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Introduction

A geographic information system (GIS) can be defined as a computer application capable of performing virtually any conceivable operation on geographic information, from acquisition and compilation through visualization, query, and analysis to modeling, sharing, and archiving (Longley *et al.*, 1999, 2010). In turn, geographic information is defined as information linking locations on or near the Earth's surface to the properties, characteristics, and phenomena found at those locations. Today GIS find applications in any area of science dealing with phenomena distributed over the Earth, from research on global climate change to the study of patterns of disease and crime or the distribution of plants and animals. It is used in a wide range of human activities from simple wayfinding using GPS (the Global Positioning System; Kennedy, 2009) to the management of utilities and natural resources, and some of its basic ideas, including the use of data derived from satellites, are now familiar to the general public.

This is a vast arena, and current estimates are that the associated commercial activity now amounts to $20 billion per year, in sales of software and data and associated consulting. While the term GIS will be used in this chapter in the broad sense implied by the definition above, several other terms are also in active use. The adjective *geospatial* is

a comparatively recent coinage and similarly broad, distinguishing the space of the Earth's surface and near-surface from other spaces, such as that of the cosmos or the human brain. The field as a whole is sometimes termed *geoinformatics* or *geomatics*; and its sytematic study, together with the fundamental issues it raises, are often termed *geographic information science*.

Numerous questions have arisen as the field has evolved from very simple and unconnected beginnings in the 1960s. If the map and globe are traditional, analog forms of geographic information, clearly satisfying the definition above, then how is it possible to store their contents in a digital machine that has only two characters in its alphabet, 0 and 1? How can such information be processed to obtain useful results? Is it possible to build a single system to handle all applications, or would separate application-specific systems be more effective? Is there a vision of GIS that extends beyond the metaphor of the static map to a more universal conceptualization of geographic information that includes the third spatial dimension and time? Where does GIS belong in the traditional academic structure? Answers to all of these questions have emerged in the past 40 years, and all have been the result of visionary leadership by a remarkable set of individuals.

The chapter is structured in historical sequence, beginning with the very early imaginings of the 1960s, moving through a period of consensus-building to the emergence of the first comprehensive and reliable GIS software of the late 1970s, the spread of GIS across the scientific community beginning in the early 1980s, the funding of major research centers in the late 1980s and early 1990s, the impacts of the Internet and Web, and very recent developments. Behind all of this is a sense that despite four decades of progress, the field is still in an early phase of its growth, and that digital

geographic information and associated tools will have an even greater impact on science, government, and society at large in the years to come. Moreover while there are enormous benefits to be gained from GIS, there are impacts in the areas of surveillance and invasion of privacy that demand careful attention.

Early Beginnings

The roots of GIS lie in the 1960s, in at least five distinct and independent threads, each of which attempted to address a distinct problem associated with maps for which computers appeared to offer a possible solution (Foresman, 1998). In Ottawa, the Government of Canada was conducting the Canada Land Inventory, a massive program in collaboration with the provincial governments to assay the huge Canadian land resource, and to recommend policy options that would lead to its more effective exploitation. Roger Tomlinson, trained as a geographer and with a background of employment in the aerial surveying industry, recognized that the program would require estimates of land area of various types from tens of thousands of individual map sheets.

Measurement from maps is notoriously time-consuming and unreliable when done by hand (Maling, 1989). Manual measurement of area uses one of two techniques: overlaying a sheet printed with dots and counting the dots falling into the area of interest, or using a mechanical device known as a *planimeter*. Moreover the goals of the program would require the *overlay* of maps of the same area representing different themes -- for example, soil capability for agriculture overlaid on current land use -- in order to produce useful responses to questions such as "How much land is currently in forest but capable of productive agriculture?" Tomlinson estimated that it would be necessary to employ

hundreds of clerical staff for years in order to produce the statistics that the program had promised, and persuaded the government to contract for a computing system to convert the maps to digital form, on the assumption that algorithms could be devised to obtain the necessary statistics at electronic speed. The system would focus on one and only one task, the production of area statistics -- other functions such as the display of data in map form were only added later as the concept of GIS evolved.

