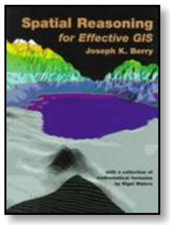
Beyond Mapping II

Topic 6 – Alternative Data Structures


Spatial Reasoning book

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Are You a GIS Dead Head?

(GeoWorld, May 1995)

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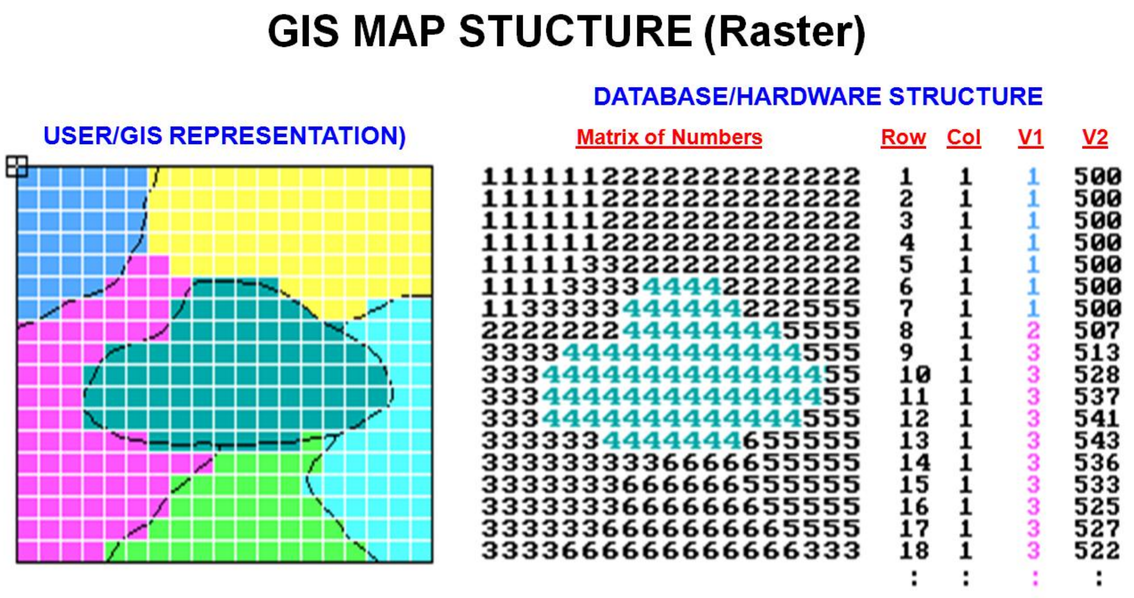
Even if you're new to GIS, you may have encountered the scholarly skirmishes between the raster heads and the vector heads. Like other religious crusades, the principles in these debates often are lost to mind-sets reflecting cultural exposure and past experience. More often than not, however, most of us just become catatonic when the discussion turns to GIS data structures. But what the heck-it's worth another try.

Let's review the basic tenets of vector and raster data, then extend this knowledge to the actual data structures involved. Vector data use sets of X,Y coordinates to locate three basic types of landscape features: points, Iines, and areas. For example, a typical water map identifies a spring as a dot (one X,Y coordinate pair), a stream as a squiggle (a set of connected X,Y coordinates), and a lake as a glob (a set of connected X,Y coordinates closing on itself and implying its interior). Raster data use an imaginary grid of cells to represent the landscape. Point features are stored as individual column/row entries in the grid; lines are identified as a set of connected cells; and areas are distinguished as all of the cells comprising a feature.

That traditional representation constrains geographical phenomena to three user-defined conditions (points, lines, and areas) and two GIS expressions (vector and raster). I bet this conceptual organization is fairly comfortable, and might even be familiar. But that's only half the problem— the user/GIS representation has to be translated into a database/hardware structure. At that step most of us simply glaze over and leave such details to the GIS jocks. Actually, the concepts aren't too difficult and they can help us understand much about different systems, the frustrations we may encounter, and the future direction of GIS.



Matrix of Numbers	Row	Col	V1	V2
1111112222222222222	1	1	1	500
1111112222222222222	2	1	1	500
1111112222222222222	3	1	1	500
1111112222222222222	4	1	1	500
1111133222222222222	5	1	1	500
1111333344444222222	6	1	1	500
1133333444444222555	7	1	1	500
2222222444444445555	8	1	2	507
3333444444444444555	9	1	3	513
3334444444444444455	10	1	3	528
3334444444444444455	11	1	3	537
3334444444444444555	12	1	3	541
3333334444444655555	13	1	3	543
3333333336666655555	14	1	3	536
3333333666666555555	15	1	3	533
3333333666666655555	16	1	3	525
3333336666666665555	17	1	3	527
3333666666666666333	18	1	3	522
	:	:	:	:

Figure 1. A file containing a matrix of numbers (attribute values) characterizes each cell of an imaginary grid. An alternative structure uses a standard database file containing the column/row identifiers for each cell followed by attribute fields, such as soil type and elevation.

