GIS: History

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> We shall not cease from exploration
> And the end of all our exploring
> Will be to arrive where we started
> And know the place for the first time.
> Little Gidding, T. S. Eliot (http://www.columbia.edu/itc/history/winter/w3206/edit/tseliotlittlegidding.html)

Before geographic information systems (GIS) were introduced to the world, and to the world of academic geography, place and the uniqueness of place was considered all-important. In the 1950s and early 1960s the uniqueness of place was challenged by the rise of quantitative and theoretical approaches to geography. In the 1960s the rise of geographic information systems gradually led to an ascendancy of a spatial and scientific approach to geography. By the late 1980s, GIS were providing jobs for students who were educated and trained to use and develop these new software tools. However, throughout the decades since GIS were developed there were those in the discipline who celebrated the uniqueness of place and the value of qualitative geography and a plethora of nonquantitative and aspatial approaches to geography. This entry will show how, during the last two decades, GIS have attempted to accommodate and assimilate these approaches and how those working in GIS have come to respect both the uniqueness and similarities of places.

Antecedents to geographic information systems

Historical accounts of the origins of GIS invariably pay tribute to the intellectual debt owed to those who sought to organize, visualize, and interpret spatial data. Commonly these discussions reach back into the distant past, frequently referencing the map overlays of troop movements created by the French cartographer, Berthier, during the Battle of Yorktown in the American War of Independence. Equally ubiquitous are references to the work of Dr John Snow, the British physician who, in 1854, mapped the incidence of cholera in London, thus providing strong evidence that the disease was water- and not air-borne (Waters 1998). Both Berthier and Snow sought to map their data so that it might be used to understand the underlying processes that produced the data and provide operational insights as to how it might be exploited.

Despite these promising beginnings it was not until almost a century later that planners and professional geographers once again began to utilize the mapping of combinations of spatial data in the overlay process that was to become one of the most quintessential of GIS operations. The origins of the overlaying of mapped data in planning are described by Steinetz, Parker, and Jordan (1976). Their research shows that in the United States the method of overlay analysis was implicit in the work of Warren Manning in his 1912 study of the town of Billerica, MA, work that was subsequently published in the journal *Landscape Architecture Quarterly* in 1913.

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Steinetz, Parker, and Jordan also recognized the implied use of overlay analysis in the results of a competition for the design of a new plan for the city of Düsseldorf in Germany that were published in 1912. Steinetz and his colleagues described other studies that used overlay procedures throughout the first half of the twentieth century, but it was not until the work of Jacqueline Tyrwhitt and Jack Whittle appeared in the *Town and Country Planning Textbook; An Indispensable Book for Town Planners, Architects, and Students* (cited and discussed by Steinetz, Parker, and Jordan 1976) that detailed and explicit accounts of the overlay process and ensuing spatial analysis were explained. The technique was quickly popularized by many others including, most famously, Ian McHarg (1969). Because of the popularity of McHarg's book, *Design with Nature* (now cited well over 3000 times in the academic literature), he is regarded as having had a prodigious influence on the development of GIS, but *Design with Nature* did not provide a description of a methodology for computerizing the overlay process, although such a methodology is indeed articulated in the article by Steinetz, Parker, and Jordan (1976).

It is important to note that before software and hardware systems were developed that were formally recognized as "geographic information systems" there were numerous developments that occurred within the classified military arena. Clarke and Cloud (2000), for example, have provided a detailed assessment of the importance to the development of the associated field of analytical cartography of the US CORONA program of reconnaissance satellites that was operated by the Central Intelligence Agency from 1959 to 1972 along with the associated SAGE program for processing the imagery.

