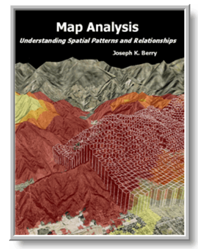
Beyond Mapping III

Topic 27: *GIS Evolution and Future Trends*



[Map Analysis](#) book with companion CD-ROM for hands-on exercises and further reading

Note: The processing and figures discussed in this topic were derived using MapCalc™ software. See [www.innovativegis.com](#) to download a free MapCalc Learner version with tutorial materials for classroom and self-learning map analysis concepts and procedures.

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Early GIS Technology and Its Expression

(GeoWorld October, 2006)

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Considerable changes in both expectations and capabilities have taken place since GIS's birth in the late 1960s. In this and a few subsequent columns, I hope to share a brief history and a probable future of this rapidly maturing field as viewed from grey-beard experience from over 30 years involvement in the field (see Author's Note).

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 Database 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.

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 very nature and utility of maps. The next section focuses on contemporary GIS expressions (2010s) and its probable future directions.

Contemporary GIS and Future Directions

(GeoWorld November, 2006)

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The previous section 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.

Multimedia Mapping (2010s, Full Cycle)

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 options 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 Buffalo Springfield'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.

Pathways to GIS

(GeoWorld December, 2006)

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When did you get involved with GIS technology? How did you get involved? What was your background? What were your application objectives? Answers to these questions define your personal Geotechnology Adoption Path and are unique as you are.

Reflection on generalized adoption pathways for different disciplines can shed light on why a one-sized, all-purpose GIS paradigm is so illusive. Figure 1 is an attempt at describing alternate pathways for several disciplines in which I have experience (and considerable scar tissue) since the mid-1970s.

Geotechnology Adoption Pathways

Discipline	Mapping Legacy	Entry Applications	Initial Ownership Groups	Extended Applications
Natural Resources	Considerable paper map legacy involving discrete spatial objects primarily polygons (e.g., land cover, elevation)	Forest Inventory and mapping (RS, GIS, GPS)	Inventory and Planning (Research)	- Visual exposure analysis - Surface flow analysis - Wildfire modeling
Facilities Management	Considerable paper map legacy involving discrete spatial objects primarily points and lines (e.g., valves, utility lines)	Inventory and recordkeeping (GPS, GIS)	Engineering and Maintenance	- Routing and siting - Off-line impacts/response - Multimedia mapping
Public Health	Minimal paper map legacy involving discrete spatial objects, primarily points and polygons (e.g., counties)	Reporting and communications (GIS)	Publications and Extension (Research)	- Environmental monitoring - Disease vector modeling - Spatial correlation analysis
Business	Negligible paper map legacy involving discrete spatial objects, primarily polygons (e.g., sales districts)	Desktop and online mapping (GIS)	Sales and Real Estate	- Competition analysis - Customer segmentation - Sales prediction
Agriculture	Negligible paper map legacy (e.g., soil maps)	Yield mapping and farm records (RS, GPS, GIS, IDI)	Producers and Consultants (Research)	- Fertilization optimization - Planting decisions - Organic/Genetic tracking

Figure1. Adoption pathways vary in mapping legacies, early applications and initial ownership groups to form differing geotechnology paradigms.

The ordering of the list is neither arbitrary nor chronological. It reflects the similarities among mapping legacies, early applications and initial ownership groups that characterize various pathways to GIS. It is interesting to note that while Natural Resources and Agriculture share common sociological, cultural, political and biological footings, their geotechnology adoption paths are radically different, and in fact, form polar extremes.

The Natural Resources community was one of the earliest groups to follow the geographers' rallying cry in the mid-1970s; enticed by the prospect of automating the mapping process. Their extensive paper-map legacy involved tedious aerial photo interpretation and manual cartography to graphically depict resource inventories over very large areas. The early GIS environment was a natural niche for their well-defined mapping processes and products.

Agriculture, on the other hand had little use for traditional maps, as soil maps are far too generalized and broadly report soil properties instead of nutrient concentrations and other field inputs that farmers manage. Their primary uses for traditional maps were in Boy Scouts or hunting/fishing in mountainous terrain far away from the family farm. This perspective changed in the mid-1990s with the advent of yield mapping that tracks where things are going well and not so good for a crop— a field-level glimpse of the geographic distribution of productivity leading to entirely new site-specific crop management practices.

The alternative perspectives of maps as *Images* of inventory or as *Information* for decision-making are the dominant determinants of geotechnology adoption paths. GIS entry was early and committed for those with considerable paper-map legacy and well-defined, easily extended applications. While immensely valuable, automation of traditional applications focus on efficiency, flexibility and cost savings and rarely challenge "how things are done," or move beyond mapping and basic spatial database management.

Disciplines with minimal paper-map legacies, on the other hand, tend to develop entirely new and innovative applications—the adoption tends to be less evolutionary and more revolutionary. For example, precision agriculture is an application that while barely a decade old, is radically changing crop management practices, as well as guidance and control of farm machinery by extending the traditional spatial triad of RS, GIS and GPS to Intelligent Devices and Implements (IDI) for on-the-fly applications.

The character and constituency of the initial ownership group in a discipline also determines the adoption pathway. For example in the U.S. Forest Service and most Natural Resource entities, the nudge toward GIS was primarily controlled by inventory units at regional and higher bureaucracy levels. The early emphasis of this group was on compiling very large and complex spatial databases over a couple of decades before extensive application of these data—sort of "build it and they (applications) will come."

Contrast this with the Agriculture ownership group comprised of independent crop consultants and individual farmers focusing on a farm landscape of a few hundred acres per field. The database compilation demands are comparatively minor, and more importantly the return on investment stream must be immediate, not decades. Since they didn't have a mapping legacy, efficiency and cost saving of data collection/management weren't the drivers; rather crop productivity and stewardship advancements guided the adoption pathway.

Now turn your attention to the relative positions of the three disciplines in the center of the table. Business' heritage closely follows that of Agriculture— negligible mapping legacy with radically innovative applications involving a relatively diverse, unstructured and independent user community. Mapping in the traditional sense of "precise placement of physical features" is the farthest thing from the mind of a sales/marketing executive. But a cognitive map that segments a city into different consumer groups, or characterizes travel-time advantages of different stores, or forms a sales prediction surface by product type for a city are fodder for decisions that fully consider spatial information and patterns. From the start, geo-business focused on new ways of doing business and return on investment, not traditional mapping extensions.

Contrast this paradigm with that of a Facilities Management engineer responsible for a transportation district, or an electric transmission network, or an oil pipeline—considerable mapping legacy that exploits basic mapping and spatial database capabilities to better inventory installed assets within a large, structured, utility-based industry. Like Natural Resources, the initial on-the-line mapping entry to GIS is broadening to more advanced applications, such as optimal path routing, off-the-line human/environmental impact analysis and integration of video mapping of assets and surrounding conditions.

Now consider Public Health's pathway— minimal paper-map legacy primarily for graphic display of aggregated statistics within very large governmental agencies. Its adoption of geotechnology has lagged the other disciplines. This is particularly curious as it has a well-developed and well-funded research component similar to those in Natural Resources and Agriculture. While these units have been proactive in GIS adoption, the heritage of Public Health research is deeply rooted in traditional statistics and non-spatial modeling that has hindered acceptance of advanced spatial statistics and map analysis techniques. The combination of minimal paper-map legacy and minimal enthusiasm for new applications within large bureaucracies has delayed geotechnology adoption in Public Health—a revolution in waiting.

I have used the Geotechnology Adoption Pathways table in numerous workshops and college courses. Invariably, it incites considerable discussion as students ponder their own pathway and extrapolate personal experiences to those of other students and related disciplines. At a minimum, the lively discussion encourages students to think outside their disciplinary box and confirms the multifaceted GIS community that we'll explore in the next section.

A Multifaceted GIS Community

(GeoWorld January, 2007)

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While mapping has been around for thousands of years, its digital expression is only a few decades old. My first encounter with a digital map was as an undergrad research assistant in the 1960s with Bob Colwell's cutting-edge remote sensing program at UC Berkeley. A grad student had hooked up some potentiometers to the mechanical drafting arm of a stereographic mapping device.

The operator would trace a dot at a constant elevation around the 3D terrain model of hills and valleys created by a stereo pair of aerial photos. Normally, the mechanical movements of the dot would drag a pen on a piece of paper to draw a contour line. But the research unit translated the movement into X, Y coordinates that were fed into a keypunch machine—kawapa, kawapa, kawapa. After a few months of tinkering, the "digital contour lines" for the school forest were imprisoned in a couple of boxes of punch cards.

The next phase of simply connecting the dots proved the hardest. Although UC Berkeley was a leading research university with over 42,000 students, there was only one plotter available. And like the Egyptian period there were only a couple of folks on campus who could write the programming hieroglyphics needed to control the beast. Heck, computer science itself was just a fledgling discipline and GIS was barely a gleam in a few researchers' eyes.

