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Geography and geographic information science: An evolving relationship

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Key Messages

- GISystems have their roots in Geography, but that relationship has passed through three clearly identifiable phases.
- In the second phase Geography assumed responsibility for developing the intellectual basis of GIScience, and for the social critique of GISystems.
- Today the growth of data science and the consumerization of GISystems are creating a new phase in the relationship.

GISystems have strong and longstanding roots in Geography, stemming from early developments in the 1960s and 1970s that defined a first phase of their relationship. But as the uses and sophistication of geospatial technology have grown and spread across virtually all areas of the academy, reducing Geography's claim to ownership, that relationship to Geography has evolved in new directions, forming a second phase. The critiques of the early 1990s have led to research into the societal context and social implications of GISystems that remains largely centred in Geography; techniques for the analysis of data embedded in space and time remain strongly associated with Geography; and rigorous principles have been discovered under the umbrella of GIScience that are widely recognized within and outside Geography. Today the relationship has entered a third phase, defined by the new opportunities that are being created by the growth of data science, by new sensors, and by new areas of application, suggesting that the relationship between Geography and GIScience will continue to evolve in interesting and exciting ways.

Keywords: Geography, GISystems, GIScience, data science

Géographie et science de l'information géographique : une relation en évolution

Les SIG ont des racines solides et de longue date en géographie qui originent des premiers développements au cours des années 1960 et 1970, lesquels ont défini une première phase de leur relation. Mais les utilisations et la sophistication de la technologie géospatiale ont augmenté et se sont répandus dans pratiquement tous les domaines universitaires, réduisant ainsi la revendication de propriété de la géographie envers les SIG. La relation des SIG à la géographie a ensuite évolué dans de nouvelles directions, formant une seconde phase. Les critiques du début des années 1990 ont mené à la prise en compte du contexte social et des implications sociales des systèmes de SIG, considérations qui demeurent largement limitées au champ de la géographie. Ainsi, les techniques pour l'analyse des données intégrées dans le temps et l'espace demeurent fortement associées à la géographie alors que les principes qui ont été développés sous l'égide de la science des SIG sont reconnus à la fois au sein et à l'extérieur de la géographie. Aujourd'hui, la relation entre les SIG et la géographie est entrée dans une troisième phase qui est caractérisée par de nouvelles possibilités créées par la croissance de la science des données, par de nouveaux capteurs et par de nouveaux domaines d'application. Tous ces changements suggérent que la relation entre la géographie et la science des SIG continuera d'évoluer de manières originales et intéressantes.

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Introduction

The early computers of the 1950s were largely seen as expensive but powerful machines for performing calculations, tabulating data, and breaking secret codes. By the mid-1960s, however, a number of projects around the world had found effective ways to use the power of these early computers to handle geographic information: for cartographic composition and editing, by analogy to word processing; for making accurate calculations of properties such as map area that would be tedious if performed manually; and for processing images that had been captured by satellites or aircraft. Many of those engaged in these projects were geographers who had seen the advantages of using computers in this way, and were able to tap and apply their knowledge of remote sensing, cartography, and related disciplines.

In the mid-1960s Roger Tomlinson used the term “geographic information system” (GIS; to avoid confusion with geographic information science, a term defined in a later section, the acronym will be written GISystem in this paper). To Tomlinson, the term was an appropriate description of a project he was leading for the Government of Canada to compile and analyze the map data being gathered by the Canada Land Inventory, with particular emphasis on the measurement of irregularly shaped areas on maps. By the early 1970s, Tomlinson had become aware of many other projects that were using computers to handle geographic information (GI; that is, information about what is where in the geographic world), and was able to bring together their leaders in two international meetings under the auspices of the International Geographical Union’s Commission on Geographical Data Sensing and Processing (Tomlinson 1971; Tomlinson 1972; for other accounts of the early history of GIS see Foresman 1998). All of these projects were concerned in one way or another with the handling of spatial data, and today the term “spatial data handling” still persists in the title of a biennial conference series.

