54 Geographic Information Systems

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Abstract

GISs are defined as software systems, and their relationships to other activities having to do with geographic information are reviewed. Their role in the social and behavioral sciences is discussed, as increasingly essential components of the research infrastructure and as tools for acquiring and communicating geographic knowledge. Examples are used to discuss the importance of GIS across the social and behavioral sciences. Sources of data are reviewed, and GIS is discussed from the perspectives of client-server architectures, the Internet, Internet-based services, data archives, and digital libraries. GIS use is intimately related to the role of space in scientific explanation. The contribution ends with a discussion of the future of GIS.

1. Introduction

A geographic information system (GIS) is best defined as a software system designed to provide services related to geographic data: such services include storage, analysis, transformation, maintenance, editing, visualization, modeling, and many more. That somewhat dry definition masks a record of rapid growth and widespread applications, beginning some 30 years ago. GIS is now the focus of a substantial software industry and a user community that probably numbers in the hundreds of thousands or even millions worldwide. While many of those applications lie in areas of social and behavioral science, they also extend across the full range of sciences, industries, and government agencies that deal in one way or another with information about the surface of the Earth, the subsurface, and the atmosphere.

GISs are one of several geographic information technologies that have appeared or evolved rapidly in recent years. Geographic information is also handled in image processing systems, in the form of aerial photographs or images from space satellites, and many GISs include image processing capabilities. The Global Positioning System (Kennedy 1996) and its Russian equivalent use satellites to allow users to measure their positions on the Earth's surface, with accuracies that range from millimeters to tens of meters depending on the complexity of the measuring device. Earth-observing satellites (Jensen 1996) capture images of the surface, and are now widely used to map, detect change, discover and inventory resources, forecast weather, and measure variables of importance to Earth science. The Internet and the World Wide Web (WWW) are widely used to distribute geographic data from data archives and digital libraries, and to provide GIS services to remote users.

Today, the potential user of GIS might take advantage of any of a number of hardware and software configurations. The examples that follow are ordered by increasing cost and power:

(a) A simple WWW browser, running on a laptop or office machine, and used to access WWW sites that offer a range of GIS services. Such services include generation of standard map products, and simple analysis and mapping of data. In this configuration the browser software might be free, and the hardware might cost on the order of $1000.

(b) A desktop system, such as a PC or Macintosh, running a relatively simple GIS such as ArcView (Environmental Systems Research Institute, *www.esri.com*) or MapInfo (MapInfo Corporation, *www.mapinfo.com*), acquired at a cost on the order of $1000. Data would be resident on the system's hard drive, and might have been created locally, or obtained from a data supplier. The operating system would likely be a Microsoft or Apple product.

(c) A networked workstation, linked to other workstations and servers in a local area network, perhaps under the Windows NT or Unix operating system. The software would be more complex than in the first option, perhaps ESRI's ARC/INFO or Spatial Database Engine, costing several thousand dollars.

A social scientist 'doing GIS' might use any one of these configurations, depending on personal skills and needs. The system would provide services that include preparation of simple maps; manipulation of data to overcome issues of map projections; running of statistical tests; and fitting of complex models to data.

Courses in the use of GIS and in methods of spatial analysis and modeling are now offered in almost all universities and colleges, and in many high schools. A wide range of educational materials are available in the form of textbooks (see, for example, DeMers 1997; Clarke 1997; Heywood et al. 1998; Burrough and McDonnell 1998), WWW sites (see, for example, *www.esri.com* and *www.geoplace.com*), and WWW-based courses (see, for example, *www.unigis.com*). GIS software vendors maintain WWW sites with much useful information, and trade magazines (*GeoWorld* and *GeoInfo Systems*) carry information about new products and initiatives.