Let's consider some structures for raster data. The left side of figure l shows an imaginary grid superimposed on a typical soil map (more appropriately termed a "data layer'). The center portion of the figure identifies a matrix of numbers with a numerical value assigned to each cell. In that case, the value represents a particular type of soil, and its position in the matrix indicates its location. To the computer, however, the matrix isn't a two dimensional array but simply one long list of numbers. The first number represents the upper-left corner of the matrix and the rest are ordered from left to right, top to bottom. Another map for the same area, say elevation, would be stored as a separate ordered sequential file: This is the simplest and most frequently used raster data structure.

An offshoot of raster structure is used for most remote sensing data. Each cell in the grid represents a small area of Earth's surface where a satellite collected spectral data. The numbers record relative amounts of energy, such as blue, green, and red light radiating from the surface. The set of values for each energy level represents a single data layer that can be arranged as a matrix and stored separately. These data, however, are stored more efficiently as an interlaced matrix, with all of the measurements for each cell stored sequentially. For example, the first three values might represent the blue, green, and red light measurements for the upper-left cell, with the following triplets of values for the other cells sequenced as before-left to right, top to bottom.

The interlaced structure has a significant advantage in point-by-point processing, because all information is contained in a single file and available as the computer methodically steps through the matrix. The computer doesn't have to open three separate files, then read blue, green, and red values scattered all over the disk. As a result, you have a lot less disk thrashing and a happier computer. That may not seem like a big deal, but considering that a typical Landsat Thematic Mapper scene contains seven data layers for about 36 million cells (that's more than 250 million numbers), even a slight increase in storage efficiency is cyber heaven.

The interlaced structure might be neat and tidy for remote sensing data, but it's inappropriate for a general GIS. First, it's tough to add a new map. It means extra room must be made to insert the new values by reading the first three values from the original file, writing them to a new file, inserting the first new value, and then repeating the process for the other million or so cells. Oh yes, and then delete the original file. And you have the same problem if you want to delete a map. Second, because the information for each data layer is dispersed (every third value), it's difficult to compress the redundancy found in a typical map. Finally, any processing involving neighboring cells requires extra work as the computer must continually jump back and forth in the file to get values for the ceils above, below, right, and left of the target ceil. In short, the interlaced structure is best for specialized applications involving a fixed number of maps constrained to cell-by-cell processing, such as most remote sensing data processing.

So what else do we have in raster structures? Consider the right side of figure 1. The structure uses a standard database file (a "database table") with the column/row entries of the matrix explicitly stored as "fields" (i.e., separate columns). The subsequent fields contain the listing of values for various data layers. Note that the set of soil values under V1 corresponds to the left-hand column of the matrix. If there was room in the figure to list the rest of the values in the field, the next set would replicate the next column to the right in the matrix, then the next, and so on. The V2 listing depicts similarly organized elevation values.

Now comes the advantage. Suppose you want to find all locations (i.e., cells) that contain soil type 4 and are more than 550 feet in elevation. Simply enter a Structured Query Language (SQL) command and the computer searches field columns V1 and V2 for the specified condition. A new field (V3) will be appended containing the results. It's easy, because you use a standard database file under the control of a standard database management program. A standardized structure makes it easy for GIS programmers, because they don't have to write all the code that's already in the database "engine." Also, it allows you to store and process text string designations, as well as numerical values. More importantly, it makes it easy on the user, because the command uses the same format as a normal office database.

The problem lies with the computer. It hates appending new fields to an existing table. Also, the number of fields in a single table is constrained. The solution is a series of indexed tables, with each cell's designation serving as the common link. With an indexed structure the computer can easily "thread" from one table to another. Actually, there are good arguments for storing each data layer as a separate indexed table. Creating, modifying, or deleting a map is a breeze, because it affects only one table rather than a field embedded in a complex table. That seems to brings us back to where we began— one map, one file. In that instance however, each map is a standard indexed database table with all of the rights, privileges, and responsibilities of your office database. It puts raster GIS where it should be— right in the middle of standard database technology. As we'll see in the next section, vector GIS has been there all along.

