2 Data Models

Introduction

Data in a GIS represent a simplified view of the real world. Physical *entities* or phenomena are approximated by data in a GIS. These data include information on the spatial location and extent of the physical entities, and information on their non-spatial properties.

Each entity is represented by a *spatial feature* or *cartogaphic object* in the GIS, and so there is an entity-object correspondence. Because every computer system has limits, only a subset of the essential characteristics are represented for each entity. As illustrated in Figure 2-1, we may represent lakes in a region by a set of polygons. These polygons are associated with a set of essential characteristics that define each lake. All other information for the area may be ignored, e.g., information on the roads, buildings, slope, or soil characteristics. Only lake boundaries and essential lake characteristics have been saved in this example.

Essential characteristics are defined by the person, group, or organization that develops the spatial data or uses the GIS. The set of characteristics used to represent an entity

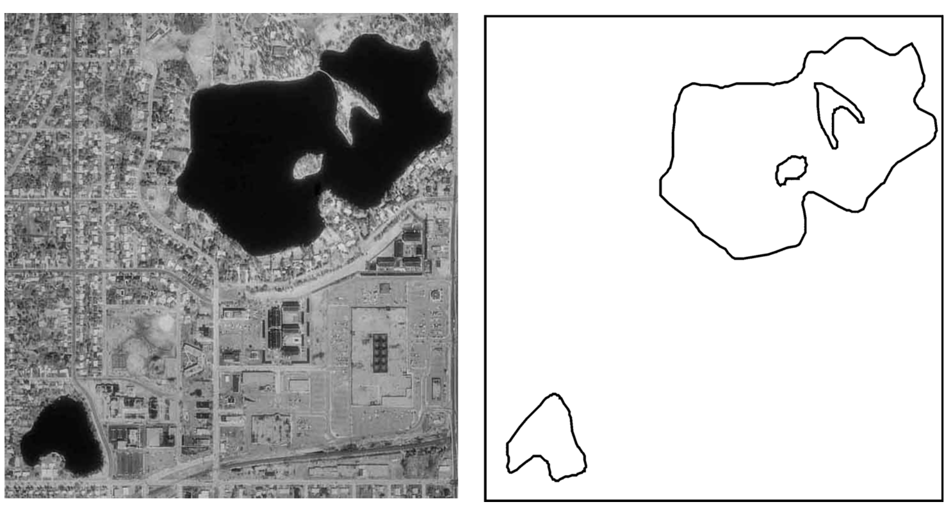


Figure 2-1: A physical entity is represented by a spatial object in a GIS. Here, the physical boundaries of lakes are represented by lines.

is subjectively chosen. What is essential to describe a forest for one person, for example a logger, would be different than what is essential to another person, such as a typical member of the Sierra Club. Objects are abstractions in a spatial database, because we can only record and maintain a subset of characteristics of any entity, and no one abstraction is universally better than any other.

A *data model* may be defined as the objects in a spatial database plus the relationships among them. The term model is fraught with ambiguity, because it is used in many disciplines to describe many things. Here the purpose of a spatial data model is to provide a formal means of representing and manipulating spatially-referenced information. In our lake example our data model consists of two parts. The first part is a set of polygons (closed areas) recording the shoreline of the lake, and the second part is a set of numbers or letters associated with each polygon. A data model may be considered the most recognizable level in our computer abstraction of the real world. Data structures and binary machine code are successively less recognizable, but more computer-compatible forms of the spatial data (Figure 2-2).

Coordinates are used to define the spatial location and extent of geographic objects. A coordinate most often consists of a pair of numbers that specify location in relation to an origin. The coordinates quan-

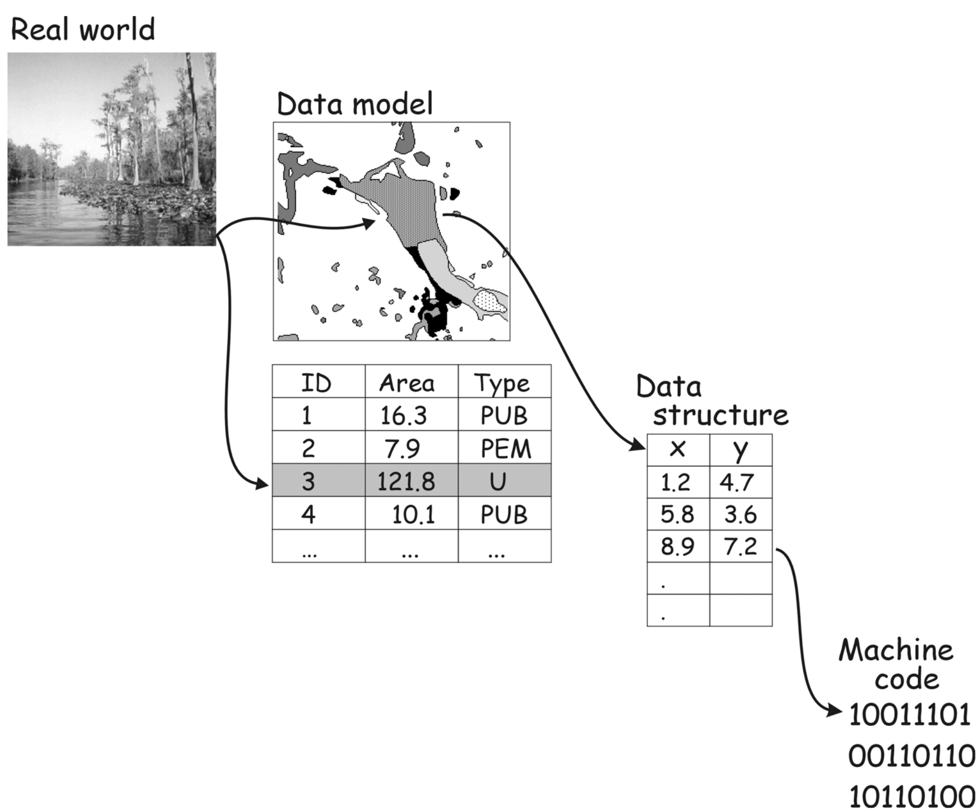


Figure 2-2: Levels of abstraction in the representation of spatial entities. The real world is represented in successively more machine-compatible but humanly obscure forms.

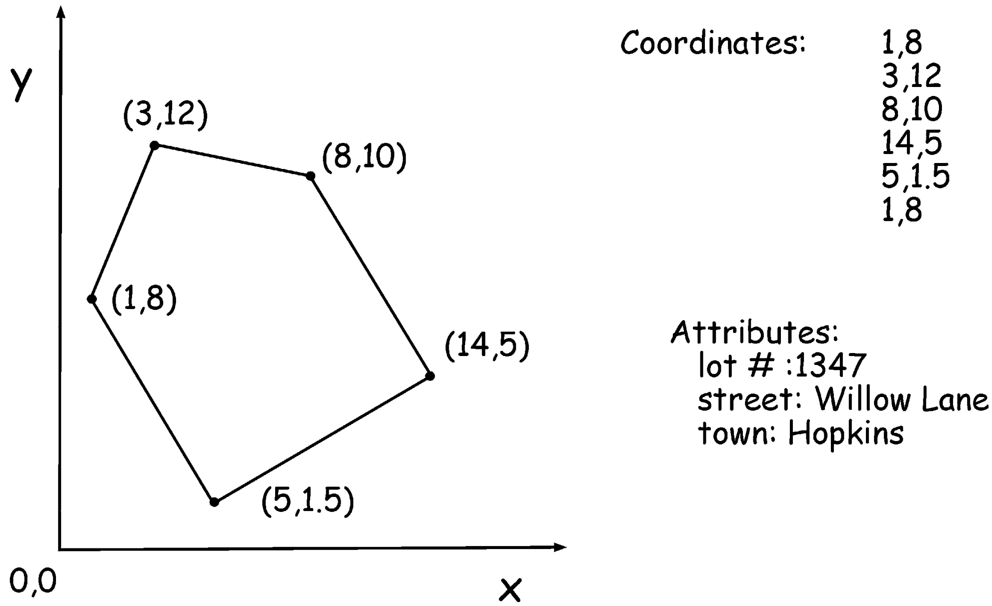


Figure 2-3: Coordinate and attribute data are used to represent entities.

tify the distance from the origin when measured along a standard direction. Single or groups of coordinates are organized to represent the shapes and boundaries that define the objects. Coordinate information is an important part of the data model, and models differ in how they represent these coordinates. Coordinates are usually expressed in one of many standard coordinate systems. The coordinate systems are usually based upon standardized map projections (discussed in Chapter 3) that unambiguously define the coordinate values for every point in an area.

Typically there are two distinct types of data used to define cartographic objects (Figure 2-3). First, coordinate or geometric data define the location and shape of the objects. Second, attribute data are collected and referenced to each object. These attribute data record the non-spatial components of an object, such as a name, color, pH, or cash value.

Attribute data are linked with coordinate data to help define each cartographic object in the GIS. The attribute data are linked to the corresponding cartographic objects in the spatial part of the GIS database. Keys, labels, or other indices are used so that the spatial and attribute data may be viewed, related, and manipulated together.

Most conceptualizations view the world as a set of layers (Figure 2-4). Each layer organizes the spatial and attribute data for a given set of cartographic objects in the region of interest. These are often referred to as *thematic layers*. As an example consider a GIS database that includes a soils data layer, a population data layer, an elevation data layer, and a roads data layer. The roads layer "contains" only roads data, including the location and properties of roads in the analysis area. There are no data regarding the location and properties of any other geographic entities in the roads layer. Information on soils, population, and elevation are

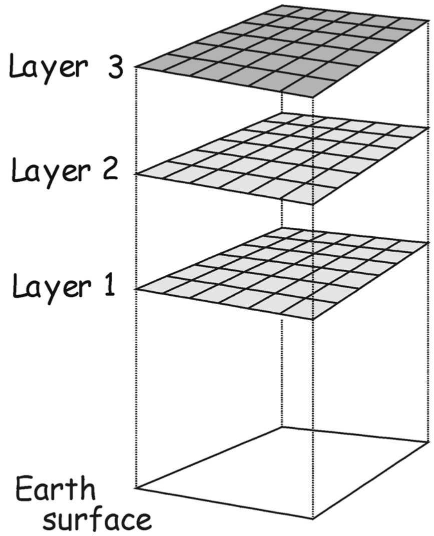


Figure 2-4: Spatial data are most often viewed as a set of thematically distinct layers.

contained in their respective data layers. Through analyses we may combine data to create a new data layer, e.g., we may identify areas that are "high" elevation and join this information with the soils data. This join creates a new data layer with a new, composite soils/elevation variable mapped.

Coordinate Data

Coordinates define location in two or three-dimensional space. Coordinate pairs, e.g., x and y, or coordinate triples, x, y, and z, are used to define the shape and location of each spatial object or phenomenon.

