WAYS TO UNDERSTAND GIS OPERATIONS

There are many ways to understand the operations performed by a GIS. Dana Tomlin (1990) developed one sequence to present map operations, ranging from the simple to the complex. It makes good sense to consider the simple operations that work on a single map, then those that work locally on two maps, and so on. However, Tomlin's scheme fails to include all possibilities (and thus provide the "algebra" promised) because it forces all measurements into a single raster representation and does not distinguish between a representation scheme and a measurement framework. Furthermore, Tomlin's terminology for the operations becomes a bit obscure for the more complex operations. Goodchild (1987) followed the flow of Tomlin's basic operation, adding some elements, such as information attached to pairs of objects—introduced as relationship control in Chapter 2. Burrough (1992) argued for "intelligent GIS" essentially by recognizing more spatial relationships. This book adopts a composite approach to operations developed on the basis of the measurement frameworks described in Part 1 (see also Chrisman 1999b).

ATTRIBUTE-BASED OPERATIONS

CHAPTER OVERVIEW

- Present operations that modify attributes without involving the spatial component.
- Describe interactions of spatial and attribute components caused by attribute operations.

The spatial aspects of GIS distinguish it from other kinds of information handling. The bulk of Part 2 will deal with operations rooted in geometry or spatial relationships, but this concentration on the spatial component should not ignore tools based on attributes. Despite their simplicity, operations based on attributes are important because they play a constant role in the applications world. Almost every operation of a more complex nature is preceded or followed by some form of housekeeping requiring this set of tools.

Attribute operations will be treated in two stages in this chapter. First, simple mathematical or set operators convert existing values into new ones, operating within one measurement framework. Some operations reduce information content, while others attempt to increase it, using some source of external information. As discussed in the second section, attribute operations for geographic information interact with the spatial component. These simple operations can also produce apparent changes in the measurement framework.

MANIPULATING ATTRIBUTES

Attribute values often encapsulate the final objective of GIS analysis. A forest products company wants to know the expected volume of timber to be harvested over a series of years. A transit authority wants to estimate changes in ridership on its route system. A tax assessor must determine a fair market value for every parcel in the county. The attributes intended at the end of the analytical process are rarely the items originally measured; they must be estimated from other information. The procedures available to manipulate attributes depend on the numerical properties of the measurement scale and external assumptions provided.

Reducing the Information Content

It may sound wasteful to throw information away, but many circumstances involve reducing a detailed source into a simpler form. These operations often occur as preparation for other more complex steps discussed in later chapters. There are many possible techniques, but a few common examples will serve to describe the general character. Each of these can be organized based on the level of measurement input and output.

Group A grouping procedure (Figure 4-1) takes a detailed classification and produces a cruder classification by merging some of the classes. An external source must specify which categories belong together in the resulting classification. For example, a detailed land use classification could be simplified into urban/rural groupings or into groups based on the degree that humans disturb ecological processes.

The syntax for grouping can vary. Some software provides complicated text commands such as `recode land_use assigning 3 thru 5 to 9 assigning 6 thru 14 to 6`. Other systems may use a string of interactive queries or conversion tables that specify the output value for each value input. No matter how the command is entered, the mathematics remains simple. Nominal data should be treated by enumeration of the possibilities. For convenience, some languages might provide a range of values to recode to a new value. This shortcut may save much time in entering the commands when the categories are ordered based on some hierarchy.

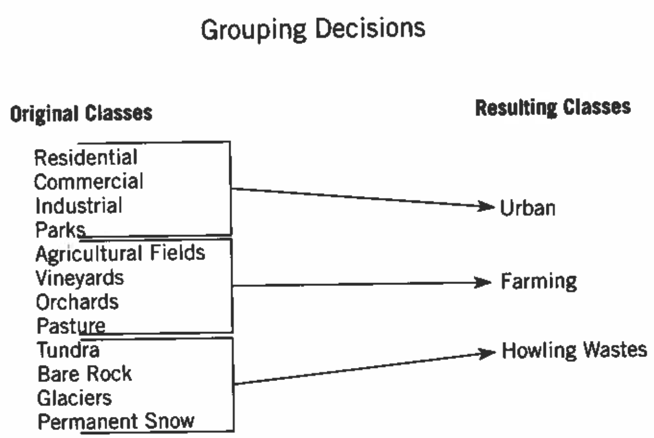

Figure 4-1 Grouping procedure reduces information content.

For instance, all the forest categories of a land use coding scheme might be given consecutive numeric values without implying any ordinal or interval scale. While a nominal classification simply states that each category is different, some differences are invariably larger than others.

