CHAPTER 11: GIS LABORATORY

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INTRODUCTION

Geographic information systems (GIS) have evolved over the past four decades to provide a unique lens on the Earth's surface and near-surface – a lens that is increasingly important in a wide range of tasks associated with geographic information, from simple inventory and map-making to analysis, modeling, and spatial decision support. The power of the lens has grown steadily as its functionality, and the methods of representation that underlie it, have grown more and more sophisticated. GIS has become an indispensable tool in the geographical kit, as well as in the broader set of disciplines whose domain covers the surface and near-surface of the Earth. This essay begins with a review of the evolution and current status of GIS, and the nature of the specific perspective that it provides.

GIS was born at an early stage in the development of computers, at a time when the costs of computing were far higher than they are now, when the most powerful computers had no more power than today's laptop, and when there were no electronic networks to connect computers and users. In today's world of the Internet, wireless connections, and the World Wide Web the power and scope of digital geographic information has expanded enormously, far outstripping any earlier conception of GIS and bringing the ideas and tools of GIS within everyday reach of anyone on the enabled side of the digital divide. Exactly what part of this domain should still be termed GIS is debatable, and several other terms are in current use, perhaps the most popular of which is the adjective *geospatial*. In this essay I will take a broad view, and equate GIS with systems designed for the acquisition, compilation, analysis, storage, and display of geographic information. Thus the later sections describe this much larger world, and the ways in which it complements and builds on the earlier, limited view of the GIS lens.

GIS AS A LENS: THE EARLY YEARS

The paper map and its relatives the atlas and the globe have long played a key role in expressing humanity's knowledge of the geographic space it calls home. Maps are informative, playing a vital role in way-finding, and are also often decorative. As ways of storing information they are remarkably efficient, since it would take many pages of text or speech to express the contents of a single topographical map with comparable precision. Maps are also effective devices for answering simple queries of the form "What is at $\mathbf{x}$?" or "Where is z?" or "How do I get from $\mathbf{x}_1$ to $\mathbf{x}_2$?" Nevertheless maps are distinctly limited in their ability to express geographic knowledge, in several ways. First, their emphasis on linking properties z to locations $\mathbf{x}$ addresses only one form of geographic knowledge, about the specific properties of places, knowledge that is often termed *idiographic*. However many geographers, and the academy in general, place much greater value on *nomothetic* knowledge, or knowledge that is abstracted from space and time and thus true everywhere at all times. Newton's Laws of Motion would be of little value, for example, if they applied only on Tuesdays and only in Belgium. In this context, the descriptive nature of maps is both their strength and their weakness.

Second, the traditional process of map-making, involving field observation, compilation, drafting, printing, and distribution, is both time-consuming and expensive. Only national governments and large corporations have traditionally been able to afford the very high initial costs of establishing a map-making enterprise, with its stereoplotters, drafting tables, large-format cameras, and highly trained staff. To justify these costs, it has been important to ensure that maps once printed are of long-lasting value, in as many applications as possible. Thus maps have tended to emphasize the relatively static aspects of the Earth's surface, such as its topography, climate, rivers, roads, and buildings, rather than its more transitory aspects of weather, events, and human movements (Goodchild, 1988). Third, since maps are designed to be used by all it is essential that their methods of representation be well-defined and that the techniques used be replicable. There is no room in this process for the subjective; instead, the contents of maps tend to be viewed in the same way as one would view measurements of temperature or voltage. Finally, maps are necessarily of limited accuracy, since symbols must be of finite size and a paper substrate is not perfectly stable.

GIS owes its origin to a very simple failure of maps: the difficulty of making accurate measurements of such properties as length or area from a paper document. While it is possible to measure the length of a feature such as a river or the area of a feature such as a lake using mechanical devices, the process is tedious, time-consuming, and unreliable. In the mid 1960s the Government of Canada faced the task of obtaining estimates of land area from a series of tens of thousands of maps produced by the Canada Land Inventory.