Spatial data in a GIS most often use a *Cartesian* coordinate system, so named after Rene Descartes, a French mathematician. Cartesian systems define two or three *orthogonal* (right-angle) axes. Two-dimensional Cartesian systems define x and y axes in a plane (Figure 2-5, left) Three-dimensional Cartesian systems define a z axis, orthogonal to both the x and y axes. An origin is defined with zero values at the inter-

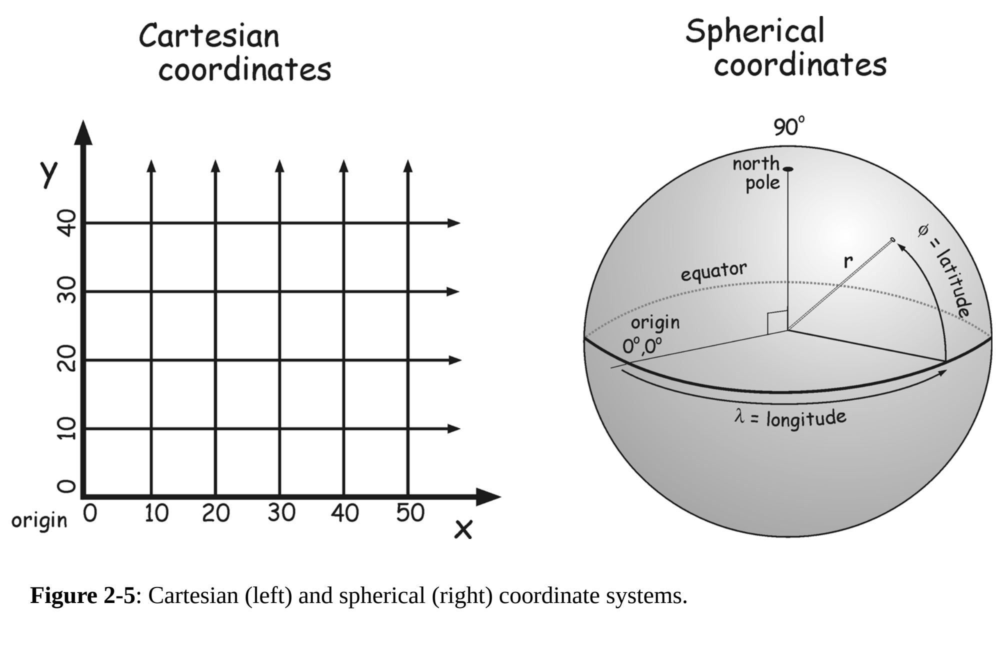


Figure 2-5: Cartesian (left) and spherical (right) coordinate systems.

section of the orthogonal axes. Cartesian coordinates are usually specified as decimal numbers, by convention increasing from bottom to top and from left to right.

Coordinate data may also be specified in a *spherical* coordinate system. Hipparchus, a Greek mathematician of the 2nd century B.C., was among the first to specify locations on the Earth using angular measurements on a sphere. The most common spherical system uses two angles of rotation and a radius distance, r, to specify locations on a modeled earth surface (Figure 2-5, right). These angles of rotation occur around a polar axis to define a longitude (λ) and with reference to an equatorial plane to define a latitude (ϕ). Latitudes increase from zero at the Equator to 90 degrees at the poles. Northern latitudes are preceded by an N and southern latitudes by an S, e.g., N90^o, S10^o. Longitudes increase east and west of an origin. Longitude values are preceded by an E and W, respectively, e.g., W110^o. Northern and eastern directions are designated as positive and southern and western designated as negative when signed coordinates are required. Spherical coordinates are most often recorded in a degrees-minutes-seconds (DMS) notation, e.g. N43^o 35′ 20″, signifying 43 degrees, 35 minutes, and 20 seconds of latitude. Minutes and seconds range from zero to sixty. Alternatively, spherical coordinates may be expressed as decimal degrees (DD). DMS may be converted to DD by:

$$DD = DEG + MIN/60 + SEC/3600 \qquad (2.1)$$

Attribute Data and Types

Attribute data are used to record the non-spatial characteristics of an entity. Attributes are also called items or variables. Attributes may be envisioned as a list of characteristics that help describe and define the features we wish to represent in a GIS. Color, depth, weight, owner, component vegetation type, or landuse are examples of variables that may be used as attributes. Attributes have values, e.g., color may be blue, black or brown, weight from 0.0 to 500.0, or landuse may be urban, agriculture, or undeveloped. Attributes are often presented in tables, with attributes arranged in rows and columns (Figure 2-2). Each row corresponds to an individual spatial object, and each column corresponds to an attribute. Tables are often organized and managed using a specialized computer program called a database management system (DBMS, described fully in Chapter 8).

Attributes of different types may be grouped together to describe the non-spatial properties of each object in the database. These attribute data may take many forms, but all attributes can be categorized as nominal, ordinal, or interval/ratio attributes.

Nominal attributes are variables that provide descriptive information about an object. Color, a vegetation type, a city name, the owner of a parcel, or soil series are all examples of nominal attributes. There is no implied order, size, or quantitative information contained in the nominal attributes.

Nominal attributes may also be images, film clips, audio recordings, or other descriptive information. Just as the color or type attributes provide nominal information for an entity, an image may also provide descriptive information. GIS for real estate management and sales often have images of the buildings or surroundings as part of the database. Digital images provide information not easily conveyed in any other manner. These image or sound attributes are sometimes referred to as BLOBs for binary large objects, but they are best considered as a special case of a nominal attribute.

Ordinal attributes imply a rank order or scale by their values. An ordinal attribute may be descriptive such as small, medium, or large, or they may be numeric, such as an erosion class which takes values from 1 through 10. The order reflects only rank, and does not specify the form of the scale. An object with an ordinal attribute that has a value of four has a higher rank for that attribute than an object with a value of two. However we cannot infer that the attribute value is twice as large, because we cannot assume the scale is linear.

Interval/ratio attributes are used for numeric items where both order and absolute difference in magnitudes are reflected in the numbers. These data are often recorded as real numbers, most often on a linear scale. Area, length, weight, value, height, or depth are a few examples of attributes which are represented by interval/ratio variables.

Common Spatial Data Models

Spatial data models begin with a conceptualization, a view of real world phenomena or entities. Consider a road map suitable for use at a statewide or provincial level. This map is based on a conceptualization that defines roads as lines. These lines connect cities and towns that are shown as discrete points or polygons on the map. Road properties may include only the road type, e.g., a limited access interstate, state highway, county road, or some other type of road. The roads have a width represented by the drawing symbol on the map, however this width, when scaled, may not represent the true road width. This conceptualization identifies each road as a linear feature that fits into a small number of categories. All state highways are represented by the same type of line, even though the state highways may vary. Some may be paved with concrete, others with bitumen. Some may have wide shoulders, others not, or dividing barriers of concrete, versus a broad vegetated median. We realize these differences can exist within this conceptualization.

There are two main conceptualizations used for digital spatial data. The first conceptualization defines discrete objects using a *vector* data model. Vector data models use discrete elements such as points, lines, and polygons to represent the geometry of real-world entities (Figure 2-6).

A farm field, a road, a wetland, cities, and census tracts are examples of discrete entities that may be represented by discrete objects. Points are used to define the locations of "small" objects such as wells, buildings, or ponds. Lines may be used to represent linear objects, e.g., rivers or roads, or to identify the boundary between what is a part of the object and what is not a part of the object. We may map landcover for a region of interest, and we categorize discrete areas as a uniform landcover type. A forest may share an edge with a pasture, and this boundary is represented by lines. The boundaries between two polygons may not be discrete on the ground, for example, a forest edge may grade into a mix of trees and grass, then to pasture; however in the vector conceptualization, a line between two landcover types will be drawn to indicate a discrete, abrupt transition between the two types. Lines and points have coordinate locations, but points have no dimension, and lines have no dimension perpendicular to their direction. Area features may be defined by a closed, connected set of lines.

The second common conceptualization identifies and represents grid cells for a given region of interest. This conceptualization employs a *raster* data model (Figure 2-6). Raster cells are arrayed in a row and column pattern to provide "wall-to-wall" coverage of a study region. Cell values are used to represent the type or quality of mapped variables. The raster model is used most commonly with variables that may change continuously across a region. Elevation, mean temperature, slope, average rainfall, cumulative ozone exposure, or soil moisture are examples of phenomena that are often represented as continuous fields. Raster representations are commonly used to represent discrete features, for example, class maps such as vegetation or political units.

Data models are at times interchangeable in that many phenomena may be represented with either the vector or raster conceptual approach. For example, elevation may be represented as a surface (continuous field) or as series of lines representing contours of equal elevation (discrete objects). Data may be converted from one conceptual view to another, e.g., the location of contour lines (lines of equal elevation) may be determined by evaluating the raster surface, or a raster data layer may be derived from a set of contour lines. These conversions entail some costs both computationally and perhaps in data accuracy.

The selection of a raster or vector conceptualization often depends on the type of operations to be performed. For example, slope is more easily determined when elevation is represented as a continuous field in a raster data set. However, discrete contours are often the preferred format for printed maps, so the discrete conceptualization of a vector data model may be preferred for this application. The best data model for a given organization or application depends on the most common operations, the experiences and views of the GIS users, the form of available data, and the influence of the data model on data quality.

In addition to the two main data models, there are other data models that may be described as variants, hybrids, or special forms by some GIS users, and as different families of data models by others. A triangulated irregular network (TIN) is an example of such a data model. This model is most often used to represent surfaces, such as elevations, through a combination of point, line, and area features. Many consider this a special, admittedly well-developed, type of vector data model. Variants or other representations related to raster data models also exist. We choose two broad categories for clarity in an introductory text, and introduce variants as appropriate later in this and other chapters.

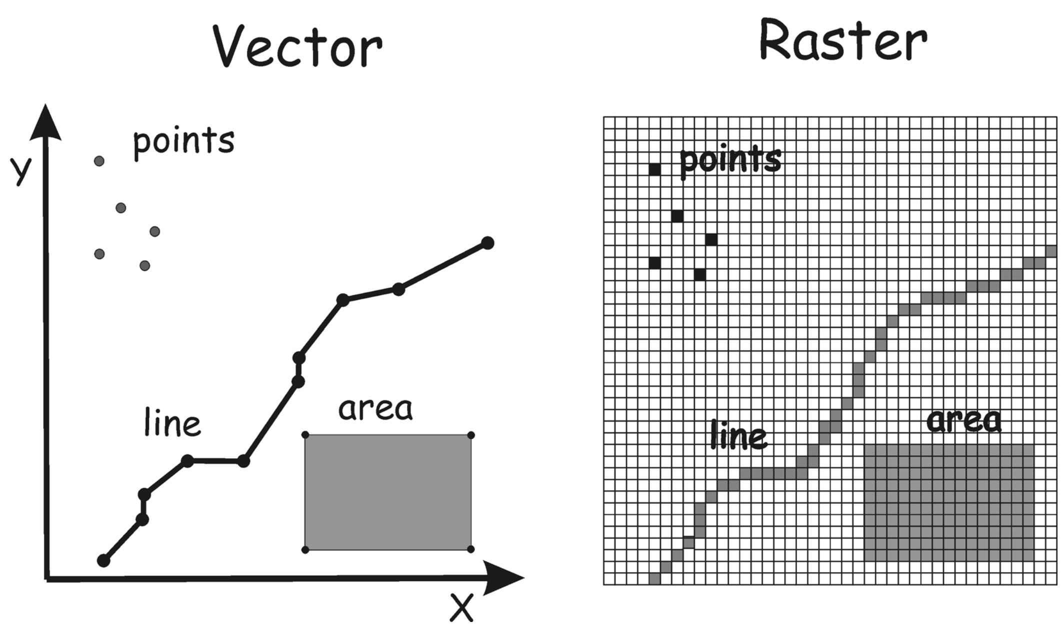


Figure 2-6: Vector and raster data models.

Vector data models will be described in the next section, including commonly found variants. Sections describing raster data models, TIN data models, and data structure then follow.

Vector Data Models

A vector data model uses sets of coordinates and associated attribute data to define discrete objects. Groups of coordinates define the location and boundaries of discrete objects, and these coordinate data plus associated attributes are used to create vector objects representing the real-world entities (Figure 2-7).

There are three basic types of vector objects: points, lines, and polygons (Figure 2-8). A point uses a single coordinate pair to represent the location of an entity that is considered to have no dimension. Gas wells, light poles, accident location, and survey points are examples of entities often represented as point objects in a spatial database. Some of these have real physical dimension, but for the purposes of the GIS users they may be represented as points. In effect, this means the size or dimension of the entity is not important spatial information, only the central location. Attribute data are attached to each point, and these attribute data record the important non-spatial characteristics of the point entities. When using a point to represent a light pole, important attribute information might be the height of the pole, the type of light and power source, and the last date the pole was serviced.