Tomlinson was a geographer, and for the next 40-plus years a tireless missionary for GISystems and their importance to his discipline. His enthusiasm was infectious, and many other geographers were drawn to the cause. But while few would have doubted the essential relationship between Geography and GISystems in those early days, dramatic changes have occurred in the ensuing decades. The purpose of this paper is to trace this evolution, to identify its major phases, and to speculate on its future. The implications of these changes for Geography and GIScience today are addressed in the concluding section. Inevitably the views expressed in this paper are to some degree personal, based on the author’s involvement with Geography, GISystems, and GIScience over more than half a century.

The relationship, Phase 1

Because the computers of the 1960s and 1970s were expensive, with very limited power, it was necessary to make certain choices and assumptions. This section explores those choices, using Tomlinson’s efforts as a case in point, and shows that they were consistent with existing practices in Geography, and especially in cartography, remote sensing, and related geographic fields. The early efforts of Tomlinson and others clearly set GISystems on a path that reflected those practices, and the legacy of those choices and assumptions are still in many cases with us today.

Early choices

The Canada Land Inventory was a collaboration between the federal and provincial governments of Canada, driven by concern over the vastness of the Canadian land resource and what was believed at the time to be its significant under-utilization. It aimed to investigate the use of land, asking questions about its current use and its possible conversion to other uses. Large numbers of maps were made at a detailed scale, focusing on the parts of southern Canada near the United States border, and using seven separately mapped layers or themes that included current land use, as well as land capability for agriculture, forestry, recreation, and hunting. Tomlinson’s key insight was to recognize that in order to deliver the vast numbers of statistics that had been promised to the sponsors, computers would have to be used to overlay the various layers of data and to measure areas with specific combinations of thematic values.

IBM was hired to build the system, to be known as the Canada Geographic Information System

(CGIS). But at that time no methods existed to convert the contents of large numbers of maps to digital data, and there were no algorithms to perform the necessary manipulations. Moreover the mainframe computers of the mid-1960s would require all data to be stored and processed sequentially on magnetic tape, would cost millions of dollars, and would have very much less computing power than the smartphones of today. Given these limitations, several key decisions had to be made, some of which still underlie the operations of GISystems today (Goodchild 2018b).

First, the input maps, which showed areas of apparent homogeneity surrounded by thin cartographic lines, would have to be accepted as the definitive representation of reality. No allowance was to be made for uncertainty, that is, for the essential non-replicability of the data, since it is virtually certain that independent measurements of the location of a point would not be identical; similarly, it is certain that two experts, asked to map the same variable (e.g., soil capability for agriculture) over the same area, would not produce identical maps if acting independently. Boundary lines between areas would be measured from maps and precisely located in the database as sequences of points connected by straight lines; in the language of today, maps would be represented as layers using vectors assembled into polylines.

Second, the maps would have been projected in order to render the curved surface of the Earth on flat paper; and given the size of Canada, the consequent distortions might be substantial. Nevertheless the database would preserve these distortions.

A very elegant solution was found for the storage of maps on sequential magnetic tape. Instead of polygons, each section of common boundary between two polygons (and each section of the map boundary bordering a single polygon) would be represented as a polyline, along with pointers to the attributes of the polygons on each side, in a solution we would now call topological.

In the mid-1960s no graphic output devices existed, and no devices for mass digitizing of input. A custom map scanner was built, and algorithms developed for conversion of the raster scan to vectors. But the original design allowed only for numerical output in the form of tables; plotters and graphic display devices were not available until the early 1970s.

Enlarging the vision

The two IGU commission meetings mentioned previously brought together a number of apparently disparate ways of handling GI in computers, for a range of purposes, and, like CGIS, making a range of enabling assumptions. From this, however, a clear vision emerged, of a GISystem capable of handling many different kinds of GI in a single, monolithic computer application. The package would allow for data acquisition, storage, editing and compilation, analysis, visualization—indeed, for almost anything one could imagine doing with digital GI obtained from maps. By 1980, many commercial companies were engaged in developing and marketing products that largely met the requirements of the vision, and geographers were engaged in teaching about GISystems and researching their applications. These geographers saw GISystems as a way of implementing geographic techniques of data analysis; as a way of formalizing, discovering, and sharing geographic knowledge; and as a significant source of employment for their students.

