16 Geography and the Information Society

Michael F. Goodchild

Abstract

Geographic information in the form of maps and text and increasingly of digital data has always played a fundamental role in the discipline of geography. The chapter provides a brief outline of the history of GIS, including the role played by a commission of the IGU. Significant events in its development are discussed, including the social critique that began in the late 1980s and the Internet that emerged in the early 1990s. Spatial data infrastructure and Digital Earth are comparatively recent reformulations of the vision of GIS. The chapter ends with a new and comprehensive vision of geospatial infrastructure and with a suggested new role for the IGU.

Keywords

Geographic information system (GIS) · Geographic information · Social critique · Geospatial infrastructure

16.1 Introduction

Information has always played a central role in the discipline of geography. Early humans relied on spoken narratives to share information about food sources, hazards, and enemies and used song and gesture to add effectiveness (Chatwin 1988). The idea of a map, a simple and approximate rendering of nearby geographic features, would have emerged very early in human society, perhaps as lines scratched on dirt surfaces or preserved on rock walls. By the Age of Discovery which began in Europe in the late fifteenth century, the science of map-making had advanced to the point where maps could be *planimetric*, scaling the surface of the Earth to a model globe or a sheet of paper, such that distances on the map or globe were approximately proportional to distances on the Earth. Such maps had become a very efficient and valuable means of compiling, storing, and sharing geographic information, which we can define simply as information about *what* is *where* (and sometimes *when*). Mercator (Crane 2003) made some of the first globes and invented a way of creating a flat representation of the curved surface of the Earth such that a ship sailing on a constant bearing would follow a straight line (a *rhumb* line or *loxodrome*) on the map. Gutenberg's invention of printing ensured that maps could be reproduced and distributed in quantity. Books also became important repositories of geographic

M. F. Goodchild (✉)
University of California, Santa Barbara, USA
e-mail: good@geog.ucsb.edu

V. Kolosov et al. (eds.), *A Geographical Century*,
https://doi.org/10.1007/978-3-031-05419-8_16

information, in the form of narrative descriptions of places: descriptions that could be reproduced, stored, bought, and sold with little concern for international boundaries.

This chapter traces the relationship between geographic information and the discipline of geography, from those early beginnings to today, and speculates on where all of this is leading us. First, I describe geographic information as we think of it today, following what we might call the digital revolution and the advent of the information society. Second, I describe its role in everyday human activities, and how the technical world of geographic information technologies is attempting to engage with the human world of verbal description. Third, I discuss various ethical and societal issues that arise as a result of the massive investments that have been made in geographic information and associated technologies in recent decades. Finally, I discuss how visions of the role of geographic information have changed over the past half-century, and speculate on what the future might hold.

References have been included to provide further explanation where appropriate. One further point should also be made at the outset: while I have attempted as far as possible to explore the international dimensions of the topic, this perspective inevitably reflects my experience as an academic geographer based in Canada and the US.

16.2 Geographic Information Today

16.2.1 The Roots of GIS

By the mid-1960s, computers were becoming ubiquitous in universities and large organizations, and ideas for using them to process geographic information began to take shape. Perhaps the best-known of these was the Canada Geographic Information System, a component of a federal-provincial project known as the Canada Land Inventory. Roger Tomlinson, a British–Canadian geographer, conceived of using computers to measure the quantities of land that could be available for specific uses, and led a contract that the Government of Canada signed with IBM. Measurement of area was the only purpose and statistics were the only product; at the time there was no available means to produce output in map form (Tomlinson and Toomey 1999).