Isolate An isolation procedure (Figure 4-2) produces a simple nominal classification (selected and not selected) from a broader range of input. It can be applied to identify a single category from a larger nominal classification or a range of values from an ordinal classification. For example, an industrial category in a land use coverage could be isolated to depict industry as an isolated object. Similarly, using an ordinal class, an attribute of expected soil loss could be simplified to isolate those areas over a particular threshold.

Since an ordinal class can be constructed using a range in any higher measurement, isolation operators commonly apply to any kind of measurement. Isolation is one of a broader range of selection operations. Some selection works by region, a spatial component. When selection works through the attribute, the result isolates certain geographic information from its context. Database query languages such as Structured Query Language (**SQL**) give primary attention to selection with commands such as `select parcels where owner = 'Smith'` or `select soils where permeability > 0.785 and texture = 'silt_loam'`.

Classify A classification procedure (Figure 4-3) produces ordinal categories from a higher level of measurement, such as ratio. A set of class intervals establish the breakpoints between adjacent categories of the ordered output. Classes can be constructed for different objectives as commonly applied in thematic cartography. An

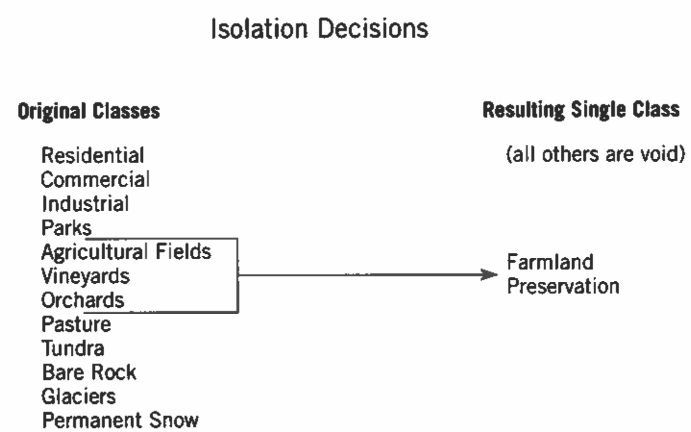

Figure 4-2 Isolation procedure reduces information content.

SQL: Structured Query Language; a standard interface for access to a relational database through queries that select records matching logical expressions.

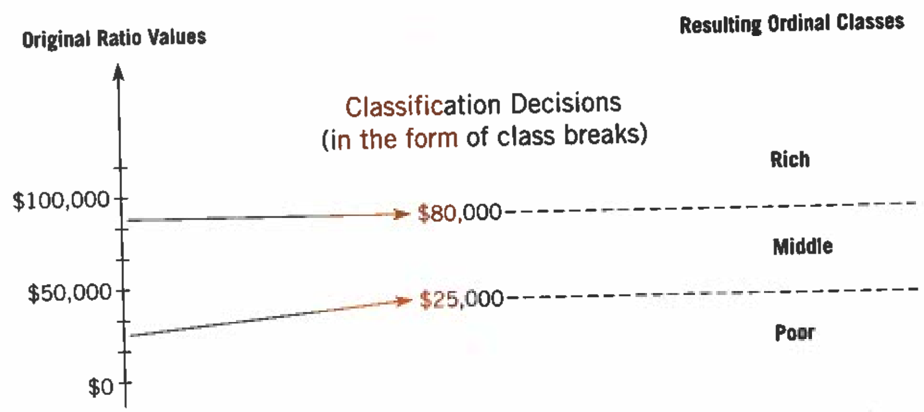

Figure 4-3 Classification procedure reduces information content.

equal interval classification preserves some of the numerical properties of an interval or higher scale. A **quantile** classification chooses the breakpoints between classes based on a count of the objects in each class. Frequently the breakpoints come from a regulation or a technical specification. For example, the Conservation Reserve Program targeted lands higher than a particular ratio of soil loss compared to the "tolerable" quantity. Land over the threshold is eligible; land under it is not.

Scale A scaling procedure (Figure 4-4) simply changes the units of measure for a ratio or a count. For example, elevation can be converted from feet to meters or money from dollars ($) to pounds sterling (£). If the representation of numbers were

Figure 4-4 Scaling procedure does not necessarily reduce information content.

Equal interval: A classification procedure that divides the total range of attribute values by the number of classes; breakpoints are spaced at equal intervals, whether the class has any members or not.