Raster is Faster, but Vector is Correcter

(GeoWorld, June 1995)

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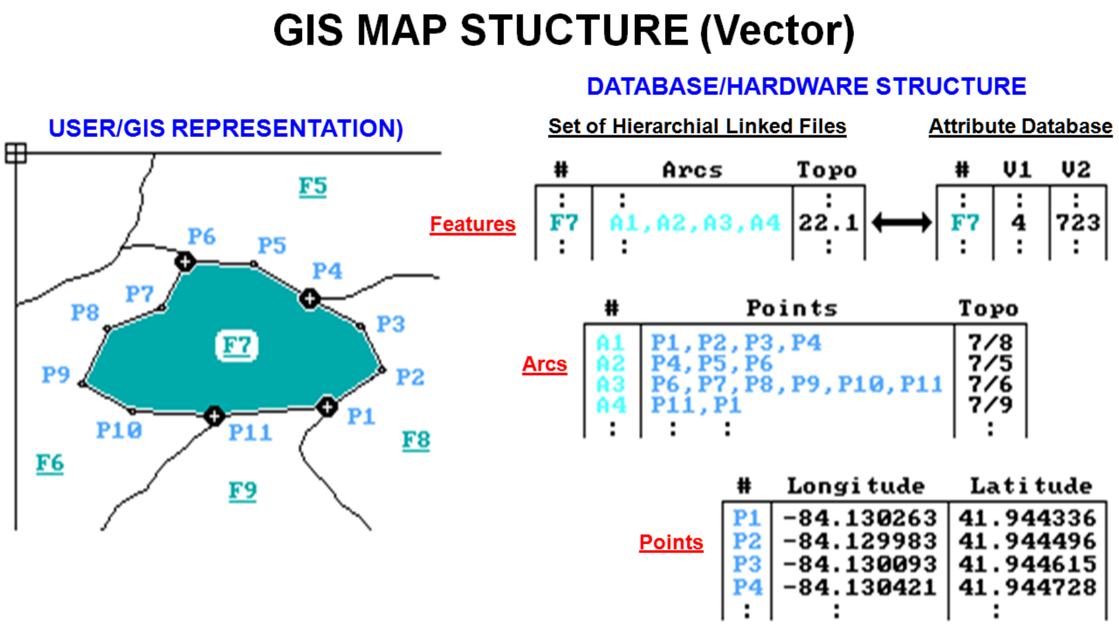
Your computer really loves raster data— a cell on one map is at the same position on all others. A couple of "hits-to-disk" and it knows everything about a cell location. A few more hits up, down, left and right and it knows everything about a location's entire neighborhood. In fact, it can "walk" from one location to another and find everything it needs to know along the way, right from the hard disk. Its world is pre-defined in little byte-size pieces that are just right.

However, the computer-endearing qualities of consistency and uniformity put raster data at odds with the human psyche (and a lot of reality). We see the unique character of each map feature— a cute little jog here, a little bulge there. The thought of generalizing these details into a set of uniform globs is cartographic heresy.

So what does it cost your computer, in terms of data structure, to retain the spatial precision you demand? First, because every map feature is unique, a complex data structure is required. Consistency and uniformity are out; uniqueness and irregularity are in. More importantly, processing involves threading through a series of linked files (called "tables" in database speak), mathematically constructing map features, calculating the implied coincidence, then reconstructing the new data structure linkages; all that just to know the property line isn't 100 feet over there ... picky, picky.

Figure 1 identifies the basic elements of vector data structure. It begins with a points table, attaching coordinates to each point used in the construction of map features. Most systems use latitude and longitude as their base coordinates. That's a good choice, as it's a spherical coordinate system that accurately locates points anywhere on Earth's surface. It's a problem, however, when you want to relate points, such as measuring distances, bearings, or planimetric areas.



#	Arcs	Topo
:	:	:
F7	A1,A2,A3,A4	22.1
:	:	:

#	V1	V2
:	:	:
F7	4	723
:	:	:

#	Points	Topo
A1	P1,P2,P3,P4	7/8
A2	P4,P5,P6	7/5
A3	P6,P7,P8,P9,P10,P11	7/6
A4	P11,P1	7/9
:	: :	:

#	Longitude	Latitude
P1	-84.130263	41.944336
P2	-84.129983	41.944496
P3	-84.130093	41.944615
P4	-84.130421	41.944728
:	:	:

Figure 1. A set of f files links coordinates, arcs, and features to describe location. A standard database file links each feature to its attributes, such as soil type and elevation.

In three dimensions, seemingly simple calculations involve solid geometry and ugly equations that bring even powerful computers to their knees. Plus, the three-dimensional answers can't be drawn on a flat screen. The solution is to carry a user-specified map projection scheme and planar coordinate system (e.g., Universal Transverse Mercator), then translate on-the.fly. Now the computer can work in any two-dimensional rendering you choose and easily display the results on your screen or plotter ... happy computer, happy you.

For point features, the point table and its two-dimensional translation specifications are linked directly to another indexed file containing descriptive information, called "attributes," about each point. If this information depicted soil samples, you could query the attribute table for all of the samples that have a pH less than 7 and available phosphorus exceeding 30 parts per million. The results from the attribute query simply "threads" to the coordinates of the subset of points meeting the conditions, then plots them at blinding speed in the vibrant color of your choice.

