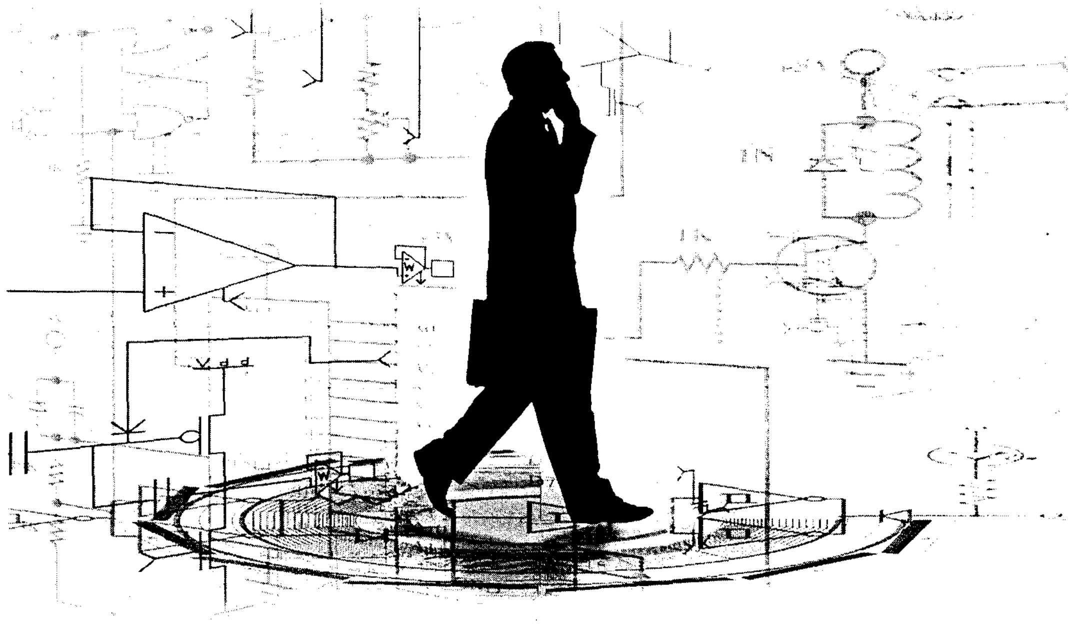
NEW HORIZONS FOR THE SOCIAL SCIENCES

Geographic Information Systems



BY **MICHAEL F. GOODCHILD**

RÉSUMÉ ► Les systèmes d'information à référence spatiale (SIRS), maintenant très répandus dans le monde scientifique, sont reconnus comme des outils valables dans toutes les disciplines qui s'intéressent à la surface de la Terre et à ses populations. Les SIRS sont également considérés comme une technologie d'intégration qui recouvre plusieurs disciplines et brouille les frontières qui les séparent, deux importants préalables à toute infrastructure de recherche d'utilité générale. L'auteur examine la possibilité d'étendre l'utilisation des SIRS à une gamme plus vaste de sciences sociales et de sujets de recherche dont elles traitent. Il évalue les forces et les faiblesses de cette technologie et fait ressortir six principes clés qui sous-tendent l'application des SIRS aux sciences sociales. Il termine par une analyse du concept de Terre numérique et de son potentiel de motivation. (Traduction: **www.isuma.net**)

ABSTRACT ► The use of geographic information systems (GIS) has spread very widely among the sciences, and it is now an accepted tool among all of the disciplines that deal with the surface of the Earth and its human population. GIS is also considered to be an integrating technology, spanning disciplines and blurring the distinctions between them, both important prerequisites for any broadly useful research infrastructure. The author considers the potential for applying GIS to a broader range of social sciences and social science research issues. He assesses the technology's strengths and weaknesses, and outlines six key concepts that underlie applications of GIS to the social sciences. He closes with a discussion of the concept of Digital Earth and its possible value as a motivating force.

Introduction

GEOGRAPHIC information systems are part of a complex of geographic information technologies that include remote sensing, the Global Positioning System, and geographic information services offered on the World Wide Web (WWW). The acronym "GIS" is used increasingly to encompass all of these, and phrases such as "doing GIS", "GIS data", the "GIS community" suggest a willingness to see "GIS" as a shorthand for anything that is both digital and geographic in nature. Longley et al. provide a recent review of all aspects of GIS.[1]

The use of GIS has now spread very widely among the sciences, and it is now an accepted tool among all of the disciplines that deal with the surface of the Earth and its human population. GIS is also considered to be an integrating technology, spanning disciplines and blurring the distinctions between them, both important prerequisites for any broadly useful research infrastructure. The use of GIS has prompted interest in a number of fundamental issues that are collectively identified as geographic information science.

