and thus available at very low prices. Such low-cost GIS software is provided on an 'as is' base, without any warranty or service, but often service is available for a cost from another source.

There are also a number of GIS packages which can be run on personal computers. Mostly they are specialized for specific tasks, e.g. presenting attribute data in a spatial context, using some given topographic map background. Such packages are well suited to solving limited problems. On the other hand, there are the large general purpose GIS products, able to tackle the problems of complex applications with large data collections. It is important to match the functionality of the product with the demands of the application to achieve cost effective implementations. The problem is primarily to determine the processes the organization needs support for and to match them with the offerings of the software packages.

There is also a very large market for secondary services, assisting users in converting existing data or adapting one of the commercial GIS products to their particular situation, training the clients, personnel etc. In general, it is recommended that first-time users avail themselves of the knowledge and experience of these Consulting companies, because the selection and introduction of a GIS in an organization is a complex process.

8.0 Current Limitations on GIS Usage

A GIS consists of an organization that uses the GIS, the data in the GIS, the GIS software and the hardware. The components should be considered in this order. The organization that uses a GIS is most difficult to change, the data in a GIS uses by far the largest share of the expenses over the lifetime of a GIS -something in the order of 90% of total expenses go towards data collection and update. The technical problems of hard- and software, of which we understand most, are less crucial; more important are major changes - 'enabling technology' - which allow new approaches.

8.1 Hardware Limitations

Despite the fact that hardware today is only a small part of total expenses for a GIS, it is still a primary focus of discussion, but only few GIS limits are imposed by the lack of hardware. The hardware development relevant to GIS is the shift from a shared mainframe to the personal computer. Now, every user has his own, personal machine on his desk. Results are available instantaneously. The network connects the personal machine with the central computing services and allows data sharing. This has revolutionized the use we make of computers, but not all commercial GIS can use this new method.

The reduction in size and weight from a desktop box to a notebook is pushing further in the same direction. The personal computer is available even when outside of the office. This facilitates data collection in the field and will reduce the cost of data collection and update considerably. It also has the potential to change the job description of field work, which is an extremely difficult process.

8.2 Limitations of Current Software

The development of software is much slower than that of hardware. It is - contrary to the experience with hardware - slower than one would expect. The best known commercial GIS were designed 15 years ago, but there are also a few that were developed only a few years ago.

A GIS is a special example of an information system, and as a such, a major part of its functionality is storage and retrieval of data. GIS therefore require standard database services [Frank, 1988]. In particular, databases offer 'transaction management', i.e. comprehensive set of methods that permit the secure use of the data by several people at once. The newer systems are better integrated with database management system, but no commercial system uses an object-oriented database today .

In addition to databases, other specialized functions in a GIS can be provided from specialized packages. This ranges from computer-graphics to the tools for Graphical User Interfaces. More consistent user interfaces should make GIS much easier to learn. Pen based interfaces are a new development that will be used in some special applications - primarily on notebooks that are used in the field for data collection.

The integration of GIS in larger sets of applications is difficult to achieve today, but is often demanded. A more modular design respecting standard interfaces to other programs should make the treatment of geographic data an integral feature of many applications, which could not use a specialized GIS but need support for this type of problem. For example in a taxi cab dispatch system, an algorithm to find the shortest path in a street network would be an important part.

9.0 GIS Development in Response to Social Demand

In order to understand the development of GIS, one must not only consider the technical development, which seems to fuel the growth of GIS, one must also consider the 'social demand' for this particular technology. The best technology could not be sold, if it were not fulfilling a social need. There are three societal needs that propel GIS:

- the concern for the environment,
- the increasing demand for information, and
- the need for savings in public administration.

GIS as a technology makes the assurance that all information regarding a piece of land can be coordinated and brought together, both on a local and a global scale. Data that is already available can be combined spatially. In principle, such integration of data from different sources has been possible before, but now it can be done quickly and economically with computer assistance.

10.0 GIS Research Frontiers

Hard- and software development alone will not resolve all the limitations of today's GIS. Further development of GIS requires research in different domains, from geography, cognitive science, business administration, to computer science. The three most important ones are briefly listed subsequently, and conclude with problems where contributions could come from computer graphics.

10.1 Models of Space

Current GIS provide the user with vendor specific tools to model the spatial situation. These models are motivated more by implementation considerations and less by the requirements of the applications. Sometimes they are well adapted to one application but not to others. The differences in spatial models limit the integration of data from different sources and the models from different sciences. For example, in a GIS dealing with coastal areas, it would be desirable to integrate physical models of sea currents with marine biology models, but this is difficult, because space is conceptualized and then represented differently.

The difficulty with all these models is that they are based on the standard concept of space as used in physics and engineering. They are not suitable to represent the vague, incomplete or imprecise knowledge usually used by humans. For example it is not possible to record in a GIS that 'the church is on the right-hand side of the street' without putting precise coordinate values to its locations. Space is often conceptually structured in a hierarchical manner, for example the political subdivisions of county, province, state. Current geometric models do not include this feature.