The history of GIS (Foresman 1998) originated in the 1960s, with the development of the Canada Geographic Information System (CGIS). Analysis of paper maps is notoriously difficult, because of the awkwardness and unreliability of techniques for measuring simple properties such as length or area, and because of the difficulties associated with overlaying different maps of the same area. Computer technology was applied in the late 1960s and early 1970s to the editing of maps by producing agencies such as the U.S. Geological Survey, and to the automation of various functions associated with the taking of the Census. But early efforts were crude and expensive, and GIS became widely available to government agencies and corporations only in the early 1980s. Today, the general public is increasingly aware of GIS through WWW sites such as *www.mapquest.com*, which generates several million maps a day for users who need driving directions, and through simple mapping packages such as Microsoft's MapPoint 2000.

2. GIS essentials

General computer packages to support analysis of data began to appear in the 1960s, led by BMD, SAS, and SPSS. The table is a powerful model for organizing data, by arraying cases in the rows and devoting each column to some property of each case, and early packages took advantage of this commonality by organizing housekeeping and analytic functions around it. Thus means and variances could be computed by column; regression could be readily applied to two columns; and data could be aggregated by computing the mean value of a column for every unique value of some other, categorical column. In essence, these packages exploited an economy of scale in software production: once the housekeeping functions for a simple data model like a table had been built, it became very cost-effective to add new functions based on the same data model.

GIS similarly exploits economies of scale, but in this case by supporting not one but several data models, all of them effective ways of representing the information content of a map or image. The real geographic world is enormously complex, and there are many different ways of capturing its contents in digital form, all of them involving some form of approximation. Remotely sensed images use a *raster* model, capturing the Earth's reflectance in each of an array of square cells. Because of its simplicity, the raster model has been used as the basis for many GISs, each of them representing data as a series of *layers* of co-registered raster cells (Fig. 1), with each layer capturing some distinct variable, such as land elevation, county name, average income, population, or class of land use.

In the *vector* model the world is viewed as occupied by collections of points, lines, and areas. Points are located by *coordinates*, often latitude and longitude or some universal coordinate system such as the Universal Transverse Mercator (UTM). Lines are represented as *polylines* by connecting an ordered sequence of points with straight lines. Areas are similarly represented as *polygons* or figures with point vertices connected by straight edges. Each point, line, or area object in the vector model is associated with one or more *attributes* which capture the object's significant characteristics. A set of objects of the same type is associated with an *attribute table* by assigning one row of the table to each object, and one column to each characteristic.

Figure 2 shows a simple example of raster and vector data. The same set of census tracts is shown in Fig. 2a in the form of a raster, and in Fig. 2b in vector form. Today, most GISs include support for both models, and for transformations between them. They also support various kinds of map projections, allowing the user to switch readily between latitude and longitude, UTM, and other coordinate systems, and to display any part of the Earth's surface in the form of a flat paper map.

One of the most compelling arguments for GIS relies on the ability to integrate information around a common geographic location. A project might involve many different kinds of information, about different themes or variables for a geographic area. Every point, line, area, or raster cell in a GIS database has an associated location, so it is possible to determine the distance between two locations, or to place locations correctly on a map. But more significantly, it is also possible to identify all of the information available about a location, or to link together two data sets through common location. GISs include functions to determine how much overlap exists between two areas, or whether a given point lies inside a given area, or to select all of the points lying within a given distance of a line. To return to a point made earlier, the economics of software production provide great advantages to GIS designers once a basic structure has been laid down, because new functions that work on the same structure can be added very easily.

Certain key GIS functions are particularly relevant to social and behavioral science applications:

(a) *Geocoding*, or the ability to convert street addresses to geographic coordinates, and vice versa. This function might be used to associate coordinates with surveyed households, allowing locations to be mapped, integrated with other data, or subjected to various kinds of analysis.

(b) The *point-in-polygon* function, or the ability to compare a set of points to a set of polygons, to identify the polygon containing each point, and to combine the characteristics of the containing polygon with those of the point. For example, this function might be used to associate census tract properties with those of the individuals who live there.