Line and area features are a bit more complicated because the various connections among sets of points need to be specified. When you view a human-compatible map of water features you intuitively note which stream is connected to which stream by the network of blue squiggles. You note that lakes are blue globs with a squiggle in and another out. But the computer's point file is just a huge pile of unrelated numbers. The first level of organization is a linked arcs table. The file groups the points into connected sets of arcs, forming the map features. In figure 1, points Pl, P2, P3, and P4 are connected to form arc A1. Similarly, arcs A2, A3, and A4 are defined by their linked coordinates.

The features table puts it all together in geographic space by linking the "*arcs*" to actual map features. In the example, feature F7 is formed by linking arcs A1, A2, A3, and A4. The corresponding arcs table identifies which points are involved, with the coordinates in the points table ultimately tying everything to the ground. At the top of this scheme is a linked info table with the attribute data for each map feature. In the example, feature F7 is identified as having soil type 4 (field V1) and an average elevation o1723 (field V2).

There, that's not too bad—conceptually. The tough part comes when you try to put it all into practice with about 100,000 polygons. That's when each vendor's "secret ingredients" of the general vector recipe take hold. Without giving away any corporate secrets, let's take a look at some of the "tweaking" possibilities.

In addition to the link to the points, the arc and feature tables often contain topological and other information. For example, note that arc A1 forms a shared boundary between features F7 and F8 as listed in the "Topo" field of the arcs table (7/8). For maps composed of contiguous polygons (e.g., soils, cover type, ownership, and census tracts) a search of this field immediately identifies the adjoining neighbors for any map feature. Many systems store frequently used geometric measurements— such areas as depicted in the "Topo" field of the features table (22.1 acres). The alternative to these tweaks in data-structure design is a lot of computational thrashing and bashing each time they're needed.

Line networks use topological information to establish which arcs are interconnected and the nature of their connections. In a stream network it depicts the direction of water flow. In a road network it characterizes all possible routes from any location to ail other locations. To describe the linkage embedded fully, however, a new element must be introduced: the "*node*." These special points are indicated in the figure as the large dots at the ends of each arc (P1, P4, P6, and P11). Nodes represent locations where things are changing, such as the separation of adjacent soil units along a soil boundary. Some systems store nodes in a separate table, while others simply give them special recognition in the points table. The information associated with a node reflects the type of data and the intended processing.

If the length of each arc is stored, the computer can find the distance from a location to all other locations by simply summing the intervening arcs along a route. If an average speed is stored for each arc, the answer will be in travel-time. But what about one-way streets and the relative difficulty of left and right turns at each intersection or node? Attach that information to the nodes and the computer will make the appropriate corrections as it encounters the intersections along a route. Similarly, an accumulated distance from a location to its surroundings can be determined by keeping a running sum of the arc distances, respecting the "turntable" information at each node. Once that's known it's an easy matter to determine the optimal path (shortest time or distance) from any location to the starting point.

All is for naught, though, if your data structure hasn't been tweaked to carry the extra topological and calibration information. It should be apparent that, unlike raster data structures, vector data structures can be radically different. Ingenuity and programming dexterity are critical factors, as is the matching of data design to intended applications and hardware. That's the tough part; there isn't a universal truth in vector data structure. The onus is on you to pick the right one for your applications, then understand it enough to take it to its limits.

How are your QUADS and TINS?

(GeoWorld, July 1995)

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The original raster and vector data structures have been around a long time. The basic concepts of representing a landscape as a set of grid cells or a set of connected points are about as old as cartography itself. The technical refinements required for a functioning GIS, however, evolve continually. About the time I think we've reached the pinnacle of data structure design, someone comes out with a new offshoot. The only folks who think they have it all are overzealous marketers. The technical types keep their heads down, constantly looking for more effective ways to characterize mapped data.

Most raster systems can perform *run-length compression*, which compacts along the rows or the columns. For example, consider the matrix and its row-compressed translation in Table 1. The run-length data structure uses just 44 numbers to represent the 162 numbers in the full matrix. It uses "value through column" pairs of numbers to compact redundancy along a row. For example, the first row is read "value from column 1 (assumed) through column 7, value 2 from column 8 (last column plus one) through column 17, and value 3 from column 18 through column 18." That format is particularly useful in map display. Instead of "hitting disk" for the color-fill-pattern value at each cell, the computer reads the pattern designation and simply repeats the pattern specified by the column spread. That's a savings in storage and increased performance-a win-win situation.