To accommodate new kinds of GI, Tomlinson's basic topological model of vectorized boundaries for CGIS was extended and modified in numerous ways, and extensions were also made to other systems that had evolved from very different roots. Relational database management systems (RDBMS) were adopted in the late 1970s to store the topological links between polygons and boundary segments. But storing the polyline coordinates proved impossibly awkward in these early systems, leading to the concept of a hybrid database in which the RDBMS stored the topological links and polygon attributes (INFO in the case of Esri's ARC/INFO) and a second database stored the strings of coordinates (ARC in Esri's case). Instead of the vectors of CGIS, some GISystems were built based entirely on layers that were represented using a single rectangular mesh or raster, a solution which made the overlaying of layers much easier and simplified various other algorithms; area could be measured, for example, simply by counting cells. Other GISystems allowed for the representation of road networks by adapting the boundary networks of CGIS to permit one-valent nodes (dead ends).

Yet early GISystems fell far short of providing a comprehensive approach to the representation of GI. We might think of GI as a cube (Berry 1964), ignoring for a moment the Earth's curvature, and using the two horizontal geographic dimensions plus time (the basis of today's concept of the data cube). Instead of time, the third dimension might represent the different themes mapped over the horizontal dimensions (Sinton 1978). If time, themes, and the third spatial dimension are all included, the result is a five-dimensional hypercube. Then it is in principle possible to slice the cube or hypercube in any number of ways. Horizontal slices would produce the familiar maps, and the layers of GISystems, but a social scientist or ecologist might also track a single point through time or across themes (a single column of the cube), and an atmospheric scientist might generate a profile of the atmosphere through time at a single point. Nevertheless the layer remains a central concept in GISystems, and it remains much easier to analyze and display the variation of a single variable across space, than the variation of multiple variables, variation across time, or variation in the third spatial dimension at a single point. Thus the query "tell me everything that is known about this point (in two-dimensional space)" is still difficult to answer even in today's GISystems, despite the oft-repeated claim that they are "the integrating technology."

Moreover it is not only the layer that remains a central concept in today's GISystems, but also the flattening that occurs when the curved surface of the Earth is represented on a paper map using one of a multitude of map projections. The distortions of map projections are largely irrelevant when GISystems are used to analyze small areas, but become important when scales approach the global, or when interrupted or multi-zone projections, such as the Universal Transverse Mercator (UTM), are adopted and used to analyze areas that span interruptions or multiple zones. For example, the widely used six-degree UTM has discontinuities roughly every 470 km in an east-west direction at latitude 45. To be sure, the use of projections is helpful in maintaining the link between GISystems and maps, and reinforcing the central role of the map metaphor, allowing a GISystem to be explained as "a collection of maps in a computer" and thus tapping the human fascination with maps.

A very different history of GISystems can be imagined (Goodchild 2018b) if Tomlinson's original decision had been to base CGIS on digital globes rather than digital maps. At the time physical globes were familiar, but expensive to produce and difficult to store and ship, and limited to scales of 1:12,000,000 or so; moreover, the technical complications of computing on the curved surface of the Earth using trigonometric functions would likely have been insurmountable. But today digital globes are generally familiar as a result of services such as Google Earth, and lack of computing power and appropriate algorithms is no longer a major impediment. GISystems based on digital globes rather than digital maps would avoid all of the distortions that occur in GISystem databases as a result of the prior use of map projections. If the Earth needs to be flattened in order to see its entire surface at once, or to create paper prints, then a projection step can be invoked in order to display the database contents in flattened form. But distorting the GISystem database itself always runs the risk that simple mistakes will be made by analysts who are not alert to the consequences—see, for example, National Research Council (2006, 146), where concentric circles have been drawn on a Mercator projection in the mistaken belief that each such circle connects points of equal distance from the centre.

