Generalization in Digital Cartography

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Library of Congress Card Number 92-25730
ISBN 8-89291-209-X

Library of Congress Cataloging-in-Publication Data

McMaster, Robert Brainerd.
Generalization in digital cartography/Robert B. McMaster and K. Stuart Shea.
p. cm.—(Resource publications for college geography)
Includes bibliographical references.
ISBN 8-89291-209-X
1. Digital Mapping. I. Shea, K. Stuart, 1957–. II. Title
III. Series
GA139.M38 1992 92-25730
526—dc20 CIP

Publication Supported by the A.A.G.

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An Historical Perspective

It is clear that a rich body of literature on the topic of generalization has appeared in both the American and European literature and that any attempt to understand this process must carefully consider this research. Additionally, with the rapid progress that is currently being made in the fields of digital cartography and GIS, it is necessary to rethink and redefine the process for an automated or semi-automated environment. The purpose of this chapter is to carefully document the significant work in cartographic generalization over the past eighty years and trace the metamorphosis in conceptual thinking from manual to digital techniques. The emphasis, throughout the chapter, will be on the established definitions and conceptual frameworks of the process. Lastly, the concept of digital generalization operators, as the transformations crucial in the digital environment, is detailed.

Existing Definitions of Generalization

Not surprisingly, cartographers have struggled for centuries with the difficulties of map generalization and the representation of Earth features. It could be argued that the first published work that addressed the problem of cartographic generalization was produced in the early twentieth century by the German cartographer Max Eckert, who published his voluminous Die Kartenwissenschaft in 1921. In fact, it was during this period that Eckert created the concept of a *scientific* cartography, which, as Eckert argued, should be dedicated to the historical research on maps, map projections, map deduction, map criticism, and the representation of the third dimension. In his writings, Eckert took the position that cartographic generalization bridged between the *artistic* and *scientific* side of the field. Specifically, in a 1907 paper read before the German Geographical Meeting at Nuremberg and later published in the Bulletin of the American Geographical Society (1908) Eckert asserted:

> *In generalizing lies the difficulty of scientific map-making, for it no longer allows the cartographer to rely merely on objective facts but requires him to interpret them subjectively. To be sure the selection of the subject matter is controlled by considerations regarding its suitability and value, but the manner in which this material is to be rendered graphically depends on personal and subjective feeling. But the latter must not predominate: the dictates of science will prevent any erratic flight of the imagination and impart to the map a fundamentally objective character in spite of all subjective impulses. It is in this respect that maps are distinguished from fine products of art. Generalized maps and, in fact, all abstract maps should, therefore, be products of art clarified by science (Eckert 1908, 347).*

It is not until the early 1940s that other significant writings on the map generalization process appear in the geographical literature. Like Eckert, J.K. Wright detailed a *scientific integrity* of maps (Wright 1942). "Not all cartographers," Wright posited, "are above attempting to make their maps seem more accurate than they actually are by drawing rivers, coasts, form lines, and so on with an intricacy of detail derived largely from the imagination" (1942, 528). Cartographic generalization, as described by Wright, distinctly affects this scientific integrity and consists of two components: simplification and amplification. **Simplification** was identified as the manipulation of *raw* information that was too intricate or abundant to be fully reproduced; **amplification** was explained as the manipulation of information that is too scanty. These terms may, in fact, represent one of the first attempts to isolate and define the precise elements within the comprehensive activity of generalization.

Erwin Raisz's General Cartography, the first comprehensive textbook on this subject, presented an overly simplistic view of generalization, focusing on the modification of specific types of contour lines, such as those representing badland and lava bed topography (Raisz 1948). In a later version of the book, Raisz's discussion on generalization had been greatly expanded. Generalization had no rules, according to Raisz, but consisted of the processes of **combination, omission,** and **simplification** (Raisz 1962). Raisz also realized the critical linkage between geography and cartography and proposed that, "Intelligent generalization demands a good knowledge of geography and a sense of proportion" (1962, 38).

Work by Arthur Robinson over a period of four decades traced developments in generalization. From the period 1953 to 1984, Robinson's (and eventually Sale, Morrison, and Muehrcke also) textbook Elements of Cartography summarized most of the significant research in generalization (Robinson 1953, 1960; Robinson and Sale 1969; Robinson, et al. 1978, 1984). By 1960, in the second edition of this seminal book, several pages had been devoted to this topic. Specifically, Robinson identified the generalization process as having three significant components: (1) to make a selection of the objects to be shown; (2) to simplify their form; and (3) to evaluate the relative significance of the items being portrayed (in order to make the appearance of the important items more prominent).

Robinson also speculated on the significance of subjectivity in the generalization process. Despite attempts to analyze the process of generalization, Robinson, in 1960, proposed that it would be impossible to set forth a consistent set of rules that could prescribe, exactly, the procedures for unbiased map generalization. Generalization, Robinson suspected, would forever remain an intrinsically creative process and would thus escape the modern tendency towards standardization. At the same time, Robinson distinguished the processes of intellectual generalization, or the *selection and portrayal of map items*, and visual generalization, which focuses on the visual effect, such as the precise character of the line.

By the fourth edition of the text (Robinson, Sale, and Morrison 1978), one entire chapter had been devoted to the topic of cartographic generalization, where both the four elements of the process — simplification, classification, symbolization, and induction — and the four controls — objective, scale, graphic limits, and quality of data — were detailed. **Simplification** was defined as the determination of the important characteristics of the data, the retention and possible exaggeration of these important characteristics, and the elimination of unwanted detail. **Classification** was identified as the ordering or scaling and grouping of data, while **symbolization** defines the process of graphically encoding these scaled and/or grouped characteristics. The more abstract element of **induction** was identified as, "the logical process of inference" (Robinson, Sale, and Morrison 1978, 150). This formal structure of generalization, as developed by Robinson and his colleagues over a period of two decades, became the standard reference for academic cartographers during the 1970s and early 1980s.

Historical Attempts at Automation

Over the last twenty-five years, research efforts in both academia and industry have wrestled with the difficulties in automating the generalization process. Many who have conducted that research are still not convinced it is possible to automate. Eduard Imhof perhaps articulated it best when he asserted: '...the content and graphical structure of a complex, demanding map image can never be rendered in a completely automatic way. Machines, equipment, electronic brains posses *[sic]* neither geographical judgment nor graphic-aesthetic sensitivity. Thus the content and graphic creation remain essentially reserved for the critical work of the compiler and drawer of a map' (Imhof 1982, 357–358).

Although some authors are less convinced of the professed futility of automation, many are still reticent about presenting the possibilities, and simply offer cursory treatment of the topic (Keates 1973). The most common sentiment purports that automated generalization is merely elusive (Robinson, Sale, and Morrison 1978). Brophy (1972, 8), for example, suggests that this is due to "... a consequence of the ambiguous, creative nature ... which lacks definitive rules, guidelines, or systemization." Nonetheless, many have endeavored to automate various aspects of the generalization process (Shea 1991).

Beginning with the theoretical work on map generalization by Perkal (1966) and Tobler (1966), the foundation for future efforts in digital generalization was established. Many others extended these initial efforts by primarily focusing on the generalization of linear digital data (Deveau 1985; Dettori and Falcidieno 1982; Jenks 1981; Douglas and Peucker 1973; Boyle 1970; Lang 1969). Although these efforts helped to establish several algorithms for conducting linear generalization, recent work has focused on the identification of the appropriateness of algorithm selection (McMaster 1987a, 1987b, 1986, 1983b), and the relationship of the algorithm's point selection techniques to that of perceptual criticality (Jenks 1985; White 1985, 1983; Marino 1979, 1978). The generalization of point and area features has also been addressed by several authors (Monmonier 1983; Chrisman 1983; Lichtner 1978; Töpfer and Pillewizer 1966), but has not received the same level of attention that line generalization has had in the literature.

One of the prevailing issues with these automation attempts is that these efforts have often focused on a single generalization problem in *isolation* from other aspects of generalization, and, more often than not, have dealt with *abstract* graphic entities, rather than digital graphic objects that were representations based upon an underlying geographical frame of reference. Though many authors have repeatedly emphasized that manual generalization not be conducted in isolation or in the abstract (Robinson, Sale, and Morrison 1978; Raisz 1962), many of the early attempts at automation often disregarded that guidance. For example, several automation efforts targeted a single generalization process (such as the selection of point features), and addressed it partially, if not completely, in isolation from other generalization decisions (Catlow and Du

1984; Chrisman 1983; Lichtner 1979). Moreover, development of these generalization techniques rarely considered the underlying geographic significance of the features, and often performed generalization operations on abstract graphic entities. Linear simplification activities are an ideal example (Vanicek and Woolnough 1975; Gottschalk 1973; Douglas and Peucker 1973; Boyle 1970; Maling 1968).

Recently authors have begun to address the issues of isolation and abstraction. McMaster (1989) recently investigated the integration of simplification and smoothing algorithms, which have heretofore been examined in isolation, and has shown some promising results. Mark (1989), in his work on the preservation of the geographic process, and Monmonier (1989) in his examination of the interrelationships between features during scale change, have each explored the issues of abstract generalization, and both provide strong arguments for considering the geographic implications of generalization decisions.

Conceptual Models

At the same time that cartographers have attempted to both precisely define and identify the elements of map generalization, attempts have been made at developing comprehensive conceptual models. Several models from both the European and American literature typify the intellectual work in this area.

The Ratajski Model

A significant conceptual model from the European literature was developed by the late Polish cartographer, Lech Ratajski, in the work entitled, "Phenommenes des points de generalisation" (Ratajski 1967). The conceptual framework of Ratajski identified two fundamental types of generalization processes: (1) **quantitative** generalization, which consists of a gradual reduction in map content depending on scale change; and (2) **qualitative** generalization, which results from the transformation of elementary forms of symbolization to the more abstract forms (Figure 2.1). Critical to Ratajski's argument is the concept of a generalization point. A generalization point is reached when map capacity is decreased to the level where a change in the cartographic method of representation is necessary. The changing capacity of the map may be represented by a triangle where the base of the triangle depicts maximum capacity and the apex depicts the limit (minimum capacity). Each horizontal slice through the triangle represents a given level of generalization and when map capacity approaches the apex of the triangle, a new cartographic method must be applied. At this stage, as is illustrated on Figure 2.1, the individual homes must be replaced with new symbolization for the settlement as a whole, which now represents a point or line method of qualitative generalization.

Under further reduction, an additional generalization point occurs with an accumulation of qualitative facts. Now the generalized form of the built-up areas are converted to quantitative symbolization and, specifically, the populations of the original houses are aggregated into settlements and represented with graduated circles. This particular transformation would be termed quantitative. A further abstraction of these data involves the application of interval methods where the settlements, now classified according to raw magnitude, are converted into intervals of

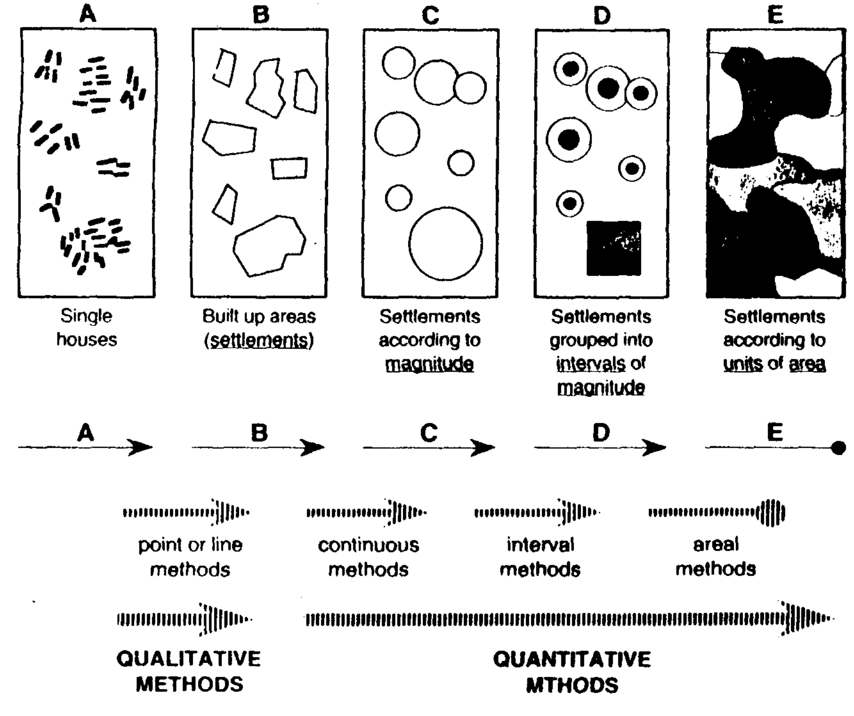

FIGURE 2.1 THE RATAJSKI MODEL OF GENERALIZATION. Ratajski's model of generalization consists of two components: quantitative and qualitative generalization. A combination of these two components results in a successively abstract representation of features as a generalization point is reached. This point indicates the map capacity has decreased to the level where a change in the cartographic method of representation is necessary.

magnitude. A last transformation represents the intervals as areas and applies areal symbolization.

