A BRIEF HISTORY AND PROBABLE FUTURE OF GEOTECHNOLOGY

Joseph K. Berry
Keck Visiting Scholar in Geosciences, University of Denver
Berry and Associates // Spatial Information Systems, Colorado USA

Note: This paper is a distillation of several keynotes, presentations and papers; see Author's Note at the end of the paper.
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OVERVIEW

Information has always been the cornerstone of effective decisions. Spatial information is particularly complex as it requires two descriptors—Where is What. For thousands of years the link between the two descriptors has been the traditional, manually drafted map involving pens, rub-on shading, rulers, planimeters, dot grids, and acetate sheets. Its historical use was for navigation through unfamiliar terrain and seas, emphasizing the accurate location of physical features.

More recently, analysis of mapped data has become an important part of understanding and managing geographic space. This new perspective marks a turning point in the use of maps from one emphasizing physical description of geographic space, to one of interpreting mapped data, combining map layers and finally, to spatially characterizing and communicating complex spatial relationships. This movement from "where is what" (descriptive) to "so what and why" (prescriptive) has set the stage for entirely new geospatial concepts and tools.

Since the 1960's, the decision-making process has become increasingly quantitative, and mathematical models have become commonplace. Prior to the computerized map, most spatial analyses were severely limited by their manual processing procedures. The computer has provided the means for both efficient handling of voluminous data and effective spatial analysis capabilities. From this perspective, all geographic information systems are rooted in the digital nature of the computerized map.

The coining of the term Geographic Information Systems reinforces this movement from maps as images to mapped data. In fact, information is GIS's middle name. Of course, there have been other, more descriptive definitions of the acronym, such as "Gee It's Stupid," or "Guessing Is Simpler," or my personal favorite, "Guaranteed Income Stream."

COMPUTER MAPPING *(1970s, Beginning Years)*

The early 1970's saw *computer mapping* automate map drafting. The points, lines and areas defining geographic features on a map are represented as an organized set of X, Y coordinates. These data drive pen plotters that can rapidly redraw the connections at a variety of colors, scales, and projections with the map image, itself, as the focus of the processing.

The pioneering work during this period established many of the underlying concepts and procedures of modern GIS technology. An obvious advantage with computer mapping is the ability to change a portion of a map and quickly redraft the entire area. Updates to resource maps which could take weeks, such as a forest fire burn, can be done in a few hours. The less obvious advantage is the radical change in the format of mapped data— from analog inked lines on paper, to digital values stored on disk.

SPATIAL DATA MANAGEMENT *(1980s, Adolescent Years)*

During 1980's, the change in data format and computer environment was exploited. *Spatial database management systems* were developed that linked computer mapping capabilities with traditional database management capabilities. In these systems, identification numbers are assigned to each geographic feature, such as a timber harvest unit or ownership parcel. For example, a user is able to point to any location on a map and instantly retrieve information about that location. Alternatively, a user can specify a set of conditions, such as a specific forest and soil combination, then direct the results of the geographic search to be displayed as a map.

Early in the development of GIS, two alternative data structures for encoding maps were debated. The *vector data model* closely mimics the manual drafting process by representing map features (discrete spatial objects) as a set of lines which, in turn, are stores as a series of X,Y coordinates. An alternative structure, termed the *raster data model*, establishes an imaginary grid over a project area, and then stores resource information for each cell in the grid (continuous map surface). The early debate attempted to determine the universally best structure. The relative advantages and disadvantages of both were viewed in a competitive manner that failed to recognize the overall strengths of a GIS approach encompassing both formats.

By the mid-1980's, the general consensus within the GIS community was that the nature of the data and the processing desired determines the appropriate data structure. This realization of the duality of mapped data structure had significant impact on geographic information systems. From one perspective, maps form sharp boundaries that are best represented as lines. Property ownership, timber sale boundaries, and road networks are examples where lines are real and the data are certain. Other maps, such as soils, site index, and slope are interpretations of terrain conditions. The placement of lines identifying these conditions is subject to judgment and broad classification of continuous spatial distributions. From this perspective, a sharp boundary implied by a line is artificial and the data itself is based on probability.