The era of geographic information systems

In their account of the early history of GIS, published as part of the first major review of the field, Coppock and Rhind (1991) divided their retrospective into four periods: (i) the pioneer period from the mid-1950s to approximately 1975; (ii) the government-supported, experimental period beginning in the mid-1970s and ending in the early 1980s; (iii) the commercial period from the early 1980s to 1990; and (iv) the user dominance era starting in 1990. For all four periods Coppock and Rhind discuss the significance of conceptual developments, progress and improvements in software and hardware, and the contributions of academia, commercial enterprises, and governments. This discussion follows Copock and Rhind's schema. For an alternative view of the early days of GIS see Foresman (1998). Foresman's edited book is noteworthy for providing a more operational and raster-oriented coverage of the origins of GIS, and for including many chapters written by the "pioneers" of GIS. His chronology of the evolution of GIS includes a number of overlapping "ages": the pioneer age, mid-1950s to the early 1970s; the research and development age, the very early 1970s to the mid-1980s; the implementation and vendor age, the early 1980s to the the mid-1990s; the client applications age, the early 1990s to the early 2000s; the local and global network age, the late 1990s onwards into the 2000s. These developments are then correlated with developments in academic geography, computing, and environmental awareness.

The pioneer period: the mid-1950s to the mid-1970s

Conceptual developments during this period included the overlay or "layer-cake" model for the organization of geographical data discussed previously and the popularization of the geographical data matrix by Brian Berry. Originally, the data matrix was organized with the columns representing places and the rows representing their attributes. When Berry's model was incorporated into early GIS software this arrangement was transposed to make the geographical matrix more compatible with standard database technology. Waters (1998) discusses contributions from the field of operations research, where work on decision support systems by IBM researchers was being incorporated into planning-based software.

During the 1960s the first fully functional vector-based GIS, the Canada Geographic Information System (CGIS), was developed. The CGIS, initially a collaboration between Roger Tomlinson's company, Spartan Air Services of Ottawa, and the Canadian Government's Canada Land Inventory, produced a series of innovations, including hardware for laser scanning technology and software for vectorizing the resulting images (Waters 1998) and for storing raster layers efficiently, with such developments as Morton ordering. Because of Roger Tomlinson's seminal contribution to the origins and development of GIS he has often being credited with being the "father of GIS". In these early years, those working in the field of GIS were not simply taking advantage of developments in the field of computer science, as computer science did not offer all that was needed for the development of GIS. As the field matured, GIS would indeed take advantage of computer hardware developments and the move away from mainframe computing. External developments in database technology also proved beneficial to the development of GIS.

During this seminal period the Harvard Laboratory for Computer Graphics and Spatial Analysis, established in 1965 by Howard Fisher, laid the foundations for subsequent developments. Thus, the Harvard Laboratory made major algorithmic contributions and produced widely adopted computer mapping packages, such as SYMAP, CALFORM, SYMVU, GRID, POLYVRT, and ODYSSEY. The first three packages for producing line printer maps and 2-D and 3-D plots, respectively, were adopted throughout North American universities. William Warntz became the Director of the Harvard Laboratory in 1969 and made further conceptual contributions, including a recognition that the critical features of surfaces could be used to produce triangulated irregular network (TIN) models to provide more compact storage of surface features. Associated with the Harvard Laboratory at various times was Jack Dangermond, founder (in 1969) and co-owner of the world's leading GIS company, Esri, which now produces the industry-dominant ArcGIS software. For a complete history of the early days of the Harvard Laboratory see Chrisman (2006). In the United Kingdom, the experimental cartography unit (ECU) was founded in 1967 by David Bickmore, head of the cartography unit at the Clarendon Press. Like the Harvard Laboratory, the ECU stimulated and championed the possibilities of computer-based mapping, providing the incentive for the British Ordnance Survey to move into automated, computer-based mapping.

In 1970 the US Census Bureau produced the first geocoded census. The topological structure of street segments was coded by identifying the IDs of right and left blocks and "from" and "to" nodes. Also recorded, using X,Y coordinates, were the address ranges of street segments. These files were known as DIME (dual independent map encoding) files and were the forerunner of the US Census Bureau's more sophisticated TIGER (topologically integrated geographic encoding and referencing) files (Mark *et al.* 1997).

One of the primary ways in which new knowledge about GIS has been disseminated is through the organizations that have catered to academia, government, and industry. The Urban and Regional Information Systems Association (URISA) is one of the oldest such organizations. URISA held its first conference in 1963 and has continued to hold annual conferences up to the present. Over the decades the proceedings of the URISA annual conferences have been a major source of information concerning new developments in the evolution of GIS.