The main contract for the Canada Geographic Information System (CGIS) was won by IBM, which then set about the daunting task of building an automated map scanner, developing the software to detect boundaries in the scanned images, devising a way of representing map contents on magnetic tape, and inventing the necessary algorithms. None of this had been done before, and many of the major breakthroughs that ultimately enabled GIS were made in this period, largely by IBM staff. A key concept was to focus not on individual patches of land with uniform characteristics, but on the common boundaries between adjacent pairs of such patches, in other words the *edges* of the boundary network, since this ensured that internal boundaries were stored only once, roughly halving storage volume and computing time. The algorithm for computing patch or *face* area from a single pass through these edge records remains a key achievement of the field. Guy Morton devised a system for ordering the map sheets on magnetic tape such that maps of areas that were adjacent on the ground were maximally likely to be adjacent on tape, and in doing so rediscovered the Hilbert curve.

A second thread originated in the Bureau of the Census, and in the problems of consistently and correctly aggregating census returns to a suite of reporting zones, from blocks to census tracts, counties, and states. To assign a household to its correct county it

is necessary to convert the address of the household to geographic coordinates, and then to determine the containing county based on a representation of the county's boundary, in the form of a polygon defined by an ordered sequence of vertices. The Bureau developed a database of street segments and address ranges (the GBF/DIME or Geographic Base File/Dual Independent Map Encoding) for the 1970 census, together with tools for *address matching* and for *point in polygon* allocation. Topological properties, such as the necessity of bounding a two-dimensional block with one-dimensional street segments and zero-dimensional street intersections, gave a strong mathematical basis to the enterprise. Moreover the notion of street segments as the common boundary between pairs of adjacent blocks clearly had much in common with the edges that formed the basic element of CGIS.

During this same period mapping agencies around the world were grappling with the high cost of map-making. The traditional process of making a topographic map began with aerial photography and field surveys, used expensive machines to extract contours and transfer them to physical media, employed highly trained cartographers to compile and edit the content, and then reproduced the results using elaborate large-format printing systems. The process required massive economies of scale because of the high initial costs, so map production was typically centralized at the national level in agencies such as the US Geological Survey. As in word processing, the computer could offer very substantial savings, in fast editing, high-quality linework and annotation, and process control, but it would first be necessary to find ways of storing the complex content of a map in digital form.

At the same time an influential and controversial landscape architect at the University of Pennsylvania, Ian McHarg, was promoting the idea of putting his discipline on a more substantial scientific footing (McHarg, 1969). While design is in many ways an art, design applied to large-scale landscape planning could clearly benefit from the emerging understanding of the Earth's surface and its processes in disciplines such as hydrology, ecology, and geology. A link with hydrology, for example, would allow planners to evaluate the impacts of proposed developments on water resources and downstream pollution. McHarg advocated a design paradigm that first reduced each area of concern to a map, and then overlaid the maps to examine their composite effects. The parallels between this and CGIS, which had developed tools for the overlay of different map themes, were not lost on anyone familiar with both efforts.

Meanwhile at Harvard, Howard Fisher, recipient of a large Ford Foundation grant, had formed a Laboratory for Computer Graphics to develop mapping software (Chrisman, 2006). Like many subsequent efforts, Fisher's vision was to provide through software the kinds of skills needed to make simple, rapid maps of data, thus bypassing the need for professional cartographic expertise and the slow process of map production. The result was SYMAP, a package to create thematic and topographic maps using a mainframe computer and a line printer. The outputs were impossibly crude by today's standards, since the line printer was limited to numbers, a standard upper-case alphabet, and a few special characters, printed in black in a fixed array of six rows per inch and 10 columns per inch. Nevertheless by overprinting up to four characters at a time, hanging the map on the wall, and standing a long way back, it was possible to think that researchers had solved the problem of how to store and visualize geographic information

using computers. The package was adopted by many universities and agencies around the world, until it was overtaken by advances in pen plotters and on-screen graphic visualization in the early 1970s.