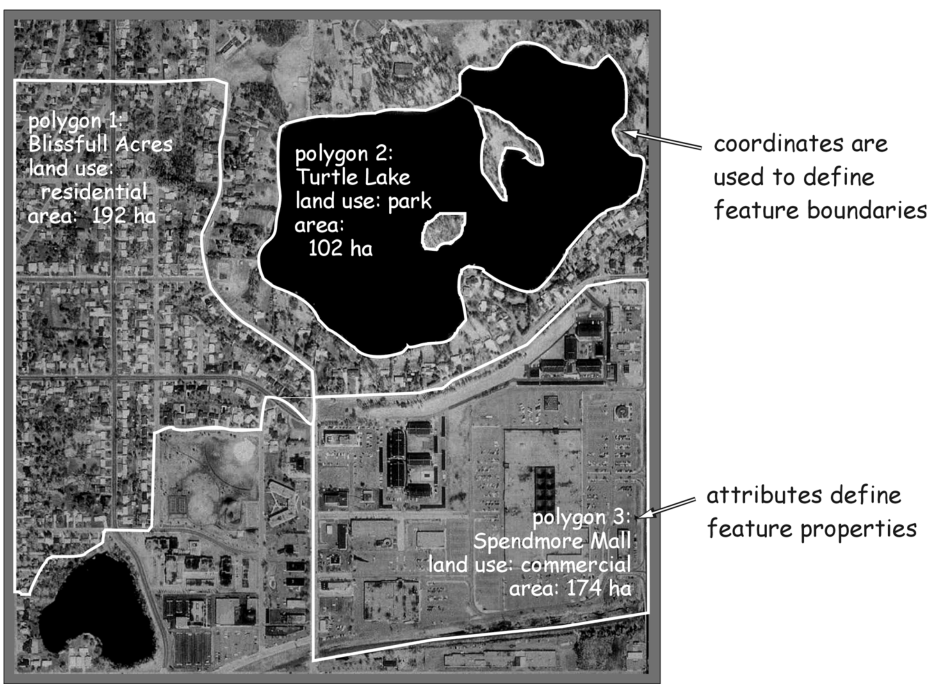


Figure 2-7: Coordinates define spatial location and shape. Attributes record the important non-spatial characteristics of features in a vector data model.

Linear features, often referred to as *arcs*, are represented as lines when using vector data models. Lines are most often represented as an ordered set of coordinate pairs. Each line is made up of line segments that run between adjacent coordinates in the ordered set (Figure 2-8). A long, straight line may be represented by two coordinate pairs, one at the start and one at the end of the line. Curved linear entities are most often represented as a collection of short, straight, line segments, although curved lines are at times represented by a mathematical equation describing a geometric shape. Lines typically have a starting point, an ending point, and intermediate points to represent the shape of the linear entity. Starting points and ending points for a line are sometimes referred to as *nodes*, while intermediate points in a line are referred to as *vertices* (Figure 2-8). Attributes may be attached to the whole line, line segments, or to nodes and vertices along the lines

Area entities are most often represented by closed polygons. These polygons are formed by a set of connected lines, either one line with an ending point that connects back to the starting point, or as a set of lines connected start-to-end (Figure 2-8). Polygons have an interior region and may entirely enclose other polygons in this region. Polygons may be adjacent to other polygons and thus share “bordering” or “edge” lines with other polygons. Attribute data may be attached to the polygons, e.g., area, perimeter, landcover type, or county name may be linked to each polygon.

The Spaghetti Vector Model

The *spaghetti* model is an early vector data model that was originally developed to organize and manipulate line data. Lines are captured individually with explicit starting and ending nodes, and intervening vertices used to define the shape of the line. The spaghetti model records each line separately. The model does not explicitly enforce or record connections of line segments when they cross, nor when two line ends meet (Figure 2-9a). A shared polygon boundary may be represented twice, with a line for each polygon on either side of the boundary. Data in this form are similar in some

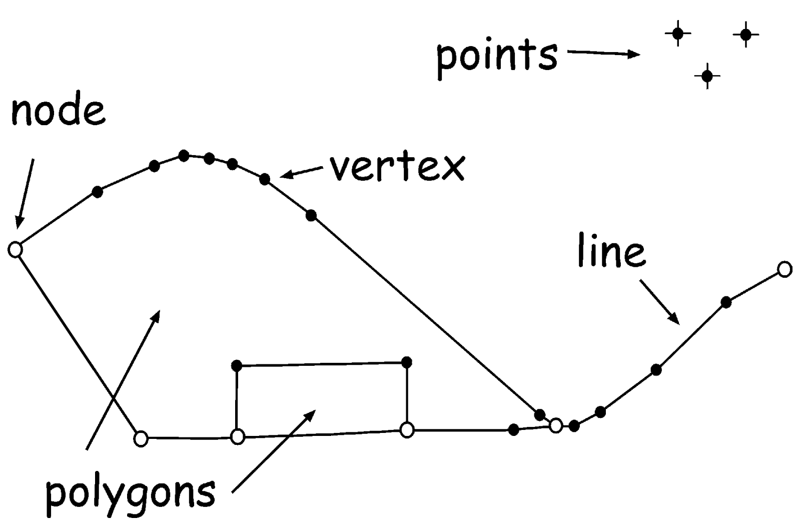


Figure 2-8: Points, nodes and vertices define points, line, and polygon features in a vector data model.

respects to a plate of cooked spaghetti, with no ends connected and no intersections when lines cross.

The spaghetti model is a relatively unstructured way of representing vector data. Because connections among lines are not enforced there may be breaks or overlaps in what should be a connected set of lines. The set of lines that defines a polygon may not form a closed area, so it is not possible to specify the region inside vs. the region outside of the polygon. Coordinates for points, lines, and polygons are often stored sequentially, such that data for nearby areas may be stored quite far apart. This significantly slows data access.

The spaghetti model severely limits spatial data analysis and is little used except when entering spatial data. Because lines often do not connect when they should, many common spatial analyses are inefficient and the results incorrect. For example, analyses such as determining an optimum set of bus routes are precluded if all street connections are not represented in a roads data layer. Area calculation, layer overlay, and many other analyses require "clean" spatial data in which all polygons close and lines meet correctly.

Topological Vector Models

Topological vector models specifically address many of the shortcomings of spaghetti data models. Early GIS developers realized that they could greatly improve the speed, accuracy, and utility of many spatial data operations by enforcing strict connectivity, by recording connectivity and adjacency, and by maintaining information on the relationships between and among points, lines, and polygons in spatial data. These early developers found it useful to record information on the *topological* characteristics of data sets.

Topology is the study of geometric properties that do not change when the forms are bent, stretched or undergo similar transformations. Polygon adjacency is an example of a topologically invariant property, because the list of neighbors to any given polygon does not change during geometric stretching or bending (Figure 2-9, b and c). *Topological vector models* explicitly record topological relationships such as adjacency and connec-

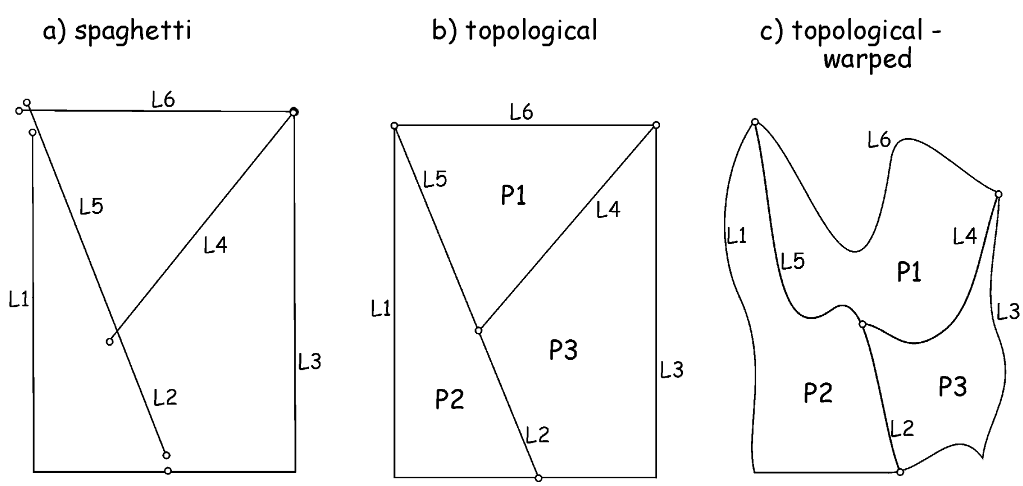


Figure 2-9: Spaghetti (a), topological (b), and topological-warped (c) vector data. Figures b and c are topologically identical because they have the same connectivity and adjacency.

tivity in the data files. These relationships may be recorded separately from the coordinate data and hence do not change when data are stretched or bent, e.g., when converting between coordinate systems.

Topological vector models may also enforce particular types of topological relationships. *Planar topology* requires that all features occur on a two-dimensional surface. There can be no overlaps among lines or polygons in the same layer (Figure 2-10). When planar topology is enforced, lines may not cross over or under other lines. At each line crossing there must be an intersection. The top left of Figure 2-10 shows a non-planar graph. Four line segments coincide. At some locations the lines intersect and a node is present, but at some locations a line passes over or under another line segment. These lines are non-planar because if forced to be in the same plane, all line crossings would intersect at a node. The top right of Figure 2-10 shows planar topology enforced for these same four line segments. Nodes, shown as white-filled circles, are found at each line crossing.

Non-planarity may also occur for polygons, as shown at the bottom of Figure 2-10. Two polygons overlap slightly at an edge. This may be due to an error, e.g., the two polygons share a boundary but have been recorded with an overlap, or there may be two areas that overlap in some way. On the left the polygons are non-planar, that is, they occur one above the other. If topological planarity is enforced, these two polygons must be resolved into three separate, non-overlapping polygons. Nodes are placed at the intersections of the polygon boundaries (lower right, Figure 2-10).

There are additional topological constructs besides planarity that may be recorded or enforced in topological data structures. For example, polygons may be exhaustive, in that there are no gaps, holes or "islands" in a set of polygons. Line direction may be recorded, so that a "from" and "to" node are identified in each line. Directionality aids the representation of river or street networks, where there may be a natural flow direction.

There is no single, uniform set of topological relationships that are included in all topological data models. Different researchers or software vendors have incorporated different topological information in their data structures. Planar topology is often included, as are representations of *adjacency* (which polygons are next to which) and *connectivity* (which lines connect to which). However, much of this information can be generated "on-the-fly", during processing. Topological relationships may be constructed only as needed, each time a data layer is accessed. Some GIS software packages create and maintain detailed topological relationships in their data. This results in more complex and perhaps larger data structures, but access is often faster, and topology provides more consistent, "cleaner" data. Other systems maintain little topological information in the data structures, but compute and act upon topology as needed during specific processing.

Topological vector models often use codes and tables to record topology. As described above, nodes are the starting and ending points of lines. Each node and line is given a unique identifier. Sequences of nodes and lines are recorded as a list of identifiers, and point, line, and polygon topology recorded in a set of tables. The vector features and tables in Figure 2-11 illustrate one form of this topological coding.

Point topology is often quite simple. Points are typically independent of each other, so they may be recorded as individual identifiers, perhaps with coordinates included, and in no particular order (Figure 2-11, top).