The government-funded experimental research period: the mid-1970s to the early 1980s

Conceptual and software developments during this period were taking place within academia, government agencies, and industry. For example, algorithms to solve location-allocation problems that had been developed in the mid-1960s were now available in stand-alone programs and were also being integrated into software systems, such as GADS (geodata analysis and software display system) developed by IBM's research division (Waters 1998). In Europe, government-sponsored research led to the development of the Swedish road data bank and other computerized spatial databases.

Developments in GIS reflected advances in the field of computer science. During this period, mainframe systems had given way to minicomputers based on time sharing and, eventually, to desktop microcomputers, enabling the gradual movement of GIS software to these new computing platforms. One of the most prominent and earliest of the government-supported, mainframe GIS of this period was the Minnesota land management information system (MLMIS). This was a raster-based (as opposed to the vector-based CGIS) resource inventory, where the pixel cells had a resolution of 40 acres. By the end of this period, such mainframe systems were gradually becoming obsolete, due to high maintenance costs, the problem of data currency, access issues, and nonuser-friendly command line interfaces. The introduction of powerful workstations in the early 1980s led to the gradual demise of large mainframe systems.

In 1974 the first Auto-Carto conference was held. These conferences, although not held annually, are still held on a regular basis and are now sponsored by the Cartography and Geographic Information Society. Similarly, in Europe, a series of fourteen EuroCarto meetings were held from 1981 to 1997 (every year except for 1982, 1988, and 1996). In 2015, these conferences re-emerged under the sponsorship of the International Cartographic Association (ICA) as the 1st ICA European Symposium on Cartography (EuroCarto 2015).

The commercial period: the early 1980s to the late 1980s

Tomlinson (1987), writing in the first volume of what was to become a flagship journal of GIS, provided a state-of-the-art review of this newly emerging subdiscipline of geography. He noted that significant progress had been made in adopting GIS software in government and commercial organizations, including in the transport and facility planning and management, cadastral systems, agriculture and the environment, and the forestry and civil engineering sectors. He argued that in the future new innovations would come from academia and from government rather than the commercial sector. This was only to be partially true for, in 1982, Esri released ARC/INFO, the first commercial GIS. ARC/INFO adapted the CGIS model of handling the spatial and attribute data separately. The former used Esri's topological

ARC structure while the latter were stored in the INFO relational database. In 1986, Esri released PC ARC/INFO due to the popularity of the IBM PC desktop computer. By 1988, Esri had become a $40 million a year company with clients in forestry applications and other government departments.

Tomlinson (1987) had been correct in arguing that the expansion of commercial GIS was being curtailed by the lack of educational opportunities to produce personnel who could run and maintain GIS facilities, conduct basic research, stimulate new innovations, and staff university departments. In 1988, to motivate fundamental research into the development of GIS, the US National Science Foundation (NSF) made a grant to a consortium of universities that included the departments of geography at the University of Santa Barbara (the lead institution where Mike Goodchild was the Executive Director), the State University of New York at Buffalo, and the surveying engineering department at the University of Maine. This consortium is now funded with a grant from the NSF of $5 million annually. In addition to its primary focus on research, which manifested itself in a series of research initiatives, the NCGIA (National Center for Geographic Information and Analysis) also developed a core curriculum in GIS comprised of 75 lectures, grouped into three semesters each of 25 lectures. The lectures were initially written by 35 different authors and contained additional laboratory material. They were remarkably successful and by January 1995 over 1300 copies had been distributed to over 70 countries. Eventually, the original core curriculum was made available in Chinese, French, Hungarian, Japanese, Korean, Polish, Portuguese, and Russian. The core curriculum was intended to provide a core set of knowledge that would allow faculty teaching GIS courses to cover a broad set of topics to students new to the discipline.

In February 1987, the UK's Economic and Social Research Council established four regional research laboratories (RRLs), in London, Edinburgh, Cardiff, and Newcastle. Their mandate involved four primary functions: data management (the provision of a spatial data archive); software development; spatial analysis; and research training together with professional development. Concurrent with the development of the RRLs, the UK's Lord Roger Chorley chaired the Committee of Inquiry into the Handling of Geographic Information. The Committee's Report was made public in 1987 (Waters 1998) and made recommendations (subsequently acted upon) that the British Ordnance Survey, the primary supplier of maps to the British public, should move to a fully digital environment.