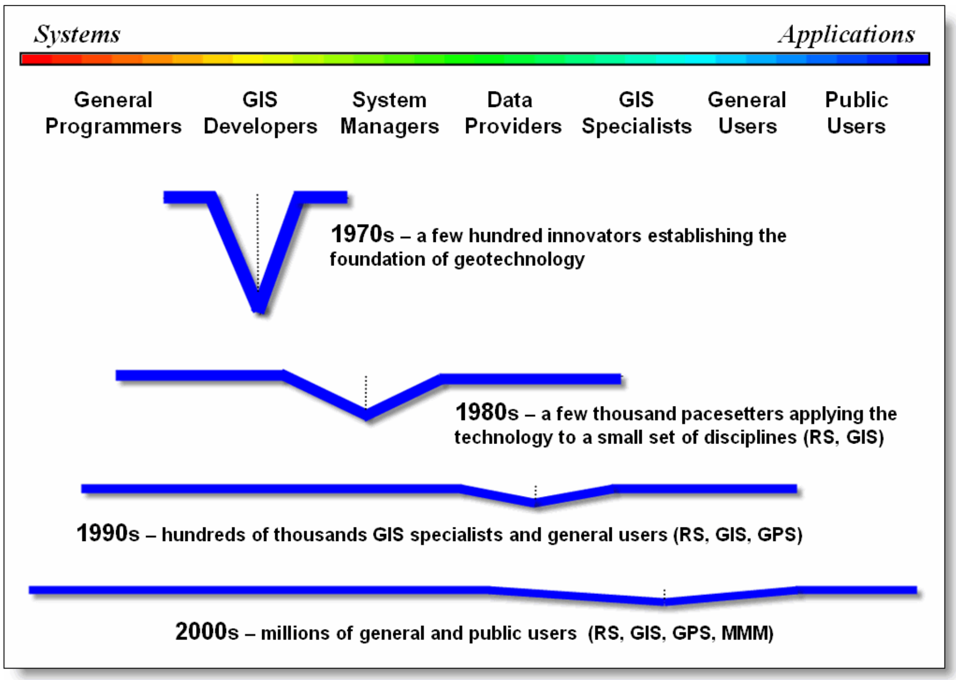

Figure 1. The evolution of the Geotechnology Community has broadened its membership in numbers, interests, backgrounds and depth of understanding.

The old-timer's story sets the stage for a discussion of the human-ware evolution in geotechnology (see figure 1). In the 1970s the GIS community consisted of a few hundred research types chipping away at the foundation. A shared focus of just getting the technology to work emphasized appropriate data structures, display capabilities and a few rudimentary operations. In fact, during this early period a "universal truth" in data structure was sought that fueled a decade of academic crusades between vector-heads and raster-heads. My remote sensing background put me in the dwindling raster camp that eventually circled the wagons around the pixel (picture element) and image processing that effectively split GIS and RS for a decade.

The 1980s saw steady growth in GIS and the community expanded from few hundred researchers to a few thousand pacesetters focused on applying the infant technology. The community mix enlarged to include more traditional programmers on the systems side and systems managers, data providers and GIS specialists in a few of the mapping-oriented organizations on the application side. Most of this effort focused on vector processing of discrete spatial objects (point, line and polygon features). While the greatest effort was on developing databases, great strides in cartographic modeling were made to mimic manual map analysis, such as intersection, overlay, buffer and geo-query. At the same time, advances in hardware and software began to bring GIS in reach of more and more organizations; however GIS continued to be a specialized unit "down the hall and to the right."

Now compare the community lines for the 1970s and 1980s in the figure. First note the extension to more professional experiences—some defining entirely new fields, such as GIS specialist. In addition, the 1980s line flattens a bit to indicate that the average "depth of expert spatial knowledge" within the community declined from that of the laser-focused research types. Finally note that the "keel of knowledge" shifted right toward the system managers and application focus.

These trends in the GIS community mix accelerated in the 1990s. On the system side professional programmers restructured, extended and enhanced the old unstructured FORTRAN and BASIC code of the early innovators into comprehensive flagship GIS systems with graphical interfaces. The GIS developers stopped coding their own systems and used the toolkits to develop customized solutions for individual industries and organizations. System managers, data providers and GIS specialists provided the utility and day-to-day attention demanded by the operational systems coming on line.

On the application side, a maturing GPS industry was fully integrated and RS returned to the geotechnology fold. As a result, hundreds of thousands of general users of these systems with varying backgrounds and application interests found GIS on their desktops and joined the community mix. The shift toward applications diminished the depth of knowledge and further shifted its keel to the right. At one point this prompted me to suggest that GIS was "a mile wide and an inch deep," as many in the wave of new comers to GIS did so through an enlarged job description and a couple of training courses.

If that is the case, then we are now ten miles wide and a quarter-inch deep. In retrospect and a bit of reflection on the 2000s community line suggests that is exactly where we should be. While there are large numbers of deeply-keeled GIS experts, there are orders of magnitude more users of geotechnology. The evolution from a research-dominated to a user-dominated field confirms that geotechnology has come of age. In part, this is a natural condition of all computer-based disciplines brought on by ubiquitous personal computers and Internet connections. The dominant focus of this phase, from webmaster to the end user, is on accessing spatial information. Couple this with the current multimedia clamor and 3D visualization, such as Google Earth, a whole new form of a map is becoming the norm.

So what is under the flap of the ever enlarging tent of GIS? My guess is that it will become a fabric of society with most public users not even knowing (or caring) that they are using geotechnology. At the same time, a growing number of general users will become more comfortable with the technology and demand increased capabilities, particularly in spatial analysis, statistics and modeling.

This will translate into new demands on developers for schizophrenic systems that are tiered for various levels of users. Most users will be satisfied with simply accessing digital forms of traditional maps, geo-query and driving directions, while other more knowledgeable users, will access GIS models to run sophisticated map analyses and scenarios for planning and decision-making.

Also I suspect that the 2010s will see a whole new community line with two keels like a catamaran—one on the right (GIS specialist, General Users and Public Users) emphasizing applications involving millions and another on the left (General Programmers, GIS Developers and System Managers) emphasizing systems involving thousands. This dualistic community will completely change the evolutionary character of the GIS community into a radically different revolutionary group.

The biggest challenge we face is educating future GIS professionals and users to "think with maps" instead of just "mapping." The digital nature of modern maps has forever changed what a map is and how it can be used. Map analysis capabilities will serve as the catalyst that enables us to fully address cognitive aspects of geographic space, as well as characterizing discrete physical features.

Innovation Drives GIS Evolution

(GeoWorld August, 2007)

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What I find interesting is that current geospatial innovation is being driven more and more by users. In the early years of GIS one would dream up a new spatial widget, code it, and then attempt to explain to others how and why they ought to use it. This sounds a bit like the proverbial "cart in front of the horse" but such backward practical logic is often what moves technology in entirely new directions.

"User-driven innovation," on the other hand, is in part an oxymoron, as innovation—"*a creation, a new device or process resulting from study and experimentation*" (Dictionary.com)—is usually thought of as canonic advancements <u>leading technology</u> and not market-driven solutions <u>following demand</u>. At the moment, the over 500 billion dollar advertising market with a rapidly growing share in digital media is dominating attention and the competition for eyeballs is directing geospatial innovation with a host of new display/visualization capabilities.

User-driven GIS innovation will become more and more schizophrenic with a growing gap between the two clans of the GIS user community as shown in figure 1.

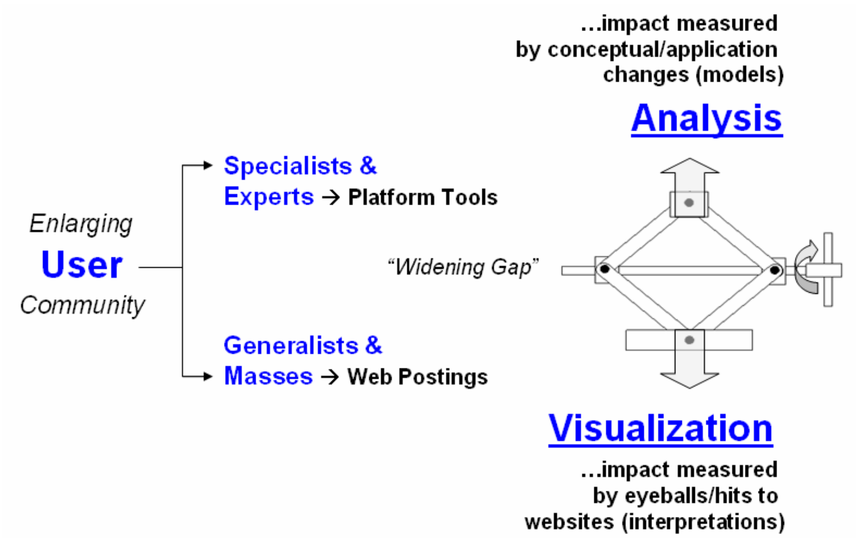

Figure 1. Widening gap in the GIS user community.

