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Geographic information systems as a tool in science and technology education

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Geographic information systems (GIS) are one of a number of related new technologies that are revolutionizing the role played by geographic information in society. They solve many of the traditional impediments to working with maps; give new power to location as a way of organizing and examining data and allow decisions affecting geographical locations to be made in a better informed, more systematic manner. The paper first defines GIS and gives a brief overview of its many applications. The next section looks at the more fundamental aspects of the significance of GIS, through its role in developing spatial thinking, analysis, and decision-making. Geographic information science is defined and introduced as the set of fundamental issues being raised through the development and application of GIS that has led to the growth of a significant research community. Introduction of GIS into the higher education curriculum has been relatively straightforward to date, but many other and more challenging issues arise in connection with possible roles of GIS in the K-12 classroom (compulsory education for ages 5 through 18). The paper ends with a series of speculations about the longer-term significance of GIS and related activities, both in education and in society at large.

Keywords: Geographic information systems; geographic information science; spatial analysis; technology education; geographic education.

Introduction: what is GIS?

A geographic information system (GIS) is an information system designed specifically to handle geographically referenced information, i.e., information that is tied to specific locations on the surface of the Earth. It must include capabilities for data input, storage, manipulation, analysis, and output, and its applications range from simple responses to queries ("Show me the location of Angola"; "What is the name of this place?"; "How many producing oil wells are located within 10 miles of this point?") to complex decision-making ("What is the quickest route from here to here?") and modelling ("What flow rates are predicted at Vicksburg, Mississippi, if this much rain falls in the state of Iowa?"). The input to a GIS is often obtained from maps, but may also include images from air photos or satellites, survey measurements, and field observations. Output may be in the form of text, tables, maps, complex visualizations, or even computer-generated voice instructions. Recent texts on GIS including Laurini and Thompson [1]; Star and Estes [2]; Burrough [3]; and Maguire, *et al.* [4] provide a comprehensive review of the field.

GIS first began to appear in the 1960s. Despite the very expensive and crude computers and peripherals available at the time, it was argued that computerization of geographic data would lead to cost savings in the drafting and editing of maps; to cost-effective analysis and inventory of land and environmental resources and to ways of overcoming the problems of merging different kinds of geographic data from different sources, with variable scales, projections, quality, and formats. All of these arguments ultimately proved true, but it was only in the early 1980s that the cost of dedicated, high-performance computers and data storage declined to the point where GIS became economically feasible. The typical GIS application of today runs on a networked high-end personal computer or workstation, and makes use of map digitizers, scanners, and plotters.

GIS is one of a number of exciting technological developments that have impacted the way geographic information is handled and used in contemporary society. Remote sensing, or the capturing of images from aircraft or space, has provided a reliable source of data on the Earth's surface, allowing us to monitor daily changes in the ozone layer, the El Niño phenomenon in the Eastern Pacific, deforestation in the tropics, and a host of other activities. GIS allows such remotely sensed data to be combined with other information from maps or field observations, and analysed to make useful forecasts or decisions. Recently, the task of locating oneself on the Earth's surface has become immensely easier with the advent of the Global Positioning System (GPS), a satellite-based system that allows anyone with a $500 receiver to determine latitude and longitude to an accuracy of about 40m (50% of positions will be within 40m of their correct locations; relative position can be determined to better than 1m if an appropriate base station is installed). Although essentially a military system, GPS has found applications in surveying, air traffic control, tracking shipments of hazardous materials, dispatching emergency vehicles, and even in agriculture, where it is being used to achieve more precise control over the application of fertilizers and pesticides. One of the unintended consequences of GPS has been a growing awareness of the poor quality of much of our existing knowledge of geographical position, much of it still based on astronomical observations made over 100 years ago.

