EVOLUTION OF GEOGRAPHIC INFORMATION AND VISUALIZATION SYSTEMS

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Summary

Geographic information and visualization systems have evolved, to some extent, similarly. Both of their origins predate the computer age and both continue to evolve as society changes and the need for more spatial information to support decision making in many different contexts increases. The evolution of geographic information and

visualization systems has also occurred as advances in computer technology have been made, although this relationship is somewhat contested. Geographic information systems, or GIS, have always used the idea of visualization through map displays, but that use is increasing both in sophistication and variety due to real and perceived user needs and the technology that allows for faster visual display. Both geographic information and visualization systems are comprised of contributions from many different disciplines and thus are used by many different disciplines. GIS and some of the associated visualization tools are becoming increasingly accessible to everyone with access to a computer. Many of the more sophisticated advances in visualization such as virtual workbenches remain out of reach to most beyond the dedicated research environment.

1. Introduction

Given their complementary nature, the evolution of geographic information (hereafter GIS) and visualization systems for monitoring geospatial data are described together. Both are interdisciplinary, drawing from and being used in a broad range of backgrounds and disciplines. They both enjoy a history that predates computer technology and one that was spurred on by similar technological advancements. Perhaps, most importantly, GIS and visualization systems are both approaches to discovering and understanding patterns and issues found in geospatial data.

This paper will briefly describe the process by which GIS and visualization systems have changed over time. The purpose is to provide the reader with a general overview rather than technical details regarding the hardware and software associated with these systems. References to specific software and hardware manufacturers and data purveyors will be avoided.

GIS and visualization systems will be defined with respect to each other, particularly in the case of visualization where its many applications extend well beyond the realm of geospatial data. Once these approaches have been defined, the actual evolution will be outlined starting with GIS. The evolution of GIS will be related based on the circumstances and people that have propelled it to its present state. Likewise, the evolution of visualization systems will be described, but again with specific reference to the change it experienced relative to GIS and the use of geospatial data.

The evolution of GIS and visualization systems is, of late, very much tied to accessibility. In other words, the fact that these approaches to working with geospatial data are becoming increasingly available to people regardless of expertise is indicative of their evolution. By the same token, it is also accessibility and the lack of it that is an obstacle to progress. Thus, issues associated with access will also be discussed. Accessibility in this context means more than just availability of the hardware and software. It also includes the financial and cultural costs, both of which can make access to GIS and visualization systems difficult, and perhaps even undesirable, for users from all over the world and from all socioeconomic backgrounds.

The remaining sections of this paper will present what is considered to be the state of the art and the prognosis for future growth in GIS and visualization systems. As with the preceding parts of the paper, these sections will focus on general issues rather than the specific technical characteristics.

2. Geographic Information and Visualization Systems

Visualization is at the core of GIS. Indeed, GIS is very much dependent on visualization for its effectiveness. Without the graphic map displays and related spatial analysis that GIS offers, there would be little to distinguish GIS from other information systems. Granted, the graphic displays available in GIS do not usually come close to exploiting the potential of visualization systems, but even the crude line printer images that were output by earlier GIS helped to trigger the visualization process in the minds of those who were studying them. Visualization systems, on the other hand, do not need geographic information to be useful; take, for example, exploratory data analysis. Visualization systems can be used to aid in the exploration of any data whether it is geospatial or not. Thus, visualization systems provide GIS with an important tool.

2.1. What are Geographic Information Systems (GIS)?

A GIS is generally accepted to be a system for capturing, storing, checking, manipulating, analyzing, and displaying data that are geographically referenced. GIS can be applied in numerous contexts, as is evidenced by the ever-increasing availability of specialized extensions to GIS software packages. For example, GIS applications have been developed for business, health, human services, transportation, oil exploration, and fire risk, to identify just a very few. Occasionally, the definition of GIS is expanded to include the organization that implements the GIS and the individual users. The aspect that sets GIS apart from other systems is its attention to data that are referenced geographically. In other words, data that are tied to some location on the mappable surface, such as the latitude and longitude location of an earthquake's epicenter. Data can also be geographically referenced by street address, postal code, administrative units, statistical units, or any one of the myriad coordinate systems available. Thus, rather than relying on a list of earthquake epicenters and associated data over a ten-year period, a user can see where those epicenters are on a map of the world and combine them with this data for geostatistical analysis. The overarching appeal of GIS is its potential use in a wide array of applications.

