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Geographic Information Systems: The Developer's Perspective

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GEOGRAPHIC INFORMATION SYSTEMS: THE DEVELOPER'S PERSPECTIVE

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ABSTRACT

Geographic information systems, which manage data describing the surface of the earth, are becoming increasingly popular. This research details the current state of the art of geographic data processing in terms of the needs of the geographic information system developer.

The research focuses chiefly on the geographic data model--the basic building block of the geographic information system. The two most popular models, tessellation and vector, are studied in detail, as well as a number of hybrid data models.

In addition, geographic database management is discussed in terms of geographic data access and query processing. Finally, a pragmatic discussion of geographic information system design is presented covering such topics as distributed database considerations and artificial intelligence considerations.

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INTRODUCTION

Geographic data processing involves the management of data describing the surface of the earth. The data involved describes both natural and man-made features. This data has traditionally been stored in the form of paper maps and charts; however, the computer is now becoming an increasingly important tool for the storage and management of geographic data. Modern computer technology offers almost unlimited potential for automating maps and making them more effective and easier to use.

Computerized geographic data processing involves many different areas, including geography, cartography, remote sensing, computer graphics, and many others. All of these areas come together to form a dynamic and exciting new science, with great potential for the future.

The chief product to come out of the relatively young field of computerized geographic data processing has been the Geographic Information System (GIS). A GIS is a system of hardware and software components used to manage geographic data. This report describes the basic technology behind the geographic information system from the GIS developer's perspective.

The earliest geographic data processing software was developed chiefly by geographers and cartographers, as opposed to computer scientists. This early software, therefore, tended not to take full advantage of all the facets of computer science; the algorithms were simple and straightforward, designed to get the job done. As geographic data processing grew in popularity, however, a new breed of geographer appeared on the scene, a geoprapher/computer scientist. This new professional brought together the skills necessary to carry geographic data processing to its present advanced state.

The principle factors which aided in the development of the modern geographer, and in turn of modern geographic data processing, were the advances in data structure theory and data modeling theory which occurred in the late 1960's and early 1970's. These advances fostered the development of modern database analysis and design, on which geographic data processing is based.

The material in this report should be considered essential to both the researcher just beginning in the geographic data processing field, and the professional embarking on the design and implementation of a GIS. The first, and largest, section of the report focuses on the basic building block of the geographic information system:

the geographic data model. Although important to both the researcher and the professional, this section is probably most important to the researcher, who will likely spend more time working at this fundamental level than the professional.

The next section of the report discusses geographic database management. As opposed to the previous section, this section is probably more important to the professional, since it discusses database management in terms of geographic data access and query processing.

Finally, a pragmatic discussion of geographic information system design is presented in the last section. This material is equally important to both the researcher and the professional. This discussion includes general design considerations, distributed database considerations, and artificial intelligence considerations.

As mentioned previously, computer graphics play an important role in computerized geographic data processing. In fact, the graphics capabilities of a geographic information system are often one of the chief decision criteria considered by potential users. However, because this report concentrates on geographic data models, and data management and design factors directly related to geographic data modeling, a discussion of computer graphics is not included.

GEOGRAPHIC DATA MODELS

A data model is an abstraction of reality. It can be thought of as an intuitive conceptualization of the real world. A data model is the first of a number of levels of abstraction necessary to represent real world data in digital format. Peuquet (1984) describes these levels of abstraction as:

> Reality - the phenomenon as it actually exists, including all aspects which may or may not be perceived by individuals;
>
> Data Model - an abstraction of the real world which incorporates only those properties thought to be relevant to the application or applications at hand;
>
> Data Structure - a representation of the data model often expressed in terms of diagrams, lists, and arrays designed to reflect the recording of the data in computer code;
>
> File Structure - the representation of the data in storage hardware.

These last three levels are precisely the major steps involved in database design and implementation.

In the past, common usage had tended to consider the terms "data model" and "data structure" synonymous. However, advances in data structure theory and computing technology have fostered the creation of the "level of abstraction" definition of a data model. Thus, the data model "has evolved to connote a human conceptualization of reality, without consideration of hardware and other implementation conventions or restrictions" (Peuquet 1984, 69).

Data modeling is by far the most important component of database design. There are always a number of ways (file structures) to represent any type of data in digital form. The key element which makes this digital data a viable database, however, is the efficiency with which the data can be stored and retrieved. It is the data model which provides the framework for storage and retrieval.

The most common data models in use today are those used in the processing of non-spatially referenced data. While the locations in space of geographic entities are the chief subject of geographic data processing, there is more to geographic data than just location. Other data describing non-spatially related details of the entities, known as attribute data, are better stored using more conventional non-spatial data models. Examples of these models are the relational model, the hierarchical model, and the network model.

Spatially referenced data are the major component of a GIS, and spatial data modeling is therefore the heart of geographic data processing. The remainder of this section details the major developments in the field of spatial data modeling.

At this point, the reader should note that this section of the report is an update of Peuquet's 1984 landmark article in Cartographica, entitled "A Conceptual Framework and Comparison of Spatial Data Models."

Since the advent of geographic data processing, two main data models have been developed for representing geographic spatial data: vector and tessellation (Figure 1). Vector and tessellation models are logical duals. In other words, the basic logical unit of a vector data model is the map entity for which spatial information is stored, while the basic logical unit of a tessellation model is a unit of space for which map entity information is stored.

Vector Models

The basic logical unit of the vector data model is the single vector, or map line. The vector data model represents geographic spatial data in terms of three different elements: points, line segments, and polygons.

A point represents the endpoint of a line segment or the location of a significant map feature. A feature can be a mountain, lake, building, or similar object. Points are also known as nodes, junctions, and intersections.

A line segment represents the line connecting two nodes. Note that a line segment does not represent the shape of the line; that is defined separately. Line segments are also known as arcs, edges, faces, and links.

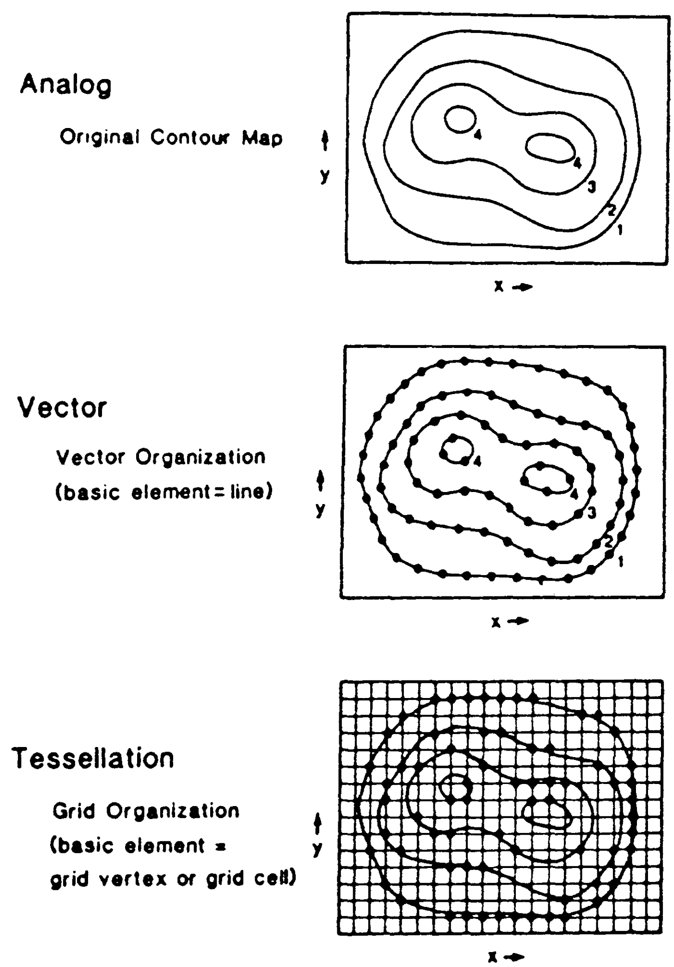


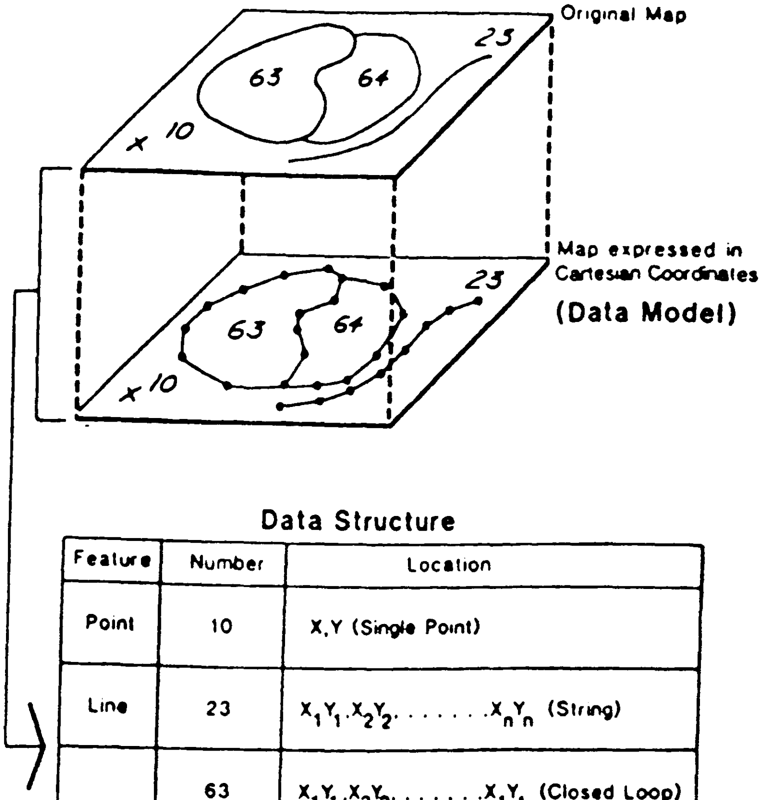
Fig. 1. Geographic data models. (Peuquet 1984)

A polygon represents the smallest area formed by a connected set of line segments. Polygons are also known as areas and regions.

Spaghetti Model

The simplest form of the vector data model is known as the "spaghetti model." It is a direct line-for-line translation of a paper map in which each entity on the map becomes a separate logical record in the digital file. Entities are represented as connected series of line segments. The line segments are stored by recording the x-y coordinates of their endpoints in the digital file, as shown in Figure 2. A polygon is stored as a closed loop of line segments. The occurrence of adjacent polygons, therefore, introduces data redundancy in the spaghetti model because the line segments shared by adjacent polygons are stored twice.

In the spaghetti model, the map remains the conceptual model, and the x-y coordinate file is actually a data structure. Although the entities themselves are spatially defined, the relationships between them are not retained. The spaghetti model is therefore simply a collection of coordinate strings grouped together with no inherent structure.



Data Structure

Feature	Number	Location
Point	10	X,Y (Single Point)
Line	23	$X_1Y_1, X_2Y_2, \ldots\ldots X_nY_n$ (String)
Polygon	63	$X_1Y_1, X_2Y_2, \ldots\ldots X_1Y_1$ (Closed Loop)
	64	$X_1Y_1, X_2Y_2, \ldots\ldots X_1Y_1$ (Data Structure)

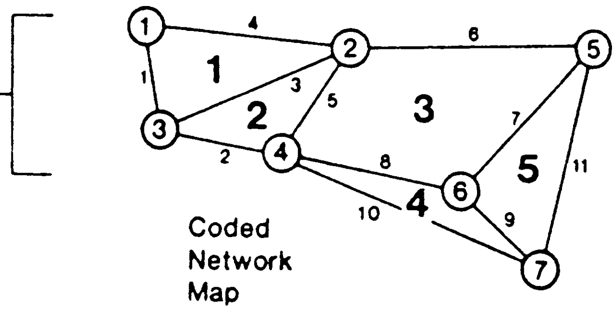
Fig. 2. Spaghetti model. (Peuquet 1984)

The lack of an implicit unifying structure makes the spaghetti model extremely inefficient for analytical purposes. Spatial relationships between entities must be computed using complicated algorithms. The model, however, is well suited for graphic output operations because the missing structural relationships are unnecessary to the output process. As a result, the spaghetti model is only used in simple geographic data processing functions which involve little or no analysis.