Quantile: A classification procedure that assigns an equal number of objects into each class. The interval of each class will vary unless the distribution is completely uniform.

ideal, multiplying a ratio measurement by a constant should retain all the information content. However, it is common to round off measurements at some level of resolution. For example, the population of a city may be given in millions with one decimal point for hundred thousands. The integer nature of the original count has been lost, but the result retains the most significant portion of the measurement.

These four procedures show how an attribute can be changed toward a lower information content. Each involves some external decisions, such as the categories to isolate or group or the ranges to isolate or classify. Figure 4-5 organizes all four in terms of levels of measurement input and output. This schematic form will be used to illustrate the more complex operations below.

Increasing the Information Content

The levels of measurement set up a rough hierarchy of information content. While it is possible to reduce the information content easily, increases in measurement level do not come for free. What appears as an increase in information requires an external source. The information from outside is merged with the database, thus making it seem that the database has been upgraded. Three procedures: rank, evaluate, and rescale provide examples (Figure 4-6).

Rank A set of nominal categories, such as vegetation types, should be considered unordered. Using additional information about preferences, the categories can be converted into an ordinal scale (top of Figure 4-6). For example, one ordering could rank the habitat potential of each vegetation class for a species of reptiles; another ordering of the same vegetation classes would rank preferences for a bird species.

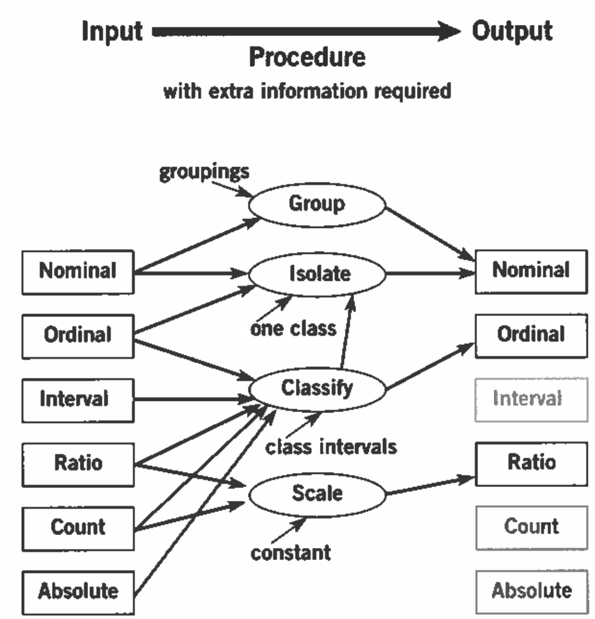

Figure 4-5 Procedures with one attribute input that reduce information content.

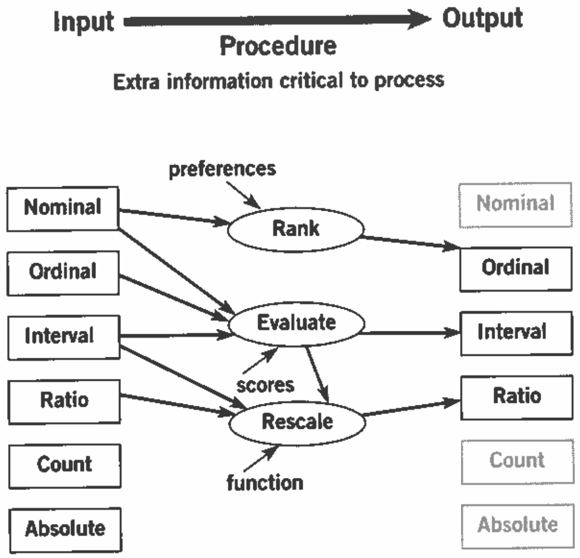

Figure 4-6 Procedures with one attribute input that increase information content.

Sometimes rankings are very simple, with fewer categories than the original nominal system, but the new categories are ordered from high to low. The soil capability information presented in Table 2-5 ranks limitations from slight to moderate to severe. These values are assigned using indirect measurement through the soil series categories. It might seem odd that a conversion from 113 categories to three ranks is taken as an increase in information, yet from the standpoint of analytical use, the original soil categories are simply different from each other, while the scale (High, Medium, Low) permits greater interpretation and comparison.

Evaluate The process of indirect measurement can also upgrade lower levels into interval and ratio scales (middle of Figure 4-6). An evaluation process takes a category and assigns it an interval (or higher) measurement. For example, vegetation classes might be assigned the expected density of a species of reptile. In some GIS applications, ordinal scales are given interval values more out of convenience. For instance, slight limitations could be scored "0," moderate gets a "1," and severe gets a "2." For this assignment to mean anything, there must be some justification that severe limitations are just as much worse compared to moderate as moderate are from slight. Without a basis for the number scale, an evaluation procedure is likely to obscure more than it reveals. It takes a careful research program, such as the soil loss experiments at the University of Missouri, to be able to assign numerical values (such as the soil erodability K factor) to specific soil types. This research project is the source of the information content that can be shared from place to place, within some range of environmental applicability.