(c) The *polygon overlay* function, or the ability to combine two sets of polygons, creating a new polygon for every unique area of overlap, and associating it with the attributes of the two polygons that overlap to create the area. By overlaying a map of county boundaries on a map of school districts, it would be possible to estimate the number of children living in each school district based on knowledge of the population density of each county (subject to the assumption that population densities are uniform within each county).

(d) The *buffer* function, which identifies the area lying within a specified distance of a given point, line, or area, and gives it the attributes of this object. By combining this with the geocoding and point in polygon functions it would be possible, for example, to determine the addresses of households within a certain distance of a shopping center.

3. GIS as research infrastructure

GIS software first became widely affordable in the late 1980s, when personal computers powerful enough to manipulate geographic data became available for a few thousand dollars. Social and behavioral scientists began to invest in its capabilities, particularly in those disciplines that had traditionally adopted a spatial perspective. Archaeologists and anthropologists, for example, began to use GIS software to map and store artifacts at the scale of the dig, to build digital maps of reconstructed landscapes, and to make use of spatial analysis to understand how early societies operated in space (Aldenderfer and Maschner 1996). Criminologists use GIS to map crime, correlate crime rates with social variables, and examine detailed spatio-temporal patterns of criminal behavior. Political scientists use GIS to evaluate districting schemes, and to explore the spatial diffusion of political movements (Eagles 1995). Market researchers and location analysts use GIS to map market potential, model the spatial behavior and choices of consumers, and search for optimal locational strategies (Martin 1996).

Of all the social and behavioral disciplines, geographers have long claimed a special interest in space, and much of the early work on GIS design and application was strongly associated with the discipline. Geography is often the home department of GIS, though many other arrangements exist, especially at institutions lacking a geography department. GIS courses are frequently offered by geography departments, and geography is often the sponsor of campus GIS infrastructure, in the form of labs, software licenses, and data repositories.

In recent years efforts have been made to develop wider linkages. In the U.S. the University Consortium for Geographic Information Science (*www.ucgis.org*) now links over 60 member institutions in an organization dedicated to advancing GIS and its applications through research and education. In Europe, the Association of Geographic Information Laboratories in Europe (AGILE) has a similar mission, and the European Science Foundation has sponsored a major study of GIS in the social sciences through its GISDATA program. National centers have been funded in several countries to pursue GIS research: in the U.S., the National Center for Geographic Information and Analysis (*www.ncgia.org*) was founded by the National Science Foundation in 1988, while in Canada the GEOID network was founded by the three national research councils in 1998.

Several journals are devoted to advances in GIS, including the *International Journal of Geographical Information Science*, *Cartography and Geographic Information Systems*, *Geoinformatica*, the *Journal of Geographical Systems*, and *Transactions in GIS*. Descriptions of research using GIS can be found in major journals in many application disciplines.

Comparisons have often been drawn between GIS and statistics, since both can be seen as generic tools and concepts used widely across the sciences (e.g., Goodchild 1987). It is argued that GIS provides the implementation of methods of spatial data analysis in easy-to-use computer tools, just as the statistical packages implement methods of statistical analysis. In this context spatial data analysis can be defined as a set of analytic methods whose results are not invariant under changes in the locations of the objects of analysis—in other words, location matters. This serves to distinguish these techniques from more familiar numerical and statistical analyses, such as the calculation of a mean, or the preparation of a scatterplot, that do not normally include location or respond to it. Spatial analysis predates GIS, and major texts include those by Berry and Marble (1968), Haining (1990), and Bailey and Gatrell (1995). But the advent of GIS has greatly improved access to these methods. Moreover, it has come at a time when there is increasing interest in visual, intuitive, and exploratory techniques, all characteristics that are readily compatible with GIS. For discussions of the impacts of GIS on spatial analysis see, for example, Fotheringham and Rogerson (1994), Goodchild and Longley (1999), and Fischer et al. (1996).