Topologic Models

The topologic model is the most common vector data model in use today. Based on the principles of graph theory, the topologic model "defines a location of geographic phenomena relative to other phenomena, but does not require the use of the concept of distance in defining these relationships" (Dangermond 1982). In other words, the topologic model retains the relationships between entities by explicitly storing adjacency information.

Figure 3 shows an example of a topological model (called a topologically coded network map). Two separate files comprise the model. One file stores the coordinates of the network's line segment endpoints, or nodes; the other stores each line segment along with references to its endpoint nodes and to the polygons which appear to the left



Link #	Right Polygon	Left Polygon	Node 1	Node 2
1	1	0	3	1
2	2	0	4	3
3	2	1	3	2
4	1	0	1	2
5	3	2	4	2
6	3	0	2	5
7	5	3	5	6
8	4	3	6	4
9	5	4	7	6
10	4	0	7	4
11	0	5	5	7

Topologically Coded Network & Polygon File

Node #	X Coordinate	Y Coordinate
1	23	8
2	17	17
3	29	15
4	26	21
5	8	26
6	22	30
7	24	38

X,Y Coordinate Node File

Fig. 3. Topologic model. (Peuquet 1984)

and right of it. The basic spatial relationships between entities are implicit in the topologic model. This greatly enhances the usefulness of the model in analytical functions. Furthermore, data redundancy, as can occur in the case of adjacent polygons, is eliminated.

GBF/DIME-file. The GBF/DIME-file (Geographic Base File/Dual Independent Map Encoding) model is the most well-known of all topologically based models. Developed in the early 1970's by the United States Census Bureau, GBF/DIME-files added the technology of topological coding to the Bureau's older Address Coding Guide (ACG) model.

In a GBF/DIME-file, map lines are represented by straight line segments. Segment endpoints, or nodes, occur where two or more map lines intersect, or where a map line changes direction. Figure 4 shows a portion of a Census Bureau map and the associated part of its GBF/DIME-file. The GBF/DIME-file in Figure 4 shows the information represented on the map, including the range of addresses occurring on Main Street, and the associated adjacent block numbers and census tracts.

GBF/DIME-files add the feature of assignment of a direction to the line segments. This results in a directed graph, and proves especially useful in automating the editing process. Numerous algorithms exist for efficiently tracing directed graphs and therefore the computer can automatically check for missing line segments and other errors.

The chief disadvantage of the GBF/DIME-file model is that the line segments are not stored in any particular order. To retrieve a line segment, an exhaustive search must be performed on the entire file. To retrieve all the line segments associated with a polygon, the exhaustive search must be performed as many times as there are segments in the polygon.

TIGER File. The TIGER (Topologically Integrated Geographic Encoding and Referencing) file data model is a new topologically based model being developed by the United States Bureau of the Census (Marx 1986). The TIGER file model is being designed to take full advantage of the science of graph theory. The TIGER file model is one of the best examples of the topological model in actual practice and so will be described in detail.

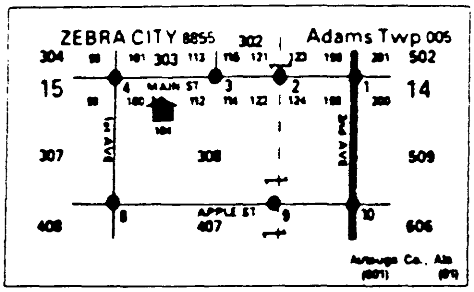
The basic elements of the TIGER file model are the points, line segments, and polygons mentioned previously. In the TIGER file model, however, these elements are referred to as 0-cells, 1-cells, and 2-cells. These names arise from the dimensions of the elements; a point is a zero-dimensional object; a line segment is a one-dimensional object; a polygon is a two-dimensional object.

The TIGER file model consists of lists of 0-cells, 1-cells, and 2-cells, along with directories which are matched to the 0-cell and 2-cell lists. Directories are stored as B-trees, an efficient data structure which optimizes storage and retrieval.

The 0-cell files, namely the 0-cell list and its directory, contain the coordinates of the line segment endpoints and features on the map. The 0-cell directory has a one-to-one correspondence with the 0-cell list; each directory entry has a pointer to its corresponding entry in the 0-cell list.

The 0-cell directory aids in the quick retrieval of the nearest point in the TIGER file given any point on the map. The TIGER file model uses a Peano key indexing system based on bit-interleaving to accomplish this. A Peano key is created by merging alternate binary bits from the latitude and longitude values of the given point. This creates a new unique binary number which is used as an index into the one-dimensional 0-cell directory (Figure 5).

Two-cells are the areas enclosed by connected series of 1-cells. Two-cells are also stored in terms of a 2-cell directory and a 2-cell list. Groups of 2-cells are often grouped together into what are known as "coverages." These aggregate 2-cells aid in large scale data tabulation operations.



Street Name	From	To	Place	Census Tract	Left Block	Right Block
MAIN ST.	4	3	8855	15	303 101-113	308 100-112
MAIN ST.	3	2	8855	15	302 115-121	308 114-122
MAIN ST.	2	1	—	15	302 123-199	308 124-198

Fig. 4. GBF/DIME-file model. (Marx 1986)

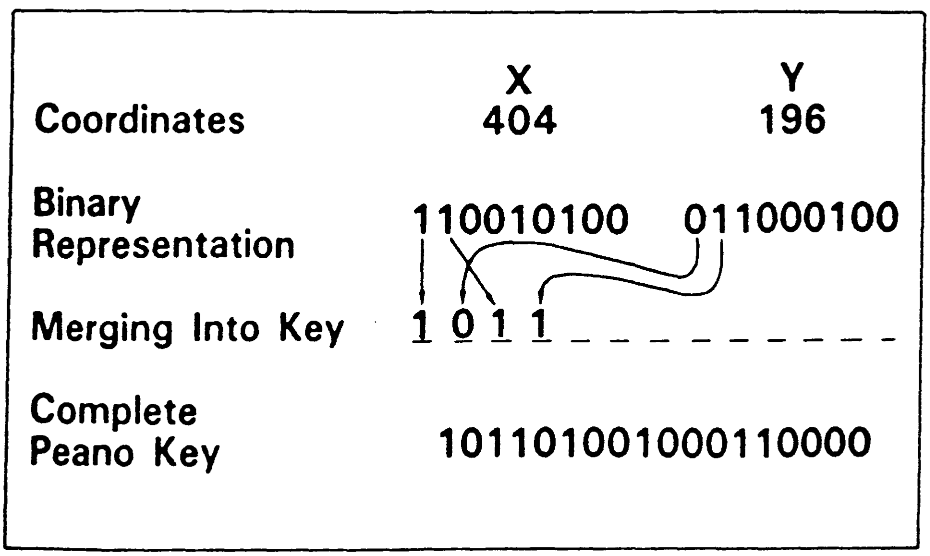


Fig. 5. Bit-interleaving to create Peano key. (Marx 1986)

The 1-cells represent map lines and are the most important element of the TIGER file model. There is not a directory for the 1-cell list because access to this list is obtained by referring to the endpoints of a 1-cell (the 0-cells), the surrounding 2-cells, or the non-topologically referenced attribute data associated with a group of 1-cells.

Often, certain information is common to a number of 1-cells. In these cases, the information is stored separately and the 1-cell records contain pointers to it. One-cell records also contain information on their shapes. This data is stored in a curvature list file. This file contains coordinates which completely describe the shape of a 1-cell. This includes what is known as the envelope of the 1-cell, which is the rectangle that encloses the 1-cell with its intermediate curvature coordinates (Marx 1986).

A unique feature included in the TIGER file model, which greatly increases its efficiency, is the use of a technique known as "threading." In threading, each 0-cell entry points to no more than one 1-cell, no matter how many map lines may actually intersect at that point. The 1-cell record then contains pointers to any other 1-cells which may occur at that point, and those 1-cells to still others. This technique reduces computer storage requirements and also helps alleviate the retrieval problem associated with the GBF/DIME-file model.

The use of directories for accessing TIGER file records greatly enhances the efficiency of the TIGER file model. A directory only needs to contain two fields per entry: the unique reference to the 0-cell or 2-cell itself, and the pointer to the record in the corresponding list. The list can then grow quite large and contain many data fields. Because the directory stays small, it can be quickly searched, and access to any 0-cell or 2-cell is still fast, regardless of the amount of data associated with it.

DLG-3. The DLG-3 (Digital Line Graph 3) model is a fully topologic external data exchange structure, as opposed to the TIGER file model, which is an internal applications structure.

The major components of the DLG-3 model are the node, line, and area, which are analogous to the 0-cell, 1-cell, and 2-cell of the TIGER file model. The model centers around the line. Line records contain pointers to nodes and areas. The model is designed to "provide the minimal information needed for a topological structure" (Marx 1986, 198).

Topologic models are popular because they are based on the well-developed mathematics of graph theory. The three topologic models cited in this section, GBF/DIME-file, TIGER file, and DLG-3, show the integral part that topologic modeling has played in geographic data processing and the part it will play in the future (Figure 6 provides a schematic comparison of these models). The GBF/DIME-file model has been, and still is, the most commonly used topologic model. The TIGER file model, with its improved technology, represents the future of topologic modeling. Finally, the DLG-3 model, with its simple but complete topologic basis, has become the closest thing to a geographic data exchange standard.

POLYVRT. The POLYVRT (POLYgon conVeRTer) topologic data model was developed at Harvard University in the late 1970's. It is the technology developed in this model which provided the basis for the TIGER file model mentioned previously.

The POLYVRT model introduced the concept of threading. In doing so, the model eliminated the need for the exhaustive search necessary in the GBF/DIME model. The POLYVRT model also added the advantage that queries involving polygon adjacency need only deal with the polygon and [threaded] chain data. Actual coordinate data need not be retrieved until explicitly needed, such as for distance calculations and plotting. This is another one of the advantages apparent in the TIGER file model.

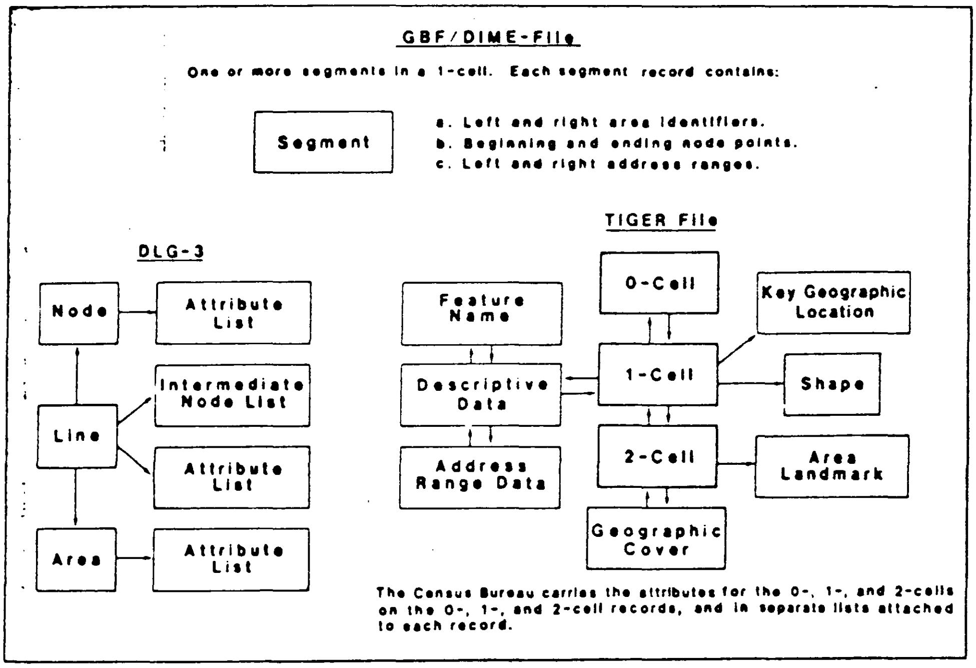


Fig. 6. Comparison of three topologic models. (Marx 1986)

Chaincodes. Chaincodes are, technically, not a data model; they are more precisely a method of data compaction. However, chaincode techniques have proved invaluable to spatial data handling and have come to be viewed as a data model in their own right (Peuquet 1984).