Tomlinson began to promote the idea of a geographic information system (GIS), an integrated computer application that would acquire, store, and process many types of geographic information for a range of purposes. Those purposes became clearer as Tomlinson built a worldwide network of researchers with interests in computer applications of geographic information, and convened international conferences in 1970 and 1972 (Tomlinson 1971, 1972) under the auspices of the IGU's Commission on Geographical Data Sensing and Processing. Digital maps could be created and edited during the map compilation process, just as word processors are used to compose text. Images from satellite-based or aerial remote sensing could be digitized, and computers could be used to classify the raw images and to search for specific features. Digital maps could be used for planning, by combining layers representing variables such as groundwater, surficial hydrology and geology, transportation networks, human settlements, and soil characteristics, following the ideas then being advanced by the landscape architect McHarg (1969). Geographic information about transportation could be converted to digital form and processed in the development of transportation plans. All of these projects and more began to fuel the development of GIS (for histories of the early development of GIS see Coppock and Rhind 1991; Foresman 1998), and the IGU played a significant role as a host for international discussions and exchange (see, for example, Mounsey 1988). By the end of the 1970s, several companies were marketing GIS software, forming the beginning of what is now a global GIS industry with annual sales of software, data, and expertise in the hundreds of billions of US dollars.

16.2.2 New Types of Data

The geographic information that drove the development of CGIS was of a single type which today we would describe as an *area-class* map: lines on a map that partitioned the area into irregularly shaped zones of specific classes. Area-class maps include themes of soil, forest types, current land use, and land cover, and constitute a very significant percentage of all maps. But there are many other types of geographic information, and many of the developments of the 1970s and 1980s were directed at advancing GIS to accommodate them, thus opening an array of new applications and allowing geographers to ask new kinds of questions.

Many other developments followed. While the map remains the dominant metaphor for the contents of a GIS, there are many types of geographic information—information about what is where (and perhaps when)—that are not easily expressed in map form using standard map-making tools (Goodchild 1988). They include the third spatial dimension, since maps are of necessity two-dimensional; dynamics since maps are inherently static; and gradients, which are difficult to portray with a pen. All of these were addressed in the 1990s and early 2000s, driven in part by some well-publicized critiques of GIS in the early 1990s, and enabling a range of new applications that used types of data that had never been mapped in the past. Today, GIS has advanced to the point where it can accommodate virtually any type of geographic information, but there remain important exceptions. There may be subjective feelings about places that are better expressed in other media, such as text or song, and there may even be esthetic aspects of maps that are hard to capture and reproduce in the algorithmic environment of a GIS.

16.2.3 Sources of Geographic Information

One of the factors driving interest in geographic information in the past three decades has been the increasing ease with which it can now be produced. The advent of the Global Positioning System (GPS) in the late 1980s had dramatic influence, especially after 2010 with the inclusion of GPS chips in smartphones and vehicles. With advances in software, it became possible for the small organization and even the individual to acquire the means of map-making, and the newly available Internet was clearly capable of supporting the widespread sharing of digital information of all kinds. The vision of a spatial data infrastructure emerged in response to these changes, first in the US (NRC 1993) and subsequently in many other parts of the world. Its central argument was that the federal government would adopt a new role, as a setter of standards and coordinator of activities, rather than as a dominant producer. It would sponsor a national clearinghouse of digital geographic data (Goodchild et al. 2007), a national standard for metadata (methods for describing the essential features of data sets), and national standards for the quality of geographic information.

With GPS, drones with aerial cameras that could capture fine detail, easy access to existing digital data via the Internet, and inexpensive mapping software, it was clear that the citizen could become both a consumer and producer of geographic information. Projects such as OpenStreetMap (openstreetmap.org) recruited volunteers to create digital maps, by traveling around their own neighborhoods, and by interpreting fine-resolution imagery of other parts of the world. It soon became apparent that any distinction between the trained professional and the amateur was disappearing, as citizens began to acquire skills that had previously been limited to experts. The term *neogeography* (Turner 2006) provided a suitable way of describing this development, and the term *volunteered geographic information* (Goodchild 2007; Sui et al. 2012) was coined to describe geography's own subset of crowdsourcing and citizen science.