2.2. What is a Visualization System Relative to GIS?

A visualization system is characterized by three-dimensional representations of space thereby enhancing the functional scope and efficiency of graphic representations of data in a wide variety of scientific investigations to say nothing of commercial applications, in general. In the case of GIS, visualization provides such tools as the depiction of three-dimensional undulating surfaces or temporal cartographic animations, to satisfy the expanding array of tasks to which it is applied.

Visualization systems are typically referred to as ViSC, visualization in scientific computing. These are systems that allow users to explore, confirm, synthesize, and present voluminous and complex data based on tools that vary in degree of abstraction. These tools can mimic what the user might actually see from a particular perspective, such as a photo of the eroded face of a slope, to graphics that represent relationships that may or may not be visible, such as subsurface structural formations. Thus, GIS clearly uses ViSC, to varying degrees. There are, however, many other examples of ViSC that are used in any instance to support the human process of visualization, for example, medical imaging, process model visualization, and molecular chemistry.

Geographic visualization or geovisualization is not to be confused with ViSC. MacEachren and Kraak describe geovisualization as an integration of ViSC along with approaches from cartography, image analysis, information visualization, exploratory data analysis, and GIS. The results of this integration are, according to MacEachren and Kraak, the "theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data (with data having geospatial referencing)." Research in geovisualization is a reaction to the current application of ViSC methods and tools to geospatial data with little or no consideration for its inherent differences from other kinds of data, including its structure, the importance of names, and geographic scale. Thus, geovisualization goes beyond both ViSC and GIS, affording users the opportunity to more effectively process geographic information so that they can better decipher patterns and connections in complex data sets and discover the knowledge to explain those patterns and connections via the users' experiences processing those data.

3. Factors Spurring the Evolution of Geographic Information and Visualization Systems

Given the complementary nature of GIS and ViSC, some aspects of their development are shared and build on each other. For example, part of GIS's development occurred through the increased use of ViSC tools. While a reasonably thorough address of the evolution of GIS is included, only the aspects of ViSC's evolution that are relevant to geographic information will be included.

3.1. The Growth of Geographic Information Systems

Geographic information systems (GIS) have evolved from geography and cartography with contributions from a variety of disciplines, including, for example, engineering, computer science, and mathematics. Given that GIS is known to many as a means for superimposing different layers of mapped data and relating data geographically, it should not be surprising that the origins of GIS, or rather the aforementioned analysis it facilitates, predate the computer era. There are, in fact, many examples of the historic use of maps to aid in the decision-making process, as cited in Lecture 23 of the National Center for Geographic Information and Analysis (NCGIA) Core Curriculum. In the mid-nineteenth century, an "Atlas to Accompany the Second Report of the Irish Railway Commissioners" showed population, traffic flow, geology, and topography superimposed on one map. Perhaps the most often cited historic example is that of Dr. John Snow's use of a map to show the locations of death by cholera in central London in 1854 to track the source of the outbreak—a contaminated well.

Thus, the kinds of analysis GIS fosters have been around for centuries, but what of the GIS with which most are familiar, that is the one associated with computer technology? The GIS History Project, conducted by an international team of researchers led by

David Mark of the Department of Geography at the State University of New York at Buffalo, is in the process of documenting the history of GIS, among other activities. Thus, for a detailed chronology of GIS, the reader is referred to the links from The GIS History Project Web site, <www.geog.buffalo.edu/ncgia/gishist>. Timothy Foresman's 1998 edited volume, *The History of Geographic Information Systems: Perspectives from the Pioneers*, is another valuable source.

The process of change regarding GIS technology occurred during the 1950s and 1960s primarily in North America and the United Kingdom due to a variety of factors. As the reader will soon recognize, there were a number of efforts occurring simultaneously in different laboratories on different continents with minimal cross-fertilization. In other words, those in London, for example, had little idea what those in Ottawa were doing and vice versa. Certainly, part of this lack of awareness was due to the fact that communication technology then was not what it today, but perhaps more importantly, it was because the researchers involved were completely immersed in the problems at hand. The purpose behind the innovations that culminated in GIS was to solve a very tangible problem in the workplace—the laborious process of making maps and analyzing geospatial data manually. As Tomlinson observed in reference to the development of the Canada Geographic Information System in the 1960s, "Contacts with other lines of activity in automatic cartography and quantitative geography were minimal. For our part, we were far too busy to write papers…"

3.1.1. GIS in Canada

In Canada, the Canada Geographic Information System (CGIS) is one of the earliest GIS, as they are currently perceived, developed that is still operating today. It was started in the very early 1960s through Canada's Department of Agriculture with a specific purpose in mind: to analyze the data collected by the Canada Land Inventory (CLI) and to produce statistics to be used in developing land management plans for large areas of rural Canada. To achieve this purpose, a number of conceptual and technical innovations were necessary. At this time, there was no precedent for such a system given the state of technology at that time. Thus, those closely involved in this project, in particular Roger Tomlinson of Spartan Air Services, had to, among many other innovations, build a scanner to input map data, engineer the vectorization of the scanned images, and design and code the various GIS operations required such as overlay and area measurement. Much of this work was carried out through contracts and collaboration between the Canadian Federal Department of Agriculture, Spartan Air Services, and IBM.