Line topology typically includes substantial structure, and identifies at a minimum the beginning and ending points of each line (Figure 2-11, middle). Variables record the topology and may be organized in a table. These variables may include a line identifier, the starting node, and the ending node for each line. In addition, lines may be

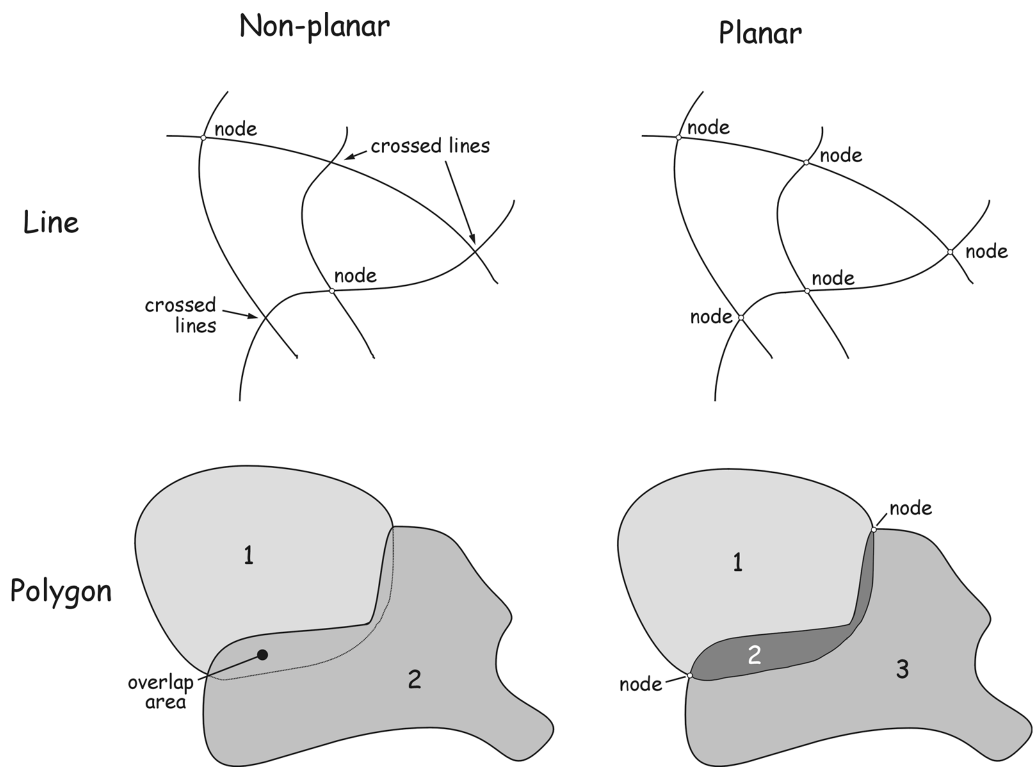


Figure 2-10: Non-planar and planar topology in lines and polygons.

assigned a direction, and the polygons to the left and right of the lines recorded. In most cases left and right are defined in relation to the direction of travel from the starting node to the ending node.

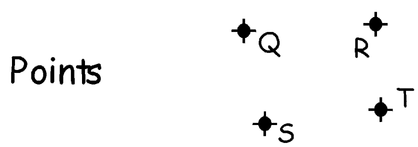
Polygon topology may also be defined by tables (Figure 2-11, bottom). The tables may record the polygon identifiers and the list of connected lines that define the polygon. Edge lines are often recorded in sequential order. The lines for a polygon form a closed loop, resulting in the starting node of the first line in the list that also serves as the ending node for the last line in the list. Note that there may be a "background" polygon defined by the outside area. This background polygon is not a closed polygon as all the rest, however it may be defined for consistency and to provide entries in the line topology table.

Finally, note that there may be coordinate tables (not shown in Figure 2-11) that record the identifiers and locations of each node, and coordinates for each vertex within a line or polygon. Node locations are recorded with coordinate pairs for each node, while line locations are represented by an identifier and a list of vertex coordinates for each line.

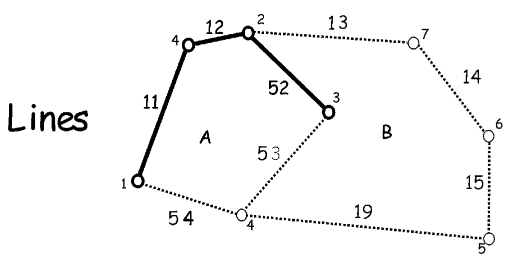
Figure 2-11 illustrates the inter-related structure inherent in the tables that record topology. Point or node records may be related to lines, which in turn may be related to polygons. All these may then be linked in complex ways to coordinate tables that record location.

Topological vector models greatly enhance many vector data operations. Adjacency analyses are reduced to a table look up, an operation that is relatively simple to program and quick to execute in most software systems. For example, an analyst may want to identify all polygons adjacent to a city. Assume the city is represented as a single polygon. The operation reduces to 1) scanning the polygon topology table to find the polygon labeled city and reading the list of lines that bound the polygon, and 2) scanning this list of lines for the city polygon, accumulating a list of all left and right polygons. Polygons adjacent to the city may be identified from this list. List searches on topological tables are typically much faster than searches involving coordinate data.

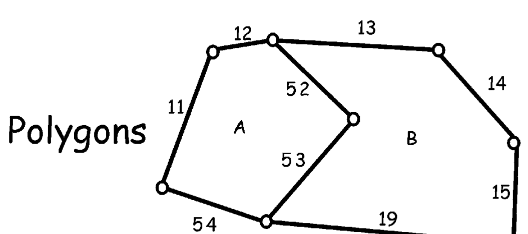
Topological vector models also enhance many other spatial data operations. Network and other connectivity analyses are concerned with the flow of resources through defined pathways. Topological vector models explicitly record the connections of a set of pathways and so facilitate network analyses. Overlay operations are also enhanced when using topological vector models. The mechanics of overlay operations are discussed in greater detail in Chapter 9, however we will state here that they involve identifying line adjacency, intersection, and resultant polygon formation. The interior and exterior regions of existing and new polygons must be determined, and these regions depend on polygon topology. Hence,



Point ID	X	Y
Q	32.7	45.6
R	76.3	19.5
S	22.7	15.8
etc...		



Line ID	Begin node	End node	Left poly	Right poly
11	1	4	...	A
12	4	2	...	A
52	2	3	B	A
etc ..				



Polygon ID	Lines
A	11,12,52,53,54
B	52,53,19, 15,14,13

Figure 2-11: An example of possible vector feature topology and tables. Additional or different tables and data may be recorded to store topological information.

topological data are useful in many spatial analyses.

There are limitations and disadvantages to topological vector models. First, there are computational costs in defining the topological structure of a vector data layer. Software must determine the connectivity and adjacency information, assign codes, and build the topological tables. Computational costs are typically quite modest with current computer technologies.

Second, the data must be very "clean", in that all lines must begin and end with a node, all lines must connect correctly, and all polygons must be closed. Unconnected lines or unclosed polygons will cause errors during analyses. Significant human effort may be required to ensure clean vector data because each line and polygon must be checked. Software may help by flagging or fixing "dangling" nodes that do not connect to other nodes, and by automatically identifying all polygons. Each dangling node and polygon may then be checked, and edited as needed to correct errors.

These limitations are far outweighed by the gains in efficiency and analytical capabilities provided by topological vector models. Many current vector GIS packages use topological vector models in some form.

Raster Data Models

Models and Cells

Raster data models define the world as a regular set of cells in a grid pattern (Figure 2-12). Typically these cells are square and evenly spaced in the x and y directions. The phenomena or entities of interest are represented by attribute values associated with each cell location. Raster data sets have a cell dimension, defining the size of the cell. The cell dimension specifies the length and width of the cell in surface units, e.g. the *cell dimension* may be specified as a square 30 meters on each side. The cells are usually oriented parallel to the x and y directions. Thus, if we know the cell dimension and the coordinates of any one cell e.g., the lower left corner, we may calculate the coordinate of any other cell location.

Raster data models are the natural means to represent "continuous" spatial features or phenomena. Elevation, precipitation, slope, and pollutant concentration are examples of continuous spatial variables. These variables characteristically show significant changes in value over broad areas. The gradients can be quite steep (e.g., at cliffs), gentle (long, sloping ridges), or quite variable (rolling hills). Because raster data may be a dense sampling of points in two dimensions, they easily represent all variations in the changing surface. Raster data models depict these gradients by changes in the values associated with each cell.

Square raster cells have a characteristic cell dimension or cell size (Figure 2-12). This cell dimension is the edge length of each cell, and cell dimension is typically constant for a raster data layer. The cell dimension is important because it affects many properties of a raster data set, including coordinate data volume.

The volume of data required to cover a given area increases as the cell dimension gets smaller. The number of cells increases by the square of the reduction in cell dimension. Cutting the cell dimension in half causes a factor of four increase in the number of cells (Figure 2-13a and b). Reducing the cell dimension by four causes a sixteenfold increase in the number of cells (Figure 2-13a and c). There is a trade-off between cell size and data volumes. Smaller cells may be preferred because they provide greater spatial detail, but this detail comes at the cost of larger data sets.

The cell dimension also affects the spatial precision of the data set, and hence positional accuracy. The cell coordinate is

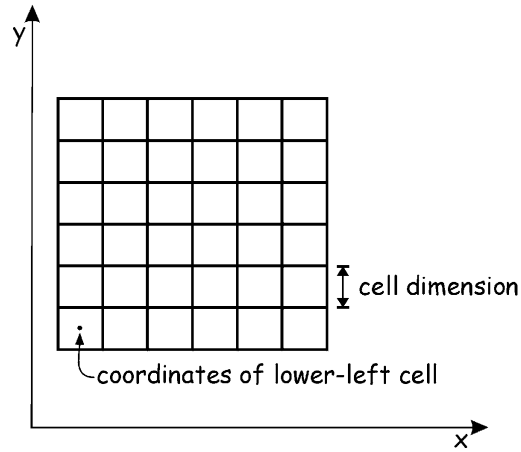


Figure 2-12: Important defining characteristics of a raster data model.

usually defined at a point in the center of the cell. The coordinate applies to the entire area covered by the cell. Positional accuracy is typically expected to be no better than approximately one-half the cell size. No matter the true location of a feature, coordinates are truncated or rounded up to the nearest cell center coordinate. Thus, the cell size should be no more than twice the desired accuracy and precision for the data layer represented in the raster, and should be smaller.

Each raster cell represents a given area on the ground and is assigned a value that may be considered to apply for the cell. In some instances the variable may be uniform over the raster cell, and hence the value is correct over the cell. However, under most conditions there is within-cell variation, and the raster cell value represents the average, central, or most common value found in the cell. Consider a raster data set representing annual weekly income with a cell dimension that is 300 meters (980 feet) on a side. Further suppose that there is a raster cell with a value of 710. The entire 300 by 300 meters area is considered to have this value of 710 dollars per week. There may be many households within the raster cell, none of which may earn exactly 710 dollars per week. However the 710 dollars may be the average, the highest point, or some other representative value for the area covered by the cell. While raster cells often represent the average or the value measured at the center of the cell, they may also represent the median, maximum, or other statistic for the cell area.

An alternative interpretation of the raster cell applies the value to the central point of the cell. Consider a raster grid containing

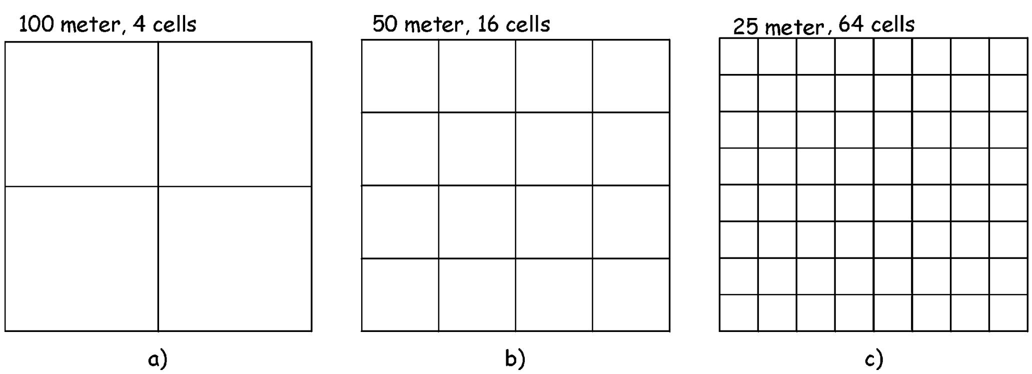


Figure 2-13: The number of cells in a raster data set depends on the cell size. For a given area, a linear decrease in cell size cause an exponential increase in cell number, e.g., halving the cell size causes a four-fold increase in cell number.

elevation values. Cells may be specified that are 200 meters square, and an elevation value assigned to each square. A cell with a value of 8000 meters (26,200 feet) may be assumed to have that value at the center of the cell, and not for the entire cell.