Other ways of determining what is where began to emerge following further technical developments. Vast amounts of geographic information were being generated by the GPS receivers being carried by individuals and vehicles. Largely unbeknownst to their users, their locations were generating "pings" at frequent intervals that were being captured by vendors, aggregated, and sold on to a rapidly growing industry where they would be used to build models of the owner's spatial behavior. In principle, the user has the ability to turn off these functions, but few are aware of their implications and sufficiently skilled to do so. While we are assured that the pings have been anonymized by stripping them of any reference to an individual, it is nevertheless easy to string together the pings generated by an individual device and to make accurate inferences about the identity of the owner, his or her home and work locations, the identity of his or her doctor, and many other attributes that people would not normally be willing to share (Valentino-DeVries et al. 2018).

GPS is a powerful way of determining location, but many other tools now exist with a similar purpose. RFID (radio frequency identification) is the technology underlying many smartcards and can be used to determine when and where these cards are used: when taking money out of a bank machine, or when boarding public transit, for example. QR codes are increasingly popular and have a similar effect. Bluetooth also allows the determination of position and can be used to determine the exact location of a shopper's phone inside a store. Wifi is another emerging technology for determining position indoors (Chen and Chen 2021).

With GPS, it has also become easy to tag many kinds of records with the geographic location of the user. Social media services such as Facebook and Twitter allow the user to do this, and geographers have been quick to explore the implications of knowing where and when a particular message was posted. It is possible now to trace the spread of a disease as people post messages or to provide early detection of disasters (Issa et al. 2017). Other projects have shown how it is possible to attach additional sensors to smartphones or to Internet-connected vehicles; for example, suitable sensors can be used to create detailed maps of air pollution or urban heat islands as they follow their users around a city (Schneider et al. 2017).

Finally, a large group of technologies form what is known as the Internet of Things (IoT), and contribute to the concept of the "smart city." Many new vehicles are now fitted with sensing devices and access to the Internet, allowing others such as truck fleet managers or insurance agencies to know much about the driver's locations and driving habits. Home security devices may be connected to the Internet, allowing homeowners to monitor the home while away. Sensor networks are widely deployed in major cities, to monitor and control traffic, urban air pollution, or noise. Closed-circuit television (CCTV) cameras image cities and highways and provide information that is widely used in fighting crime. By combining CCTV with facial recognition, cities are now able to identify and track a specific individual and to signal alerts when any unusual activity occurs. At time of writing, there were an estimated 630,000 CCTV cameras in London and 1.15 million in Beijing. Perhaps most frightening is the imbalance between the credibility of CCTV video on the one hand, and the ease with which it can now be fabricated on the other. In short, it is now possible to imagine a world in which we know the location of everything, at all times, and in which any form of personal privacy has become impossible. Alarms have been sounded for many years about the implications of all of this, from the Panopticon (Schofield 2009) to 1984 (Orwell 1949). I discuss these implications in detail below.

16.3 Consumerization

As geographic information and its uses have become more ubiquitous it has been necessary to pay more attention to how humans learn and think about their surroundings. One effect has been a growing importance for concepts of *place* alongside the expert's concept of *space*. Another has been a remarkable shift in mapping practice, as geographers and others have tried to escape the limitations of past practice by acquiring geographic information about an entirely new range of phenomena. These two topics form the subsections of this discussion of consumerization.

16.3.1 Space and Place

In cartography, surveying, and geodesy the question of "where" is addressed with measurements, to an accuracy determined by the measuring instrument. Latitude and longitude are perhaps the most universal measurements, using the Equator and the Prime Meridian, and expressing distances from these reference lines as angles; but there are many other coordinate systems in use. These coordinates are the basis for representing all data types in GIS, and in geographic information technologies in general.

Yet all of this has little to no direct relevance to the day-to-day life of humans. Almost no one can recall the latitude and longitude of his or her home when asked, though they almost certainly use mapping and wayfinding technologies every day. Instead, humans learn about and discuss the world through a hierarchy of named places: room, house, street, neighborhood, city, county, state, country, or continent. When humans interact with geographic information technologies, they do so in the language of place names and rely on the technology to translate these into coordinates. Thus, in using a wayfinding app the user will first specify a destination as a place name or by pointing on a map and perhaps work through a number of steps designed to autocorrect and disambiguate in order to confirm the exact desired destination.