Increasing demands for mapped data focused attention on data availability, accuracy and standards, as well as data structure issues. Hardware vendors continued to improve digitizing equipment, with manual digitizing tablets giving way to automated scanners at many GIS facilities. A new industry for map encoding and database design emerged, as well as a marketplace for the sales of digital map products. Regional, national and international organizations began addressing the necessary standards for digital maps to insure compatibility among systems. This era saw GIS database development move from project costing to equity investment justification in the development of corporate databases.

MAP ANALYSIS AND MODELING *(1990s, Maturing Years)*

As GIS continued its evolution, the emphasis turned from descriptive query to prescriptive analysis of maps. If early GIS users had to repeatedly overlay several maps on a light-table, an analogous procedure was developed within the GIS. Similarly, if repeated distance and bearing calculations were needed, the GIS system was programmed with a mathematical solution. The result of this effort was GIS functionality that mimicked the manual procedures in a user's daily activities. The value of these systems was the savings gained by automating tedious and repetitive operations.

By the mid-1980's, the bulk of descriptive query operations were available in most GIS systems and attention turned to a comprehensive theory of map analysis. The dominant feature of this theory is that spatial information is represented numerically, rather than in analog fashion as inked lines on a map. These digital maps are frequently conceptualized as a set of "floating maps" with a common registration, allowing the computer to "look" down and across the stack of digital maps. The spatial relationships of the data can be summarized (database queries) or mathematically manipulated (analytic processing). Because of the analog nature of traditional map sheets, manual analytic techniques are limited in their quantitative processing. Digital representation, on the other hand, makes a wealth of quantitative (as well as qualitative) processing possible. The application of this new theory to mapping was revolutionary and its application takes two forms—spatial statistics and spatial analysis.

Meteorologists and geophysicists have used *spatial statistics* for decades to characterize the geographic distribution, or pattern, of mapped data. The statistics describe the spatial variation in the data, rather than assuming a typical response is everywhere. For example, field measurements of snow depth can be made at several plots within a watershed. Traditionally, these data are analyzed for a single value (the average depth) to characterize an entire watershed. Spatial statistics, on the other hand, uses both the location and the measurements at sample locations to generate a map of relative snow depth throughout the watershed. This numeric-based processing is a direct extension of traditional non-spatial statistics.

Spatial analysis applications, on the other hand, involve context-based processing. For example, forester's can characterize timber supply by considering the relative skidding and log-hauling accessibility of harvesting parcels. Wildlife managers can consider such factors as proximity to roads and relative housing density to map human activity and incorporate this information into habitat delineation. Land planners can assess the visual exposure of alternative sites for a facility to sensitive viewing locations, such as roads and scenic overlooks.

Spatial mathematics has evolved similar to spatial statistics by extending conventional concepts. This "map algebra" uses sequential processing of spatial operators to perform complex map analyses. It is similar to traditional algebra in which primitive operations (e.g., add, subtract, exponentiate) are logically sequenced on variables to form equations. However in map algebra, entire maps composed of thousands or millions of numbers represent the variables of the spatial equation.

Most of the traditional mathematical capabilities, plus an extensive set of advanced map processing operations, are available in modern GIS packages. You can add, subtract, multiply, divide, exponentiate, root, log, cosine, differentiate and even integrate maps. After all, maps in a GIS are just organized sets of numbers. However, with map-ematics, the spatial coincidence and juxtaposition of values among and within maps create new operations, such as effective distance, optimal path routing, visual exposure density and landscape diversity, shape and pattern. These new tools and modeling approach to spatial information combine to extend record-keeping systems and decision-making models into effective decision support systems.

MULTIMEDIA MAPPING ***(2010s, Full Cycle)***

The previous discussion focused on early GIS technology and its expressions as three evolutionary phases— Computer Mapping (70s), Spatial Database Management (80s) and Map Analysis/Modeling (90s). These efforts established the underlying concepts, structures and tools supporting modern geotechnology. What is radically different today is the broad adoption of GIS and its new map forms.

In the early years, GIS was considered the domain of a relatively few cloistered techno-geeks "down the hall and to the right." Today, it is on everyone's desk, PDA and even cell phone. In just three decades it has evolved from an emerging science to a fabric of society that depends on its products from getting driving directions to sharing interactive maps of the family vacation.