Such estimates were intended to be the main product of the inventory, but the task was complicated by the need to overlay pairs of maps. For example, to estimate the amount of land that was *both* currently forest *and* suitable for agriculture one would have to overlay the forest cover and soil inventory maps, ensuring a perfect alignment, before measuring the areas of each patch of land with the requisite characteristics. The process was clearly going to be enormously expensive given the thousands of maps and tabulations involved and the small size of many of the patches.

The Canada Geographic Information System was developed directly in response to this need, as a computer-based machine for producing statistical summaries from maps. If the maps could be computerized, it was argued, then areas could be calculated and summed at electronic speed -- no matter that the devices to reduce the maps to digital form did not exist, or the strategies for reducing the contents of the maps to the binary language of the digital computer, or the algorithms for performing the calculations. All of these problems were successfully solved by contractors, many of the key inventions and breakthroughs in GIS development were made, and by the early 1970s the system was in operation.

The task of measuring area from maps is challenging, but scarcely worth the attention that was later lavished on GIS. But during the 1970s a series of parallel developments converged to the realization that it was possible to build a single software package that would eventually be capable of performing almost any conceivable operation on any kind of mapped information. Notable among these developments were efforts to build large integrated databases of the many kinds of map data needed by city government; the efforts of the U.S. Bureau of the Census to modernize its data collection and tabulation; the work of such landscape architects as Ian McHarg (1971) to place planning on a scientific, multidisciplinary basis; and the supply of Earth images from satellites that began with the LandSat program. The first commercial GIS software products appeared around 1980, and by the end of that decade a viable software industry was in place. Functions have been added steadily, and GIS is now a standard part of the toolkit of anyone working with data about the surface and near-surface of the Earth. GIS has become an indispensable tool in research, in the management of distributed resources by utility companies, in the operations of local government, and in a host of other applications.

However these early conceptualizations of GIS provided a lens that delivered an extremely limited view of the Earth's surface. Although GIS was often justified on the grounds that different properties of a place, such as topography and hydrography, could be readily integrated, such properties tended to be separated into different layers of representation, making it difficult to see the multidimensional nature of geographic variation and the full geographic context of places. Functions were largely analytic: precise and powerful, but able to answer only very limited, well-formed queries, such as "Tell me the area of this lake", or "Find for me the optimum location for a new grocery store using this specified criterion." Nevertheless GIS clearly satisfied many of the expectations of geographical analysis, and by the 1990s had become a powerful analytic engine, and the platform of choice for quantitatively minded geographers. Comparisons were made to statistics, and the role of statistical packages in implementing statistical methods, and a number of texts appeared describing the analytic power of GIS (Burrough, 1986).

In the late 1980s the discipline of cartography was taken in a new and in many ways exciting direction by the work of Brian Harley (2002), who argued that maps could be seen as text and deconstructed to reveal the agendas of their makers – in short, that maps were social constructions. GIS users, on the other hand, could be portrayed as somewhat blindly accepting those same maps as scientific truth, as the input for complex analytic procedures. Within a few years a substantial critique of GIS had emerged, as critical social theorists turned their attention to what they saw as the somewhat naïve practices of GIS. The collection of essays edited by Pickles (1995) is perhaps the best compilation of this work. Other lines of argument quickly surfaced: GIS failed to acknowledge the importance of its military roots (Smith, 1992); its representations were simplistic and missed much of what was important to our understanding of the world; and its spatial detail and power to link information based on common location presented a significant threat to personal privacy (Curry, 1998).

IMPROVING THE LENS

The growth of critical GIS, along with the recognition that many aspects of early GIS were limited and problematic, and advances being made in computer science, led during the 1990s and the early years of this century to a greatly improved GIS, and to a rich research agenda that held the seeds of future improvements.