Summary

By the 1980s, a strong relationship had emerged between Geography and GISystems (the concept of GIScience emerged only later). Geographers led the field, and dominated both education and research (and those geographers were almost exclusively male; significant contributions by women did not emerge until later). Traditional practices in cartography and remote sensing were evident in the basic assumptions implemented in the technology, and the design of GISystems was steadily moving toward a comprehensive approach to the handling of geographic information.

The relationship, Phase 2

Challenges to Geography's dominance

Two major developments of the early 1990s presented challenges to the until-then comfortable relationship between Geography and GISystems. First, many prominent geographers began to question the intellectual merits of GISystems; and the widespread adoption of GISystems as a useful tool by other disciplines tended to reinforce this view. Second, GISystems came under another line of attack because of an apparent disregard for their social implications, ranging from their role in surveillance and the invasion of individual privacy to their strong military roots. The ensuing debates led to the emergence of GIScience and a rethinking of Geography's role vis-à-vis geospatial technology.

The intellectual critique

By the late 1980s, virtually all disciplines that deal with phenomena embedded in geographic space—essentially all of the environmental and social sciences—had explored and adopted GISystems (Maguire et al. 1991). If Geography ever had a monopoly over these systems, that monopoly was fast disappearing as courses on GISystems began to appear in disciplines as diverse as geology, archaeology, and landscape ecology.

Yet even in Geography, serious questions were being asked about this fast-growing computer application. Was it simply a tool, of no greater intellectual interest than Microsoft Office? If so, what justified teaching it in universities, and occupying students in complex but essentially mechanical exercises at computer keyboards? GISystems were described by a leading geographer as "non-intellectual expertise" (Jordan 1988), and departments often pushed back against the high costs of maintaining a program in GISystems, with its accompanying labs and technical support. Were GISystems merely collections of facts about the geographic world rather than repositories of geographic knowledge; were they, indeed, the "quantifier's revenge" for earlier critiques of scientific geography (Taylor 1990)?

It seemed clear at the time (circa 1990) to many in the GISystems research community that if these arguments were to be countered, it could only be through the identification of rigorous principles; that is, theoretically or empirically based concepts that were fundamental to the architecture of GISystems, or provided the essential framework for the effective use of GISystems. Were GISystems a tool, or were they the expression of a science (Wright et al. 1997)? What should go on in the head of the experienced user of GISystems, or of a student learning about them? Was this mental activity no more sophisticated than what occurs in the rote application of known procedures, and of no more intellectual interest than the use of a hammer, or was it instead something more profound, what one might term "critical spatial thinking"?

The decision by the US National Science Foundation (NSF) to make a major investment in what became the National Center for Geographic Information and Analysis (Abler 1987) precipitated a number of efforts along these lines, with the aim of raising the intellectual importance of GISystems. Significant contributions by women and people of colour began to appear at about this time, encouraged by NSF. Goodchild (1992) proposed the term "geographic information science" (GIScience) as an umbrella for these efforts, many of which were longstanding and sometimes predated the advent of GISystems. The proposal clearly resonated with many academics, especially with geographers, although the term has also been interpreted somewhat differently as addressing the advancement of knowledge in domain sciences through the use of GISystems. In a 1999 paper (Goodchild et al. 1999), the authors argued that topics in GIScience could be positioned in a triangular space anchored by three vertices, respectively denoting computers, and the computational representation of geographic forms and processes; users, and the cognitive issues that arise when humans and computers interact; and society, and the broader societal implications of geospatial technology.

Today a rich set of principles is recognized as forming a fundamental basis of GIScience. Some are theoretical, such as the nine-intersection (Egenhofer and Franzosa 1991). Others are empirical, representing tendencies that are observed for all types of geographic information, including the principles of spatial dependence (Tobler 1970) and spatial heterogeneity (Anselin 1989). Another principle emerges from the modifiable areal unit problem (MAUP; Openshaw 1984), which asserts that the results of any analysis of geographic information will depend on the basic spatial units that underlie the data. Uncertainty in geographic information (Zhang and Goodchild 2002) is another essential area of GIScience, reflecting the fact that it is impossible for any item of geographic information—any statement of what is where—to be completely free of every possible kind of uncertainty. Longley et al. (2015) provide a general overview of these principles and their relationship to GISystems.