Despite the obvious parallels between these five threads, it nevertheless required vision to motivate their integration. Roger Tomlinson, by the early 1970s enrolled in a PhD program at the University of London and otherwise without regular employment, kept up a steady and highly personal effort to build a community around the concept of GIS, working through the International Geographical Union. He organized two international meetings, in 1970 and 1972, to bring together like-minded people from around the world. At Harvard the lab began the development of Odyssey, a multi-function GIS based on the ideas initiated by CGIS and the Bureau of the Census. Then in 1977 the lab organized a symposium on topological data structures, inviting a potent mix of academics, government employees, and visionaries for what for many became the final acknowledgment that all of the various threads could be united into a single vision.

Rasters and Vectors

In the 1970s GIS was dominated by two alternative ways of capturing the content of maps. The raster approach, used by CGIS for scanning maps, divides the space of the map into a rectangular array, and captures the content in each cell sequentially, often row by row from the top left. Coordinates defining the location of each cell on the Earth do not need to be stored explicitly, since they can be computed from knowledge of where the cell occurs in the sequence, and of how the array as a whole is positioned in geographic space. But rasters obtain this simplicity by insisting on a fixed spatial resolution and

ignoring all variation within cells. A vector approach, on the other hand, captures the contents of a map as a collection of points, lines, and areas. Points are given coordinates; areas are represented as polygons by recording ordered sequences of points; and lines are similarly represented as *polylines*. Since points are infinitely small, polylines are infinitely thin, and polygons have infinitely sharp boundaries, vector data sets give the impression of infinitely fine spatial resolution, and are in general less voluminous than their raster equivalents. Hence the aphorism "raster is vaster but vector is correcter". Unfortunately this tends to be largely illusory because though vector positions may be very precise, they are not necessarily very accurate, and because the volume of a raster can often be reduced by simple compression techniques.

For many years in the 1970s it appeared that raster GIS was winning. It benefited from the large quantities of data becoming available in raster form from remote sensing, beginning in 1972 with the Landsat program. It was much simpler to program, especially in the key function of overlay, since two maps of the same area could easily be combined cell by cell, but the equivalent vector operation was hard to program, error-prone, and computationally intense. The results of raster overlay could be readily visualized on a printer or on one of the new interactive visual screens employing the cathode-ray tube. Several raster-based GIS appeared in this period, one of the more interesting being a Canadian commercial product, SPANS, which used the same order as that developed by Guy Morton for CGIS, in the form of a *quad-tree*, to organize and compress its rasters.

This state of affairs changed dramatically in 1980, however. Jack Dangermond, a Californian trained as a landscape architect, who had spent several years at Harvard in the late 1960s and had founded a small consulting company, Environmental Systems

Research Institute (ESRI) in Redlands in 1969, joined forces with Scott Morehouse, one

of the designers of Odyssey at the Harvard lab, to develop a vector GIS based on the

relational database management system INFO. The advantages of using INFO were novel

and compelling. First, the programmer would no longer have to deal directly with the

complexities of storage on tape or disk, but instead would work through a simple and

general interface. Second, the topological relationships -- linking boundary edges to the

areas on both sides and to the intersections at their ends -- would fit naturally with the

pointers and tables of INFO. Attributes of nodes, edges, and faces would be stored in

INFO tables. Only one major problem had to be addressed: the number of vertices varied

from edge to edge, could reach several thousand, and would clearly not fit into the fixed

dimensions of an INFO table. Morehouse's solution was ARC, a separate sub-system in

which vertex coordinates were stored, in a format that remains proprietary to this day.

ARC/INFO was launched in 1980. Its routine for overlay was robust and reliable,

and the ease of use and integrity of the entire system immediately shifted the balance in

the raster/vector debate. Later additions of raster functionality to ARC/INFO, and vector

functionality to the leading raster GISs, finally laid the issue to rest in the 1980s.

The Dominance of ESRI

It is easy to underestimate the influence of ESRI and its leader on the subsequent

development of GIS. The company, formed by Jack and Laura Dangermond to advance

environmental design, has grown over four decades into the dominant force in the GIS

industry with a worldwide employment of roughly 5,000. While design remains its

compelling vision, the company supplies software for a vast array of applications,

supporting local government, utilities, the military and intelligence communities, resource management, agriculture, and transportation. Jack Dangermond remains a compelling visionary, and the annual International User Conference in San Diego is for many thousands an opportunity to reaffirm their faith in GIS as a viable approach to many human and environmental problems.

