CHAPTER 2

MEASUREMENT FRAMEWORKS

CHAPTER OVERVIEW

- Present a scheme to guide measurement of geographic phenomena.
- Provide examples of major measurement frameworks.
- Explain basic principles of two-dimensional topology.

As the discussion of levels of measurement and reference systems in the previous chapter demonstrates, measurement is fundamental to geographic analysis and it depends on rules. Establishing a reference system for time, space, and attributes is not enough. The most basic step in creating a geographic database identifies the objects that can be measured and the nature of relationships between them. Stevens (1946) tried to construct a system based on "assigning numbers to objects according to rules," and many social science disciplines found his scheme helpful. In most situations confronted by these disciplines, the identity of objects was not a complex question. Psychologists study people, economists study businesses, and so on. When dealing with geographic information, however, the nature of the object is not that simple. In fact, much of the diversity in geographic information arises from the objects studied and their relationships. Differences between frameworks explain many of the seemingly incompatible viewpoints within the GIS community as well as many of the technical problems in GIS applications. A set of rules for measurement and relationships between objects will be called a **measurement framework** in this book.

Measurement framework: A scheme that establishes rules for control of other components of a phenomenon that permit the measurement of one component. Geographic information has three components: time, space, and attribute.

Relationship of Measurement Frameworks to Database Literature

In the database literature, the term **data model** applies to the logical structure of entities and relationships. In GIS, however, the term has been attached to a more primitive role of describing representation, discussed in the next chapter. What are termed data models usually developed directly from map display techniques, which are often the final results of a series of operations, each with its own assumptions. Because a measurement framework precedes any choices about the storage or symbolization of the data, it will avoid potential confusion when separated from the issues of representation.

There are a number of ways to develop a systematic description of a **database.** Many collections of data are assembled with little attention to fundamental assumptions; thus, the distinct steps of measurement and representation might be very hard to discern. The database layout may be inherited from some other application or developed to suit technical issues of representation; thus those aspects will be treated in Chapter 3. In the more formal approach of a mathematical theory, a model contains symbols, relationships, and **axioms.** Codd (1981) recognized the same three components in structuring a data model and used the terms object types, operators, and integrity constraints. In a mathematical context, axioms are asserted without proof. Similarly, a geographic database makes some assumptions about the nature of the landscape. These assumptions form the basis for a measurement framework and the subject of this chapter.

A SIMPLE MEASUREMENT FRAMEWORK

One framework for geographic data has been a workhorse of quantitative geography since the 1960s. The *geographical matrix* (Berry 1964) lists places in rows adding columns for attributes of these places (Table 2-1). Structurally, there is no real difference between the geographical matrix and the **flat file** of **cases** and variables in social science statistical packages. Both approaches could be implemented in the matrix metaphor of a spreadsheet. The geographical matrix approach takes the identity of the objects for granted and then attaches attributes for each object. In the case of cities, the definition of each city is open to challenge. The political boundaries used in official statistics often fail to capture the social and economic life of a city. More important, the rows of the matrix simply record different cities as isolated labels for attributes, with no provision for their spatial relationships. One may add additional columns to the matrix for location, but coordinates relate to a spatial reference system with different rules compared to attribute reference systems. Although quantitative geographers, such as Haggett (1965) and Berry in his later work, recognized that geographic objects are not such "independent spaceships floating in the void" (Berry 1973, p. 18), the simpler matrix vision still dominates the view of quantitative geography.

A geographical matrix for cities can be explained in terms of the three elements: entities, relationships, and axioms. Together, these define a measurement framework—a set of rules to structure the process. In the simple matrix form, cities exist and have attributes such as a tax rate and a population. This list of facts hides the relationships and assumptions behind each statement (Figure 2-1). Some attributes, like the tax rate or municipal debt, belong to the corporate entity of the city and apply uniformly everywhere within. Other attributes are not so directly attached. It is much more constructive to recast the measurement of population as a relationship between the city and another class of entities: people. A person can have the relationship "lives in" with respect to a city (Tomlinson lives in Ottawa, Goodchild lives in Santa Barbara, Dangermond lives in Redlands, etc.). The population measurement attached to a city comes from a rule to aggregate these relationships into a number.

Such a simplified framework serves important functions, but each step in the process deserves attention. Various definitions of population can best be described

Data model: In the database literature, general description of sets of entities and the relationships between these sets of entities (Ullman 1982); collection of object types, collection of operators on those object types, and a collection of integrity constraints (Codd 1981). In a GIS, composed of a measurement framework and a scheme for representation.

Database: Structured collection of data with software to provide access in different ways; has a data model, a data structure, and an implementation (representation).

Axiom: A proposition accepted as true without proof; an assumption that is formally recognized.

Flat file: A data structure with a simple, uniform arrangement of values attached to each record, all records (rows) have the same slots (columns).

Case: In statistics, an individual unit of observation. Selecting the unit of analysis (discrete unit of control) establishes the measurement framework for statistically based studies.

TABLE 2-1 Geographical Matrix for Selected U.S. Cities

City Name	*Population 1990*	*% Office Vacancy*	*Debt/Person*	*Rainy Days*
New York	7,072,000	18.1	$4,778	111
Los Angeles	3,485,000	14.3	2,296	35
Chicago	2,784,000	22.1	2,160	114
Houston	1,631,000	19.1	2,430	90
Philadelphia	1,586,000	18.9	2,418	153
San Diego	1,111,000	22.7	1,482	42
Seattle	516,000	15.0	2,074	155

Source: All figures from Statistical Abstract of the United States, 1994 (Washington DC: Government Printing Office); % vacant from Table 1228; percentage vacant for existing office buildings, June 1993; municipal debt in dollars per capita, 1992 from Table 489; average days per year with precipation of .01 inch or more from Table 385.

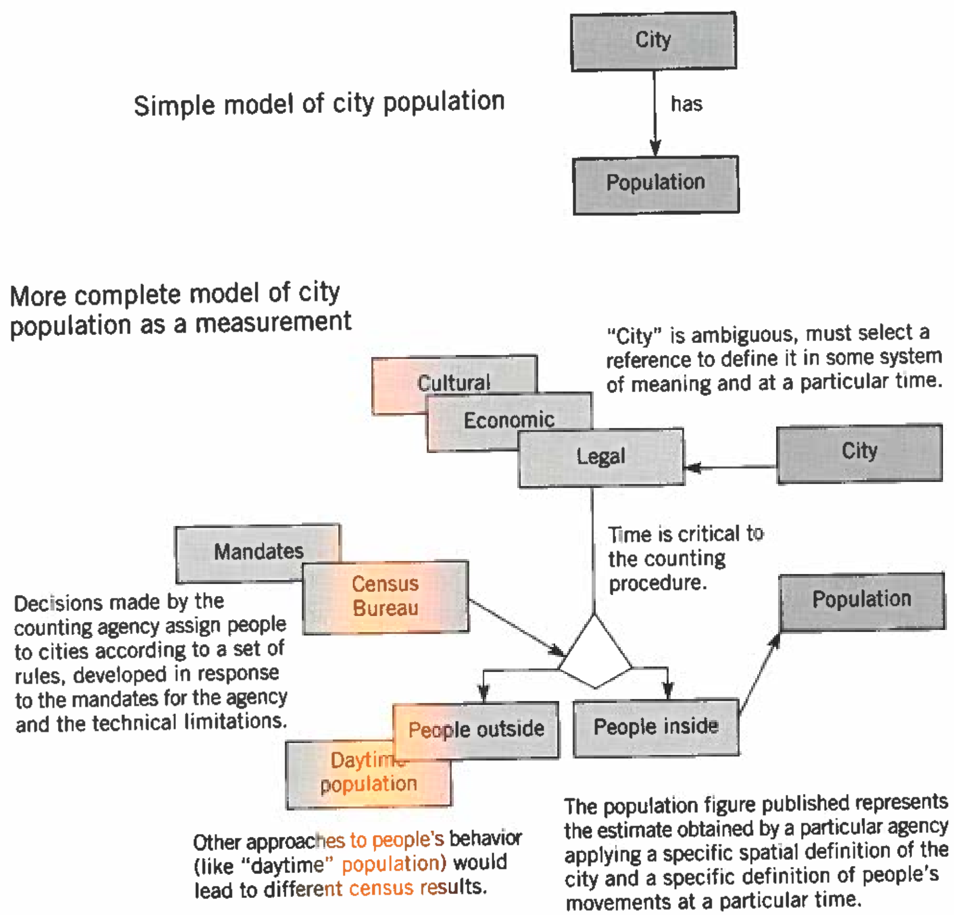

Figure 2-1 Two versions of city data model. In the simple formulation, a city "has" a population, as a kind of inherent property. In a more careful examination, a city is a spatial unit, and people move in and out of the city. A measurement procedure such as a census, applied at a specific time, produces a particular result as a sum of the number of people found in the city. This procedure requires a number of assumptions and definitions.

as assumptions about the relationship between people and cities. For example, we might say that a person can only live in one city at a time. But which city do we count: the place of work, the location at 13:15 on April 1, or the city of most recent voter registration? The choice between such axioms for geographic information is not a mathematical issue; the institutional, social, and cultural context for the information system motivates the basic assumptions. The case and variable format of the simple geographical matrix fails to reveal the geographic questions of time, space, and attribute because it makes everything simply an attribute. Thus, a full understanding of GIS requires a richer set of measurement frameworks.

CONTROL AND MEASUREMENT

Geographic information has three components: time, space, and attribute, as introduced in the previous chapter. In an ideal setting, it seems possible to obtain simultaneous measurements of all three at once. A field ecologist at La Selva Reserve could be carrying an accurate time measurement device, an accurate spatial measurement device, and an accurate instrument for some environmental variable, such as temperature. The thermometer records a temperature at all times; the observer simply tabulates this value alongside a reading from a watch. Current satellite technology can provide a spatial measurement for the location of the thermometer at that time.

Each component could be resolved down to any degree of numerical precision, but here the simplicity begins to break down. The thermometer does not measure an infinitely small point, it operates by coming into thermal equilibrium with the ambient air. The spatial location may not be useful any closer than a single meter, since the air mass in contact with the thermometer hardly varies that quickly. Temperature measurements, to be comparable to weather stations, must be recorded under standardized conditions, ideally in a shaded volume of air at a particular height from the ground. Under a plant canopy or in contact with the soil results are not strictly comparable. The watch on the wrist may be offset from standard clocks, and the value of microseconds might have no meaning to this application anyway. Thus, even something this simple becomes full of little footnotes.

If you had a database full of individual temperature readings, each for a different place and a different time, what would you do with it anyway? You would need to limit the variation in the other components to deal with a chosen one. For example, you would limit the spatial mobility by establishing specified weather stations, or you might decide on a particular time of day for your reading. Thus you could compare the variation over time at one place, or the variation between similar measurements on a single day. While the ideal ability to sample the environment exists, it is almost always constrained to emphasize one component over another.