First, the set of representations has expanded dramatically, and continues to do so. While early GIS focused on the contents of maps, and thus on a two-dimensional, static view of the world that could be separated into thematic layers, today's GIS has moved substantially beyond the map metaphor, to embrace types of geographic information that have never been mapped or associated with maps. The principles known as object-oriented database design (Zeiler, 1999; Arctur and Zeiler, 2004), developed in computer science and widely adopted by the computing industry, began to influence GIS in the early 1990s, and by 2000 had been implemented in the leading software products. They allowed designs to be developed graphically, dealt with the hierarchical relationships that exist between many geographic features, such as counties and states, and addressed the specialization and generalization processes that are so common in cartography. Standard templates, or data models, have been developed in many areas of GIS application, allowing users to standardize database designs and associated terminology. The concept of layers that received so much critical attention has been largely replaced by a much more fluid concept of feature classes.

Second, a rich area for research and development emerged around the concept of uncertainty, based on the realization that no GIS representation could ever be perfect, and no position on the Earth's surface could ever be perfectly known (Zhang and Goodchild, 2002). The classification schemes used by the makers of soil, land cover, and geologic maps are inherently vague, such that two such map-makers will always produce somewhat different maps of the same area. Yet GIS was increasingly popular among regulatory agencies because of the apparent replicability of its analytic processes. GIS made it easy to use the contents of maps for purposes for which they were never intended, exposing their users to expensive lawsuits. Critical social theorists pointed out that a technology that presented the boundaries between distinctly classified areas as precise and infinitely thin was ignoring the obvious vagueness and uncertainty inherent in classification – that GIS had too willingly embraced simplistic Boolean classification. Today information on data quality is much more widely available, representations of vagueness are widely employed, and it is no longer usual for analyses to be presented without any discussion of uncertainty.

Third, there was a growing acceptance that the early model of a GIS populated with scientific truth and placed in the hands of altruistic government decision makers was far out of line with social reality. Efforts were made to allow for multiple criteria, reflecting the distinct viewpoints of different stakeholders in a decision, by implementing a range of methods such as the Analytical Hierarchy Process (Saaty and Alexander, 1989) as GIS functions. Much interest was expressed in a completely re-designed GIS, termed GIS/2, that would be capable of representing individual viewpoints rather than a single God's-eye view. A new subdiscipline termed *public-participation GIS* (Craig, Harris, and Weiner, 2002) captured the imagination of planners and policy specialists, and remains a lively research area.

It was abundantly clear from these and related arguments that there was more to GIS than a mere tool – that the use of the tool raised questions of a fundamental nature that were all too easily overpowered by the need to manipulate a complex user interface. They included scale, and related concepts of generalization and inferential fallacy; uncertainty, and the statistical modeling that allows the effects of uncertainty to be analyzed; the social context of GIS, and its role as a social construction; and the extension of representations to include a more complete range of forms of geographic knowledge. More traditionally, they included the knowledge accumulated in the disciplines of cartography, photogrammetry, surveying, and geodesy, each of which is essential to the successful operation of GIS. Various terms emerged to describe this set of issues; perhaps the most successful of these at the international level has been *geographic information science* (GIScience; Duckham, Goodchild, and Worboys, 2003). In addition to the more traditional disciplines, it also draws on work in spatial statistics (uncertainty), spatial cognition (representation and user-interface design), and spatial databases that is housed in a number of other disciplines. GIScience can be defined as the science behind the systems, or the body of scientific knowledge that guides the design of the systems and is implemented by them. GIScience is now reflected in the names of a number of journals, conference series, degree programs, and even academic departments.

BROADENING THE LIMITS OF GIS

GIS has always been seen as just one of a number of technologies associated with geographic information. Remote sensing, dating from the 1970s but echoing much earlier work in aerial photography, has evolved into a very rich and profligate source of data, supplied by a mix of satellites, aircraft, and unmanned drones. Some of these systems are sponsored by government agencies, such as NASA, while others are commercial, and even developing countries such as China and India now have significant remote-sensing programs.