Another interesting point is that "radical" innovation often comes from fields with minimal or no paper map legacy, such as agriculture and retail sales, because these fields do not have pre-conceived mapping applications to constrain spatial reasoning and innovation.

In the case of *Precision Agriculture*, geospatial technology (GIS/RS/GPS) is coupled with robotics for "on-the-fly" data collection and prescription application as tractors move throughout a field. In *Geo-business*, when you swipe your credit card an analytic process knows what you bought, where you bought it, where you live and can combine this information with lifestyle and demographic data through spatial data mining to derive maps of "propensity to buy" various products throughout a market area. Keep in mind that these map analysis applications were non-existent a dozen years ago but now millions of acres and billions of transactions are part of the geospatial "stone soup" mix.

As shown in figure 2 the evolution of GIS is more cyclical than linear. My greybeard perspective of over 30 years in GIS suggests that we have been here before. In the 1970s the research and early applications centered on *Computer Mapping* (display focus) that yielded to *Spatial Data Management* (data structure/management focus) in the next decade as we linked digital maps to attribute databases for geo-query. The 1990s centered on *GIS Modeling* (analysis focus) that laid the groundwork for whole new ways of assessing spatial patterns and relations, as well as entirely new applications such as precision agriculture and geo-business.

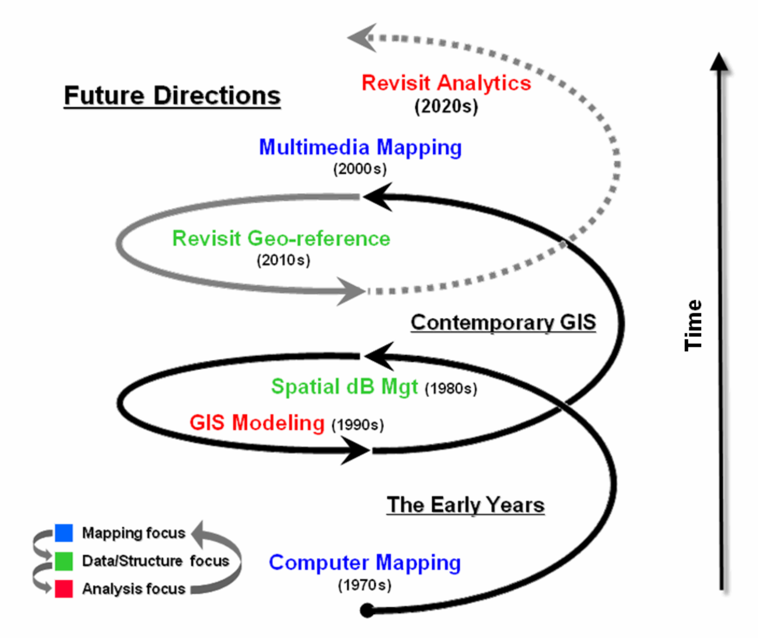

Figure 2. GIS Innovation/Development cycles.

Today, GIS is centered on *Multimedia Mapping* (mapping focus) which brings us full circle to our beginnings. While advances in virtual reality and 3D visualization can "knock-your-socks-off" they represent incremental progress in visualizing maps that exploit dramatic computer hardware/software advances. The truly geospatial innovation awaits the next re-focusing on data/structure and analysis.

The bulk of the current state of geospatial analysis relies on "*static coincidence modeling*" using a stack of geo-registered map layers. But the frontier of GIS research is shifting focus to "*dynamic flows modeling*" that tracks movement over space and time in three-dimensional geographic space. But a wholesale revamping of data structure is needed to make this leap.

The impact of the next decade's evolution will be huge and shake the very core of GIS—the Cartesian coordinate system itself …a spatial referencing concept introduced by mathematician Rene Descartes 400 years ago.

The current 2D square for geographic referencing is fine for "static coincidence" analysis over relatively small land areas, but woefully lacking for "dynamic 3D flows." It is likely that Descartes' 2D squares will be replaced by hexagons (like the patches forming a soccer ball) that better represent our curved earth's surface …and the 3D cubes replaced by nesting polyhedrals for a consistent and seamless representation of three-dimensional geographic space. This change in referencing extends the current six-sides of a cube for flow modeling to the twelve-sides (facets) of a polyhedral—radically changing our algorithms as well as our historical perspective of mapping (see April 2007 Beyond Mapping column for more discussion).

The new geo-referencing framework provides a needed foothold for solving complex spatial problems, such as intercepting a nuclear missile using supersonic evasive maneuvers or tracking the air, surface and groundwater flows and concentrations of a toxic release. While the advanced map analysis applications coming our way aren't the bread and butter of mass applications based on historical map usage (visualization and geo-query of data layers) they represent natural extensions of geospatial conceptualization and analysis …built upon an entirely new set analytic tools, geo-referencing framework and a more realistic paradigm of geographic space.

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Author's Note: *I have been involved in research, teaching, consulting and GIS software development since 1971 and presented my first graduate course in GIS Modeling in 1977. The discussion in these columns is a distillation of this experience and several keynotes, plenary presentations and other papers—many are posted online at www.innovativegis.com/basis/basis/cv_berry.htm.*

GIS and the Cloud Computing Conundrum

(GeoWorld September, 2009)

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I think my first encounter with the concept of cloud computing was more than a dozen years ago when tackling a Beyond Mapping column on object-oriented computing. It dealt with the new buzzwords of "object-oriented" user interface (OOUI), programming system (OOPS) and database management (OODBM) that promised to revolutionize computer interactions and code sets (see Author's Note). Since then there has been a string of new evolutionary terms from enterprise GIS, to geography network, interoperability, distributed computing, web-services, mobile GIS, grid computing and mash-ups that have captured geotechnology's imagination, as well as attention.

"Cloud computing" is the latest in this trajectory of terminology and computing advances that appears to be coalescing these seemingly disparate evolutionary perspectives. While my technical skills are such that I can't fully address its architecture or enabling technologies, I might be able to contribute to a basic grasp of what cloud technology is, some of its advantages/disadvantages and what its near-term fate might be.

Uncharacteristic of the Wikipedia, the definition for cloud computing is riddled with techy-speak, as are most of the blogs. However, what I am able to decipher is that there are three distinguishing characteristics defining it (see figure 1)—

1) it involves ***virtualized*** resources …meaning that workloads are allocated among a multitude of interconnected computers acting as a single device;
2) it is dynamically ***scalable*** …meaning that the system can be readily enlarged;

3) it acts as a ***service*** …meaning that the software and data components are shared over the Internet.

The result is a “hosted elsewhere” environment for data and services …meaning that cloud computing is basically the movement of applications, services, and data from local storage to a dispersed set of servers and datacenters— an advantageous environment for many data heavy and computationally demanding applications, such as geotechnology.

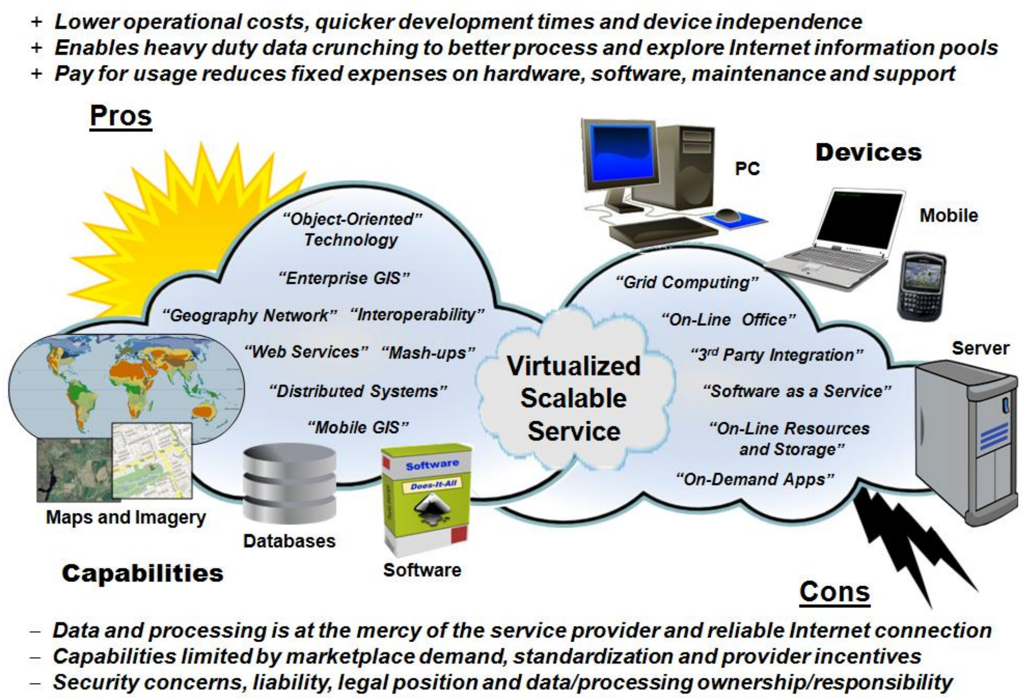

Figure 1. Cloud Computing characteristics, components and considerations.

