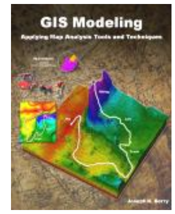
Beyond Mapping IV

Introduction – Extending Basic GIS Concepts



GIS Modeling book

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Finding Common Ground in Paper and Digital Worlds

(GeoWorld, February 2007)

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In the real world, landscapes are composed rocks, dirt, water, green stuff and furry/feathered friends. In a "paper world" these things are represented by words, tables and graphics. The traditional paper map is a graphical representation with inked lines, shadings and symbols used to locate landscape features using three basic building blocks— *Points*, *Lines* and *Areas*. For example, a typical water map might identify a well as a dot, a stream as a squiggle and a lake as a blue blob (figure 1). Each feature is considered a well-defined "discrete spatial object" with unique spatial character, positioning and dimension.

In geometry a point is considered dimensionless, however, the corresponding concept in cartography is a dot of ink having a physical dimension of a few inches to several miles depending on the scale of a paper map. Similarly, a line in mathematical theory has only length but is manually mapped as a thin serpentine polygon of the pen's width. An area feature has both length and width in two-dimensional space. The interplay of mapping precision and accuracy in a digital world involves a discussion of scale and resolution reserved for the next section. For now, let's consider the revolutionary changes in map form and content brought on by the digital map as outlined in the rest of figure 1.

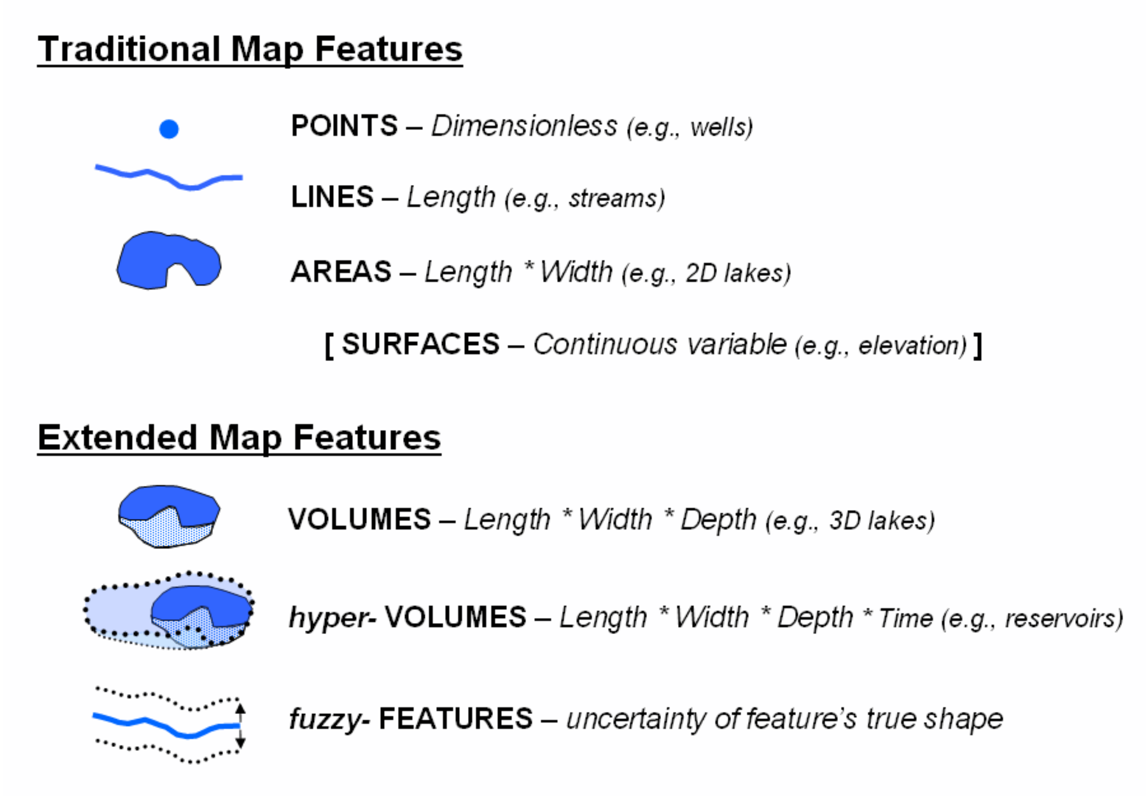

Figure 1. Traditional and Extended Map Features.