Other indicators of the intellectual context of GISystems are not hard to find. The term GIScience, and related terms such as "geoinformatics," "geomatics," "spatial information science," "or geoinformation science," are now embedded in the titles of journals, conferences, and programs, and several academic geographers have been elected to national academies, such as the US National Academy of Sciences or the United Kingdom's Royal Society, based on the advances they have made in the intellectually important field of GIScience.

The social critique

Around 1990 another kind of onslaught began to challenge the accepted view regarding GISystems, especially among geographers, beginning perhaps with the work of the cartographer Brian Harley (Harley 2002). Maps are often assumed to be the result of a rigorous process of scientific observation, in which well-defined features, such as mountain peaks and contour lines, settlements, lakes, rivers, and roads, are measured, compiled, and accurately depicted. It follows then, that the processing of GI using computer algorithms will produce scientifically valid results. Yet reference has already been made to the possibility of non-replicability, when two or more experts fail to produce the same map, and also to the essential uncertainty of geographic information. Harley took this one step further, by arguing that despite the appearance of scientific objectivity, maps were in many ways social constructions that could be analyzed as such, in other words treated as text and deconstructed, to reveal the motives and agendas of their makers. If maps are social constructions, then so too are any GISystem databases that may have been created from them. In his book *The power of maps*, Wood (1992) titled one of his chapters "Whose agenda is in your glove compartment?"—referring to the then common practice, long since made obsolete, of keeping a collection of paper tourist maps or a road atlas in the family car.

Several other lines of thought helped to move GIScience away from its roots in a quantitative, science-based approach to geographic information. They included the exploration of qualitative methods (Cope and Elwood 2009), the study of public decision making (Jankowski 2001), and the feminist perspective (Kwan 2002a; Kwan 2002b).

A second theme emerged from the work of the geographer Neil Smith (1992), who argued in an insightful paper that proponents and historians of GISystems had, perhaps unconsciously but nevertheless systematically, failed to acknowledge the role played in the development of the technology by the intelligence community and Eisenhower's "military-industrial complex" (see also Clarke and Cloud 2000). Should the developers of GISystems be held responsible for their misuse, or use in questionable activities such as surveillance? Did GISystems (which remained expensive in the early 1990s) necessarily empower the already powerful? Did GISystem data models oversimplify the world, reducing shades of grey to stark black and white and drawing sharp boundaries where there were only gradations (see, for example, Sheppard 1993)? Ideas such as these were brought together by Pickles in an edited volume titled *Ground truth*: *The social implications of geographic information systems* (Pickles 1995) and led in time to the emergence of the research field of Critical GIS, which today remains largely dominated by geographers. At the end of the 1990s, Schuurman (2000) provided a comprehensive analysis of the discord between human geographers and GIScientists in this period.

Summary

By the late 1990s, the relationship between Geography and GISystems had changed dramatically. GISystems were being taught in many disciplines, and basic geospatial research had taken root in computer science, and to a lesser extent in cognitive psychology and spatial statistics. The simplistic representations that were common in Phase 1 had led to numerous extensions to basic data models. The study of the social implications of GISystems had widened the research agenda substantially and had significant impact on the teaching of GISystems, while a new field dedicated to the discovery of empirical and theoretical principles had emerged in the form of GIScience. Significant contributions by women and people of colour also began to appear in the 1990s, encouraged in part by NSF's emphasis on increasing diversity.

The relationship, Phase 3

New directions

By the end of the 1990s, Geography's relationship with GIScience had bifurcated. While geographers continued to teach and develop GISystems, and use them in their research, their roles in these areas were no longer unique. But the intellectual claim for a special relationship between Geography and

GIScience was now based on two arguments: a focus on the theoretical and empirical principles of GIScience on the one hand, and the examination of the societal context of GI technologies on the other.