The classic chaincode model is the Freeman-Hoffman chaincode model (Freeman 1974). In this model, vectors are assigned a unique directional code from 0 to 7. The codes represent the eight unit length vectors shown in Figure 7, which are the four main compass directions and diagonals. Using this technique, vector data is encoded on a grid, where each grid cell contains a single vector. Only the x-y coordinates of the start of a line must be retained, the line direction is implicit in the code. Spatial data stored in this fashion requires significantly less space than that of other vector models.

Over the years, a number of variations of the chaincode data model have been developed. The simplest variations involve a different number of directional vectors. For example, chaincode models exist with 4-, 16-, and 32-directional vectors. The 4-direction model offers the advantage that each code requires only two bits of computer storage, as opposed to the three bits required by the Freeman-Hoffman model. The 4-directional model is sufficient in cases where the data consists of mainly long, straight lines which are perpendicular to one another. The 16- and 32-directional models are better suited to data which consist of arbitrary-shaped curves. The increased number of directions available in these models helps smooth out the staircase effect introduced when models with fewer directions are used. The disadvantage of the 16- and 32-directional models, however, is that they require more storage space and so do not provide as much compaction. In fact, there is a direct relationship between the number of directions in a chaincode model and the unit vector length required for any given accuracy. Peuquet points out that, "in terms of compaction, this obviously presents a tradeoff between the number of direction-vector codes required to represent a given line and the number of bits required to represent each code" (Peuquet 1984, 83).

Another variation of the chaincode model which has gained acceptance is the Raster Chaincode, or RC Code, model. The raster chaincode model was designed to process data in raster order (in horizontal strips, moving one strip at a time from top to bottom, scanning each strip left to right). As shown in Figure 8, this method requires only half the directional vectors of the previously mentioned chaincode models. One difficulty associated with the raster chaincode model, however, is that directional continuity of

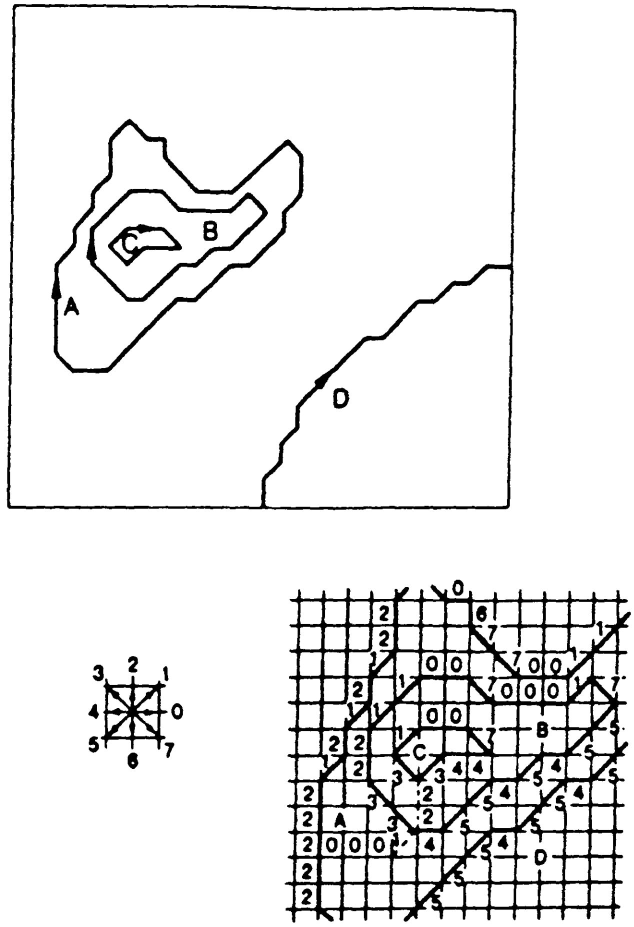


Fig. 7. Chaincode model. (Peuquet 1984)

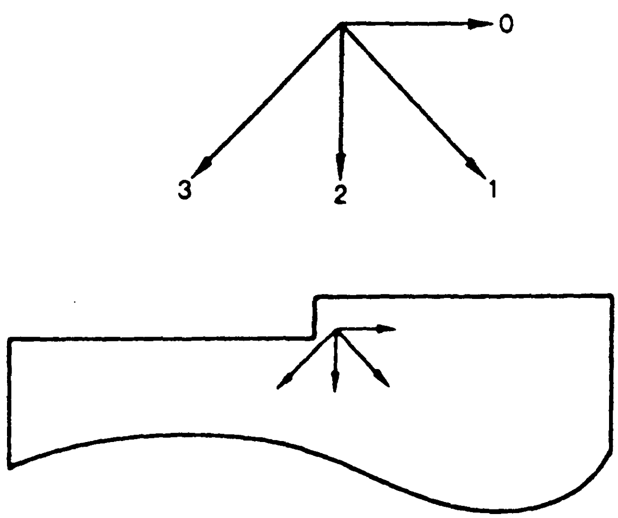


Fig. 8. Raster chaincode model. (Peuquet 1984)

arbitrary lines is not preserved. Fortunately, this problem is easily solved by a simple conversion from RC code to Freeman-Hoffman chaincode format.

The compaction ability afforded by chaincode models makes them especially useful in encoding the huge amounts of data occurring in modern geographic data processing. Also, certain measurement and analytical procedures can be performed more efficiently on chaincoded data.

The major disadvantage of chaincode models is that they cannot retain spatial relationships; they are, in fact, compact spaghetti models. For this reason, chaincode models are most often used in conjunction with other spatial data models which preserve spatial relationships.

Tessellation Models

Tessellation data models are the logical dual of vector data models. The basic logical unit of a tessellation model is a unit of space, as opposed to the map entity, which is the basic logical unit of a vector data model. Although the more technical term "tessellation" is used throughout this report, the reader should note that the term "raster" has come to be synonymous with the term "tessellation" and so appears quite often in the literature. Tessellation models occur in three basic forms: regular, hierarchical, and irregular. In addition, scan-line and Peano scan models are commonly classified as tessellation models and so will be discussed in this section.

Regular Tessellation Models

A regular tessellation model is one in which the tessellation, or grid, is composed of cells which are of equal size and shape. There are three types of regular tessellations: square, triangular, and hexagonal (See Figure 9).

Square Tessellations. The square tessellation model is the oldest and most common of all tessellation models. Its development can be attributed to two factors. First, the square grid is compatible with the array data structure common to most programming languages. Second, the square grid is compatible with most common methods of geographic data capture and display (Peuquet 1984).

A square tessellation model can best be thought of as a checkerboard-like matrix, or grid. Individual grid elements are addressed with an X,Y coordinate pair, with the lower left corner of the matrix being the origin, 0,0. The X value locates an element along the horizontal axis and the Y value along the vertical axis. It should be noted that the origin does not have to be in the lower left corner; it can in fact be located anywhere on the grid. However, for the purposes of this example, the lower left corner is the best location for the origin because all elements can then be addressed with positive X and Y values only.

The size of a square tessellation data model's grid elements can vary from quite small to extremely large. The difference is apparent in the resolution offered by the model and the amount of storage space required for the model. To illustrate these differences, the reader can imagine a clear plastic overlay, with grid cells etched into it, laid over a map.

If the etched grid elements are very small, the overlay corresponds to a square tessellation model with a high resolution. The reader can imagine that the grid elements which are positioned over map lines are colored in. The clear overlay is then a tessellated representation of the map. This is essentially the method which raster scanners use to input data from analog maps.

If the etched grid elements are quite large, the overlay corresponds to a square tessellation model with a low resolution. In this case, far too many map lines occur in any one grid element to allow representation like that in a high resolution grid. Instead, grid elements can be assigned aggregate values representing the major quality or qualities within the element. For example, if the area within a grid element consists of 45% marsh and 55% forest, the grid element will be assigned a value representing forest. This is the method which is used by most remote sensing devices.

Apart from resolution, the chief difference between square tessellation models with small and large grid elements is the amount of storage space each requires. While the grid elements in both models require about the same amount of space per element (each consists of a simple code), the number of elements is drastically different. A square tessellation model with small grid elements requires more storage space than one with large elements because more small elements are needed to represent any given area.

Triangular Tessellations. Triangular tessellation models, both regular and irregular, possess the quality that the triangles do not all have the same orientation. This makes triangular tessellation models particularly well suited for representing terrain and other surface data. The disadvantage of this quality, however, is that certain operations involving single cells, which are easy to perform on the square and hexagonal tessellations, are more difficult on a triangular tessellation.

A surface is represented in a triangular tessellation by assigning an elevation value to each triangle vertex (See Figure 10). Note that the same surface data could be represented by assigning a slope and direction to each triangle face. Clearly, each of these representations can be derived from the other.

Although it has been proven that the interpolation of surface contours is easier using a regular tessellation (Bengtsson and Nordbeck 1964), regular triangular tessellations are rarely used for surface data. Irregular triangular tessellations are far more common. This is probably because surface data are not usually captured in a regular spatial sampling pattern.

Hexagonal Tessellations. Regular hexagonal tessellation models possess the unique feature of radial symmetry (all neighboring cells of a given cell are equidistant from that cell's centerpoint). The hexagonal model, therefore, is particularly well suited to radial search and retrieval procedures.

Specific details of the geographic data processing algorithms used on the three regular tessellations differ, as the geometries of the three polygons differ. Certain procedures are more straightforward on one tessellation than on others; however, equivalent algorithms for each of the three tessellations have been shown to have the same order of complexity (Ahuja 1983).

Hierarchical Tessellation Models

A hierarchical tessellation model is one in which the grid elements are recursively subdivided into smaller occurrences of the same tessellation. Square tessellations are unique in that their subdivisions contain elements of the same original shape and orientation. Triangular hierarchical tessellations continue to possess the quality that the smaller triangles are not oriented the same themselves or as the original was. A hexagon cannot be subdivided into smaller hexagons; however, it can be subdivided into a roughly hexagonal shape called a "rosette" (See Figure 11).

Hierarchical tessellation models offer the significant advantage that they are adaptable to the qualities of the data they represent. Where data is sparse, no subdividing need be applied. Where data becomes more dense, the tessellation can be subdivided and the model in effect increases its resolution. As the data becomes increasingly more dense, the tessellation can be further subdivided. Of course, the cost of this process is increased storage volume.

One of the characteristics of the hierarchical tessellation model which helps distinguish between its different variations is the branching factor. This factor is related to the tree-like nature of the model and refers

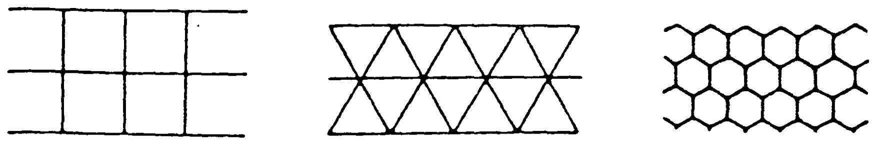


Fig. 9. Regular tessellations. (Peuquet 1984)

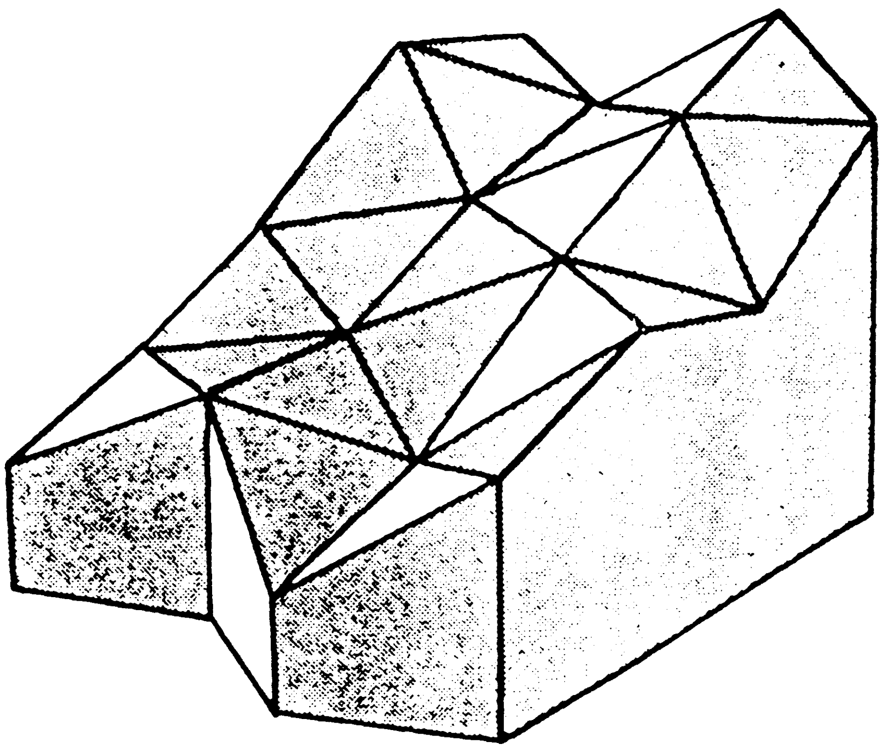


Fig. 10. Triangular tessellation. (Peuquet 1984)

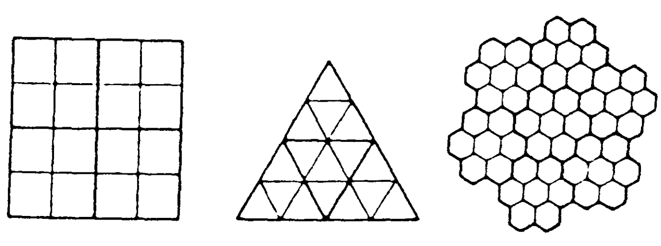


Fig. 11. Regular tessellation subdivisions. (Peuquet 1984)

to the number of subtrees a node possesses. The storage requirement of a hierarchical tessellation model is directly related to the branching factor.