For thousands of years, manual cartography has been limited to characterizing all geographic phenomena as discrete 2-dimensional spatial objects. However many map variables, such as elevation, change continuously and representation as contour lines suggests a nested series of flat layers like a wedding cake instead of the actual continuously undulating terrain. The introduction of a grid-based data structure provides for a new basic building block—a map *Surface* of continuously changing values throughout geographic space.

Another extension to the building blocks is *Volumes* that track length, width and depth in characterizing discrete or continuous variables in 3-dimensional space. For example, the Length (x-axis), Width (y-axis), Depth (z-axis) coordinates identify a specific location in a lake and a fourth value (attribute) can identify its temperature, turbidity, salinity or other condition.

A *hyper-Volume* (or hyper-point, -line, -area or -surface) introduces time as an additional abstract coordinate. For example, the weekly water volume of a reservoir might be tracked by L,W,D,T coordinates identifying a location in 3-dimensional space, as well as time combined with a fifth attribute value indicating whether water is present or not. This conceptual extension is a bit tricky and provides conceptual fodder about mixed referencing units (e.g., meters and minutes) for a subsequent discussion. However, the result is a discrete volumetric map feature that shrinks and expands throughout a year—a dynamic spatial entity that at first appears to violate orthodox mapping commandments.

Another mind-bend brought on by the digital map is the concept of *fuzzy-features*. This idea tracks the certainty of a feature or condition at each map location. For example, the boundary line of a soil polygon is a subjective interpretation, while soil parcel's actual edge could be a considerable distance away—"the boundary is likely here (high probability) but could be over there (low probability)." Another fuzzy example is a classified satellite image where statistical probabilities are used to establish which cover type is most likely.

Taken to the hilt, one can conceptualize a data structure that carries L,W,D,T and A,P (attribute and probability) descriptors that identify a location in space and time, as well as characterize its most likely condition, next most likely, and so on—sort of a sandwich of probable conditions. Such a representation challenges the infallible paradigm of mapping but opens a whole new world of error propagation modeling.

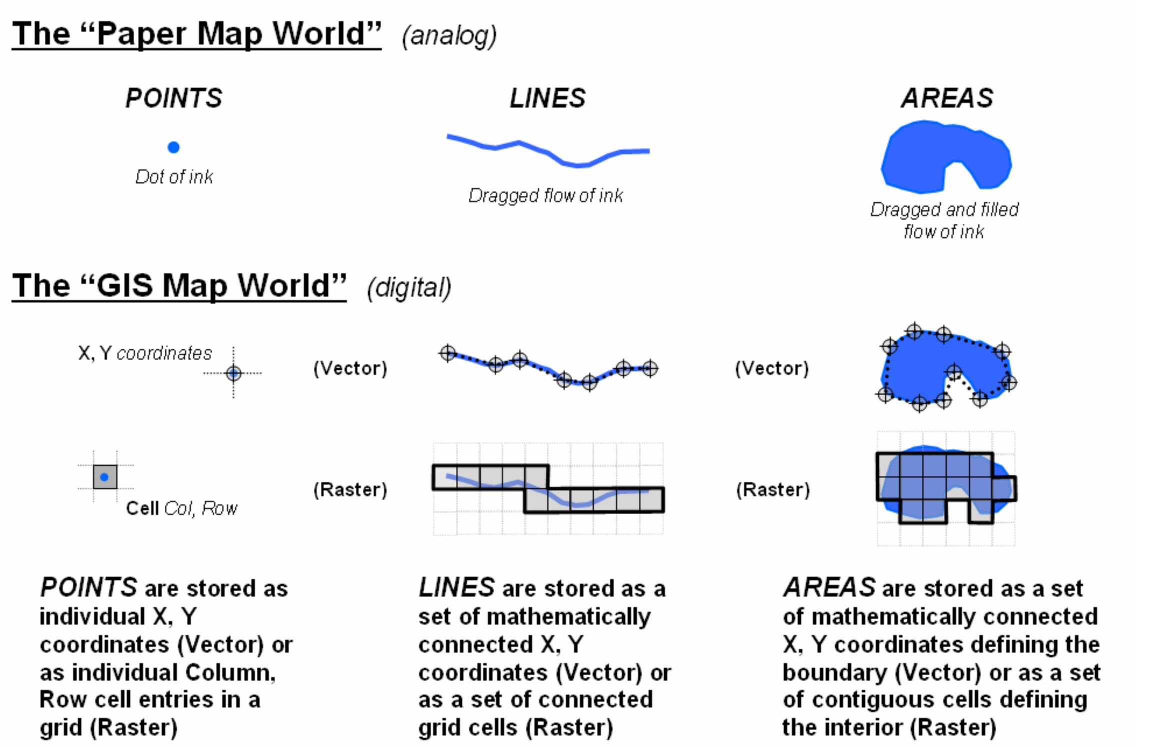

Figure 2. Basic Vector and Raster Data Structure Considerations.