A raster data model may also be used to represent discrete data, e.g., to represent landcover in an area. Raster cells typically hold numeric or single-letter alphabetic characters, so some coding scheme must be defined to identify each discrete value. Each code may be found at many raster cells (Figure 2-14).

Raster cell values may be assigned and interpreted in at least seven different ways (Table 2-1). We have describe three, a raster cell as a point physical value (elevation), as a statistical value (elevation), and as discrete data (landcover). Landcover also may be interpreted as a class code. The value for any

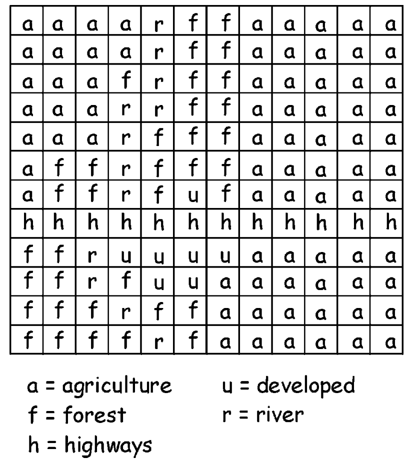


Figure 2-14: Discrete or categorical data may be represented by codes in a raster data layer.

Table 2-1: Types of data represented by raster cell values. (from L. Usery, pers. comm.)

Form	Description	Example
point ID	alpha-numeric ID of closest point	nearest hospital
line ID	alpha-numeric ID of closest line	nearest road
contiguous region ID	alpha-numeric ID for dominant region	state
class code	alpha-numeric code for general class	vegetation type
table ID	numeric position in a table	table row number
physical analog	numeric value representing surface value	elevation
statistical value	numeric value from a statistical function	population density

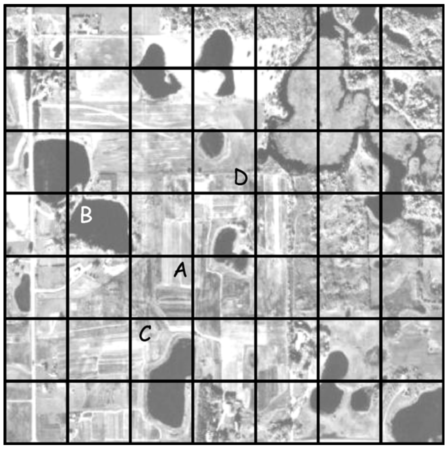


Figure 2-15: Raster cell assignment with mixed landscapes. Upland areas are lighter greys, water the darkest greys.

cell may have a given landcover value, and the cells may be discontinuous, e.g., we may have several farm fields scattered about our area with an identical landcover code. Discrete codes may also be used to identify a specific, usually continuous entity, e.g., a county, state, or country. Raster values may also be used to represent points and lines, as the IDs of lines or points that occur closest to the cell center.

Raster cell assignment may be complicated when representing what we typically think of as discrete boundaries, for example, when the raster value is interpreted as a class code or as a contiguous region ID. Consider the area in Figure 2-15. We wish to represent this area with a raster data layer, with cells assigned to one of two class codes, one each for land or water. Water bodies appear as darker areas in the image, and the raster grid is shown overlain. Cells may contain substantial areas of both land and water, and the proportion of each type may span from zero to 100 percent. Some cells are purely one class and the assignment is obvious, e.g., the cell labelled A in the Figure 2-15 contains only land. Others are mostly one type, as for cells B (water) or D (land). Some are nearly equal in their proportion of land and water, as is cell C. How do we assign classes?

One common method might be called "winner-take-all". The cell is assigned the value of the largest-area type. Cells A, C and D would be assigned the land type, cell B water. Another option places preference. If any of an "important" type is found then the cell is assigned that value, regardless of the proportion. If we specify a preference for water, then cells B, C, and D would be assigned the water type, and cell A the land type.

Regardless of the assignment method used, Figure 2-15 illustrates two considerations when discrete objects are represented using a raster data model. First, some inclusions are inevitable because cells must be assigned to a discrete class. Some mixed cells occur in nearly all raster layers. The GIS user must acknowledge these inclusions, and consider their impact on the intended spatial analyses.

Second, differences in the assignment rules may substantially alter the data layer, as shown in our simple example. More potential cell types in complex landscapes may increase the assignment sensitivity. Smaller cell sizes reduce the significance of classes in the assignment rule, but at the cost of increased data volumes.

A similar problem may occur when more than one line or point occurs within a raster cell. If two points occur, then which point ID is assigned? If two lines occur, then which line ID should be assigned?

Raster Geometry and Resampling

Raster data layers are often defined to align with cell edges parallel to the coordinate system direction. This greatly simplifies the determination of cell location. When cell edges and coordinate system axes are aligned, the calculation of a cell location is a simple process of counting and multiplication. The coordinate location of one cell is recorded, typically the lower-left or upperleft cell in the data set. With a known lower-left cell coordinate, all other cell coordinates may be determined by the formulas:

$$N_{cell} = N_{lower\text{-}left} + row * cell\ size \qquad (2.2)$$

$$E_{cell} = E_{lower\text{-}left} + column * cell\ size \qquad (2.3)$$

where N is the coordinate in the north direction (y), E is the coordinate in the east direction (x), and the row and column are counted from the lower left cell. Formulas are considerably more complicated when the cell edges are not parallel with the coordinate system axes.

Because cell edges and coordinate system axes are typically aligned, data often must be *resampled* when converting between coordinate systems or changing the cell size (Figure 2-16). Resampling involves reassigning the cell values when changing raster coordinates or geometry. Cells must be resampled because the new and old raster cells represent different areas. Cell centers in the old coordinate system do not coincide with cell centers in the new coordinate system and so the average value represented by each cell must be re-computed. Common resampling approaches include the *nearest neighbor* (taking the output layer value from the nearest input layer cell center), *bilinear interpolation* (distance-based averaging of the four nearest cells), and *cubic convolution* (a weighted average of the sixteen nearest cells).

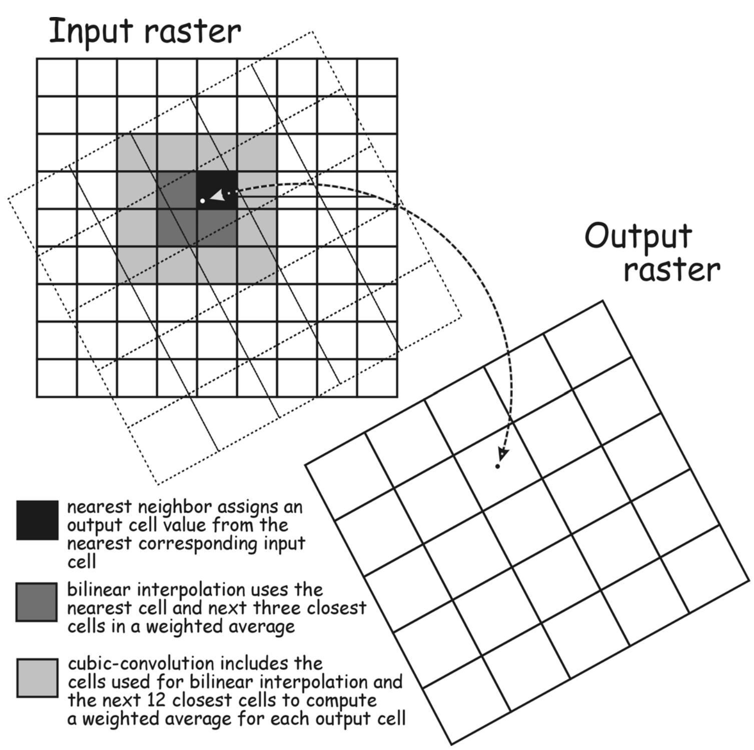


Figure 2-16: Raster resampling. When the orientation or cell size of a raster data set is changed, output cell values are calculated based on the closest (nearest neighbor), four nearest (bilinear interpolation) or sixteen closest (cubic-convolution) input cell values.

A Comparison of Raster and Vector Data Models

The question often arises, "which are better, raster or vector data models?" The answer is neither and both. Neither of the two classes of data models are better in all conditions or for all data. Both have advantages and disadvantages relative to each other and to additional, more complex data models. In some instances it is preferable to maintain data in a raster model, and in others in a vector model. Most data may be represented in both, and may be converted among data models. As an example, elevation may be represented as a set of contour lines in a vector data model or as a set of elevations in a raster grid. The choice often depends on a number of factors, including the predominant type of data (discrete or continuous), the expected types of analyses, available storage, the main sources of input data, and the expertise of the human operators.

Raster data models exhibit several advantages relative to vector data models. First, raster data models are particularly suitable for representing themes or phenomena that change frequently in space. Each raster cell may contain a value different than its neighbors. Thus trends as well as more rapid variability may be represented.

Raster data structures are generally simpler, particularly when a fixed cell size is used. Most raster models store cells as sets of rows, with cells organized from left to right, and rows stored from top to bottom. This organization is quite easy to code in an array structure in most computer languages.

Raster data models also facilitate easy overlays, at least relative to vector models. Each raster cell in a layer occupies a given position corresponding to a given location on the Earth surface. Data in different layers align cell-to-cell over this position. Thus, overlay involves locating the desired grid cell in each data layer and comparing the values found for the given cell location. This cell look-up is quite rapid in most raster data structures, and hence layer overlay is quite simple and rapid when using a raster data model.

Finally, raster data structures are the most practical method for storing, displaying, and manipulating digital image data, such as aerial photographs and satellite imagery. Digital image data are an important source of information when building, viewing, and analyzing spatial databases. Image display and analysis are based on raster operations to sharpen details on the image, specify the brightness, contrast, and colors for display, and to aid in the extraction of information.

Vector data models provide some advantages relative to raster data models. First, vector models generally lead to more compact data storage, particularly for discrete objects. Large homogenous regions are recorded by the coordinate boundaries in a vector data model. These regions are recorded as a set of cells in a raster data model. The perimeter grows more slowly than the area for most feature shapes, so the amount of data required to represent an area increases much more rapidly with a raster data model. Vector data are much more compact than raster data for most themes and levels of spatial detail.

Vector data are a more natural means for representing networks and other connected linear features. Vector data by their nature store information on intersections (nodes) and the linkages between them (lines). Traffic volume, speed, timing, and other factors may be associated with lines and intersections to model many kinds of networks.

Vector data models are easily presented in a preferred map format. Humans are familiar with continuous line and rounded curve representations in hand- or machine-drawn maps, and vector-based maps show these curves. Raster data often show a "stair-step" edge for curved boundaries, particularly when the cell resolution is large relative to the resolution at which the raster is displayed. Cell edges are often visible for lines, and the width and stair-step pattern changes as lines curve. Vector data may be plotted

Table 2-2: A comparison of raster and vector data models**.**

Characteristic	Raster	Vector
data structure	usually simple	usually complex
storage requirements	large for most data sets without compression	small for most data sets
coordinate conversion	may be slow due to data volumes, and may require resampling	simple
analysis	easy for continuous data, simple for many layer combinations	preferred for network analyses, many other spatial operations more complex
positional precision	floor set by cell size	limited only by quality of positional measurements
accessibility	easy to modify or program, due to simple data structure	often complex
display and output	good for images, but discrete features may show "stairstep" edges	map-like, with continuous curves, poor for images

with more visually appealing continuous lines and rounded edges.

Vector data models facilitate the calculation and storage of topological information. Topological information aids in performing adjacency, connectivity, and other analyses in an efficient manner. Topological information also allows some forms of automated error and ambiguity detection, leading to improved data quality.