Three properties serve to differentiate imaging sensors: their spatial resolution, or the degree of detail with which variation across the Earth's surface is captured; their temporal resolution, or the frequency with which a sensor images any part of the Earth's surface; and their spectral resolution, or the degree to which the electromagnetic spectrum is partitioned by the sensor. While most sensors are passive, registering radiation emanating from the surface such as reflected sunlight, others are active, sending pulses of radiation to the surface and measuring response. In the latter category are LiDAR sensors (Light Detection and Ranging) which are now widely used to create detailed records of three-dimensional structures and topography. Some sensors are designed to detect specific properties of the Earth's surface or atmosphere, such as green vegetation or ocean temperature, while others are designed for more general mapping purposes. In the latter category are an increasing number of sensors mapping the Earth from space at spatial resolutions finer than 1m.

Remote sensing now provides much of the raw information needed by the GIS enterprise. A wide range of properties, from rainfall to population density, can be inferred from the outputs of various sensors – in the case of population density, for example, interesting work using the night-time illumination of the Earth's surface has shown that it is possible to derive reliable estimates of the distribution of population density within countries from this source. Nevertheless there will always be important properties that cannot be reliably derived from imagery, including the names of places; and properties that can only be estimated with unacceptably low levels of accuracy, such as average income or ethnicity.

The Global Positioning System (GPS) is also commonly lumped with GIS and remote sensing as an important geographic information technology. Based on a constellation of Earth-orbiting satellites, each of which follows a known orbit and emits precisely timed signals, GPS allows position to be determined to better than 10m with simple, inexpensive devices (and to much greater accuracy with more expensive devices). GPS receivers can be incorporated into mobile phones, laptops, and even wristwatches, and can be used to track moving objects, including animals and people. It has revolutionized traditional practices in surveying and map-making, and has become indispensable in fieldwork.

Early GIS was motivated by the need for an efficient set of tools that could aid researchers and others in manipulating and analyzing geographic information. Like many other computer applications, it tended to be used when tasks were too tedious, expensive, inaccurate, or time-consuming to perform by hand. To a geographer, a GIS provided a powerful lens on the geographic world that was comparable to the telescope's role in astronomy – Abler (1987) called GIS "simultaneously the microscope, telescope, and Xerox machine of geographical analysis and synthesis." But in the early 1990s the popularization of the Internet and the World Wide Web had a profound effect on this paradigm. Suddenly a means was available to share the GIS lens, and to communicate the insights it provided. By 1994 Web sites had been developed that offered simple maps, and within a few years it became common to use sites such as Mapquest to obtain both maps and driving directions.

By the early 1990s it had become clear that traditional arrangements for the production of geographic information were not sustainable – that governments were no longer willing to absorb the ever-increasing costs of compiling and publishing authoritative maps. Instead, the future would be dominated by a patchwork of local producers, sharing their outputs through a complex network, and orchestrated by national standards. In the U.S. the National Spatial Data Infrastructure (NSDI; National Research Council, 1993) emerged as an umbrella term that encompasses the producers, users, networks, software, hardware, and standards that together comprise this new order. Similar spatial data infrastructures have been developed in many countries, and efforts continue at the global level to integrate them.

All of this has profoundly impacted the world of GIS. Instead of a GIS being regarded as an intelligent personal assistant – a butler perhaps – the Internet has allowed it to evolve towards a medium for the communication of all that is known about the planet (Sui and Goodchild, 2001). Massive repositories of geographic information have been developed, known as data warehouses or digital libraries, with the necessary mechanisms that allow users to search, assess, and retrieve data sets. Today, the state of development in this area in the U.S. is perhaps best represented by the Geospatial One-Stop (Goodchild, Fu, and Rich, 2007), an effort by the current administration to provide a single point of entry into the world of online geographic information. Through a single portal, it allows users to search over the resources of more than 1,000 sites and tens of thousands of data sets. Data may be downloaded, or viewed directly through simple Web browsers. Similar efforts exist in many national and local agencies (human nature being what it is, there will always be more than one "one-stop").