The Morrison Model

A different type of model (Figure 2.2), developed by Joel Morrison in the mid–1970s, formalized the relationships among the four basic elements of generalization (**simplification**, **classification**, **symbolization**, and **induction**), as established in Robinson and Sale (1969). Morrison viewed each of these elements, or what he termed generalization processes, in terms of probable transformation characteristics of a set of elements C, where C was defined as a proper subset of SCR, or the sensory elements of the cartographer's reality (Morrison 1974, 117). The comprehensive process of mapmaking, termed composite transformation g1, related the physical elements on the map, PM (physical map) to the sensory elements of the map reader's reality, called SRR. In terms of formal set theory, Morrison viewed each of the individual transformations as having the property of one–to–one (injective), onto (surjective), or both (bijective). Selection, according to the Morrison framework, was a preprocessing step to actual generalization. Within the process of map generalization, the first element was defined as classification. Classification, in which the cartographer takes the consciously–selected set C and categorizes the features, was considered to be an onto, but not a

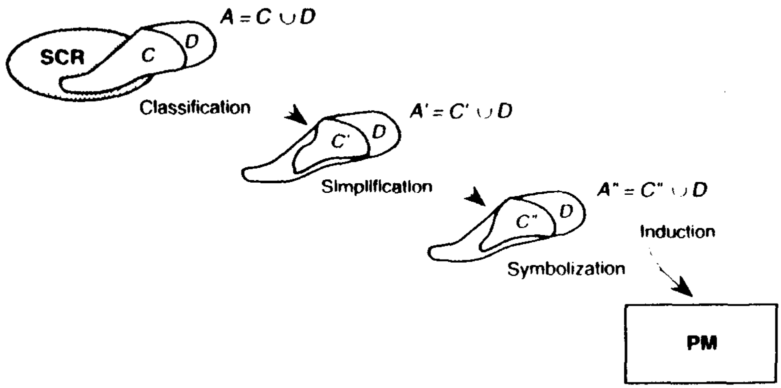

FIGURE 2.2 THE MORRISON MODEL OF GENERALIZATION. Using formal set theory, Morrison (1974) modeled the generalization process using the four generalization processes (simplification, classification, symbolization, and induction), as established in Robinson and Sale (1969). SCR here denotes the cartographer's reality, and PM denotes the physical map.

one-to-one process. Similarly, Morrison defined the transformations of simplification, symbolization, and induction.

The Brassel and Weibel Model

One of the most detailed conceptual models of map generalization to date was recently developed by Kurt Brassel and Robert Weibel of The University of Zurich (Brassel and Weibel 1988). The model published by these authors isolated five separate processes of generalization in a digital environment and thus is one of the first to focus specifically on automated generalization (Figure 2.3). The five processes include: (a) structure recognition; (b) process recognition; (c) process modelling; (d) process execution; and finally (e) data display. **Structure recognition** is the activity where specific cartographic objects, or aggregates of objects, as well the spatial relations and measures of importance, are identified. Structure recognition, which is controlled by the objectives of generalization (original database quality, target map scale, and communication rules) is followed by **process recognition**, which identifies the exact generalization process. This involves the identification of both the types of data modification and parameters of target structures that are necessary. Process

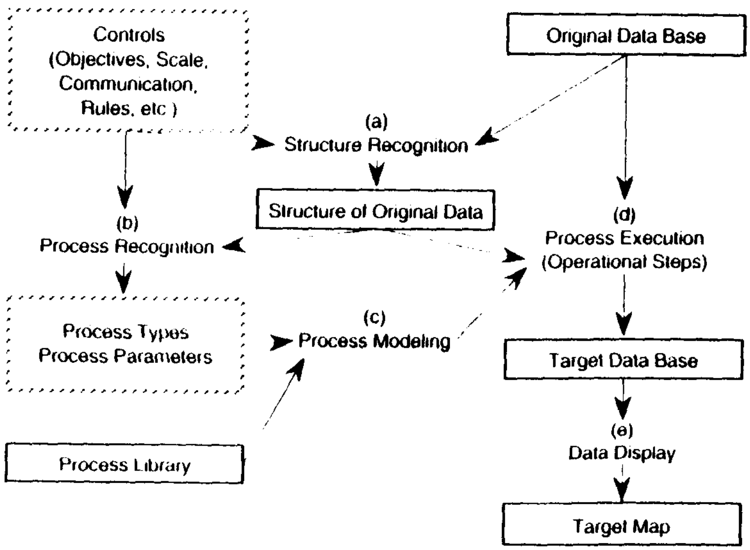

FIGURE 2.3 THE BRASSEL-WEIBEL MODEL OF GENERALIZATION. The generalization process is decomposed into five processes: (a) structure recognition, (b) process recognition, (c) process modelling, (d) process execution, and (e) data display.

recognition specifically determines (a) what is to be done with the original database, (b) what types of conflicts have to be identified and resolved, and (c) which types of objects and structures are to be carried in the target database (Brassel and Weibel 1988, 231-232). Next is **process modelling**, which compiles rules and procedures from the process library. Digital generalization takes place with **process execution**, where the rules and procedures are applied to the original database in order to create the generalized output. As a last process, **data display** converts the target data to the target map. Brassel and Weibel also focus on two distinctly different types of objectives for digital generalization: statistical and cartographic. Statistical generalization is defined as a filtering process, where the major concern is on data compaction and statistical analysis. Conversely, cartographic generalization modifies the localized structure of the map in order to improve visual effectiveness. In summary, map generalization, as defined by the authors, is part of spatial modeling. More details may be found in Brassel and Weibel (1988) or McMaster (1991).

The Nickerson and Freeman Model

In 1986, a different type of model was developed for the potential application of expert systems to cartographic generalization (Nickerson and Freeman 1986). One of the interesting ideas presented by Nickerson and Freeman was the concept of an intermediate scale map (Figure 2.4). Given a source map with known scale (denoted 1:m), symbol size a and area w * h, an intermediate scale map is derived. The intermediate scale

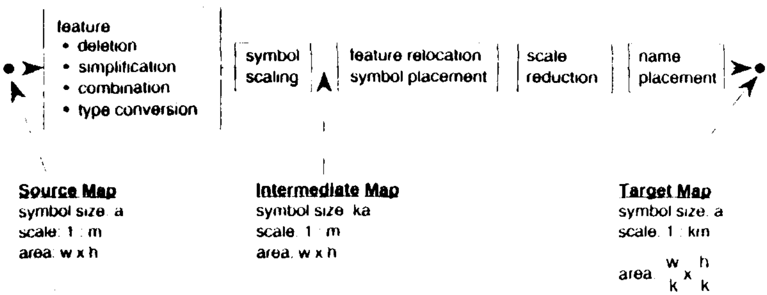

FIGURE 2.4 THE NICKERSON–FREEMAN MODEL OF GENERALIZATION. Original map is transformed to the target map by first deriving an intermediate scale map which is used for feature relocation and symbol placement. The original map undergoes the four generalization operators: deletion, simplification, combination, and type conversion.

map simply enlarged the symbol size to ka, where k is a factor greater than unity. While the initial feature modification operators (generalization operators) — **deletion, simplification, combination,** and **type conversion** — are applied to the source map, both feature relocation and symbol placement occur at the intermediate scale. Thus the authors provide an interesting solution to map generalization by displacing the modified features and selecting the position for symbols at an enlarged scale. A target map, with symbol size a, scale 1:km, and area w/k * h/k, is produced from scale reduction and subsequent name placement. An operational generalization system, based on this concept of the intermediate scale map, has been published by Nickerson (1988).

Over the past twenty years, much solid work, both in terms of defining the process of generalization (in both a manual and digital mode) and in developing models, has been completed. Unfortunately, none of the approaches thus far has attempted to define the problem of generalization from both a philosophical and technical perspective. What are the intrinsic goals of generalization? What operations do we have available to us presently that enable generalization? How do cartographers make decisions as to when they should generalize? Is it purely scale dependent? The following chapter, based on the definition established in Chapter 1, provides a comprehensive generalization model, including both philosophical and technical considerations.

3

A Comprehensive Conceptual Model

McMaster and Shea (1988) proposed the first comprehensive, conceptual generalization model based upon a philosophy of *digital* generalization. In that model, the generalization process was decomposed to three operational areas: (1) a consideration of the philosophical objectives of **why** to generalize; (2) a cartometric evaluation of the conditions which indicated **when** to generalize; and (3) the selection of the appropriate spatial and attribute transformations which provided the techniques on **how** to generalize (Figure 3.1). The discussion that follows will explore each of these three areas as they are manifested within the digital generalization process.

Philosophical Objectives

The first component of the conceptual model examines the intrinsic objectives of **why** cartographic generalization is conducted within a digital environment (Figure 3.2). These objectives include (a) an adherence to general, intuitive cartographic principles *(theoretical elements)*, (b) attendance to the specific requirements of the generalization problem being considered *(application–specific elements)*, and (c) consideration of existing

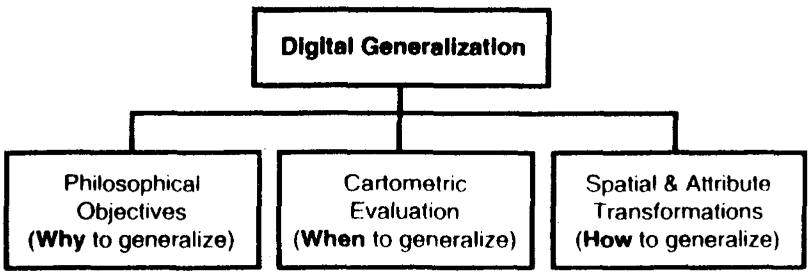

FIGURE 3.1 A CONCEPTUAL FRAMEWORK FOR DIGITAL GENERALIZATION. The digital generalization process consists of three critical components: **why**, **when**, and **how** to generalize.

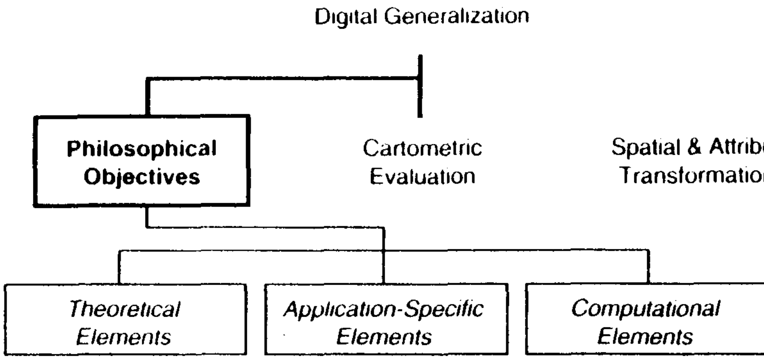

FIGURE 3.2 PHILOSOPHICAL OBJECTIVES. The **why** aspect of the digital generalization process decomposes into three elements: theoretical, application–specific, and computational.

computing technology demands and capabilities *(computational elements)* (McMaster and Shea 1988).

Theoretical Elements

From a theoretical perspective, generalization techniques help counteract the undesirable consequences of scale reduction. To guide the generalization process in the digital domain, six *theoretical elements* may be distinguished:

[1] reducing complexity,
[2] maintaining spatial accuracy,
[3] maintaining attribute accuracy,
[4] maintaining aesthetic quality,
[5] maintaining a logical hierarchy, and
[6] consistently applying generalization rules.

Each of these theoretical elements is discussed below.

Reducing Complexity. Complexity, for the purpose of this discussion, is a measure of the visual interaction of various graphic elements within a map. The number and/or diversity of these graphic elements within a given area impacts the efficacy with which the mapped information is communicated to the reader. Complexity results as the scale is reduced and features become cluttered in appearance. Identifying, analyzing, and defining appropriate levels of complexity is perhaps the most difficult problem in generalizing maps in digital mode, because it requires that many spatial and attribute transformations be applied either iteratively or simultaneously. The process of map generalization must consider this need to reduce complexity in order to develop a more effective map presentation and, therefore, improve the transmission of the map's message to the user. An example will help to illustrate this concept of map complexity.

In Figure 3.3, a portion of a large–scale map is shown along with two smaller–scales representations. The large–scale map at the top illustrates a complex map image, in that many diverse graphic elements are contained within a small physical space on the map. The scale–reduced version on the bottom left demonstrates no generalization, and illustrates a significant increase in the visual complexity as a result of the increased crowding of features. The reduction on the bottom right applies some rudimentary generalization to the original map in order to limit the effective crowding of features within the available map space. Here, the effect of the application of generalization is to greatly reduce the complexity of the smaller–scale representation.