Whereas volumes, hyper-volumes and fuzzy-features define the current realm of GIS researchers, an understanding of contemporary approaches for characterizing points, lines, and areas is necessary for all GIS users. Figure 2 outlines the two fundamental approaches—*vector* and *raster* (see Author's Notes).

A *Point* defined by X,Y coordinates in vector, and a *Cell* defined by Col,Row indices in raster, form the basic data structure units—the "smallest addressable unit of space" in a map. Lines are formed by mathematically connecting points (vector) or identifying all of the conjoined cells containing a line (raster). Areas are defined by a set of points that define a closed line encompassing a feature (vector) or by all of the contiguous cells containing a feature (raster).

While spatial precision is a major operational difference between vector and raster systems, how they characterize geographic space is important in understanding limitations and capabilities. Vector precisely identifies critical points along a line, but the intervening connections are implied. Raster, on the other hand, identifies all of the cells containing a line without any implied gaps. Similarly, vector precisely stores an area's boundary but implies its interior (must calculate); raster stores the interior but implies the boundary (must calculate).

The differences in "what is defined" and "what is implied" determine just about everything in GIS technology, except maybe the color pallet for display—data structure, storage requirements, algorithms, coding and ultimately appropriate use. Vector systems precisely and efficiently store traditional discrete map objects, such as underground cables and property boundaries (mapping and inventory). Raster systems, on the other hand, predefine continuous geographic space for rapid and enhanced processing of map layers (analysis and modeling).

So how do you think vector and raster systems store surfaces, volumes, hyper-volumes and fuzzy-features? …very poorly, or not at all for vector systems. However raster systems pre-define all of a project area (no gaps) by carrying a thematic value for each cell in a 2-dimensional storage matrix to form a *continuous map surface*. For volumes, a third geographic referencing index is added to extend the 2D cells to 3D cubes in geographic space defined by their X,Y,Z position in the storage matrix see Author's Notes).

A similar expansion is used for hyper-volumes with four indices (X,Y,Z,T) identifying the "position," except in this instance an abstract space is implied due to the differences in geographic and time units. Information about fuzzy-features can be coded into a compound attribute value describing any map feature, where the first few digits identify the character/condition at a location with the trailing two digits identifying the certainty of classification.

The bottom line is that tomorrow's maps aren't simply colorful electronic versions of your grandfather's maps. The digital map is an entirely different beast supporting radically new mapping approaches, perspectives, opportunities <u>and</u> responsibilities.

***<u>Author's Notes</u>**: Topic 6, "Alternative Data Structures," in Beyond Mapping Series book II (hardcopy book, <u>Spatial Reasoning for Effective GIS</u> (Berry 1995, Wiley)) contrasts vector and raster data structures and describes related alternative structures including TIN, Quadtree, Rasterized Lines and Vectorized Cells.*

Understand Resolution to "Think with Maps"

(GeoWorld, March 2007)

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One of the most fundamental concepts in the paper map world is *Geographic Scale*—the relationship between a distance on a map and its corresponding distance on the earth. In equation form, $scale_{ratio}$ *= map distance / ground distance* but is often expressed as a representative fraction (RF), such as $scale_{RF}$ *= 1:63,360* meaning 1 inch on the map represents 63,360 inches (or 1 mile) on the earth's surface.

However in the digital map world, this traditional concept of scale <u>does not</u> exist. While at first this might seem like cartographic heresy, note that the "map distance" component of the relationship is assumed to be fixed as ink marks on paper. In a GIS, however, the map features are stored as organized sets of numbers representing their spatial position (coordinates for "where") and thematic attribute (map values for "what"). One can zoom in and out on the data thereby creating a continuous gradient of geographic scales in the resulting display or hardcopy plot.

Hence geographic scale is a function of the display, not an inherent property of the digital mapped data set. What is important is the implied concept of informational scale, or *Resolution*—the ability to discern detail. Traditionally it is implicit that as geographic scale decreases, resolution also diminishes since drafted feature boundaries must be smoothed, simplified or not shown at all due to the width of the inked lines.

However in a GIS, the concept of resolution is explicit. In fact there are five types of resolution that need to be considered—Spatial, Mapping, Thematic, Temporal and Model. *Spatial Resolution* is the most basic and identifies the "smallest addressable unit" of geographic space (figure 1). For point features, the X,Y coordinates (vector) and cell size (raster) determine the smallest addressable unit.