A counterpoint is that the “elsewhere” conjures up visions of the old dumb terminals of the 70’s connected to an all powerful computer center serving the masses. It suggests that some of the tailoring and flexibility of the “personal” part of the PC environment might be lost to ubiquitous services primarily designed to capture millions of eyeballs. The middle ground is that desktop and cloud computing can coexist but that suggests duel markets, investments, support and maintenance.

Either way, it is important to note that cloud computing is not a technology—it is a concept. It essentially presents the idea of distributed computing that has been around for decades. While there is some credence in the argument that cloud computing is simply an extension of yesterday’s buzzwords, it ingrains considerable technical advancement. For example, the cloud offers a huge potential for capitalizing on the spatial analysis, modeling and simulation functions of a GIS, as well as tossing gigabytes around with ease …a real step-forward from the earlier expressions.

There are two broad types of clouds depending on their application:

1) "*Software as a Service*" (SaaS) delivering a single application through the browser to a multitude of customers (e.g., WeoGeo and Safe Software are making strides in SaaS for geotechnology)— on the customer side, it means minimal upfront investment in servers or software licensing and on the provider side, with just one application to maintain, costs are low compared to conventional hosting; and,
2) "*Utility Computing*" offering storage and virtual servers that can be accessed on demand by stitching together memory, I/O, storage, and computational capacity as a virtualized resource pool available over the Internet— thus creating a development environment for new services and usage accounting.

Google Earth is a good example of early-stage, cloud-like computing. It seamlessly stitches imagery from numerous datacenters to wrap the globe in a highly interactive 3D display. It provides a wealth of geography-based tools from direction finding to posting photos and YouTube videos. More importantly, it has a developer's environment (.kml) for controlling the user interface and custom display of geo-registered map layers. Like the iPhone, this open access encourages the development of applications and tools outside the strict confines of dedicated "flagship" software.

But the cloud's silver lining has some dark pockets. There are four very important non-technical aspects to consider in assessing the future of cloud computing: *1)* liability concerns, *2)* information ownership, sensitivity and privacy issues, *3)* economic and payout considerations, and *4)* legacy impediments.

<u>Liability concerns</u> arise from decoupling data and procedures from a single secure computing infrastructure— What happens if the data is lost or compromised? What if the data and processing are changed or basically wrong? Who is responsible? Who cares?

The closely related issues of <u>ownership, sensitivity and privacy</u> raise questions like: Who owns the data? Who is it shared with and under what circumstances? How secure is the data? Who determines its accuracy, viability and obsolescence? Who defines what data is sensitive? What is personal information? What is privacy? These lofty questions rival Socrates sitting on the steps of the Acropolis and asking …what is beauty? …what is truth? But these social questions need to be addressed if the cloud technology promise ever makes it down to earth.

In addition, a practical reality needs an <u>economic and payout</u> component. While SaaS is usually subscription based, the alchemy of spinning gold from "free" cyberspace straw continues to mystify me. It appears that the very big boys like Google and Virtual (Bing) Earths can do it through eyeball counts, but what happens to smaller data, software and service providers that make their livelihood from what could become ubiquitous? What is their incentive? How would a cloud computing marketplace be structured? How will its transactions be recorded and indemnified?

Governments, non-profits and open source consortiums, on the other hand, see tremendous opportunities in serving-up gigabytes of data and analysis functionality for free. Their perspective focuses on improved access and capabilities, primarily financed through cost savings. But are they able to justify large transitional investments to retool under our current economic times?

All these considerations, however, pale in light legacy impediments, such as the inherent resistance to change and inertia derived from vested systems and cultures. The old adage "*don't fix it, if it ain't broke*" often delays, if not trumps, adoption of new technology. Turning the oil tanker of GIS might take a lot longer than technical considerations suggest—so don't expect GIS to "disappear" into the clouds just yet. But the future possibility is hanging overhead.

Author's Note: *see online book Map Analysis, Topic 1, Object-Oriented Technology and Its GIS Expressions posted at www.innovativegis.com/basis/MapAnalysis/; a good online discussion of Cloud Computing is posted at www.appistry.com/cloud-info-center.*

Visualizing a Three-dimensional Reality

(GeoWorld October, 2009)

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I have always thought of geography in three-dimensions. Growing up in California's high Sierras I was surrounded by peaks and valleys. The pop-up view in a pair of aerial photos got me hooked as an undergrad in forestry at UC Berkeley during the 1960's while dodging tear gas canisters.

My doctoral work involved a three-dimensional computer model that simulated solar radiation in a vegetation canopy (SRVC). The mathematics would track a burst of light as it careened through the atmosphere and then bounce around in a wheat field or forest with probability functions determining what portion was absorbed, transmitted or reflected based on plant material and leaf angles. Solid geometry and statistics were the enabling forces, and after thousands of stochastic interactions, the model would report the spectral signature characteristics a satellite likely would see. All this was in anticipation of civilian remote sensing systems like the Earth Resources Technology Satellite (ERTS, 1973), the precursor to the Landsat program.

This experience further entrenched my view of geography as three-dimensional. However, the ensuing decades of GIS technology have focused on the traditional "pancake perspective" that flatten all of the interesting details into force-fitted plane geometry. Even more disheartening is the assumption that everything can be generalized into a finite set of hard boundaries identifying discrete spatial objects defined by points, lines and polygons. While this approach has served us well for thousands of years and we have avoided sailing off the edge of the earth, geotechnology is taking us "where no *mapper* has gone before," at least not without a digital map and a fairly hefty computer.

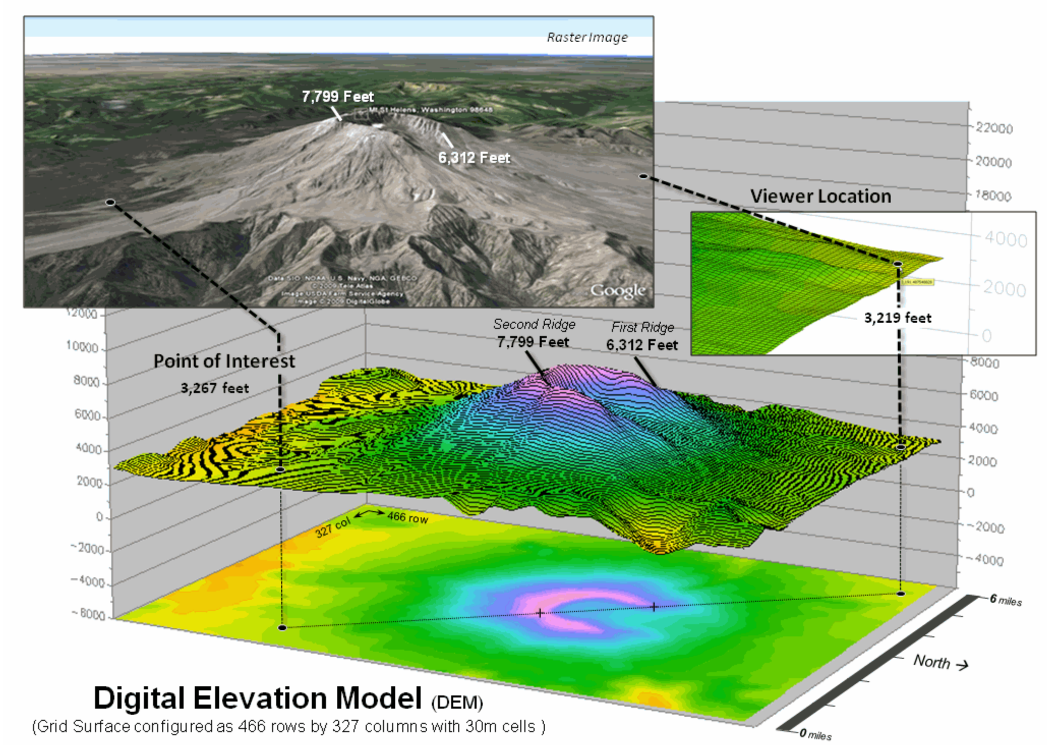

Figure 1. Mount St. Helens topography.

Consider the Google Earth image of Mount St. Helens in the upper-left portion of figure 1. The peaks poke-up and the valleys dip down with a realistic land cover wrapper. This three-dimensional rendering of geography is a far cry from the traditional flat map with pastel colors imparting an abstract impression of the area. You can zoom-in and out, spin around and even fly through the landscape or gaze skyward to the stars and other galaxies.