Maintaining Spatial Accuracy. Shiryaev (1987, 11) states that the principal requirement in cartographic representation is the "... spatial conformity of the qualitative and quantitative parameters of objects and phenomena to their actual distribution." On small–scale maps these requirements prove to be impracticable because of generalizations entailing the diminution of images. On large–scale maps, however, Shiryaev notes that the "accurate representation of metric parameters of objects and their outward geometrical likeness (accurate representation of boundaries, areas, extent of objects, etc.)" are of paramount importance. In effect, what Shiryaev is referring to is the maintenance of spatial, or positional, accuracy of the depiction. The goal of maintaining spatial accuracy is clear and measurable since spatial accuracy can be directly related to displacement between the original and generalized features. Displacement refers here to the planimetric difference, and can be assessed by vector or areal displacement measures, such as those documented by McMaster (1986). One goal of generalization is to limit the total displacement *error* between each feature and their generalized representations. Jenks (1989) provides an excellent summary of this process. Figure 3.4 illustrates this concept.

Maintaining Attribute Accuracy. The retention of spatial accuracy deals with geographical data — the cartographic features (points, lines, and areas) that build the digital database. One must also consider the accompanying attribute data associated with these spatial representations. For

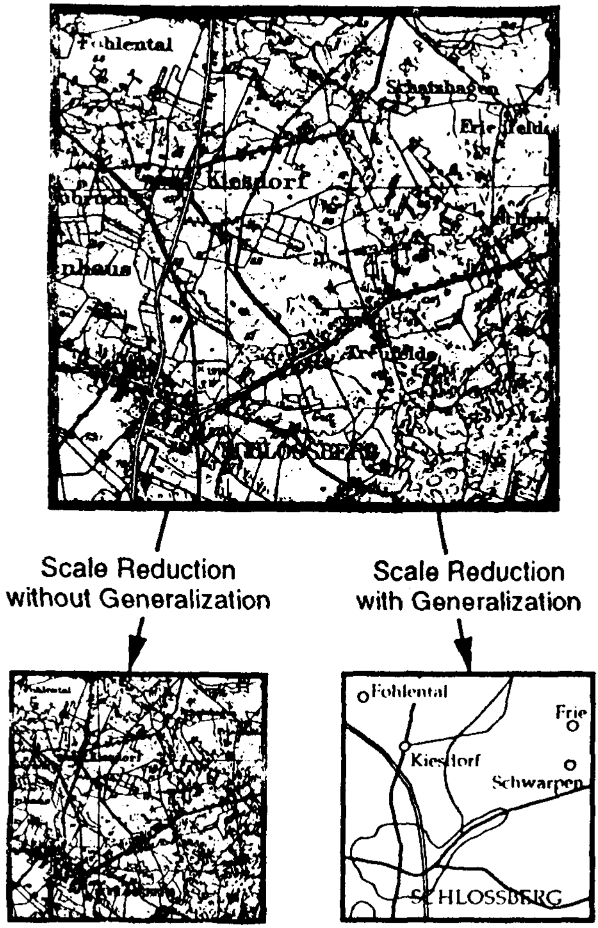

FIGURE 3.3 COMPLEXITY REDUCTION. A 1:100,000-scale map has undergone scale-reduction to 1:50,000. On the left, no generalization has been applied, resulting in a complex map graphic; on the right, a judicious application of generalization techniques has been applied. The generalized version clearly demonstrates a less complex map.

the most part, this goal is purely numerical in nature and involves both statistical analysis and classification methods. It is also a more important concern with thematic mapping than with general or topographic mapping. The overall objective here is to minimize the *unintentional* alteration of the feature attributes which will, in turn, affect the spatial representation of the features. McMaster and Monmonier (1989) discuss the concept of attribution retention as a form a *categorical generalization*. An example will help to illustrate.

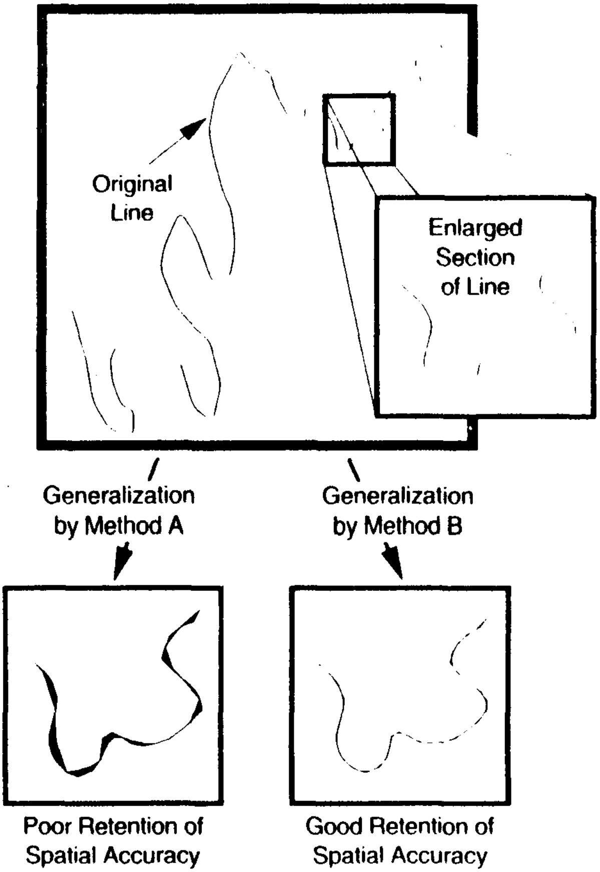

FIGURE 3.4 RETENTION OF SPATIAL ACCURACY. A linear feature has undergone simplification by two different methods. Superposition of the original and simplified lines results in lines of varying thickness. Little thickness change illustrates highly-coincident lines, while thick, or varying thicknesses illustrates locational differences between the original line and its simplified representation. An enlarged section of the line illustrates that Method B had a better retention of spatial accuracy than did Method A.

Consider the land-use/land-cover map depicted in Figure 3.5. Here, patterns of land use and land cover have been classified using the system designed by the United States Geological Survey (USGS) (Anderson, et al 1976). This system is characterized by a hierarchical structure, with two published levels of detail, representing approximately 1:250,000-scale and 1:100,000-scale classifications for Levels I and II, respectively. The classification scheme employs a technique where the first number indicates the

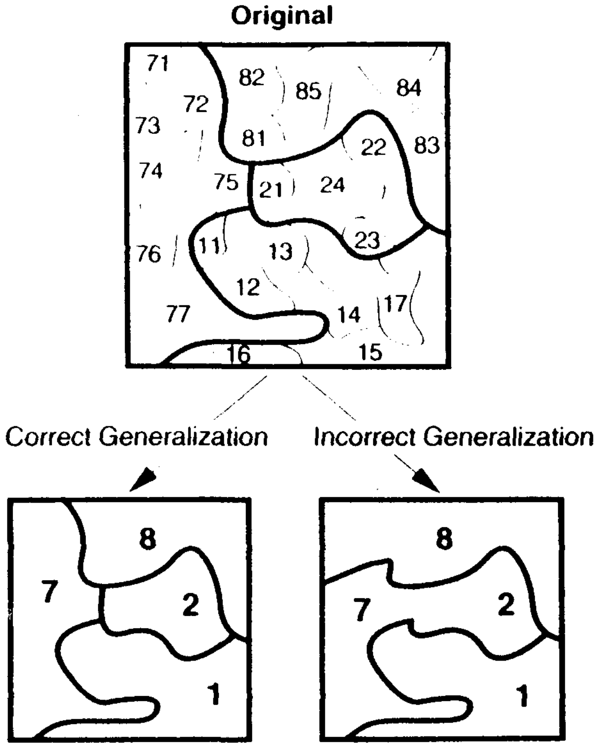

FIGURE 3.5 RETENTION OF ATTRIBUTE ACCURACY. The original land-use/land-cover map has been generalized by combining categories of like attribution. The generalization on the left has maintained the proper hierarchical structure of the land-use/land-cover classification. On the right, several areas of attribution have been incorrectly summarized into the parent class.

Level I category and the second number indicates the subcategory. For example, areas designated as 81, 82, 83, 84, and 85 represent subcategories of the Level I classification of Tundra (8); specifically, Shrub and Brush Tundra (81), Herbaceous Tundra (82), Bare Ground Tundra (83), Wet Tundra (84), and Mixed Tundra (85).

In this particular example, the detailed original map has been generalized by combining categories of like attribution. On the left, the hierarchical structure of the classification has been maintained by combining all the Level II designations into their appropriate parent Level I category. On the right, the attributes associated with the Level II designations have been incorrectly summarized into improper Level I designations in several locations. As a result, the spatial depiction of the feature classes has been

Maintaining Aesthetic Quality. The overall aesthetic quality of a map — either manually or digitally produced — is dependent upon a multitude of factors, including the appropriate and consistent use of: figure–ground relationships, overall balance, layout, typography styles and positioning, and color or gray tones. Cartographers have spent a great deal of effort trying to establish guidelines for proper cartographic design and, although specific rules for good design are difficult to formulate, general guidelines are now being established. It must be recognized, however, that imposing absolute precepts upon cartographic design is synonymous with asking an artist for rules to be used in creating a masterpiece. As is commonly stated in c<u>art</u>ography, the <u>art</u> must be retained.

Despite efforts in establishing guidelines for proper design, many fundamental elements of cartographic design will to some extent always remain subjective. Some commonly used digital generalization operations, however, may be implemented in order to maintain the aesthetic quality of the digital map. Some of these include the use of smoothing algorithms to counteract the undesirable consequences of digitization, the implementation of anti–aliasing routines to eliminate the constraints of a raster matrix, and the prudent application of displacement routines to prevent a confusing coalescence of linear detail.

Maintaining a Logical Hierarchy. A map must contain an ordering of the mapped features. Large cities must be more prominent than smaller cities, interstate highways more prominent than country roads, and oceans more prominent than ponds. This seems relatively straightforward for a single class of features like roads, but becomes more difficult when dealing with the entire mapped image in the sense that areal, linear, and point features must all be considered in a holistic sense. Importance or prominence within a particular feature category does not imply importance or prominence within the overall map image. The major determinant of the graphic hierarchy amongst the features is the map purpose.

Consider, for example, the situation where a large–scale topographic map (such as a 1:5,000–scale) is reduced to a 1:25,000–scale. Following typical generalization practices, many small streams and trails and limited access roadways would be deleted or modified in their representation as a result of the generalization effort. Other features, such as the depiction of airfields and interstate highways would then tend to dominate the map due to their *relative* importance. If, however, the purpose of this reduced–scale map is to support hikers or campers, the location of water, hiking trails, and the access to emergency facilities becomes of paramount importance. Clearly, the logic of the hierarchy has not been maintained in accordance with the map's purpose and intended audience. It is for this reason that the hierarchy of features must be logical.

Consistently Applying Generalization Rules. Many cartographers and designers of geographical information systems truly — and somewhat naively — believe that automation of the generalization process will enable the removal of subjectivity. Nothing could be farther from the truth. The problems here are clearly illustrated with Monmonier's work on raster-mode generalization (Monmonier 1983). There is probably more variation in the selection and application of a generalization algorithm in digital mode than in two manually drafted versions. In order to obtain consistent and unbiased generalizations, cartographers will have to determine three things: (1) exactly, which algorithm(s) to use; (2) the order in which to apply these algorithms; and (3) the input parameters needed to obtain a given result at a given scale. Given that this information might be available (and must be obtained through additional research), a more unbiased and less subjective result is possible.

This is not to say, however, that the cartographer should be completely removed from providing a subjective and artistic element to the cartographic product. Instead, the cartographer should not be encumbered with the mundane, repetitive, and time-consuming tasks that are more appropriately handled by a computer. The development of an intelligent digital generalization system can provide a robust and powerful set of generalization tools that can yield the personalized element to the generalization process. The application of generalization processes which are driven by some formal logic or rule-based system should concomitantly operate in a manner consistent with all other things being equal. Thus, a consistent applications of rules is necessary.

Satisfaction of Theoretical Elements. Few of the theoretical elements presented above can be completely assessed and satisfied with current computing technology. Maintaining the spatial and attribute accuracies appear within reach, since these calculations merely compute the mathematical relationships between feature locations and/or attributes. The remaining elements, however, can only be partially accomplished, primarily because of the holistic, perceptual nature of the analysis that is required. Since perception is a highly individualistic response to a visual stimulus, cartographers will interpret maps in a way that are expressive of their own needs. As such, even though they may be presented with the same generalization requirements, the individual generalizations will be both particular to, and characteristic of, each cartographer (Shea 1983; 1989).

Application–Specific Elements

The level of generalization must ultimately meet the requirements of a final published map or graphic display. Three *application–specific elements* may be identified for the final application:

[1] map purpose and intended audience,
[2] appropriateness of scale, and
[3] retention of clarity.

Each of these application–specific elements is discussed below.

Map Purpose and Intended Audience. A map is designed for a specific purpose and an intended audience, both of which contribute to the map's overall structure and selection of design elements. This is true for both manual and computer–assisted cartography, as well as those displays and products created as a result of a GIS application. Given a digital database which represents the spatial and geostatistical nature of a geographic location, two users may apply the spatial and attribute transformations differently, in a fashion which directly serves the needs of their unique applications. The generalization of most features for these two intended purposes would be accomplished with entirely different goals in mind. An example may help to illustrate this concept of map purpose (see Figure 3.6).