By the 1990s it had become essential to be able to convert a street address to coordinates, a process known as geocoding, in support of census taking, mail delivery, and the compilation of health statistics. GIS applications for vehicle routing and scheduling also became popular in the 1990s, leading to the development of "navigable" databases that would know not only where the roads and streets were, but how they were connected, what the speed limits and turn restrictions might be, and all of the other information needed to successfully route oneself from an origin to a destination.

As these tools became more available to the public, and especially following the introduction of the smartphone, more and more reliance was placed on what became known as point-of-interest (POI) databases. These link named places with coordinates, and include all businesses, all housing units, all churches, all named landscape features such as mountains and parks, and anywhere else that a person might specify as a trip origin or destination. Today the POI database for a major city will have an order of magnitude more records than the city's population. In short, the consumerization of GIS has led to a radical rebalancing of space and place, or coordinates and place names. The essential vagueness of human discourse is now encountering the precision of digital technologies, leading in turn to a host of interesting research questions.

16.3.2 What Should Be Mapped?

The traditional answer to this question reflected many realities: the difficulty and cost of obtaining detailed information about potentially remote parts of the geographic world; the limited accuracy of measuring instruments; and the high cost of compiling information in map form. Producers of maps responded by ensuring that these costs could be mitigated by the widest possible range of benefits from applications, for as long as possible. Accordingly, maps should represent only those aspects of the Earth's surface that were essentially static: physical features, settlements, the transportation infrastructure but not the vehicles that use it, and residential populations expressed as densities, but not migrants or journeys to work. Mapping practices largely originated in Europe and North America and were often imposed on other parts of the world with little respect for local cultures, concepts of land ownership and use, or the features of the local landscape that were important to its inhabitants. Mapping became a tool used by the colonial powers to impose their rule (Keay 2000), often by replacing traditional place names with references to explorers, colonial masters, or the map-makers themselves.

Underlying these practices is the belief that mapping is an objective scientific process; that the process is replicable, such that two people asked to produce the same map independently would arrive at the same result (within the bounds of measurement error). This may be an acceptable position with respect to political boundaries and property ownership, and even for many well-defined physical features. But it begins to fall apart in the case of soil maps or maps of land cover; indeed, for most of the maps that were included in the Canada Geographic Information System that was discussed above. In the 1990s a number of researchers launched a broader challenge (Harley 2001; Wood 1992), arguing that maps were social constructions that could be interrogated to reveal aspects of the agenda of their makers. From this perspective, there could be no single, true map, but only a series of maps reflecting the different perspectives of individuals, cultures, or social groups.

16.4 Ethical and Societal Issues

16.4.1 The Critique of GIS

Geographers everywhere were quick to explore the opportunities offered by digital geographic information and its associated technologies. Computers appeared to offer endless opportunities for analyzing data using the rapidly expanding set of methods commonly known as spatial analysis (Berry and Marble 1968); and it seemed that GIS might serve to integrate all of these methods in a computational infrastructure for the discipline. Yet the 1970s and 1980s also saw a swelling movement against this apparently wholesale adoption of a positivist methodology, which appeared to be reducing humans to predictable automata, and by 1990 much of this critique had come to focus on GIS and its roots in geographic information.

Another line of critique challenged the degree to which digital geographic information could capture useful representations of the geographic world. The area-class map which dominated CGIS and the early commercial software products such as Esri's ARC/INFO forced the world into a very simple model in which sharp changes occurred at boundaries, and the area within each boundary was treated as homogeneous. This "Boolean" view of the world was clearly a vast oversimplification, yet widely applied in the practices of many agencies. In effect, the world was being simplified to fit the needs of GIS.