Table 1. Example of Run-Length Encoding (**1** = Open Water, **2** = Meadow, **3** = Forest)

Full Matrix	**Run-Length (Row) Encoding**
111111122222222223	1,7,2,17,3,18 …**1** thru 7, **2** thru 17, **3** thru 18
111111122222222233	1,7,2,16,3,18 …**1** thru 7, **2** thru 16, **3** thru 18
111111122222222333	1,7,2,15,3,18 …**1** thru 7, **2** thru 15, **3** thru 18
111111222222223333	1,6,2,14,3,18 …**1** thru 6, **2** thru 14, **3** thru 18
111113333333333333	1,5,3,18 …**1** thru 5, **3** thru 18
111113333333333333	1,5,3,18 …**1** thru 5, **3** thru 18
111113333333333333	1,5,3,18 …**1** thru 5, **3** thru 18
111333333333333333	1,3,3,18 …**1** thru 3, **3** thru 18
111333333333333333	1,3,3,18 …**1** thru 3, **3** thru 18

So why don't we compress in the row and column directions at the same time and get even more?

In effect, that's what a *quadtree* data structure does. It's an interesting second cousin to the traditional raster data structure that uses a cascading set of grid resolutions to compress redundancy. Consider the map boundaries shown in figure 1. If the map window is divided in half in both the X and Y directions, four panels (quadrants) are identified. That superimposes a coarse grid of just two columns and two rows.

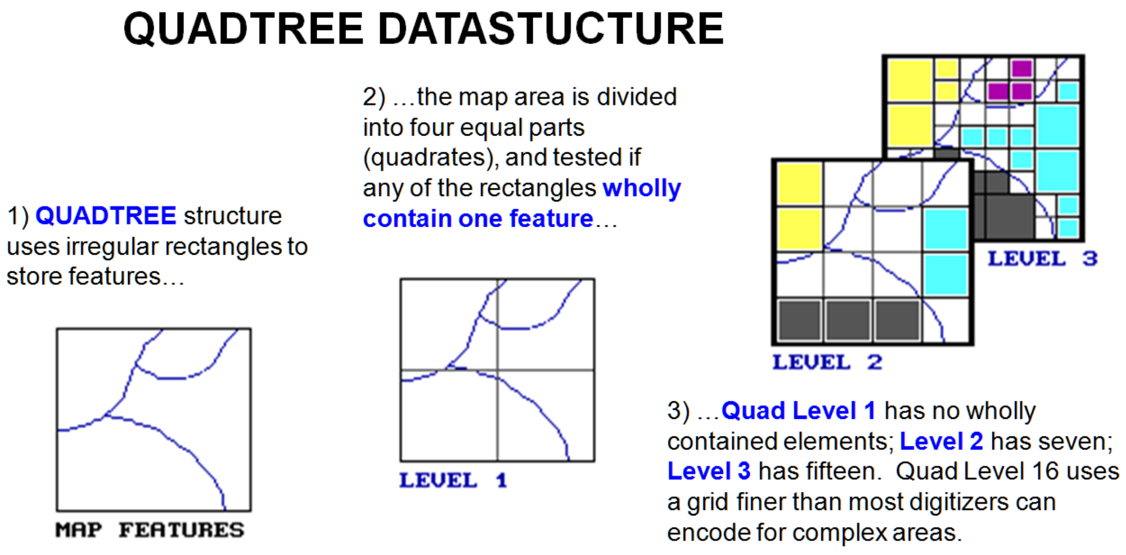

QUADTREE DATASTUCTURE
1) QUADTREE structure uses irregular rectangles to store features…
MAP FEATURES
2) …the map area is divided into four equal parts (quadrates), and tested if any of the rectangles wholly contain one feature…
LEVEL 1
LEVEL 2
LEVEL 3
3) …Quad Level 1 has no wholly contained elements; Level 2 has seven; Level 3 has fifteen. Quad Level 16 uses a grid finer than most digitizers can encode for complex areas.

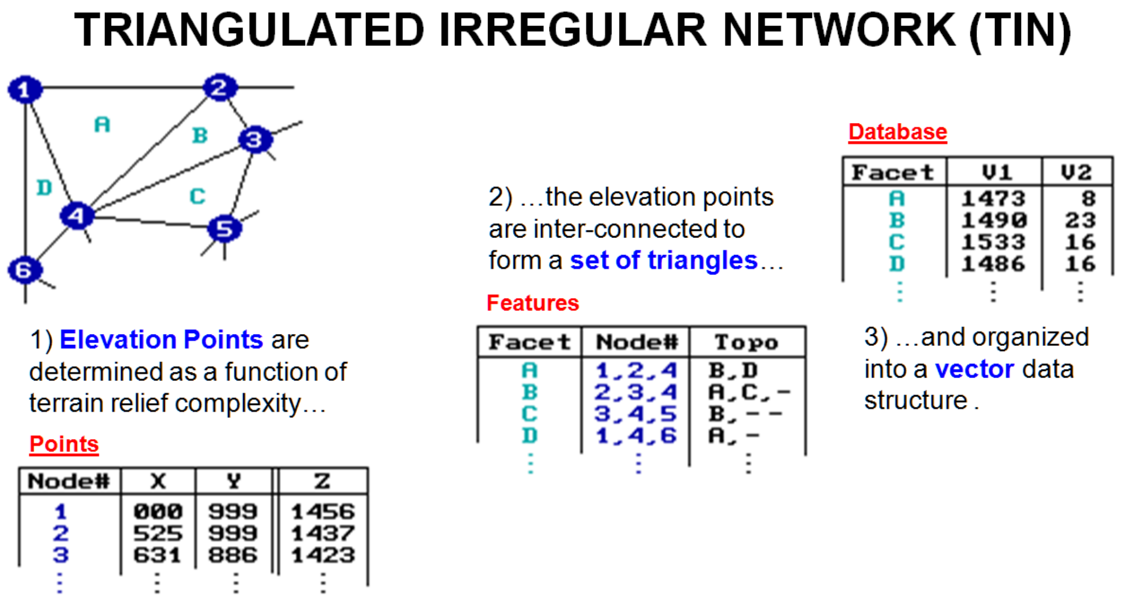
Figure 1. Quadtree data structure elements.