The period of user dominance: the end of the 1980s to the mid-1990s

Coppock and Rhind state that during the last of their four periods there was intense competition among GIS software manufacturing companies due to "user dominance" and an associated thinning out of the market to a small number of major vendors. This competition was fostered by the numerous GIS conferences and by the publication of the annual GIS World Sourcebooks (Waters 1998). These volumes were noteworthy for their annual survey of GIS companies and their software, which included detailed tables assessing the capabilities and attributes of the listed GIS software. This ongoing competition resulted in the emergence of a few dominant companies among the GIS software vendors, including Intergraph and Esri. During this period, vendors moved away from the complexity of command line interfaces to graphical user interfaces (GUIs), once again tracking ongoing developments in computer hardware and commercial operating systems (the so-called WIMP interface of windows, icons, menus, and pointers). It was in 1990 that the US Census Bureau introduced its TIGER file system: this, together with the fact that Census Bureau data was freely available, further boosted the US geodemographics industry. Other countries including Canada and the United Kingdom made census data only available on a so-called "cost recovery" basis, arguably imposing a continuing chill on what might have been a more robust market for GIS data. In recent years many countries have permitted more open access to geospatial data under the Aarhus Convention, which became law in October 2001. However, the only states that signed the agreement were from Europe and Asia.

A number of companies supplied GIS software that specialized in niche markets. For example, Caliper Corporation produced TransCAD, a software package focused on transportation planning and transportation GIS (GIS-T). Others, such as Idrisi, developed by Clark University in Worcester, MA, successfully catered to the academic market, providing detailed tutorials and accompanying datasets. It was during this period that the movement to introduce GIS instruction into the K-12 curriculum in the United States gathered momentum. These efforts were summarized and resource materials and advice for teaching GIS in primary and secondary schools were provided at the first national conference on the educational application of geographic information systems held in 1995 and sponsored by Technical Educational Research Centers (TERC). TERC has continued to provide educational resources to schools for all grade levels (and for university GIS courses as well) and now maintains an active website.

The era of geographic information science (GIScience)

The mid-1990s saw a sea-change in the development of the academic discipline of GIS. In 1992, Goodchild published a major theoretical contribution when he argued that the discipline should move from a concern with the technology of geographic information *systems* to developing answers to questions that might more properly be considered to be part of a geographic information *science* (Goodchild 1992). In the opening arguments of his paper, Goodchild stated that much of the early history of GIS was technology driven. It was concerned with how to get geographical data into an information system and with new technologies that were developed largely within government agencies, such as the CGIS and the US Census Bureau, and by remote sensing companies that were developing new technologies to acquire satellite imagery. Now, he argued, it was more appropriate to concentrate on the task of how to "handle" and exploit the data held in these GIS databases. The way forward was prepared by research that was being reported at a newly developed series of conferences, the International Geographical Union's spatial data handling symposia (the first of these conferences was held in Zurich in 1984 and the 17th of these biennial meetings in Beijing in 2016). Goodchild presented a review of the nascent discipline of GIScience, including a synopsis of three decades of algorithmic research, into a series of topics: spatial data handling; data collection and management; data capture; spatial statistics; data modeling and theories of spatial data; data structures, algorithms and processes; data display (visualization); analytical tools; and, finally, institutional, managerial, and ethical issues. While some of these developments were to benefit from progress in computing (e.g., data display from a new emphasis on scientific visualization, often referred to as the second revolution in computer science), most launched new subdisciplines in geography (e.g., spatial statistics, which now produced new stand-alone software packages such as GeoDa, and new functionality in commercial software, such as Esri's ArcGIS ToolBox, Spatial Analysis and GeoStatistical Analysis modules). Some of these new fields were now located in other academic departments such as information science and geomatics engineering, mirroring developments that had occurred decades before when fields such as geomorphology and climatology moved out of academic geography.