Rescale A continuous measurement can be rescaled using a mathematical function to represent some other property (bottom of Figure 4-6). In some cases, the rescaling can upgrade an interval measurement into a ratio scale, for example, by converting temperature data through a nonlinear equation into the biomass produced by a tree. Such a function would involve substantial understanding of the plant and its dynamics. More commonly, a ratio-scaled measure is rescaled to another ratio scale through a nonlinear function. For instance, Galileo's physics of an inclined plane demonstrated that the potential energy of soil particles (and hence the potential for erosion) does not scale directly with the angle of the gradient but rather with the sine of the angle.

All these operations that increase information content can be performed on a single attribute, with the additional information provided in the form of external tables or mathematical functions. These are the simplest operations in any GIS, usually no different from similar operations to manipulate values in other forms of software, such as spreadsheets or database managers.

Combining Pairs of Input Values

Attribute-based operations are not restricted to a single attribute. Most arithmetic functions (addition, subtraction, multiplication, and division) combine two values. If the data structure provides two values for the same entity, then a number of attribute-based operations become available (Figure 4-7). This section presents four examples and then considers how these operations are performed.

Cross-tabulate A pair of categories (for either nominal or ordinal scales) can create a cross-tabulation, thereby coding the combination of the two values (top of Figure 4-7). In the past, the codes for the categories from each source were simply con-

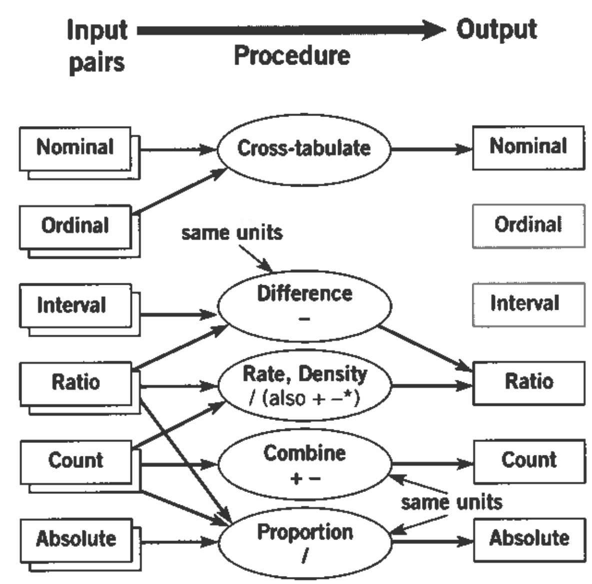

Figure 4-7 Procedures with two attributes input.

catenated. For example, the "fractional codes" used in the 1930s built up complex numeric codes by assigning a digit each to represent dozens of attributes. The U.S. National Wetlands Inventory maintains this tradition with a multicharacter code where each position can carry another attribute. Some software creates new categories for each distinct combination, giving a compact list of the actual pairs rather than the possible permutations. In any case, the new category combines information from both sources. Nothing is lost because each of the original sources can be reconstructed.

Sum and Difference The basic operations of arithmetic combine two sources at the interval or higher levels (second from top of Figure 4-7). Differences of two interval measures on the same scale produce a ratio measure. Similarly, two measures counting the same kind of objects can be combined by addition or subtraction. These operations depend on comparable units of measure. Adding ordinal categories, for example, presumes a whole series of assumptions. For example, if the scale (High, Medium, Low) is coded (1, 2, 3) the use of addition implies that High plus Low equals Medium plus Medium. This might seem reasonable, but perhaps the environmental risk of severe losses do not cancel each other out quite so neatly. The High risk might involve potential damage 10 or 100 times larger than the two Medium values.

Rate and Density Ratio measures get their name from the central role of division in their construction (third from top of Figure 4-7). A distance in meters is a ratio between the standard rod and the measurement. All kinds of rates and ratios can be constructed as derived measures from a variety of input sources. The ratio of a quantity to area is usually called a density. These functions are a key part of making attributes that can be used for choropleth maps based on unevenly sized units.

Proportion One particular form of division gives a higher level of measurement (bottom of Figure 4-7). If the two values are measured on the same scale, say population, then division produces a proportion (on an absolute scale). For example, dividing the population over 65 by the total population gives a proportion over 65. The resulting value is an absolute measure, without a particular unit of measure. Some disciplines have a convention of rescaling these proportions as percentages or rates per 100,000 depending on the prevalence of the phenomenon. The interpretation of these values remains tied to the original proportion on its absolute scale.