At that point the computer tests whether any quadrant wholly contains a single map characteristic. In the example there are none, so each of the panels is divided into its quads (Level 2). At that point, there are seven of the 16 quadrants that wholly contain a single characteristic. Their positions in the four-by-four grid are noted, and the remaining nine mixed panels are divided into their quads (Level 3). Fourteen of these are noted as completed, and the remaining 22 are divided for Level 4 of the quadtree. The process is repeated until an appropriate quad level resolution is reached. At level 16, a gridding resolution of 65,536 rows by 65,536 columns is available wherever it is needed— that equates to a fixed raster grid of 4,294,967,296 cells! But the quadtree isn't forced to use that resolution everywhere so it accurately stores most maps in less than a megabyte.

Quadtrees and run-length data structures are good at compressing raster data. However, they must be decompressed and then recompressed for most map analysis operations. Many GISs don't impose a compression routine within the data structure, but simply leave it to commercial hard disk compression packages. Such packages respond to data redundancy and optimize for disk head movement.

The *Triangulated Irregular Network* (TIN) data structure is a vector offshoot originally designed for elevation data. It avoids the redundancy of elevations in a normal raster representation and is more efficient for some terrain analysis operations, such as slope and aspect. It uses a set of irregularly spaced elevation measurements with intensive sampling in areas of complex relief and/or important features, such as ridges and streams. A bit of computer wizardry is applied to determine the network of triangular facets that best fits these data. Each facet has three interconnected elevations and can be visualized as a tilted triangular plane. The direction cosines of the plane identify its slope and aspect. The average of the three elevations generalizes the plane's height.

As shown in figure 2, the XY coordinate (location) and the z coordinate (elevation) are stored in a points table similar to traditional vector structure. The triangular facets are defined in a features table by their three nodes and adjoining facets. The final link is to an attribute table which contains descriptive information on each facet. Awesome shaded relief maps can be generated by plotting the facets in 3-D and shading them as functions of their slopes and aspects.


TRIANGULATED IRREGULAR NETWORK (TIN)
1
2
3
4
5
6
A
B
C
D
1) Elevation Points are determined as a function of terrain relief complexity…
2) …the elevation points are inter-connected to form a set of triangles…
3) …and organized into a vector data structure .
Points
Features
Database

Node#	X	Y	Z
1	000	999	1456
2	525	999	1437
3	631	886	1423
⋮	⋮	⋮	⋮

Facet	Node#	Topo
A	1,2,4	B,D
B	2,3,4	A,C,-
C	3,4,5	B,--
D	1,4,6	A,-
⋮	⋮	⋮

Facet	V1	V2
A	1473	8
B	1490	23
C	1533	16
D	1486	16
⋮	⋮	⋮

Figure 2. TIN data structure elements.

Using a TIN rather than raster structure to characterize a three-dimensional surface has some significant advantages. It usually requires fewer points, captures discontinuities such as streams and ridges, and determines slope and aspect of the facet itself. It's the data structure of choice for most civil engineering packages designed for terrain analysis. However, it's inappropriate for a generalized GIS that mixes a variety of maps. First, it's like raster, because it uses a mosaic of geographic chunks to represent a map feature. The chunks are inconsistent between maps, however, and something as simple as map overlay takes a severe hit in performance. Also, TIN two-dimensional renderings are complex and bewildering to most users compared to a normal raster display or vector contour plot.

Quadtree and TIN are useful offshoots of basic raster and vector data structures. They provide important benefits for certain data under certain conditions. If they match your needs, they're an invaluable addition to your GIS arsenal.

Rasterized Lines and Vectorized Cells

(GeoWorld, August 1995)

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Chances are your GIS is (or will be) ambidextrous. It has a vector side and a raster side, and might even have TIN or quadtree sides. The different data structures indicate various perspectives on data types and user applications. The vector approach characterizes discrete map objects and is influenced by applications in computer graphics. Raster characterizes continuous mapped data and emerges from remote sensing applications that involve multivariate statistics. Today, considerations in database/hardware structure influence future development as much as historical user/GIS representation theory. In a sense, the realities of an evolving computer environment challenge traditional ways.