The paper opens with an assessment of the technology's strengths and weaknesses. This is followed by a brief review of geographic information science. The final major section of the paper discusses the concept of Digital Earth, and its possible value as a motivating force.

The nature of GIS

GIS is defined most generally as technology for processing a specific class of information — geographic information. Processing is understood to encompass creation, acquisition, storage, editing, transformation, analysis, visualization, sharing, and any other functions amenable to execution in a digital domain. Geographic information is readily defined as information linking locations on the Earth's surface with specific properties, such as name, feature, population, elevation, temperature. More generally and precisely, it consists of atoms of information or tuples of the form location, time, property. To be communicable, a scientist would argue that all three components must be well-defined, using terms that are known to both sender and receiver of information. In the case of location, this argument clearly favours general standards such as latitude and longitude over more problematic specifications of location such as place-names. But there are strong arguments for including information in GIS that is poorly defined, vague, or subjective, because of the importance of these forms to human communication, and there has been much interest recently within the research community in the problems of handling vague geographic information.

This definition of geographic information is deceptively simple. Unfortunately the geographic world is continuous and infinitely complex, and there are therefore an infinite number of locations in space and time to be described. In practice, geographic information must somehow approximate, generalize, or simplify the world so that it can be described in a finite number of tuples. There are an unlimited number of ways of doing this, in other words an unlimited number of ways of mapping the real geographic world into the contents of a GIS database. Many such mappings or representations have been implemented in various disciplines and areas of application, and many are implemented in the standard GIS software products as data models.

Data models fall into two broad but imperfectly defined categories — raster and vector. In a raster representation, the world is divided into an array of cells of fixed size (note that some distortion is implied, since the curved surface of the Earth cannot be covered by uniformly sized, non-overlapping square cells). All properties of the surface are expressed as uniform properties of the cells, and all sub-cell information is lost. Moreover, rasters are not convenient for capturing geometric structures larger than the cell, since it is generally complicated to link cells together. In a vector representation, properties are associated with geometric points, lines, or areas, and the locations and shapes of these objects are defined by coordinates. Areas are approximated as polygonal figures by connecting points with straight lines, and curved lines are similarly approximated as polylines. Vector representations readily accommodate variable spatial resolution, links between objects, and complex geometric structures, and are strongly favored in applications of GIS to social phenomena.

Large and comprehensive software environments such as GIS are possible because of strong economies of scale in software production. Once a basic framework has been built, by implementing a limited number of basic data models along with associated tools for creating, editing, visualizing and sharing data, additional functions can be added very easily and cheaply. This principle is clearly evident in spreadsheets, word processors, statistical packages and GIS, all of which are defined by basic data models.

But herein lies one of the fundamental weaknesses of the GIS idea — there are simply too many possible geographic data models. In order to accommodate the needs of new applications, software vendors have repeatedly extended the basic data models of their products. One of the most persistent problems is associated with time, since early GIS were built largely to accommodate the static data of maps, and their data models have been extended with varying success to deal with temporal change.[2] The problems of dealing with data on networks, necessary in many transportation applications, has led to the emergence of products specifically targeted to this niche. Today, a vendor such as California-based ESRI (Environmental Systems Research Institute) offers a suite of products rather than a single, comprehensive GIS. Each product is designed for a particular class of applications, or for a user community with a particular level of sophistication. The products are able to share data, and many of the concepts on which they are based are common. But with the present trend toward unbundling of software in favour of modular code for specific applications, it seems likely that the days of monolithic GIS are numbered. Instead, we are likely to see much smaller software components that can be mixed to service particular applications, held together through common specifications and standards. Efforts are under way through the Open GIS Consortium (www.opengis.org) to standardize across the entire vendor community, but whether this will be successful, or whether standardization will be achieved only across the products of each vendor, remains to be seen.

Key concepts

The definition of GIS discussed above does little to clarify the technology's value in applications, or to explain its popularity. This section briefly reviews six key concepts that underlie applications of GIS to the social sciences and define much of its power.

First, GIS enables integration, by making it possible to link many different properties at the same place. The institutional structures of disciplines and departments that frame much academic activity partition the world by type of process and by theme, allocating economic issues to one discipline and demographic ones to another. Issues and processes come together at places (and times), and a technology based on geographic location is able to provide the essential mechanism for integration. GISs implement the operation of overlay, wherein maps of different themes are laid over each other and compared, in a suite of precise computer operations that support correlation and other forms of analysis.