Two major trends in the first two decades of the 21st century brought new perspectives and new opportunities. First, dramatic changes appeared in the supply of information, and especially of GI. New generations of Earth-observing satellites offered much finer spatial, temporal, and thematic resolution. Social media began to provide massive quantities of information, much of it geographic, about all manner of variables of social significance. Cheap sensors, some of them fixed in space and some carried on humans, made it possible to represent and portray the state of the world and of human society in unprecedented detail. From this arose the phenomenon of Big Data, and the new discipline of data science.

Second, the world of geospatial technologies was disrupted by what one might term "consumerization." What had previously been the domain of a few experts suddenly became, beginning in about 2005, a form of technology that everyone could utilize in support of their daily activities. The average person became the consumer of sophisticated geospatial services for destination-finding and route guidance. Moreover, the average person was also now empowered to act as a producer of GI, through a form of crowd-sourcing sometimes termed "neogeography" (Turner 2006) or "volunteered geographic information" (Sui et al. 2012). Armed with a GPS-enabled smartphone, any motivated individual could capture and upload real-time information about traffic congestion, corrections to the databases used by providers of way-finding services, and observations about graffiti, potholes, and other concerns of social significance.

Big Data and data science

The term Big Data, and its capitalization, acknowledges not only the vast quantities of data that have become available in the past two decades, but also the speed with which data can now be acquired, disseminated, and analyzed, and the disparate nature of the data's sources. What used to be a well-understood and well-controlled system of observation and compilation, led by national programs of census-taking and large-scale surveys, has now become an unorganized flood that is characterized by volume, velocity, and variety, the three oft-noted properties of Big Data. Provenance and quality are often unknown, with unknown effects on the results of any manipulation or analysis. Several publications have addressed the relationship between Big Data and Geography, including those by Kitchin (2013), Kitchin (2014), Barnes and Wilson (2014), and Thatcher et al. (2018).

In this environment it was inevitable that a case would be made for data as the prime mover of knowledge generation, and that the special issues associated with spatial data would be overlooked. The Fourth Paradigm (Hey et al. 2009) envisioned a science that would "let the data speak for themselves," using techniques of artificial intelligence and machine learning to extract patterns without reference to theory. Yet the concept of a data-driven Geography has a longer history, as is evident in the work of Dobson (1983), Openshaw (1988), and others. Openshaw anticipated the broader outlines of machine learning in his concept of a Geographical Analysis Machine, which would test a given dataset against a vast range of randomly generated theoretical propositions, selecting only those that provided the best statistical fit.

Vast volumes of GI have long challenged the capacity of contemporary computers. The launch of Landsat in the early 1970s produced far more data than any analyst or software package could handle at the time, so the volume property of Big Data is perhaps not the most novel, interesting, or revolutionary to geographers. But the velocity property is distinctly new to a discipline that has thought of data collection as a slow and careful process, especially when field work is involved. Similarly the variety property is novel, given the very limited and sparse sources of data that existed in the past.

Several approaches have long been used in geographic research to address the volume problem. "Divide and conquer" partitions the Earth's surface into small areas that can then be studied individually, as for example when a Landsat coverage of the globe is partitioned into 50,000 scenes, each approximately 100 km on a side. When a scene is studied in isolation it is clearly impossible to identify any processes or phenomena that span scenes—and the principle of spatial heterogeneity clearly argues against generalization from the analysis of a single scene. Other strategies for reducing data volume to manageable size include loss of spatial resolution by omitting fine detail. Yet all of these strategies impact the kinds of questions that can be asked; the advent of Big Data and high-powered computation is providing a host of new opportunities to ask the kinds of questions that have never been asked before. We can now explore the operation of environmental and social processes at much finer spatial and temporal resolution, in some cases at the individual level. We can have the potential to explore processes that work through telecoupling, that is, through interactions over very long distances (Liu 2017), and to investigate the generalizability of findings over large parts of the Earth's surface.