A *rasterized lines* structure is an interesting offshoot from traditional data structures. It's sort of a hybrid because it uses a grid structure to characterize a map's line work. An optical scanner is used to “turn on” each cell in a fine sampling matrix that corresponds to the set of lines. The process is similar to the way your office fax machine “reads" a document. The fax at the other end simply deciphers the on-off conditions in the matrix and puts a dab of black toner at spots corresponding to “on." It skips over the "off" spots, leaving just white paper. That’s it, a black-and-white rendering of map lines pushed over the phone lines.

If you use a magnifying glass, you can see the individual dots. At normal viewing distances, however, they merge to form smooth lines. Your brain easily makes sense of the pattern of lines and implied polygons embedded in the fine grid of the sampling matrix. Which streams are connected to which streams and which lakes are in which watersheds are obvious from the graphic rendering.

But that's not the case for a computer-the image is just a jumble of on and off dots. The first step in imposing order on data structure is to locate and mark as nodes all the special dots where lines meet (intersections), or just hang out by themselves (end points). Traditional vector structuring simply follows the dots between nodes and then storing the coordinates for a point whenever there is a significant X or Y deflection. The result is a series of discrete points connected by implied straight lines, as shown in inset 2 of figure 1. The nodes and intervening points then indexed files, as described in the previous section.

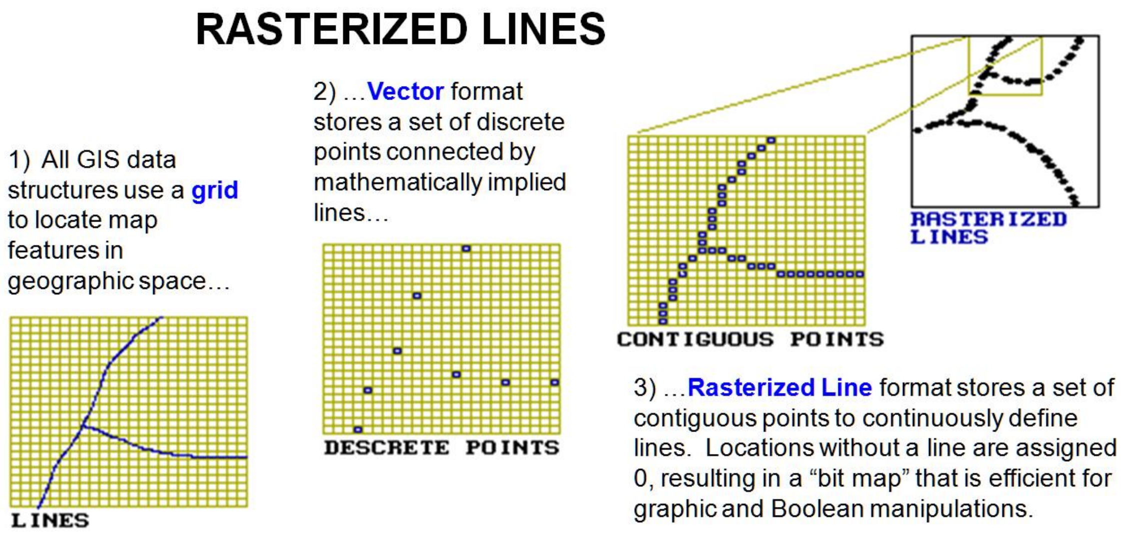

RASTERIZED LINES
1) All GIS data structures use a grid to locate map features in geographic space…
LINES
2) …Vector format stores a set of discrete points connected by mathematically implied lines…
DESCRETE POINTS
CONTIGUOUS POINTS
RASTERIZED LINES
3) …Rasterized Line format stores a set of contiguous points to continuously define lines. Locations without a line are assigned 0, resulting in a "bit map" that is efficient for graphic and Boolean manipulations.

Figure 1. Rasterized lines data structure elements.