The basis for ESRI's growing dominance of the field is not always obvious. A company with a large user base finds it difficult to respond rapidly to new ideas and new technologies with new versions, because its users will often resist the expensive step of retooling. Over time, therefore, the complexity of a package like ARC/INFO continues to grow, as new ideas are added to old ones instead of replacing them. Although the basic design, a hybrid of a standard relational database application (INFO) and a proprietary storage of coordinates (ARC), was superceded in the late 1990s by a unified approach enabled by newer and more powerful technology, in which coordinates are stored along with all other information in the cells of relational tables, the earlier design still persists in order to support customers who are still wedded to it -- and because of its explicit advantages in some applications. Companies that have arrived in the marketplace with newer and better ideas have failed to make significant dents in ESRI's market share -- only to see ESRI catch up some years later.

For an academic, a key element in ESRI's early success was the conceptualization of vector GIS as an implementation of the relational model -- the *geo*relational model. Donations of the first version of ARC/INFO to several university departments of geography led to its widespread adoption, and created a clear link to employment opportunities as GIS continued to find new applications. The software was not easy to

learn and use, especially in its early versions, but this reputation proved compatible with a world that regarded GIS as specialized, professional expertise. More recently ESRI appears to have recognized academia as a significant market sector, rather than a loss-leader, and has ramped up its license fees accordingly. But the continued willingness of Jack Dangermond to make campus visits to capture the imagination of skeptical administrators is worth a lot to struggling GIS academics, as is his willingness to participate in advisory roles that are normally open only to academics, and to appear able to separate his persona as the owner of the largest GIS company from that of a GIS missionary. Jack Dangermond is a constant and strong supporter of the discipline of geography, which in turn welcomes the greater attention it gets from a world that is increasingly familiar with GIS.

Indeed, it is possible to imagine a world in which GIS, defined narrowly as a specific type of software, might never have come into being had it not been for the actions of a few leaders. Computer-assisted design (CAD) software is vector-based and ideally suited to many of the more practical applications of GIS, and raster-based image-processing software, developed by and for the remote sensing community, is fully adequate for many of the applications in environmental research that are currently served by GIS. The existence of GIS owes much to the passion of a few visionaries, including Roger Tomlinson and Jack Dangermond, to the existence of a discipline of geography hungry for new ideas to stem what many have seen as a decades-long decline, to the importance of its applications, and to the basic emotional appeal of maps, exploration, and human knowledge of the planet's infinite complexity.

The Internet

GIS began as a mainframe application, serving local users over very short and expensive connections. The 1980s saw the introduction of the minicomputer and local-area networks, but while this expanded the scope of a GIS application to a department or agency, each application essentially saw itself as stand-alone. The advent and popularization of the Internet in the early 1990s changed this perception fundamentally, however. Geographic data could be distributed over electronic connections from digital libraries, and data could be shared among widely dispersed users. The Alexandria Digital Library, developed beginning in 1994, was one of the first *geo*libraries, a digital store whose contents could be searched based not on author, subject, and title but on geographic location. But despite ESRI's dominance, the diversity of formats, terms, and approaches used across the full suite of GIS applications created an immediate problem in any effort to support search, discovery, and retrieval of data. Efforts were made to develop special software for converting among the many hundreds of formats in use, the US Federal Government devised the Spatial Data Transfer Standard as a universal norm, and the Open GIS (later Geospatial) Consortium was founded with the explicit goal of achieving interoperability among the many flavors of GIS software and data.

The early perception of GIS, as represented for example by CGIS, was of an intelligent assistant, performing tasks that were considered too tedious, too unreliable, too labor-intensive, or too time-consuming to be performed by hand. This conceptualization matched that of computing in general in the 1960s and 1970s, and emphasized the one-to-one relationship between system and user. But the Internet changed that perception utterly, creating a network in which information could flow freely between computers

without respect for geographic location or distance. GIS was compared to conventional media, as a channel for sharing what is known about the planet's geography. Its metrics of success were no longer the extent of its functionality, or the speed of its processing, but the degree to which it was interoperable, and the degree to which its definitions and terms had shared meaning, allowing distributed users to understand each others' content.