Sinton (1978) provided a way to understand geographic measurement using three possible roles for the three basic components. In his scheme, in order to measure one component, one of the others has to be fixed while the third serves as **control.** To give an example, a predigital tide gauge has a strip recorder, one pen, and a long roll of paper that can be pulled across a drum (Figure 2-2). The location of the gauge is fixed. The speed of the paper is firmly regulated or controlled. Thus, distance along the paper directly mirrors the passage of time. Below the recording equipment is a float moving up and down with the tide. A mechanical linkage connects the pen to the float, so the pen on the paper records the float height (the intended attribute) as it varies over time. In the digital era, the control would consist of periodic samplings (discrete events in time) that measure the height of the water.

Control: A mechanism of restraint on the variation of a system to permit measurement of one component of a phenomenon while other components vary only within the limits of the control.

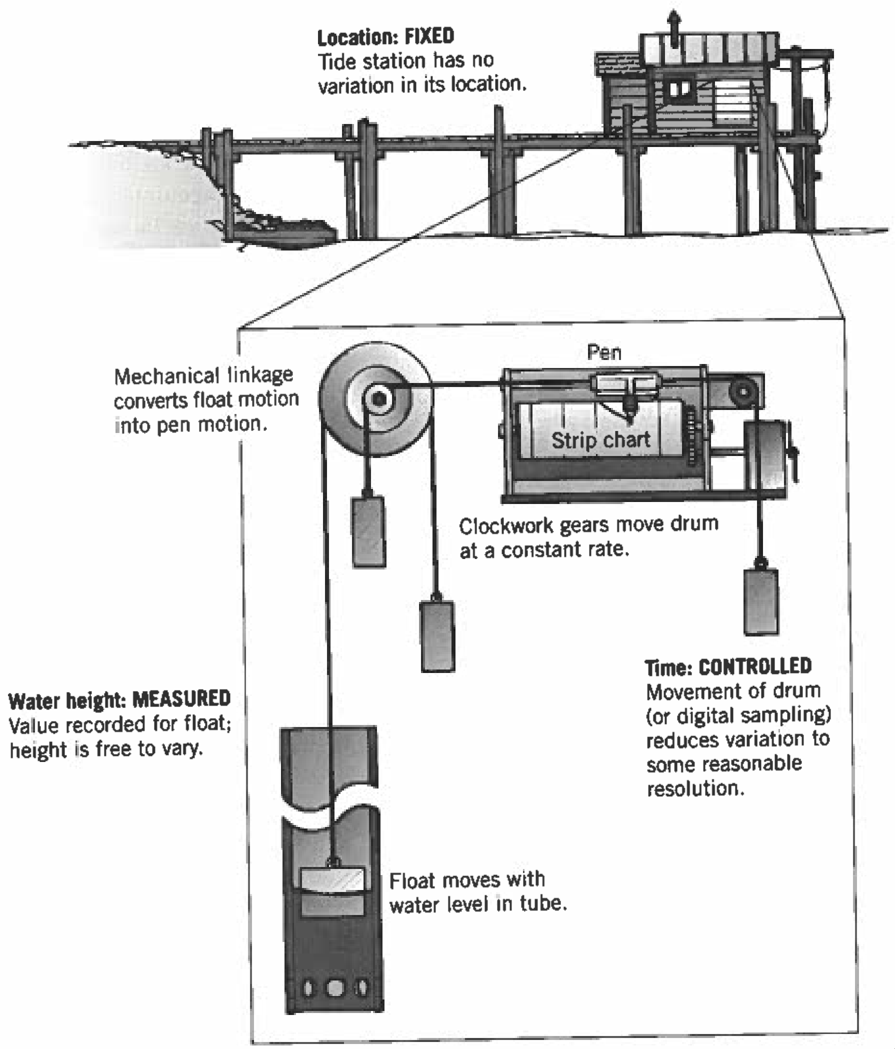

Figure 2-2 Schematic diagram of a tide gauge. Location is fixed; time controls the speed of the paper; water height is measured.

This temporal form of environmental sampling may seem totally obvious; are there any alternatives? Yes. Instead of using time as the control, a sensor could be designed that recorded the exact time that the water passes a certain fixed height. This mechanism could be designed to ring an alarm or to shut a floodgate, as well as to record the time. In this case, height becomes the control and time is measured. While the tide gauge uses a mechanical sensor for its attribute, the circumstances of control would be identical for a temperature measuring device and many other environmental measurements.

The role of control is an inescapable part of obtaining a measurement. The tide gauge example shows that measurement of height can only be accomplished by sacrificing some of the variability in time and vice versa. Control always imposes discrete divisions on one component to serve as a basis for a measurement operation on another component. These discrete divisions constrain the **resolution** of the controlled component. In turn, the resolution sets some bounds on the **accuracy** of the measurement system. These connections begin with the measurement framework, but they become more prominent in understanding the representation process discussed in the next chapter.

Most maps are conceived as snapshots in which the time element is fixed. Fixing time leaves the two components normally described as the basis for thematic cartography: space and attribute. In some abstract sense, we may conceive of a totally continuous **field** with the attribute value changing continuously as we move continuously through the space. Cartographers simplify the mathematical field to a fairly concrete concept of a **surface.** Operationally, a surface must be approximated by a measurement procedure. This chapter covers a range of different methods, starting with the two opposite approaches: control by space and control by attribute.

Spatial measurement relies upon a spatial reference system, as introduced in Chapter 1. The reference system must not be confused with the choice of control. Association of the term *geodetic control* with a spatial reference system can lead to some confusion. Geodetic measurements are used to connect local spatial measurements and a worldwide spatial reference system. Relating the coordinates to a global system does not determine which of the three components will be used as control to permit measurement of the other two.

In some cases, space is used as a control. The classic instance of spatial control involves a systematic spatial sample, such as the **TM** sensor on *Landsat* that records a value for each **pixel** spaced at 30 meters. These pixels might be carefully aligned to the UTM projection, a spatial reference system; but it is the choice to sample every 30 meters that provides the control, not the projection or the ellipsoid. In Table 2-1, the political city limits serve as control for the geographical matrix. In both cases, the

Resolution: Smallest meaningful measurement on a scale; in a geographic context, resolution applies to all components (time, space, and attribute) according to the measurement framework. Not identical to accuracy.

Accuracy: Closeness of a measurement to a value thought to be true; repeatability can be estimated by repeated measurement, measured by variance for continuous measures; accuracy of classification for categories can be summarized by a misclassification matrix when compared to a survey of greater accuracy.

Field: An abstract construct of a mathematical relationship viewed as a spatial structure. In physics, a region of space subject to a force (as a magnetic field).

Surface: A spatial distribution that associates a single value with each position in a plane (technically a field of a single-valued function), usually associated with continuous attributes.

TM: Thematic Mapper, a satellite sensing system with resolution of 30 meters, 16-day repeat cycle, 185-km scene width, and 7 bands of spectral data; launched by NASA.

Pixel: Smallest resolvable unit in an image; an area (usually rectangular) forming a part of a systematic, uniform division of a study area. Contraction of picture element.

attribute conforms to a spatial object—pixel or city. Forms of spatial control will be discussed later in this chapter.

In other cases, the attribute serves as the control. If we have a map of the forests in France, the control is the binary simplification into "forest" and "nonforest." Certainly there are variations between forests, but these distinctions are simplified to provide the control. Given this division, the lines on the map make the best attempt, under the circumstances, to measure the location of that distinction. These boundaries can be measured using UTM as a spatial reference system, without altering the role of the forest category in acting as control.

This general discussion contrasts the opposite extremes. Now, each measurement framework will be developed in detail, starting with the use of attribute as control.

ATTRIBUTE AS CONTROL

There are two basic approaches to using the attribute as the control: *isolated objects* and *connected coverages*. Each of these has two variants (Table 2-2). If a single category is taken in isolation, then the geometric objects are described in isolation, a framework termed *spatial object*. A collection of spatial objects can be developed by a systematic division of a continuous attribute into slices (or **contour** intervals). To conform to cartographic terminology, this will be called an *isoline framework*.

Alternatively, objects may have relationships to each other. A *network framework* recognizes that linear objects have relationships of connectivity. Areas based on exhaustive categorization imply a network of boundaries. This special form of a network will be termed a *categorical coverage*. Each of these frameworks is explained in the following sections.

TABLE 2-2 Summary of Attribute Control Frameworks

Isolated Objects	
Spatial object	Single category distinguishes from void
Isoline	Regular slices of continuous variable
Connected Objects	
Network	Spatial objects connect to each other, form topology (one category or more)
Categorical coverage	Network formed by exhaustive classification (multiple categories, forming an exhaustive set)

Contour/isoline: Contour line; a line connecting points of equal elevation on a topographic surface. An isoline generalizes this concept for any continuous distribution.

Isolated Object Frameworks

Control by attribute is most directly implemented by a single category surrounded by the void, meaning everything else. There are two variants: spatial objects derived from categories and isolines derived by slicing a continuous surface.

Spatial Object Framework In the simplest case, there is a single category, like an airport, to be located. Each occurrence of an airport is effectively surrounded by a void (everything that is not an airport). Because the category reduces to a simple binary yes/no, edges are sharp. Also, because the objects are isolated, objects need no relationship to other objects of the same kind. This spatial object measurement framework lies at the core of many mapping programs and virtually all computer-aided design (**CAD**) packages. This framework allows the spatial description for **features** such as oil wells, navigation buoys, highways, and wetlands using simple geometric **primitives** (point, line, or area) for each object (Figure 2-3). Each object is described as a geometric whole, since it will forcibly occur in isolation. The message of the object framework is: "Here is an airport," "Here is another airport," and so on. In the pure form of this framework, the only relationship is between the object and a position; there are no relationships between objects. Linear objects depart from this to some extent, thereby creating the need for the network framework.

Isoline Framework The spatial object approach can be extended relatively easily to handle a classified version of a continuous attribute. The intersection of a horizontal plane with a surface traces a contour for that elevation value (Figure 2-4). Repeated at a regular interval, the nested contours retain only part of the variation in the original. Each closed loop of a contour becomes an isolated polygon, sharing the geometric form of the object framework, though it is generated by an entirely different process.

Isolines make a clear case for the role of control. The original attribute is continuous, but it is reduced in measurement level to a discrete set of specific values. The variation on the surface between contour intervals is simply lost. It is quite common to treat an isolated contour as a simple category: above or below the threshold. Such simplification risks losing sight of the continuity of the original surface. Given a collection of isolines, the human visual processing system can construct an impression of shapes, but these relationships come from sophisticated image processing in the brain, not from the isolated contour lines themselves.

CAD: Computer-aided design, software packages designed to automate drafting of mechanical drawings.

Feature: Cartographic feature: an instance of a defined class of objects that cannot be divided into objects of the same type.

Primitives: Basic components that are sufficient to build a larger system; the primitives of two-dimensional geometry are points, lines, and areas.