In his retrospective essay on the transition from analogue to digital cartographic representation, Tomlinson credits a number of people with significant contributions to early GIS design. IBM's D.R. Thompson and his team engineered a scanner. Guy Morton's design of the Morton Matrix tessellation scheme was fundamental to the data structure. Don Lever is credited with much of the logic behind the conversion of scanned picture elements (pixels) into topologically encoded polygon boundaries. Others engineered the topological edgematching of polygons and their contents seamlessly over Canada and made it possible for automatic topological error recognition to occur. Data compaction methods were developed and a reference coordinate system devised. CGIS also incorporated, among many others, the ability to change map projections and scale, perform rubber-sheet stretches, dissolve and merge, smooth lines and generalize, and measure area. Tomlinson cites Peter Kingston as the architect of the overall data retrieval system and the polygon-on-polygon overlay process.

Although Tomlinson did not have time to publish his work and the work of others regarding CGIS, he and his colleagues made some personal contacts through travel to workshops and conferences. For those who were receptive to his plans for a GIS, he received encouragement and also inspired it in those who were also struggling with the time and cost associated with making maps and analyzing geospatial data.

3.1.2. GIS in the United States

In the United States, these factors were largely changing cartographic requirements, changing urban transportation plans, basic and applied research being conducted in academic institutions. In fact, many of the examples cited below would be more accurately described as automated mapping systems rather than a GIS. According to McLauglin and Coleman, automated mapping systems contributed to the evolution of GIS, where the former provides automated map making and the latter provides an analysis component in addition to automated map making.

Following World War II, there were changes in the requirements for cartographic products or maps. At a societal level, awareness of social and environmental problems was heightened, and education levels and mobility were on the rise. In the academic world, theories of spatial processes in economic and social geography, anthropology, and regional science were being developed. In the realm of government and industry, improvements in computer technology were underway, particularly in graphics hardware devices.

The cities of Detroit and Chicago were developing transportation plans that required the integration of transportation information such as routes, origins, destinations, and a temporal component. The integration of this information resulted in maps of traffic flow and volume.

Researchers in the Department of Geography at the University of Washington were doing cutting-edge work combining advanced statistical methods with computer cartography and programming. For example, Waldo Tobler was writing algorithms for map projections, William Berry was building his Geographical Matrix of places by attributes, William Bunge was constructing a geometric basis for geography, and Timothy Nystuen was operationalizing the fundamental spatial concepts of distance, orientation, and connectivity. Some of these people heard Tomlinson’s talk at Northwestern University in 1963, where he shared the work in progress of CGIS.

The Harvard Laboratory for Computer Graphics and Spatial Analysis, under the direction of Howard Fisher initially and William Warntz subsequently, developed a number of software packages that had a major influence on the development of GIS. Fisher, an architect, founded the lab in 1966 as part of the Harvard University Graduate School of Design through a grant from the Ford Foundation to investigate automated cartography. Fisher hired programmers to write SYMAP as a general-purpose mapping package with an explicitly analytical rather than a graphical focus. Fisher's programmers had no cartographic experience and thus, any details not specified by Fisher, were set by them. Although it had limited functionality and the graphic output was low quality, SYMAP was the first real demonstration of computer generated maps and thus sparked considerable interest in a previously unheard-of technology.