Performing Combinations All these operations require that two attributes attach to the same geographic object, using the same measurement framework. Consequently, the implementation differs between raster and vector representations. In the most common implementations of raster GIS software, each attribute is seen as a separate array of values, called *image planes* or *layers*. In many software implementations, each procedure generates a whole new raster file. Thus, raster operations on

pairs of attributes are effectively indistinguishable from overlay operations (described in the next chapter).

In the vector representation, the attribute values are more distinct from the geometric structure. The relational database model provides a conceptual structure—tables of records, however implemented. This model borrows the format of the geographical matrix, with one record for each object in a certain class. A new attribute value, derived from any of the procedures discussed in this chapter, becomes another column in this table (Figure 4-8). Procedures that operate on pairs of values do not require overlay if the two input values come from the same table. In the vector form, most of these operations can be performed using regular commercial databases or spreadsheets, not any particular geographic software.

In some cases, an attribute value does not contain a measurement but represents a relationship to a data table. In the example of corn yield estimates (Figure 2-17), each soil mapping unit (the polygon) is connected to a soil series (the categories in the soil survey). Initially, the identifier for the soil series may be the only attribute for the polygon. The soil series has dozens of possible attributes for different applications (see Table 2-5). The most compact (and least redundant) structure maintains the attributes of the soil series in a *table* with entries for each soil category, rather than duplicating those attributes onto the thousands of soil polygons or onto even more pixels. In the terminology of relational database management, the soil series identifier attached to the soil mapping unit is a **foreign key**, linking the two attribute tables. When needed for some purpose, the value of each soil series attribute can be associated with the polygon (Figure 4-9). This process is called a **join** in a relational database and a table lookup in other software, such as image processing packages. If the size of the table is manageable, the lookup mechanism can be quite quick, but a general-purpose join requires massive data processing. The indirect measurement techniques introduced in Chapter 2 are implemented using an evaluation or ranking operation implemented through a join or a table lookup.

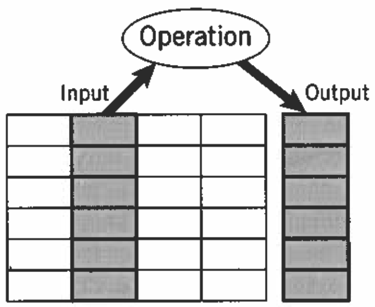

Figure 4-8 Attribute operations take values from a number of columns and produce a new column.

Foreign key: Item in a relational table that contains a value identifying rows in another table; represents a relationship between two elements of a relational database.

Join: Procedure that attaches values from a database table to another table based on matching a foreign key to its primary instance.

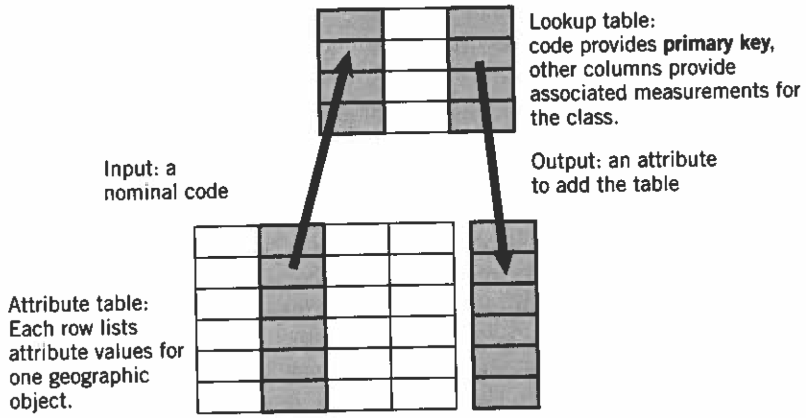

Figure 4-9 Join operation associates a geographic object to another table using a unique key. Attributes of that table can be added to the geographic objects as a new column.

INTERACTION OF ATTRIBUTE AND SPATIAL COMPONENTS

The operations described in this chapter are all designed to manipulate the attribute. However, these attributes are attached to geometric descriptions. Changing the attributes can also change the spatial component of the database. These relationships depend on the measurement framework and the system of representation. This section will consider the spatial consequence of grouping and isolating categories, and then the discussion will connect these operations to broader issues of cartographic generalization.

Spatial Consequences of Aggregation and Isolation

The grouping and isolation operations reduce the richness of detail in categorical attributes. Although these operations seem limited to the attribute component of geographic information, they also can influence the spatial component and thus the measurement framework.