Within a few years a number of journals had changed their names to reflect this new emphasis on science as opposed to systems. For example, in 1997 the *International Journal of Geographic Information Systems* had replaced the word *Systems* in its name with *Science*. The new name was explained in the introduction to that volume by then editor, Peter Fisher, who acknowledged the debt to Goodchild's seminal article in providing a rationale for the new focus to the journal and the discipline. The *American Cartographer*, which had been launched in 1974, had changed its name in 1990 to *Cartography and Geographic Information Systems*. This lasted until 1999, when it also changed the *Systems* in its title to *Science*. Other journals, such as *Transactions in GIS*, circumvented the problem by leaving the acronym in their title undefined. When the 2nd edition of *Geographical Information Systems: Principles, Techniques, Applications and Management* appeared in 1999, the word *Systems* was retained, but when the same four authors published the first edition of a textbook two years later, they included both terms, *Geographic Information Systems and Science* (Longley *et al*. 2001). The *Annals of the Association of American Geographers* requests submissions in four broad areas, one of which is *Methods, Models and Geographic Information Sciences* but its Table of Contents retains the now more ambiguous acronym, *GIS*, and its specialty group in the field prevaricates, as well, with the title *Geographic Information Science and Systems*. The new NCGIA core curriculum, which gathered lectures for its website until 2000, also used geographic information science in its title. The lectures and associated material were now all online and no print copies were created. A note posted on the website in August 2000 stated that there would be no further updates due to new educational resources becoming available, including the digital library of Earth system education, the NCGIA's own center for spatially integrated social science, and Esri's virtual campus (Waters 2013). A review of progress in the field of GIScience, twenty years after the initial discussions of the concept, has been given by Goodchild (2010).

New educational initiatives also characterized this period. In 1990, the NCGIA board of directors recommended that a new organization be developed to assist researchers in GIScience. The UCGIS (University Consortium for Geographic Information Science) website, in its brief history of the organization, states that an ad hoc steering committee was formed by the NCGIA in 1991 containing 16 members from seven different disciplines. Unfortunately, this brief historical note does not list either the members of the committee nor the seven disciplines represented. In 1994, a founding meeting was held in Boulder, CO, and in 1995 the UCGIS was formally incorporated. The UCGIS had two primary objectives listed on its website: "Advance research in the field of geographic information science" and to "Build scholarly communities and networks to foster multidisciplinary GIS research and education." The membership of UCGIS has fluctuated over the years, reaching a high of perhaps 70 US universities in about 2005 but declining to 53 US universities at the time of writing. In the initial meetings it was made quite clear that this was a US organization and non-US universities would only be granted affiliate status. No Canadian university has ever been a member and at present there are only two non-US universities that have been awarded and retained affiliate status, CentroGeo in Mexico and the University of Salzburg's department of geoinformatics.

The UCGIS has promoted annual meetings and symposia and, in partnership with the Association of American Geographers, the development of a body of knowledge (BoK) for teaching GIS. This was seen as a natural successor to the core curricula developed by the NCGIA. However, in conceptualization the BoK was vastly different. Waters (2013) provides a critical review of the development process that led to the publication of the BoK in 2006. The BoK was structured into ten knowledge areas that were then divided into 73 units that, in turn, were further subdivided into 330 topics. Contributors to the BoK had suggested that one of the primary weaknesses of the core curricula had been the lack of an explicit structure for continuous updating. Unfortunately, this was equally true of the BoK and it was not until the UCGIS held a special workshop at its summer symposium in Pasadena in 2014 that a new BoK was proposed with a formal timeline. In the field of computer science there is a process for updating the curriculum approximately every six years. This has yet to be achieved by GIScience.

Nevertheless, by the end of the 1990s Mike Phoenix, former higher education specialist for Esri, was able to claim that their GIS software products were used in more than 60 different kinds of university academic and administrative departments (Waters 1998). By this date, GIS had influenced the teaching of many of the subdisciplines of geography and would, in the following decade, go on to influence the operations of many other disciplines that used spatial data.