A group of construction engineers assessing the viability of constructing a new road between two villages require a scale of presentation and information content which can support geologic interpretation, environmental impact assessment, and political jurisdiction determination. The compilation, selection, and portrayal of information to support this need may be very esoteric. Alternatively, a farmer who owns the land through which that road will run might require a significantly different focus in the map's content, format, or style in order to develop an appropriate fertilization plan. Here, the representation of soil orders, suborders, and watershed locations to support crop yield projections would be a more veritable need. Though these two distinct applications may be developed from the same data source, the generalization processes involved, as well as the method in which they are applied, would be specific to each application.

The intended audience of a map is a related concern. Again, an example may help to illustrate this concept. Suppose a digital database contained topographic, hydrographic, and bathymetric data for a given geographical region, and this information is used for generating several

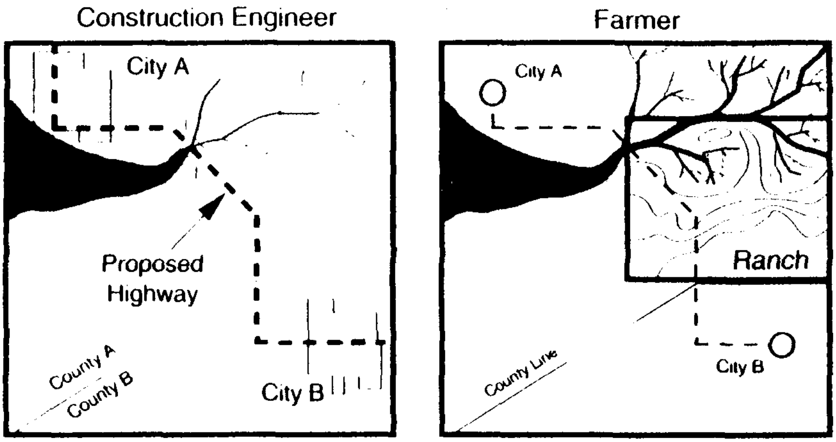

FIGURE 3.6 DIFFERENCES IN MAP CONTENT BASED ON MAP PURPOSE. The purpose of a map can significantly affect the type, numbers, and spatial representation of features placed on a map. The dominance of cities, transportation networks, and political boundaries in the map on the left is necessitated by the user's application; in this instance, a construction engineer. A farmer's needs are vastly different and, as such, the map on the right reflects these needs by the dominance of contours and drainage patterns on his land.

types of products. In addition to product scale, the cartographer also must be cognizant of the map's intended audience, since the rules of generalization required to develop a topographic map and a bathymetric chart differ. Common features located near the shoreline are affected differently during scale reduction because of these differences. In a topographic map, for example, multiple *ruins* existing in the database would be aggregated and depicted as a continuous areal feature with a label of 'ruins.' Conversely, the ruins might be deemed insignificant and dropped entirely from the bathymetric chart at the reduced scale, or perhaps depicted only as a point feature labeled 'Ru.'. Even though both products were derived from the same database at the same scale, the intended audience required a much different utilization of generalization operators.

Appropriate Scale. It is important that the selection of a final map scale coincide the map's purpose and intended audience. This target scale will determine, to a large extent, the amount and type of information which remains subsequent to the generalization. The *amount* of detail retained after generalization is a direct function of a change to a target scale, though precise mathematical relationships between features retained and scale change have not yet been clearly established. Töpfer and Pillewizer's (1966) well known Radical Law (or uniform density law) does provide a cogent measure of how many features should be retained, but it neglects the important selection and distribution of specific entities, and does not directly address local feature density, which relates more directly to map clutter than does the measure of the aggregate number of features. The extent to which details can be retained ($n_f = n_a \sqrt{M_a / M_f}$) relates the number of features n_f on a map at scale M_f to be retained from a source map at scale M_a having n_a features. Unfortunately, this Law does not address the geometric alterations that occur with scale change, such as the amalgamation of point features and associated redefinition as an area feature.

In addition to the need to decrease the absolute numbers of features at a reduced scale, the reduction of scale will also impact the manner in which features are symbolically portrayed; thus, the *type* of features will be impacted by changing scale. Area features will collapse to lines and points, multiple point features aggregate to areas, multiple area features amalgamate into new areas, and linear and point distributions are refined to depict representative patterns. Features may also undergo exaggeration or displacement to successfully communicate the intended message within the graphic constraints of the map or digital display.

Retention of Clarity. Maintaining clarity refers to the absolute legibility or readability of the map. Cartographers have long realized that it is not possible, under any circumstances, to reduce the map scale and yet retain the original level of detail. One excellent example of maintaining the clarity of the map relates to the reduction of scale to the degree at which the size and extent of features exceed the visual acuity of the eye. The reduction of objects in map space cannot be indefinite, and must terminate, at a minimum, at the limits of acuity of the human eye. Studies have shown that this relates to roughly 0.02mm at a distance of 30cm from the eye; any features smaller than 0.02mm cannot usually be distinguished.

It is not realistic, however, to reduce the objects on the map to this barely perceptible realm, since in addition to the diminishment of visual importance, the effects of lighting and printing methods on the communicative efficiency of the products can be significantly impaired. The scale reduction aspects of generalization must weigh the relationship between what *is* and what *is not* shown with the overall clarity of the resulting product. Map authors strive to maintain clarity during digital generalization by selectively manipulating the mapped image using spatial and attribute transformations.

Certainly one obvious, yet often overlooked, objective of digital generalization is to satisfy the aesthetic requirements for the final cartographic application. Although spatial databases contain a wealth of geographic information for many potential applications and areas, most of the potential uses will not require the complete data set. To achieve product clarity, in which the legibility or readability of the map is maintained, a computer–assisted feature selection process would need to eliminate features depending upon priorities wherein lower priority or non–required types of features would be suppressed in order to avoid cluttering the map. Map authors can maintain such clarity by manipulating the mapped image using a variety of operators such as simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, exaggeration, enhancement, and displacement.

Satisfaction of Application–Specific Elements. Determination of the appropriate amounts of detail for a given scale, along with the proper degree of clarity in its presentation, are probably two of the greatest unknowns in the manual generalization process. The sophistication of current computing technology is limited at best in conducting these operations in a digital environment, since these operations essentially supplant the cartographer in his most basic role. On the other hand, achieving a generalization to support a specific map purpose and intended audience is clearly a reachable goal. The ability to accomplish this is limited only by map author's ability to define these concepts and successfully communicate his ideas. The efficacy with which a map author can ultimately communicate geographic information can be limited, however, by a deficiency in his own knowledge of map structure and mapping techniques, a lack of any substantial frame of basic geographic reference, and by the perceptual variations that exist in map users (Shea 1983; 1989).

Computational Elements

The computational perspective of generalization is of significant importance in the digital domain. Here, a cartographer generalizes to balance the relationship between sampling interval of data, data complexity, storage availability and requirements, and CPU–needs. Three computational elements should be considered:

[1] cost effective algorithms,
[2] maximum data reduction, and
[3] minimum memory/disk requirements.

Each of these computational elements is discussed below.

Cost Effectiveness of Algorithms. In digital mode, a high priority goal is to reduce the information in a cost–efficient manner. This is relatively easy to achieve if one considers only the speed of the algorithmic process, but is much more complex when considering the appropriateness of the output. For instance, in the generalization of line data, the Douglas corridor simplification algorithm — as reported in Douglas and Peucker (1973) — has been shown to be one of the most cartographically sound approaches by McMaster (1983a), but one of the worst in terms of computation cost requirements. For precise mapping demands, such as the creation of digital databases for analytic purposes, the Douglas routine is perhaps most suitable. For less stringent requirements — simplification of vector data to support raster graphics displays — a more computationally efficient routine such as the Lang (1969) tolerancing algorithm is probably more appropriate.

Of particular importance here is the concept of **generalization quality**, for it is vital to know at what point quality preservation is subordinate to processing time. This will be dependent upon a variety of factors — map purpose, accuracy standards, scale — and is subject to both mathematical and perceptual evaluations. Thus, the overall goal here is to balance the cost of a computer algorithm against the quality of its generalization (McMaster 1987b). Identifying and quantifying the human element — in terms of an acceptable level of generalization quality — is necessary to conduct this type of *cost–benefit* analysis. Comparative measures of algorithm performance versus acceptability has not yet, however, played a key role in generalization studies.

Maximum Data Reduction. A similar consideration of generalization in digital mode is to reduce the data storage volumes of the digital files as much as possible. This is driven by at least three factors: (1) the final scale reduction of the map or resultant graphic display; (2) the output resolution of the graphic device; and (3) the purpose of the map. A description of the relationship between these is provided in McMaster (1987a).

Reducing storage requirements can be achieved by (a) reducing the amount of coordinate information required to represent the spatial entities, and (b) reducing the data structure to more compact, less storage–intensive, forms. In both cases, efforts here should be directed towards maintaining maximum information with a minimum of storage requirements. Significant research has been directed at solving the first of these two important needs (McMaster 1989, 1987a, 1987b, 1986, 1983a; Jenks 1989, 1981; Dunham 1986; Deveau 1985; Dettori and Falcidieno 1982; Douglas and Peucker 1973; Boyle 1970; Lang 1969). In each instance, these linear simplification efforts have investigated ways of eliminating superfluous coordinate pairs in the representation of lines and areal boundaries.

As an example of the second consideration, the development of coding schemes for vector and raster data has hinged primarily on the need for data compression, with specific concern to the type of data captured and stored, as well as the techniques utilized to process and manipulate the data. Though not typically considered a component of the generalization process, this type of data encoding can affect the selection and application of specific generalization operators.

In vector representations, the most common data structure for cartographic applications is the linear list. Here, coordinates representing the delineation of a line would be in the form of (x_1,y_1), (x_2,y_2),...(x_n,y_n). This method of storage is inefficient, however, and can be improved by recognizing that any single point in a rectilinear array has only 8 possible nearest neighbors. As such, an entire curve could be described by an initial (x,y) position followed by a sequence of directions to adjacent points. If the n^{th} point of the curve is at position (i,j), then the change in position from n^{th} point to the $(n+1)^{st}$ position could be identified by a single value. This method of data representation is known as chain coding. The chain code is a slope–intrinsic representation of a shape that has been used extensively for representing curves or sequences of points. Baudelair and Stone (1980), Pavlidis (1977), and Freeman (1961) have each reported on variations of chain coding structures. In Figure 3.7, an example of chain coding is provided.

Several variations of the basic chain code concept have been offered to improve efficiency. One of these is a differential chain code where points are represented by a difference between two successive absolute points. The number of directions is the same as the basic chain code but are given the values: 0, ±1, ±2, ±3, ±4. For smooth curves, the values 0, ±1 occur more frequently. This makes it possible to utilize a variable–length encoding scheme with the differential chain code. Pavlidis (1977) has found that such an encoding usually requires no more than two bits per point on the average.

Two variations of the differential chain code have been described by Baudelair and Stone (1980). The first one is based on the concept of quadrants and uses two bits to represent the differential increment. This scheme divides the eight possible curve directions into four quadrants represented by 0, 1, 2, or 3. Within each quadrant there are three possible directions or increments which are assigned the values 1 to 3. The encoding of a curve would start with the quadrant number (0 to 3) followed by the increment codes (1 to 3) and terminated by a 0. The second scheme divides the set of eight possible directions into eight quadrants. Within each quadrant there are only two possible directions which can be

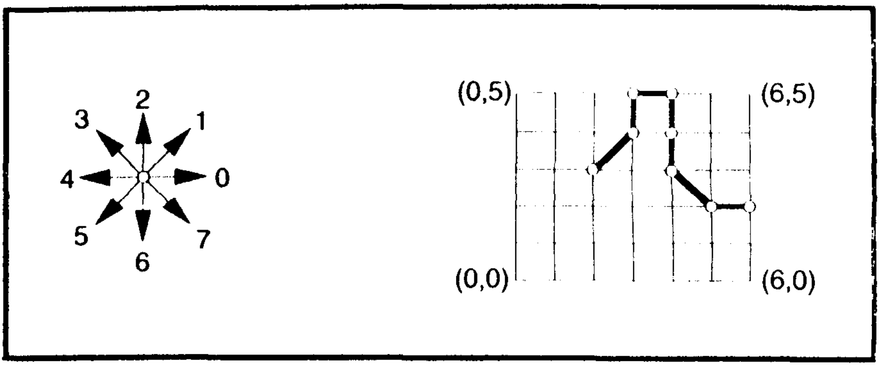

FIGURE 3.7 CHAIN CODING. Chain coding provides a method for representing coordinates in a compressed format. Any point in a rectilinear array has the 8 possible nearest neighbors as indicated by positions 0–7 on the left. In normal Cartesian coordinates, the linear feature of 8 points shown on the right would be represented in (x,y) coordinate pairs as (2,3), (3,4), (3,5), (4,5), (4,4), (3,4), (5,2), (6,2). In basic chain coding, the same line would be (2,3)1206670. Using the variable-length differential chain code, the same line would be represented as +1, +2, 0, –2, –2, –1, 0 (which would be encoded as 0101110011110111110110).

represented by one bit. Two bit streams are used: one indicates the octant followed by the number of one–bit increments; the second holds the actual one–bit increments.