Underlying all this is a Digital Elevation Model (DEM) that encapsulates the topographic undulations. It uses traditional X and Y coordinates to position a location plus a Z coordinate to establish its relative height above a reference geode (sea level in this case). However from a purist's perspective there are a couple of things that keep it from being a true three-dimensional GIS. First, the raster image is just that— a display in which thousands the "dumb" dots coalesce to form a picture in your mind, not an "intelligent" three-dimensional data structure that a computer can understand. Secondly, the rendering is still somewhat two-dimensional as the mapped information is simply "draped" on a wrinkled terrain surface and not stored in a true three-dimensional GIS—a warped pancake.

The DEM in the background forms Mt St. Helen's three-dimensional terrain surface by storing elevation values in a matrix of 30 meter grid cells of 466 rows by 327 columns (152, 382 values). In this form, the computer can "see" the terrain and perform its map-ematical magic.

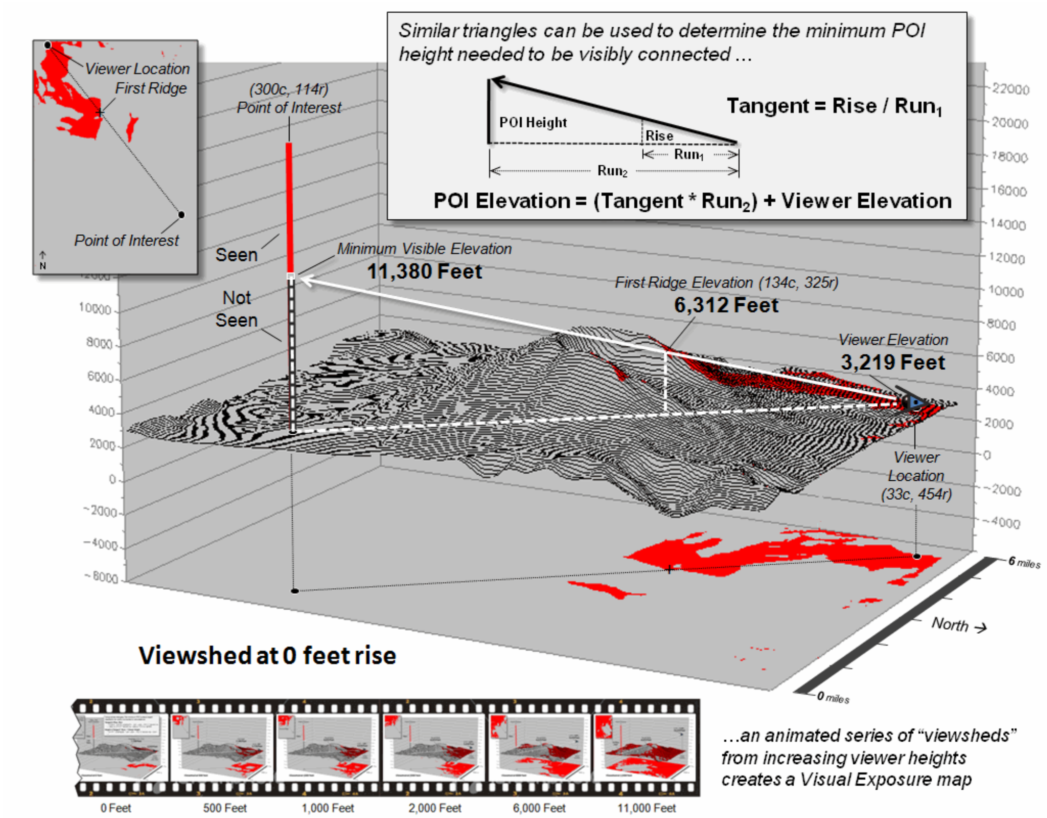

Figure 2. Basic geometric relationships determine the minimum visible height considering intervening ridges.

Figure 2 depicts a bit of computational gymnastics involving three-dimensional geography. Assume you are standing at the viewer location and looking to the southeast in the direction of the point of interest. Your elevation is 3,219 feet with the mountain's western rim towering above you at 6,312 feet and blocking your view of anything beyond it. In a sense, the computer "sees" the same thing—except in mathematical terms. Using similar triangles, it can calculate the minimum point-of-interest height needed to be visibly connected as (see author's notes for a link to discussion of the more robust "splash algorithm" for establishing visual connectivity)…

Tangent = Rise / Run
= (6312 ft – 3219 ft) / (SQRT[(134 – 33)^2 + (454 – 325)^2] * 98.4251 ft)
= 3093 ft / (163.835 * 98.4251 ft) = 3893 ft / 16125 ft = **0.1918**

Height = (Tangent * Run) + Viewer Height
= (0.1918 * (SQRT[(300 – 33)^2 + (454 – 114)^2] * 98.4251 ft)) + 3219 ft
= (0.1918 * 432.307 * 98.4251 ft) + 3219 = **11,380 Feet**

Since the computer knows that the elevation on the grid surface at that location is only 3,267 feet it knows you can't see the location. But if a plane was flying 11,380 feet over the point it would be visible and the computer would know it.

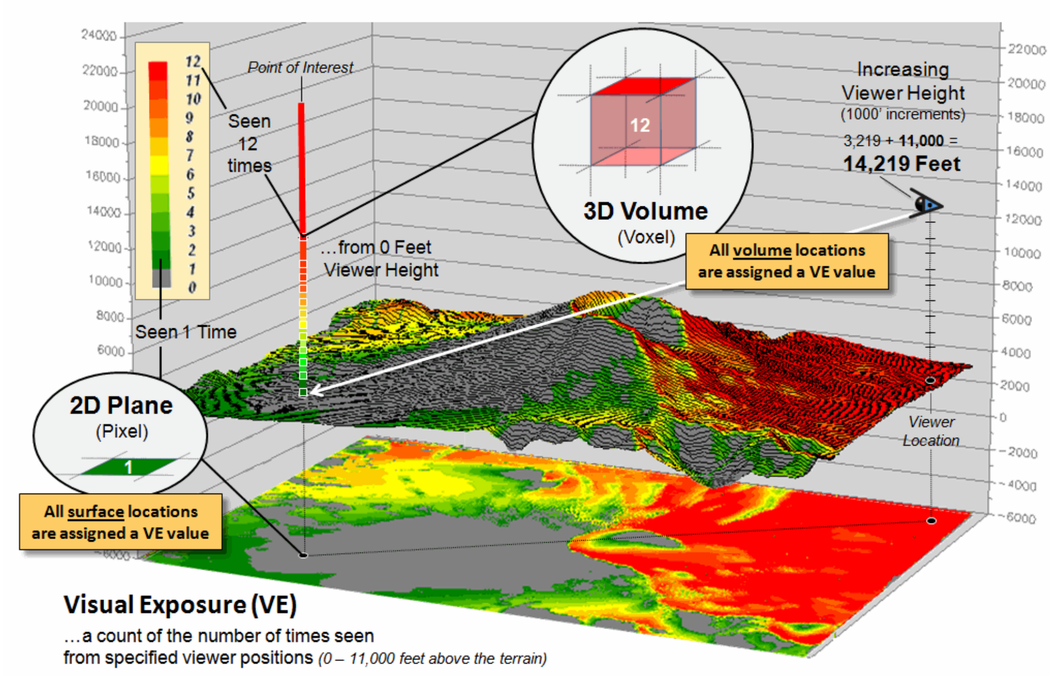

Figure 3. 3-D Grid Data Structure is a direct expansion of the 2D structure with X, Y and Z coordinates defining the position in a 3-dimensional data matrix plus a value representing the characteristic or condition (attribute) associated with that location.

Conversely, if you "helicoptered-up" 11,000 feet (to 14,219 feet elevation) you could see over both of the caldron's ridges and be visually connected to the surface at the point of interest (figure 3). Or in a military context, an enemy combatant at that location would have line-of-sight detection.

As your vertical rise increases from the terrain surface, more and more terrain comes into view (see author's notes for a link to an animated slide set). The visual exposure surface draped on the terrain and projected on the floor of the plot keeps track of the number of visual connections at every grid surface location in 1000 foot rise increments. The result is a traditional two-dimensional map of visual exposure at each surface location with warmer tones representing considerable visual exposure during your helicopter's rise.

However, the vertical bar in figure 3 depicts the radical change that is taking us beyond mapping. In this case the two-dimensional grid "cell" (termed a pixel) is replace by a three-dimensional grid "cube" (termed a voxel)—an extension from the concept of an area on a surface to a glob in a volume. The warmer colors in the column identify volumetric locations with considerable visual exposure.

Now imagine a continuous set of columns rising above and below the terrain that forms a three-dimensional project extent—a block instead of an area. How is the block defined and stored; what new analytical tools are available in a volumetric GIS; what new information is generated; how might you use it? …that's fodder for the next section. For me, it's a blast from the past that is defining the future of geotechnology.