As described in Chapter 2, a categorical coverage involves measuring the boundaries between a specified set of classes. The refinement of categories can vary enormously. For example, a land use inventory can be interpreted into the 37 classes of the Anderson Level II land use/land cover system (Anderson et al. 1976). This widely used system has one or two categories for commercial land uses and many more for natural resources. For comparison, the South East Wisconsin Regional Planning Commission (SEWRPC) used 79 classes for its 1975 inventory. This coding system approximately doubles the number of classes compared to the Anderson system, but the refinement is far from evenly distributed. There are 12 categories that match the Anderson category "Commercial and Services" (Table 4-1). Yet, in the less urban parts of the landscape, such as wetlands and forests, the Anderson system is more refined. Any survey must choose the system of classes with a balance of uses in mind.

TABLE 4-1 Relationship Between Two Land Use Coding Systems

Selected Level II Anderson Codes		*Nearest Match in SEWRPC Land Use Codes*
12 Commercial and Services	←	210 Retail Sales and Service—Intensive
		220 Retail Sales and Service—Nonintensive
		432 Retail and Service—Related Parking
		436 Government and Institution—Related Parking
		437 Recreation—Related Parking
		611 Local Government
		612 Regional Government
		641 Education–Local
		642 Education–Regional
		661 Group Quarters–Local
		711 Cultural Public
		712 Cultural Nonpublic
41 Deciduous Forest	→	940 Woodlands
42 Evergreen Forest		
43 Mixed Forest		
61 Forested Wetlands	→	910 Wetlands
62 Nonforested Wetlands		

Source: Anderson and others (1976) USGS Professional Paper 964; South East Wisconsin Regional Planning Commission.

For different applications of land use, certain distinctions between categories would not be important. For each purpose, the classes of a detailed inventory can be grouped together to assemble more general categories. Regrouping categories has consequences when that attribute served as control for the coverage. When adjacent polygons in the detailed version abut, they may now need to merge into a large, simpler region, a process termed *aggregation*. This operation is the spatial consequence of the attribute operation of grouping a category used as control.

Few GIS packages perform aggregation with direct and elegant expressions. In the vector world, a classification system can be simplified in the attribute tables. Then a simpler geometry is produced by deleting all boundaries that have the same new category on each side. This operation is called *dissolve* or "dropline" aggregation, though it will only drop lines when merged categories are contiguous. In a raster package, grouping changes the values of the pixels, and there is no further geometric process to recognize contiguous objects.

In terms of information content, an aggregation operation seems quite similar to an isolation operation. Both reduce the content of the attributes, but the *spatial* consequences differ. If everything else is aggregated into a background class, then a specific category is isolated from all others. The isolation operation must be recognized as a transformation between two measurement frameworks. Starting with a categorical coverage, it produces an isolated object view in which the specific category is surrounded by the void. This differs from other aggregations that maintain an exhaustive classification of the whole region, thus continuing the categorical coverage framework.

Cartographic Generalization

Aggregation and isolation operations are simple components in the tool kit of cartographic *generalization*. These two operations are driven by the categories, and the geometry of the input coverage simply appears or disappears. If the map had been constructed for the simpler set of categories (or for the single object surrounded by the void), there is no guarantee that the same boundary lines would have been drawn. A less refined set of categories might change the rules of line sinuosity, minimum polygon size, and minimum width. If the aggregation is relatively mild, perhaps there is little difference. Converting the detailed SEWRPC categories (Table 4-1) into some highly generalized urban/rural split may not work simply by grouping the categories. Urban and rural at a generalized scale may not depend only on the detailed category but also on the surrounding context. Figure 4-10 shows the SEWRPC and **GIRAS** maps for the same region of Walworth County, Wisconsin. The SEWRPC land use maps include the pavement of roads in a transportation category, grouped with utilities at the urban end of the list. Are they urban or rural? Roads occupy areas that continue from towns into rural areas. In town, they certainly belong to the town, but in the rural area, the road might vanish into the background of fields and forests. A geometric filter or a neighborhood recognition is far beyond the capability of this simple aggregation operation. Recent research on cartographic generalization emphasizes that there are a number of distinct tools that must be used in combination (Beard 1987; Brassel and Weibel 1988; McMaster and Shea 1992).