An advantage to the basic chain code scheme is that it provides substantial savings in storage and is computationally efficient. The octal method offers the advantage of understanding the behavior of a curve by examining the octant codes alone. The higher order chain codes appear to provide potential advantages to cartographic data because of improved efficiency in storage, smoothness, and reduced processing times. A disadvantage to chain coding, however, is that since the chain code is a slope intrinsic representation, it is not rotation invariant. In fact, rotating a curve can even change the length of the chain code. Also, higher–order chain codes are complex to encode, and this encoding time may offset storage savings.

Minimum Memory/Disk Requirements. An often overlooked consideration of generalization in digital mode is to reduce the computer memory/disk requirements for conducting generalization transformations. The use of memory–intensive and processor–intensive algorithms on a mainframe computer supporting multiple central processing units (CPUs) and large amounts of random access memory (RAM) (e.g., 32

Mbytes), may not be a deterrent to selecting a particular algorithm. A microcomputer with 640 Kbytes of RAM, however, may necessitate the selection of a slower, lower quality algorithm from a *cartographic* quality perspective due to the imposed limitations on memory and/or CPU. The availability of disk space is also of concern because of possible temporary file creation during generalization operations, and for virtual memory support should resident RAM not be sufficient. Efforts here should be directed towards maintaining maximum quality of generalization with a minimum of storage and memory size requirements.

Satisfaction of Computational Elements. All of the above computational elements can be addressed with current computing technology. Much of the current research in cartographic generalization has been formulated with these three elements in mind and, in fact, the cartographic literature is replete with many exciting research efforts that have specifically addressed at least the first two of these areas. Much research is still required, however, to coordinate these activities with the perceptual and cognitive aspects of cartography. This is necessary because a computationally-fast algorithm that performs some function of generalization speedily and reduces the data set to an exiguous portion of the original data set is of no use to the cartographer if the end product is perceptually unrecognizable from the original data or does not satisfy the purpose of the map. Reporting on the "Geographic Logic in Line Generalization," Jenks (1989) indicated that since the advent of the microcomputer, many map makers have ignored their formal training in cartography, and are losing sight of some of the fundamental tenets of map making. "Education, experience, and geographic thinking," Jenks argues, are necessary preambles to "cartographic decision making." (1989, 40) Algorithm selection must be based both within the perceptual realm of cartographic communication, as well as within the statistical domain of processing efficiency, however the overriding concern should be the geographic integrity of the mapped representation. Current research is addressing such questions.

Cartometric Evaluation

The situations in which digital generalization are required arise ideally due to the success or failure of the map product to meet its stated goals; that is, during the cartographic abstraction process, the map fails "...to maintain clarity, with appropriate content, at a given scale, for a chosen map purpose and intended audience" (McMaster and Shea 1988, 242). As illustrated in Figure 3.8, the **when** of generalization can be

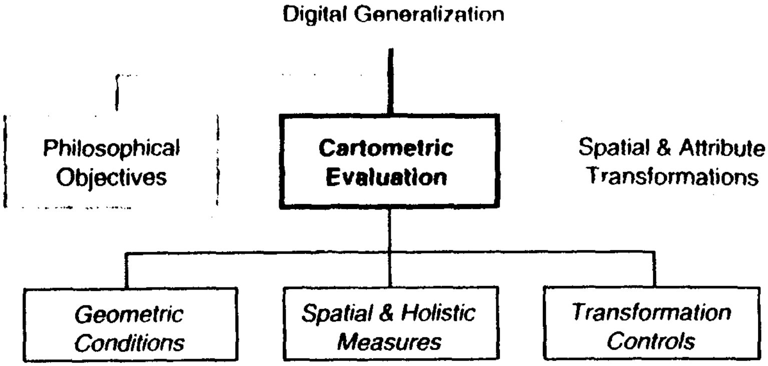

FIGURE 3.8 CARTOMETRIC EVALUATION. Decomposition of the **when** component of the digital generalization process into three parts: geometric conditions, spatial and holistic measures, and transformation controls.

examined from three distinct viewpoints by identifying: (1) the *geometric conditions* under which generalization procedures would be invoked; (2) the *spatial and holistic measures* by which that determination was made; and (3) *transformation controls* of the generalization techniques employed to accomplish the change.

Geometric Conditions

Six geometric conditions that will occur under scale reduction may be used to determine a need for generalization:

[1] congestion,
[2] coalescence,
[3] conflict,
[4] complication,
[5] inconsistency, and
[6] imperceptibility.

Each of these geometric conditions are discussed below.

Congestion. This condition refers to the problem where, under scale reduction, too many geographic features need to be represented in a limited physical space on the map. What results is an overcrowding of the symbols because the feature density is too high. If this congestion is significant, it will detract from the overall communicative efficiency of the map. The efficacy of the map as a communication medium can be greatly improved if a judicious application of one or more generalization process is used to counteract the effects of congestion.

Coalescence. In some instances, the process of scale reduction creates a condition where features are closely, partially, or completely in juxtaposition in their map or geographic coordinate locations. In these situations, features will touch as a result of either (a) the separating distance is smaller than the resolution of the output device (such as, pen width, CRT resolution), or (b) the features will touch as a result of the symbolization process. The existence of this condition represents a need for generalization prior to scale reduction.

Conflict. This condition is identified by a situation in which the spatial representation of a feature is in logical conflict with its background. To illustrate, consider when a linear feature logically exists with an area feature — such as a roadway on a bridge — and these two features have a logical relationship between two points — such as connecting two cities on opposite sides of a river. A conflict could arise during generalization if it was necessary to collapse the underlying stream separating the two cities to the point at which the stream was deleted entirely from the map. If that occurred, the original linear symbols (road and bridge) would now traverse a non-existent stream, and there would be some question as to why a bridge was being depicted. Conflict situations, such as this, must typically be resolved either through symbol alteration, interruption, displacement, or deletion because the geographic features in juxtaposition may not logically related.

Complication. In some situations, the generalization process is dependent upon the specific conditions which exist at a given point in time. Thus, complication relates to an ambiguity in performance, or application, of generalization techniques as a result of those specific conditions. The results of the generalization may consider many factors, including: complexity of spatial data, temporality, selection of iteration technique, and selection of tolerance levels. Buttenfield (1991), for example, has demonstrated the use of line geometry–based structure signatures as a means for controlling the linear generalization process. These situation-specific signatures could drive the generalization process by identifying differing algorithm tolerance values for each feature, or a selected topological component of a feature.

Inconsistency. Conditions which refer to a set of generalization decisions applied non–uniformly across a given map identify inconsistency. Here, a bias in the generalization between the mapped elements is possible. A common example of inconsistency arises when omitting individual buildings from a large-scale map (such as a USGS 1:24,000-scale topographic map). Here, single buildings are commonly represented in rural areas, but are not in urban areas; they are often aggregated, and the entire urban area is symbolized with a pink tint. As in this case, inconsistency is not always an undesirable condition and can be used to highlight or demote a specific portion of the mapped image.

Imperceptibility. During scale reduction, this condition results when a feature falls below a minimal portrayal size for the map. At this point, the feature must either be deleted, enlarged or exaggerated, or converted in appearance from its present state to that of another — for example, the combination of a set of many point features into a single area feature (Leberl 1986). Imperceptibility is one of the more dominant forces in the generalization process.

Identification of Geometric Conditions. It is the presence of the above stated geometric conditions which requires that some type of generalization process occur to counteract, or eliminate, the undesirable consequences of scale change. The conditions noted, however, are highly subjective in nature and, at best, difficult to quantify. Consider, for example, the problem of congestion. Simply stated, this refers to a condition where the density of features is greater than the available space on the map. One might question how this determination is made. Is it computed mathematically, or must we rely upon operator estimates? Is it made in the absence or presence of the symbology? Is symbology's influence on *perceived density* — that is, the percent blackness covered by the symbology — the real factor that requires evaluation? What is the unit area that is used in the density calculation? Is this unit area dynamic or fixed? As one can see, even a relatively straightforward term such as density is an enigma. Assessment of the other remaining conditions — coalescence, conflict, complication, inconsistency, and imperceptibility — can be as equally subjective.

How, then, can we begin to assess the state of a condition if the quantification of the conditions is ill–defined? It appears as though such conditions, as expressed above, may be detected by extracting a series of measurements from the original and/or generalized data to determine the presence or absence of a conditional state. These measurements may indeed be quite complicated and inconsistent between various maps or even across scales within a single map type. To eliminate these differences, the assessment of conditions must view the map as a graphic entity in its most elemental form — points, lines, and areas — and to judge the conditions based upon an analysis of those entities. This is accomplished through the evaluation of *spatial and holistic measures* which act as indicators into the geometry of individual features, and assess the spatial relationships between combined features. Significant examples of these measures can be found in the cartographic literature (Catlow and Du 1984; Christ 1976; Dutton 1981; McMaster 1986; Robinson et al. 1978).

Spatial and Holistic Measures

Conditional measures are assessed by examining basic geometric properties of inter- and intra-feature relationships. Some assessments are evaluated in a singular feature sense, others between two independent features, while still others are computed by viewing the interactions of multiple features. Many of these measures are summarized below. Although this list is by no means complete, it does provide a beginning from which to evaluate conditions within the map which do require, or might require, generalization.

[1] density measures,
[2] distribution measures,
[3] length and sinuosity measures,
[4] shape measures,
[5] distance measures,
[6] Gestalt measures, and
[7] abstract measures.

Each of these spatial and holistic measures is discussed below.

Density Measures. These measures are used to evaluate multi-feature relationships, and can include such benchmarks as the number of point, line, or area features per unit area; average density of point, line, or area features; or the number and location of cluster nuclei of point, line, or area features.

Distribution Measures. These measures are used to assess the overall distribution of the map features. For example, point features may be examined to measure the dispersion, randomness, and clustering (Davis 1973). Linear features may be assessed by their complexity. An example here could be the calculation of the overall complexity of a stream network — based on the average angular change per inch — to aid in selecting a representative depiction of the network at a reduced scale. Areal features can be compared in terms of their relative distance from a common feature or location.

Length and Sinuosity Measures. These measures apply to singular linear or areal boundary features. An example here could be the calculation of stream network lengths. Some sample length measures include: total number of coordinates; total length; and the average number of coordinates or standard deviation of coordinates per inch. Sinuosity measures can include: total angular change; average angular change per inch; average angular change per angle; sum of positive or negative angles; total number of positive or negative angles; total number of positive or negative runs; total number of runs; and mean length of runs (McMaster 1986).

Shape Measures. Shape assessments are useful in the determination of whether an area feature can be represented at its new scale (Christ 1976). Shape mensuration can be determined against both symbolized and unsymbolized features. In general, the most important components of shape are the overall elongation of the polygon and the efficiency or sinuosity of its boundary, but many metrics can be used: geometry of point, line, or area features; perimeter of area features; centroid of line or area features; X and Y variances of area features; covariance of X and Y of area features, and the standard deviation of X and Y of area features (Bachi 1973).

Distance Measures. Between the basic geometric forms — points, lines, and areas — distance calculations can also be evaluated. Distances between each of these forms can be assessed by examining the appropriate shortest perpendicular distance or shortest Euclidean distance between each form. In the case of two geometric points, only three different distance calculations exist: (1) point-to-point; (2) point buffer-to-point buffer; and (3) point-to-point buffer. Here, point buffer delineates the region around a point that accounts for the symbology. A similar buffer exists for both line and area features (Dangermond 1982). These determinations can indicate if any generalization problems exist if, for instance under scale reduction, the features or their respective buffers are in conflict.

Gestalt Measures. The use of Gestalt theory helps to indicate *perceptual* characteristics of the feature distributions through an isomorphism — that is, the structural relationship that exists between a stimulus pattern and the expression it conveys (Arnheim 1974). Common examples of this relationship include closure, continuation, proximity, and similarity (Wertheimer 1958). Although the existence of these Gestalt characteristics is well documented, few techniques have been developed which would accurately serve to identify them.

Abstract Measures. Abstract measures help to evaluate the *conceptual* nature of spatial distributions. Possible abstract measures include: complexity, homogeneity, symmetry, repetition, and recurrence. As with Gestalt Measures, even though the existence of these abstract characteristics is well documented, few techniques have been developed to accurately identify them.

Development of Spatial and Holistic Measures. Many of the above classes of measures can be easily developed for examination in a digital domain. In fact, one could argue that the basic spatial processing algorithms within any GIS can accommodate the measures cited above. The Gestalt and Abstract Measures are not as easily computed, and, therefore, have no analogous counterpart in spatial processing systems. Measurement of the spatial and/or attribute conditions that need to exist before a generalization action is taken depends on scale, purpose of the map, and many other factors. In the end, it appears as though many prototype algorithms first need to be developed and then tested and fit into the overall framework of a comprehensive generalization processing system. Ultimately, the exact guidelines on how to apply the measures designed above can not be determined without precise knowledge of the algorithms.