Author's Notes: *for a more detailed discussion of visual connectivity see the online book Beyond Mapping III, Topic 15, "Deriving and Using Visual Exposure Maps" at* www.innovativegis.com/basis/MapAnalysis/Topic15/Topic15.htm. *An annotated slide set demonstrating visual connectivity from increasing viewer heights is posted at* www.innovativegis.com/basis/MapAnalysis/Topic27/AnimatedVE.ppt.

Thinking Outside the Box *(pun intended)*

(GeoWorld November, 2009)

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Last section used a progressive series of line-of-sight connectivity examples to demonstrate thinking beyond a 2-D map world to a three-dimensional world. Since the introduction of the digital map, mapping geographic space has moved well beyond its traditional planimetric pancake perspective that flattens a curved earth onto a sheet of paper.

A contemporary Google Earth display provides an interactive 3-D image of the globe that you can fly through, zoom-up and down, tilt and turn much like Luke Skywalker's bombing run on the Death Star. However both the traditional 2-D map and virtual reality's 3-D visualization view the earth as a surface—flattened to a pancake or curved and wrinkled a bit to reflect the topography.

Figure 1 summarizes the key elements in locating yourself on the earth's surface …sort of a pop-quiz from those foggy days of Geography 101. The Prime Meridian and Equator serve as base references for establishing the angular movements expressed in degrees of Longitude (X) and Latitude (Y) of an imaginary vector from the center of the earth passing through any location. The Height (Z) of the vector positions the point on the earth's surface.

It's the determination of height that causes most of us to trip over our geodesic mental block. First, the globe is not a perfect sphere but is a squished ellipsoid that is scrunched at the poles and pushed out along the equator like love-handles. Another way to conceptualize the physical shape of the surface is to imagine blowing up a giant balloon such that it "best fits" the actual shape of the earth (termed the geoid) most often aligning with mean sea level. The result is a smooth geometric equation characterizing the general shape of the earth's surface.

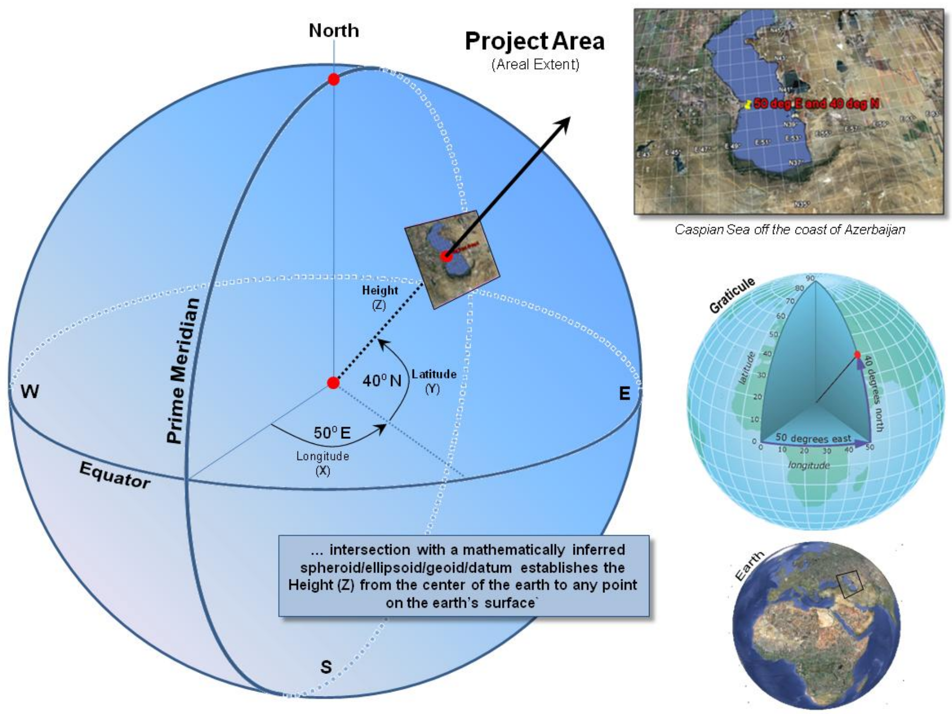

Figure 1. A 3-dimensional coordinate system uses angular measurements (X,Y) and length (Z) to locate points on the earth's surface.

But the earth's mountains bump-up and valleys bump-down from the ellipsoid so a datum is designed to fit the earth's surface that accounts for the actual wrinkling of the globe as established by orbiting satellites. The most common datum for the world is WGS 84 (World Geodetic System 1984) used by all GPS equipment and tends to have and accuracy of +/- 30 meters or less from the actual local elevation anywhere on the surface.

The final step in traditional mapping is to flatten the curved and wrinkled surface to a planimetric projection and plot it on a piece of paper or display on a computer's screen. It is at this stage all but the most fervent would-be geographers drop the course, or at least drop their attention span.

However, a true 3-D GIS simply places the surface in volumetric grid elements along with others above and below the surface. The right side of figure 2 shows a Project Block containing a million grid elements (termed "voxels") positioned by their geographic coordinates—X (easting), Y (northing) and Z (height). The left side depicts stripping off one row of the elevation values defining the terrain surface and illustrating a small portion of them in the matrix by shading the top's of the grids containing the surface.

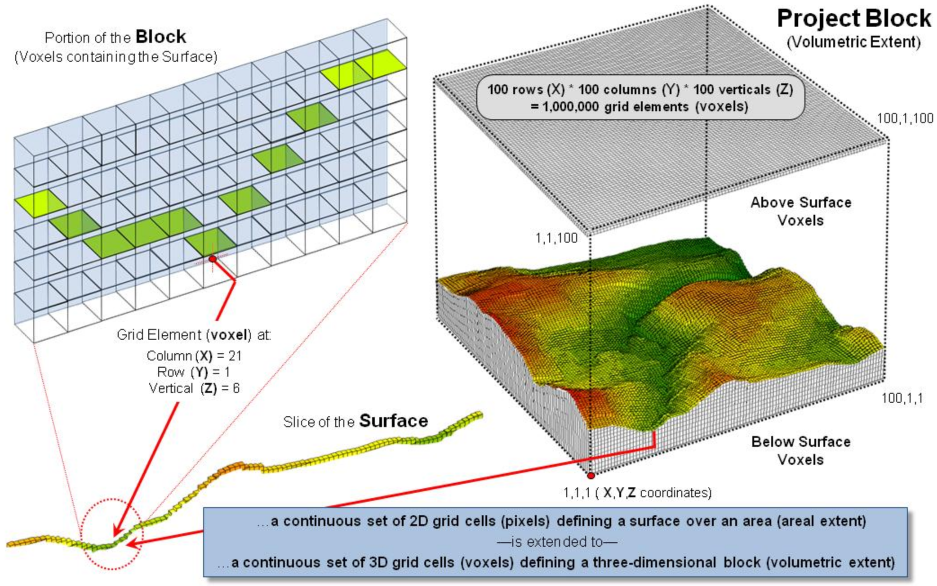

Figure 2. An implied 3-D matrix defines a volumetric Project Block, a concept analogous to areal extent in traditional mapping.

At first the representation in a true 3-D data structure seems trivial and inefficient (silly?) but its implications are huge. While topographic relief is stable (unless there is another Mount St. Helens blow that redefines local elevation) there are numerous map variables that can move about in the project block. For example, consider the weather "map" on the evening news that starts out in space and then dives down under the rain clouds. Or the National Geographic show that shows the Roman Coliseum from above then crashes through the walls to view the staircases and then proceeds through the arena's floor to the gladiators' hypogeum with its subterranean network of tunnels and cages.

Some "real cartographers" might argue that those aren't maps but just flashy graphics and architectural drawings …that there has been a train wreck among mapping, computer-aided drawing, animation and computer games. On the other hand, there are those who advocate that these disciplines are converging on a single view of space—both imaginary and geographic. If the X, Y and Z coordinates represent geographic space, nothing says that Super Mario couldn't hop around your neighborhood or that a car is stolen from your garage in Grand Theft Auto and race around the streets in your hometown.

The unifying concept is a "Project Block" composed of millions of spatially-referenced voxels. Line-of-sight connectivity determines what is seen as you peek around a corner or hover-up in a helicopter over a mountain. While the mathematics aren't for the faint-hearted or tinker-toy computers of the past, the concept of a "volumetric map" as an extension of the traditional planimetric map is easy to grasp—a bunch of three-dimensional cubic grid elements extending up and down from our current raster set of squares (bottom of figure 3).