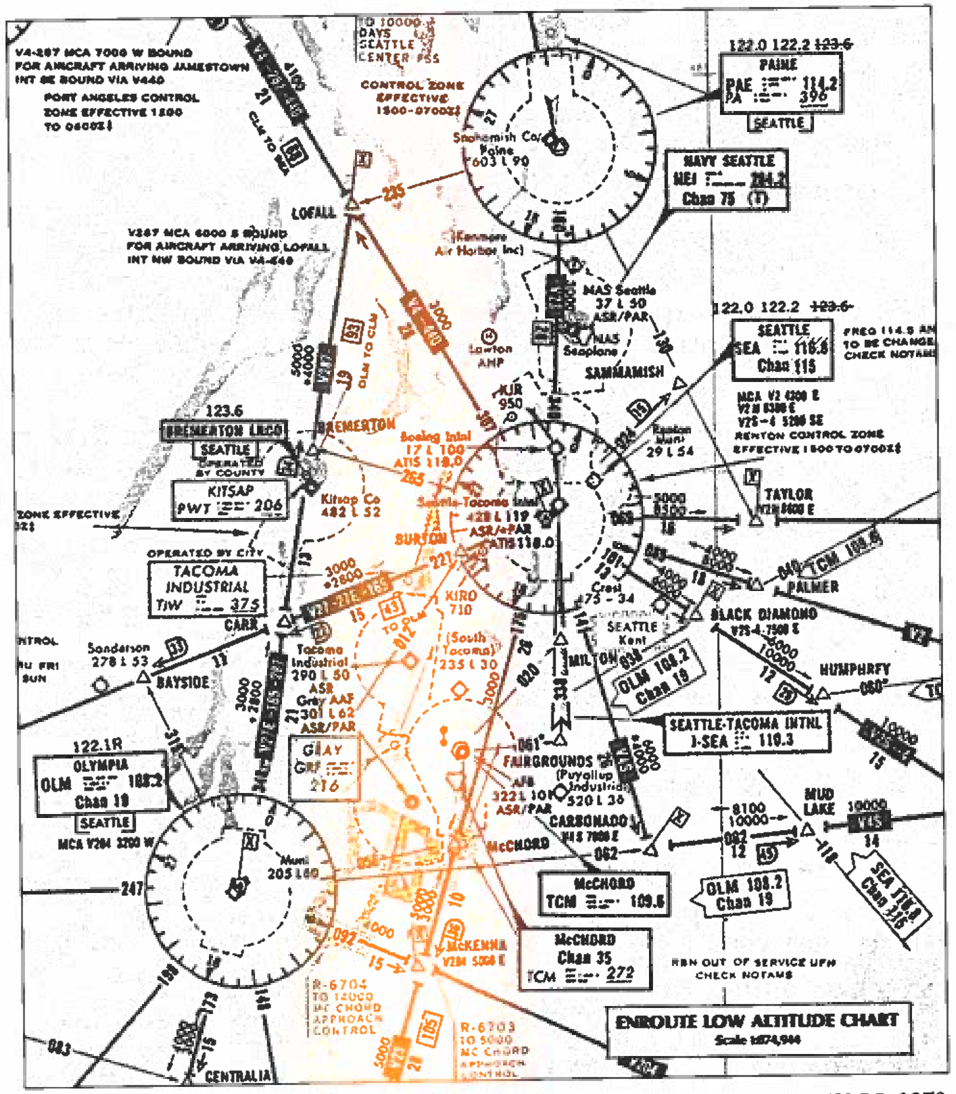

Figure 2-3 Examples of object view: Enroute low-altitude chart. (Source: USGS 1970, p. 304)

Connected Coverage Frameworks and Topological Relationships

Both the previous frameworks assume that objects remain distinct. Points, by definition, cannot merge with other points. Areas in an isolated object framework are also forcibly distinct from other areas of the same type; otherwise, the area would simply get larger. As mentioned earlier, line objects are more complicated. Most single categories of linear objects, such as "road," will connect to each other, forming a net-

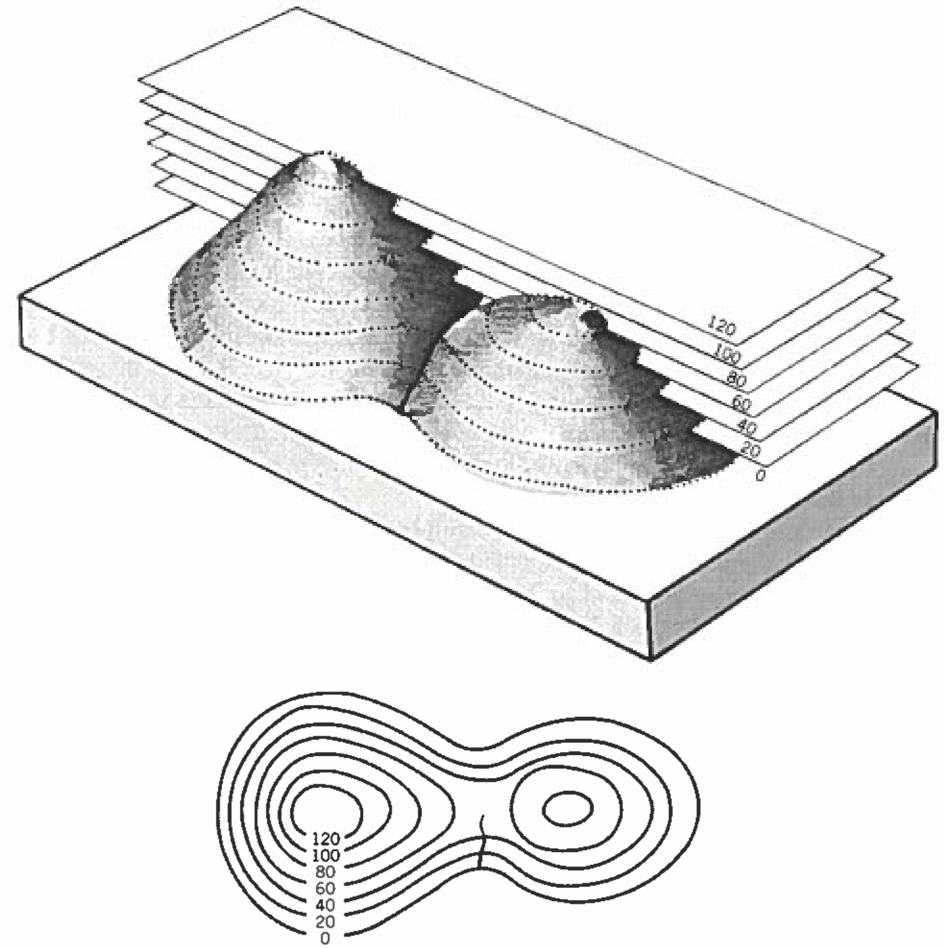

Figure 2-4 Isolines are created by controlling the variation in the attribute to certain values then measuring the location of these slices. (Redrawn from Robinson et al. 1995, p. 509)

work. In analyzing these connectivity relationships, it is important to recognize that streets (lines) connect at intersections (points). The streets also divide the area into a set of blocks or polygons. Thus, drawing lines creates points and areas as well. An isolated object framework does not recognize these relationships and thus misses much of the spatial structure of a network.

The geometric roles of points and lines and polygons can be explained most simply in terms of **topology.** Topology, as used in cartography, concerns those characteristics of geometric objects that do not depend on measurement in a coordinate sys-

Topology: A branch of mathematics concerned with those properties of geometry that are independent of distance measurement and are unchanged by any deformation that will not fold or tear a surface.

tem. The simple network formed by streets on a plane has played a critical role in the development of geographic information technology.

Topological relationships are built from the connections and contiguities of objects with different dimensions. An area (a two-dimensional entity) is surrounded by a series of boundaries (one dimensional) with adjacent areas. In turn, the one-dimensional lines begin and end at junction points (zero dimensional) where boundaries converge (Figure 2-5). Rather than treating each of these relationships as a special case, topology recognizes the common function of *boundary*. In place of informal terms, each software system requires a carefully chosen implementation of these basic principles. This text uses the terminology selected for the Spatial Data Transfer Standard. In these terms, **nodes** bound **chains** and chains bound **polygons.** (Note: Various software packages use *arc* or *edge* or *segment* for chain.) From these direct relationships, more complex ones can be built; for instance, the adjacent polygon is the other object bounded by each bounding chain. The *qualitative* relationships of connectedness and contiguity are thus more fundamental than the *quantitative* properties of length and area.

Some topological relationships need careful explanation. A closed line in the isolated object framework is frequently called a "polygon," but this line acts as a boundary of an area, not the area itself. In an isolated approach, there is no way to know if there is a hole inside the area. The terms for cartographic topology (Figure 2-5) are designed to handle these tricky situations. A polygon is an area that must be bounded

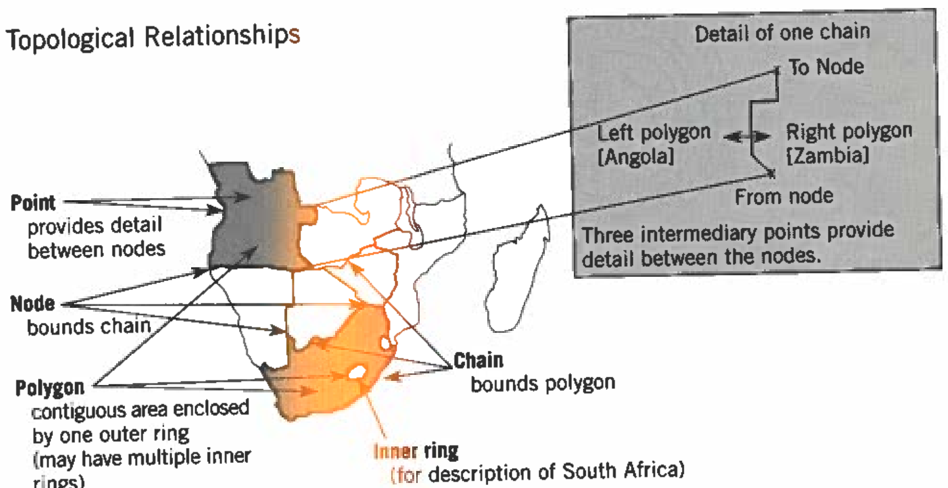

Figure 2-5 Terminology for vector data model, based on Spatial Data Transfer Format. Relationships to other primitives create a topological structure.

Node: A zero-dimensional object that is a topological junction (or endpoint).

Chain: A set of nonintersecting line segments connecting a "from" node to a "to" node and separating specific left and right polygons.