Taken together, these geographic data technologies constitute a remarkable shift in the way geographic information is accessed and used in society. GIS is now an indispensable part of the operations of every resource management agency, where it is used to maintain inventories of timber resources, wildlife habitat, and recreation. It is widely used by local governments to maintain records of land ownership, zoning, and assessment. Utility companies use GIS to keep track of underground pipes, transformers, cables, and customer records. All told, the GIS industry in the US now accounts for perhaps $1 billion (USD) annually in new investment and worldwide is moving towards $2 billion (USD). While the total annual bill for spatial data handling in the US alone is estimated at nearly $10 billion (USD). A good impression of the magnitude of interest in GIS can be gained by looking at the pages of one of the industry's magazines – *GIS World* or *Geo Info Systems*.

All of these activities depend for their justification and effectiveness on one simple principle – that there are benefits to be gained from keeping track of information through its geographic location. The next section of the paper looks at this proposition in detail. The third section examines the impacts that GIS has had to date, with particular emphasis on education. The final section speculates on where these impacts may lead in the future.

Thinking spatially

Spatial analysis

Compared to text, a map or image is a very efficient way of storing and communicating information. While a printed page may carry perhaps 600 words or 4000 bytes of information, a map of the same physical dimensions and with a modest spatial resolution of 0.2mm might contain as much as a megabyte of useful data. The human eye is an enormously powerful processor of spatial information; while it might take a minute for the average person to read 600 words of text, the eye can find certain kinds of pattern in a megabyte of image in a fraction of a second. It can make quick visual associations between features and their names; find lineations in satellite images and recognize complex well-known shapes.

Perhaps the simplest reason for organizing data geographically is that location provides a convenient method of access to information. Although a modern society keeps track of its citizens using a host of different keys, including social security numbers, dates of birth, and driver's licence numbers, residential address remains the most frequently used after a person's name. Although most of us spend less than half of our waking hours there, home address determines our voting district, which school we attend, and what expectations market researchers have of our patterns of expenditure.

At a somewhat more sophisticated level, location provides a way of linking otherwise unrelated facts. When we see cancer cases clustered on a map, we immediately search our minds for other relevant information about the same place – an overhead power line, or an industrial smelter. A GIS does this by linking so-called layers of information together through common geography, allowing the user to superimpose them, or to look for possible correlations. A geographical perspective on information can be very effective at suggesting causes, or relationships that need to be explored further, or may simply provide a way of linking otherwise unrelated activities. In a local government that has traditionally organized its information along departmental lines, a GIS can be the key to making two departments see how their activities are related and impact each other.

The geographic patterns present in data are often in themselves useful suggestions of processes at work. The theory of continental drift, or plate tectonics, owes much of its initial impetus to the simple observation that the coastlines of Africa and South America fit together remarkably well – an observation made as early as the 18th Century [5]. Geologists use remotely sensed images to search for lineations and other indicative patterns on the Earth's surface. But spatial pattern can also be misleading, when human spatial intuition is tricked by illusions. There is an important role for GIS in providing objective diagnostic tests of pattern that can distinguish true anomalies from statistical chance in areas like cancer cluster research.

The term spatial analysis refers to analysis of information in its spatial or geographical context [6, 7], or more specifically where the outcome of analysis depends on the locations of the events, cases, or objects being analysed. Most statistical analyses are not spatial, in the sense that the outcome of analysis would be invariant under relocation of the objects of analysis, and thus most statistical analyses make no use of the information that is embedded in the relative positions of events. In practice, most analysis carried out in research is not spatial, in part because of the cost and difficulty of handling the geographical component of information, at least prior to the advent of GIS, and in part because of the conceptual complexity of many areas of spatial analysis. GIS has led to a renewed interest in spatial analysis, and the insights that can be gained by looking at information spatially.

Spatial decision-making

Much of the interest in GIS stems from the increasing importance of space in decision-making and policy formulation. The world is getting more crowded, and our personal spaces correspondingly smaller. Legislation now forces us to consider the impact of one activity on another to a greater and greater extent. There are many reasons for the substantial impact of GIS on the process of spatial decision-making: its results are visual, and thus worth "a thousand words"; computers often speak louder than people in controversial situations; and the process used by a GIS to arrive at a conclusion is easily documented and thus defensible in court.