But this new emphasis on data as the foundation of science, largely ignoring the processes by which the data were assembled and the differences that inevitably exist between the data and the real world, is especially problematic for GI. It is impossible to measure location on the Earth's surface exactly; many types of GI are not replicable; and all GI are subject to processes of abstraction, generalization, and synthesis. The differences that result between GI and ground truth, or the map and the territory in the words of Korzybski (1933), are sometimes captured in statements about data quality or about the accuracy of measuring instruments, and many models of uncertainty have been published. But more often it is up to the user of GISystems to understand the impacts that data uncertainties have on the results of analysis. Imagine, for example, a GISystem analysis that produced a result that was unexpected—a result that might constitute a new addition to geographic knowledge. Would the analyst eagerly accept it and proclaim an important new discovery, or would he or she be driven to re-examine the analysis and the data that went into it, trying to bring the result into line with accepted knowledge? In the words of Kuhn (1962), will data science truly lead to a "scientific revolution," or will it act instead to preserve "normal science"?

In short, effective and scientifically rigorous analysis of data using computational tools is highly problematic when there is no knowledge of ground truth, that is, knowledge of the geographic world, either directly through field observation or indirectly through careful description and understanding of provenance and data quality. It is also problematic when there is no knowledge of the social context of the data, and of the importance of people in decisions about how and what should be represented. When data become the foundation of research, rather than the ground truth and social context represented by the data, then the balance of GIScience tilts in the direction of computation and Computer Science, with its algorithms and data models, rather than in the direction of Geography.

Consumerization

If "spatial is special" because of the principles of GIScience outlined in this paper, and if as a result the effective use of GISystems requires a level of complex thinking on the part of the analyst, then opening access to the general public will inevitably raise issues. Today, everyone has access to sophisticated wayfinding tools, to apps that track friends with the appearance of great precision, and to maps generated using readily available data, together with software that implements the elegant principles of map-making developed by cartographers. Tools such as ArcGIS Online and Tableau are promoted as giving the general user easy access to geospatial technology, without the intensive training and education needed to manipulate more traditional desktop tools such as ArcMap and ArcGIS Pro. A business analyst is fully capable of using such tools to make a map of customer and store locations, for example, without any engagement with the complex processes that assembled the digital data for the base map, or geocoded the locations.

Yet while such easy-to-generate maps look impressive, even simple questions like "What is the relationship between customer density and population density?" or "How does market penetration fall with distance from store?" require engagement with more complex GISystem tools and with the full range of critical spatial thinking: topological overlay, the MAUP, spatial dependence, uncertainty, and perhaps even spatial heterogeneity. Without such knowledge, errors, misuse, and misinterpretations are inevitable.

Conclusion

Starting in the mid-1960s, the relationship between GISystems and Geography has passed through three clearly distinct phases: Phase 1 until about 1990, Phase 2 until the first decade of the new century, and now Phase 3. In this third phase the influences of data science and consumerization are unavoidable, making it more critical than ever to recognize the importance of spatial thinking, of the ground truth that underlies all geospatial data, and of the principles of GIScience that emerged in Phase 2. As geographers, it is more important than ever for us to convince the larger world of the reasons why spatial is special, of the broader social impacts of geospatial technology, of the society in which GISystems are embedded, and of the importance of Geography as the discipline where these issues are best addressed.

Yet the application of computers to geographic problems that began half a century ago continues to expand and to stimulate thinking in GIScience and Geography. Connected and autonomous vehicles (CAV; Goodchild 2018a) and the broader area of field robotics (Sturges 2014) raise a host of important issues of a geospatial nature, ranging from the required accuracies of geospatial data to the longer-term impacts of CAV on land use and the geographic form of the city. Rich new datasets on spatial behaviour are becoming available, and stimulating new thinking about human spatial dynamics. And new developments in computer science, in the application of high-performance computing to geographic problems (Wang and Goodchild 2018), will continue to keep GISystems, GIScience, and Geography moving ahead in the coming years.

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