Square Hierarchical Tessellations. The most common hierarchical tessellation model in use today is the quadtree, which is based on the regular square tessellation. The basic quadtree model can be divided into three types: point quadtrees, area quadtrees, and line quadtrees. The reader should note that the term "quadtree" has also come to be used today in a general sense, referring to all hierarchical tessellation models.

A point quadtree can be thought of as a multidimensional generalization of a binary search tree (Knuth 1969). Each data point is a node in the tree. Each node has four subtrees, or quadrants, labeled 0, 1, 2, and 3, corresponding to the directions NW, NE, SW, and SE respectively. Quadrants are subdivided until no point data which does not already exist as a node in the tree is present (See Figure 12).

Point quadtree nodes are commonly implemented as records containing seven fields. Four fields contain pointers to the subtrees, or children, of the node; two fields contain the x and y coordinates of the node, and the last field contains attribute data associated with the node (Samet 1982).

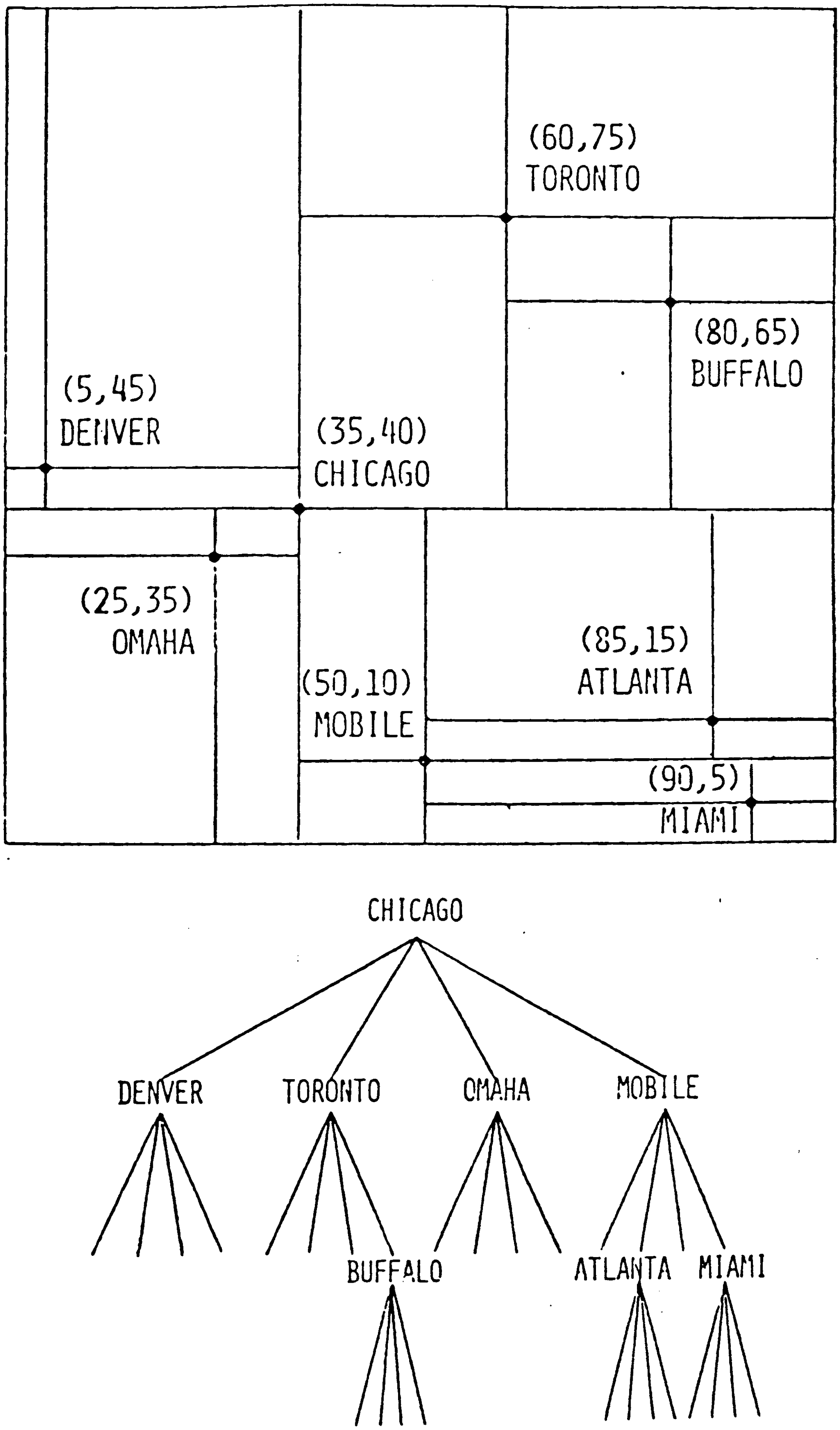


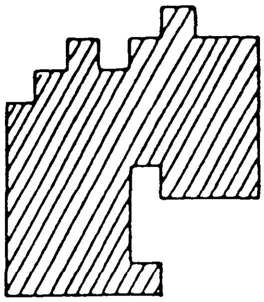
Fig. 12. Point quadtree. (Samet 1983)

Quadrants 1 and 3 are closed with respect to the x coordinate and quadrants 0 and 2 are closed with respect to the y coordinate. This convention enables the model to handle cases in which a data point falls exactly on a quadrant boundary line (Samet 1982).

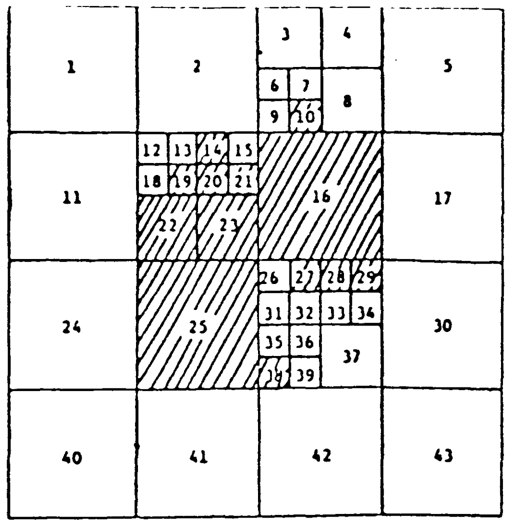
The area quadtree is similar in concept to the point quadtree. The root node of an area quadtree represents the entire region in question -- more precisely a square entirely containing the region. The four subtrees of the root represent the NW, NE, SW, and SE quadrants of the root node. Quadrants are recursively subdivided until all four subquadrants can be assigned binary values dependent upon whether or not the subquadrant entirely contains or does not contain a portion of the original region (See Figure 13).

Area quadtree nodes are usually implemented as records containing six fields. Four fields contain pointers to the children of the node, one field contains a pointer to the parent of the node, and one field contains associated attribute information (Samet 1982).

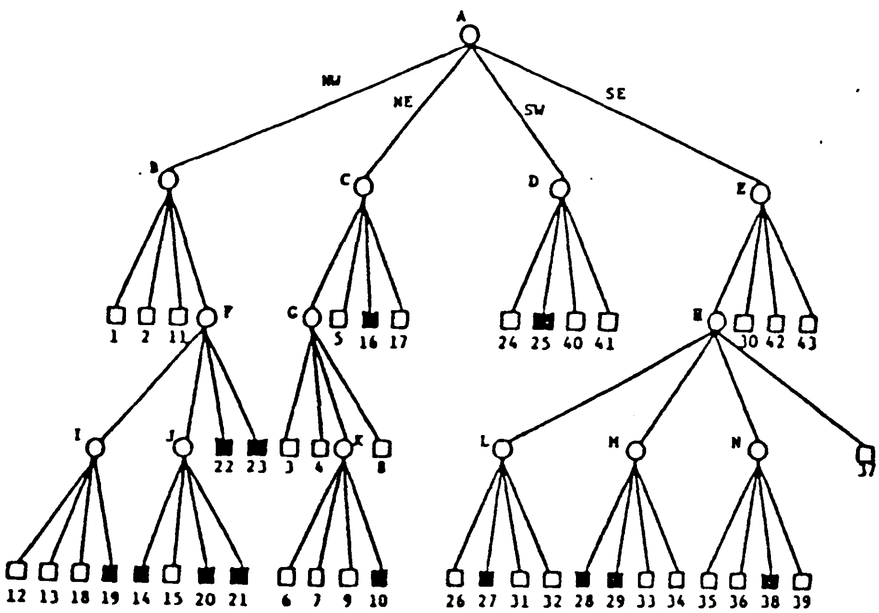
Although point quadtrees and area quadtrees are similar in many respects, there is one fundamental difference between the two. Whereas the area quadtree works with fixed partitions, the data determines how the point quadtree will partition space.



a, Region



b. Block decomposition of the region in (a).



c. Quadtree representation of the blocks in (b).

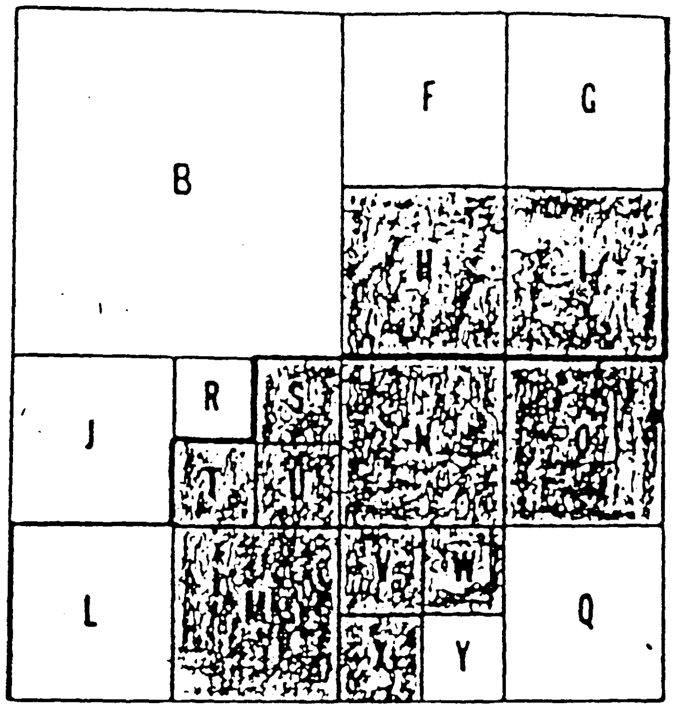
Fig. 13. Area quadtree. (Samet 1983)

Line data has proved to be more difficult to represent with hierarchical tessellation models. Since the early 1980's, however, a number of models have been developed which are beginning to solve this problem.

The edge quadtree is a hierarchical tessellation model used to represent line data (Shneier 1981). The edge quadtree is similar to both the point and area quadtrees. Like the point quadtree, the edge quadtree partitions quadrants in order to reference specific data points, namely the points of the line (locations where the line changes direction or where two or more segments intersect). Like the area quadtree, the partitions are fixed and of equal size (See Figure 14).