Yet another line of critique concerned the cost of GIS. Although the "cost of entry" was declining rapidly, in the early 1990s GIS was essentially limited to governments, corporations, and universities. This fed a sense that it was being used to strengthen the power of the already powerful, and to further marginalize those individuals and groups who were least able to afford the cost. Moreover, the perspectives of those groups, over such issues as planning proposals, were likely to involve the kinds of information—feelings, attitudes, and subjective judgments—that GIS was least able to represent. All of these critiques were assembled in a ground-breaking book edited by Pickles (1995) and titled *Ground Truth: The Social Implications of Geographic Information Systems*. The critiques led to a string of new research communities—Alt-GIS, GIS/2, Critical GIS, etc.—and to a significant degree of collaboration between the traditional GIS community, with its developers, educators and advocates on the one hand, and leading critical geographers on the other (Nyerges et al. 2011).

16.4.2 GIScience

For Tomlinson and others, the central issue of geographic information technologies was what they termed *spatial data handling*: the challenges in adapting computers, their software, and their processes of input and output to the special characteristics of geographical data. The term suggested that building and operating GIS would be a problem in engineering, although it was reasonable to expect that some of its functions could lead to new scientific knowledge. By the mid-1980s, interest was growing among scientifically oriented GIS users in the implications of some of the assumptions that had been made in building the technology. Most notable among these was the assumption that the map was the truth.

Research into these issues began in earnest in the 1980s (Burrough 1986; Goodchild and Gopal

1989), with the objectives of describing the errors in GIS input, representing the errors in GIS databases, and propagating the errors into GIS output. By the late 1980s, it was clear that the term "error" was inadequate, implying as it does the existence of a true value. Many properties being input to GIS lacked precise definitions; in the case of soil maps or land-cover maps, for example, the definitions of classes are commonly vague, using terms such as "mostly". The term "error" was replaced with "uncertainty", and researchers began to explore the potential of fuzzy sets (Frank and Mark 1991).

Interest in uncertainty led quickly to the realization that GIS was more than a simple application of computing: that it raised many issues of an intellectual nature, and contained the possibility of its own body of theory. In 1992 I published a discussion (Goodchild 1992) with the title "Geographical information science", which is now commonly abbreviated to GIScience. There are several ways of defining GIScience: as the scientific knowledge that enables GIS technology; as what the intelligent and experienced user of GIS thinks about when employing the software; as a set of principles that are generally known to be true of geographic information; and as the use of GIS to acquire scientific knowledge.

Underlying all of these is the essential truth that GIS deals not with reality, but with representations of reality that differ from reality in important ways. Korzybski (1933) expressed this succinctly as "the map is not the territory". GIS representations will always approximate, generalize, and abstract, sometimes omitting detail that turns out in hindsight to have significant impact on the results and the decisions that they support. Thus the intelligent and experienced user of GIS knows that all results must be evaluated carefully, and appreciates the value of ground truth, general geographic knowledge, and fieldwork, in their ability to reveal potentially important differences in the representation.

Two empirical principles stand out as particularly relevant to GIS (Anselin 1989). The principle of spatial dependence holds, in the words of Tobler (1970; and see also the forum edited by Sui 2004), that "nearby things are more similar than distant things". The effects of this very simple principle are profound: it enables the making of intelligent guesses about unobserved properties, by assuming that they are similar to known properties that are nearby (the function known as spatial interpolation); it enables the plotting of contours on maps of elevation; and it enables representations such as area-class maps that aggregate areas into polygons based on their degree of internal similarity. At the same time, it raises issues for any application of the methods of inferential statistics, since geographers must often deal with samples that have not been drawn independently from a parent distribution. The principle of spatial heterogeneity describes the essentially variable nature of the Earth's surface, and implies that it will always be difficult to generalize from one study about other studies in other locations, and potentially at other times.

16.4.3 Artificial Intelligence

With the growth of computer applications in geographic research, it was perhaps inevitable that the idea of automating geographic research would surface. In the 1980s Dobson (1983) advanced the notion of automated geography, and Openshaw advocated what he called a geographic analysis machine, that would take over the task of searching for suitable models based on their degree of fit to data (Openshaw et al. 1987; Openshaw and Openshaw 1997). In the case of spatial interaction, for example, where tables are compiled of the number of travelers, migrants, telephone calls, or commuting trips between origin areas and destinations, he suggested that a machine could take over the process of model formulation and analysis. The researcher would identify the likely explanatory variables—distance, travel cost, travel time, population of origin area, attractiveness of destination—and would explore every possible mathematical combination of these variables, ranking the combinations by their goodness of fit to the data.

