GEOGRAPHIC INFORMATION SYSTEMS

1. Definition

Geographic information systems (GIS) apply computer technology to the tasks of capturing, storing, manipulating, analyzing, modeling, and displaying information about the surface of the Earth, and the phenomena distributed on it. They have emerged over the past three decades as a distinct form of computer use, with its own software industry and array of products, directed at applications ranging from management of the resources of utility companies, to support for global change science. Worldwide sales of GIS software in the late 1990s were in the region of $600 million annually, with much larger investments in associated digital geographic data.

GIS deal with information that is geographically or spatially explicit, representing the spatial variation of phenomena over the Earth. Although many forms of software are capable of handling such information in limited ways, GIS is the only form designed expressly for this purpose, with a full range of necessary data structures and functions. Global change science is also inherently geographically explicit, dealing with spatial dynamics and differentiation over the surface of the planet. Thus GIS is uniquely suitable as a tool for the computing functions needed to support global change science.

It is often helpful to think of a GIS as a computer containing maps. One of the simplest reasons for manipulating maps with computers is to make them easier to construct and draw, and GIS are often used for this purpose. By computerizing the map-making process it is possible to edit easily, manipulate the map's contents without the labor-intensive task of redrafting, communicate maps electronically, and create output in any convenient form. The advent of GIS has made it possible for anyone to be a cartographer who is in possession of the necessary software, a computer to run it on, and a suitable printing device.

This view of a GIS as an automated mapping system is much too simplistic, however. The first GIS is generally agreed to have been the Canada Geographic Information System (CGIS), a project developed in the Canadian Government in the 1960s, under the direction of Roger Tomlinson. At the time there were no printers capable of making acceptable maps, even in black and white, and the design of CGIS did not include map output. Instead, the project was justified entirely on the basis of the need to analyze geographic information obtained from maps. Its original design included a thorough cost-benefit analysis that is still a model for the industry, and found substantial net benefits to computerization despite the high costs and crude technology of the time.

The case for computerizing the analysis of geographic information rests on two propositions: first, that the few traditional tools that exist are very labor intensive and crude; and second, that once geographic information is in digital form there are massive scale economies because of the many forms of analysis that are possible. For example, there are two traditional ways of measuring area from a map: use of a mechanical planimeter, and counting dots on a transparent overlay; and both are incredibly tedious and inaccurate. But measurement of area from a digital representation of a map is trivial, and virtually as accurate as the representation. Once a representation has been created, it is easy to add functions to the software to perform almost any analysis imaginable.

Today's GIS software includes functions to support the creation of digital data by manual or automated digitizing of paper maps; functions to convert between map projections; functions to integrate data from different sources by converting formats or removing spurious differences; functions to make mapped output more publishable and cosmetically pleasing; and links to specialized software for modeling physical processes or conducting statistical analyses. All of these are relevant to global change science, and GIS has become one of that science's most valuable analytic tools.

2. Principles

The most conspicuous distinction in GIS is between two competing forms of digital representation. The vector approach builds a database from digital representations of points, lines, and areas. The location of each primitive object is recorded using an appropriate combination of coordinates referenced to the Earth's surface, often in latitude and longitude but also in standard coordinate systems such as UTM (Universal Transverse Mercator, a world standard initially developed for military applications). The characteristics of each object are termed its attributes, and a vector GIS will accommodate large numbers of these, in the form of names, or measurements of various kinds. Objects are grouped into classes, each member of a class having the same dimensionality (all points, for example) and the same group of characteristics. It is convenient to think of the attributes of a class of objects as forming a table, and many vector GIS incorporate relational database management systems to handle the tables.

The raster approach covers the relevant part of the Earth's surface with an array of rectangular cells, and describes variation by allocating a value to each cell. Almost all designs allow only one value per cell, so representations of multidimensional variation are built by constructing several layers of cells, each describing the variation of one variable. A cell can contain a digital representation of a number, as in digital images of Earth from space (remote sensing) or representations of the variation of elevation (digital elevation models or DEMs); or a digital representation of a class, as in layers of land cover, vegetation classification, or land use. The fixed cell size gives the raster representation the appearance of constant spatial resolution, whereas vector representations have resolutions that are unlimited in principle, but limited in practice by the nature of the data.

Vector GIS originated in applications where this representation is most appropriate. For example, it is clearly much more reasonable to represent the links in a connected river or water supply network as lines than as collections of cells. This is particularly apparent in management of telephone networks, where the connectivity in the system is apparent only at the most detailed spatial resolution. Vector data is also dominant in social, economic, and demographic data, and thus in the human aspects of global change science, because of the practice of collecting such data for irregularly shaped regions. On the other hand it is clearly much more reasonable to process information gathered by remote sensing in a raster GIS, because the data are collected in that form. Raster GIS are similar in many ways to the image processing systems developed for handling remotely sensed data, but add functions that allow these data to be integrated with other, possibly vector data. Vector GIS are similar in many ways to computer-assisted design (CAD) systems, but add functions and capabilities that reflect the special needs of users of Earth-referenced data. Modern GIS attempt to integrate raster and vector approaches, though with only partial success, and many systems still reflect their earlier roots in one camp or the other.