For line features in vector, however, the smallest addressable unit is the line segment with larger segments capturing less detail as the implied straight line misses the subtle wiggles and waggles of a pattern. Similarly, large grid cells capture less linear detail than smaller cells.

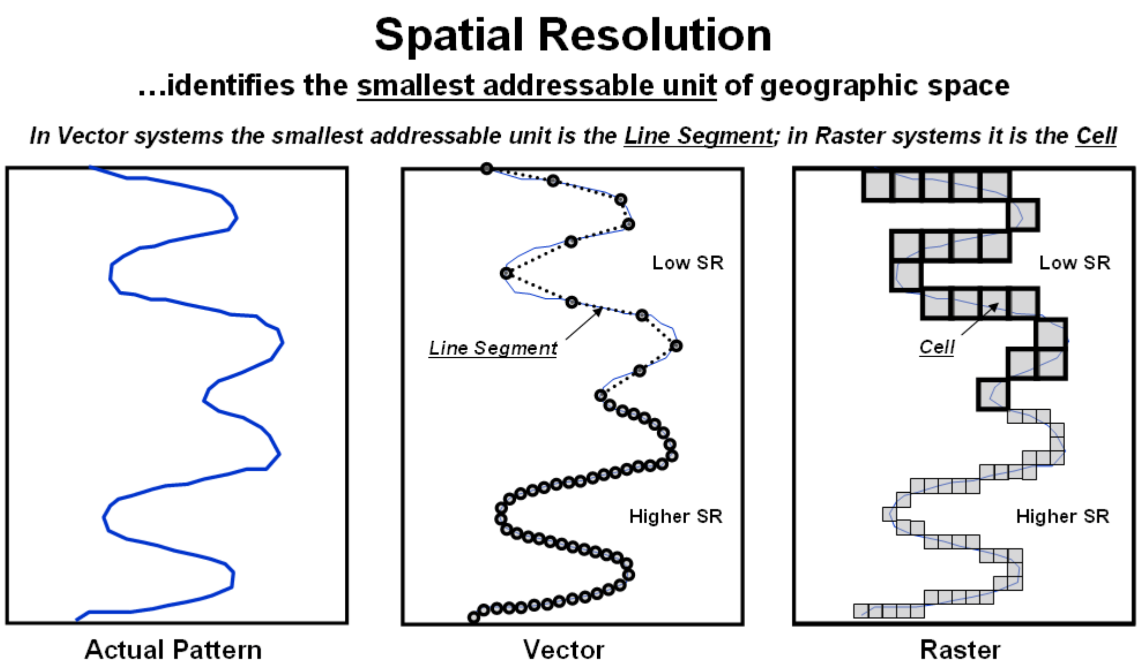

Figure 1. Spatial Resolution describes the level of positional detail used to track a geographic pattern or distribution.

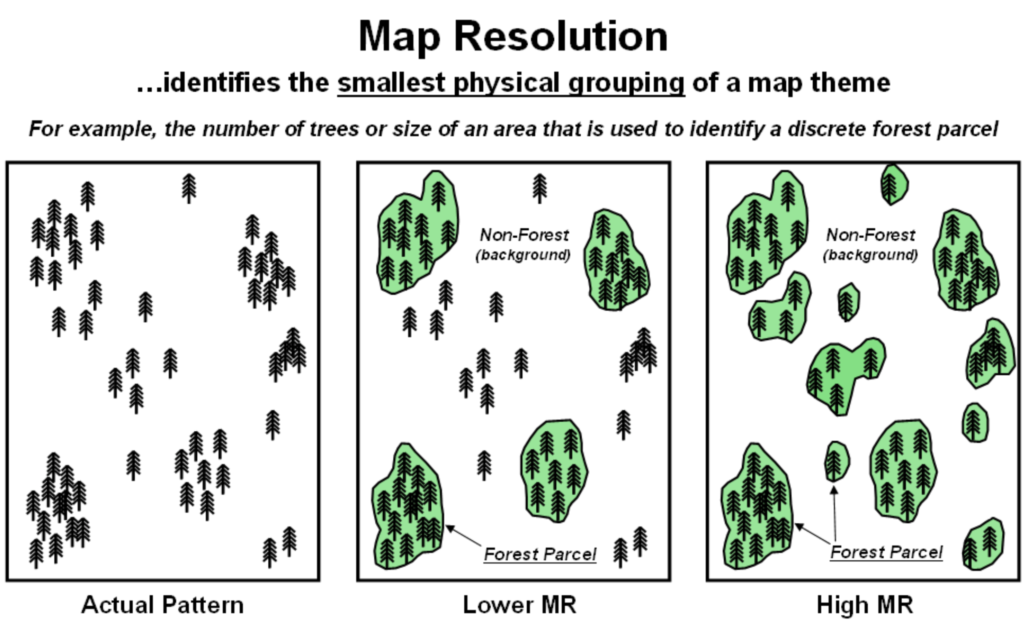

Figure 2. Minimum Mapping Resolution describes the level of physical aggregation used to depict a geographic pattern or distribution.