4. Sources of data

Maps are highly compressed representations of large amounts of information, and extremely tedious to convert to digital form. Two methods are available, both with advantages and disadvantages:

(a) *Digitizing*, a process in which a human operator traces information from a map, capturing the locations of features and their attributes using a pointing device and a keyboard. The process is very expensive, since it is difficult to capture complex geographic features rapidly and accurately.

(b) *Scanning*, in which an automated device captures the information from a map. Extensive editing and error correction is necessary, especially if the map is of low quality, such that scanning is typically as expensive as digitizing.

In the social and behavioral sciences data are often highly specific to applications, and must be rendered into digital form using one of these methods. Thus an archaeologist may have to digitize the locations of sites or artifacts from manuscript maps or drawings. But in other cases the process of database creation will take advantage of the widespread availability of *framework* data, or geographic data sets of generic use that already exist in digital form. These include:

(a) *Topographic maps*, in both raster (in the U.S., produced by the U.S. Geological Survey and known as Digital Raster Graphics, or DRGs) and vector (Digital Line Graphs, or DLGs) form. Various mapping scales are commonly available (in the U.S. the most detailed scale is 1:24 000).

(b) *Elevation data* in raster form (produced in the U.S. by the U.S. Geological Survey and known as Digital Elevation Models, or DEMs). These data sets vary according to the spacing of the grid: for the entire Earth the best spacing available is several km, but 30m spacing is available for much of the U.S.

(c) *Street centerline data* in vector form. These data sets record the locations, names, address ranges, and other information on streets. The TIGER database created and maintained by the U.S. Bureau of the Census covers all of the U.S., and includes boundaries of statistical reporting zones. These data sets represent streets by single lines, and have positional accuracies of tens of meters.

(d) *Imagery from aerial photography.* The Digital Orthophoto Quad (DOQ) is typical of these data sets, with a 1m ground resolution and a 6m positional accuracy, and available from the U.S. Geological Survey for much of the U.S.

(e) *Imagery from satellites.* These sources include images collected by the Landsat and SPOT satellites, with cell sizes down to 10m.

(f) *Municipal databases* created by local government agencies, often in collaboration with utility companies. These are in vector form and often include property boundaries, locations of buildings, and streets represented by double lines. In some countries, notably the U.K., they are produced by government for the entire land area. In the U.S. coverage is patchy. Positional accuracies are typically in the meter range.

(g) *Gazetteers*, the digital versions of the indexes found in atlases, linking placenames to geographic coordinates. These indexes make it possible to translate information recorded by placename to map form, for analysis and display.

Many of these data sets are created and maintained by longstanding programs of national mapping agencies. Recently, many countries have attempted to place them within broader policy frameworks that emphasize sharing of data, avoidance of duplication, and the setting of standards. In the U.S., the National Spatial Data Infrastructure (NRC 1993) is a leading example

These data sets provide the framework on which social and behavioral scientists can often hang their own features and attributes. For example, a criminologist might use a municipal database, adding records of crime locations; a sociologist might use reporting zone boundaries from the TIGER database to create maps and analyze data at the census tract level; and a planner might use imagery to monitor urban growth. By using data that are already in digital form the cost and tedium of database creation are greatly reduced.

Unfortunately the conditions under which such framework data sets are accessible vary widely. In the U.S., policy requires that geographic data produced by the Federal government be distributed to anyone at no greater than the cost of dissemination. It is often argued that this policy has stimulated growth in the use of GIS and in the geographic information industry generally. But while U.S. courts have held that geographic data are facts and therefore not subject to copyright, in other countries national governments have adopted cost-recovery policies, protected by copyright. Academic scientists in such countries have found various ways of accessing geographic data at lower cost, through bulk purchase agreements. Lower levels of government in the U.S. are also not subject to the cost-of-dissemination policy, and have made efforts at cost recovery under trademark protection. For more discussion of these issues see *Spatial Data Infrastructure*.