Conversion between Raster and Vector Models

Spatial data may be converted between raster and vector data models. Vector-to-raster conversion involves assigning a cell value for each position occupied by vector features. Vector point features are typically assumed to have no dimension. Points in a raster data set must be represented by a value in a raster cell, so points have at least the dimension of the raster cell after conversion from vector-to-raster models. Points are usually assigned to the cell containing the point coordinate. The cell in which the point resides is given a number or other code identifying the point feature occurring at the cell location. If the cell size is too large, two or more vector points may fall in the same cell, and either an ambiguous cell identifier assigned, or a more complex numbering and assignment scheme implemented. Typically a cell size is chosen such that the diagonal cell dimension is smaller than the distance between the two closest point features.

Vector line features in a data layer may also be converted to a raster data model. Raster cells may be coded using different criteria. One simple method assigns a value to a cell if a vector line intersects with any part of the cell (Figure 2-17, left). This ensures the maintenance of connected lines in the raster form of the data. This assignment rule often leads to wider than appropriate lines because several adjacent cells may be assigned as part of the line, particularly when the line meanders near cell edges. Other assignment rules may be applied, for example, assigning a cell as occupied by a line only when the cell center is near a vector line segment (Figure 2-17, right). "Near" may be defined as some sub-cell distance, e.g., 1/3 the cell width. Lines passing through the corner of a cell will not be recorded as in the cell. This may lead to thinner linear features in the raster data set, but often at the cost of line discontinuities.

The output from vector-to-raster conversion depends on the input algorithm used. You may get a different output data layer when a different conversion algorithm is used, even though you use the same input. This brings up an important point to remember when applying any spatial operations. The output often depends in subtle ways on the spatial operation. What appear to be quite small differences in the algorithm or key defining parameters may lead to quite different results. Small changes in the assignment distance or rule in a vector-to-raster conversion operation may result in large differences in output data sets, even with the same input. There is often no clear *a priori* best method. Empirical tests or previous experiences are often useful guides to determine the best method with a given data set or conversion problem. The ease of spatial manipulation in a GIS provides a powerful and often easy to use set of tools. The GIS user should bear in mind that these tools may be more efficient at producing errors as

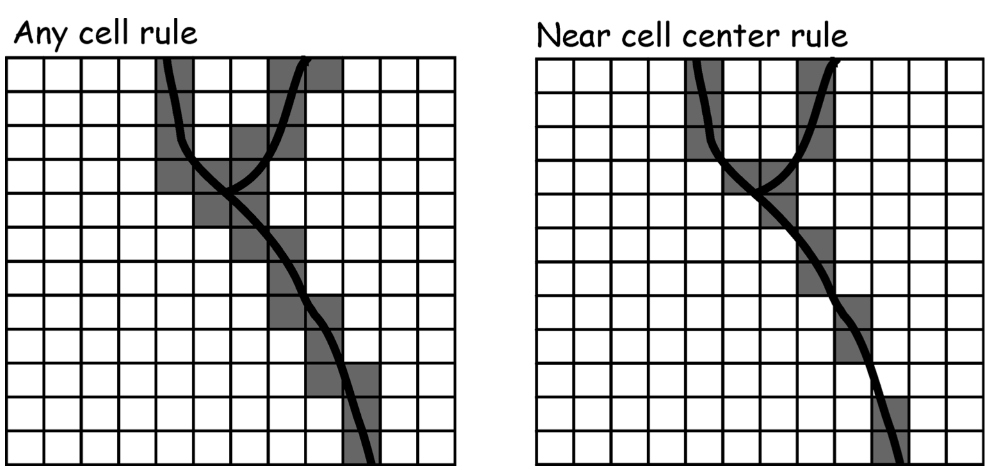


Figure 2-17: vector-to-raster conversion. Two assignment rules result in different raster coding near lines, but in this case not near points.

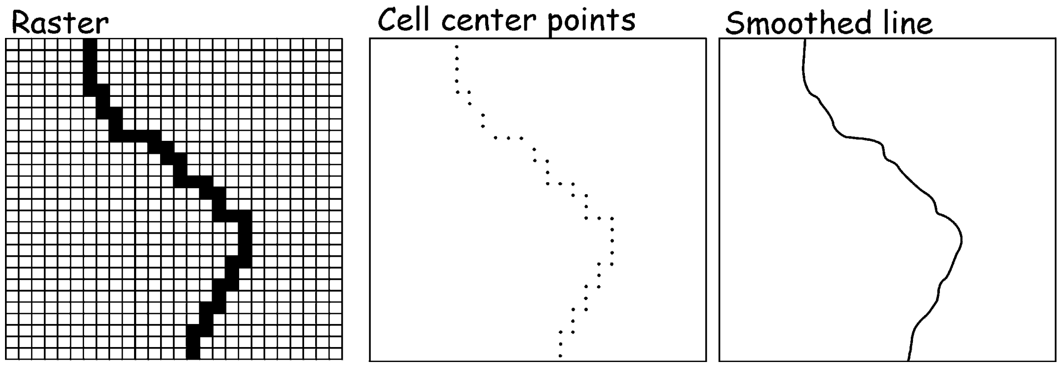


Figure 2-18: Raster data may be converted to vector formats, and may involve line smoothing or other operations to remove the "stair-step" effect.

well as more efficient at providing correct results. Until sufficient experience is obtained with a suite of algorithms, in this case vector-to-raster conversion, small, controlled tests should be performed to verify the accuracy of a given method or set of constraining parameters.

Area features are converted from vector-to-raster with methods similar to those used for vector line features. Boundaries among different polygons are identified as in vector-to-raster conversion for lines. Interior regions are then identified, and each cell in the interior region is assigned a given value. Note that the border cells containing the boundary lines must be assigned. As with vector-to-raster conversion of linear features, there are several methods to determine if a given border cell should be assigned as part of the area feature. One common method assigns the cell to the area if more than one-half the cell is within the vector polygon. Another common method assigns a raster cell to an area feature if any part of the raster cell is within the area contained within the vector polygon. Assignment results will vary with the method used.

Up to this point we have covered vector-to-raster data conversion. Data may also be converted in the opposite direction, in that raster data may be converted to vector data. Point, line, or area features represented by raster cells are converted to corresponding vector data coordinates and structures. Point features are represented as single raster cells. Each vector point feature is usually assigned the coordinate of the corresponding cell center.

Linear features represented in a raster environment may be converted to vector lines. Conversion to vector lines typically involves identifying the continuous connected set of grid cells that form the line. Cell centers are typically taken as the locations of vertices along the line (Figure 2-18). Lines may then be "smoothed" using a mathematical algorithm to remove the "stair-step" effect.

Triangulated Irregular Networks

A *triangulated irregular network* (TIN) is a data model commonly used to represent terrain heights. Typically the x, y, and z locations for measured points are entered into the TIN data model. These points are distributed in space, and the points may be connected in such a manner that the smallest triangle formed from any three points may be constructed. The TIN forms a connected network of triangles (Figure 2-19). Triangles are created such that the lines from one triangle do not cross the lines of another. Line crossings are avoided by identifying the *convergent circle* for a set of three points (Figure 2-20). The convergent circle is defined as the circle passing through all three points. A triangle is drawn only if the corresponding convergent circle contains no other sampling points. Each triangle defines a terrain surface, or facet, assumed to be of uniform slope and aspect over the triangle.

The TIN model typically uses some form of indexing to connect neighboring points. Each edge of a triangle connects to two points, which in turn each connect to other edges. These connections continue recursively until the entire network is spanned. Thus, the TIN is a rather more complicated data model than the simple raster grid when the objective is terrain representation.

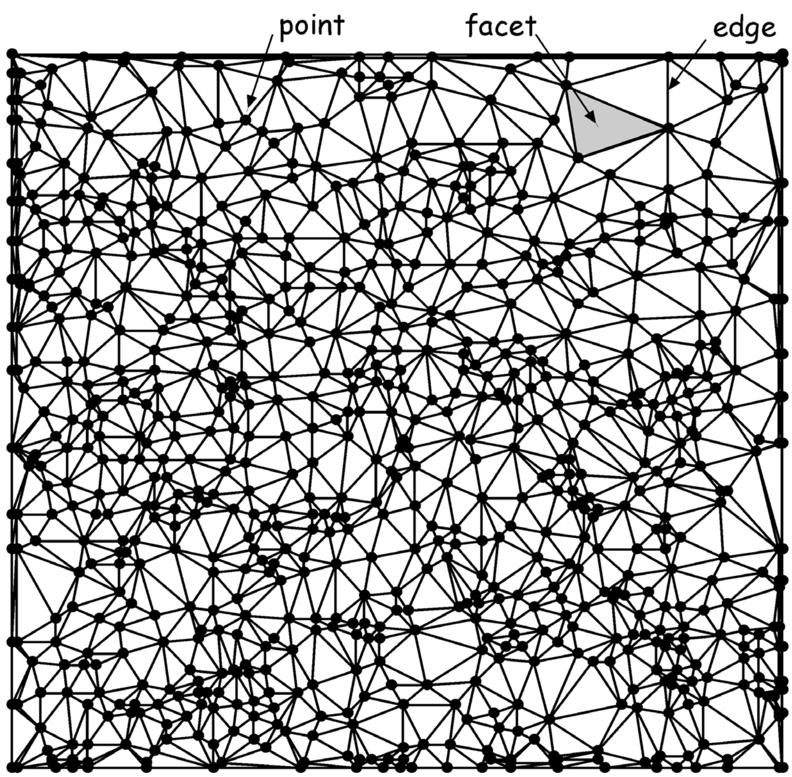


Figure 2-19: A TIN data model defines a set of adjacent triangles over a sample space. Sample points, facets, and edges are components of TIN data models.

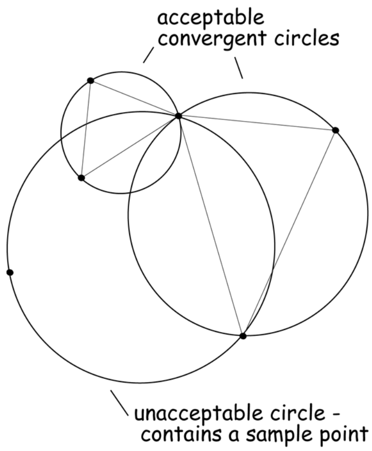


Figure 2-20: Convergent circles intersect the vertices of a triangle and contain no other possible vertices.

While the TIN model may be more complex than simple raster models, it may also be much more appropriate and efficient when storing terrain data in areas with variable relief. Relatively few points are required to represent large, flat, or smoothly continuous areas. Many more points are desirable when representing variable, discontinuous terrain. Surveyors often collect more samples per unit area where the terrain is highly variable. A TIN easily accommodates these differences in sampling density, with the result of more, smaller triangles in the densely sampled area. Rather than imposing a uniform cell size and having multiple measurements for some cells, one measurement for others, and no measurements for most cells, the TIN preserves each measurement point at each location.

Multiple Models

Digital data may often be represented using any one of several data models. The analyst must choose which representation to use. Digital elevation data are perhaps the best example of the use of multiple data models to represent the same theme (Figure 2-21). Digital representations of terrain height have a long history and widespread use in GIS. Elevation data and derived surfaces such as slope and aspect are important in hydrology, transportation, ecology, urban and regional planning, utility routing, and a number of other activities that are analyzed or modeled using GIS. Because of this widespread importance and use, digital elevation data are commonly represented in a number of data models.

Raster grids, triangulated irregular networks (TINs), and vector contours are the most common data structures used to organize and store digital elevation data. Raster and TIN data are often called digital elevation models (DEMs) or digital terrain models (DTMs) and are commonly used in terrain analysis. Contour lines are most often used as a form of input, or as a familiar form of output. Historically, hypsography (terrain heights) were depicted on maps as contour lines (Figure 2-21). Contours represent lines of equal elevation, typically spaced at fixed elevation intervals across the mapped areas. Because many important analyses and derived surfaces are more difficult using contour lines, most digital elevation data are represented in raster or TIN models.