This changed perception matched another very significant trend in the world of geographic information. By the early 1990s it was clear in many countries that the earlier centralized, government-dominated mechanisms for the production of geographic information were no longer sustainable. Agencies such as the US Geological Survey found it impossible to service rapidly increasing demand, especially for digital products; to revise maps in the face of rapidly accelerating change; and to cope with downward pressure on budgets. In the UK and other countries efforts were made to shift the burden of funding map production to the user, but in the US constitutional constraints on the Federal Government make this impossible. Instead, a visionary Mapping Science Committee of the National Research Council pointed to a future world in which geographic information production would no longer be centralized, and dissemination would no longer be radial. The National Spatial Data Infrastructure was envisioned as a patchwork, held together by national standards, but with distributed production and networked dissemination. The vision was enshrined in an Executive Order in 1994, and had an overwhelming influence on the production of geographic information worldwide.

An even more profound change occurred in 2005. One of the reasons for GIS's reputation as difficult to learn and use stemmed from its insistence on flattening or *projecting* the Earth. Unfortunately the technology of map projection is exceedingly

complex, because of the requirements of different applications and the irregular shape of the Earth, which is only crudely approximated by a mathematical surface. How much simpler it would be if the Earth could be visualized as a three-dimensional solid, like a globe -- if the digital map could evolve into the digital globe. In his 1992 book *Earth in the Balance* Al Gore had envisioned a Digital Earth, a virtual digital environment that would support a simplified, unified view of the planet. The vision was expanded in a speech he made as Vice President in 1998, and set in motion a series of technical developments that by 2001 had resulted in Earth Viewer, developed by Keyhole Inc with funding in part from the CIA. By 2005 the graphics accelerators needed by advanced video games had become standard in personal computers, allowing the user to manipulate a virtual solid in real time. Clever innovations allowed Earth Viewer to be supplied with sufficient data through the Internet to support real-time panning and zooming. In 2005 Google rebranded Earth Viewer as Google Earth and it became an overnight sensation, vastly increasing the average person's exposure to digital geographic data and technologies.

Although Tim Berners-Lee had originally conceived of the World-Wide Web as a means for physicists to communicate research-related information, its popularization beginning in 1993 cast it more as a top-down distribution mechanism, allowing companies, agencies, and organizations to create Web sites that presented general information to the public. This conceptualization began to change with the advent of sites such as E-Bay, with their emphasis on information contributed by users. The concept of *user-generated content* grew in popularity in the new century, driven by wikis, blogs, and

other ways of bottom-up content creation. The term *Web 2.0* is often used as an umbrella for this new vision of the Web, and it will be used in that sense here.

The influence of Web 2.0 on the world of GIS has been profound (Scharl and Tochterman, 2007). The widespread availability of GPS, and its integration with other devices such as third-generation phones, has made it trivially easy to determine location on the Earth's surface to better than 10m, and to track movements by periodic sampling of locations. Services have emerged on the Web that convert street addresses, place-names, and points of interest to coordinates, and it is also easy to obtain coordinates from on-line maps. The result has been a rapid rise in *georeferencing*, *georegistration*, or *geotagging*, the practice of associating accurate locations with events, observations, photographs, and many other types of information. Sites such as Flickr allow users to upload georeferenced photographs, and provide services to map photographs and to conduct simple analyses through the Flickr Application Programming Interface. In effect, the availability of hundreds of millions of georeferenced photographs provides a new, rich source of geographic information.