While the public sector has traditionally supplied many of the geographic data used by the scientific community, a growing private sector may have substantial impact in the coming years. Very large geographic databases are being created for internal purposes by insurance, retail, banking, and other corporate sectors. Point-of-sale systems now routinely capture data on grocery purchases, and direct-mail and delivery companies make use of detailed geographic data for scheduling and targeting. These activities have raised privacy concerns, and it is clear that the levels of detail now available to corporations, together with the ability integrate and merge data based on geographic location, have very significant privacy implications. Much of this activity remains largely outside any regulatory framework.

5. Networks

The Internet and World Wide Web have had major impact on GIS. They have made it much easier to share data, and to access data remotely. Data can be published and disseminated easily, as can the more sophisticated results of analysis. Indeed, the entire process of scholarly communication and publication is being radically restructured by networking technologies.

It is useful to distinguish two forms of processing of geographic information. The term 'geographic information system' suggests a combination of hardware and software that may or may not be connected to a larger network. It is likely controlled directly by a single user, and provides capabilities and functions directly related to the user's needs. On the other hand the term 'geographic information services' is used to describe WWW sites that offer specific GIS functions in response to user requests. Instead of sending the data to a GISystem, a GIService retains its data, sending only the results of analysis. The Mapquest site (*www.mapquest.com*), for example, provides a range of services from the generation of maps at user request to the geocoding of addresses supplied by the user.

GIServices are growing rapidly, and are expected to grow much further in the coming years. In addition to avoiding lengthy transmission of data, they allow the custodian of a sophisticated analysis tool to retain control, and to upgrade the tool, rather than undertake a complex process of distribution to user sites. Pricing based on services is very different, and perhaps simpler, than pricing based on data (Guenther and Mueller 1999). GIServices also assume a level of adherence to standards, and encourage the development of interoperable tools using common formats and protocols (the Open GIS Consortium, *www.opengis.org*, is a major influence toward greater interoperability in GIS).

Several major initiatives are making geographic data more easily found and accessed via the WWW. In the U.S., the Federal Geographic Data Committee sponsors the National Geospatial Data Clearinghouse (*www.fgdc.gov*), a catalog of sites offering geospatial data, linked together using the Z39.50 protocol. The Alexandria Digital Library (*alexandria.ucsb.edu*) offers the services of a map library, including search and retrieval of data, over the WWW. Other sites offer more specialized data; for example, a site at the Massachusetts Institute of Technology (*ortho.mit.edu*) offers DOQs for the Boston area. The term *geolibrary* has been coined to describe WWW sites that allow search for data based on geographic location, including search for information that is associated with a geographic area but is not a map or an image, such as a planning report. The implications of geolibraries are discussed in a recent report of the U.S. National Research Council (NRC 1999).

6. Space and scientific explanation

Ultimately, the value of GIS and related technologies in the social and behavioral sciences will be intimately tied to the role of space in scientific explanation and understanding. Before expanding on that point, however, it is useful to distinguish between normative and explanatory applications. Many applications of GIS may be scientific in their objectivity and rigor, but nevertheless aimed at supporting decisions, developing policy, or solving day-to-day problems. Such *normative* efforts often apply the principles and knowledge of social and behavioral science. Moreover, many do so in a spatial context, by combining principles about behavior and society with the specific conditions existing in a geographic area. Thus there are abundant normative applications of GIS.

In this section, however, the focus is on those applications that advance scientific knowledge about the world, through observation, experiment, hypothesis-testing, and deduction, because such explanatory efforts lie at the heart of the social and behavioral sciences. To what extent can GIS be used as a tool to advance scientific knowledge?

Ideally, scientific knowledge advances through controlled experiment, by varying the conditions under which society operates and observing the response. But although such experiments are common in areas such as agriculture, and GIS is often used as a tool to manage experimental plots, they are unlikely to be possible in the case of social and behavioral processes operating at geographic scales. Instead, science must advance through inference, either inductively by inferring the nature of a process from its geographic or temporal expression, or deductively by comparing the predictions of theory with reality.