For polygon features in vector, an entire polygon represents the smallest addressable unit as the boundary needs to be completed before the implied interior condition can be identified. In raster, the smallest addressable unit is defined by the cell size as the condition is carried for each of the cells comprising the interior and edge of a polygon feature.

The concept of spatial resolution easily extends to the level of spatial aggregation or *Minimum Mapping Resolution* that identifies the "smallest physical grouping" of a map theme (figure 2). For example, a high resolution forest map might identify individual trees (very small polygons delineating canopy extent), whereas more generally, numerous trees are used to identify a forest parcel of several acres that ignores the scattered tree occurrences. The size of the minimum polygon is determined by the interpretation process with smaller groupings capturing more detail of the pattern and distribution.

Thematic Resolution identifies the "smallest classification grouping" of a map theme. For example, a simple forest/non-forest map might provide a sufficient description of vegetation for some uses and this coarse classification has appeared for years as green on USGS topographic sheets. However, resource managers require a higher thematic resolution of vegetation cover and expand the classification scheme to include species, age, stocking level and other characteristics. The result is a finer set of classification categories of a generalized forest area into smaller more detailed parcels (figure 3).

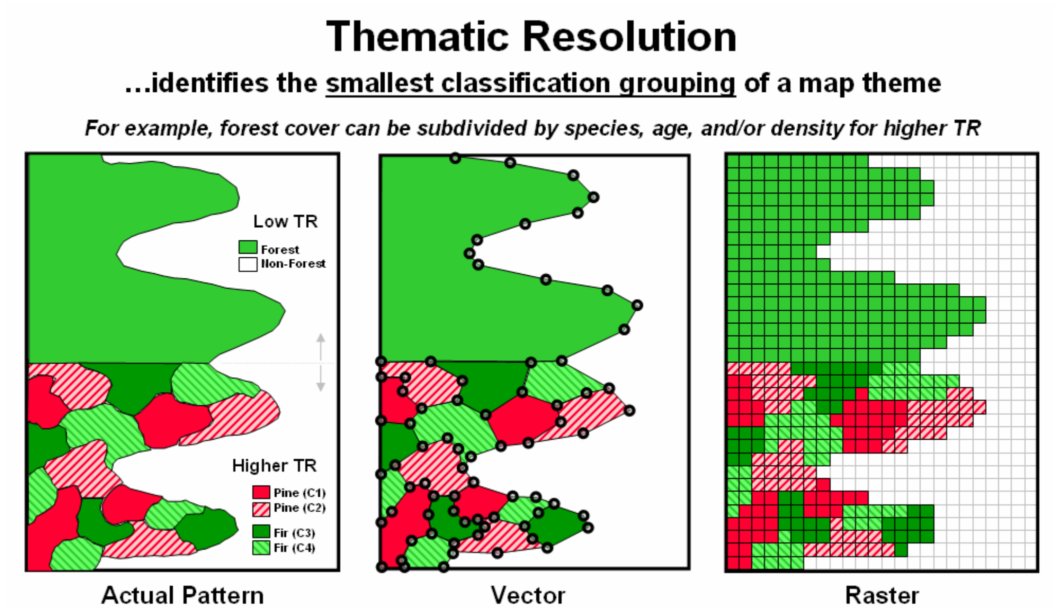

Figure 3. Thematic Resolution describes the level of classification aggregation used to depict a geographic pattern or distribution.

A fourth consideration involves *Temporal Resolution* that identifies the frequency, or time-step of map update. Some data types, such as geological and landform maps, change very slowly and do not need frequent revision. A city planner, on the other hand, needs land use maps that are updated every couple of years and include future development sites. A retail marketer needs even higher temporal resolution and will likely update sales and projection figures on a monthly, weekly or even daily basis.