If these arguments justify the use of GIS in contentious decision-making, they also surely argue for its use in learning techniques of problem-solving and conflict resolution. GIS-related games like SimCity have become very popular in recent years as tools for teaching certain kinds of skills [8]. With a GIS and a simple geographic database, it is possible to examine a host of realistic decision-making scenarios, from solid waste disposal to location of schools and fire stations, zoning and land use decisions, and evaluation of development plans. GIS offers an interactive, visual decision-making environment with close to immediate response.

Geographic information science

Although the process of converting map information to digital form, submitting it to analysis, and using it to make decisions may seem straightforward, in reality GIS has raised a number of fundamental issues, many of them longstanding in fields such as cartography that have dealt with spatial information using more traditional methods of map-making.

A spatial database captures only a vastly simplified snapshot of the immensely complex and varied real world. The question of what to capture, and how to represent it in digital form, is thus fundamental to GIS and its usefulness. Should both banks of a river be included, or both sides of a street, or will it be sufficient to store only the feature's centreline? How much detail is needed in the digital representation of the topography of this area? Is it adequate to represent the houses as points, or will we need to include details of the shape of each house's footprint?

Related to these issues of representation is the question of accuracy. If a digital database contains only an approximation to the truth, then should the database include measures of accuracy, and should these be processed to obtain "plus or minus" bounds on the results of analysis? Is it appropriate to print 6 decimal places in a computation of area, when only 2 are justified by the inherent accuracy of the data? Should maps produced by the GIS be blurred to indicate known uncertainty, or is it adequate to print a disclaimer?

The term geographic information science has been proposed for the basic research issues that surround the use of GIS [9]. In addition to data representation and accuracy, GIS research devises new internal data structures and indexes for geographic data; develops user interfaces that better match how people naturally think and reason geographically; examines the impact of GIS on organizations, institutions, and society in general; and develops methods for assessing the costs and benefits of GIS. The research agenda of the National Center for Geographic Information and Analysis (NCGIA), a research centre funded by the National Science Foundation since 1988, is a useful guide to the range of research issues surrounding the use of GIS [10, 11]. Geographic information science is a multidisciplinary field, and includes questions from disciplines as disparate as computer science, geography, cognitive psychology, surveying, statistics, and mathematics.

GIS in education

Given the arguments presented in the previous sections, it is perhaps not surprising that GIS has been seen not only as a matter of training users in the application of software to specific problems, but also as a subject for much broader education in underlying principles and concepts. GIS provides a powerful tool for spatial decision-making and analysis, and its use in a wide range of human activities suggests that there is a need to introduce it at an early level in the educational system.

To date, the most significant progress has been made in the higher education sector. GIS courses and programmes are now available in some 500 institutions worldwide. Of these, 53% [12] are taught in departments of geography, but GIS courses are also offered in civil engineering, environmental studies, forestry, surveying, and many other disciplines.

One of the biggest problems in introducing GIS courses has been the lack of suitable textbooks and other guides to suitable course content. In 1990 the NCGIA published its Core Curriculum in GIS [13, 14], a series of instructor notes for 75 one-hour modules, together with handouts, slides, overheads, and discussion questions. The Core Curriculum has been distributed to over 1000 institutions in 75 countries and has been translated into 9 languages. A recent study reported that the Core Curriculum is used in 52% [12] of GIS courses in higher education.

In higher education, GIS might logically be taught in any of the disciplines that make significant use of GIS in their own research, including geography, anthropology, forestry, or ecology. Logic also suggests that it should be taught in any of the disciplines of geographic information science, including surveying, computer science, or information technology. Of all of these, geography is perhaps the discipline that has the greatest claim to GIS both as a discipline of application and also as a discipline uniquely concerned with geographic information. Goodchild *et al.* [15] review the case for geography as the "home" discipline of GIS in higher education.

In the K-12 curriculum the case seems much more complex. First, at least four arguments can be advanced to support the introduction of GIS at some point or points in the curriculum. GIS is part of everyday life, and students should have some knowledge of it to prepare them for the workplace of the 21st century. GIS is a good way to motivate students to rediscover the study of geography. GIS is a vital part of environmental science and conservation. And finally, as argued earlier in this paper, GIS provides an attractive environment in which to learn problem-solving skills.