Flickr is only one example of a phenomenon that has been termed *volunteered geographic information* (VGI). The term *neogeography* is sometimes used to convey a sense of a new geography in which the traditional distinction between expert map-maker and amateur map user has broken down (Turner, 2006). One of the most spectacularly successful VGI efforts was started by Steve Coast when he was a graduate student at University College, London. Unlike the US, where comprehensive databases of street centerlines have been freely available since the late 1970s, and have spawned a major industry of GPS-based personal navigation, such databases in the rest of the world have

been available only at substantial cost. Coast conceived of a detailed world map that would be created entirely by volunteers, and made available on the Web for use by anyone at no cost. He enlisted the help, initially of friends, to survey streets, trails, and any other features of interest using GPS, to record street names and other useful attributes, and to upload the resulting data so that it could be assembled and rendered as a composite map. The movement spread rapidly, and within a few years Open Street Map (OSM) had become an accurate, viable, and popular alternative to traditional sources. Where authoritative data was available with no cost or restrictions, such as in the US, it was merged with OSM and augmented with volunteered contributions.

The OSM story reached a new zenith early in 2010 when volunteers all over the world, networked into what were termed *crisis camps*, conducted a systematic effort to enrich the OSM coverage of Haiti. Sources of fine-resolution imagery were identified on the Web, and augmented with donations from corporations. Attributes not visible from above, such as street names, were obtained by tapping the memories of expatriate Haitians. Within days of the January earthquake the OSM coverage had become the best available for the relief effort, and was adopted by the United Nations as the official base map.

VGI raises significant issues. Who volunteers, and what kinds of data are they willing to volunteer? If a citizen is enabled to make a map of anything, what will he or she choose to map? What is the role of social networks in enabling VGI production? What areas of the world are people interested in contributing information about -- their own back yard, or remote areas they may have visited as tourists? And what can be done

to ensure the quality of the contributed information? In the past few years a significant theme has emerged that has captured the imagination of many researchers.

GIS in Academia

One of the most attractive aspects of GIS is its ability to span the academic, commercial, and government worlds. This has its advantages, especially the ability of a major market to sustain the development of an advanced technology, with many benefits for academic teaching and research. It has its disadvantages also, when the norms of the commercial world conflict with those of the comparatively rigorous world of science. Documentation of commercial software, for example, may not meet the scientific standard of sufficient detail to permit replication, and issues of intellectual property and proprietary ownership may conflict with the comparatively open culture of academia. Nevertheless GIS has had a major impact on the academic world, in three senses: as a tool to support research in all of the disciplines that deal with phenomena distributed over the Earth, from ecology to criminology; as a subject for teaching in geography, computer science, and many other fields; and as a subject for research aimed both at understanding the nature of geographic information, and at improving future generations of the technology.

Academics were involved in some of the earliest developments in GIS. Mention has already been made of the Harvard lab and its software development; of the conceptual framework provided by Ian McHarg's vision of a scientifically grounded landscape architecture; and of the conference on topological data structures of 1977 that for the first time brought together many academics interested in GIS. The author's own interest in GIS dates from a two-week workshop on SYMAP at the Harvard lab in 1967,

and from a research project funded in 1972 by Environment Canada to develop a set of raster GIS functionality on the CGIS database. His first course in GIS was offered at the University of Western Ontario beginning in 1975, and by 1976 he was collaborating with Roger Tomlinson on a series of consulting engagements with government agencies in Canada and the US. Mention has also been made of ESRI's role in donating software to universities beginning in the early 1980s, which had the effect of guaranteeing a flow of graduates experienced in manipulating ARC/INFO.

A significant event occurred in 1985 at the annual meeting of the Canadian Association of Geographers at Trois-Rivières, Québec. A special session convened by the author was devoted to teaching GIS, with presentations by Tom Poiker of Simon Fraser University, Robert Maher from the Nova Scotia Land Survey Institute, and others. Several of the speakers distinguished between GIS *training*, focusing on navigating the user interface of a complex technology, and GIS *education* and an emphasis on the fundamental principles underlying GIS. The second topic resonated especially well with Ronald Abler, one of the attendees and recently appointed as program officer for the Geography and Regional Science program at the US National Science Foundation. During the next two years Abler and others worked energetically to develop a new NSF initiative in GIS research, and in 1987 a solicitation appeared for a national center that would conduct research, work to enhance GIS education, and reach out to many different communities (Abler, 1987). The kinds of research that the center might undertake were summarized in five bullets:

- spatial analysis and spatial statistics;
- spatial relationships and database structures;

- artifical intelligence and expert systems;

- visualization; and

- social, economic, and institutional issues.

