INTRODUCTION

Early GIS Technology and Its Expressions

Considerable changes in expectations and capabilities have taken place since GIS' birth in the late 1960s. I hope to share a brief history and a probable future of this rapidly maturing field as viewed from my "gray-beard" experience of more than 30 years involvement in GIS.

Historical Overview

Information has always been the cornerstone of effective decisions. Spatial information is particularly complex, because 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, 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 1960s, 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 efficient handling of voluminous data and impact effective spatial-analysis capabilities. From this perspective, all GISs are rooted in the digital nature of the computerized map.

The coining of the term "geographic information system" reinforced this movement from maps as images to mapped data. Keep in mind, information is GIS' 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 1970s 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. The map image, itself, is the focus of this 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 the 1980s, 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 wildlife-management parcel.

For example, users can point to any location on a map and instantly retrieve information about that location. Alternatively, users can specify a set of conditions, such as a specific forest and soil combination, and direct the result 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 as sets of lines that, in turn, are stored 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. The early debate attempted to determine the universally best structure. The relative advantages and disadvantages were viewed in a competitive manner that failed to recognize the overall strengths of a GIS approach encompassing both formats.

By the mid-1980s, the general consensus within the GIS community was that the nature of the data and the processing desired determined the appropriate data structure. This realization of the duality of the mapped data structure had significant impact on GISs.

From one perspective, resource maps form sharp boundaries that are best represented as lines. Property ownership, timber-sale boundaries and haul-road networks are examples in which 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, statistical analysis of field data and broad classification of continuous spatial distributions. From this perspective, the sharp boundary implied by a line is artificial, and the data themselves are 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 ensure 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 was programmed with a mathematical solution.

The result of this effort was GIS functionality that mimicked the manual procedures in a resource manager’s daily activities. The value of these systems was the savings gained by automating tedious and repetitive operations.

By the mid-1980s, most descriptive query operations were available in most GISs, and a comprehensive theory of map analysis began to emerge. 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 a computer to “look” down and across a 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, however, makes a wealth of quantitative (as well as qualitative) processing possible. The application of this new theory to mapping is revolutionary. Its application takes two forms: spatial statistics and spatial modeling.

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 that a typical response is everywhere.

For example, field measurements of snow depth can be made at several plots within a watershed. Traditionally, such data are analyzed for a single value (the average depth) to characterize the watershed. Spatial statistics, however, uses the location and the measurements at sample locations to generate a map of relative snow depth throughout the entire watershed.

Spatial analysis, on the other hand, has a rapidly growing number of current resource applications. For example, natural-resource managers can characterize timber supplies 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. Natural-resource planners can assess the visual exposure of alternative sites for a facility to sensitive viewing locations, such as roads and scenic overlooks.

Enter Map Algebra

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’s similar to traditional algebra in which primitive operations (e.g., add, subtract, exponentiate, etc.) 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 as well as an extensive set of advanced map-processing operations are available in modern GIS packages. Users can add, subtract, multiply, divide, exponentiate, root, log, cosine, differentiate and 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 approaches to natural-resource information combine to extend record-keeping systems and decision-making models into effective decision support systems.

In many ways, GIS is “as different as it is similar” to traditional mapping. Its early expressions simply automated existing capabilities, but, in its modern form, it challenges the nature and utility of maps.

Contemporary GIS and Future Directions

Early GIS technology and its expressions as three evolutionary phases: Computer Mapping (1970s), Spatial Database Management (1980s) and Map Analysis/Modeling (1990s) established the underlying concepts, structures and tools supporting modern geospatial technology. What’s 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’s 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 to get driving directions and share interactive maps of the family vacation.

Multimedia Mapping (2010s, Full Cycle)

In fact, the U.S. Department of Labor has designated geospatial technology 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. People 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 GISs, previously heralded as "toolboxes," are giving way to Web services and tailored application solutions.

There's a growing number of Web sites 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), hiding the complexity of data manipulation and obscure command sequences. In this new environment, users focus on the spatial logic of a solution and are hardly aware that GIS is involved.

Another characteristic of the new processing environment is the full integration of Global Positioning System (GPS) 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 2-D planimetric paper map. Users now expect to be able to drape spatial information on a 3-D 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 users to interactively pan and zoom in all directions within a display.

4-D GIS (X,Y,Z 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. Future 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's pushing well beyond mapping, management, modeling, and multimedia to spatial reasoning and dialog.

Previously, analytical models focused on management options that are technically optimal: the scientific solution. But, in reality, there's another set of perspectives that must be considered—the social solution.

It's 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 aren't the usual quantitative measures amenable to computer algorithms and traditional decision-making models.

The step from technically feasible to socially acceptable options isn't 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 it occurs during the alternative formulation phase. It involves a specialist's translation into a spatial model of various considerations raised by a decision team. After completion, the model is executed under a variety of conditions, and the differences in outcome are noted.

From this perspective, an individual map isn't the objective—it's 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.

Nobody Is Right

Often, seemingly divergent philosophical views result in slightly different map views. This realization, coupled with active involvement in the decision process, can lead to group consensus.

However, if consensus isn't obtained, mechanisms for resolving conflict come into play. Conflict resolution extends the Buffalo Springfield's lyrics, "nobody is right, if everybody is wrong," by seeking an acceptable management action through the melding of different perspectives. Socially driven communication occurs during the decision-formulation phase.

It involves the creation of a "conflicts map" that 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, campground and timber harvest. As these alternatives are mutually exclusive, a single use must be assigned. The assignment, however, involves a holistic perspective that 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's often 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 such as, "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 dialog is far from a mathematical optimization, but it 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 as well as its unique distribution of conditions and potential uses.

Critical Issues (Future Challenges)

The technical hurdles surrounding GIS have been aggressively tackled during the last four decades. Comprehensive spatial databases are taking form, GIS applications are accelerating, and office-automation packages are including a "mapping button." So what's 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? Users can figure it out for themselves. They quickly grasped the operational concepts of the toaster and indoor plumbing.

We've been mapping for thousands of years, and its second nature. GIS technology just automated the process and made it easier.

Admittedly, this is a bit of an overstatement, but it sets the stage for GIS' 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 isn't 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 to access mapped data and translate them into information for decisions. More attention needs to be focused beyond mapping to that of spatial reasoning, the "softer," less-traditional side of geospatial technology.

The development of GIS has been more evolutionary than revolutionary. It responds to contemporary needs as much as technical breakthroughs. Planning and management have always required information as the cornerstone, and early information systems relied on physical storage of data and manual processing.

With the advent of the computer, most data and procedures have been automated. As a result, the focus of GIS has expanded from descriptive inventories to new applications involving prescriptive analysis. In this transition, map analysis has become more quantitative. Such a wealth of new processing capabilities provides an opportunity to address complex spatial issues in entirely new ways.

It's clear that GIS technology has greatly changed our perspective of a map. It moved mapping from a historical role of provider of input to an active and vital ingredient in the "throughput" process of decision making. Today's professionals are challenged to understand this new environment and formulate innovative applications that meet the complexity and accelerating needs of the 21st century.

Further Reading

Hands-On Experience