Polygon: An area (bounded continuous two-dimensional object) consisting of an interior area, one outer ring, and zero or more nonintersecting nonnested inner rings.

by one **ring** (its outer ring). In the simple case, the outer ring suffices, and the ring looks like an isolated object. If there are holes inside the area, they are represented by additional *inner rings*. In some cases such as the land–water coverage of a glaciated region, there can be thousands of inner rings in a single polygon. The area inside the inner ring is not a part of the enclosing polygon, so there is no need to construct infinite recursions of nested structures. Figure 2-6 shows a series of maps of Isle Royale National Park in Lake Superior. Lake Superior is one polygon with a number of inner rings for islands. Isle Royale is one polygon with many inner rings, one of them for Siskiwit Lake. Siskiwit Lake, in turn, has an inner ring for Ryan Island, at the most detailed scale. Ryan Island is the biggest island in the biggest lake in the biggest island in the biggest lake in North America. Each of these polygons has

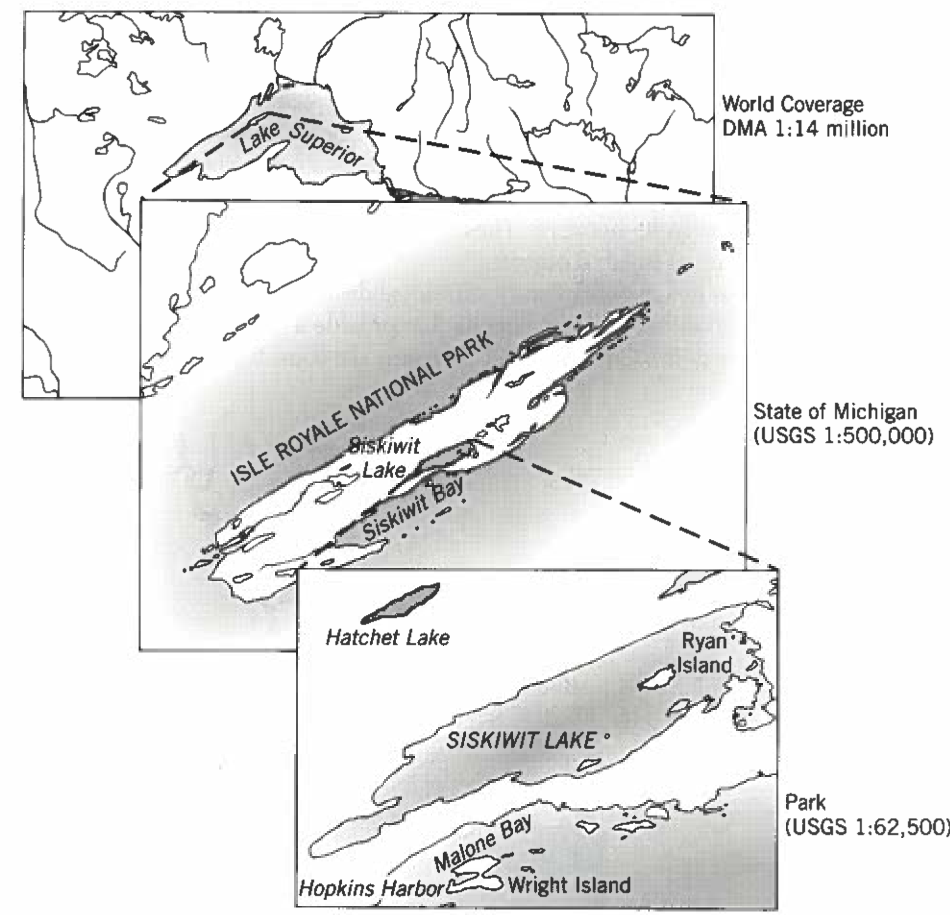

Figure 2-6 Nested inner rings: Ryan Island in Lake Siskiwit in Isle Royale in Lake Superior in North America.

Ring: A sequence of nonintersecting chains that close.

attributes (such as land or water), but there is no topological need to record how deeply nested the inner rings are because the polygon is defined by being continuously connected, not based on the attribute of land or water. All the land may belong to the state of Michigan and to the national park, but these groupings are political not geometric.

The relationships of topology apply to any geometric information, whether these interactions are recognized or not. Checking topological integrity provides a powerful means to verify data quality, which is developed in the next chapter. Despite the commonality of topology, two distinct measurement frameworks emphasize different aspects of these relationships. A network framework focuses on the connectivity of linear elements by themselves. A coverage framework uses a linear network of boundaries to define a set of contiguous areal units. Both of these frameworks, though they are unified by a similar topological model, make different assumptions about measurement.

Network Framework A network framework is based on identifying a particular category, much like an isolated object framework, but the network recognizes the interaction of the identified objects in a coherent structure. A category such as "river" or "road" is still surrounded by the void, but the meaning of each requires connection to other elements in its network. These relationships require a more comprehensive approach than an isolated object.

The relationships in a network create additional distinctions. Some networks can be treelike (dendritic) if they have no circuits that provide a circular path back to the original node (Figure 2-7a). Conventionally, streams are considered to fit this model,

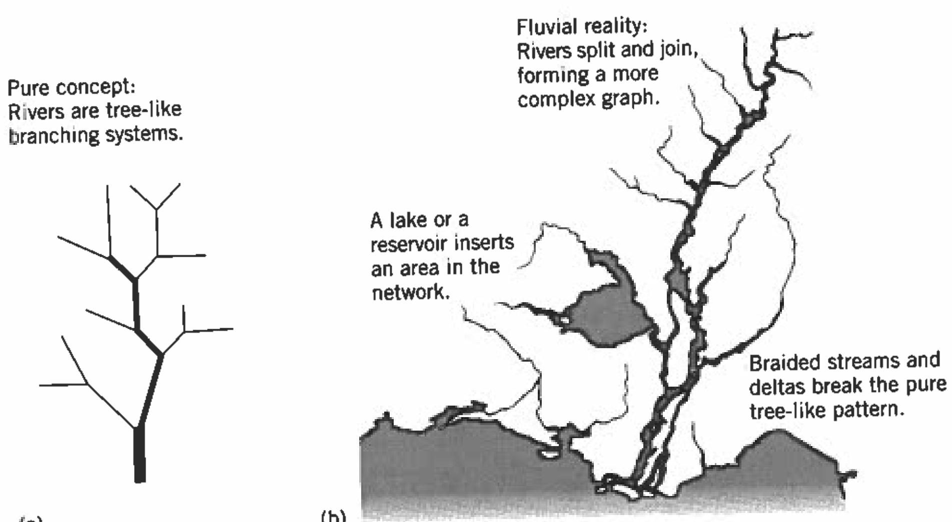

Figure 2-7 Comparison of pure forms and geographic application I—Dendritic networks: (a) Pure dendritic model exhibits tree structure; all branching in one direction; (b) river systems may include cycles, and branch in both directions.

but there are all sorts of exceptions in practical application (Figure 2-7b). Lakes and reservoirs form areas that do not behave as simple points in a tree network. There are also stream networks that diverge into deltas. At a detailed scale, braided stream channels, with islands inside the stream bed, become most confusing to the assumption of treelike behavior.

The model of a **planar graph** applies to most road networks, but the complexities of overpasses, tunnels, one-way streets, and various three-dimensional structures violate assumptions of planarity (Figure 2-8). A highway network requires a nonplanar graph model that relaxes the strict interpretation of some nodes. Nevertheless, topological relationships are still required to ensure connectivity throughout the structure, even if it is not on a single plane.

Categorical Coverage Framework The other connected coverage framework, the **categorical coverage,** uses another form of control by attribute (Chrisman 1982a; Frank et al. 1997). Whereas the spatial object approach depended on a single category surrounded by the void, this framework confronts the problem of multiple categories. A set of mutually exclusive categories can be used to carve up a region so that all the region belongs in one and only one category. The discrete nature of the categories provides the control, differentiating a categorical coverage from the meth-

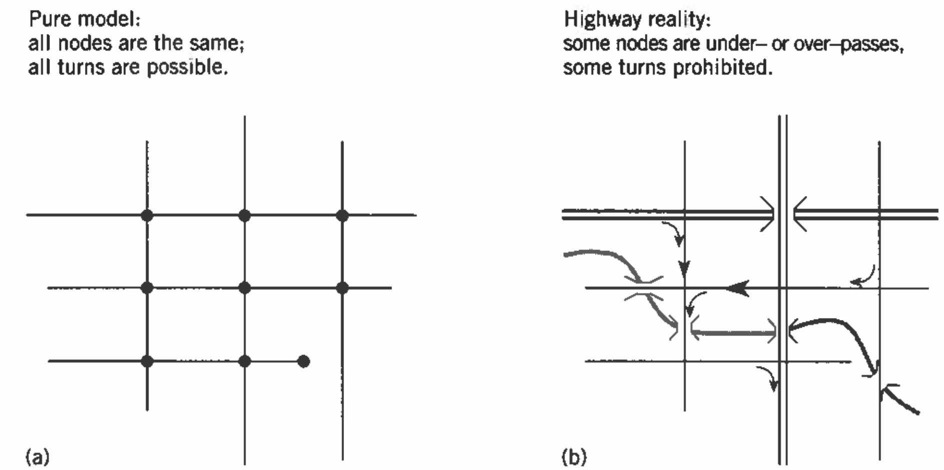

Figure 2-8 Comparison of pure forms and geographic application II—Cyclic graphs: (a) Planar graph model permits cycles, but all intersections are the same; (b) most highway systems are built on the earth's surface, but some connections bypass each other in the third dimension.

Planar graph: An arrangement of nodes and lines such that the lines intersect only at nodes, thus remaining embedded in a plane (or a surface topologically transformable onto a plane).

Categorical coverage: An exhaustive partitioning of a two-dimensional region into arbitrarily shaped zones that are defined by membership in a particular category of a classification system.

ods of surface measurement that provide a continuous value at all points. Because the different categories must abut, a boundary is required to separate them. Thus, each boundary measures the location of the transition between a specific pair of categories. The topological model applies particularly to this framework.

For example, a network of boundaries distinguishes a set of land use categories around Cwmbran in Wales (Figure 2-9). The basic logic of this land use map started with the list of classes, serving as control. This particular list was derived from the Anderson codes (Anderson et al. 1976), with specific interpretations for the British landscape. Each point on the map was placed in the category that fit best, within certain limitations of resolution. Each boundary line acts as the break between the adjacent categories.