Raster DEMs are a grid of regularly spaced elevation samples (Figure 2-21). These samples, or postings, typically have equal frequency in the grid x and y directions. Derived surfaces such as slope or aspect are easily and quickly computed from raster DEMs, and storage, processing, compression, and display are well understood and efficiently implemented. However, as described earlier, sampling density cannot be increased in areas where terrain changes are abrupt, so either flat areas will be oversampled or variable areas undersampled. A linear increase in raster resolution causes a geometric increase in the number of raster cells, so there may be significant storage and processing costs to oversampling. TINs solve these problems, at the expense of a more complicated data structure.

Other Geographic Data Models

A number of other data models have been proposed and implemented, although they are all currently uncommon. Some of these data models are appropriate for specialized applications, while others have been tried and largely discarded. Some have been partially adopted, or are slowly being incorporated into available software tools.

The *object-oriented* data model incorporates much of the philosophy of object oriented programming into a spatial data model. A main goal is to encapsulate the information and operations (often called methods) into discrete objects. These objects could be geographic features, e.g., a city might be defined as an object. Spatial and attribute data associated with a given city would be incorporated in a single city object. This may include not only information on

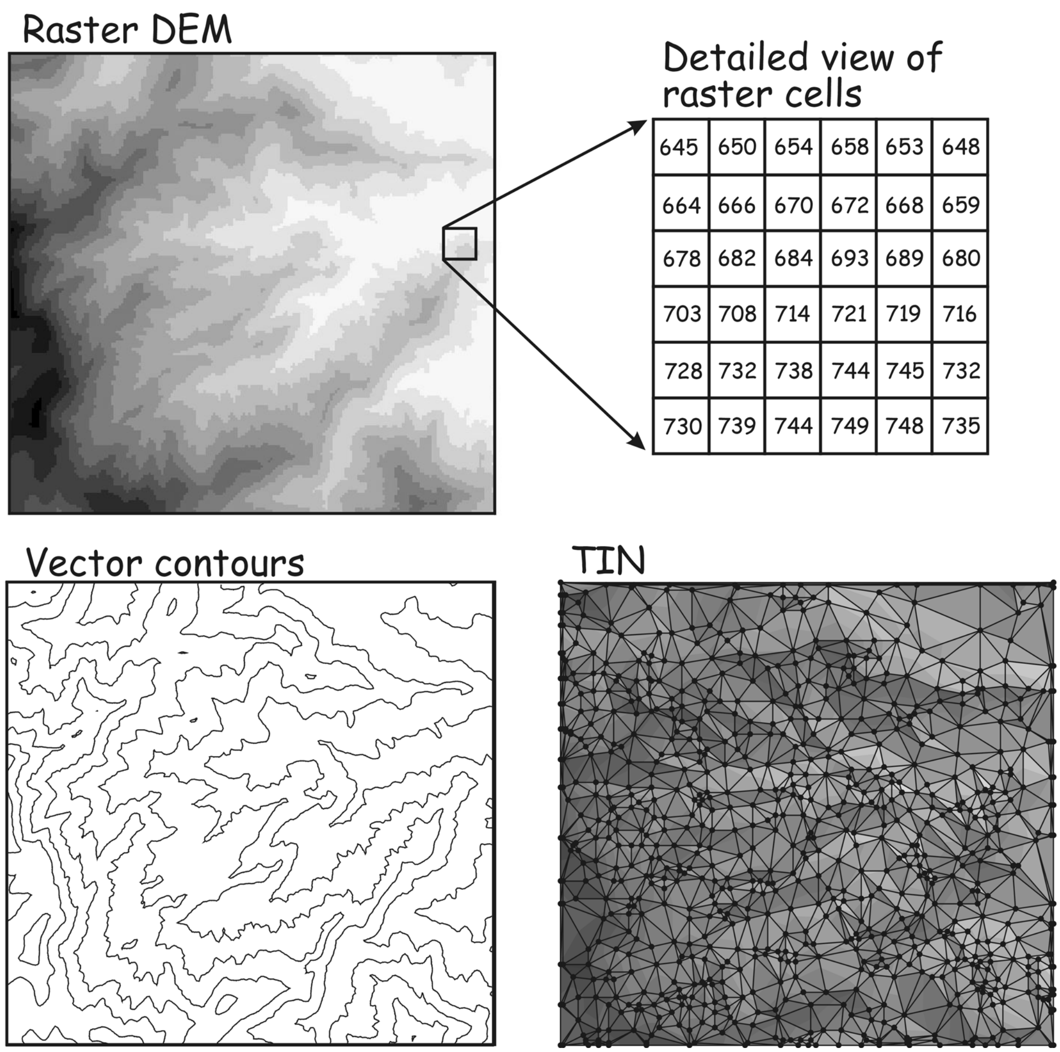


Figure 2-21: Data may often be represented in several data models. Digital elevation data are commonly represented in raster (DEM), vector (contours), and TIN data models.

the city boundary, but also streets, building locations, waterways, or other features that might be in separate data structures in a layered topological vector model. The topology could be included, but would likely be incorporated within the single object. Topological relationships to exterior objects may also be represented, e.g., relationships to adjacent cities or counties.

The object-oriented data model has both advantages and disadvantages when compared to traditional topological vector and raster data models. Some geographic entities may be naturally and easily identified as discrete units for particular problems, and so may be naturally amenable to an object-oriented approach. A power or water distribution system may be defined in this manner, where entities such as pumping stations or holding reservoirs may be discretely defined. However, it is more difficult to represent continuously varying features, such as elevation, with an object-oriented approach. In addition, for many problems the definition and indexing of objects may be quite complex. It has proven difficult to develop generic tools that may quickly and efficiently implement object-oriented models.

Data and File Structures

Binary and ASCII Numbers

No matter what spatial data model is used, the concepts must be translated into a set of numbers stored on a computer. All information stored on a computer in a digital format may be represented as a series of 0's and 1's. These data are often referred to as stored in a binary format, because each digit may contain one of two values, 0 or 1. Binary numbers are in a base of 2, so each successive column of a number represents a power of two.

We use a similar column convention in our familiar ten-based (decimal) numbering system. As an example, consider the number 47 that we represent using two columns. The seven in the first column indicates there are seven units of one. The four in the tens column indicates there are four units of ten. Each higher column represents a higher power of ten. The first column represents one (10^0=1), the next column represents tens (10^1=10), the next column hundreds (10^2=100) and upward for successive powers of ten. We add up the values represented in the columns to decipher the number.

Binary numbers are also formed by representing values in columns. In a binary system each column represents a successively higher power of two (Figure 2-22). The first (right-most) column represents 1 ($2^0 = 1$), the second column (from right) represents twos ($2^1 = 2$), the third (from right) represents fours ($2^2 = 4$), then eight ($2^3 = 8$), sixteen ($2^4 = 16$), and upward for successive powers of two. Thus, the binary number 1001 represent the decimal number 9: a one from the rightmost column, and eight from the fourth column (Figure 2-22).

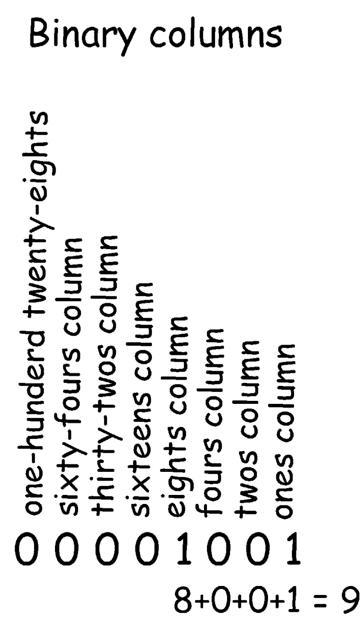
Each digit or column in a binary number is called a *bit*, and 8 columns, or bits, are called a *byte*. A byte is a common unit for defining data types and numbers, e.g., a data file may be referred to as containing 4-byte integer numbers. This means each number is represented by 4 bytes of binary data (or 8 x 4 = 32 bits).

Several bytes are required when representing larger numbers. For example, one byte may be used to represent 256 different values. When a byte is used for non-negative integer numbers, then only values from 0 to 255 may be recorded. This will work when all values are below 255, but consider an elevation data layer with values greater than 255. If the data are not rescaled, then more than one byte of storage are required for each value. Two bytes will store a number greater than 65,500. Terrestrial elevations measured in feet or meters are all below this value, so two bytes of data are often used to store elevation data. Real numbers such as 12.19 or 865.3 typically require more bytes, and are effectively split, e.g., two bytes for the whole part of the real number, and four bytes for the fractional portion.

Binary numbers are often used to represent codes. Spatial and attribute data may then be represented as text or as standard codes. This is particularly common when raster or vector data are converted for export or import among different GIS software systems. For example, Arc/Info, a widely used GIS, produces several export formats that are in text or binary formats. Idrisi, another popular GIS, supports binary and alphanumeric raster formats.

One of the most common number coding schemes uses ASCII designators. ASCII stands for the American Standard Code for Information Interchange. ASCII is a standardized, widespread data format that uses seven bits, or the numbers 0 through 126, to represent text and other characters. An extended ASCII, or ANSI scheme, uses these same codes, plus an extra binary bit to represent numbers between 127 and 255. These codes are then used in many programs, including GIS, particularly for data export or exchange.

ASCII codes allow us to easily and uniformly represent alphanumeric characters such as letters, punctuation, other characters, and numbers. ASCII converts binary numbers to alphanumeric characters through an index. Each alphanumeric character corresponds to a specific number between 0 and 255, which allows any sequence of characters to be represented by a number. One byte is required to represent each character in extended ASCII coding, so ASCII data sets are typically much larger than binary data sets. Geographic data in a GIS may use a combination of binary and ASCII data stored in files. Binary data are typically used for



Equivalent numbers

binary	decimal
00000001	1
00000010	2
00000011	3
00000100	4
00000101	5
00000110	6
00000111	7
00001000	8
00001001	9
00001010	10
....	....

Figure 2-22: Binary representation of decimal numbers.

coordinate information, and ASCII or other codes may be used for attribute data.

Pointers

Files may be linked by file *pointers* or other structures. A pointer is an address or index that connects one file location to another. Pointers are a common way to organize information within and across multiple files. Figure 2-23 depicts an example of the use of pointers to organize spatial data. In Figure 2-23, a polygon is composed of a set of lines. Pointers are used to link the set of lines that form each polygon. There is a pointer from each line to the successive string of lines that form the polygon.

Pointers help by organizing data in such a way as to improve access speed. Unorganized data would require time-consuming searches each time a polygon boundary was to be identified. Pointers also allow efficient use of storage space. In our example, each line segment is stored only once. Several polygons may point to the line segment as it is typically much more space-efficient to add pointers than to duplicate the line segment.

Data Compression

Data compression is common in GIS. Compressions are based on algorithms that reduce the size of a computer file while maintaining the information contained in the file. Compression algorithms may be "lossless", in that all information is maintained during compression, or "lossy", in that some information is lost. A lossless compression algorithm will produce an exact copy when it is applied and then the appropriate decompression algorithm applied. A lossy algorithm will alter the data when it is applied and the appropriate decompression algorithm applied. Lossy algorithms are most often used with image data, and uncommonly applied to thematic spatial data.

Data compression is most often applied to discrete raster data, for example, when representing polygon or area information in a raster GIS. There are redundant data elements in raster representations of large homogenous areas. Each raster cell within a homogenous area will have the same code as most or all of the adjacent cells. Data compression algorithms remove much of this redundancy.