In 1992, NCGIA launched its Secondary Education Project (SEP), an effort to develop GIS in the K-12 curriculum in collaboration with other groups working towards similar objectives. The SEP began with an attempt to identify existing GIS activities for the US high schools. At that point, in early 1992, very few GIS activities were found. This initial investigation did show, however, that countries such as the UK and Canada had made more bold strides in bringing geographic information analysis and GIS into the classroom. This difference was due, in large part, to the better established nature of geography as a discipline in their schools.

In the UK, the *Education Reform Act* 1988 created a national curriculum. The information technology and geography portion of the national curriculum explicitly mentions GIS in Attainment Level 10. In many other areas of the geography curriculum the objectives could clearly be supported by a GIS approach [16]. With this mandate, teachers in the UK are beginning to utilize GIS in their instruction. Rob Wheatley at Langdon Park School in London's Docklands, for example, has instituted a three-part course for his students which includes GIS, remote sensing, and computerized weather tracking. To support these teachers in their efforts to implement the curriculum, a GIS package, AEGIS, was developed for use in the schools. Lesson plans accompany example data sets provided with the AEGIS software [17].

In Canada, especially in the province of Ontario, there have been links between universities with GIS programmes and local school boards. Dr Doug Banting of Ryerson Polytechnic has conducted a number of special Saturday sessions for teachers. Dr Roland Tinline of Queen's University has developed a programme with the Ontario Ministry of Education, local school boards, and software companies that first brought both teachers and students into the university GIS labs and is now helping teachers use GIS in their classrooms. The programme begins by using the commonly available Computer Aided Drafting (CAD) software to demonstrate some basic GIS principles, then progresses through a few GIS software packages that increase in difficulty and emphasize different data models and spatial analysis techniques. The attention to GIS as a tool for pre-collegiate educators has been increasing significantly in the past two years. A professional organization for teachers, the Ontario Association for Geographic and Environmental Education, included GIS as significant component of their 1993 annual meeting.

In Spain, since 1990 over 500 high school students have attended a special summer programme at the University of Girona which utilizes GIS to study data from the Natural Park of Gavarres. In various other countries from Australia to Austria, there are efforts to introduce GIS concepts and software into the schools.

In the past two years in the US, there has also been significant growth in the number of teachers and students that are beginning to learn about and use GIS. Much of this increased awareness and use is a natural outgrowth of a renewed interest in geography. Much of this interest has been generated by the activities of the Geographic Alliance Network – sponsored by the National Geographic Society. These alliances are state-based consortiums of teachers, academic and professional geographers, and other concerned individuals from business, government, and the community-at-large, working to improve geographic instruction in the schools. The alliances have begun to include modern geographic technologies, including GIS, in their summer institutes, professional meetings, and collaborative curriculum development projects. A key collaborator with the Alliances has been the Environmental Systems Research Institute (ESRI), one of the GIS industry leaders. ESRI has distributed their ARCVIEW GIS software to hundreds of schools at low or no cost.

The NCGIA's SEP has also played an important role in these developments. It has served as a link between the different parties bringing GIS to the schools, has held summer workshops for teachers, and has produced materials designed to help introduce GIS to teachers and students [18, 19].

This influx of software and information has heightened interest in GIS as a part of pre-collegiate education. This led to a national planning meeting in January 1994 funded by the National Science Foundation, bringing educators and GIS specialists together to develop strategic directions for GIS software and concepts in the schools and to give guidance to curriculum and software development activities.

Prospects for the future

There seems no doubt that geographic information, and the tools to collect, access, and handle it, will play an increasingly important role as society moves into the new century. We live in a society that values information more and more as a key commodity, to be bought and sold, shared with others, and used to make well-informed and widely discussed decisions. The electronic highways of tomorrow will provide the essential means to supply and access geographic data. In a few years, for example, it will be possible for someone planning a visit to a distant city to use the household television to download a comprehensive and up-to-date database on the locations of all hotels, restaurants, and attractions into his or her laptop and to display and manipulate the information using advanced GIS software. Libraries and high schools will have access to the Internet, and to vast stores of geographical data that can be searched and downloaded in seconds. The impediments to access and manipulation that have traditionally trapped geographic information in specialized map libraries will no longer exist.