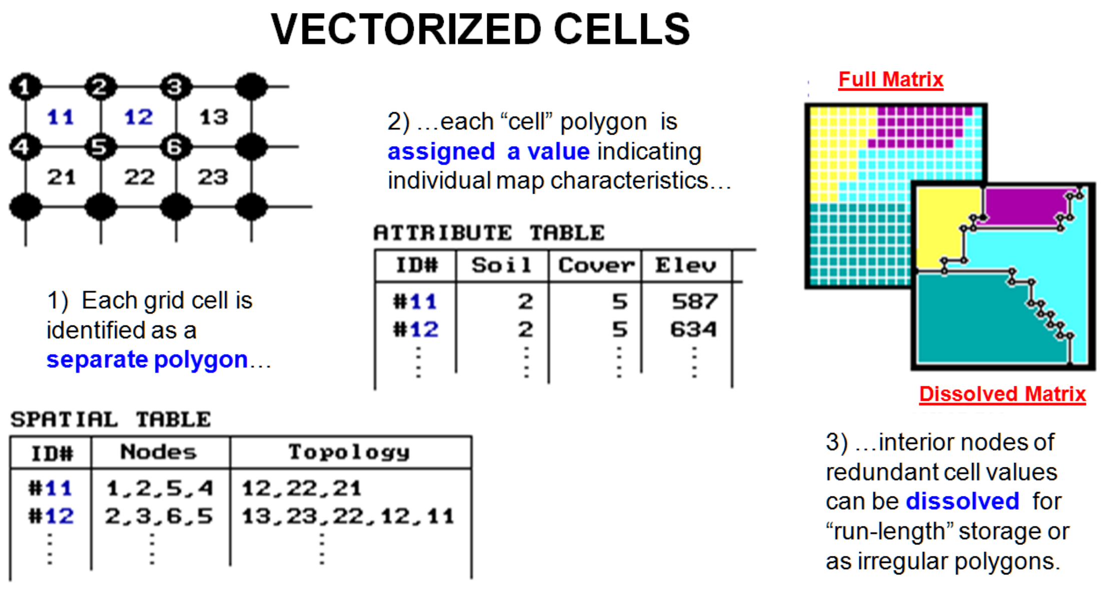
Rasterized lines retain all the dots along the lines. At first that seems stupid, because the points file is huge. Where an arc might require 10 discrete points, a rasterized line might require 100 or more. Some tricks in data compression and coordinate referencing can help, but it requires a lot more storage any way you look at it. So why would anybody use a rasterized line structure? Primarily because it's a format hardware loves. Faxes, scanners, screens, plotters and printers are based on dot patterns. As a result, much attention is paid to handling dotted data efficiently. Also, advances in optical disk storage and memory chips are redefining our concept of a "storage hog" so these files seem smaller each year.

More important, however, are advancements in central processing units (CPUs). Most computers still use a "kur-plunk-a" processing approach developed in the 1940s. It mimics our linear thinking and the way we do things-do A, then B, then C. Array and parallel processors, however, operate simultaneously on whole sets of data, provided they're organized properly.

Suppose you want to overlay a couple of traditional vector maps. In an instant, the computer reads the coordinates for two points on one map, and then has to figure out if the implied line segment between them crosses any implied line segment on the other map. If it does, it mathematically calculates the point of intersection, splits the two lines into four, and then updates all the indexed tables. Whew! That approach is a lot of work, and it's a purely linear process and a mismatch for array processing.

If the data are in rasterized line format, however, an array processor merely reads the corresponding chunks of cells on both maps and multiplies them together (a Boolean operation for you techy types). The product array identifies the composite of the two maps and highlights the new nodes where lines cross. Don't get me wrong: I'm not advocating you run out and buy rasterized line systems, but they have some interesting features for tomorrow's computers.

Another interesting offshoot, *vectorized cells*, cheats by storing each cell of an analysis grid as an individual polygon (figure 2). It just so happens that all of the polygons have the same square configuration and adjoin their neighbors. From a traditional vector perspective, each point defining a cell is a node; each cell side is an arc composed of just two nodes; and each cell is a polygonal feature composed of just four arcs. That approach uses the existing vector structure without impacting the existing code. It simply imposes consistency and uniformity in the polygons. All that's needed is an import module to generate the appropriate configuration of vectorized cells and read the raster values into a field in the corresponding attribute table. Raster-to-vector conversion can be completed by dissolving the pseudo-boundaries between adjoining polygons with the same value. Line features can be converted by connecting the centers of cells with similar value. Point features are represented by the coordinates of isolated cell centers.



1) Each grid cell is identified as a **separate polygon**…

2) …each "cell" polygon is **assigned a value** indicating individual map characteristics…

3) …interior nodes of redundant cell values can be **dissolved** for "run-length" storage or as irregular polygons.

ATTRIBUTE TABLE

ID#	Soil	Cover	Elev
#11	2	5	587
#12	2	5	634
⋮	⋮	⋮	⋮

SPATIAL TABLE

ID#	Nodes	Topology
#11	1,2,5,4	12,22,21
#12	2,3,6,5	13,23,22,12,11
⋮	⋮	⋮

Figure 2. Vectorized cells data structure elements.

Vectorized cells initially were used to "kludge" a link from raster to vector systems. However, the inherent consistency and uniformity of the structure (four points to a polygon), coupled with advances in data compression and database technology, might spark a resurgence in interest. Things as fluid because computers are becoming less bounded by storage requirements and the industry is shifting toward new processors and operating systems. Keep in mind that there are only two things certain about data structures: (1) tomorrow there will be new ones, and (2) what's good for one application isn't necessarily the best for another.

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