GIS is most strongly associated with *cross-sectional* approaches to observation and inference. A phenomenon is compared across a geographic area, and its spatial variation is compared with the variation in relevant conditions. Inferences are drawn about process, but since the process is not observed directly it is impossible for inference to be definitive. Alternatively, patterns may be used to provide confirmation of hypothesized processes, though again confirmation is never definite. The tradition of using maps as a basis for inference has a very long history, one of the most compelling historic examples being the map made by Dr. John Snow of a cholera outbreak in the Soho district of London in the 1850s, which provided evidence of the role of drinking water as the disease vector.

It is often argued that *longitudinal* observation and inference based on change through time is more definitive than cross-sectional inference. But cross-sectional data are widely available from sources such as the Census, and powerful technologies like GIS increasingly make it possible to examine data from both cross-sectional and longitudinal perspectives.

Geographers draw a distinction between the properties of a *site*, and the site's *situation* in spatial context. Many social processes respond both to the conditions at a place, and to the conditions in the place's surrounding area. For example, choice of residential location is affected both by the properties of the available sites, and by their surrounding communities and neighborhoods. GIS makes it possible to observe and analyze a site's situation, in the form of maps and images, and also to link one property of a site to other properties through their common geographic location. Further discussions of the spatial dimension of explanation, and of the role of GIS, are available in many sources (e.g., Abler et al. 1992, NRC 1997a).

7. GIS in the future

There is every indication that the use of computers to handle geographic information will continue to increase dramatically in the future, and that the user base will continue to broaden. But trends in the software industry and in society more generally suggest that the nature of GIS will continue to evolve.

In 1997 the U.S. National Research Council sponsored a workshop on the Future of Spatial Data and Society (NRC 1997b). It found strong support for continued increases in technical power, in the form of computer speed, network bandwidth, and storage capacity, at constant or diminishing cost. But it also identified a large number of societal trends that are likely to affect GIS, and also fundamental trends in the nature of software.

The report found a discernible trend in recent years towards the solution of problems at the local level. It is reflected, for example, in the popularity of *place-based decision-making* in the U.S. Environmental Protection Agency, a policy that encourages the solution of problems locally, by local stakeholders. It is also reflected in efforts to devolve power to lower levels in the administrative hierarchy.

In the 1960s, the so-called *quantitative revolution* in geography emphasized the *nomothetic* search for general laws affecting spatial phenomena, and saw traditional geography's approach as *idiographic*, with its stress on cataloging the unique properties of places. Today, there is much interest in quantitative techniques that accommodate spatial variation in parameters, and emphasize the role of spatial analysis in exploring local variation. Fotheringham, for example, has identified this as one of the most important themes in contemporary spatial analysis (Fotheringham 1997). GIS provides an ideal platform for such methods, since it makes it easy to analyze spatial data, and to display spatial variation.

At the same time, there is increasing interest in several disciplines in the incorporation of spatial effects directly into theory, on the grounds that a system that is spatially distributed, and forced to communicate over distance, is fundamentally different from one that is infinitely connected. Spatial economics and spatial ecology are now significant areas within the theoretical wings of those disciplines, while geography has a long tradition of explicit theorizing about space. Again, GIS provides an ideal platform for subjecting such spatially explicit theory to empirical test.

Finally, the spatially explicit nature of GIS provides an ideal environment for linking normative and explanatory science. The implications of theories for real geographic areas are readily evaluated, and models that incorporate social and behavioral processes can be combined with geographic boundary conditions to provide readily visualized predictions. Thus GIS offers an ideal environment for bridging the gap between theory and practice, and a significant clue in the eternal search for relevance.

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Figure Captions

Figure 1

The concept of layers. Geographic reality is represented by a set (5 in this case) of co-registered rasters, each representing the spatial pattern of one variable. Example layers might include soil type, vegetation cover type, ownership, mean annual temperature, or elevation.

Figure 2

Representation of three adjacent census tracts using raster cells (left) and vector polygons (right). In the raster case cell size determines the accuracy of boundary positions. In the vector case each tract is located by specifying the coordinates of its vertices in order.