Among other problems, the edge quadtree suffers from an inability to handle, except with the simplest of solutions, cases in which two or more edges meet at a single point. Numerous variations of the edge quadtree have been developed to solve this and other problems associated with hierarchical tessellation based models of line data. Clearly, this is one of the many areas of geographic data processing still requiring further research.

The strip tree is another model being used to represent line data. Although the strip tree might be classified as a hierarchical tessellation model, it is more commonly classified as a hybrid, and so will be discussed in the Hybrid Data Models section.



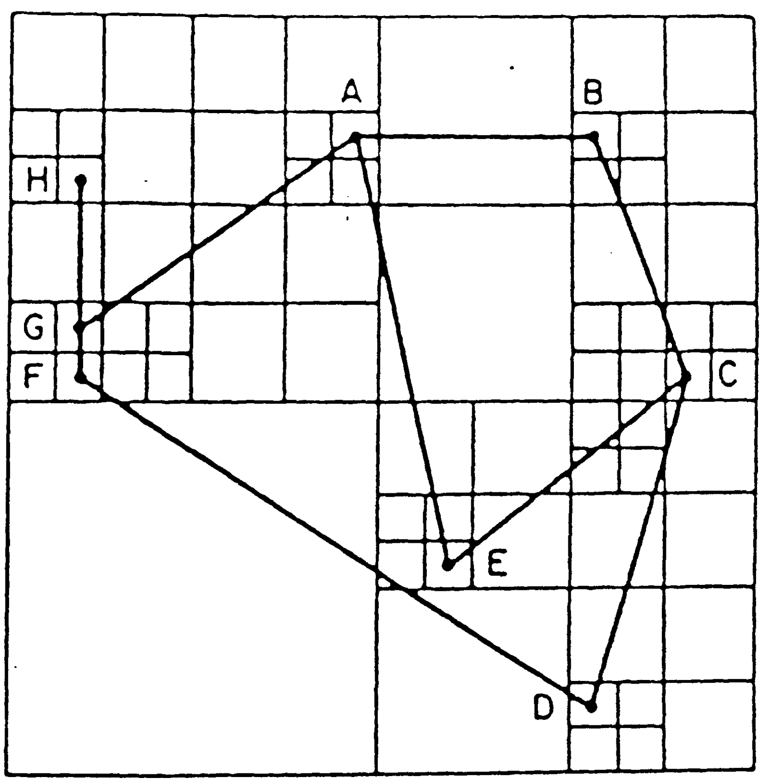


Fig. 14. Edge quadtree. (Samet 1986)

Triangular Hierarchical Tessellations. Hierarchical tessellation models based on the triangular tessellation are equivalent to the models based on the square tessellation just described--both models have a branching factor of four. The triangular model is in fact called a triangular quadtree. The triangular quadtree has the same advantages and disadvantages of the regular triangular tessellation, combined with the advantages of the hierarchical tree structure.

Hexagonal Hierarchical Tessellations. The hierarchical tessellation model based on the hexagonal tessellation is known as the septree. This model has a branching factor of seven. The model therefore requires a base seven addressing scheme known as Generalized Balanced Ternary (GBT). The advantage of this scheme is that many calculations may be performed directly on the GBT addresses without conversion. The model suffers from the disadvantage that because a hexagon cannot be subdivided into smaller hexagons, the resolution of the tessellation must be predetermined.

Multiple Dimension Hierarchical Models. Although the examples of hierarchical tessellation models cited so far deal in only two dimensions, each model can be generalized to n dimensions. Of course, doing so would cause the branching factor to become very large (i.e., at least 2k for k dimensions). The model would then require significantly more storage space.

The multi-dimensional k-d tree (Bentley 1975) offers an improvement on the quadtree by avoiding the complicating growth of the branching factor. The k-d tree is essentially a binary search tree with the distinction that areas are divided into two parts instead of four. The direction of the division is alternated with successive levels of the tree. For instance, in the case of two dimensions, space could be divided in the x direction on even levels of the tree, and the y direction on odd levels (Samet 1986).

Hierarchical Model Implementation. The hierarchical tessellation models described have commonly used pointers in the implementation of their tree structures. However, recent implementations of the models have begun to use direct addressing schemes instead of pointers. These models have been termed linear quadtrees. The name is derived from the fact that a direct addressing scheme allows the data to be physically organized in a linear fashion, as in a list.

Linear quadtrees offer the advantage of more efficient data storage. Nodes in a linear quadtree are arranged in a list, and each node has a key which uniquely identifies it. Keys are created by a technique known as bit interleaving.

When sorted in ascending order on the key value, the node list will be in an order identical to that which would be obtained from a top-to-bottom traversal of the tree (Samet 1986). Also, the node list is usually stored in a B-tree data structure, which further improves the model's efficiency.

The tree-like nature of hierarchical tessellation models makes them especially efficient for procedures which involve search. The tree structure of these models serves as a pruning device on the amount of search required for a given query. Furthermore, the tree data structure is among the most well documented and researched in computer science. Numerous algorithms exist for quick, efficient processing of trees.

Another advantage of hierarchical tessellation models is that they lead to aggregation. "Aggregation is an abstraction through which relationships are treated as higher level entities" (Korth and Silberschatz 1986). The result of this is that algorithms that use hierarchical tessellations have execution times proportional to the number of aggregated units rather than to the actual size of the aggregated units (Samet 1986).

Irregular Tessellation Models

An irregular tessellation model is one in which the grid elements vary in size, orientation, and density over space. The three most common irregular tessellation models in use today are the square, triangular, and variable (or Thiessen) models.

Irregular tessellation models share one of the advantages of hierarchical tessellation models. Namely, irregular tessellation models are adaptable to the qualities of the data they represent. By stipulating that each grid element hold the same amount of data, the model can be made to reflect the density of the data. Where the data is sparse, the grid elements will be bigger. Where the data is dense, the grid elements will be smaller. In addition, irregular tessellation models have the advantage that, because each grid element is different, the need for redundant data is eliminated.

Square Irregular Tessellations. The square irregular tessellation model is the least popular of the irregular models. The main reason for its unpopularity is the "saddle point problem" (Mark 1975). This is a problem which often arises when drawing contour lines on a square irregular tessellation. A saddle point is a point on a surface for which the graph of the surface lies on both sides of the tangent plane to the point. The occurrence of saddle points causes ambiguity in the tracing of contour lines.

<u>Triangular Irregular Tessellations</u>. The triangular irregular tessellation model, also known as the triangulated irregular network (TIN), is by far the most common of the irregular models (See Figure 15). TINs enjoy a number of advantages over regular tessellation models. For one, TINs have been shown to result in more accurate surface representations while requiring less storage space (Mark 1975; Peucker et al. 1976). Also, TIN surfaces can be generated much faster than regular tessellation surfaces (McCullagh and Ross 1980). This is because most topographic surfaces are highly irregular, and fitting a regular tessellation grid to an irregular surface requires extensive interpolation of the original data--an expensive process in terms of processing time (McKenna 1985).

A significant drawback to the use of regular tessellation models is the fact that they cannot represent vertical surfaces, irregular boundaries, or interior surface holes. TINs, however, can easily represent all of these features. Furthermore, the resolution of a regular tessellation model is limited by the resolution of the superimposed grid, while TIN resolutions are only limited by the resolution of the data (McKenna 1985).

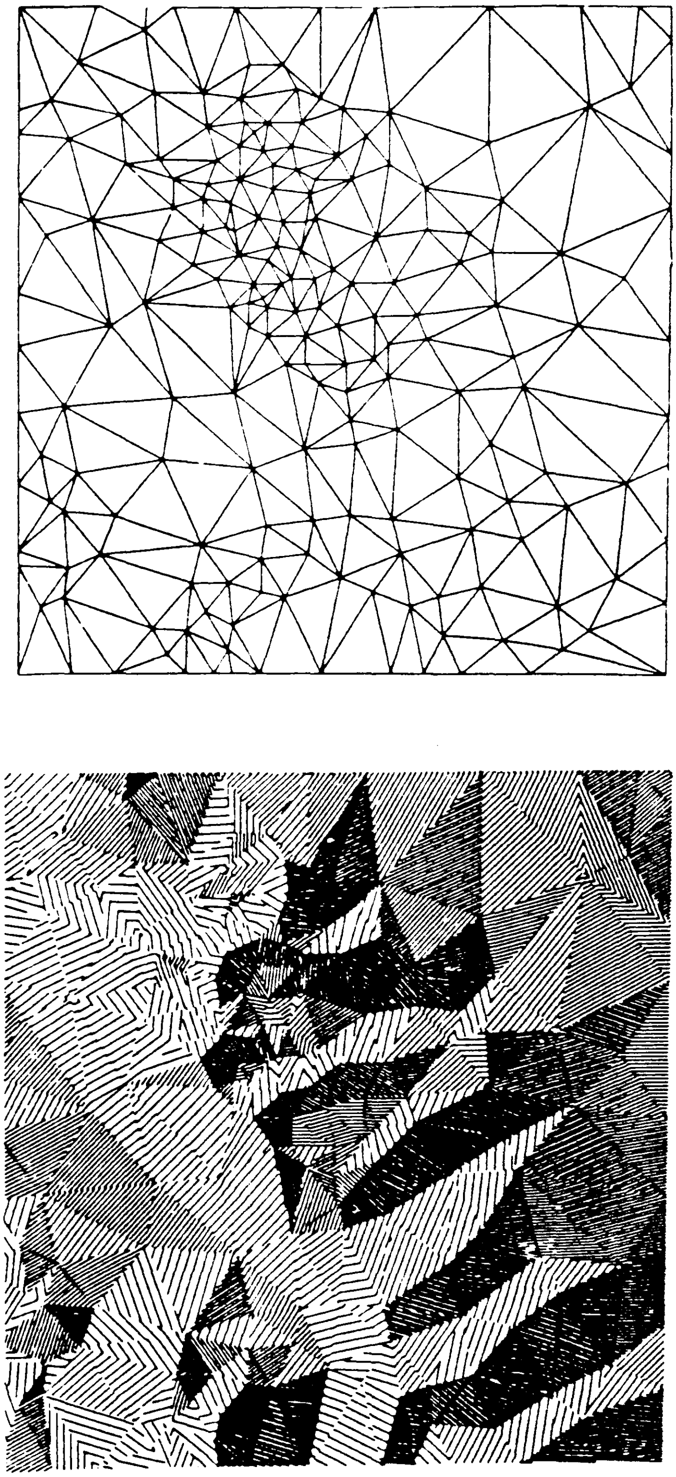


Fig. 15. Triangulated irregular network. (Peuquet 1984)

In addition to the advantages described above, TINs also have a unique property, described by McKenna as underutilized, which should prove very useful in GIS display operations. "The irregular nature of the TIN allows the surface to be freely manipulated and edited" (McKenna 1985, 946). This means that surface points can be moved, added, and deleted without affecting the data structure of the original surface.

The main disadvantage of triangulated irregular networks is that there are many possible triangular networks which can be generated from the same set of point data. There are, therefore, many different triangulation algorithms for a single surface.

Variable Irregular Tessellations. The variable irregular tessellation model, also known as the Thiessen Polygon model, is the logical dual of the triangular irregular tessellation model. Thiessen polygons are formed by bisecting the side of each triangle in a TIN at a 90 degree angle. The result is an irregular polygon grid composed of convex polygons having a variable number of sides (See Figure 16).