Mapquest was perhaps the first example of a trend that has accelerated recently: the offering of GIS functions as Web-based services, obviating the need for users to install and operate their own complex software. Instead of a personal GIS operating on a personal database, Mapquest allows anyone to send the key parameters of a search for driving directions – an origin and a destination as street addresses – and to obtain directions in return. Today, GIS services are available from a multitude of Web sites, encompassing virtually any function traditionally performed by a GIS. The term *service-oriented architecture* is the currently fashionable way of referring to this phenomenon, which in essence allows anyone with a Web browser to become a GIS user.

In summary, by the early years of the current century GIS had evolved from a desktop application akin to a statistical package or word processor into a complex set of arrangements for the acquisition, compilation, storage, analysis, and display of geographic information, based on a range of technologies. Its functions could be installed at the user's desktop, or obtained from numerous Web sites. Arrangements for the production of data had evolved from a radial system centered on massive investment by national governments into a complex network of producers and users, sustained by a collection of standards. Data continued to be drawn from maps, but augmented by massive flows from Earth-observing satellites and from field measurements with GPS. The number of trained GIS experts was on the order of 100,000 worldwide, each of them having taken courses at the post-secondary level.

DEMOCRATIZATION

In early 1998 then-Vice-President Al Gore distributed the content of a speech that had been intended for delivery at the opening of the California Science Center in Los Angeles on the subject of Digital Earth, a term he had coined earlier in a 1992 book (Gore, 1992). The speech describes a future vision for access to geographic information:

> "Imagine, for example, a young child going to a Digital Earth exhibit at a local museum. After donning a head-mounted display, she sees Earth as it appears from space. Using a data glove, she zooms in, using higher and higher levels of resolution, to see continents, then regions, countries, cities, and finally individual houses, trees, and other natural and man-made objects. Having found an area of the planet she is interested in exploring, she takes the equivalent of a 'magic carpet ride' through a 3-D visualization of the terrain."

At the time the concept of virtual environments implemented through head-mounted displays was well known, but the idea of accessing geographic information down to spatial resolutions of 1m or finer seemed far beyond then-current capabilities. There are, after all, 5×10^{12} square meters of Earth surface, and dynamic three-dimensional display was still an expensive option. Nevertheless the Clinton Administration pursued the idea at some length, establishing an office in NASA and encouraging the development of

Digital Earth prototypes. By 2001 a small group of inspired developers working under contract had produced Earthviewer, a software package that allowed an online user to display and manipulate a representation of the globe, to zoom down to resolutions as fine as 1m, and to create Gore's "magic carpet ride", a function commonly termed a *fly-by*. Earthviewer required a sophisticated graphics capability, but by 2005 this had become standard in PCs. In 2005 Google acquired Earthviewer, rebranded it, redesigned its look and feel, and released it as Google Earth.

Google Earth falls somewhat short of the Gore vision in several respects. It is implemented as a standard application rather than a virtual environment, in which the screen provides a two-dimensional window on a three-dimensional world. Gore referred in the speech to being able to travel into the past, to explore representations of historic worlds, and while many types of historic data are available for viewing from third parties, the imagery provided by Google is more or less current (it is difficult to discover the precise date on which any part of the imagery coverage was acquired). Gore also referred to simulations of future worlds. However a central part of the Gore vision – the ability of average citizens to access information about the Earth – is certainly made compellingly real.

Perhaps the most significant achievement of Google Earth, and of the many services that have since followed in its footsteps, is its user interface design. Unlike traditional GIS, with its need for extensive training at an advanced level, the interface of Google Earth can be mastered by a child of ten in ten minutes. While fly-by was often reserved as an end-of-course treat, its generation in Google Earth is almost trivially easy. All of the complications of map projections disappear in an environment that presents the Earth's surface as curved, and difficult concepts such as scale are treated using simple metaphors. I have argued that Google Earth represents the democratization of GIS (Butler, 2006) – an opening up of the pandora's box to the average citizen, and an opportunity for the basic ideas of digital geographic information to become broadly familiar to all.