The research literature on geographic information is full of challenges to the measurement assumptions made in constructing such categorical coverages. Some of these come from the mismatch between Stevens' view of nominal categories and the

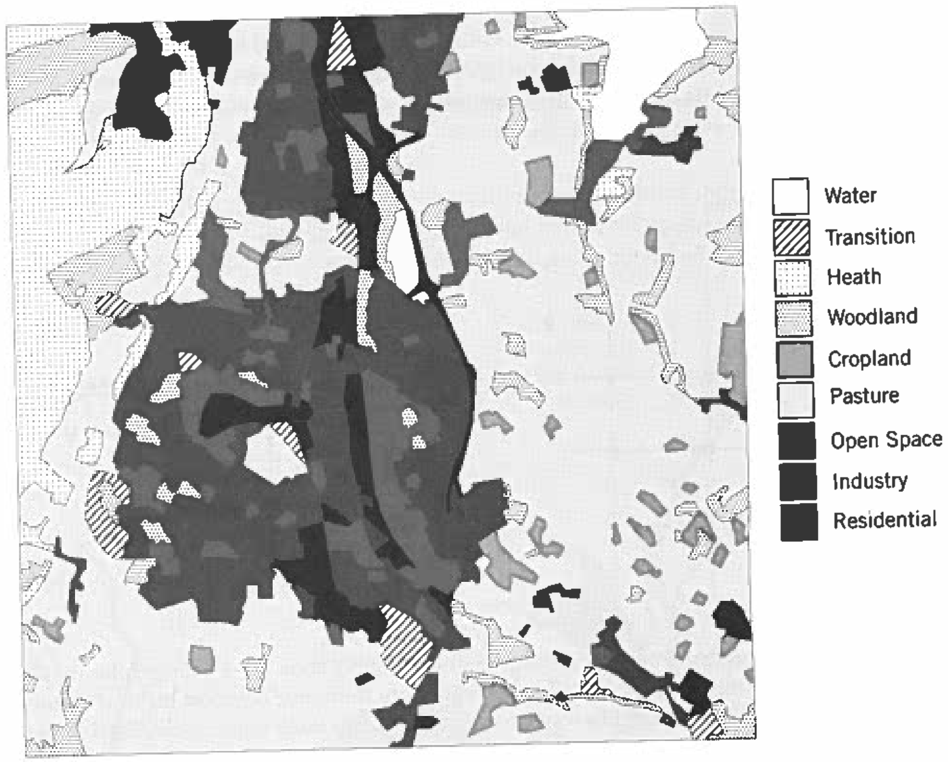

Figure 2-9 Categorical coverages partition the whole plane into an exhaustive set of categories. Example shows land use for Cwmbran, Gwent, UK, during May 1981. Region covered is 8 × 8 km on the UK National Grid. Land use classification by Chrisman (1982a) using field methods compiled on OS 1 : 25,000 topographic map ST 29/39.

actual interpretation of land use from prototypes (mentioned in Chapter 1). Many of the boundaries in Cwmbran are quite sharp, where a land use category stops at a fence or a property parcel boundary. Some boundaries at this scale are rather wide because they follow roads or hedges. Some categories in the system are less well defined, such as *heath*, which represents various vegetation types including gorse, bracken, and tundralike sedges. The transition from improved sheep pasture to heath may not be sharp. In addition, the process of making this particular map was far from exact. I sketched some of the lines in pencil onto a copy of the 1 : 25,000 topographic map. These imperfections are quite typical in implementing the categorical coverage framework. A categorical coverage intentionally simplifies by choosing a single category to represent each location. This framework is common in many forms of land inventory such as soil surveys, forest stand mapping, and land use/land cover mapping. The representation issues discussed in the next chapter will analyze the generalization inherent in geographic representations.

SPATIAL CONTROL

To handle a surface with continuous measurements, another kind of measurement framework is required. Attribute-controlled frameworks presented earlier do not offer direct tools to handle continuous attributes. The traditional contour map limits the information to the position of selected elevations, not the full continuum. In a sense, positions on a surface are less critical than they are in the object-based frameworks because any point on a surface can be measured. Ideally, a surface takes on continuously varying values—an infinite number of values between any given pair of points, no matter how close. Of course, it is impractical to measure each of these infinitely many points; a subset of points must be used to characterize the variation in the rest. A spatial control framework, then, controls spatial position to obtain measurements of the attribute (the height of the surface, or any other attribute distribution).

Several distinct possibilities exist to obtain a measurement of a continuous attribute. An ideal field can be observed at a point, a location with no extent. We could conceive of moving an ideally tiny thermometer around and recording the value obtained at each sampling point. In practice, though, instruments have some spatial extent. At the other extreme from the pure point, a sample could be an average or a sum over an area as large as the spacing between samples. For example, a satellite sensor records the number of photons in a particular wavelength for each position (cell or pixel) it observes. If the cell is small enough, there will not be much variability within the cell, and any rule would tend to come up with the same value. As cells become coarse, the distinctions between the rules become more critical.

Just as attribute control subdivided into a number of distinct frameworks, spatial control has a number of variants. These alternatives can be organized first according to whether they use points or areas, then based on the rules applied (Table 2-3).

TABLE 2-3 Summary of Spatial Control Frameworks

Point-based Control	
Center point	Systematic sampling in regular grid
Systematic unaligned	Random point chosen within cell
Area-based Control	
Extreme value	Maximum (or minimum) of values in cell
Total	Sum of quantities (e.g., reflected light) in cell
Predominant type	Most common category in cell
Presence/absence	Binary result for single category
Percent cover	Amount of cell covered by single category
Precedence of types	Highest ranking category present in cell

Point-based Frameworks

A point-based measurement does not require much consideration about measurement rules. The main issue concerns how to choose the points. There is one primary option—center point—and some other possible techniques rarely encountered in practice.

Center Point Framework The purest form of a space-controlled method records the measurement at a regular lattice of points. If drawn as a grid of parallel lines, the point samples can be taken at the intersections (Figure 2-10), or these points can be seen as a center point of the cell. This method could also be labeled "systematic aligned" (Berry and Baker 1968) because the points are all lined up. The center point system creates a regular arrangement of points and applies a simple rule at each point.

Digital Elevation Matrices (**DEM**) are based on this framework, though they may not be measured originally as point samples. Some form of interpolation may be involved to produce the point values. This topic is covered in Chapter 9.

The center point measurement framework may also be applied to measure categorical attributes. In principle, the category at the point is recorded, though it may be hard to determine certain categories at an infinitely small point. For instance, if the point falls on a leaf of a tree, does that imply a forest? The tree could be in a garden of a residence, in a parking lot of a huge factory, or in many kinds of nonforest land use. The Swiss Arealstatistik project conducted its land use inventory based on a 100-meter spacing of sampling points. Despite the point sample, there is usually an area component to land use determination. The Swiss Federal Bureau of Statistics (1992) developed a rule book to examine the land use in the vicinity of the sample point. Figure 2-11 shows one of the rules used to distinguish two forms of agricultural land. Large fields that can support mechanical agriculture belong in category 81. If obstructions to agricultural machines occur within 50 meters of the point, the sample point is downgraded to the lower quality category (82). Thus, in practice, point-based methods may actually borrow some of the more complex rules from area-based methods (discussed below).

DEM: A framework for recording spot elevations in a regular rectangular grid (matrix); an acronym originally created from Digital Elevation Model at the U.S. Geological Survey. To avoid ambiguity, DEM will be used exclusively for a spatially controlled framework, so it can be read "matrix."

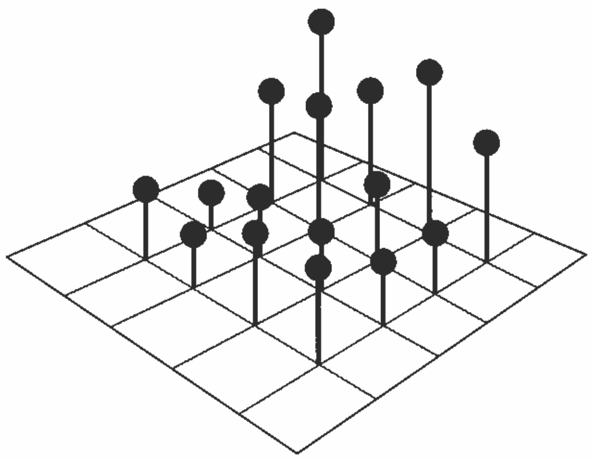

Figure 2-10 Point-based space-controlled measurement framework: Attribute value recorded at a regular lattice of points.

For both continuous and categorical attributes, the spacing of the grid may interact with the features of the landscape. For instance, in the American Midwest, the landownership and road networks are laid out on a rectangular grid following the Public Land Survey System. The rural roads are very likely to occur at one-mile intervals. Consider a regular grid laid over this terrain with the axes oriented north–south and east–west. If sample points are spaced every mile, then the chance of hitting a road at some sample point is totally dependent on the location of the initial point (Figure 2-12). If the initial point misses the road, then all the other points will avoid the roads. Not all landscapes are as rigorously rectangular as the roads of Adair County, Iowa, but there are periodic elements to many land systems.

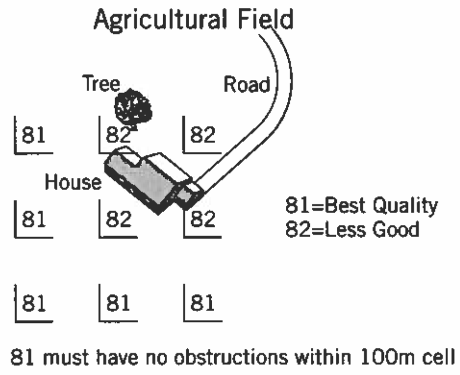

Figure 2-11 Example of a rule to classify land use in the vicinity of a point sample. Drawing simplified from Category 81 Günstiges Wies- und Ackerland & 82 Übriges Wies- und Ackerland (Swiss Federal Bureau of Statisics 1992).

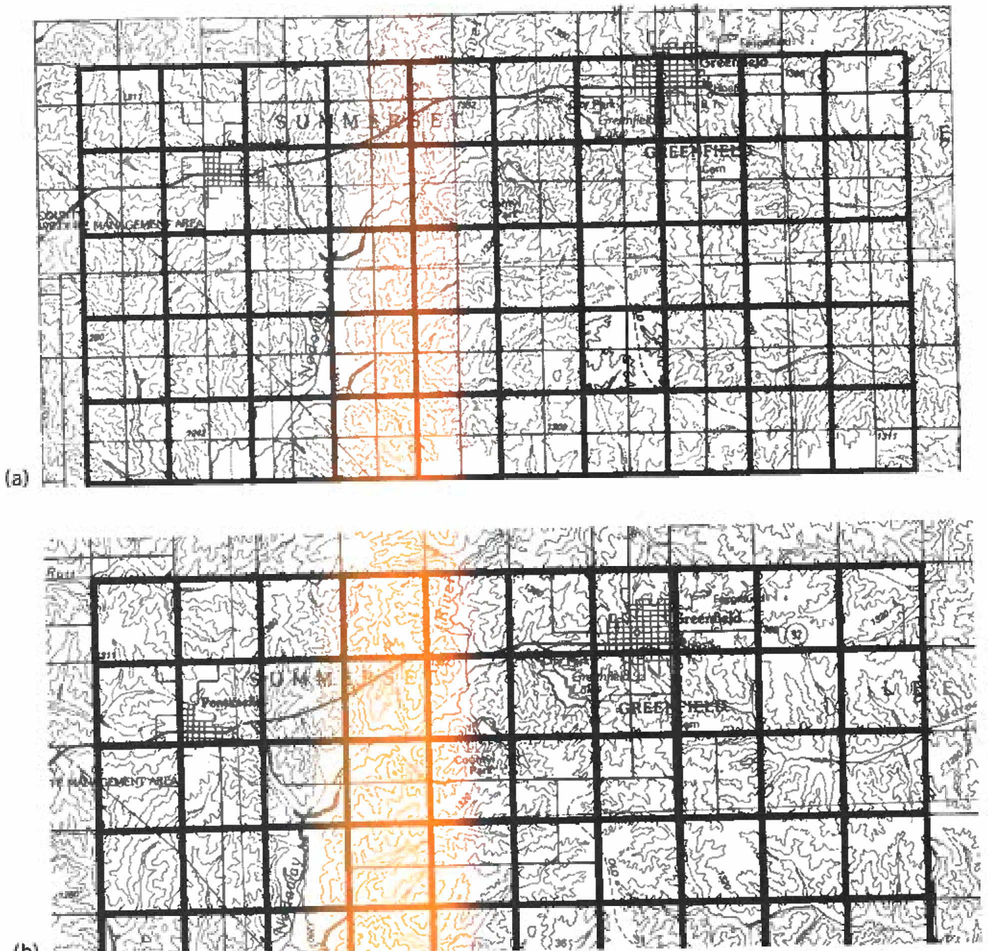

Figure 2-12 Interaction between regular point sampling and regularities in the landscape. Example based on USGS 1:100,000 topographic map 41094-C4-CF-100 for Adair County, Iowa. Grid spacing of 1600 m approximates the spacing of section lines of the Public Land Survey. (a) Initial point located in center of section rarely falls on a road and (b) initial point on road intersection often falls on road.