But this distinction between raster and vector is only one instance of a much more general issue: that geographic reality is infinitely complex, and there are always many possible ways of representing the same phenomena. One very important form of this issue concerns scale. In order to have any chance of creating a representation of real geographic complexity in the limited space of a digital computer it is always necessary to generalize. Cartographers know this as the scale problem, and define scale as the ratio between distance on a paper map, and the equivalent distance on the ground. Traditionally this measure, the representative fraction, has defined the level of detail of a map. Unfortunately there is no easy translation between it and what a scientist recognizes as spatial resolution, because a small object can always be shown on a map of any scale using an appropriate symbol. But useful rules of thumb exist, and it is often assumed that the spatial resolution of a data set obtained from a map at a given scale can be estimated by computing the ground distance corresponding to 0.5mm on the map. Thus a map at scale 1:24,000 will tend not to show features smaller than 12m across, though there are clearly exceptions.

In addition to scale, builders of geographic databases must deal with the distinction between two different conceptualizations of geographic variation. Many scientific laws, including those of fluid motion, are written in terms of variables that change continuously in space, forming what a mathematician would call a field, a function of the two spatial dimensions. But maps are more likely conceived as showing collections of discrete entities, embedded in an otherwise empty space. The distinction between fields and discrete features is apparent in weather forecasting: atmospheric models are written in field variables such as pressure, and predict fields of precipitation or temperature; but weather is often understood in terms of the behavior of discrete highs, lows, or fronts. Both field and discrete entity conceptualizations can be represented in either raster or vector form, and yet the meaning and legitimacy of operations carried out on them can be entirely different. An area of homogeneous vegetation may be treated as a discrete patch in a landscape model, but as a continuous field when variation within the patch becomes important. A model of ant behavior may deal at one scale with individual ants as discrete features, then at another scale with the population as a continuous density, related perhaps to the continuous variation of some resource. Unfortunately, then, a single digital representation can have very different meanings; and a single phenomenon can have many different representations. This *n:m* mapping between reality and its digital representation is a source of endless and profound challenges for GIS.

3. The geographic information technologies

GIS is only one of a number of new technologies for handling geographic information in digital form. Another is remote sensing, which provides an increasingly important source of data, with the powerful advantage that it is global in scope. The Global Positioning System (GPS) is a constellation of satellites designed to allow position on the Earth's surface to be determined to a known level of accuracy. Each satellite transmits signals that are precisely timed by on-board atomic clocks; a receiver on Earth is able to resolve position in three dimensions if at least four satellite signals are being received. A simple hand-held receiver, available for a few hundred dollars, is capable of determining position to an accuracy of tens of meters, and versions of the technology exist capable of determining relative position to centimeter accuracy, and to meters in vehicles moving at speed. A technically distinct Russian system can be used in conjunction with GPS to improve positioning.

One unexpected consequence of the widespread use of GIS, for ocean and air navigation and for positioning scientific observations, is that it exposes the inaccuracies in much of the world's published mapping, and the inconsistencies between the mathematical figures of the Earth that support mapping. Unfortunately for global change science, mapping remains an activity of strategic importance in many parts of the Earth, and there are very significant gaps in scientific access to good base mapping.

GIS makes increasing use of electronic communication. There are now many archives of geographic information of value to global change science that are accessible to anyone connected to the Internet. The EOS (Earth Observing System) Data and Information System (EOSDIS) is one prominent example. With no more than a standard World Wide Web browser, a user is able to access the archive, browse its contents, and in many cases download large and potentially valuable data sets. Such archives of geographic information are being sponsored by national and state governments, non-governmental organizations, universities, and research libraries. It is also increasingly possible to manipulate the data in an archive at its source, allowing full use of GIS functions without the necessity to download what is often a very large set of data.

4. Recent trends

GIS is a new and rapidly developing technology, positioned to take advantage of broader trends in computing. At the same time, its origins in the paper map have established a legacy that is on the one hand an advantage, because it allows the user of a GIS to understand its potential in terms of a familiar metaphor, but on the other hand limiting, because it fails to acknowledge the true potential of GIS. In recent years much work has gone into developing GIS in directions that go beyond the metaphor of a map inside a computer. Today, GIS users can expect functions that process data that have significant temporal elements (maps are inherently static); that deal effectively with uncertainty (maps present the world as simpler than it really is); and that handle the third dimension (maps are inherently two-dimensional). A development of particular significance to global change science is the ability to analyze data distributed on the curved surface of the Earth; early GIS took the distorting projections of maps for granted, and processed information as if it were planar. Such distinctions are moot over small areas, but become very important if GIS is used to estimate the mean of the global temperature field, for example.

Of particular significance for global change science is the role of GIS in facilitating integration of data. Integrated assessments require access to data relating to both social and physical themes, ranging from demographic and economic statistics to climate, soil class and land cover. Often the only way of integrating such data is within a common geographic framework implemented in a GIS. Inevitably the data of one discipline adopts that discipline's conventions, which may be very different from those of another discipline. Point records of climate must be merged with raster databases from remote sensing, and statistics for the irregularly shaped reporting zones commonly used by statistical agencies. Scales vary widely, as do map projections. The impact of GIS on global change science has been greatest in two areas: first, where data must be integrated across such displinary differences; and second, where the results and predictions of global change science must be integrated with other concerns in support of policy decisions. Thus GIS is as likely to be used in a policy agency as in a global change science laboratory.

The explicit representation of geographic distributions and spatial relationships in a GIS has led to a much broader recognition of the issues and problems involved in working with spatial data. Besides scale, and the difficulties associated with scaling up and scaling down, these issues include data quality and the assessment of the accuracy of maps of such variables as land cover or soil type; the complex ways in which data errors propagate in models of spatially distributed systems, such as global climate models; and the uncertainties inherent in data which must be generalized from spatially limited samples. Recently, the term 'geographic information science' has emerged as an umbrella for the fundamental issues raised by the use of GIS; the field has an active international research community and a rapidly growing literature.

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