The lens of a virtual globe such as Google Earth is fundamentally different from that of the traditional GIS. Instead of emphasizing precise and powerful analysis, these systems achieve their power through visual representation, with a base layer of imagery warped onto topography, on which features of interest can be superimposed. The spatial context of features is always visible, whereas it is often lost in GIS displays. I find Google Earth a powerful complement to GIS, allowing patterns and anomalies detected in GIS to be examined in spatial context.

For example, Figure 11.1 shows a GIS-generated map of Milwaukee, showing percent black by census tract, as reported by the 1990 U.S. census. Standard tools in GIS allow the distribution to be summarized and compared to the distribution of the population as a whole. Thus it is clear that the black population is strongly clustered, in a pattern that extends from downtown to the northwest. But there is also evidence of a remarkable outlier, and statistical tests available in GIS allow the significance of the outlier to be tested. But the broader context is missing in this analysis based largely on a single variable. What historic events explain the pattern, and why the anomaly?

[Figure 11.1 about here]

Figure 11.2 shows the Google Earth coverage of the area of the anomalous tract. The population of the tract is a mere 332, far lower than the norm, and it is clear from the coverage that the tract is occupied not by residential land use but by a variety of institutions. A quick search using Google establishes that the tract is a former fairground that is now occupied by a low-security prison, a medical school, parkland, and an industrial park. Although this example is almost trivially simple, it serves to illustrate the differences between the lenses of traditional GIS, Google Earth, and the contents of the Web, contrasting the precise formal analysis of GIS with much more informal and often serendipitous techniques.

[Figure 11.2 about here]

Figure 11.3 shows a second example, in this case in the realm of physical geography. Standard GIS tools allow representations of topography to be used to predict the directions followed by run-off, and thus the development of drainage systems. The *d8* algorithm (O'Callaghan and Mark, 1984) performs this analysis based on a raster representation of topography, in which the elevation of the Earth's surface is recorded at every intersection of a square grid. A digital elevation model (DEM) with 30m spacing covering part of Orange County, California, has been analyzed to obtain the drainage patterns shown in the figure. When the real hydrography is superimposed, it is clear that a major difference occurs where the Santa Ana River enters the coastal plain. The predicted path of the river enters the ocean more than 10km away from its actual estuary.

[Figure 11.3 about here]

While this large difference is spectacular, it is common for small differences to exist between predicted and actual hydrography. As noted earlier, any GIS representation must miss detail to some degree, and in this case any topographic detail less than 30m across may be missed. Again Google Earth allows the spatial context of the DEM to be explored. A quick search of the Web shows that the lower Santa Ana River experienced numerous shifts of course following major flood events. The levees that now constrain the course are too small to be evident in the DEM, though they are clearly visible in the Google Earth imagery (Figure 11.4). Once again the GIS and Google Earth lenses demonstrate their complementarity.

[Figure 11.4 about here]

The early Web implemented a vision of rapid access to information, with a simple browser able to display text and simple images, and to use hyperlinks to skip from one site to another related one. The first browser software became available in 1993, and shortly thereafter commercial versions followed in the form of Netscape and Microsoft Internet Explorer. Web sites were developed with increasingly rich information resources, but in the early years the flow of information was strictly one-way, from a site acting as server to a user as client.