Transformation Controls

The generalization process is accomplished through the application of a variety of generalization operators — each attacking specific problems — each of which can employ a variety of algorithms. To obtain unbiased generalizations successfully, the order in which the generalization operators are applied becomes as critical as the selection of the algorithms employed by those operators. In addition, the input parameters required to obtain a given result at a given scale plays a significant role in affecting generalization transformations. Concomitantly, there may be permutations, combinations, and iterations of operators, each employing the same convoluted structure of both algorithms and parameters. The three transformation controls critical to generalization are:

[1] generalization operator selection,
[2] algorithm selection, and
[3] parameter selection.

Each of these transformation controls is discussed below.

Generalization Operator Selection. The control of generalization operators is probably the most difficult process in the entire concept of automating the digital generalization process. These control decisions must be based upon (a) the importance of the individual features (this is, of course, related to the map purpose and intended audience), (b) the complexity of feature relationships both in an inter- and intra-feature sense, (c) the presence and resulting influence of map clutter on the communicative efficiency of the map, (d) the need to vary generalization amount, type, or order on different features, and (e) the availability and robustness of generalization operators and computer algorithms.

To date, the selection of a generalization operator has always been a relatively straightforward task, primarily since generalization operations have typically taken place in isolation and in the abstraction (see Chapter 2). Today, however, as generalization operations examine multiple, disparate data types, there is a greater need for assessing the combinatorial nature of operators. Chapter 5 discusses the types of operators, and examines their sequencing and integration.

Algorithm Selection. The relative obscurity of complex generalization algorithms, coupled with a limited understanding of the digital generalization process, requires that many of the concepts need to be prototyped, tested, and evaluated against actual requirements. The evaluation process is usually the one that gets ignored or, at best, is only given a cursory review. One contrary example to this is the extensive work done on evaluating linear simplification algorithms. Over the past twenty-five years, perhaps more research has focused on the development and comparison of simplification algorithms than all other aspects of generalization combined. Still, only recently have these efforts considered the relationships between algorithm selection and perceptual results, the implications of algorithm ordering, and the relationship between algorithms and characteristics.

Nonetheless, algorithm selection continues to be a concern. Suppose that the generalization operators are selected — for example, an initial smoothing, followed by a database simplification, mapping simplification and secondary smoothing — two, and perhaps as many as four, specific algorithms may be necessary in order to simplify a line. Consider then the increased complexity if more than one algorithm is needed within any one of those steps. Processing efficiency and accuracy are two important factors in making the appropriate algorithm selection.

Parameter Selection. The input parameter (tolerance) selection most probably results in more variation in the final results than either the generalization operator or algorithm selection as discussed above. Consider, for example, the six lines illustrated in Figure 3.9. Jenks (1989, 29) used these lines to illustrate the varying character of the lines resulting from increasingly simplified representations. Using one of the lines originally employed by Marino (1979, 1978) in her assessment of characteristic points on naturally occurring lines, Jenks, starting with a digital file containing 875 coordinate pairs, reduced it through a downward geometric

Jenks' Simplification

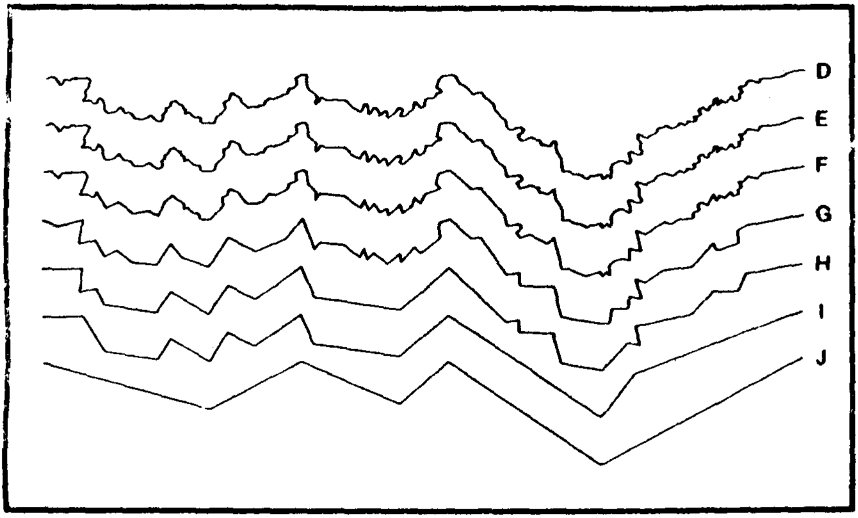

FIGURE 3.9 EFFECTS OF PARAMETER SELECTION ON GENERALIZATION. Lines D through J represent increasingly simplified representations of the Fall River of Utah and Colorado. Starting with a digital file containing 875 coordinate pairs, the original line has been reduced downward through a geometric progression by applying the Douglas simplification algorithm. The resulting simplified lines contain coordinate counts of: D=439, E=220, F=112, G=54, H=28, I=15, and J=7 (after Jenks 1989).

progression by applying the simplification algorithm developed by David Douglas (Douglas and Peucker 1973) and modifying the tolerance band parameter (Jenks 1989).

It is obvious that the increasingly simplified representations have been significantly affected by the modification of the tolerance band parameter. This is true both from a perceptual perspective as well as a more quantitative assessment. In the same article, Jenks evaluated the differences between the lines by using the mathematical measures developed by McMaster (1983b), and found that an 83–fold difference in the sum of the absolute vectors, and a 42–fold difference in the mean absolute vector error existed at the extremes (line D versus line J). These vast differences were proportionally evident even at the moderate simplifications.

Other than some very basic guidelines on the selection of weights for smoothing routines, and the derivation of simplified lines as reported above, practically no empirical work exists for other generalization routines. One recent exception to this is the work by Buttenfield (1991, 1986, 1985) which is directed at quantifying information contained in digitized lines. Once refined, this technique can be used to segment lines according to their *structure signatures* based upon their intrinsic geometry, in order to adjust tolerance parameters of simplification algorithms to each segment (McMaster 1987a).

Ability to Control the Transformations. Current trends in sequential data processing require the establishment of a logical sequence of the generalization process. This is done in order to avoid repetitions of processes and frequent corrections (Morrison 1975). This sequence is determined by how the generalization processes affect the location and representation of features at the reduced scale. Algorithms required to accomplish these changes should be selected based upon cognitive studies, mathematical evaluation, and design and implementation trade–offs. Once candidate algorithms exist, they should be assessed in terms of their applicability to specific generalization requirements. Finally, specific applications may require different algorithms depending on the data types, and/or scale.

Spatial and Attribute Transformations

The final area of discussion considers the component of the generalization process that actually performs the actions of generalization in support of scale and data reduction. This **how** component of generalization is most commonly thought of as the operators which perform the generalization process. These operators have developed from the emulation of manual cartographic practices, and from the development of techniques based solely on more mathematical efforts (Shea and McMaster 1989). Generalization operators perform both *spatial and attribute transformations* to achieve their goals. Spatial and attribute transformations are those modifications made to the digital data, or its method of representation, which strive to alter the method in which the data is statistically categorized or symbolically portrayed. The two types of transformations — spatial and attribute — are not necessarily independent and in many cases are intricately related.

A structural framework for the generalization operators is presented in Figure 3.10. The framework — from McMaster (1989, 1991), McMaster and Monmonier (1989), and Monmonier and McMaster (1991) — illustrates that generalization may address either the *geographical* elements of features (that is, dealing with the spatial component) or the *statistical* elements (focusing upon the attributes). This differentiation identifies the two principal forms of data encoded in digital cartography in the representation of features.

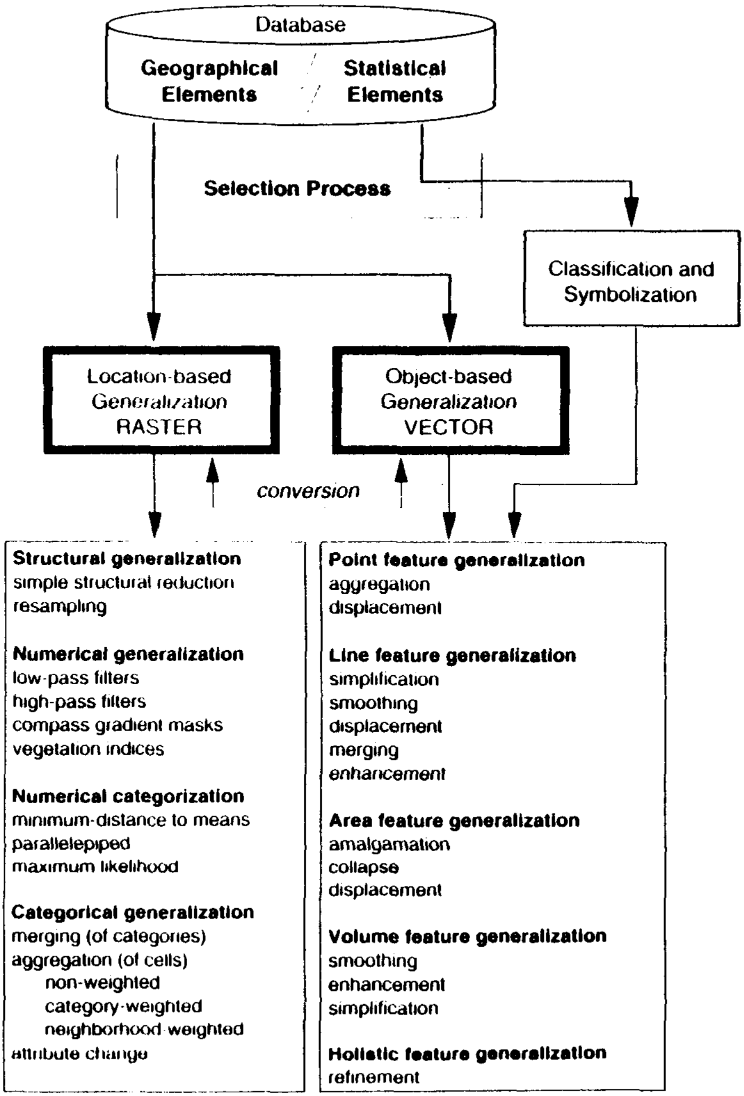

FIGURE 3.10 A FRAMEWORK FOR GENERALIZATION OPERATORS. The structural framework identifies the types of operators which apply to both raster and vector data types.

In considering the process of digital cartographic generalization, nearly all applications of the process have as their first step the *selection* of objects and attributes from the initial database for representation. Although the selection process conceptually is not part of generalization, it must be considered a necessary preprocessing step to the spatial and attribute transformations discussed in this chapter. Before geographical objects or their statistical attributes can be manipulated by the generalization operators, a decision must be made to either include or exclude the object and/or attribute in the generalized map. In Figure 3.10, this initial step is illustrated with the shaded box labeled SELECTION PROCESS. Generalization occurs after the selection process, although, subsequent to generalization, further selection may be necessary.

Once a object or attribute is initially selected, the generalization process continues by the application of *spatial or attribute transformations*, respectively. Geographical generalization involves the geometric manipulation of the object's spatial information, either in *vector* or *raster* format. Statistical generalization involves the processes of either classification and/or symbolization. These two types of generalization, of course, are strongly interrelated. For example, the aggregation of fifty point features may require an adjustment to both the existing classification and symbolization, for instance, for the creation of an area with a fill pattern. Conversely, the classification of three adjacent polygons into the same category may result in the elimination of boundaries.

The division of generalization operators, subsequent to the selection process, into raster and vector is based on the logical organization of geographical space into the two data models. A vector data model is also known as *object-based*, while a raster model may be termed *location-based* (Peuquet, 1988). The vector representation depicts the individual map features, which normally have one or a series of attributes, as points, lines, and areas. The well-known DIME and TIGER data structures developed by the United States Bureau of the Census are vector representations of urban systems. Individual points, such as road intersections are called 0-cells; street segments, or arcs, are called 1-cells; and blocks and other enumeration units used by the census, or polygons, are called 2-cells. Entities in the urban system, then, are represented by point, line, and area features in the database. The location-based, or raster, representation, however, views space differently. Space is divided into homogeneous units, or tiled, thus creating a tessellation, which may be defined as a regular or irregular division of space. Each of the individual cells, or pixels, which may be a variety of shapes including squares, hexagons, or rectangles, within the tessellation is a location and attribute data are gathered for each cell (location). The cells have a spatial resolution such as 10 meters (Système Probatoire pour l'Observation de la Terre (SPOT) panchromatic imagery), 20 meters (SPOT XS multispectral imagery), 30 meters (Landsat Thematic Mapper (TM) Imagery), 79 meters (Landsat Multispectral Scanner System (MSS) Imagery), or 40 acres (Minnesota

Land Information Management Center database). It should be noted that, by gathering information on a cell-by-cell basis, attributes are already generalized. For instance, a Landsat TM image averages reflectance values for the 30m by 30m cell.