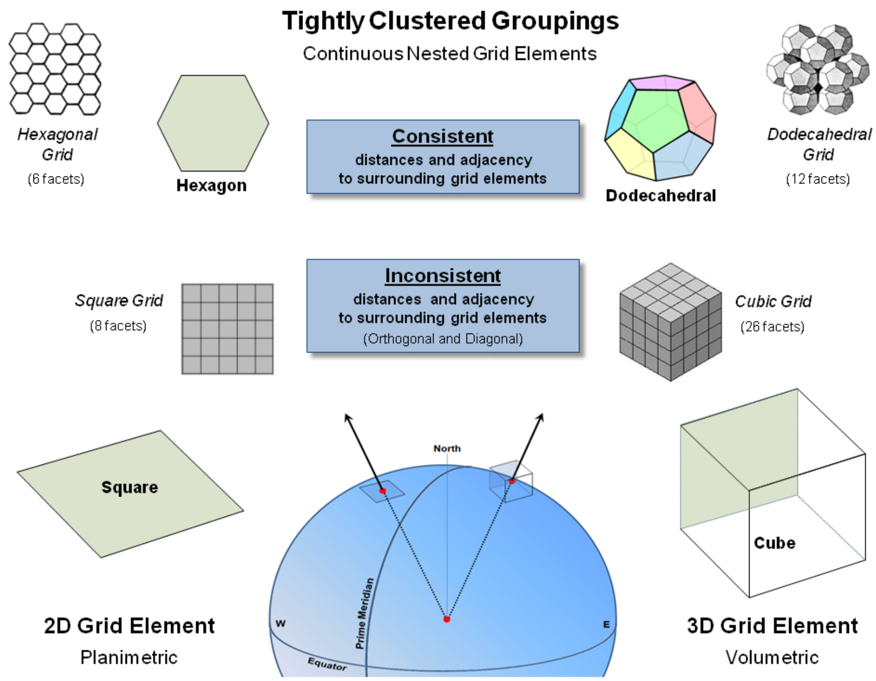

Figure 3. The hexagon and dodecahedral are alternative grid elements with consistent nesting geometry.

However, akin to the seemingly byzantine details in planimetric mapping, things aren't that simple. Like the big bang of the universe, geographic space expands from the center of the earth and a simple stacking of fixed cubes like wooden blocks won't align without significant gaps. In addition, the geometry of a cube does not have a consistent distance to all of its surrounding grid elements and of its twenty six neighbors only six share a complete side with the remaining neighbors sharing just a line or a single point. This inconsistent geometry makes a cube a poor grid element for 3-D data storage.

Similarly, it suggests that the traditional "square" of the Cartesian grid is a bit limited—only four complete sides (orthogonal elements) and four point adjacencies (diagonal). Also, the distances to surrounding elements are different (a ratio of 1:1.414). However, a 2D hexagon shape (beehive honey comb) abuts completely without gaps in planimetric space (termed "fully nested"); as does a combination of pentagon and hexagon shapes nests to form the surface of a spheroid (soccer ball).

To help envision an alternative 3-D grid element shape (top-right of figure 3) it is helpful to recall Buckminster Fuller's book *Synergetics* and his classic treatise of various "close-packing" arrangements for a group of spheres. Except in this instance, the sphere-shaped grid elements are replaced by "pentagonal dodecahedrons"— a set of uniform solid shapes with 12 pentagonal faces (termed geometric “facets”) that when packed abut completely without gaps (termed fully “nested”).

All of the facets are identical, as are the distances between the centroids of the adjoining clustered elements defining a very “natural” building block (see Author’s Note). But as always, “the Devil is in the details” and that discussion is dealt with in the next section.

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Author’s Note: *In 2003, a team of cosmologists and mathematicians used NASA’s WMAP cosmic background radiation data to develop a model for the shape of the universe. The study analyzed a variety of different shapes for the universe, including finite versus infinite, flat, negatively- curved (saddle-shaped), positively- curved (spherical) space and a torus (cylindrical). The study revealed that the math adds up if the universe is finite and shaped like a pentagonal dodecahedron (http://physicsworld.com/cws/article/news/18368). And if one connects all the points in one of the pentagon facets, a 5-pointed star is formed. The ratios of the lengths of the resulting line segments of the star are all based on phi, Φ, or 1.618… which is the “Golden Number” mentioned in the Da Vinci Code as the universal constant of design and appears in the proportions of many things in nature from DNA to the human body and the solar system—isn’t mathematics wonderful!*

From a Mapping Pancake to a Soufflé

(GeoWorld November, 2009)

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As the Time Traveller noted in H. G. Wells’ classic “The Time Machine,” the real world has three geometric dimensions not simply the two we commonly use in mapping. In fact, he further suggested that “...any real body must have extension in four directions: Length, Breadth, Thickness—and Duration (time)” …but that’s a whole other story.

Recall from last section’s discussion of 3D GIS that *Geodetic Referencing* (geographic position) used in identifying an “areal extent” in two-dimensions on the earth’s surface can be extended to a *Database Referencing* system (matrix location) effectively defining a 3-dimensional “project block” (see the left side of figure 1). The key is the use of *Geodetic Height* above and below the earth’s ellipsoid as measured along the perpendicular from the ellipsoid to provide the vertical (Z) axis for any location in 3-dimensional space.

The result is a coordinate system of columns (X), rows (Y), and verticals (Z) defining an imaginary matrix of grid elements, or “voxels,” that are a direct conceptual extension of the “pixels” in a 2D raster image. For example, the top-right inset in figure 1 shows a 3D map of a cave system using ArcGIS 3D Analyst software. The X, Y and Z positioning forms a 3-dimensional display of the network of interconnecting subterranean passages. The lower-right inset shows an analogous network of blood vessels for the human body except at much different scale. The important point is that both renderings are 3D visualizations and not a 3D GIS as they are unable to perform volumetric analyzes, such as directional flows along the passageways.

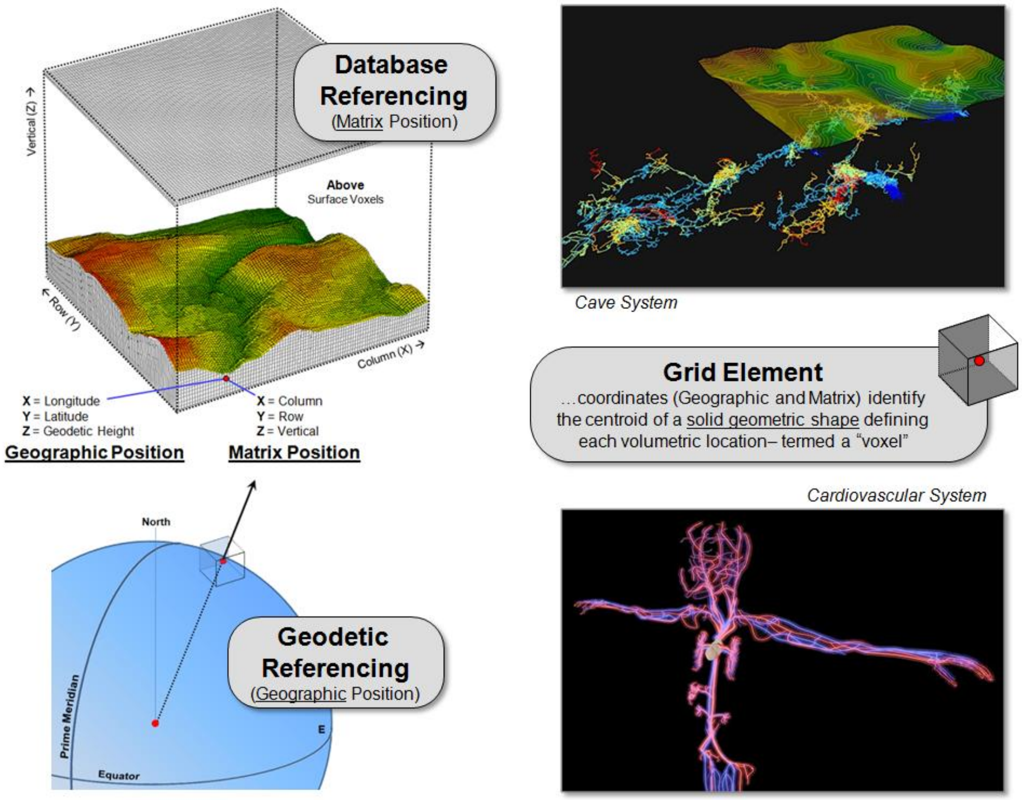
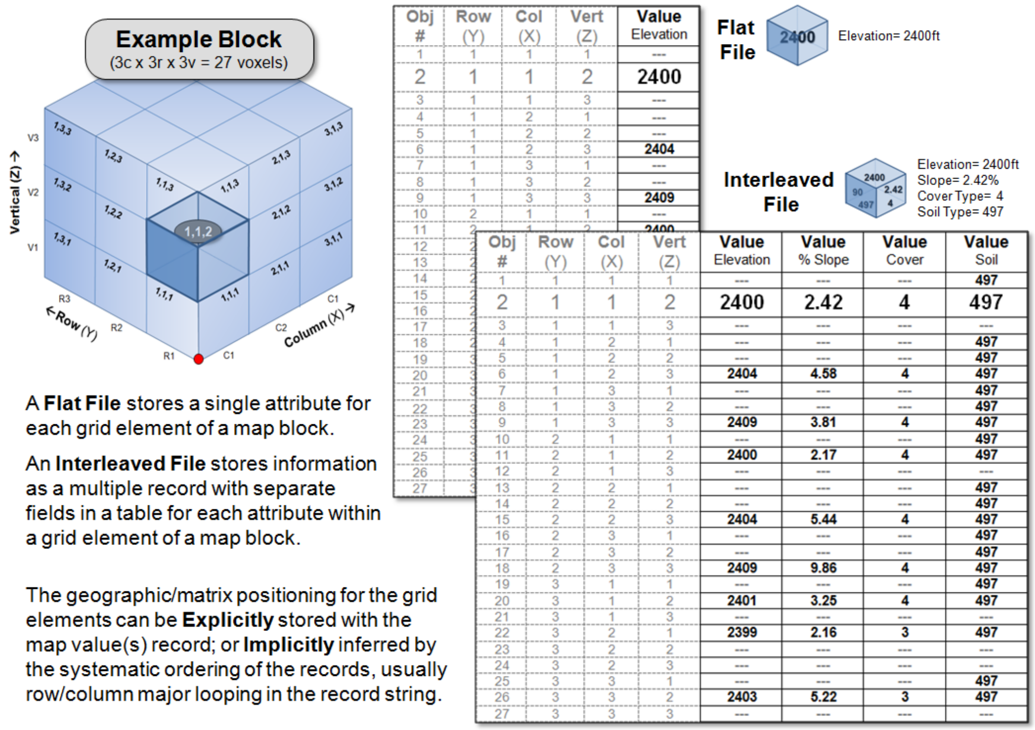