An intense period of jostling among contending universities followed, with several significant migrations of academic leaders: among them, Duane Marble, who had made significant contributions to GIS and spatial analysis beginning in the 1960s was persuaded to move from the State University of New York at Buffalo to Ohio State University, and the author was persuaded to move from the University of Western Ontario to the University of California, Santa Barbara. Eight proposals were submitted, and after a period of review the winners were announced in August 1988 to be a consortium led by the University of California, Santa Barbara (UCSB), joined by the University of Maine and SUNY at Buffalo. Funding began in December 1988, and was limited to eight years (NCGIA, 1989).

A key leader in the establishment of NCGIA was David Simonett, a specialist in remote sensing, who became the initial Principal Investigator. Attracted to Santa Barbara in the mid 1970s, he had set about establishing a novel kind of geography department in which science and technical tools were dominant, and in which interdisciplinary collaboration was endemic. He saw GIS as potentially providing the same scientific underpinning to human geography that remote sensing had provided for physical geography, and threw all of his energy into the UCSB bid. Simonett was convinced that GIS suffered potentially from the same weakness as remote sensing -- a lack of theory and a willingness on the part of others to see it as a mere tool, and no more worthy than word processing of a place in the academy. Thus NCGIA was conceived from the start as

building the case for GIS as a science, with an emphasis on lasting principles rather than on the constantly shifting state of a technology.

Simonett's untimely death in 1990 was a severe blow to NCGIA. The author took over as director, and in two keynote addresses and eventually a 1992 journal article argued the case for a *geographic information science* (GIScience), an area of intellectual activity that addressed the fundamental issues raised by GIS, the impediments to its evolution, and the scientific knowledge that the technology implemented (Goodchild, 1992; Wright, Goodchild, and Proctor, 1997; Duckham, Goodchild, and Worboys, 2003). NCGIA developed links with areas of science that offered related interests: spatial statistics, a basis for understanding the role of uncertainty in GIS analysis; spatial cognition, a branch of cognitive science that focuses on how humans learn about spaces, and that could inform the design of GIS user interfaces; computational geometry, with its interest in algorithms and data structures for dealing with spatial data; and the developing interest in computer science in spatial databases.

The concept of GIScience resonated well with the expanding academic interest in GIS. Several journals were renamed, and a University Consortium for Geographic Information Science was established in 1996 as a forum for national activities (McMaster and Usery, 2004). A biennial international conference series in GIScience was started in 2000. Parallel efforts to NCGIA emerged in several other countries; indeed, the comparable UK effort, the Regional Research Laboratories, predated NCGIA. The NCGIA award was followed by a string of related NSF awards to UCSB, including the Alexandria Digital Library (1993), a pioneering effort to build a geolibrary as an online extension of UCSB's Map and Imagery Laboratory; the National Center for Ecological

Analysis and Synthesis (1994), a center devoted to integrating ecological knowledge in an environment strongly supported by information technology; Project Varenius (1996), conceived as an NCGIA follow-on that would provide a concerted focus on GIScience (Goodchild *et al.*, 1999); the Center for Spatially Integrated Social Science (1999), devoted to enhancing GIS applications in the social sciences; and Project Battuta (2000), focusing on the tools and applications of a field version of GIS.

Several significant shifts have occurred in the GIScience paradigm in the past two decades, each of them involving leadership from visionary academics. Until the early 1990s the approach taken to uncertainty had emphasized the view that GIS databases were the results of scientific measurement of the geographic world (Maling, 1989). This led to concepts of error as expressed in differences between observations and truth. But many types of geographic information are inherently vague, defying any effort to define a truth or to achieve replicability across observers. Peter Fisher and others introduced concepts of fuzzy sets and rough sets (Fisher and Pathirana, 1990), and in doing so added another distinct approach to the understanding of uncertainty.