Most of the research in digital generalization has been on the development of algorithms, or what have been called the generalization operators, for object-based generalization. The conceptual generalization model presented in this chapter reflects that bias. The remainder of this chapter focuses on the twelve categories of generalization operators that dominate in vector generalization (Figure 3.11). Although these spatial and attribute transformations focused primarily on vector processing, there are, in many instances, logical equivalents to several of the operators in the raster domain. In the following two chapters, more detailed discussions on the various algorithms developed for several of these generalization operators is presented. Chapter 4 reviews methods that have been developed for vector-based generalization, while Chapter 5 reviews methods for raster–based generalization. In both chapters, an attempt has been made to concentrate only on those operators most commonly utilized in current systems and presented in the literature, not to invent approaches that are, as yet, unproved against real generalization problems.

Spatial Transformations

Spatial transformations are those operators that alter the data representation from a geographical or topological perspective. Here, the focus is primarily on the locational aspects of the data and, for the most part, ignores the associated statistical component. Since a map is a reduced representation of the Earth's surface, and as all other phenomena are shown in relation to this, the scale of the resultant map largely determines the amount of information which can be shown. As a result, the generalization of cartographic features to support scale reduction must obviously change the way features look in order to fit them within the constraints of the map.

Data sources for map production and geographic information system applications are typically of variable scale, resolution, projection, and accuracy. Each of these factors contribute to the method in which cartographic information is presented at map scale. The information that is contained within the map has two components — location and meaning — and generalization affects both (Keates 1973). As the amount of space available for portraying the cartographic information decreases with decreasing scale, less locational information can be given about features,

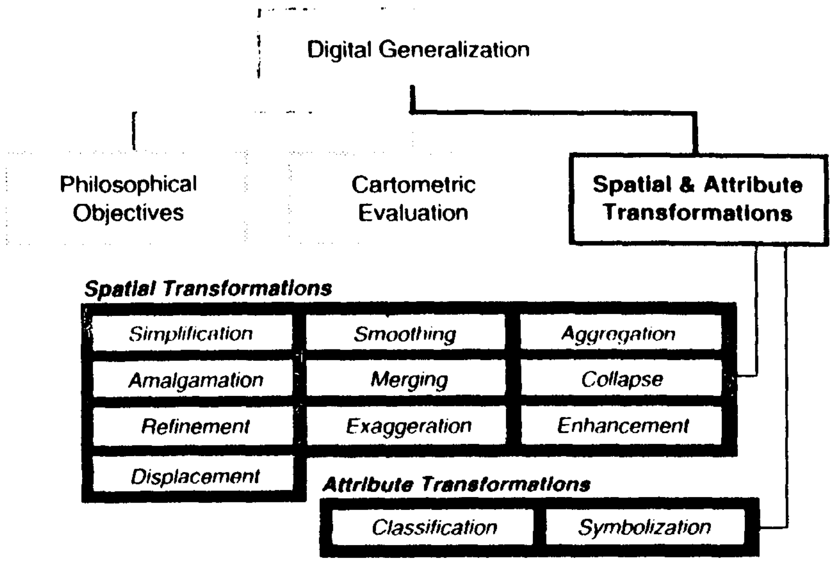

FIGURE 3.11 SPATIAL AND ATTRIBUTE TRANSFORMATIONS. The **how** aspect of the digital generalization process consists of ten spatial transformations and two attribute transformations.

both individually and collectively. As a result, the graphic depiction of the features changes to suit the scale–specific needs. Ten spatial transformations have been identified which control this graphic modification:

[1] simplification,
[2] smoothing,
[3] aggregation,
[4] amalgamation,
[5] merging,
[6] collapse,
[7] refinement,
[8] exaggeration,
[9] enhancement, and
[10] displacement.

In Chapter 4, several of these generalization operators will be examined in greater detail. A quick synopsis of each, however, is provided below. Figures 3.12 through 3.21 provide a set of concise graphics depicting examples of each in a format similar to that employed by Lichtner (1979). Each spatial transformation operator is depicted to illustrate the changes

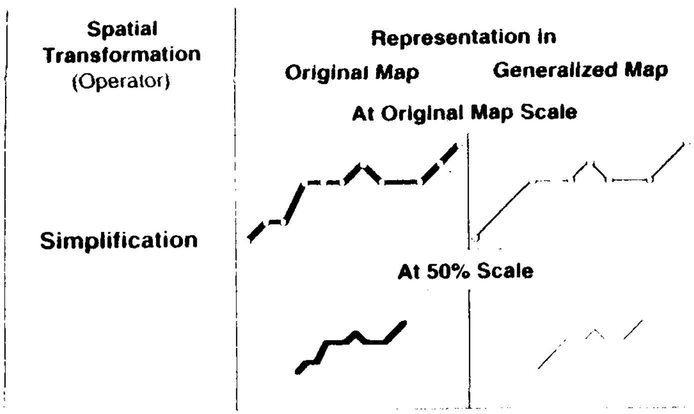

FIGURE 3.12 SIMPLIFICATION OPERATOR. A line feature is represented by 11 coordinate pairs. At a 50% reduction, the line is too wide to clearly depict its character (e.g., sinuosity), and several coordinate pairs are coalescing. On the right, the same original line has undergone a minor simplification to reduce the 11 coordinates down to 7. At a 50% reduction the simplified line has much improved clarity of presentation. In addition, the digital storage requirements have been reduced by 36%.

in feature representation at the scale of the original map and at a reduced (50%) scale.

Simplification. (see Figure 3.12) A digitized representation of a map feature should be accurate in its representation of the feature (shape, location, and character), yet also efficient in terms of retaining a lower number of data points necessary to represent the character. A profligate density of coordinates captured in the digitization stage should be reduced by selecting a subset of the original coordinate pairs, while retaining those points considered to be most representative of the line (Jenks 1981). Glitches should also be removed. Simplification operators will select the characteristic, or shape–describing, points to retain, or will reject the redundant point considered to be unnecessary to display the line's character. Simplification operators produce a reduction in the number of derived data points which are unchanged in their (x,y) coordinate positions. Some practical benefits of simplification includes reduced plotting time, increased line crispness due to higher plotting speeds, reduced storage, less problems in attaining plotter resolution due to scale change, and quicker vector to raster conversion (McMaster 1987a).

Smoothing. (see Figure 3.13) These operators act on a line by relocating or shifting coordinate pairs in an attempt to plane away small perturbations and capture only the most significant trends of the line. A

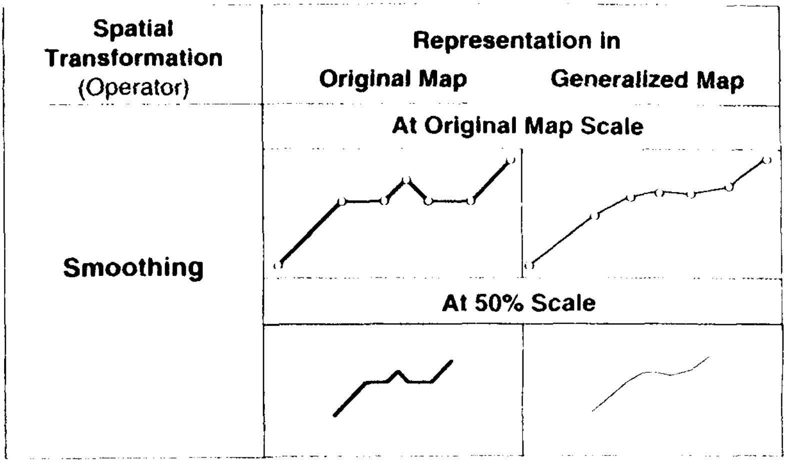

FIGURE 3.13 SMOOTHING OPERATOR. The linear feature represented has undergone a minor smoothing operation to remove the small perturbations in the line. Though the same number of coordinate pairs are found in both the generalized and ungeneralized versions, the generalized version offers a more aesthetically pleasing representation. In addition, as a preprocessing step to simplification, smoothing helps to reduce the overall displacement error between the original and simplified representations.

result of the application of this process is to reduce the sharp angularity imposed by digitizers (Töpfer and Pillewizer 1966). Essentially, these operators produce a derived data set which has had a cosmetic modification in order to produce a line with a more aesthetically pleasing caricature. Here, coordinates are shifted from their digitized locations and the digitized line is moved towards the center of the intended line (Brophy 1972; Gottschalk 1973; Rhind 1973).

The following three operators, *Aggregation, Amalgamation,* and *Merging* are similar in that each, by some geometric approach, joins features together. The difference between the three is that each operates on a different dimensionality of features. Aggregation, for instance, lassos a group of individual *point* features in close proximity and represents this group as one continuous area. This is a 0-dimensional operator. Amalgamation joins together contiguous polygonal units and drops the intervening boundaries. It thus works only on *areal* features or is 2-dimensional. Merging fuses two parallel or closely spaced *linear* features into a single line and as such is a 1-dimensional, or linear, operator.

Aggregation. (see Figure 3.14) There are many instances when the number or density of like point features within a region prohibits each

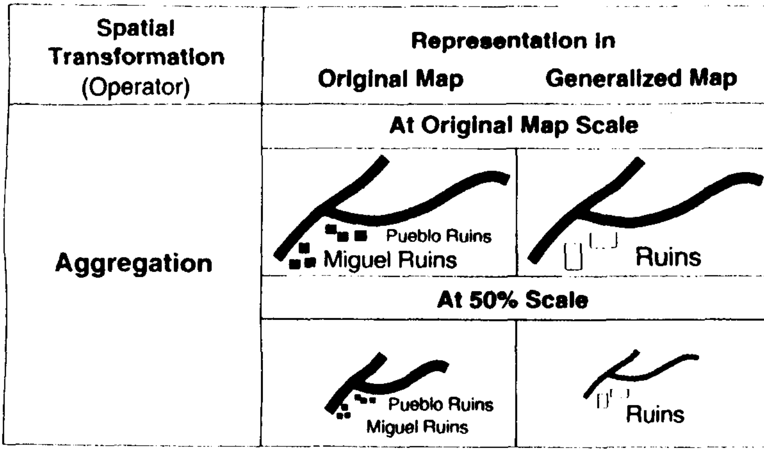

FIGURE 3.14 AGGREGATION OPERATOR. Several point features have represented the location of the Miguel and Pueblo Ruins alongside a road network. In an ungeneralized 50% reduction, the point features have coalesced, and the Ruins and the road network are nearly in juxtaposition. In the generalized version of the same features, the numerous Ruins have been aggregated and undergone a dimensionality change in their representation to become two area features, with a single label of merely 'Ruins.' The 50% generalized reduction is less complex, and still depicts the location and type of features.

from being portrayed and symbolized individually within the map. This notwithstanding, from the perspective of the map's purpose, the importance of those features requires that they still be portrayed. To accomplish that goal, the point features must be aggregated into a higher order class feature areas and symbolized as such. For example, if the intervening spaces between houses are smaller than the physical extent of the buildings themselves, the buildings can be aggregated and resymbolized as *built-up areas* (Keates 1973).

Amalgamation. (see Figure 3.15) Through amalgamation of individual features into a larger element, it is often possible to retain the general characteristics of a region despite the scale reduction (Morrison 1975). To illustrate, an area containing numerous small lakes — each too small to be depicted separately — could with a judicious combination of the areas, retain the original map characteristic. One of the limiting factors of this process is that there is no fixed rule for the degree of detail to be shown at various scales; the end-user must dictate what is of most value. This process is extremely germane to the needs of most mapping applications. Tomlinson and Boyle (1981) term this process *dissolving and merging*.

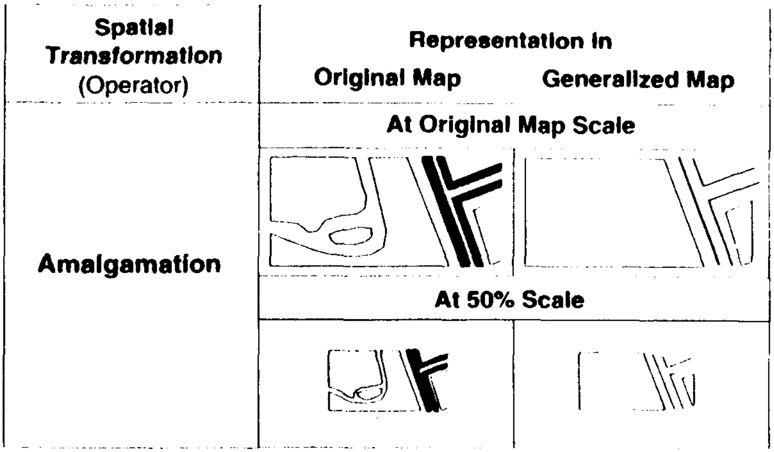

FIGURE 3.15 AMALGAMATION OPERATOR. The three small area features on the left side of the cased road in the full-scale original map coalesce at the 50% reduction when no generalization occurs. Assuming these areas were identified with similar attribution, they could be combined, or amalgamated, into a larger area feature which represents the sum of the others. In the generalized representation this has occurred, and the resultant maps — both at the original scale as well as the 50% reduction — have a clearer demarcation of the boundaries of the amalgamated areas.