Second, GIS supports spatial analysis, a set of analytic techniques that reinforce the human ability to detect pattern and anomalies in data that have been arrayed spatially. The properties of a point can be compared to properties of the surrounding neighbourhood, or to properties of places to which the point is connected, adjacent or near. Abundant cross-sectional data are available from sources such as national censuses, and although they can never confirm causality, they are nevertheless useful for visual exploration, hypothesis generation, and confirmation of spatial statistical models.

Third, GIS plays a key role in spatially explicit theory and modeling. Spatial variables, including location, distance or connectivity, can play an important role in models, especially where it is necessary to include the effects of distance on transportation costs, migration, innovation adoption or information access. Spatially explicit theory is an important area in economics, demography and planning, among other fields. Models that incorporate space explicitly are easy to implement in the software environment of a GIS, and in recent years GISs have been used to implement and test cellular automata, spatial interaction models, and models of urban growth.

Fourth, GIS addresses the long-standing debate over whether science should be concerned only with the identification of laws that are universal in application, or whether it should also be concerned with the description of the unique characteristics of places. Recently, there has been much interest in developing methods of local analysis, that explicitly recognize and search for spatial variation in model parameters, rather than attempting a single, universal calibration (Fotheringham[3] provides a recent review of this literature). For example, geographically weighted regression (GWR) allows the parameters in a regression model to vary spatially. The results can be interpreted in terms of missing variables (model mis-specification), or in terms of spatially heterogeneous response to stimuli.

Fifth, a GIS combines the properties and facts stored in its database with the power of algorithms to transform, model or predict. The ability to do this is essential if the results of science are to be implemented in policy, because general truths represented as laws, models or theories must be combined with local conditions to obtain specific predictions or to evaluate alternative scenarios. In this sense GIS provides a key link between science and policy, and is widely used for practical problem-solving by governmental agencies and local community organizations.

Finally, and most recently, there is the concept of place-based search. Location and time are valuable bases on which to organize and search for information, yet traditional libraries have tended instead to implement author, title and subject as search keys in their catalogs, for a variety of practical reasons. Search has become a critical issue on the Internet, where the WWW is a massive but largely uncatalogued information resource. New search mechanisms based on location and time are entirely possible in the digital world of the Internet, and there is much interest in implementing the concept of a geolibrary, or a library whose primary search mechanism is based on location. A recent report of the US National Research Council[4] elaborates on the concept and describes many current prototype implementations.

Geographic information science

GIS has developed as complicated and sophisticated technology for support of science and policy-making, but it has done so largely in the absence of a coherent body of theory or language. In this it stands in sharp contrast to the statistical packages, which developed to support an existing and widely used set of techniques underpinned by well-defined theory. If the statistical packages are implementations of statistical theory, then where is the theory that GIS implements?

One consequence of this lack of pre-existing theory is the diversity of languages and standards that have emerged from a largely uncoordinated GIS software industry. GIS products appear to their users as highly intuitive and pragmatic, rather than as implementations of some universally accepted set of principles, which perhaps explains their popularity. But it means that the GIS community is deeply divided into distinct information communities, each with its own set of norms, standards, and terms. There are very high costs associated with moving data from one product to another, or with retraining staff.

Geographic information science seeks to develop the science behind the systems, and to address the fundamental issues raised by GIS. Its focus is well described by the research agenda of the University Consortium for Geographic Information Science, an organization of major US research universities that now includes some 60 members (www.ucgis.org). The agenda was developed by consensus at the Annual Assembly of UCGIS in Columbus in 1996,[5] and contains ten topics:

- Extensions to representations, or research to elaborate the set of data models that form the basis of GIS, notably to include time, the third spatial dimension, and level of detail.
- Scale, or research on the characterization of level of detail, transformations that aggregate or disaggregate, and the role of scale in modeling process.
- Uncertainty, or research on the characterization of data quality, its impacts on the results of modeling and analysis, and its visualization and communication.
- Cognition, or research on the ways humans understand, reason about, and work with geographic information.
- Spatial analysis, and the development of new techniques and tools for analysis of spatial data.
- Distributed and mobile computing, and the opportunities offered by new technology for new uses of GIS in the field and distributed over electronic networks.