Each convex polygon in a Thiessen grid possesses a unique control point (the center of mass) which is actually the original TIN data point. The grid is partitioned such

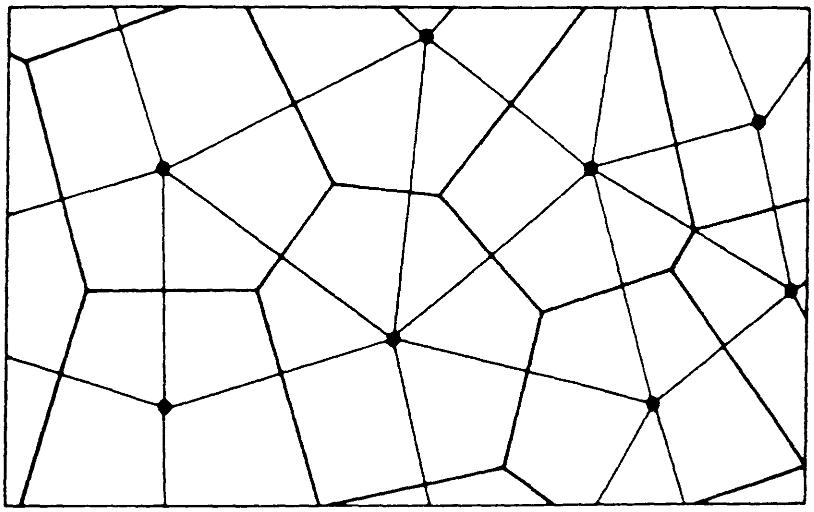


Fig. 16. Thiessen polygon network. (Monmonier 1982)

that each convex polygon is the collection of points lying closer to the control point of that region than to any other control point (Monmonier 1982). An alternate logical derivation of a Thiessen polygon grid is based on this quality. Given a finite number of data points (at least three) distributed in a bounded plane, each point begins to propagate a circle at a constant rate. These circles continue to grow until one circle encounters another or the boundary of the plane. The result is a Thiessen polygon grid (Rhynsburger 1973).

Thiessen polygons are also known as Voronoi diagrams or dirichlet tessellations. Thiessen polygons were first applied in the determination of recipitation averages over drainage basins by A. H. Thiessen in 1911, after whom they were named (Rhynsburger 1973).

One particularly useful advantage of irregular tessellation models stems from the ability of the size, shape, and orientation of their grid elements to reflect the size, shape, and orientation of the actual data elements. This quality proves very useful in visual inspection and related operations.

Although irregular tessellation models are well suited to a few specific procedures, such as visual inspection, they are, as a rule, not good general spatial data models.

There are two chief reasons for this. First, irregular tessellations are extremely hard to generate; they are complex and take a good deal of computer time. Second, overlaying of two or more tessellations, one of the most basic geographic data processing operations, is difficult and sometimes even impossible when dealing with irregular tessellations.

Scan-line Models

Scan-line, or raster, models are compact versions of the more traditional regular tessellation data model. The main difference between the two model types is that the grid elements of the scan-line model are swaths of the data surface. Although these swaths, or rows, are usually oriented horizontally, they do sometimes appear vertically.

The compaction feature of the scan-line model arises from the way in which the model forms the scan-line rows. Rows can be thought of as lists of regular tessellation grid elements. The grid elements which do not contain a map entity, or any piece of a map entity, are discarded. The scan-line row, then, consists of only the essential grid elements -- no empty elements.

The main disadvantage of scan-line models is that they do not preserve vertical relationships between scan-line rows. Although some procedures can operate on the data in this compact form, procedures which involve any vertical relationships between scan-line rows cannot. In these cases, the data must be converted back into grid form.

Peano Scan Models

Peano scan models, or space filling curves, convert n-dimensional space into a one-dimensional line, and vice versa. Peano curves accomplish this by tracing an unbroken line through space. These curves possess three primary properties, described by Stevens, Lehar, and Preston (1983):

1. The unbroken curve passes once through every locational element in the dataspace.
2. Points close to each other in the curve are also close to each other in space, and vice versa.
3. The curve acts as a transform to and from itself and n-dimensional space.

Figure 17 provides examples of two-dimensional and three-dimensional Peano curves.

Peano curve models were first implemented in the geographic data processing field within the Canada Geographic Information System (CGIS) (Tomlinson 1973). This implementation is based on a Z-shaped Peano curve. The curve divides space into "unit frames." The frames are referenced using an indexing scheme known as the Morton matrix (Morton 1966). Figure 18a presents a portion of the Morton matrix indexing scheme, and Figure 18b shows the

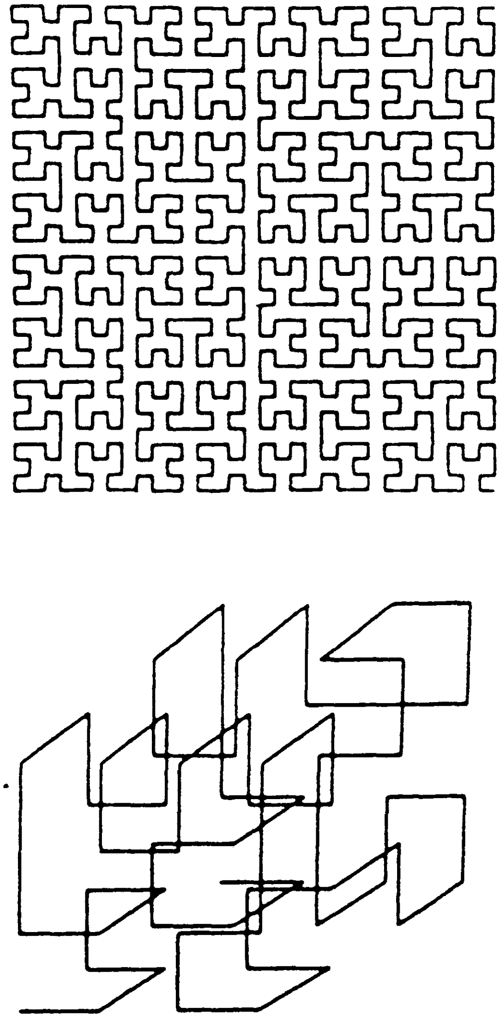


Fig. 17. 2- and 3-dimensional Peano curves. (Peuquet 1984)

	0	1	2	3	x →			
0	0 0000	2 0010	8 1000	10 1010	32	34	40	42
1	1 0001	3 0011	9 1001	11 1011	33	35	41	43
2	4 0100	6 0110	12 1100	14 1110	36	38	44	46
3	5 0101	7 0111	13 1101	15 1111	37	39	45	47
y	16	18	24	26	48	50	56	58
↓	17	19	25	27	49	51	57	59
	20	22	28	30	52	54	60	62
	21	23	29	31	53	55	61	63

Fig. 18a. Morton matrix indexing scheme. (Peuquet 1984)

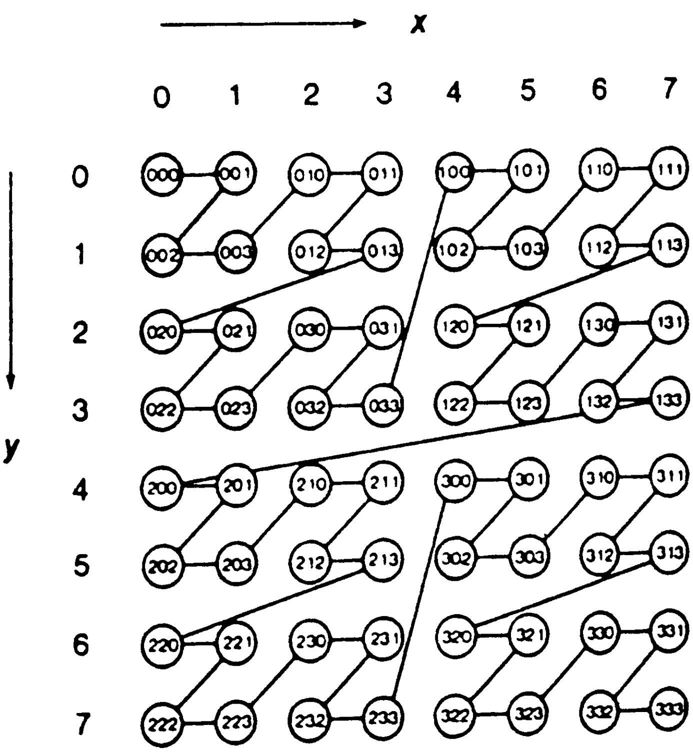


Fig. 18b. Z-shaped Peano curve. (Peuquet 1984)

relationship between the Morton matrix and the Z-shaped Peano curve.

The Z-shaped Peano curve has a direct correspondence with the quadtree data model. Specifically, by using the bit interleaving indexing technique, a unique address can be generated for a grid element from the elements binary X and Y coordinates. When converted to base 4, the address corresponds to the location of the same element in a base 4 indexed hierarchical tessellation grid (a quadtree).

In summary, vector and tessellation models both have advantages and disadvantages associated with them. Neither model is ideal for all applications.

Vector data models are direct digital translations of lines from a paper map. Therefore, vector algorithms also tend to be direct translations of traditional manual methods. Consequently, these algorithms have been well-developed. The chief disadvantage of vector models is that spatial relationships between map entities must be explicitly stored.

Tessellation data models, on the other hand, contain spatial relationships implicitly. Also, they are compatible with methods of high-speed input and output. The major disadvantage of tessellation data models, however, is that they take up a great deal of storage space. Furthermore, tessellation algorithms are less developed than vector algorithms, although this fact is changing quickly.

Hybrid Models

Recently, a great deal of research has gone into resolving the classic storage and processing tradeoffs which exist between the vector and tessellation data models. One approach has been to store geographic data in tessellation format and convert it to vector format only when absolutely necessary. This technique is popular because it is intuitively straightforward; however, conversion between data models can quickly become an insurmountable bottleneck.

Although conversion from vector format to tessellation format is fast and efficient, conversion in the other direction is quite a different story. Conversion from tessellation format to vector format requires some form of intricate line-following because cartographic lines are characteristically complex and unpredictable. This process, therefore, entails significant overhead and its use needs to be limited.

Another approach to the tradeoff problem between vector and tessellation data models has been to develop tessellation-based algorithms which are as fast and efficient as their vector counterparts. This combination would capture the advantages of both data models in a single [tessellation] model and would eliminate the need for vector data models. In fact, many efficient tessellation-based algorithms have already been developed (especially within the field of image processing), but there are still some processes which seem to be intrinsically vector-oriented. Furthermore, certain procedures, such as network shortest-path and optimal-routing, are so much more efficiently performed in vector format that even the added cost of conversion makes them desirable over the most efficient tessellation-based algorithms (Peuquet 1984).

Perhaps a better solution to the vector/tessellation problem than those just mentioned is the use of hybrid data models which incorporate characteristics of both the vector and tessellation data models. The remainder of this section will describe some of the recent developments in the area of hybrid data model design.

Vaster Model

The basic idea of the vaster data model is the storage of cartographic data in the tessellation-based form of horizonatal swaths, or rasters, and the storage of data within each swath in vector format (See Figure 19) (Peuquet 1982). The vaster model, therefore, removes the need for conversion between tessellation and vector formats.

Specifically, the leading edge (line corresponding to minimum y value) of a swath is stored in raster format and

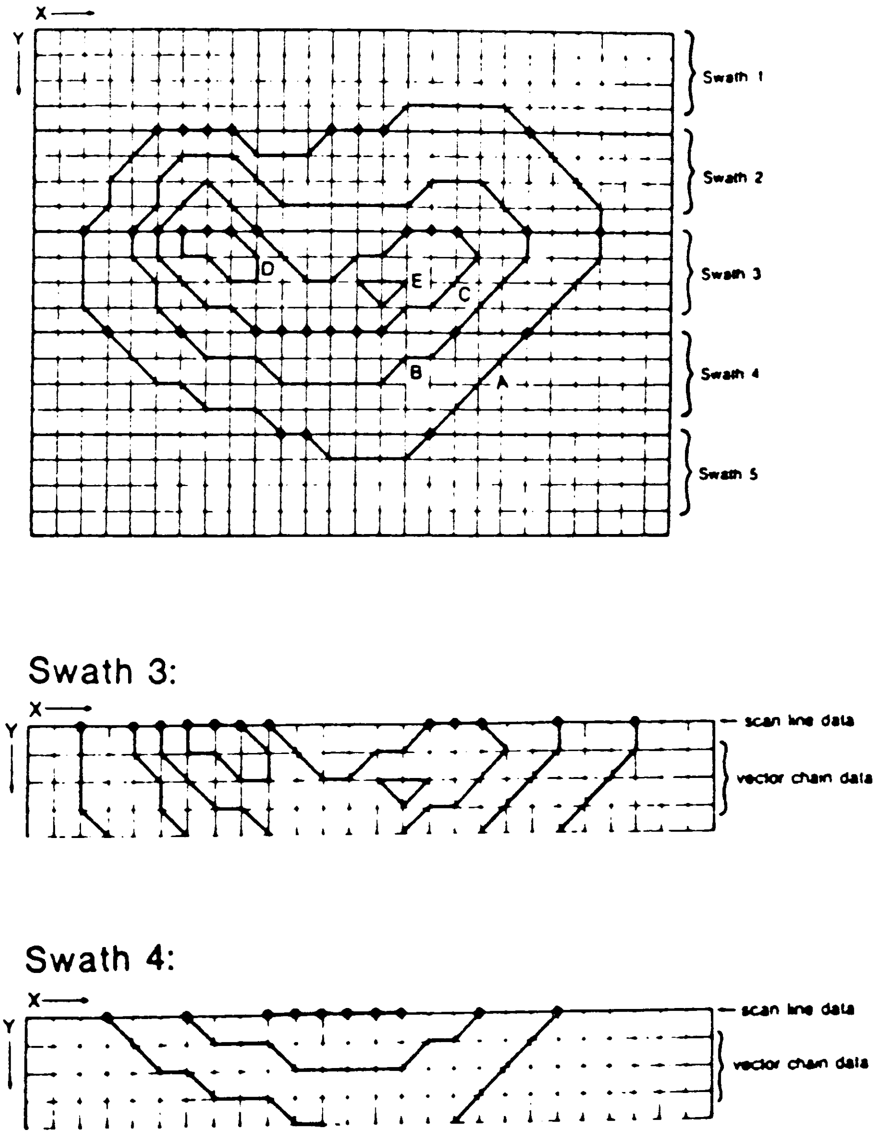


Fig. 19. Vaster data model. (Peuquet 1984)

is used as an index into the swath itself. This is accomplished by associating an identifier and x-value with each intersection of a map line with the leading edge. Polygons and lines which appear in but do not intersect the raster are stored seperately but still within the swath record. This intra-swath data is stored in compact chain-coded vector format.