Systematic Unaligned Sample Theoretically, a sample of points that is not so rigidly aligned would provide a more robust description of variation over the region. Random location of the point within the cell would respond more flexibly to the periodic landscape of Adair County. However, a *systematic unaligned* sample is rarely, if ever, used for mapping. This form of spatially stratified sampling has been used to obtain reliable overall statistics for a region. For continuous attributes, the irregular spacing would complicate many vital neighborhood operations (such as slope calculation, presented in Chapter 7).

Area-based Measurement Frameworks

A regular system of spatial control can also be seen as an exhaustive partitioning into regular geometric figures (a *tessellation*). In most cases, the basic cells are rectangular, or nearly so. (Satellite sensors see trapezoids due to the motion of the platform relative to the earth.) Systems of equilateral triangles or hexagons have been proposed, but they are not used in very many applications. For ease of discussion, the spatial unit will be called a *cell*. Within this spatial control, the measurement of the attribute depends on the attribute values present within the cell. The area-based frameworks apply different rules.

Extreme Value One simple rule takes the highest (or lowest) value available inside the cell. For example, on aeronautical charts, there is a lowest flight altitude given for rather crude cells (Figure 2-13). This value is based on the safe clearance over the

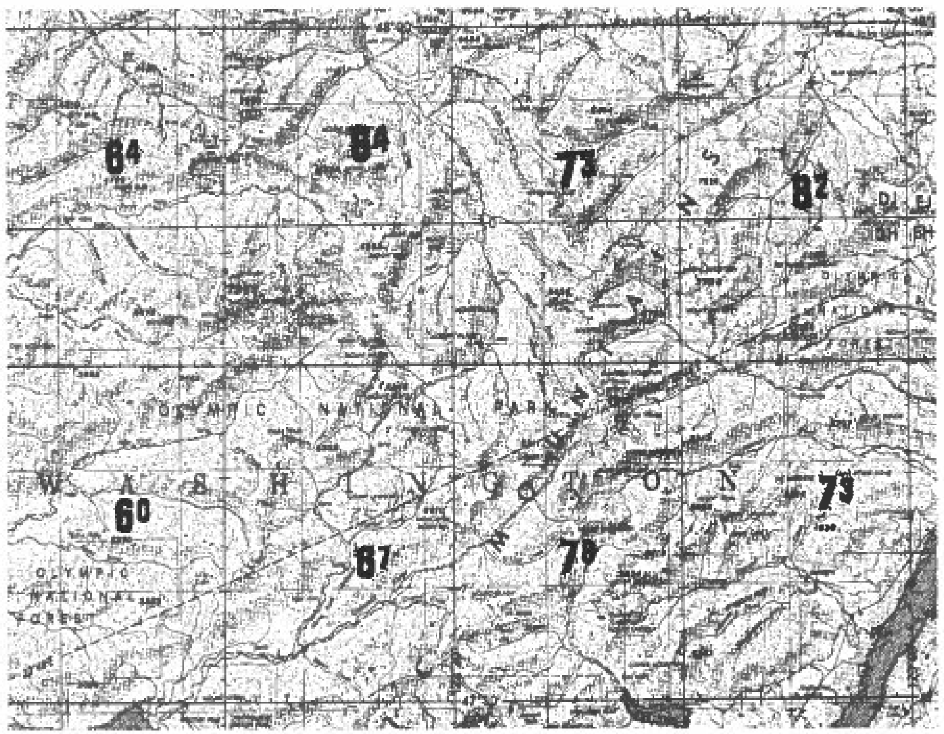

Figure 2-13 Example of an area-based space-controlled measurement framework for elevation data. Aeronautical chart shows minimum safe flying altitude based on maximum obstruction within a cell (in this case, 15-minute quadrangle). Taken from DMA Joint Operations Graphic, published at 1:250,000. Figures given in 1000 foot units with superscript for hundreds: 8^4 means 8,400 feet.

highest obstruction in the cell. For flight safety this is a reasonable rule, but for other purposes it overestimates the elevation. Extreme value is an example of a rule that can be applied to ordinal and higher levels of measurement because they establish an ordering.

Total Value Compared to the extreme value rule that simply selects one value, other rules can use all the values available to contribute to the final result. Various arithmetic functions can be applied to measurements at the ordinal or higher levels, though there must be some assumptions about spatial resolution to identify the candidate values.

Measurement hardware often imposes the rule for assigning a value to a cell. A satellite sensor records the total number of photons detected over a certain period while passing over a certain cell (Figure 2-14). This is an area-based value, not a spot reading. The total photons reflected or emitted depend on the mixture of materials on the surface, intervening atmosphere, and other factors. Certain highly reflective objects can contribute the bulk of the light, even though they cover a small portion of the cell. These sensors actually use time as the control because they sum the energy as the satellite moves. Coupled with the geometry of the flight path, the time sample converts to a ground position, though it is not easy to identify the cell on the ground. For practical purposes, satellite images have to be treated as area-controlled sources.

Predominant Type For categorical attributes, the rules of arithmetic do not apply to the attribute values. Instead, there are a number of methods to characterize the distribution in a cell. All of them depend on measuring the amounts of the various categories within the cell. This information is assembled, the cell value is decided, and most of the detailed information is discarded.

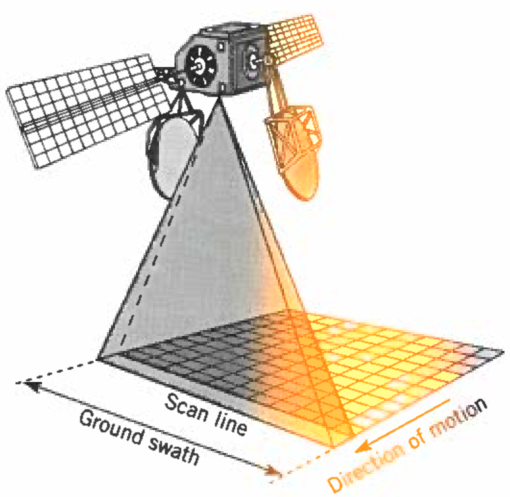

Figure 2-14 Satellite sensor records light reflected from an area.

The *predominant type* rule assigns the cell to the largest category within the cell. This amounts to the *mode* of the distribution within the cell (the most frequent category). When the cells are fine and only one category appears in most cells, the choice of rule will make little difference. While predominant type seems to ensure the best result for the particular cell, this rule will underrepresent categories that tend to be thin relative to the cell width. Predominant type is the closest approximation to a categorical coverage, given the choice of spatial, not attribute, control.

Presence/Absence and Percent Cover For categorical attributes, an isolated object approach is an alternative to comprehensive coverage. Similarly, with spatial control, there are frameworks for isolated as well as comprehensive viewpoints. If a particular category has been selected, the cell can record whether or not that category is present. Such a presence/absence rule ignores all other categories, a step that may be necessary to encode linear networks such as streams or roads without losing them in surrounding categories. Separate grids for each category can be stored in binary layers as a *bit map*. Of course, there will be no way to tell which category was more important within a cell that contained multiple categories.

One way to salvage more information would be to record the percent of cover, that is, an estimate of the proportion of the cell covered by that category. This measurement of graded membership (see Table 1-3) retains more information about the cell, but without the spatial distribution. The percent cover measurement framework applies particularly to coarse cells, such as the one-degree latitude–longitude resolution used for world soil and wetland data (Matthews 1993). The spectral mixture approach to remote sensing (Adams et al. 1986) also uses graded membership. Rather than classifying a cell into one category or another, this procedure estimates the mixture of various known types for each cell.

Precedence of Types If categories of a coverage can be ranked by importance, then another coding method could select the most important category within the cell—*precedence of types*. For example, one natural precedence occurs in treating the highway network, which has an ordering based on importance and traffic. A cell is usually coded for the highest class of road present. Once the cell has been given its single value, it is not possible to reorder the priorities.

Although spatial control simplifies the measurement process, there are still many decisions to make in choosing what value to record. Much of the regularly sampled geographic data currently available comes from automated equipment such as satellite sensors or scanned aerial photographs. The measurement rules for these situations are built into the hardware logic or the postprocessing of these data streams. These rules will influence the use of these sources.

RELATIONSHIP CONTROL

So far, the presentation of measurement frameworks reinforces the opposition between the attribute control and spatial control methods. Sinton's (1978) original purpose was to show the different motivations behind these two, but the choice of control by either space or attribute does not exhaust all possibilities.

When controlling space or attribute, the variation in that component is deliberately limited to discrete units. These units permit measurement in the other component. Another way to make a measurement is to define the unit through relationships between objects. This creates a new class of measurement frameworks, which includes some alternatives that do not fit into the orthodoxy of spatial or attribute control. These frameworks will not fit very neatly into software developed around the classical measurement frameworks.

Measurement by Pair

Measurements can apply to pairs of objects (Goodchild 1987). For example, trade statistics measure the flow of products and finance between countries (Table 2-4) but not the physical path taken by these flows. An interaction table has as many cells as the number of sources times destinations. The measurement does not belong to either the source or the destination but to the combination. Thus the control comes from the relationship between two objects.

These interactions have formed a major topic in economic geography for many years (Ullman 1954), but they are hard to represent with simple object–attribute models and to portray with standard cartographic techniques (Figure 2-15). These measurements could be attached to lines between the two endpoints, but these lines do not necessarily follow the geometric path on the ground. Since the interaction pairs do not have a direct spatial meaning, current GIS software provides few facilities to manage them.

Triangulated Irregular Networks (TIN)

Another example of a relationship control framework is the system of terrain representation called triangulated irregular network (**TIN**). A TIN provides a way to represent a surface (Peucker and Chrisman 1975) without controlling either elevation or space as one must with the isoline or center point frameworks, respectively. Each triangle in a TIN connects three neighboring points so that the plane of the triangle approximates the surface (Figure 2-16). A TIN can be formed from a scattered collection of points, but it works best when they include surface-specific points, such as peaks, passes, and samplings along ridgelines and stream courses. These points are measured using an object framework that provides a spot height measurement. The triangle establishes a relationship between three points, simplifying that portion of the surface to an inclined plane with a particular slope (see Chapter 7). The whole region is covered by triangles, so every point can be associated with an elevation value.

A TIN is not controlled by an attribute value, as in the isoline framework. Nor is it spatially controlled as in a grid of points. Because a TIN uses such a distinctive method of encoding elevation, it is not surprising that TIN data are hard to integrate with other more traditional systems of control. TIN is often presented as a data structure, a system of representation, but it must be recognized as a distinct form of measurement as well. Chapter 7 discusses TIN representation and surfaces in greater detail.