- Interoperability, or research on the problems caused by lack of standard protocols and specifications, and the development of new theory-based terminology.
- Acquisition and integration, or research on new sources of geographic information, and their integration with existing sources.
- Spatial information infrastructure, or policy-oriented research on the production, dissemination, and use of geographic information.
- GIS and society, or research on the impacts of GIS on society, and the context provided by society for GIS.

Digital Earth

In a speech written for presentation at the opening of the California Science Center in Los Angeles in January 1998, US Vice President Al Gore proposed "a multi-resolution, three-dimensional representation of the planet, into which we can embed vast quantities of georeferenced data" (www.opengis.org/info/pubaffairs/ALGORE.htm). In the speech, Digital Earth is an immersive environment through which a user, particularly a child, could explore the planet, its environment, and its human societies. It might be available at museums or libraries, and a more modest version might be available through standard www browsers running on a simple personal computer.

Digital Earth is interesting for several reasons, and the concept has attracted widespread interest (the first International Symposium on Digital Earth was held in Beijing in December 1999). First, it has some of the properties of a moonshot, or a vision that can motivate a wide range of research and development activities, in many disciplines. It challenges our state of knowledge about the planet, not only in terms of raw data, but also in terms of data access, and the ability to communicate data through visualization. How, for example, would one portray state of human health or quality of life to a child? Moreover, it challenges our understanding of process in the invitation to model, simulate, and predict, since the concept should not be limited to static portrayal.

Second, Digital Earth is interesting because of its implications for the organization of information. The prevailing metaphor of user interface design is the office or desktop, with its filing cabinets and clipboards. Many prototype digital libraries employ the library metaphor, with its stacks and card catalogs. But Digital Earth suggests a much more powerful and compelling metaphor for the organization of geographic information, by portraying its existence on a rendering of the surface of the Earth. The idea can be seen in limited form in many current products and services, including Microsoft's Encarta Atlas.

Digital Earth suggests a powerful and compelling metaphor for the organization of geographic information, by portraying its existence on a rendering of the surface of the Earth.

Finally, Digital Earth is a fascinating example of Gelernter's mirror worlds.[6] Just as a map, it captures a particular state of understanding of the planet's surface, and the data and information available to its builders. But since it cannot be a complete representation, it is interesting in what it leaves out, and in how it reveals the agendas of its builders.

Closing comments

GIS seen narrowly is an important and growing application of computing technology. It includes software, today largely developed and marketed by the private sector; data, increasingly available in large quantities through the medium of the www; and tools for analysis and modeling that focus on the spatial aspects of data, and increasingly on the temporal aspects. As such, GIS is of increasing importance to those social sciences that deal in one way or another with activities and phenomena that distribute themselves over the surface of the Earth, and with understanding the processes that lie behind them.

GIS seen broadly raises a number of challenging and fundamental issues that range from human spatial cognition to the modeling of complex spatial processes. Collectively, they motivate a multidisciplinary effort to advance what can be termed geographic information science, and many of these issues intersect and engage the social sciences.

Finally, GIS seen broadly is intimately related to the concept of Digital Earth, or the development of an accessible, unified emulation of the surface of the planet and the processes that affect it, both human and physical. As a vision, Digital Earth may or may not be achievable, depending on the assumptions one is willing to make about future technologies, the availability of information, and our ability to characterize and understand process. But as a moonshot it is an idea that can motivate a broad spectrum of activities across many disciplines.

Michael F. Goodchild is Professor of Geography at the University of California, Santa Barbara, and Chair of the Executive Committee, National Center for Geographic Information and Analysis (NCGIA).

Endnotes

1. P.A. Longley, M.F. Goodchild, D.J. Maquire and D.W. Rhind (eds.) *Geographical Information Systems: Principles, Techniques, Management and Applications* (New York: Wiley, 1999).
2. G. Langran, *Time in Geographic Information Systems* (London: Taylor and Francis, 1992).
3. A.S. Fotheringham "Trends in quantitative methods. 1. Stressing the local," *Progress in Human Geography* Vol. 21, no. 1, 1997, pp. 88-96.
4. National Research Council, *Distributed Geolibraries: Spatial Information Resources* (National Academy Press, 1999).
5. University Consortium for Geographic Information Science "Research priorities for geographic information science," *Cartography and Geographic Information Science* Vol. 23, no.3, 1996, pp. 115-127.
6. D. Gelernter, *Mirror Worlds: Or the Day Software Puts the University in a Shoebox. How it will happen and what it will mean* (New York: Oxford University Press, 1992).