In fact, the U.S. Department of Labor has designated Geotechnology as one of the three "mega-technologies" of the 21st century—right up there with Nanotechnology and Biotechnology. This broad acceptance and impact is in large part the result of the general wave of computer pervasiveness in modern society. We expect information to be just a click away and spatial information is no exception.

However, societal acceptance also is the result of the new map forms and processing environments. Flagship GIS systems, once heralded as "toolboxes," are giving way to web services and tailored application solutions. There is growing number of websites with extensive sets of map layers that enable users to mix and match their own custom views. Data exchange and interoperability standards are taking hold to extend this flexibility to multiple nodes on the web, with some data from here, analytic tools from there and display capabilities from over there. The results are high-level applications that speak in a user's idiom (not GIS-speak) and hide the complexity of data manipulation and obscure command sequences. In this new environment, the user focuses on the spatial logic of a solution and is hardly aware that GIS even is involved.

Another characteristic of the new processing environment is the full integration the global positioning system and remote sensing imagery with GIS. GPS and the digital map bring geographic positioning to the palm of your hand. Toggling on and off an aerial photograph provides reality as a backdrop to GIS summarized and modeled information. Add ancillary systems, such as robotics, to the mix and new automated procedures for data collection and on-the-fly applications arise.

In addition to the changes in the processing environment, contemporary maps have radical new forms of display beyond the historical 2D planimetric paper map. Today, one expects to be able to drape spatial information on a 3D view of the terrain. Virtual reality can transform the information from pastel polygons to rendered objects of trees, lakes and buildings for near photographic realism. Embedded hyperlinks access actual photos, video, audio, text and data associated with map locations. Immersive imaging enables the user to interactively pan and zoom in all directions within a display.

4D GIS (XYZ and time) is the next major frontier. Currently, time is handled as a series of stored map layers that can be animated to view changes on the landscape. Add predictive modeling to the mix and proposed management actions (e.g., timber harvesting and subsequent vegetation growth) can be introduced to look into the future. Tomorrow's data structures will accommodate time as a stored dimension and completely change the conventional mapping paradigm.

SPATIAL REASONING AND DIALOG *(Future, Communicating Perceptions)*

The future also will build on the cognitive basis, as well as the databases, of GIS technology. Information systems are at a threshold that is pushing well beyond mapping, management, modeling, and multimedia to spatial reasoning and dialogue. In the past, analytical models have focused on management options that are technically optimal— the scientific solution. Yet in reality, there is another set of perspectives that must be considered— the social solution. It is this final sieve of management alternatives that most often confounds geographic-based decisions. It uses elusive measures, such as human values, attitudes, beliefs, judgment, trust and understanding. These are not the usual quantitative measures amenable to computer algorithms and traditional decision-making models.

The step from technically feasible to socially acceptable is not so much increased scientific and econometric modeling, as it is communication. Basic to effective communication is involvement of interested parties throughout the decision process. This new participatory environment has two main elements— consensus building and conflict resolution.

Consensus Building involves technically-driven communication and occurs during the alternative formulation phase. It involves a specialist's translation of various considerations raised by a decision team into a spatial model. Once completed, the model is executed under a wide variety of conditions and the differences in outcome are noted.

From this perspective, an individual map is not the objective. It is how maps change as the different scenarios are tried that becomes information. "What if avoidance of visual exposure is more important than avoidance of steep slopes in siting a new electric transmission line? Where does the proposed route change, if at all?" What if slope is more important? Answers to these analytical queries (scenarios) focus attention on the effects of differing perspectives. Often, seemingly divergent philosophical views result in only slightly different map views. This realization, coupled with active involvement in the decision process, can lead to group consensus.

However, if consensus is not obtained, mechanisms for resolving conflict come into play. *Conflict Resolution* extends the Grateful Dead's lyrics, "nobody is right, if everybody is wrong," by seeking an acceptable management action through the melding of different perspectives. The socially-driven communication occurs during the decision formulation phase.

It involves the creation of a "conflicts map" which compares the outcomes from two or more competing uses. Each map location is assigned a numeric code describing the actual conflict of various perspectives. For example, a parcel might be identified as ideal for a wildlife preserve, a campground and a timber harvest. As these alternatives are mutually exclusive, a single use must be assigned. The assignment, however, involves a holistic perspective which simultaneously considers the assignments of all other locations in a project area.