TABLE 2-4 Example of Measurement for Pairs of Objects

Exports From/To	*North America*	*Europe*	*Japan*	*Australia & N.Z.*
North America	22,550	10,954	4,592	914
Europe	11,056	101,485	2,673	961
Japan	8,954	6,016	0	680
Australia & N.Z.	495	644	1,015	349

Average monthly trade between countries belonging to the Organization for Economic Cooperation and Development, by region, 1992. In millions of US $.

Source: OECD Statistics Directorate: February 1995 *Monthly Statistics of Foreign Trade.* Each region contains multiple countries, except Japan, thus the diagonal (shaded) shows export trade between countries within the region.

TIN: Triangulated Irregular Network: a system of terrain representation that builds triangular facets to connect point heights. The points and triangles are chosen to represent a surface within some limits.

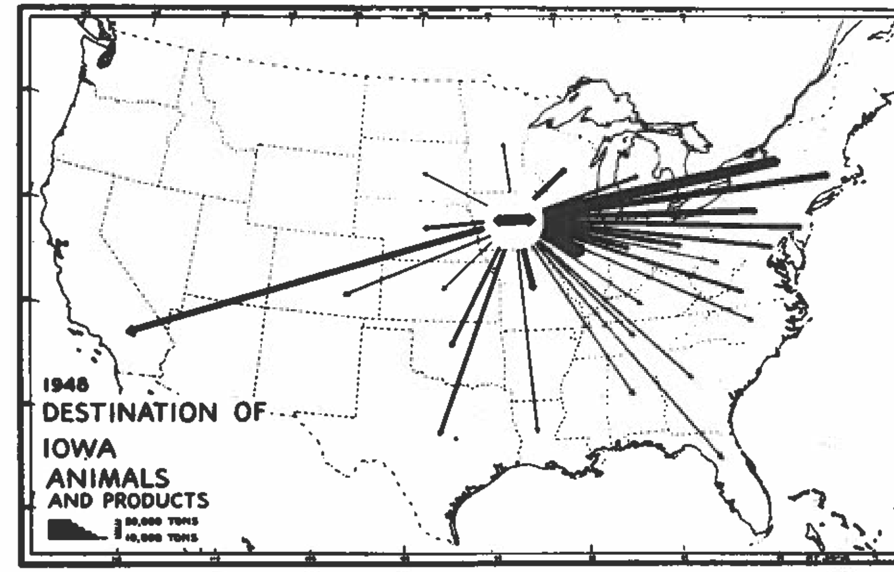

Figure 2-15 Example of cartographic treatment of commodity flow. Trade in animals leaving Iowa by rail in 1948. Reproduced from Map 5.3 in Ullman (1954).

COMPOSITE FRAMEWORKS

Each of the measurement frameworks described so far abide by Sinton's (1978) sequence in which the control precedes the measurement. Applying this simple scheme can run into many contradictions in actual practice. Measurement is more

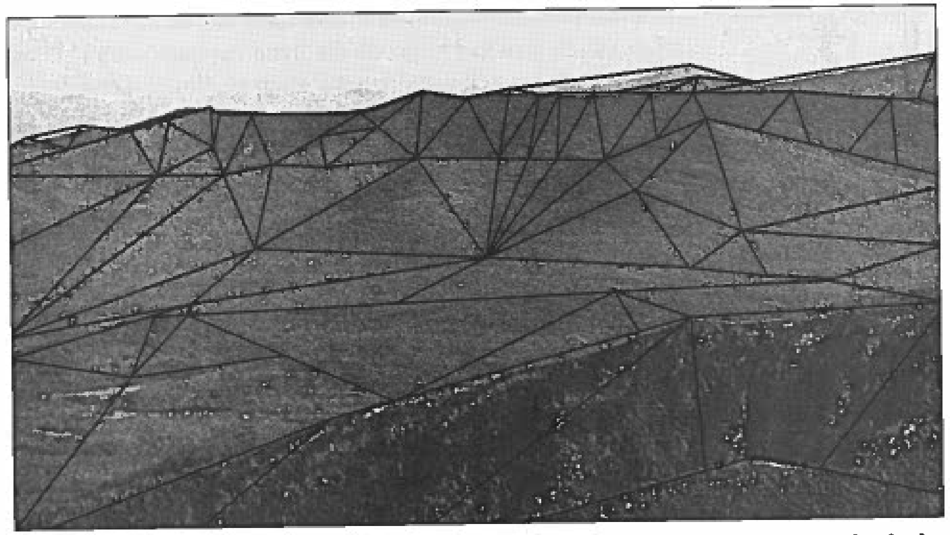

Figure 2-16 A triangular irregular network (TIN) draped over a terrain. Photograph of Pilot Range, New Hampshire.

complicated and may involve a series of steps in which the role of control alternates from one component to another. This section cannot list all the variations that might occur, but it will treat three very common situations that lead to potential misinterpretation.

Scattered Point Samples

As described at the start of this chapter, a collection of points can seem to have the best of all worlds. Location is not constrained, and the attribute value is directly measured. A specific time could be attached to each value. In some cases, such as a roving pollution monitor, the measurement of each component (time, space, and attribute) is fully measured. If the sample point was only occupied once, then the sample location might never be recovered precisely. In practice, it is much more common for the locations of the sampling sites to be given by some external distribution. For example, weather stations are often located at airports and other places with personnel to maintain them. The spatial measurement is really controlled by the identity of that object. A field titled "Name" in the data table often signals that the seemingly scattered points were located as a set of discrete spatial objects, then a secondary attribute measurement was obtained at that location. Once a network of sample locations is established, it makes much more sense to repeat measurements over some temporal series as well. Thus, what might appear as an aberration actually fits Sinton's (1978) scheme rather well. The final attribute measurement is controlled by a specific set of point locations and a repeated pattern of temporal sampling. In many applications, these particular sampling locations are not the places that really matter.

A process of interpolation is usually applied (see Chapter 9) to convert these points to some other measurement framework.

Associating Attributes—Indirect Measurement

In the physical sciences, measurement is rarely direct. Temperature is measured by the expansion of mercury up a glass tube (a distance), or it is measured by the difference in thermal expansion of two metals wrapped in a spiral. These measures of distance are converted into temperature using various physical laws. While geographic relationships may not be as deterministic, indirect measurement is quite common. Indirect measurement operates by observing one quantity that can be linked, by a set of assumptions, to another quantity. Under these conditions there may be multiple stages of control, which produce a composite of measurement frameworks.

Based on a categorical coverage, many different thematic interpretations can be constructed using a lookup table form of indirect measurement. For example, soil surveys contain large tables with all kinds of attributes for the soil mapping units. The SOIL-5 database from the U.S. Natural Resource Conservation Service lists dozens of such attributes, each with a different unit of measure—nominal, ordinal, and ratio. A selection of variables gives a sense of this diversity (Table 2-5). Of course, the soil mapping units were not designed to portray permeability, erosion hazard, corn yield, slope, and suitability for playgrounds with equal accuracy. Soil boundaries are drawn to distinguish a given set of categories, subject to a set of cartographic and pedological limitations. These are not necessarily the boundaries that one would obtain in a direct measurement of each attribute.

The simplest form of indirect measurement takes the basic categories of a categorical coverage and ranks them with respect to some particular purpose. This process upgrades the nominal categories to an ordinal scale by importing the ordering related to the purpose. In the soil survey report, each soil mapping unit is ranked "Slight," "Moderate," or "Severe" in terms of its limitation for a host of activities. Of course, the ranking orders the whole soil class, not the specific instance. Each polygon of the class gets an identical rank.

A soil survey in the Corn Belt lists an estimate of corn yield for each soil class. This ratio figure may be obtained from a few sample fields or from expert opinion. When this value is applied through indirect measurement to the soil polygons, many repetitions of the same value occur all over the map (Figure 2-17). The abrupt nature of the categories remains, although yield would likely be more continuous. The shaded map maintains the illusion of a continuous attribute by showing ranges of possible values, yet there are only 19 distinct values of yield given in the lookup table for the 113 soil classes in this particular county. Thus, indirect measurement cannot hide the abrupt change between classes implicit in the measurement framework. The map is a composite that can only be understood by explaining the two processes: first, control by attribute (soil class) to measure boundary locations and then conversion to another attribute (corn yield) on a seemingly higher scale. In addition, indirect mea-

TABLE 2-5 Selected Attributes for Soil Mapping Units

Estimated Soil Properties (each attribute by soil horizon)	
Attribute	*Measurement scale*
Texture	Classified by USDA, AASHTO, "Unified"
Clay content	Percent range
Moist bulk density	Grams/cm^3
Permeability	Inches/hour
Available water capacity	Inches of water/inch of soil
Soil reaction	pH
Salinity	mm halides/cm
Shrink-swell potential	Low/moderate/high
Erosion factor (*K*)	Proportion of standard soil loss
Wind erosion group	Numerical class
Suitability for Sanitary Facilities (by slope class)	
Septic tank absorption fields	Slight/moderate/severe
Suitability for Building Site Development (by slope class)	
Dwellings without basements	Slight/moderate/severe
Local roads and streets	Slight/moderate/severe
Recreational Development	
Picnic areas	Slight/moderate/severe
Playgrounds	Slight/moderate/severe
Capability and Yields per acre of Crops (Figures shown for irrigated and nonirrigated by slope Class)	
Corn	Bushels/acre
Soybeans	Bushels/acre
Alfalfa hay	Tons/acre
Windbreaks	
<species - up to 20 listed	height>

Source: Headings on Soil Interpretations Records for Christian County, Missouri, dated 1983, given to landowners on request at the USDA Soil Conservation Service (SCS) District Office. These are extracts from a larger database and may be regionally specific. Original table lists 110 attributes.

surement makes the assumption of homogeneity despite the careful recognition of **soil inclusions** in the text of the soil report.

Assigning a ratio measure to a category might seem rather innocuous, particularly if it is merely a guide to expected yield for farmers. However, information has a way of moving into many unanticipated applications. In Ohio, Indiana, Missouri, Iowa, Nebraska, and neighboring states, various forms of expected crop yield assigned to soil mapping units are used in the assessment of agricultural land for taxa-

Soil inclusions: A category of soil expected to occur inside the units mapped as another category.