Reactions to a formal geographic information science approach to GIS

Some academic geographers reacted with dismay to the new emphasis on geographic information science, seeing it as a reassertion of the aridity of the spatial paradigm of the so-called "quantitative revolution," which had been disavowed by some members of the discipline in the 1970s. The most widely cited critique of the spatial paradigm within GIS came in the form of John Pickles' edited volume, *Ground Truth* (Pickles 1995). Although some of the leading proponents of GIScience contributed essays to the book, most of the papers were written by academics unsympathetic to the achievements of those working in GIS.

Shortly after the publication of *Ground Truth*, the public participation in GIS (PPGIS) movement was launched at an NCGIA sponsored workshop held at the University of Maine. PPGIS may be defined as an approach to community planning that privileges the traditionally marginalized segments of society (the poor, the old, the young, the physically challenged, and members of ethnic minorities, among many others). It leverages GIS software to allow these individuals to participate in the planning of their communities and their environments. To achieve these goals PPGIS broadened traditional approaches to GIS by including a wide range of social science methodologies and theories. It is closely aligned with participatory GIS, a cognate set of methodologies and approaches and low-tech solutions, such as sketch maps, to the acquisition of geographic information. Typically PPGIS and PGIS involve the interaction and collaboration of academics with GIS expertise with members of the community wishing to participate in the planning of their communities. These approaches had antecedents, paradoxically in the later work of Bill Bunge, one of the pioneers of the quantitative revolution (Miller and Goodchild 2015). PPGIS has also produced new lines of research, such as the current concern with the design of age-friendly communities.

In the twenty-first century, stimulated by the popularity of PPGIS, which had spawned a series of conferences in conjunction with the annual URISA meetings, GIS began to embrace a host of traditionally nonscientific approaches to geography, including qualitative, feminist, and critical GIS to name a few. PPGIS itself had rarely spelled out whether it was concerned with geographic information systems or science, the latter being somewhat of an anathema to those practicing PPGIS. The more important of these new approaches to GIS included formal adoptions of critical GIS and feminist approaches to the use of the technology. The possibility of the former was introduced in an article by Nadine Schuurman (2000) who identified three waves of criticism of the GIS community. She argued that the first wave had lasted from 1990 to 1994 and the debate had centered on the merits of the positivist approach adopted by GIS practitioners. The second wave occurred in the mid-1990s and represented the beginning of a dialogue between GIS specialists and those concerned with both the social effects and implications of GIS technology. The catalyst for this discourse was the NCGIA's "Research Initiative 19, GIS and Society: The Social Implications of How People, Space, and Environment Are Represented in GIS." According to Schuurman, in the third wave, at the end of the 1990s, there was a greater commitment to the technology of GIS. This led to the rise of PPGIS in that decade and ever since. Quite separately, there was a call for a "critical GIS" or "GIS2" that would incorporate the various perspectives of social theorists (see Sheppard *et al*. (1999) for a discussion of the societal implications of the NCGIA's Varenius Project, and also the papers in the special issue of *Cartographica*, 2009, 44(1)).

GIS developments since 2005: the world of volunteered GIS, web-based mapping and mobile GIS, and cloud computing and big data

Since 2005, developments in GIS have again mirrored the importance of progress in computing technology. Crowdsourcing and social networks have been hugely influential developments in the social application and individual use of computing technology, but these changes have been reflected in the move away from the use of authoritative data in GIS and the rise in influence and use of volunteered geographic information (VGI). The attractions of VGI are well described in Goodchild's (2007) seminal paper on the topic: VGI is inexpensive, timely and available to all on the right side of the digital divide. Goodchild (2010), in reviewing progress in the field of GIScience, notes that the breaking down of the barriers between expert and nonexpert is also referred to as neogeography and that VGI itself has been called crowdsourced geographic information and community mapping, and thus has strong links to PPGIS. VGI has been aided by the move to web-based mapping and the availability of online GIS technology such as ArcGIS Online and the almost universal availability of map-based apps on smartphones and in-car GPS navigation systems (see Miller (2007) for a review of these technologies that have produced a time–space convergence and aided the processes of globalization). GIS and computing hardware are becoming invisible technologies whose benefits can be leveraged and enjoyed seamlessly by wide sectors of the population in industrialized and developing countries.