Human beings conceptualize space differently and construct mental maps which are quite different from 'geometrically correct' ones. Humans then use these mental maps to make their decisions. Thus models that attempt to describe and predict human activities must take into account the 'human spatial conceptualization' and cannot be content with only physical space.

10.2 Models of Time

To the best of my knowledge, no commercial GIS has explicit provision for dealing with temporal data, which is required by a large number of applications. Planning needs the analysis of time series to understand the development of a town, archeology wants to represent location of finds and the epoch from which they date. Administration, in particular property registration has developed an elaborate set of rules for how time related data is used [Al-Taha, 1992; Al-Taha, and Frank, 1991].

The simple models of time that DBMS will provide are designed mainly for administrative uses. Time in geographic data sets needs some adaptation which are currently being researched. It will also be possible to document all changes applied to a dataset over time, so their justification can be assessed later.

10.3 Data Quality and Error

All data describing reality is only an approximation and contains inevitable errors; these errors are caused by

- the measurement process (precision),
- the time delay between data collection and use of the data (temporal update level),
- the classification method applied, i.e. how many classes of land use are differentiated,
- the consistency of the data collection, i.e. are the same rules always applied,
- the completeness of the data.

Data quality directly influences the cost of data collection. An organization will therefore request only the data quality necessary for its task. If the data is then shared with other agencies, other requirements may be imposed. There is the danger that data is used for tasks for which it is not suitable, because the quality is not sufficient. Of course, this is not limited to precision alone, but applies also to all other aspects, e.g. completeness or update level. For companies providing data for a fee this opens the question of exposure to liability for errors made by the user.

11.0 Challenges for Computer Graphics

11.1 User Interfaces

The design of the user interface is one of the major problems with today's GIS. The problem is more complex than just the visual representation of the user interface: many commercial systems use state-of-the-art graphical user interfaces (GUI). Adding a GUI to a large and complex program does not necessarily make it easier to use, and may have even a negative effect for beginners. The difficulty that a new user encounters is understanding the concepts and terminology that is used. One commercial GIS has 1800 commands to skim to find the appropriate one and the conceptional base combines notions from the application area with terms from computer technology.

The complexity of the user interface and the time it takes to master it is a serious impediment to widespread use of GIS technology. If it can be overcome, a very large set of users and many applications beyond the ones now using GIS become viable. It will become possible for politicians, managers and even ordinary citizens can access spatial data and draw their own conclusions. GIS can also be used when selling real estate, when selecting vacation destinations, or when selecting driving routes. GIS has enormous potential to reduce transportation cost for large distributors or service organizations. However, all this is only possible, if the system is easy to use and does not require extensive training.

11.2 Cartographic Output

Cartography has developed rules, over hundreds of years, to communicate geographic information graphically. A skilled cartographer considers geography, other application domain concepts and the rules of graphic communication, [Bertin, 1977; Bertin, 1983] and optimizes the graphics to communicate spatial information. The quality of a map produced by a skilled cartographer is currently not matched by any program.

There are a number of rules described in cartographic literature, the ones most often discussed concern cartographic generalization [Buttenfield, and McMaster, 1991], necessary for deducing a map from another map at a larger scale. Substantial improvements would also result, if users were assisted with rules for the selection of color and other graphical means to represent geographic data on a map. It is very likely, that AI methods could be applied, but it remains an essentially graphical and cartographic problem.

11.3 Visualization of Data Quality

Data quality often determines if a data set can be used for a specific task or not. It is not only necessary to assess the data quality but to communicate it to the user. Visualization of data quality in parallel with the visualization of the data itself is required and complicates the visualization problem further [Beard, and Buttenfield, 1991].

11.4 Cartography as a Transformation from the Geometric Model

A specific problem, perhaps of crucial importance, is the structure of the cartographic output software. Current standard packages are rendering routines, that render the stored graphics on the screen and the transformation from the stored format to the rendered graphics is minimal (originally, maps were sometimes stored as a sequence of graphics commands). If one wants to build a geographic database, from which to deduce maps of different scales, a number of transformation programs, selection the data to be presented, changing the scale etc., are needed.

12.0 Conclusions

GIS has enormous potential because it is an enabling technology, allowing us to do things that were not possible before. GIS produce spatial information, which is crucial to a rational use of our environment, ranging from questions for the future of mankind in general - global ecology - to issues for immediate personal concerns - e.g. building permits. There are a large number of applications that do not yet use GIS technology and some of them have mass appeal (e.g. system to assist car drivers to find their way). In order to realize this, potential impediments, some of which fall in the area of computer graphics, must be overcome. Much research is needed for progress in GIS. Finally, many of the problems and limitations are not of a technical nature, but of administrative, organizational, legal, and social nature. Even here, computer graphics can contribute to improved communication and thus reduce some of these limitations.

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