The vaster data model can thus be used at two different resolutions. The first, coarser resolution is realized by using only the tessellation-based raster structures. This resolution is useful for browsing and for a great deal of general applications where approximate solutions are required. These include centroid, area, perimeter, and arc-length calculations.

The second, full-detail resolution available with the vaster data model makes use of the vector data within each raster. A complete vector representation of the data can be constructed by rectifying the indices of the rasters. The data would then be suitable for more detailed analysis.

Fully realizing the potential of the vaster data model to combine the advantages of both the tessellation and vector data models, however, involves solving a couple of related problems. First, there is the data sampling problem analogous to the grid cell size problem associated with tessellation data models. What size should the rasters be so as to most efficiently represent the data at the coarser resolution? If rasters are too big, many map lines and entities will be "stranded" and representable only in vector format. If the rasters are too small, map lines will be intersected many times and the model will become unmanageably large. Ideally, "each significant map line should be intersected at least once by a scan line..." (Peuquet 1984, 104).

The second problem involved in implementing the vaster data model arises from the hybrid nature of the model. What raster/vector data volume ratio would provide optimum performance given the set of raster and vector algorithms necessary for the intended applications (Peuquet 1984)? Concentrating data in vector format when the application uses mainly raster algorithms, for instance, would hardly be considered optimal.

Strip Tree Model

The strip tree data model represents geographic data by using a hierarchy of bounding rectangles (Samet 1982). The strip tree is classified as a hybrid data model because its basic logical entity is the map line, but the lines themselves are not explicitly recorded. This representation allows optimum performance of union, intersection, and curve length operations.

Individual strips, or segments of a line or curve, consist of four elements: E1, E2, W1, and W2. E1 and E2 are points locating the beginning and end of the strip, respectively. W1 and W2 denote the right and left distances of the strip borders from the directed line segment (See Figure 20).

A strip tree for a given line segment between two points is formed by first finding the smallest bounding rectangle between the two points. Next, a point which touches one of the two sides of the rectangle is selected and the process is repeated for the two sublists. The result is two subtrees which are children of the original line segment, or root node. This process is terminated when the lowest level rectangles reach a predetermined size.

The strip tree model can be thought of as the vector counterpart to the quadtree data model since each is based on the hierarchical structure of the underlying map entity. The main difference between the two, however, is that quadtrees must be spatially registered before they can be used in most processes but strip trees can be arbitrarily translated and scaled since they are grid independent.

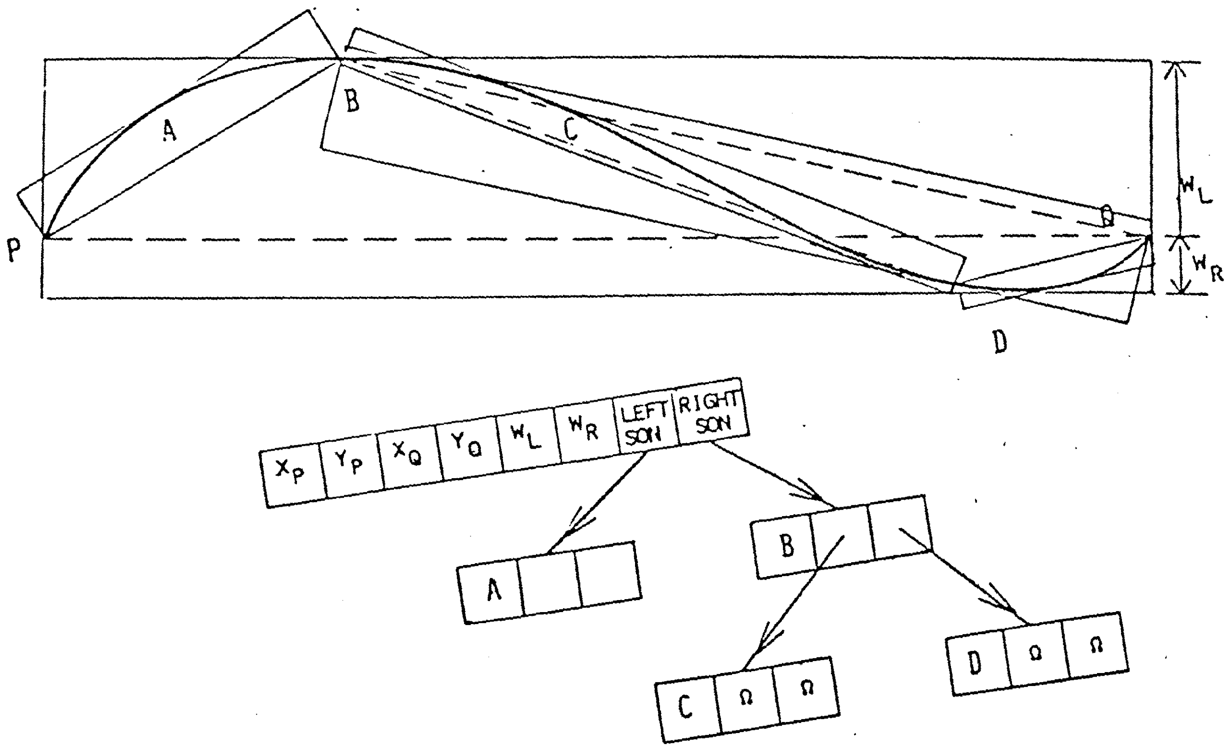


Fig. 20. Strip tree data model. (Peuquet 1984)

GEOGRAPHIC DATABASE MANAGEMENT

The sheer volume of geographic data available today, and the magnitude of the tasks required of today's geographic data processing systems, demands the optimum performance from geographic database management systems. Intricate data models, such as those described in the previous section, can be devised to very acurately represent large geographic areas. However, the real test of a geographic database is how easily this data can be maintained and how efficiently it can be accessed in processing queries.

Geographic database queries involve requests for data which are subject to two types of constraints. The first type deals with spatial data. This is data which represents the actual location in space of a map entity. The second type of constraint deals with attribute data. This is the non-spatially registered data associated with a map entity. Attribute related constraints can usually be handled easily with simple table lookups. Spatially related constraints, however, typically involve some manipulation of vector or tessellation data. Combining these two types of constraints can lead to complex queries. For example, consider the following sample query:

> Find the locations of all parcels of land within a 25 mile radius of Orlando, FL which are less than 50% developed, hold more than 5 lakes, and do not contain at least 2 intersecting state roads.

The above query specifies two attribute related constraints. The first stipulates that parcels be less than 50% developed, and the second that five or more lakes be located on the parcel. The query also specifies the spatial constraint that the parcels lie within a 25 mile radius of Orlando, FL. The last constraint specified by the query could be either attribute or spatially related. If the original designers of the database anticipated queries about intersections of state roads, they might have included an attribute in parcel records which represented the number of state road intersections in that parcel, in which case the query processor has simply to read this attribute. However, if state road intersection data is not included as an attribute of parcels, then the DBMS must perform a spatial analysis routine to determine which, if any, state roads intersect on each parcel it checks.

This simple example introduces a couple of important points relating to geographic database management which will be discussed in this section. These points have to do with the methods used to access geographic attribute and spatial data, and methods for efficiently processing both anticipated and unanticipated queries.

Geographic Data Access

Spatial geographic data and its related attribute data are stored separately. Although this practice may not be intuitively straightforward, it greatly increases the efficiency of the geographic database. This is because many geographic data processing functions are performed using only one of these two datasets at a time.

Geographic attribute data is far easier for the geographic data processing system to manipulate than geographic spatial data. Most geographic data processing systems now use the relational data model to store and maintain attribute data. These systems either maintain themselves, or offer access to, a fully developed relational data management system for this purpose.

The relational data model has been well studied and documented. The literature abounds with material on the subject and therefore the model will only be discussed here in terms of how it is being used in the field of geographic data processing.

For the storage and maintenance of attribute data, a geographic database management system associates attribute data (stored in a relational database) with spatial data through a linking mechanism. A code, such as a simple numbering scheme, is usually used for this purpose. For example, consider the imaginary system which was queried earlier in this section. Assume each parcel of land is given a unique parcel number. Then a relational table called "Parcel" can be created with parcel number being the key. The parcel table can then be used to store attributes such as percentage of development, number of lakes, and number of intersecting state roads (all information used by the earlier sample query). The parcel number is the key which associates spatial and attribute information.

As was described in the section on Data Models, the science of geographic spatial data modeling has not yet been fully developed. For that reason, the methods for accessing geographic spatial data, both vector and tessellation based, are not as well developed as those for accessing non-spatial data.

At the lowest level, the vector data model is very similar in appearance to the relational data model. Geographic spatial data stored in vector format occurs in the form of tables (arc, node, and polygon tables), similar to the relational data model. For this reason, many geographic data processing systems on the market today use a relational database system to implement a vector spatial data model. The most notable of these are ESRI's Arc/Info and Arc/Oracle systems.

Spatial data, however, is fundamentally different from the data which is usually managed by relational database management systems. Specifically, the concept of dimension introduces complex relationships among spatial data entities which are not easily represented by conventional relational database systems. For this reason, the relational database management systems used to manage vector data, such as those in Arc/Info and Arc/Oracle, are adapted versions of the conventional relational data model. Recently, a great deal of research has been devoted to normalizing spatial data to allow future spatial data models to fully utilize the rich theory of relational data modeling (van Roessel 1986).

Because the basic logical entity of the tessellation data model is the unit of space, tessellation data is accessed quite differently than vector data. While vector data tables offer natural indices on spatial data and bounds on the amount of search required for most operations, tessellation data models typically do not. Tessellation data, therefore, must be accessed by referring to specific data cell addresses as opposed to referring to specific map entities.

The addressing schemes used to access tessellation data range from very simple, such as the X,Y coordinate pairs used with the square tessellation grid, to complex, such as the GBT scheme used with the septree model.

It is important to note, however, that these addressing schemes do not aid in searching for specific geographic entities; in this case, tessellation data must usually be searched sequentially.

Another method which can greatly increase the efficiency of accessing a large geographic database is the use of a virtual memory system. Virtual memory describes a set of techniques which allow a system to execute a program (or in the case of geographic data processing, display a map) which is not entirely in memory at the time (Peterson and Silberschatz 1985).

A virtual memory system essentially works by storing in main memory the data which it anticipates is likely to be required. In other words, if, in a GIS which utilizes virtual memory, a user requests a certain map parcel to be displayed, the system may load in that parcel and all parcels which border it, anticipating that the user will wish to view data only in this area. If the user wishes to access data which is not currently in memory, the system uses one of a number of methods to determine a portion of the data currently in main memory to remove and replace with the required data.