Other software developments that have led to the almost universal use of geographic information and related technologies include Google Earth, OpenStreetMap, and software for finding directions, such as MapQuest. The familiarity of large sections of affluent populations with this type of software has led to the rise of location-based services and to new developments such as OpenImageMap and web mapping services.

Advances in computer technology, including cyberinfrastructure (leading to CyberGIS), cloud computing, and the rise in importance of "big data," are almost immediately integrated into GIS software, with leading GIS companies such as Esri providing online guides to how big data may be used in such GIS applications as predictive modeling and social media. A review of the implications for the discipline of geography in general, and GIS in particular, specifically a move to a "data driven" geography, is provided by Miller and Goodchild (2015). Traditionally, big data was concerned with the three "Vs": volume, velocity, and variety. The terms are self-explanatory and geographic data often qualify on all three counts. More recently, computer scientists have added additional "Vs" to the list, including veracity (relating to the provenance of the data: thus, for example, VGI might have lower veracity than authoritative data) (Miller and Goodchild 2015), value, validation (whether the data conforms to a priori model expectations), and voracity (the rate of ingestion, which is important in the use of virtual reality simulations with a GIS framework). Vagueness (or uncertainty) might also be added to the list as it is endemic to much GIS data.

GIS returns to its roots in geography and GIS

It can be argued that GIS has returned to its origins, from earlier concerns common to many geographers, at least on the human geography side of the discipline. Miller and Goodchild (2015) summarize the history of geography's concerns with idiographic (description-seeking) and nomothetic (law-seeking) approaches. At various times over the centuries one approach has been dominant and the other subordinate, disparaged, or overlooked. Miller and Goodchild argue that Strabo and Ptolemy were concerned with both approaches, for they provided detailed descriptions of specific places as well as generalizations that applied to the Earth or large regions. However, Miller and Goodchild also state that such an integration has rarely been adopted by researchers in the two millennia since Strabo and Ptolemy wrote. GIS, with its emphasis on software and algorithms and its concern with creating spatial databases, is seen by Miller and Goodchild as an intellectual activity that permits a dialogue between the idiographic and nomothetic world views. Perhaps this is best demonstrated in the various spatial interpolation algorithms, some of which produce global models (trend surface analysis, for example) while others emphasize local differences (e.g., geographically weighted regression). Miller's (2007) call for a people-based approach to GIS also emphasizes individual differences.

A recent trend in GIS has been the recognition of the importance of geodesign. This is now the focus of a new series of conferences being held annually in Redlands and also in Europe and China. It has led to new undergraduate and graduate degree programs. Geodesign has been championed by Esri cofounder, Jack Dangermond, and reflects his graduate education in landscape architecture. Dangermond (2014) has defined geodesign as taking geographic information and linking "it to the design, decision-making, and planning process using collaboration ... by building the power of GIS into the process, allowing alternative plans to be visualized, compared, and evaluated." He credits his former Harvard University professor Carl Steinitz as introducing him to "this methodology" and so the history of GIS returns to its roots.

In 2007, the NSF began supporting research into "transformative science." There is little doubt that over the past fifty years GIS has been a transformative science for both the academic discipline of geography and the world we inhabit. The impact of GIS on the discipline of geography has been compared often to the impact of the telescope on astronomy but, as with the telescope, people choose what they want to see through the GIS lens. The NSF is interested in how transformative science has changed the world. It would behoove the discipline of geography to do as Sheppard *et al*. (1999) suggested and study how GIS has transformed the world.

SEE ALSO: Cloud computing; Critical geography; CyberGIS; Digital divide; Feminist geography; Geodemographic profiling; Geodesign; Geographic information science; Geographic information system; Geostatistics; GIS for transportation; Local statistics and place-based analysis; Location-allocation models; Network analysis; Overlay, graphical; Participatory geographies; Public-participation GIS; Qualitative GIS; Spatial analysis; Spatial crowdsourcing; Spatial social networks; Volunteered geographic information; Volunteered geographic information: quality assurance; Web-mapping services

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