Today these early ideas of automated research as a form of artificial intelligence have evolved into the field of machine learning, which has scored many successes in classification and prediction. Geographers have begun using machine learning (or *GeoAI*) to classify images, and to search for features in vast collections of images (Janowicz et al. 2020; Li 2020). But many questions have been raised about the use of machine learning in science, and its implication that the human actor is playing less and less of a role in research. The kinds of scientific knowledge, explanation, and understanding that have traditionally formed the goal of science are hardly satisfied by classification and prediction, and Pearl and Mackenzie (2018) have described machine learning as an elaborate form of curve fitting. The detailed outputs are hard to interpret, consisting of large collections of weights, and the concept of replicability, which lies at the heart of the scientific tradition, may be beyond the capabilities of machine learning: how can one compare the results of machine learning in order to determine if a result has indeed been replicated?

16.4.4 The Role of Geographers

Geographers played a key role in the development of GIS, as discussed above, and many methods of spatial analysis have been invented by geographers (see, for example, Anselin 1995; Fotheringham et al. 2002, 2017). But by the advent of the twenty-first century, many other disciplines had staked out their claim to geographic information technologies, leaving geographers to wonder what their long-term role might be. Computer scientists had contributed many of the original ideas to projects such as CGIS, and have long seen such topics as spatial (and spatiotemporal) databases, computational geometry, spatial reasoning, and human-computer interface design as important topics within their discipline. As applications of GIS spread across many university campuses, courses and programs were established in many departments, including geology, archaeology, and even religious studies. Many universities responded by establishing interdisciplinary centers to provide essential support to what had become a truly cross-disciplinary activity.

If ever there was a case for geography as the owner of GIS, that case has long been lost. One response has been to argue that geographers have the greatest expertise in the technology and its use, and can and should play essential roles in the kinds of team-based research that are now increasingly common. But this is to argue that GIS is a service, just as the library is a service, which should therefore be the responsibility of units that are budgeted and managed as services, rather than by an academic department. On the other hand, the kinds of issues that were addressed above are well suited to the interests of geographers, and not only geographers of a technical bent. So also are the issues addressed above: the principles of GIScience, and the degree to which they enable the technology.

Geography attracts a wide range of students into its majors and graduate programs, from those with a strong technical interest to those whose preferred approach is more humanistic. This has always had a strong beneficial effect on GIS, as students come to combine the mindset reflected in the technology with one that responds to the issues that have been addressed in this section. Moreover, it implies a willingness to reach out beyond the limits of the discipline, into engineering, the social and environmental sciences, and even the arts and humanities. Geography is in many ways an ideal home for the integrating technology of GIS, ideally suited to guiding the development of the technology so that it reflects all dimensions of human activity and concern, and ideally suited to taking a critical perspective on its societal impacts.

16.5 Evolving Visions

The early vision of GIS was grounded in maps, and much of the early content of GIS was derived from maps. By the late 1980s, however, advances in computer graphics and display devices had opened the possibility of displaying, rotating, and zooming into a globe in real-time. The term *Digital Earth* (Guo et al. 2020) was mentioned by then-Vice-President Al Gore in his book *Earth in the Balance* (Gore 1992) and fleshed out in a speech prepared for his delivery in 1998. By 2000 the average personal computer was capable of wrapping an image over a simulated sphere, and in 2005 Google released Google Earth, in effect the first consumer-oriented implementation of the Digital Earth vision. The early vision of GIS was enhanced again when the Internet became popular in the early 1990s, allowing the development of a national spatial data infrastructure. Now geographic information was seen as something to be shared, enabled by the Internet as the channel of communication.