Model Resolution is the least defined and involves factors affecting the level of detail used in creating a derived map, such as an optimal corridor for an electric transmission line or areas of suitable wildlife habitat. Model resolution considers detail ingrained in 1) the interpretation/analysis assumptions (logic) and 2) the algorithms/procedures (processing) used in implementing a spatial model. For example, a proposed transmission line could be routed considering just terrain steepness for a low model resolution, or extended to include other engineering factors (soils, road proximity, etc.), environmental concerns (wetlands, wildlife habitats, etc.) and social considerations (visual exposure, housing density, etc.) for much higher model resolution.

So why should we care about digital map resolution? Because accounting for informational scale is just as important as adjusting for a common geographic scale and projection when interacting with a stack of maps. Our paper map heritage focused on descriptive mapping (inventory of physical phenomena) whereas an increasing part of the GIS revolution focuses on prescriptive mapping (spatial relationships of physical and cognitive interactions). This "thinking with maps" requires a thorough understanding of the spatial, map, thematic, temporal and model resolutions of the maps involved or you will surely be burned.

Geo-Referencing Is the Cornerstone of GIS

(GeoWorld, April 2007)

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In the mid-1600s the French mathematician, René Descartes established the Cartesian coordinate system that is still in use today. The system determines the location of each point in a plane as defined by two numbers—a "*x-coordinate*" and a "*y-coordinate.*"

A third *z-coordinate* is used to extend the system to 3-dimensional geographic space (see Author's Notes). In mapping, these coordinates reference a refined ellipsoid (geodetic datum) that can be conceptualized as a curved surface approximating the mean ocean surface of the earth.

The location and shape of map features can be established by X and Y distances measured along flattened portions of the reference surface (figure 1). The familiar Universal Transverse Mercator (UTM) coordinates represent E-W and N-S movements in meters along the plane. The rub is that UTM zones are need to break the curved earth surface into a series of small flat, projected subsections that are difficult to edge-match.

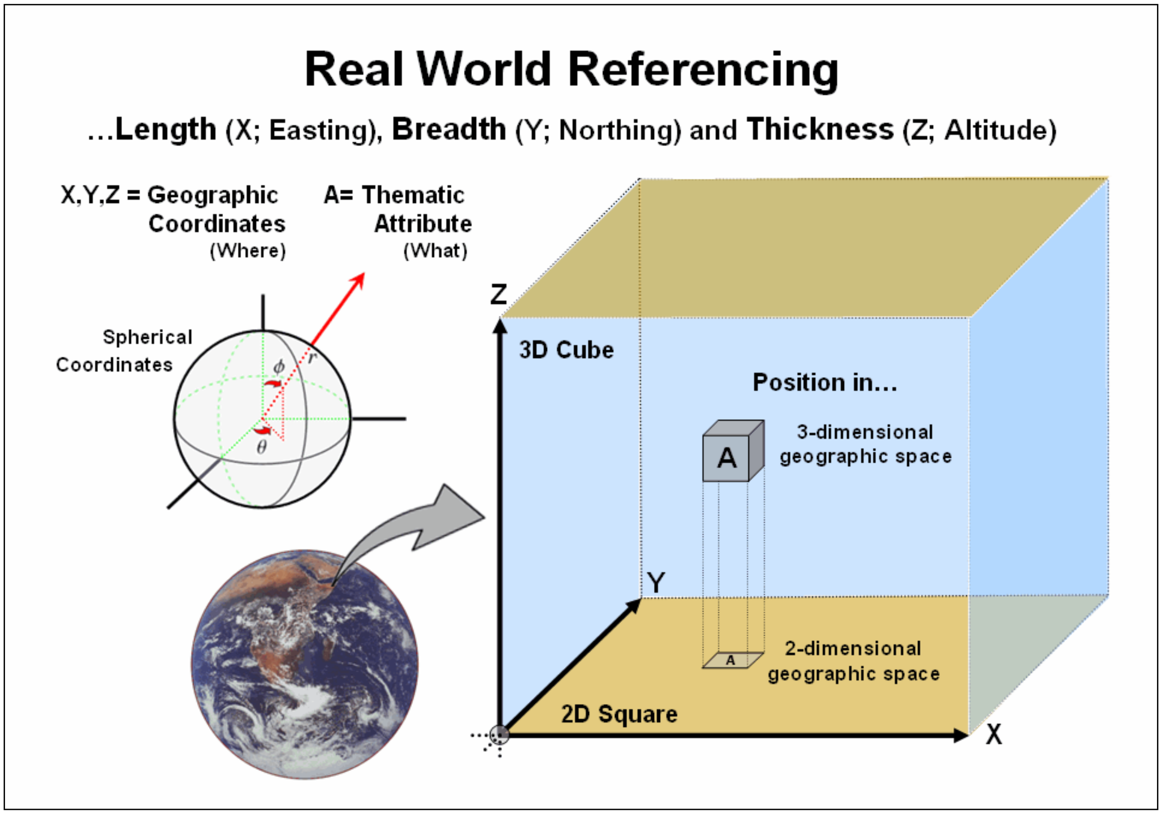

Figure 1. Geographic referencing uses three coordinates to locate map features in real world space.