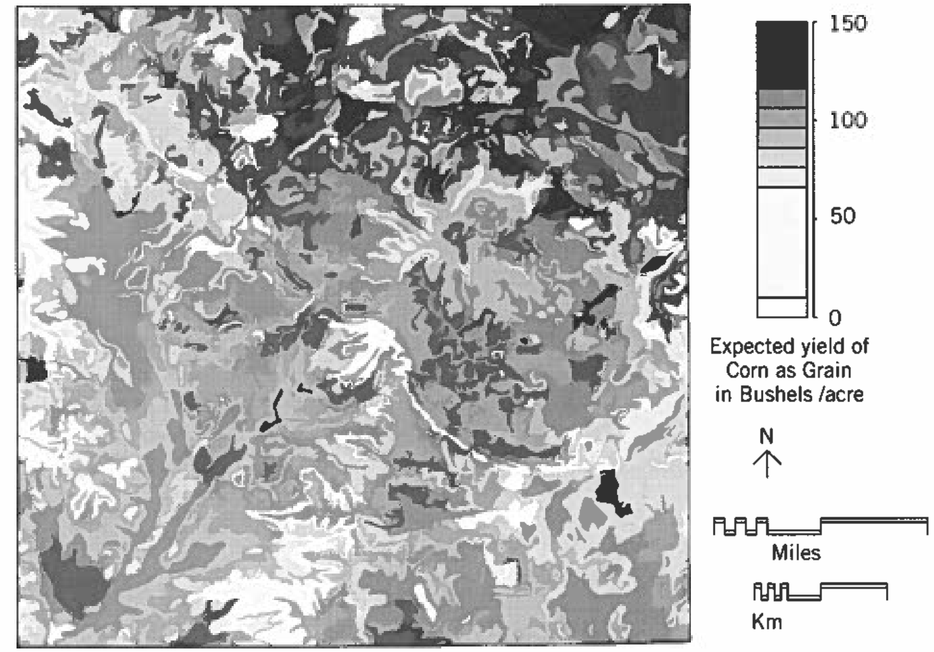

Figure 2-17 Estimated yield of corn in bushels per acre. Area covered: Oregon, Wisconsin approximate dimensions 10 × 10 km. Digital data developed by Dane County Land Records Project (Niemann et al. 1987) in cooperation with USDA Soils Conservation Service Wisconsin Office. Attribute table from Dane County Soil Survey, 1976.

tion. This kind of use of indirect measurement for important public decisions raises many questions about the trade-off between special-purpose measurement and general-purpose surveys (a topic revisited in Chapter 10).

Choropleth Framework

One of the most common geographic measurement frameworks, the **choropleth framework,** also cannot be explained as a direct measurement. Consider the classic choropleth map of counties (or provinces, census tracts, or some other jurisdiction) with the title "Population Density by County, 1960" (Figure 2-18). It is well understood that county boundaries do not necessarily conform to regions of uniform population density. County boundaries seem to be taken as a fact of life—a base map rather than any kind of measurement. But even base maps must be measured. County base maps are categorical coverages because an exhaustive set of categories (counties) serve as control to delineate (measure) a network of spatial boundaries.

Choropleth framework: Measurement framework whose spatial units (derived from a categorical coverage of named objects) serve as control for attribute measurement (e.g., census tabulation).

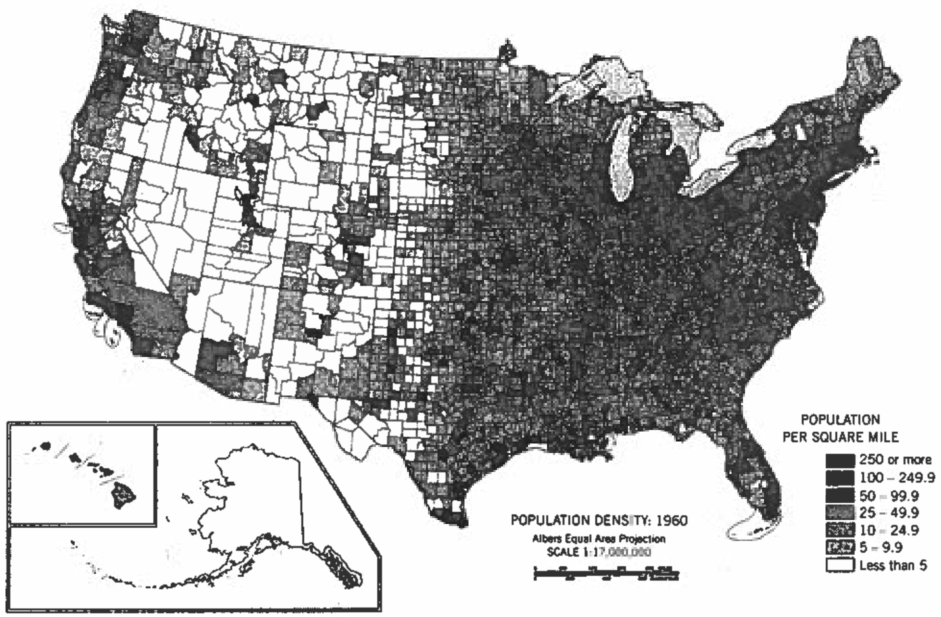

Figure 2-18 Choropleth map: Population density of the United States by county 1960. (Source: USGS 1970, p. 241.)

The location of these boundaries is not constrained; even the most minuscule county has its own outline. What is measured here is the location of the boundary.

In the next step, the Census Bureau aggregates its raw tabulations for these spatial divisions. The county name now serves as a *spatial* control for the attribute measurement process. Thus, at the most immediate level, the choropleth framework has an irregular form of spatial control that permits a continuous measurement of an attribute. This spatial control arises from a base map whose combination of control and measurement is reversed. The boundaries on Figure 2-18 do not relate to the attribute shown but to the categorical coverage of counties.

Demographic attributes such as population, housing, and income do not necessarily change character crisply on the edges of the tabulating units. An attribute tabulated for one set of fine choropleth zones may be quite different from the same variable tabulated for another coarser set of zones. The real units of measurement, households in the case of the census, are so many that it makes little sense to treat each one as a distinct spatial unit. Furthermore, the protection of privacy may require deliberately reduced resolution in both space and attribute.

Tabulation by collection units extends beyond the classic case of the census. Various kinds of areal collection zones are used in different applications; such zones range from school attendance areas to television viewer areas to watersheds. Not all spatial aggregations are areas, however. In dealing with highway statistics, the records of accidents and other activities are often tabulated by a variety of levels from intersection to highway route number. Most commonly, the highway is segmented into tabulation units that are homogeneous according to some property such as traffic flow or pavement type. The process of designing different segments along a network for different purposes has come to be called **dynamic segmentation,** though it has no particular temporal nature (Nyerges 1990; Dueker and Vrana 1992).

Despite sharing some of the procedures, the choropleth framework differs from the indirect measurement of soils discussed earlier. In the soil case, the ranking or attribute was attached to the whole class that had provided the control for the original coverage. In some sense, the corn yield by soil class is an attribute of the attribute. In the choropleth case, the attributes have been aggregated from a more detailed distribution, thus imposing a form of spatial control. The choropleth boundaries have little to do with the variability in the attribute; by contrast, the soil boundaries retain most of their meaning after indirect measurement. Although they might look similar, particularly when displayed using choropleth maps, these measurement frameworks do differ.

TEMPORAL FRAMEWORKS

Time lies at the heart of many geographic problems. For example, the ultimate purpose of an analysis might be to explain the processes behind some changes or to predict future configurations of the landscape. Yet, time remains the weakest part in the measurement frameworks used for geographic information. The snapshot model, in which time is fixed, lies at the base of most geographic information models, just as it did for printed maps. However, it is important to recognize that time is not always fixed. If temporal control is introduced by a series of discrete *periods,* a database can contain attributes from different times, as long as the spatial units remain consistent. In many cases, the attributes are not obtained at a single moment, but instead, averages or sums are calculated over some period. These rules are similar to the rules used for spatial control by area.

The remote-sensing approach to change detection places a series of snapshot maps into a kind of jerky motion picture. Time graduates to a kind of control, as long as the measurement structure of the map has not changed. Thus, a *snapshot framework* can be created that simply repeats any other framework (based on attributes and space) at a controlled set of times. The calculation of change requires the overlay techniques presented in Chapter 5. Of course, errors in the maps may become inextricably confused with changes. It becomes technically challenging to retain adequate control over the spatial and attribute components, so that the repeated snapshots actually repeat the same measurement procedure.

Dynamic segmentation: A method for referencing attribute information along a network that does not divide each segment of the network wherever any attribute changes.

Most nongeographic databases are not structured as snapshots; rather, they center on *transactions*. These events target specific records and make changes piecemeal. Database software expends substantial effort at ensuring the integrity of a database as transactions occur over time. The working world of GIS in a local government, for example, similarly involves a daily flow of permits and inspections that cause revisions in the attribute database. Tragically all the temporal richness gets lost if the geographic software erases the past to remain current. A transaction-based framework would have to maintain the history of spatial and attribute information, a demanding task. As geographic measurement moves away from the limitations of snapshots, databases will be able to reflect change in the landscape more flexibly. Some conceptual advances have occurred (Langran 1991; Egenhofer and Golledge 1998), but few of these concepts have been translated into the regular GIS tool kit.

Environmental modeling has always had a strong temporal component. This kind of model provides a system of relationships that link particular measurements into a larger structure, eventually seeking to predict future configurations. These relationships come from an understanding of environmental processes, not just from the map patterns. Still, the elements of the model do not escape the basic trade-off described in this chapter, that is, some components must serve as control to allow measurement of another component.

Measurement Frameworks in La Selva Project

Because the sources were traditional paper maps, the measurement frameworks in the La Selva project were mostly attribute controlled. The stumps coverage is a simple example of isolated objects. Each stump (a specific category) was identified and its location measured. Streams, roads, and trails are also isolated objects, but they are subject to the constraints of connectivity, so they are networks. The land use layer was an exhaustive set of polygons. The whole annex was assigned to one of the categories. The categories act as the control, and the boundaries were drawn to follow the distribution. This is a categorical coverage in a fairly classic form. The soils map was originally created the same way, although it was made available in a gridded representation. In the case of the soils there would be a large table of potential attributes to attach to the soil classes. If these values are selected for display, the map would appear to present permeability or some other numerical value, but the boundaries would still be the same ones created for the categorical coverage. The elevation data, by contrast with all the others, were made available as a digital elevation matrix, a center point version of spatial control with a 10-meter cell size. This source was probably constructed from some other source (such as a contour map), but its lineage was not complete.

SUMMARY

The measurement frameworks for geographic information introduced in this chapter are not intended to exhaust all possibilities, although they do cover the bulk of current applications. Each framework involves choices in recognizing objects and relationships inside a system of axioms (Table 2-6). These frameworks then serve as the guiding concepts for the systems of representation used to implement the information system—the topic of the next chapter.

TABLE 2-6 Summary of Geographic Measurement Frameworks

Control by Attribute	
Isolated Objects	
Spatial object	Single category distinguishes from void
Isoline	Regular slices of continuous variable
Connected Objects	
Network	Spatial objects connect to each other, form topology
Categorical coverage	Network formed by exhaustive classification
Control by Space	
Point-based Control	
Center point	Systematic sampling in regular grid
Systematic unaligned	Random point chosen within cell
Area-based Control	
Extreme value	Maximum (or minimum) of values in cell
Total	Sum of quantities (e.g., reflected light) in cell
Predominant type	Most common category in cell
Presence/absence	Binary result for single category
Percent cover	Amount of cell covered by single category
Precedence of types	Highest ranking category present in cell
Control by Relationships	
Measurement by pair	Control by pairs of objects
Triangular irregular network (TIN)	Control by uniform slope
Composite Control	
Choropleth	Control by categories (name of zones) then by space