Traditional scientific approaches rarely are effective in addressing the holistic problem of conflict resolution. Even if a scientific solution is reached, it often is viewed with suspicion by less technically-versed decision-makers. Modern resource information systems provide an alternative approach involving human rationalization and tradeoffs.

This process involves statements like, "If you let me harvest this parcel, I will let you set aside that one as a wildlife preserve." The statement is followed by a persuasive argument and group discussion. The dialogue is far from a mathematical optimization, but often comes closer to an acceptable decision. It uses the information system to focus discussion away from broad philosophical positions, to a specific project area and its unique distribution of conditions and potential uses.

CRITICAL ISSUES *(Future Challenges)*

The technical hurdles surrounding GIS have been aggressively tackled over the past four decades. Comprehensive spatial databases are taking form, GIS applications are accelerating and even office automation packages are including a "mapping button." So what is the most pressing issue confronting GIS in the next millennium?

Calvin, of the Calvin and Hobbes comic strip, puts it in perspective: "Why waste time learning, when ignorance is instantaneous?" Why should time be wasted in GIS training and education? It's just a tool, isn't it? The users can figure it out for themselves. They quickly grasped the operational concepts of the toaster and indoor plumbing. We have been mapping for thousands of years and it is second nature. GIS technology just automated the process and made it easier.

Admittedly, this is a bit of an overstatement, but it does set the stage for GIS's largest hurdle—educating the masses of potential users on what GIS is (and isn't) and developing spatial reasoning skills. In many respects, GIS technology is not mapping as usual. The rights, privileges and responsibilities of interacting with mapped variables are much more demanding than interactions with traditional maps and spatial records.

At least as much attention (and ultimately, direct investment) should go into geospatial application development and training as is given to hardware, software and database development. Like the automobile and indoor plumbing, GIS won't be an important technology until it becomes second nature for both accessing mapped data and translating it into information for decisions. Much more attention needs to be focused beyond mapping to that of spatial reasoning, the "softer," less traditional side of geotechnology.

GIS's development has been more evolutionary, than revolutionary. It responds to contemporary needs as much as it responds to technical breakthroughs. Planning and management have always required information as the cornerstone. Early information systems relied on physical storage of data and manual processing. With the advent of the computer, most of these data and procedures have been automated. As a result, the focus of GIS has expanded from descriptive inventories to entirely new applications involving prescriptive analysis. In this transition, map analysis has become more quantitative. This wealth of new processing capabilities provides an opportunity to address complex spatial issues in entirely new ways.

It is clear that GIS technology has greatly changed our perspective of a map. It has moved mapping from a historical role of provider of input, to an active and vital ingredient in the "thruput" process of decision-making. Today's professional is challenged to understand this new environment and formulate innovative applications that meet the complexity and accelerating needs of the twenty-first century.

Author's Note: *This paper is a distillation of several keynotes, presentations and papers. Online references include:*

- ***Spatial Reasoning in a World of Maps**, GeoAlberta Conference, Edmonton, Alberta, Canada, May, 2006. Keynote Address.*
  http://www.innovativegis.com/basis/present/GeoAlberta06/GeoAlberta06.htm
- ***Getting Your Arms Around Geospatial Technology**, Geospatial Information Systems and Science Forum, Washington University, St. Louis, Missouri, November, 2004. Keynote address.*
  http://www.gis.wustl.edu/a-brief-history-and-probable-future.html
- ***GIS Technology in Environmental Management: A Brief History, Trends and Probable Future**, Global Environmental Policy and Administration, Soden and Steel editors, Marcel Dekker Publishers, 1999, pgs. 49-76. J.K. Berry. Book chapter.*
  http://www.innovativegis.com/basis/present/Global/global3.htm
- ***Where Is GIS?** — Driving Forces, Trends and Probable Future of GIS Technology in Natural Resource Applications, Earth Observation Magazine, July, 1995. J.K. Berry.*
  http://www.eomonline.com/Common/Archives/1995jul/95jul_berry.html

Additional papers, presentations and other materials on GIS concepts, considerations and procedures are available online at www.innovativegis.com/basis.