A variant of the traditional referencing system uses spherical coordinates that are based on solid angles measured from the center of the earth. This natural form for describing positions on a sphere is defined by three coordinates—an *azimuthal angle* (θ) in the X,Y plane from the x-axis, the *polar angle* (φ) from the z-axis, and the *radial distance* (r) from the earth's center (origin). The advantage of a spherical referencing system is that it is seamless throughout the globe and doesn't require projecting to a localized flat plane.

Digital map storage is rapidly moving toward spherical referencing that uses latitude and longitude in decimal degrees for internal storage and on-the-fly conversion to any planar projection. This radical change from our paper map heritage is fueled by ubiquitous use of GPS and a desire for global databases that easily walk across political and administrative boundaries.

Since the digital map is a radical departure from the paper map, other alternative referencing schemes are possible. For example, hexagons can replace the Cartesian grid squares we have used for hundreds of years (top portion of figure 2). The hexagon naturally nests to form a continuous network like a beehive's honeycomb. An important property of a hexagon grid is that it better represents curved surfaces than a square grid— a soccer ball stitched from squares wouldn't roll the same *[Note: actually a soccer ball is a composite of hexagons (white) and pentagons (black)]*.

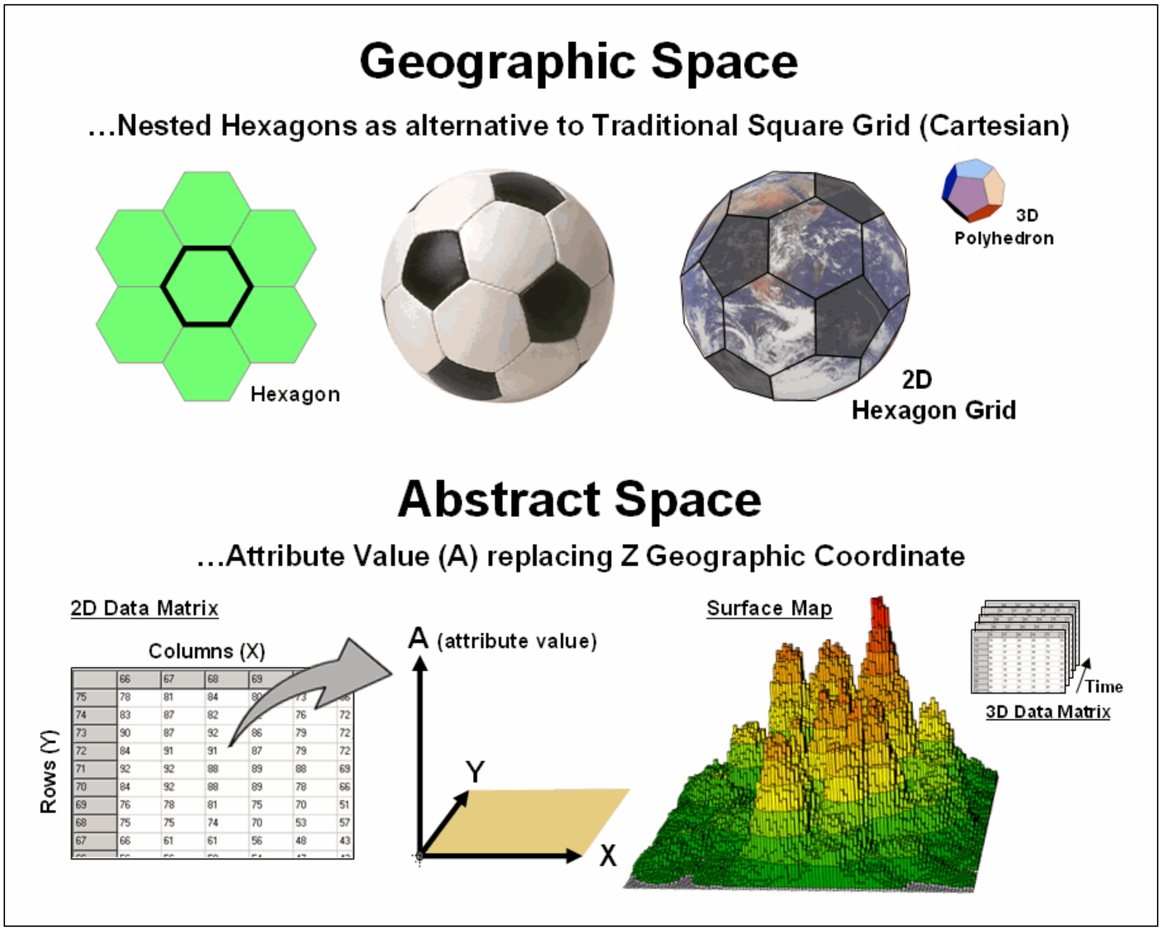

Figure 2. Alternative referencing systems and abstract space characterization are possible through the digital nature of modern maps.

However the most important property is that a hexagon has six sides instead of four. The added directions provide a foothold for more precise measurement of continuous movement— one can turn right- and left-oblique as well as just right and left. Traditional routing models using Least

Cost Path would benefit greatly.

Expanding to 3-dimensional geographic space provides for polyhedrons to replace cubes. For example, a dodecahedron is a nesting twelve-sided object that can be used instead of the six-sided cube. Weather and ground water flow modeling could be greatly enhanced by the increased options for transfer from a location to its larger set of adjoining locations. The computations for cross-products of vectors, such as warp-speed cruise missiles, could be greatly assisted as they are affected by different atmospheric conditions and evasive trajectories.

Another extension involves the use of abstract space (bottom portion of figure 2). For example, the Z-coordinate can be replaced with an attribute value to generate a map surface, such as customer density. In this instance, the abstract referencing is a mixture of spatial and attribute "coordinates" and doesn't imply 3-dimensional, real word geographic occurrences. Instead, it relates geography and conditions in an extremely useful way for conceptualizing patterns. Normalization along the abstract coordinate axis is an important consideration for both visualization and analysis.