GIS software will continue to develop, and to make geographical data easier to use for everyday purposes. An industry now driven by software sales will increasingly see data as the source of revenue, and software as merely the essential means of access.

In recent years, geographical data and GIS have received increasing attention at the national level. The 1993 report of the Gore Commission, *Reinventing Government*, includes a commitment to the development of the National Spatial Data Infrastructure [20], which is conceived as "the means to assemble geographic information that describes the arrangement and attributes of features and phenomena on the Earth". Ready access to appropriate geographic information is a cornerstone of NASA's Mission to Planet Earth, the commitment to launch a new series of Earth observing satellites. The Office of Management and Budget's Circular A-16 mandates the Federal Geographic Data Committee, currently chaired by the Secretary of the Interior, in a continuing commitment to coordinate spatial data activities across agencies of the US government. Finally, a number of initiatives have been taken in recent years to improve the state of geographic education in the nation's schools.

But the future of GIS and geographic information is probably greater than any of these programmatic initiatives would suggest. As argued earlier in this paper, the spatial perspective on information amounts to much more than access to appropriate and up-to-date information, because it reveals dimensions of data and insights that are not available by any other means. Spatial analysis will be an essential component of any comprehensive effort to monitor the state of the nation's health; to plan for emergencies and respond to natural hazards; to map and manage the nation's biological resources and to maintain and improve the nation's environment. Spatial analysis and spatial thinking, implemented and made feasible through the medium of GIS, amount to nothing less than a novel and exciting way of looking at information.

It seems likely that education at all levels will put more emphasis on developing these spatial skills in students. At the University level, GIS software will play an increasing role in scientific analysis and learning. As GIS continues to expand its role in society as a tool for uses ranging from government policy formulation and implementation to everyday uses such as serving as a locational aid for travellers, the study of the underlying principles of geographic information science that apply to these uses will also become a greater responsibility of university-level education.

At the K-12 level, the future role for GIS is still being determined, but it is apparent that many of the trends in education call for new strategies that may find a natural ally in GIS. GIS represents great promise as a means of invigorating instruction in geography, environmental education, science, and technology. For example, the visual presentation of data in a spatial structure may hold the interest of students better than traditional presentations of scientific data. The ability to rapidly manipulate and analyse data will enhance problem-solving skills. In some cases, group projects will benefit from the familiarity of using data on local problems. Already students and teachers in concert with natural resource management agencies are using GIS to monitor their local environments. Many of these GIS-based problem-solving activities will be necessarily interdisciplinary.

The aspect of spatial learning inherent in GIS activities may turn out to be the most significant. Although spatial skills are fundamental in our early childhood ordering of the world, emphasis on their development is quickly supplanted by language acquisition and the quantification of our world through counting and mathematics. A renewed emphasis on developing spatial skills, in concert with literacy and numeracy, as students move through the schools is very likely to draw on GIS as an important aid. Despite this speculation, the actual cognitive implications of the spatial perspective provided by a GIS view of the world are just beginning to be studied [21].

Students who do not opt to enter the four-year universities and colleges may continue their GIS-based education at a two-year community college or technical school. One of the key mandates for these institutions in the future will be to train and retrain workers for the modern high-technology, information-based economy. The training of GIS technicians will be likely to be emphasized in addition to instruction in basic geographic information science concepts for both the technicians and those students transferring to universities.

In order to maintain relevance to society, future classrooms, at all levels, will make even greater use of computers and other multimedia technology. Whether or not multimedia and student-directed learning activities take the place of the traditional didactic form of education, an increased role for GIS software and concepts is likely. GIS will be the cornerstone of the geographic technologies that will be employed both to provide a link to a student's future education, employment and daily living uses of geographic information, and to promote a spatial analytical perspective in investigations of traditional curriculum content.

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