SYMAP's vector model did not, however, support the analysis required by landscape architects that were closely affiliated with the Harvard Lab. Thus, in the mid-1960s, David Sinton developed GRID to permit multilayer analysis, which eventually grew into IMGRID. ERDAS' geographic imaging software, in fact, evolved from IMGRID. By 1972, when the Lab no longer had an academic leader to generate ideas for implementation, Nicholas Chrisman joined the programming staff and developed POLYVRT to topologically structure data in response to the need for flexible input of data, the transfer of boundary files between systems, and the growing supply of data in digital form. Tom Peucker (now Poiker) joined Chrisman in 1973 and POLYVRT became the basis for an academic contribution to the literature. Denis White, Jim Dougenik, Scott Morehouse, and Chrisman extended POLYVRT into ODYSSEY to focus on the challenges of developing a more efficient polygon overlay algorithm. Although ODYSSEY never reached any users until 1982 and then without commercial backing, remnants can be found in ArcInfo, ESRI's (Environmental Systems Research Institute) flagship GIS product within their ArcGIS software suite. In Chrisman's words, "Scott Morehouse left [the Harvard Lab] to join ESRI where he became lead designer of ArcInfo [a precursor to ArcGIS]. In this way, no matter what happened to ODYSSEY, some of the experience has been used to transform the cartographic toolkit." Thus, several Harvard packages essentially helped to build the application base for GIS.

As in the case of CGIS, much of the research conducted by the Lab did not have much of an impact on the field of geography. This was due to the fact that the Lab was primarily a research group; thus few students were produced to spread computer mapping and analysis throughout their profession. Also, particularly under the direction of Warntz, research that was published appeared in a Lab-sponsored series of photocopied papers rather than in academic journals. Peucker and Chrisman's 1975 seminal article, "Cartographic Data Structures," in *The American Cartographer* was a notable exception.

In the mid to late 1960s, the US Bureau of the Census found that it needed a method of assigning census returns to correct geographical locations and a comprehensive approach to census geography. This very real need resulted in the development of a topological data structure that coded street segments between intersections allowing for address matching, the conversion of street addresses to geographic coordinates and census reporting zones. Using this topological data structure meant that these reporting zones could be related hierarchically, in other words, smaller enumeration units could be nested within in the corresponding larger units. The result is considered the first truly useful nationwide general-purpose spatial dataset.

The first geocoded census in the US was taken in 1970 using the ACG/DIME (Address Coding Guide/Dual Independent Map Encoding, formerly Dual Incidence Matrix Encoding) file structure. DIME revolutionized the classical cartography process by digitally recording all of the annotation, editing and correcting it topologically, and then inserting digitized node coordinates. This file structure was upgraded to GBF/DIME (Geographic Base File/DIME) for the 1980 census in an effort to decrease labor-intensive corrections and updates. By the 1990 census, the huge spatial database of census geography was now being managed using an on-line, topologically structured paradigm called TIGER (Topologically Integrated Geographically Encoding and Referencing). As Don Cooke, one of the architects of the DIME file system, observed in T. Foresman’s 1998 *The History of Geographic Information Systems: Perspectives from the Pioneers*, “Today’s nationwide TIGER file is the backbone of the adoption of GIS in business geographics applications.” He credits the importance of key people in getting this landmark innovation adopted at the Census Bureau rather than the technical innovation itself.

The Census Bureau's production of urban atlases of computer generated maps for selected census variables demonstrated yet another series of applications for statistical mapping packages, in particular the eventual development of PC-based packages. Systematic map databases were being developed around the same time as the computer mapping packages. The CIA's (Central Intelligence Agency) World Data Bank was a digital map of coastlines, rivers, and State boundaries. The World Data Bank is still in use today and is now known as the Relational World Data Bank II (RWDBII). The RWDBII is a regularly updated data file that continues to be used in automated mapping and GIS environments.

Given its role as a supplier of data, the USGS (United States Geological Survey) developed the DEM (Digital Elevation Model) as an automated alternative to digitizing elevation data. They also generated DLGs (Digital Line Graphs) of their 7.5-minute map series using semiautomated digitizing. USGS has also been active in providing public domain software for use with their digital datasets. Thus, activity toward GIS in the US occurred in a variety of settings and for different reasons. There is, however, a common theme: in most instances GIS activity occurred in response to a human need for management and governance in a variety of contexts.

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Biographical Sketch

Ann K. Deakin, PhD is an associate professor in the department of Geosciences at the SUNY College at Fredonia in western New York State. She coordinates the Interdisciplinary Studies in GIS minor. She has also worked as a cartographer for a US federal mapping agency and as a project manager for a GIS data conversion firm. Currently, she serves as a member of the State of New York Office for Technology GIS Coordinating Body and is very active in local community GIS activities. Her PhD is in geography from the SUNY at Buffalo, and her M.S. and B.S. degrees, also in geography, are from Penn State University. Her research interests include the use of maps for navigation in urban environments, GIS applications in rural environments, spatial patterns of municipal level voter turnout, and barriers to movement in rural landscapes.