Query Processing

In the process of designing a geographic data processing system, the developers will certainly have in mind a number of standard queries, or types of queries, which they are fairly certain will be posed frequently. The developers may therefore choose to augment the system in some way which will help it process these standard queries as efficiently as possible. There are three common methods for achieving this goal: indexing, hashing, and clustering.

Indexing and hashing are very common in the conventional database field. They both involve the addition of structures to the data model which improve retrieval efficiency for a specific dataset (i.e., a relational data table). The disadvantage of these methods is the increased overhead involved with their implementation. However, their benefits far outweigh their costs. For further information regarding indexing and hashing, the reader is referred to Korth and Silberschatz (1986).

Clustering refers to the process of storing related data contiguously in memory. This allows data to be accessed more efficiently than if it were distributed in memory. Clustering, like indexing and hashing, is also very common in the conventional database field. For further information, the reader is referred to Korth and Silberschatz (1986).

Although the methods mentioned above are often implemented in the database design phase, they are also used in the day-to-day operation of the database. One or more of the three can be temporarily implemented to optimize processing of queries which may not have been anticipated by the system designers. The lives of these temporary aids may be as short as one query, or they may be left as permanent additions to the database.

GEOGRAPHIC INFORMATION SYSTEM DESIGN

Geographic data processing and geographic database management share with the more traditional database management field at least one very important quality--the design phases of both the database and the Database Management System (DBMS) are the most crucial factors affecting the life of the system. Calkins reports that "in the software development field it has been shown that fully 65% of the errors found during implementation and testing of a system can be traced to poor design" (Calkins 1983, 92). In fact, there have been numerous system failures in the GIS field and this has led to the creation of a "credibility gap" between the promoters of geographic data processing systems and the people who most benefit from their existence--the users (Marble and Peuquet 1983).

General Design Considerations

An organization embarking on the design of a GIS will certainly have in mind a number of basic requirements for the new system. However, the GIS developers will not want to limit the growth potential of an expensive, long-lived piece of software such as a GIS. Therefore, they will likely develop as general a set of specifications as possible. In this way, the developers can attempt to allow for future implementation of new methods and technologies, assuring an efficient, productive life for the GIS.

Although speaking in such general terms about the requirements of the GIS makes it appear that the system could live up to any and all expectations, there is a danger involved here. A loose set of specifications means that there will be no clear idea of when an adequate design has been reached (Calkins 1983). This is one of the classic pitfalls of database design and it played a major role in the GIS system failures mentioned at the beginning of this section.

So what can the developers do when they truly do not have a definite set of specifications for their GIS? There are two options available here. Either they could decide upon a definite set of specifications--a subset of the very general class which has been discussed so far, or they can proceed with the general class of specifications--working carefully to avoid the problem discussed in the preceeding paragraph. Deciding on a limited set of specifications essentially defeats the purpose of the long-term goals for a GIS. So the answer seems to be: implement the most general system available, with the plan that the system can be continually updated as new requirements are adopted and new technology is developed.

By planning to implement the most general system available, however, the developers again face the problem of too general a scope. Clearly, this danger is in part unavoidable. However, there are other factors which affect the quality of a database which are more in contol of the designers. Chief among these factors is the design of the database itself.

Accurate modeling of real-world relationships within attribute datasets is the most important part of the design phase of a GIS--and in fact of any database system. This is not to play down the importance of spatial data modeling, but the relationships between spatial data entities are far more straightforward than those between non-spatial data entities. Futhermore, the attribute and spatial data modeling disciplines are at quite different levels of development.

In a still developing field like spatial data modeling, there is always the possibility that a revolutionary new discovery will come along which would render current methods obsolete. On the other hand, attribute data modeling technology, especially the relational data model, is well established. Therefore, additional time and effort devoted to the attribute data modeling process would help guarantee the usefulness and long lifespan of a GIS.

The usefulness and effectiveness of the GIS will be directly related to the extent to which the GIS is linked to existing and future non-geographic databases used by the organization. The most advanced GIS, possessing state-of-the-art analysis and display capabilities, is nothing more than a glorified map viewing device if it is not linked to the existing databases within the organization implementing it. In such a situation, the only way to make the GIS effective, apart from going back to square one and creating the links, involves duplicating already existing data. This introduces data redundancy, an ailment which wastes valuable memory space and complicates database maintenance.

As a simplified example of the advantage of links to existing databases, consider the case of an imaginary market research firm which is planning to implement a new GIS. Imagine that the firm has extensive data about consumers and products at different cities around the country.

The firm's GIS could be designed to include a U.S. map dataset consisting chiefly of spatial data. This would include data which facilitated detailed spatial analysis and output of maps of any portion of the U.S. There would be a minimum of attribute data associated with this U.S. geography dataset, the idea here being that existing non-geographic databases, such as the consumer and product databases of the previous paragraph, could be linked to this dataset to act as attribute data. Specifically, the city name could be used as a code to link consumer data contained in the existing database to point data in the U.S. geography dataset--namely the city locations.

Making the consumer information database act as attribute data for a U.S. geography database, then, opens up new possibilities for market queries. For example, users could compute travel times between consumer groups and product distribution sites, or optimize distribution within a network of sites. Also, comparison of spatially based data from different sites could be performed easily.

An approach similar to the scenario described above would minimize the effort required to implement a GIS, promote data independence, and prevent data redundancy, the last two factors being of critical importance to assuring a long life for the GIS.

Accordingly, during the process of designing the GIS and its related components, a significant amount of effort should be devoted to determining where links exist which could tie existing database elements to the new GIS. The fact that this attribute data can be fully normalized according to the techniques of relational data modeling guarantees that it will be useful in satisfying the general specifications written of earlier.

As far as geographic spatial data modeling is concerned, the choice of a spatial data model is almost irrelevant--stress almost. Certainly, in terms of getting a GIS up and functional as quickly as possible, a spatial data model, or more to the point, a fully operational GIS with supporting spatial data model, must be decided upon. However, the organization needs to approach the implementation of their GIS with the knowledge that, in the event that the original spatial data model needs to be updated or replaced, their sizable investment in spatial attribute data is safe.

All this is not to say that a commercially available GIS on the market today could not be implemented by the organization and function effectively for many years. However, in a situation where the original specifications (by necessity) are very loose, and where such a large investment in already existing databases could be at stake, responsibility dictates that the worst case scenario must be considered.

Distributed Database Considerations

The large size of a GIS and its associated components makes it an ideal candidate for implementation as a distributed database. A distributed database is one that consists of a collection of sites, each of which maintains its own local database system. Sites may process local transactions, those that access data located only at that site, or global transactions, those that access data located at a number of different sites (Korth and Silberschatz 1986).

By maintaining site specific geographic (and non-geographic) data at the actual site location, the organization could assure the timely and accurate update of its entire geographic database. Distribution is also more economically feasible than maintaining the entire geographic database at one location. In order to be maintained at one location, such a large database would require a sizable investment in hardware, software, and personnel.

Although distribution of a GIS would be beneficial in terms of data sharing, data reliability, and speedup of query processing, there would also be disadvantages associated with it. Specifically, increased software development costs, greater potential for bugs, and increased processing overhead are problems associated with database distribution.

Artificial Intelligence Considerations

Artificial Intelligence (AI) can best be described as "the study of how to make computers do things at which, for the moment, people are better" (Rich 1983, 1). AI has received a great deal of publicity lately, and research is being conducted which attempts to apply AI techniques to almost all forms of data processing--geographic data processing is no exception.

The most useful development to stem from the field of artificial intelligence has been the expert system. An expert system is a computer system which assists in the solution of real-world problems which require an expert's knowledge to solve. An expert system uses a computer model of expert human reasoning to arrive at the same conclusion which the human expert would, given the same information (Weiss and Kulikowski 1984).

The most important characteristic of an expert system is that it is based on a large database of knowledge. An expert system's knowledge base consists of two types of knowledge: facts and rules. Facts are, as the name implies, declarative facts regarding the problem domain. Rules are a mechanism for control. A rule consists of a left side and a right side. The left side is a pattern to be matched against a problem state; the right side is a change to be made to the current problem state. For example, an expert system for identifying animals might have in its knowledge base a rule such as: "If the animal in question bears live young, then the animal is a mammal." The left side of the above rule is that part which appears before the comma, the right side is that part which appears after the comma.

Very few, if any, artifical intelligence applications for general spatial data processing are developed enough yet to be of practical use. This fact, however, does not mean that applications for artificial intelligence (specifically the expert system) do not exist within more specific domains of spatial data processing and attribute data processing.

Expert systems which deal with non-spatially referenced (attribute) data are far more developed than those that deal with spatially referenced data. The likelihood that there is already a large amount of attribute data existing in any organization and the importance of that data to a new GIS make the implementation of expert systems dealing with this data an option worth considering.

The possible applications of expert systems to attribute data are as varied as the applications of the GIS. However, generally speaking, any organization involved in geographic planning and decision-making has experts whose experience helps them make sound decisions. In arriving at their conclusions, these experts deal almost exclusively with attribute data. This is not to say that spatial data is not required--indeed, spatial data is the heart of geographic data processing--but almost all spatial data can in essence be boiled down into attribute data.

This last point is precisely the main point made in the geographic database management section: if the GIS developer determines that certain spatial data characteristics will be required often, he can represent them as attribute data. Therefore, in the simplest example of a GIS expert system, every constraint within the left-hand side of a rule would simply correspond to some data field within the GIS's attribute database.

Clearly, a system configured as that described in the previous paragraph would defeat the purpose of a GIS--there would be no need for a spatial data model. A more realistic system would allow certain constraints within the left-hand sides of rules to be fulfilled by queries to the spatial data model. For example, consider the hypothetical expert system rule which states: "If all the parcels of land within a 25 mile radius of Orlando are more than 50% developed, then consider expansion of Orlando area utility services." A simple spatial analysis routine can identify those parcels which are geographically located within a 25 mile radius of Orlando. Then, a quick table lookup identifies those parcels which are more than 50% developed.

Since it is now clear that there is indeed potential for the expert system within a GIS, and that the combination is technically feasible, the main issue then becomes the development of the knowledge base. This is in fact the main issue involved in the implementation of an expert system in any field.

The building of the knowledge base is the chief bottleneck in the implementation of an expert system. And yet, this will always be the case, since an expert system's usefulness and efficiency are directly related to the amount of work put into the building of its knowledge base.

Translating the knowledge of one or more experts into a form suitable for use in an expert system requires a great deal of careful, patient effort. This effort, or at least part of it, could be incorporated into the system design phase which an organization carries out long before they implement a GIS. This is not to say that effort should be wasted on trying to develop (too soon) an expert system with the loose set of requirements which were discussed earlier. Indeed, one fact is certain: an expert system must be based on a rigorously structured set of requirements. However, the organization should keep in mind that the "rules" they use throughout the course of their work in modeling real-world spatial entity and attribute relationships are precisely the rules which a future expert system would use.

CONCLUSION

Computerized geographic data processing is still a relatively young science; and yet, the chief product to come out of the field, the Geographic Information System (GIS), is already a great commercial success. Advances in GIS technology are occurring regularly, and the future of the GIS, and its supporting industry, appears bright.

This report has presented the most basic technology behind the geographic information system. The material covered in this report should be considered essential by both researchers just entering the geographic data processing field, and professionals embarking on the design and implementation of a GIS.

The first, and largest, part of the report concentrated on the basic building block of geographic information systems: the geographic data model. The two main types of geographic data models, vector and tessellation, were presented and examined in detail. In addition, a discussion was included which described hybrid data models--models which attempt to capture the advantages of both the vector and tessellation models.

The next section of the report discussed geographic database management in terms of geographic data access and query processing. This section concentrated on factors which affect the day-to-day performance of a geographic information system.

Finally, the last section of the report presented a pragmatic discussion of geographic information system design. This section developed a short, "real-life" scenario to stress the importance of the design phase to the performance of a database system. The section also presented discussions on distributed database considerations and artificial intelligence considerations in the design of a geographic information system.

The field of geographic data processing is a complex and dynamic one. The researcher or professional working in the field needs to devote considerable effort to the "education process," both initially and throughout their work. This report has hopefully served that purpose--to provide the researcher or professional with the basic knowledge necessary to study and develop geographic information systems.

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