It was soon apparent, however, that small extensions of the Web protocols would allow powerful applications to be developed that relied in part on content generated by users. Airline reservation systems, for example, allow users to complete forms, the contents of which are then compiled in databases, largely avoiding the need for travel agents and reservations clerks. Users of Ebay are able to contribute information directly to the site, and to see it displayed along with the information contributed by others, within a framework provided by the site. By the turn of the century these concepts had expanded into the blogs, wikis, and other services that emphasize user-generated content (UGC), often as a result of collaborative effort among networks of users. Wikipedia is perhaps the most successful example: a collaborative effort to build a free, open encyclopedia of human knowledge. Various mechanisms, including constant monitoring by volunteers and the ability of anyone to edit and correct, help to ensure that the results are reasonably accurate. The terms *crowdsourcing* and *collective intelligence* describe the notion that the results of collective compilation can be surprisingly reliable.

In recent months this trend, generally known as *Web 2.0* to distinguish it from the earlier one-way Web, has emerged as a potent force in the world of geographic information. Efforts are under way to create a global gazetteer (Wikimapia), a global map (OpenStreetMap), a global collection of georegistered photographs (Flickr), and many more. All of these efforts rely on simple standardized references to location, known as geo-tags, and on the willingness of thousands of amateurs to compile extensive collections of geographic information. Along with sites such as Google Earth, Google Maps, and Microsoft Virtual Earth it has brought the concepts of GIS, remote sensing, and georeferencing to the attention of the average citizen, and opened the possibility of a far more intensive engagement between individuals and geographic information technology.

That said, it is important to recognize that all this applies only on one side of the digital divide, and that these ideas are still largely beyond the reach of the majority of the world's population. Nevertheless tools such as these are making it possible for communities that have never had access to maps to create them with minimal skills, and in countries such as India where maps have long been regarded as matters of national security and have been hard for the average citizen to obtain, Web 2.0 tools present a powerful opportunity.

CONCLUDING COMMENTS

The emphasis in this chapter has been on the role of digital technologies in providing a window to the geographic world. That window was initially almost opaque, as the functions of early GIS provided for little more than simple measurement and calculation. As the tools developed, it became possible to believe in a GIS that would eventually be capable of performing virtually any conceivable operation on geographic information. Yet the advent of Google Earth in 2005 made it abundantly clear that GIS had fallen far short of that goal, and that while the lens it provided was precise, powerful, and analytic, it nevertheless made it difficult to see the multidimensional spatial context of geographic features and events; required intensive and advanced training; and made it difficult to represent the more uncertain and subjective aspects of geographic understanding.

Today, that balance has shifted dramatically as a result of new technologies. It is now easy for a child of ten to learn to manipulate large quantities of geographic information, and to explore the world in much the way Al Gore envisioned in 1998. The average citizen lucky enough to be on the enabled side of the digital divide is now quite familiar with digital geographic information, the systems that allow it to be shared across the Internet, and the products and services that can be obtained from it. Neighborhoods can be explored from above and even from street level, information on individual land parcels is readily available (*e.g.*, zillow.com), and services exist to allow individuals to describe their neighborhoods and favorite places in great detail.

One of the most striking features of Web 2.0 services is the willingness of large numbers of amateurs to volunteer information. This willingness stands in sharp contrast to the problems national governments have experienced in recent years in persuading their citizens to contribute to census data collection, and suggests a new vision for the role of information in a democratic society. The key difference between the census and Web 2.0 services may be the ability of contributors to keep track of the data they provide. Photographs contributed to Flickr are identified with the contributor, who thus gains some sense of ownership, perhaps mistakenly, over these digital records. Contributing to Wikimapia is altruistic, but at the same time implies some degree of self-promotion, and some sense of territorial extension over part of the ever-increasing volume of Web content.

The past forty years have seen a steady and at times dramatic change in the role of geographic information in society. Traditional arrangements, which placed government-sponsored mapping agencies in unique positions of authority, have been substantially eroded, though they continue to survive in some areas, such as the official naming authorities. The new world is one of bidirectional information flow; empowerment of local governments and even citizens in both the creation and use of geographic information; the replacement of uniformity of coverage with an increasingly diverse patchwork; and the emergence of important and rich new sources of information. In this climate of accelerating change it is difficult to see where it is headed – whether the Web will eventually collapse under the weight of its ever-expanding content; whether issues of national security will lead to draconian restrictions; whether the altruism of UGC will give way to an increasingly insecure world of malicious attacks, as it has with email; and whether the majority of the world's population will ever gain access. In all of this, however, it is clear that the GIS laboratory will continue to evolve and to provide interesting insights into the geographic world.