Another shift away from an exclusively scientific paradigm, with its rigorously defined terms, occurred as a result of an effort to improve the user interface by making it less imposing, and more consistent with patterns of human thought (Mark and Frank, 1991). The plain-language interface was one goal of this approach, together with a belief that different cultures might have different ways of thinking about the world and its contents. Strong ties were developed with linguistics and cognitive science in the early 1990s that continue to flourish today.

Like other social sciences, geography was strongly influenced in the 1980s by critical social theory, and its insistence that science itself was a social construction that sometimes revealed as much about its proponents and their agendas as about the natural world that was its focus of study. By the early 1990s the critical guns had been turned on GIS, and a strong critique developed that emphasized first the degree to which a simplistic set of GIS representations imposed themselves on the world, and defined what could and could not be captured and analyzed; second, the more sinister aspects of GIS as a technology of surveillance and war; and third, the degree to which GIS with its attempt at scientifically correct representation of the world conflicted with the many views of a post-modern society (Pickles, 1995). A series of meetings, and a degree of soul-searching, led to a much different GIScience in which ethics, social impacts, and social context are a constant concern.

Today, GIScience is a recognized field with all of the trappings of an academic discipline (Fisher, 2006). Other terms have similar meaning: geomatics and geoinformatics, for example. The rapid expansion of the field has vastly enlarged the academic community concerned with geographic information, and it seems increasingly unlikely that any single term, or any single organization or conference series, will be able to dominate the entire field. The Association for Computing Machinery recently approved the establishment of a Special Interest Group SIG/SPATIAL, a very significant move that recognizes the importance of spatial computing as a core concern in computer science (Samet, 1990a,b). The field of remote sensing also sees GIS as a natural ally, if not a part of its domain, and many advances in GIScience are reported through the conferences of the International Society for Photogrammetry and Remote Sensing.

One measure of academic leadership is elected membership in such organizations as the US National Academy of Sciences, or the UK's Royal Society, which signals acceptance by the broader academic community of the importance both of a field and of the work of a leading individual in that field. Brian Berry, former Director of the Harvard lab, was elected to the NAS in 1975, and Waldo Tobler in 1982; and by 2010 the list of members with interests in GIScience had grown to at least six. The fellowship of the Royal Society now includes three leaders of GIScience.

Conclusion

The brief nature of this review has meant that justice could be done to only a small fraction of the leaders who have had a significant impact on the field. More extensive treatments of the history of GIS have done a much better job, and have mapped the linkages between individuals that were so important in the development of ideas. It is notable that much of the leadership and vision came from outside academia, from individuals with the necessary passion who found themselves in the right place at the right time. If the Government of Canada had not devised the Canada Land Inventory, and if Roger Tomlinson, the leading candidate for the title "Father of GIS", had not been in a position to advise on its analysis; or if Jack Dangermond had not spent time at Harvard in the early days of the Harvard lab; or if countless other co-locations and conversations had not occurred, then the field would not have evolved to the form in which we see it today.

It is characteristic of the field that much of the leadership has come from outside the academic community. Many of the key inventions were made by individuals working in the software industry, or by government employees. However, the development of a

body of theory, and the emergence of a science of geographic information, are advances to which the academic community can lay clear claim. The commercial bottom line is influenced very little by research on uncertainty in GIS, for example, though in the long term it is clear that GIS applications cannot continue to ignore what is often a very substantial uncertainty in results, driven by imperfect data and uncertainty in models.

Like any area of human activity, GIS and GIScience must look to the future and to the next generation of leaders. Humans have never been good at predicting leadership, by identifying its potential in individuals. Who could have predicted that Jack Dangermond, a student of landscape architecture who grew up in Redlands, California, would one day own the leading GIS company and be ranked among the wealthiest Americans? Or that the system that Roger Tomlinson envisioned in the mid 1960s would become a major research field at the interface between geography, computer science, statistics, and cognitive science?

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Cross-references

See also 003 Cognitive Science, 033 Technoscience, 035 Urban and Regional Planning,

053 Open Source Software Development, 065 Digital Library Initiative, 066 Information

Technology Research, 069 Fuzzy Logic, 079 The New Media, 093 Internet

Biography

Michael F. Goodchild is Professor of Geography at the University of California, Santa

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