The isolation operation creates the same generalization difficulties as aggregation, but it also includes a transformation from an exhaustive framework to an isolated object view. Exhaustive measurement requires compromise between the various classes, and the selected class may not be represented as it would have been if it had been mapped alone. A simple example arises from land uses that coexist in three dimensions. A road may pass underneath a building, or even through a mountain. In downtown Seattle, Interstate 5 passes under the Convention Center for a few blocks (Figure 4-11). From the land cover perspective, the road is not visible. If the road is then selected out of a land cover map, it may have disturbing gaps. To most network-oriented applications, the land cover approach destroys critical continuity. The interstate continues to connect the traffic, even if the helicopter cannot see it. Hence, just because there is a category "Road" in an exhaustive coverage, one cannot assume that it is represented as one would construct a road for some other purpose. Differences

GIRAS: A digital mapping project conducted by the U.S. Geological Survey in the 1970s. Resulted in complete coverage of all but Alaska at a scale of 1:250,000 (and selected areas of 1:100,000) using Anderson Level II categories.

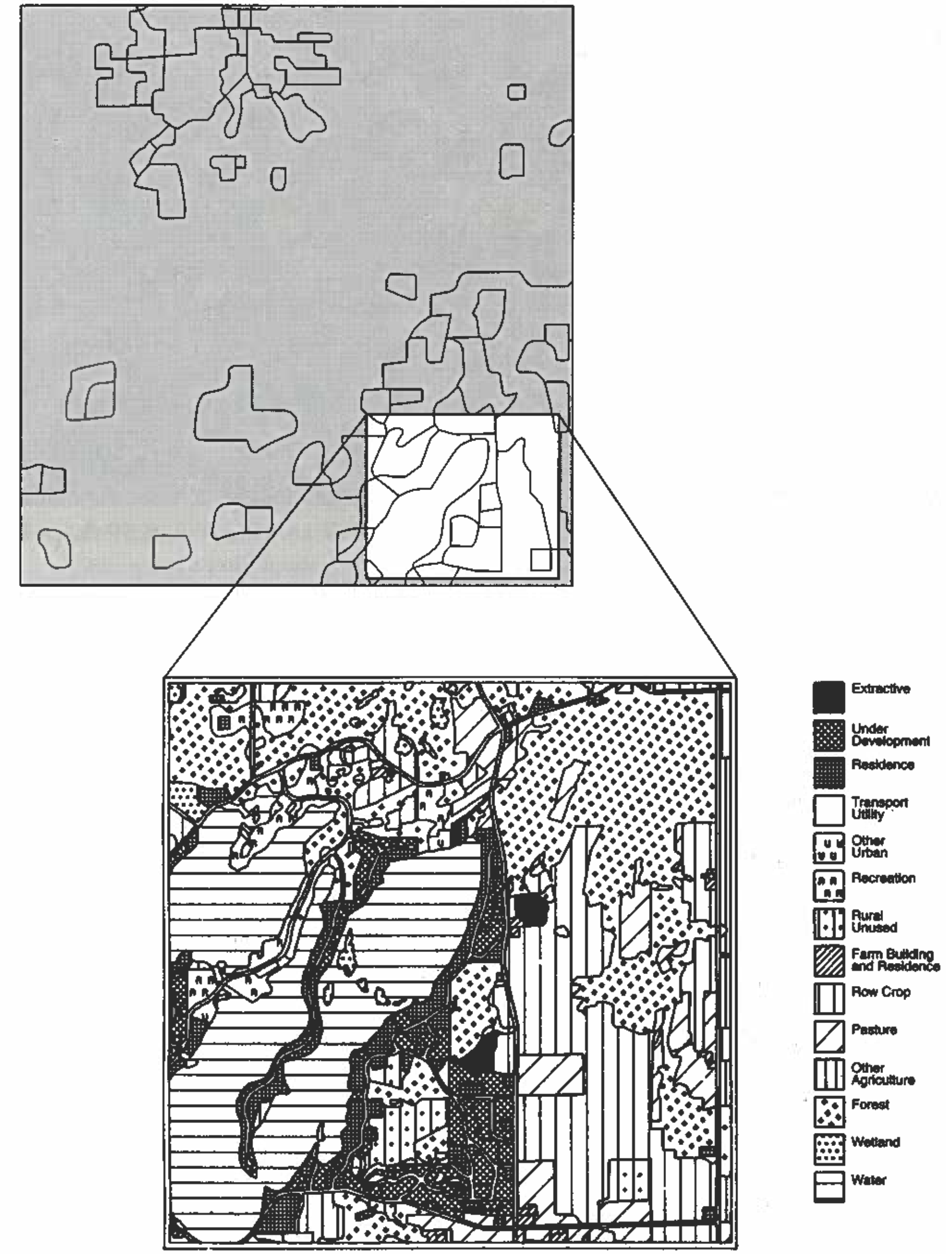

Figure 4-10 Land use/land cover maps for a portion of Walworth County, Wisconsin: (a) from GIRAS digital data, 1976 photos, produced by USGS for display at 1:250,000; (b) from SEWRPC, 1975 photos, produced at a scale of 1:4,800. Both sources classified using respective systems described in Table 4-1. (Source: Beard, 1987, p. 61)