REFERENCES

Abler, R.F., 1987. The National Science Foundation National Center for Geographic Information and Analysis. *International Journal of Geographical Information Systems* 1: 303-326.

Arctur, D. and M. Zeiler, 2004. *Designing Geodatabases: Case Studies in GIS Data Modeling*. Redlands, CA: ESRI Press.

Burrough, P.A., 1986. *Principles of Geographical Information Systems for Land Resources Assessment*. Oxford: Clarendon Press.

Butler, D., 2006. Virtual globes: the web-wide world. *Nature* 439: 776-778.

Craig, W.J., T.M. Harris, and D. Weiner, editors, 2002. *Community Participation and Geographic Information Systems*. New York: Taylor and Francis.

Curry, M.R., 1998. *Digital Places: Living with Geographic Information Technologies*. New York: Routledge.

Duckham, M., M.F. Goodchild, and M.F. Worboys, editors, 2003. *Foundations of Geographic Information Science*. New York: Taylor and Francis.

Goodchild, M.F., 1988. Stepping over the line: technological constraints and the new cartography. *American Cartographer* 15: 311-319.

Goodchild, M.F., P. Fu, and P. Rich, 2007. Sharing geographic information: an assessment of the Geospatial One-Stop. *Annals of the Association of American Geographers* 97(2): 249–265.

Gore, A., 1992. *Earth in the Balance: Ecology and the Human Spirit*. Boston: Houghton Mifflin.

Harley, J.B., 2002. *The New Nature of Maps: Essays in the History of Cartography*. Baltimore: John Hopkins University Press.

McHarg, I., 1971. *Design with Nature*. Garden City, NY: Natural History Press.

National Research Council, 1993. *Toward a Coordinated Spatial Data Infrastructure for the Nation*. Washington, DC: National Academy Press.

O'Callaghan, J.F. and D.M. Mark, 1984. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and ImageProcessing* 28: 323-344.

Pickles, J., editor, 1995. *Ground Truth: The Social Implications of Geographic Information Systems*. New York: Guilford.

Saaty, T.L. and J.M. Alexander, 1989. *Conflict Resolution: The Analytic Hierarchy Approach*. New York: Praeger.

Smith, N., 1992. Real wars, theory wars. *Progress in Human Geography* 16: 257-271.

Sui, D.Z. and M.F. Goodchild, 2001. Guest Editorial: GIS as media? *International Journal of Geographical Information Science* 15(5): 387-389.

Zeiler, M., 1999. *Modeling Our World: The ESRI Guide to Geodatabase Design*. Redlands, CA: ESRI Press.

Zhang, J.X. and M.F. Goodchild, 2002. *Uncertainty in Geographical Information*. New York: Taylor and Francis.

BIOSKETCH

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FIGURE CAPTIONS

11.1. Milwaukee by census tract, showing percent black in the 1990 census. The highlighted tract is significantly anomalous: high percent black surrounded by tracts with low percent black.

11.2. Google Earth's coverage of the anomalous tract in November 2007 showing land uses that are clearly institutional.

11.3. Predicted surface hydrology (thin white lines) computed from a 30m DEM, with actual hydrology from USGS mapping superimposed. Note the divergence in the approximate center of the figure, where the real Santa Ana River turns south.

11.4. Google Earth's coverage of the area of diversion. The Santa Ana River emerges onto the coastal plain in the middle right, and is constrained by a concrete channel and levees as it turns south to the coast. Its predicted path flows further west before turning south, as predicted by analysis of the DEM.