In the future, the prevailing vision of GIS and the relationship between GIS, the discipline of geography, and the information society might best be captured in the concept of an international geospatial infrastructure (Dangermond and Goodchild 2019). Designed to support a vast range of human activities, from courses and programs in universities to wayfinding by the citizen and decision-making by planners, geospatial infrastructure will encompass the data, the software, the users, and the devices that they use to interface with the technology. It will be supported by standards: standards of accuracy and metadata, communications protocols, credentialing of users and developers, and standard data formats. Geographers will play an essential role in this infrastructure, in reflecting critically on its societal impacts, researching standards, acquiring scientific knowledge in the domain of GIScience, and applying GIS to the solution of problems and the support of decisions.

The vision of GIS has always been international, based in part on the early efforts of Tomlinson to build a global network of committed GIS developers, and in part by the global nature of GIS subject matter. Although the IGU played an essential role in those early efforts, the momentum they established has long sustained itself. But there continues to be a need for active participation by the IGU, especially in overcoming international differences in access to software and data, in addressing issues of language in a field that continues to be dominated by English, and in ensuring worldwide access to GIS education.

References

Anselin L (1989) What is special about spatial data? Alternative perspectives on spatial data analysis. Technical Paper 89-4. National Center for Geographic Information and Analysis, Santa Barbara, CA

Anselin L (1995) Local indicators of spatial association—LISA. Geogr Anal 27(2):93–115

Berry BJL, Marble DF (eds) (1968) Spatial analysis: a reader in statistical geography. Prentice Hall, Englewood Cliffs, NJ

Burrough PA (1986) Principles of geographical information systems for land resources assessment. Clarendon, Oxford

Chatwin B (1988) The songlines. Picador, London

Chen F, Chen L (2021) Smartphone-based indoor positioning technologies. In: Shi WZ et al (eds) Urban informatics. Springer, Beijing

Coppock JT, Rhind DW (1991) The history of GIS. In: Maguire DJ, Goodchild MF, Rhind DW (eds) Geographical information systems: principles and applications. Longman Scientific and Technical, Harlow, UK, pp 21–43

Crane N (2003) Mercator: the man who mapped the planet. Henry Holt, New York

Dangermond J, Goodchild MF (2019) Building geospatial infrastructure. Geo-Spatial Inf Sci 23(1):1–9. https://doi.org/10.1080/10095020.2019.1698274

Dobson JE (1983) Automated geography. Prof Geogr 35(2):135–143

Foresman TW (ed) (1998) The history of GIS: perspectives of the pioneers. Prentice Hall, Englewood Cliffs, NJ

Fotheringham AS, Brunsdon C, Charlton M (2002) Geographically weighted regression: the analysis of spatially varying relationships. Wiley, Hoboken, NJ

Fotheringham AS, Yang W, Kang W (2017) Multiscale geographically weighted regression (MGWR). Ann Am Assoc Geogr 107(6):1247–1265

Frank AU, Mark DM (1991) Language issues for GIS. In: Maguire DJ, Goodchild MF, Rhind DW (eds) Geographical information systems: principles and applications. Longman Scientific and Technical, Harlow, UK, pp 147–163

Goodchild MF (1988) Stepping over the line: technological constraints and the new cartography. Am Cartogr 15:311–319

Goodchild MF (1992) Geographical information science. Int J Geogr Inf Syst 6(1):31–45

Goodchild MF (2007) Citizens as sensors: the world of volunteered geography. GeoJournal 69(4):211–221

Goodchild MF, Gopal S (eds) (1989) Accuracy of spatial databases. Taylor and Francis, Basingstoke

Goodchild MF, Fu P, Rich P (2007) Sharing geographic information: an assessment of the Geospatial One-Stop. Ann Assoc Am Geogr 97(2):249–265

Gore A (1992) Earth in the balance: ecology and the human spirit. Houghton Mifflin, Boston, MA