Figure 1. Storage of a vertical (Z) coordinate extends traditional 2D mapping to 3D volumetric representation.

The distinction between 3D visualization and analytical systems arises from differences in their data structures. A 3D visualization system stores just three values—X and Y for "where" and Z for "what (elevation)." A 3-dimensional mapping system stores at least four values—X, Y and Z for "where" and an attribute value for "what" describing the characteristic/condition at each location within a project block.

Figure 2 illustrates two ways of storing 3-dimensional grid data. A *Flat File* stores a single map value for each grid element in a map block. The individual records can explicitly identify each grid element (grayed columns—"where") along with the attribute (black column—"what"). Or, much more efficiently, the information can be implicitly organized as a header line containing the grid block configuration/size/referencing followed by a long string of numbers with each value's position in the string determining its location in the block through standard nested programming loops. This shortened format provides for advanced compression techniques similar to those used in image files to greatly reduce file size.



Obj #	Row (Y)	Col (X)	Vert (Z)	Value Elevation	Value % Slope	Value Cover	Value Soil
1	1	1	1	---	---	---	497
2	1	1	2	2400	2.42	4	497
3	1	1	3	---	---	---	---
4	1	2	1	---	---	---	497
5	1	2	2	---	---	---	497
6	1	2	3	2404	4.58	4	497
7	1	3	1	---	---	---	497
8	1	3	2	---	---	---	497
9	1	3	3	2409	3.81	4	497
10	2	1	1	---	---	---	497
11	2	1	2	2400	2.17	4	497
12	2	1	3	---	---	---	---
13	2	2	1	---	---	---	497
14	2	2	2	---	---	---	497
15	2	2	3	2404	5.44	4	497
16	2	3	1	---	---	---	497
17	2	3	2	---	---	---	497
18	2	3	3	2409	9.86	4	497
19	3	1	1	---	---	---	497
20	3	1	2	2401	3.25	4	497
21	3	1	3	---	---	---	---
22	3	2	1	2399	2.16	3	497
23	3	2	2	---	---	---	---
24	3	2	3	---	---	---	---
25	3	3	1	---	---	---	497
26	3	3	2	2403	5.22	3	497
27	3	3	3	---	---	---	---

Figure 2. A 3-dimensional matrix structure can be used to organize volumetric mapped data.

An alternative strategy, termed an *Interleaved File*, stores a series of map attributes as separate fields for each record that in turn represents each grid element, either implicitly or explicitly organized into a table. Note that in the interleaved file in figure 2, the map values for Elevation, %Slope and Cover type identify surface characteristics with a "null value (---)" assigned to grid elements both above and below the surface. Soil type, on the other hand, contains values for the grid elements on and immediately below the surface with null values only assigned to locations above ground. This format reduces the number of files in a data set but complicates compression and has high table maintenance overhead for adding and deleting maps.

Figure 3 outlines some broader issues and future directions in 3D GIS data storage and processing. The top portion suggests that the inconsistent geometry of the traditional *Cube* results in differing distances and facet adjacency relationship to the surrounding twenty six neighbors, thereby making a cube a poor grid element for 3D data storage. A *Dodecahedron*, on the other hand, aligns with a consistent set of 12 equidistant pentagonal faces that "nest" without gaps ...an important condition in spatial analysis of movements, flows and proximal conditions.

The lower portion of figure 3 illustrates the knurly reality of geographic referencing in 3-dimensions—things change as distance from the center of the earth or bounding ellipsoid changes. Nicely nesting grid elements of a fixed size separate as distance increases (diverge); overlap as distance decreases (converge). To maintain a "close-packing" arrangement either the size of the grid element needs to adjust or the progressive errors of fixed size zones are tolerated.

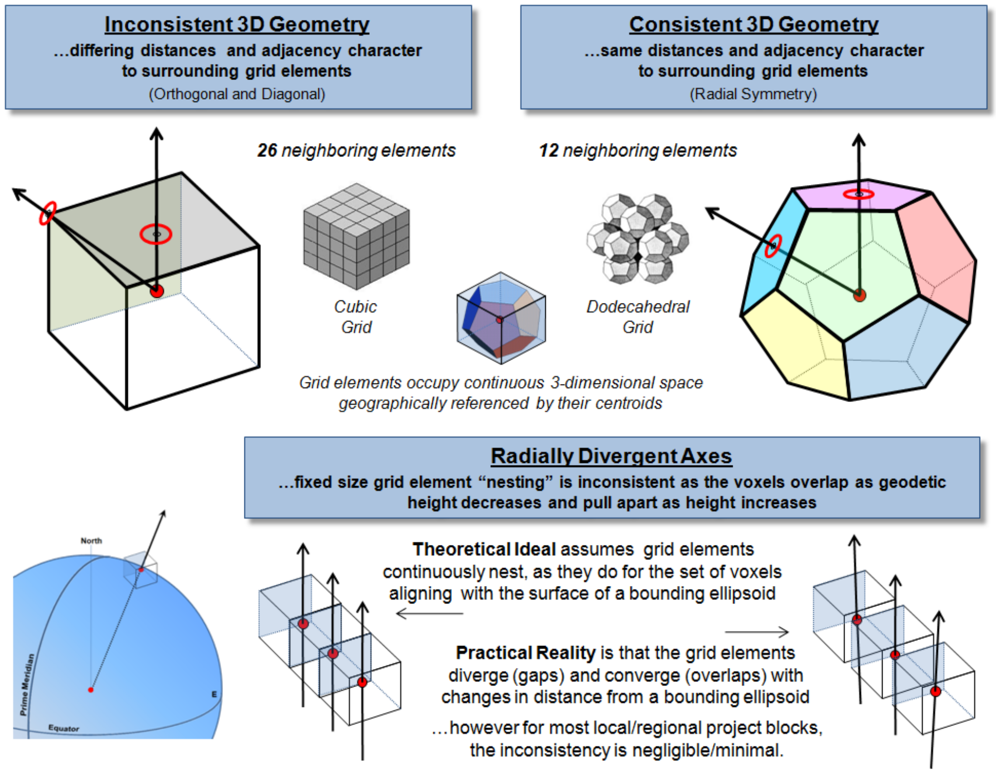


Figure 3. Alternative grid element shapes and new procedures for dealing with radial divergence form the basis for continued 3D GIS research and development.

Similar historical changes in mapping paradigms and procedures occurred when we moved from a flat earth perspective to a round earth one that generated a lot of room for rethinking. There are likely some soon-to-be-famous mathematicians and geographers who will match the likes of Claudius Ptolemy (90-170), Gerardus Mercator (1512-1594) and Rene Descartes (1596-1650)— I wonder who among us will take us beyond mapping as we know it?

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Author's Notes: *A good discussion of polyhedral and other 3-dimensional coordinate systems is in Topic 12, "Modeling locational uncertainty via hierarchical tessellation," by Geoffrey Dutton in Accuracy of Spatial Databases edited by Goodchild and Gopal. In his discussion he notes that "One common objection to polyhedral data models for GIS is that computations on the sphere are quite cumbersome … and for many applications the spherical/geographical coordinates … must be converted to and from Cartesian coordinates for input and output."*

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