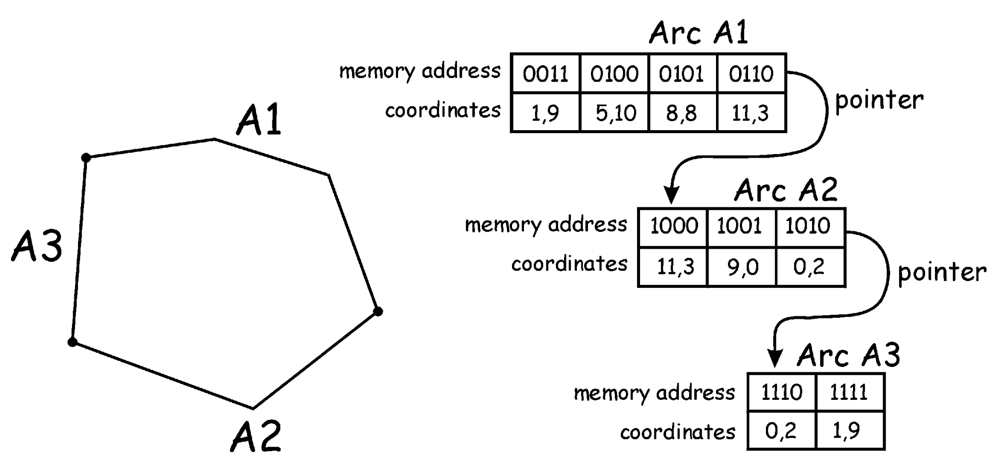


Figure 2-23: Pointers are used to organize vector data. Pointers reduce redundant storage and increase speed of access.

Raster								Run-length codes
9	9	6	6	6	6	6	7	2:9, 5:6, 1:7
6	6	6	6	6	6	6	6	8:6
9	9	6	6	6	6	7	7	2:9, 4:6, 2:7
9	8	9	6	6	7	7	5	1:9, 1:8, 1:9, 2:6, 2:7, 1:5

Figure 2-24: Run-length coding is a common and relatively simple method for compressing raster data. The left number in the run-length pair is the number of cells in the run, and the right is the cell value. Thus, the 2:9 listed at the start of the first line indicates a run of length two for the cell value 9.

Run-length coding is a common data compression method. This compression technique is based on recording sequential runs of raster cell values. Each run is recorded as the value and the run length. Seven sequential cells of type A might be listed as A7 instead of AAAAAAA. Thus, seven cells would be represented by two characters. Consider the data recorded in Figure 2-24, where each line of raster cells is represented by a set of run-length codes. In general run-length coding reduces data volume, as shown for the top three rows in Figure 2-24. Note that in some instances run-length coding increases the data volume, most often when there are no long runs. This occurs in the last line of Figure 2-24, where frequent changes in adjacent cell values result in many short runs. However, for most thematic data sets containing area information, run length coding substantially reduces the size of raster data sets.

There is also some data access cost in run-length coding. Standard raster data access involves simply counting the number of cells across a row to locate a given cell. Access to a cell in run-length coding must be computed by summing along the run-length codes. This is typically a minor additional cost, but in some applications the trade-off between speed and data volume may be objectionable.

Quad tree representations are another raster compression method. Quad trees are similar to run-length codings in that they are most often used to compress raster data sets when representing area features. Quad trees may be viewed as a raster data structure with a variable spatial resolution. Raster cell sizes are combined and adjusted within the data layer to fit into each specific area feature (Figure 2-25). Large raster cells that fit entirely into one uniform area are assigned. Successively smaller cells are then fit, halving the cell dimension at each iteration, until the smallest cell size is reached.

The dynamically varying cell size in a quad tree representation requires more sophisticated indexing than simple raster data sets. Pointers are used to link data elements in a tree-like structure, hence the name quad trees. There are many ways to structure the data pointers, from large to small, or by dividing quandrants, and these methods are beyond the scope of an introductory text. Further information on the structure of quad trees may be found in the references at the end of this chapter.

A quad tree representation may save considerable space when a raster data set includes large homogeneous areas. Each large area may be represented mostly by a few large cells representing the main body, and sets of recursively smaller cells along

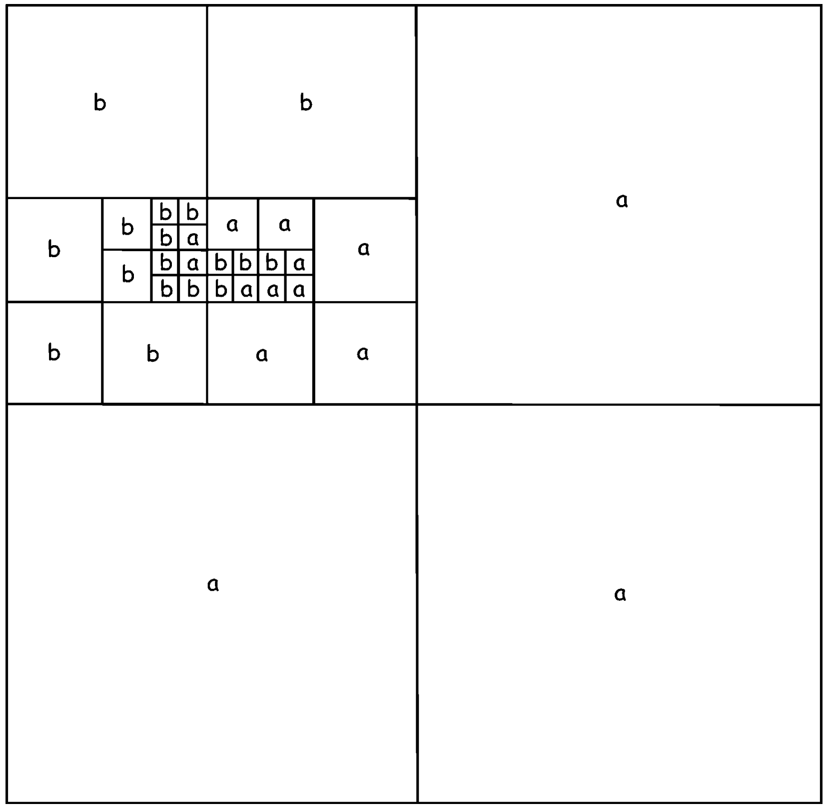


Figure 2-25: Quad tree compression.

the margins to represent the spatial detail at the edges of homogenous areas. As with most data compression algorithms, space savings are not guaranteed. There may be conditions where the additional indexing overhead requires more space than is saved. As with run-length coding, this most often occurs in spatially complex areas.

There are many other data compression methods that are commonly applied. JPEG and wavelet compression algorithms are often applied to reduce the size of spatial data, particularly image or other data. Generic bit and byte-level compression methods may be applied to any files for compression or communications. There is usually some cost in time to the compression and decompression.

Summary

In this chapter we have described our main ways of conceptualizing spatial entities, and of representing these entities as spatial features in a computer. We commonly employ two conceptualizations, also called spatial data models: a raster data model and a vector data model. Both models use a combination of coordinates, defined in a Cartesian or spherical system, and attributes, to represent our spatial features. Features are usually segregated by thematic type in layers.

Vector data models describe the world as a set of point, line, and area features. Attributes may be associated with each feature. A vector data model splits that world into discrete features, and often supports topological relationships. Vector models are most often used to represent features that are considered discrete, and are compatible with vector maps, a common output form.

Raster data models are based on grid cells, and represent the world as a "checkerboard", with uniform values within each cell. A raster data model is a natural choice for representing features that vary continuously across space, such as temperature or precipitation. Data may be converted between raster and vector data models.

We use data structures and computer codes to represent our conceptualizations in more abstract, but computer-compatible forms. These structures may be optimized to reduce storage space and increase access speed, or to enhance processing based on the nature of our spatial data.

Suggested Reading

Batty, M and Xie, Y., Model structures, exploratory spatial data analysis, and aggregation, *International Journal of Geographical Information Systems*, 1994, 8:291-307.

Bhalla, N., Object-oriented data models: a perspective and comparative review, *Journal of Information Science*, 1991, 17:145-160.

Bregt, A. K., Denneboom, J, Gesink, H. J., and van Randen, Y., Determination of rasterizing error: a case study with the soil map of The Netherlands, *International Journal of Geographical Information Systems*, 1991, 5:361-367.

Carrara, A., Bitelli, G., and Carla, R., Comparison of techniques for generating digital terrain models from contour lines, *International Journal of Geographical Information Systems*, 1997, 11:451-473.

Congalton, R.G., Exploring and evaluating the consequences of vector-to-raster and raster-to-vector conversion, *Photogrammetric Engineering and Remote Sensing*, 63:425-434.

Holroyd, F. and Bell, S. B. M., Raster GIS: Models of raster encoding, *Computers and Geosciences*, 1992, 18:419-426.

Joao, E. M., Causes and Consequences of Map Generalization, Taylor and Francis, London, 1998.

Kumler, M.P., An intensive comparison of triangulated irregular networks (TINs) and digital elevation models, *Cartographica*, 1994, 31:1-99.

Langram, G., Time in Geographical Information Systems, Taylor and Francis, London, 1992.

Laurini, R. and Thompson, D., Fundamentals of Spatial Information Systems, Academic Press, London, 1992.

Lee, J., Comparison of existing methods for building triangular irregular network models of terrain from grid digital elevation models, *International Journal of Geographical Information Systems*, 5:267-285.

Maquire, D. J., Goodchild, M. F., and Rhind, D. eds., Geographical Information Systems: Principles and Applications, Longman Scientific, Harlow, 1991.

Nagy, G. and Wagle, S. G., Approximation of polygonal maps by cellular maps, *Communications of the Association of Computational Machinery,* 1979, 22:518-525.

Peuquet, D. J., A conceptual framework and comparison of spatial data models, *Cartographica*, 1984, 21:66-113.

Peuquet, D. J., An examination of techniques for reformatting digital cartographic data. Part II: the raster to vector process, *Cartographica*, 1981, 18:375-394.

Piwowar, J. M., LeDrew, E. F., and Dudycha, D. J., Integration of spatial data in vector and raster formats in geographical information systems, *International Journal of Geographical Information Systems*, 1990, 4:429-444.

Peuker, T. K. and Chrisman, N., Cartographic Data Structures, *The American Cartographer*, 1975, 2:55-69.

Rossiter, D. G., A theoretical framework for land evaluation, *Geoderma*, 1996, 72:165-190.

Shaffer, C.A., Samet, H., and Nelson R. C., QUILT: a geographic information system based on quadtrees, *International Journal of Geographical Information Systems*, 1990, 4:103-132.

Sklar, F. and Costanza, R. Quantitative methods in landscape ecology: the analysis and interpretation of landscape heterogeneity. in: Turner, M. and Gardner, R., editors. The development of dynamic spatial models for landscape ecology: A review and prognosis. New York: Springer-Verlag; 90:239-288.

Tomlinson, R. F., The impact of the transition from analogue to digital cartographic representation, *The American Cartographer*, 1988, 15:249-262.

Wedhe, M., Grid cell size in relation to errors in maps and inventories produced by computerized map processes, *Photogrammetric Engineering and Remote Sensing*, 48:1289-1298.

Worboys, M. F., GIS: A Computing Perspective, Taylor and Francis, London, 1995.

Zeiler, M., Modeling Our World: The ESRI Guide to Geodatabase Design, ESRI Press, Redlands, 1999.

Study Questions

How is an entity different from a cartographic object?

Describe the successive levels of abstraction when representing real-world spatial phenomena on a computer. Why are there multiple levels, instead of just one level in our representation?

Define a data model and describe the two most commonly used data models.

What is topology, and why is it important? What is planar topology, and when might you want non-planar vs. planar topology?

What are the respective advantages and disadvantages of vector data models vs. raster data models?

Under what conditions are mixed cells a problem in raster data models? In what ways may the problem of mixed cells be addressed?

What is raster resampling, and why do we need to resample raster data?

What is a triangulated irregular network?

What are binary and ASCII numbers? Can you convert the following decimal numbers to a binary form: 8, 12, 244?

Why do we need to compress data? Which are most commonly compressed, raster data or vector data? Why?

What is a pointer when used in the context of spatial data, and how are they helpful in organizing spatial data?