Guo H, Goodchild MF, Annoni A (eds) (2020) Manual of digital earth. Springer, Singapore. https://doi.org/10.1007/978-981-32-9915-3
Harley JB (2001) In: Laxton P (ed) The new nature of maps: essays in the history of cartography. The Johns Hopkins University Press, Baltimore and London
Issa E et al (2017) Understanding spatio-temporal characteristics of Twitter data with geotagged and non-geotagged content: two case studies with topic of flu and ted-movie. Ann GIS 23(3):219–235. https://doi.org/10.1080/19475683.2017.1343257
Janowicz K et al (2020) GeoAI: spatially explicit artificial intelligence techniques for geographic knowledge discovery and beyond. Int J Geogr Inf Sci 34(4):625–636
Keay J (2000) The great arc: the dramatic tale of how India was mapped and Everest was named. Harper Collins, London
Korzybski A (1933) Science and sanity: an introduction to non-Aristotelian systems and general semantics. International Non-Aristotelian Publishing Co, Lakeville, CT
Li W (2020) GeoAI: where machine learning and big data converge in GIScience. J Spat Inf Sci 20:71–77
McHarg IL (1969) Design with nature. American Museum of Natural History, New York
Mounsey H (ed) (1988) Building databases for global science. Taylor and Francis, London
National Research Council (1993) Toward a coordinated spatial data infrastructure for the nation. National Academy Press, Washington, DC
Nyerges TL, Couclelis H, McMaster R (eds) (2011) The SAGE handbook of GIS and society. Sage, Los Angeles
Openshaw S et al (1987) A Mark I Geographical Analysis Machine for the automated analysis of point data sets. Int J Geogr Inf Syst 1:359–377
Openshaw S, Openshaw C (1997) artificial intelligence in geography. Wiley, Chichester UK
Orwell G (1949) 1984: a novel. New American Library, New York
Pearl J, Mackenzie D (2018) The book of why: the new science of cause and effect. Basic Books, New York
Pickles J (ed) (1995) Ground truth: the social implications of geographic information systems. Guilford, New York
Schneider P et al (2017) Mapping urban air quality in near real-time using observations from low-cost sensors and model information. Environ Int 106:234–247
Schofield P (2009) Bentham: a guide for the perplexed. Continuum, London
Sui DZ (2004) Tobler's first law of geography: a big idea for a small world? Ann Assoc Am Geogr 94(2):269–277
Sui DZ, Elwood S, Goodchild MF (eds) (2012) Crowdsourcing geographic knowledge: volunteered geographic information (VGI) in theory and practice. Springer, New York
Tobler WR (1970) A computer movie simulating urban growth in the Detroit region. Econ Geogr 46:234–240
Tomlinson RF (1971) International Geographical Union. Commission on Geographical Data Sensing and Processing, Ottawa
Tomlinson RF (1972) Geographical data handling. International Geographical Union, Commission on Geographical Data Sensing and Processing, Ottawa
Tomlinson RF, Toomey MAG (1999) GIS and LIS in Canada. In: McGrath G, Sebert L (eds) Mapping a northern land: the survey of Canada 1947–1994. McGill–Queen's University Press, Montreal (chapter 15)
Turner A (2006) Introduction to neogeography. O'Reilly, Sebastopol, CA
Valentino-DeVries J et al (2018) Your apps know where you were last night, and they are not keeping it secret. New York Times, 10 Dec. https://www.nytimes.com/interactive/2018/12/10/business/location-data-privacy-apps.html?searchResultPosition=1. Accessed 21 Feb 2021
Wood D (with Fels J) (1992) The power of maps. Guilford, New York

Michael F. Goodchild is Emeritus Professor of Geography at the University of California, Santa Barbara. He received his BA degree from Cambridge University in Physics in 1965 and his Ph.D. in geography from McMaster University in 1969, and has received five honorary doctorates. He was elected member of the National Academy of Sciences and Foreign Member of the Royal Society of Canada in 2002, member of the American Academy of Arts and Sciences in 2006, and Foreign Member of the Royal Society and Corresponding Fellow of the British Academy in 2010; and in 2007 he received the Prix Vautrin Lud.