This brings us to space-time referencing. During a recent panel discussion I was challenged for suggesting such a combination is possible within a GIS. The idea has been debated for years by philosophers and physicists but H.G. Wells' succinct description is one of the best—

'Clearly,' the Time Traveller proceeded, 'any real body must have extension in four directions: it must have Length, Breadth, Thickness, and - Duration. But through a natural infirmity of the flesh, which I will explain to you in a moment, we incline to overlook this fact. There are really four dimensions, three which we call the three planes of Space, and a fourth, Time. There is, however, a tendency to draw an unreal distinction between the former three dimensions and the latter, because it happens that our consciousness moves intermittently in one direction along the latter from the beginning to the end of our lives.' (Chapter 1, Time Machine).

The upshot seems to be that a fourth dimension exists (see Author's Notes), it is just you can't go there in person. But a GIS can easily take you there—conceptually that is. For example, an additional abstract "coordinate" representing time can be added to form a 3-dimensional data matrix. The GIS picks off the customer density data for the first "page" and displays it as in the figure. Then it uses the data on the on the second page (one time step forward) and displays it. This is repeated to cycle through time and you see an animation where the peaks and valleys of the density surface move with time.

So animation enables you to move around a city (X,Y) viewing the space-time relationship of customer density (A). In a similar manner you could evaluate a forest "green-up" model to predict re-growth at a series of time steps after harvesting to look into future landscape conditions. Or you can watch the progression over time of ground water pollutant flow in 3D space (4D data matrix) using a semi-transparent dodecahedron solid grid just for fun and increased modeling accuracy. In fact, it can be argued that GIS is inherently *n*-dimensional when you consider a map stack of multiple attributes and time is simply another abstract dimension.

My suspicions are that revolutions in referencing will be a big part of GIS's frontier in the 2010s. See you there?

Author's Notes: *an excellent online reference for the basic geometry concepts underlying traditional and future geo-referencing techniques is the Wolfram MathWorld pages, such as the posting describing the dodecahedron at http://mathworld.wolfram.com/Dodecahedron.html; a BBC posting at http://www.bbc.co.uk/science/space/exploration/timetravel/index.shtml contains an interesting discussion of the space/time reality. See the online book Beyond Mapping III, Topic 27, "GIS Evolution and Future Trends," for a discussion of 3-dimensional GIS posted at www.innovativegis.com/basis/MapAnalysis/.*

Further Online Reading: *(Chronological listing posted at **www.innovativegis.com/basis/BeyondMappingSeries/**)*

Is it Soup Yet? — *describes the evolution in GIS definitions and terminology (February 2009)*

What's in a Name — *suggests and defines the new more comprehensive term "Geotechnology" (March 2009)*

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