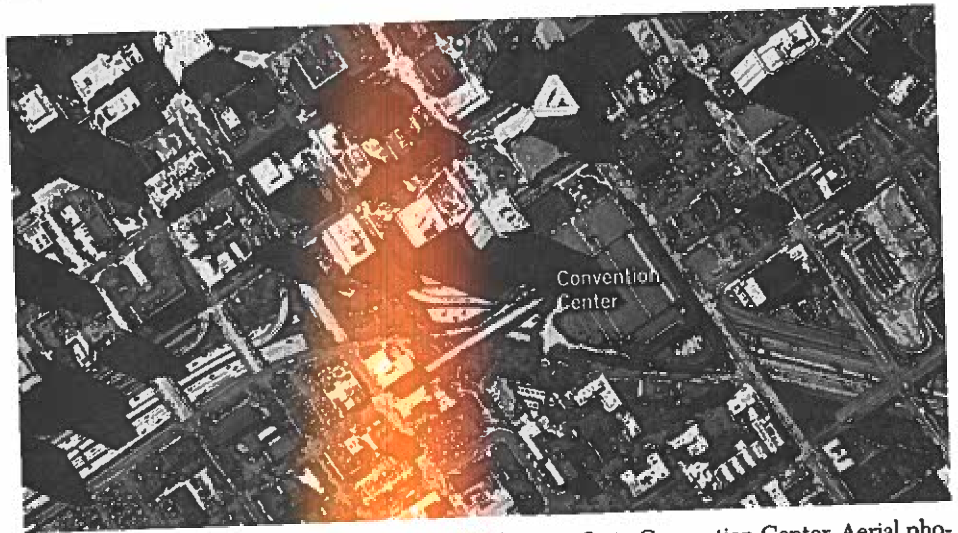

Figure 4-11 Interstate 5 disappears under Washington State Convention Center. Aerial photograph taken April 25, 1995, by Washington Department of Natural Resources.

in measurement framework are particularly apparent in the conversion between raster representations. It makes sense to code an isolated object into a raster representation using a rule such as presence/absence, where a road is shown in all cells it crosses. By contrast, an exhaustive classification is usually controlled by some area rule such as predominant type in the cell. Thus, a selection of one class from an exhaustive coverage may not match the desired object view, particularly for linear features narrower than a pixel.

An analyst must know the limits of the source materials before assuming that any particular mathematics apply directly. On first impression, these problems appear to be inaccuracies in the data, but they arise as much from the assumptions of the model and the measurement framework.

SUMMARY

The simple attribute-based operations introduced in this chapter play a critical, though far from flashy, role in GIS applications. As a general limitation, a derivative representation cannot contain higher resolution (or information content) without having some external source (and the assumptions that go along with incorporating that external information). Although they manipulate the attributes alone, these operations influence the spatial component. In some cases, even simple operations act as transformations between measurement frameworks.

C H A P T E R 5

OVERLAY: INTEGRATION OF DISPARATE SOURCES

CHAPTER OVERVIEW

- Review origins of map overlay analysis.
- Describe geometric operations that establish connections between diverse sources.
- Present rules for combining attributes.

The tools presented in Chapter 4 treat attributes related to a single set of geometric objects. Many problems in geographical analysis require integration from a number of sources. The process of overlay discovers the basic spatial relationship between objects using geometric measurements. Then, attributes from the sources can be analyzed or combined. Overlay serves many purposes, but change detection and error investigations provide the simplest examples. Attribute combination also applies to any circumstance with multiple attributes, even if the attributes attach to the same geometric objects. The combination process forms the major part of this chapter.

DEVELOPMENT OF MAP OVERLAY

Geographic understanding has some contrary tendencies; at times it seems important to talk of the unity of the earth as a complete entity, and at times an analyst can cut things apart into small elements treated separately. As the discipline of geography became formalized, the sweeping holism of the nineteenth century was turned into simpler operational techniques (Harvey 1997). The metaphor of a stack of maps came into regular use by the 1930s both in Germany and the United States. In some texts, it is clear that these were transparent maps, and the analyst expected to look through them. Somewhere in this process, map overlay was born.