Merging. (see Figure 3.16) If the scale change is substantial, it may be impossible to preserve the character of individual linear features. As such, these linear features must be merged (Nickerson and Freeman 1986). To illustrate, divided highways are normally represented by two or more adjacent lines, with a separating distance between them. Upon scale reduction, these lines require that they be merged into one positioned approximately halfway between the original two and representative of both.

Collapse. (see Figure 3.17) As scale is reduced, many areal features must eventually be symbolized as points or lines. The decomposition of line and area features to point features, or area features to line feature, is a common generalization process. Settlements, airports, rivers, lakes, islands, and buildings, often portrayed as area features on large scale maps, can become point or line features at smaller scales and areal tolerances often guide this transformation (Nickerson and Freeman 1986).

Refinement. (see Figure 3.18) In many cases, where like features are either too numerous or too small to show to scale, no attempt should be made to show all the features. Instead, a selective number and pattern of

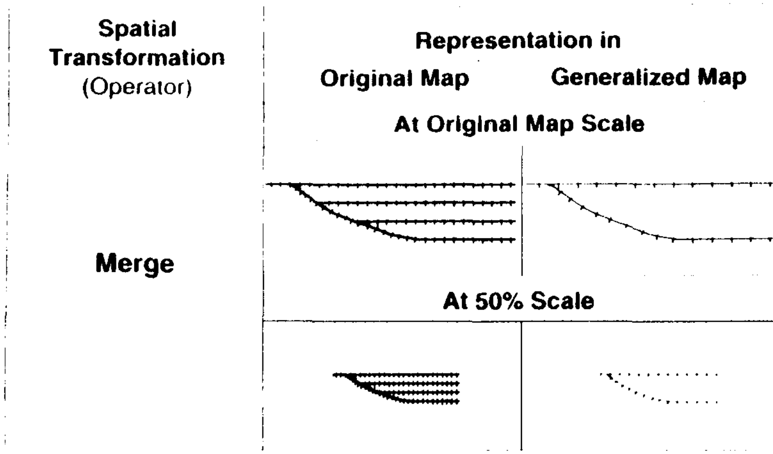

FIGURE 3.16 MERGE OPERATOR. In the ungeneralized, original map scale example, a railroad yard is depicted with 4 tracks, each merging into a main track. Without generalization, the 50% reduction results in a poor depiction of the rail yard because — as the physical separating distance between many of the tracks begins to diminish in an effort to maintain the tracks' true positions and size — they begin to coalesce at the new map scale. A merging together of every second track as depicted in the generalized representation, thereby allowing for this coalescence by limiting the number of features that need to be represented in the limited space on the graphic.

the symbols are depicted. Generally, this is accomplished by leaving out the smallest features, or those which add little to the general impression of the distribution, but can be accomplished by using a representative pattern of the symbols, augmented by an appropriate explanatory note (Lichtner 1979). Though the overall initial features are thinned out, the general pattern of the features is maintained. Examples of this can be found in the excellent treatise on generalization by the Swiss Society of Cartography (1977). This refinement process retains the general characteristics of the features at a greatly reduced complexity.

Exaggeration. (see Figure 3.19) The shapes and sizes of features may need to be exaggerated to meet the specific requirements of a map. In fact, many elements of a map need to be exaggerated because their true physical size at the scale of the map does not support them being depicted in a way that supports the requirements of the map audience. The amplification of environmental features on the map is an important part of the cartographic abstraction process (Muehrcke 1986). The exaggeration

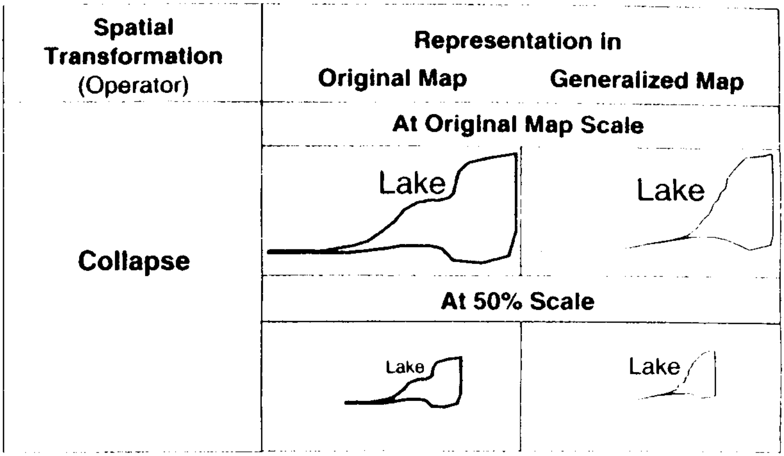

FIGURE 3.17 COLLAPSE OPERATOR. When a river or stream, which is represented by a linear feature, widens into a lake, which is represented as an areal feature, the linear feature reaches a bifurcation point at which time the areal representation can be clearly delineated with no coalescence of the intervening space between the two diverging sides of the areal feature. During scale reduction, the exact opposite process occurs. As the intervening space between two sides of the lake approach coalescence, there is a dimensionality change to a linear feature representation.

process does tend to lead to features which are in conflict and thereby require displacement (Caldwell, Zoraster, and Hugus 1984).

Enhancement. (see Figure 3.20) The shapes and size of features may need to be exaggerated or emphasized to meet the specific requirements of a map (Leberl 1986). As compared to the exaggeration operator, enhancement deals primarily with the symbolization component and not with the spatial dimensions of the feature although some spatial enhancements do exist (such as, fractalization). Proportionate symbols would be unidentifiable at map scale so it is common practice to alter the physical size and shape of these symbols. The delineation of a bridge under an existing road is portrayed as a series of cased lines may represent a feature with a ground distance far greater than actual. This enhancement of the symbology applied is not to exaggerate its meaning, but merely to accommodate the associated symbology.

Displacement. (see Figure 3.21) Feature displacement techniques are used to counteract the problems that arise when two or more features are in conflict (either by proximity, overlap, or coincidence). More specifically, the interest here lies in the ability to offset feature locations to allow

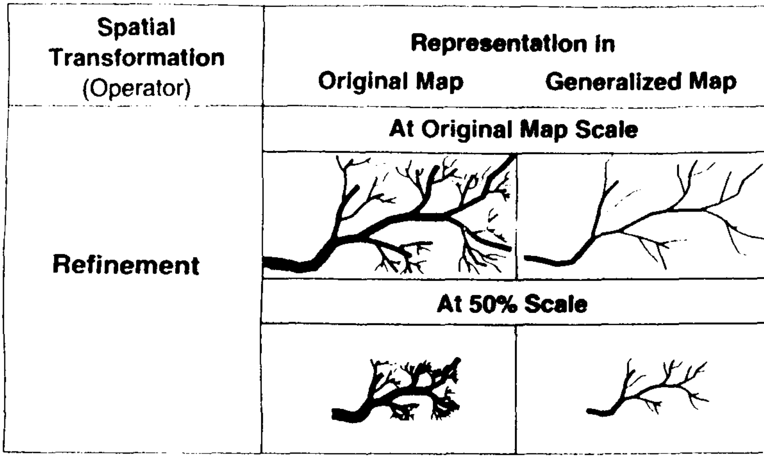

FIGURE 3.18 REFINEMENT OPERATOR. A stream network at the scale of the original map depicts many elements of the network — from the largest stream, to the smallest tributary. As a 50% reduction is done on this complex drainage basin, the sheer number of these tributaries complicates the map almost to the point of limited usefulness. A limited generalization through a refinement of this network distribution — that is, a selection of the essential components of the network — provides the reader with a more effective presentation of the salient aspects of the network both at the original scale and at the reduced scale.

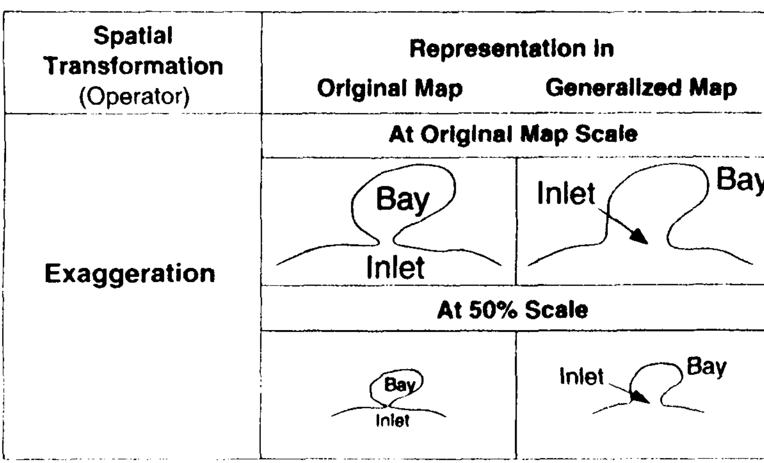

FIGURE 3.19 EXAGGERATION OPERATOR. In the above example, the inlet to the bay — which would normally close down upon itself as a result of a scale reduction — is widened to allow the the map to depict important navigational information for shipping.

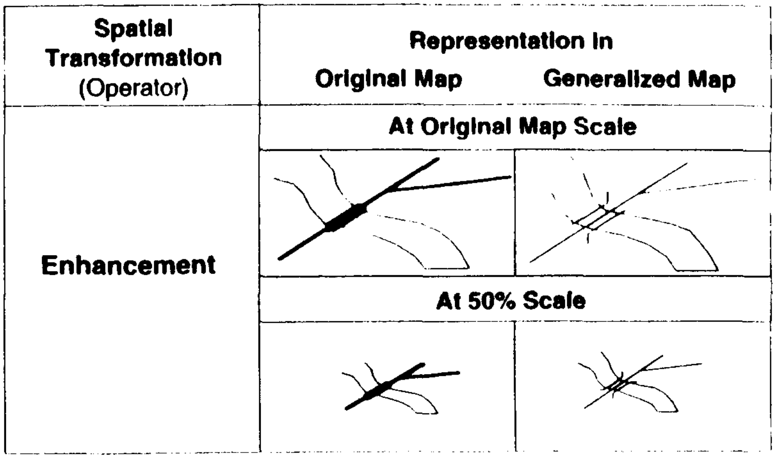

FIGURE 3.20 ENHANCEMENT OPERATOR. A road bridge crossing a stream cannot be accurately depicted at many scales. Since the width of the road is typically the same as the width of the bridge, the bridge must be enhanced in its representation to show that it 'surrounds' the portion of the road that crosses the bridge. In addition, without generalization, a scale reduction of that bridge symbol makes it nearly indecipherable without additional enhancement.

for the application of symbology (Christ 1978; Schittenhelm 1976). The graphic limits of a map make it necessary to move features from what would otherwise be their true planimetric locations. If every feature could realistically be represented at its true scale and location, this displacement would not be necessary. Unfortunately, however, feature boundaries are often an infinitesimal width; when that boundary is represented as a cartographic line, it has a finite width and thereby occupies a finite area on the map surface. These conflicts need to be resolved by (a) shifting the features from their true locations (displacement), (b) modifying the features (by symbol alteration or interruption), or (c) or deleting them entirely from the map.

Attribute Transformations

Attribute transformations manipulate the underlying statistical characteristics of a feature, with the subsequent spatial changes necessary only to depict the changes in attribute information. The reclassification of deciduous and coniferous tree farms into a forest, for instance, is one example. Two attribute transformations have been identified:

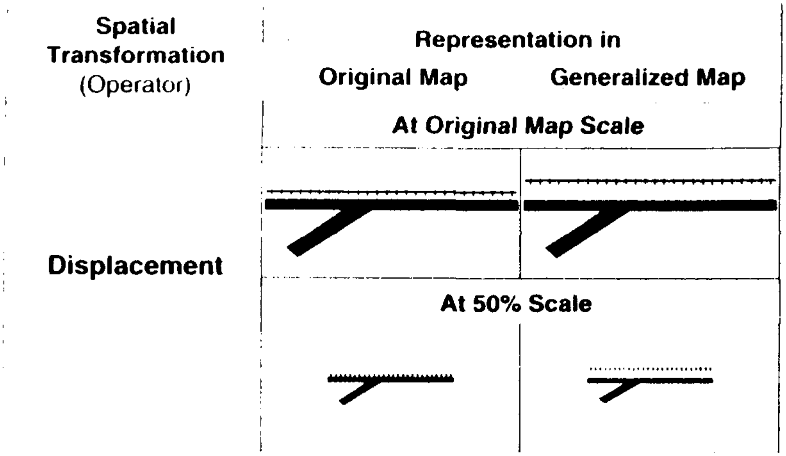

FIGURE 3.21 DISPLACEMENT OPERATOR. Due to the limited physical space available on a map, many features will coalesce after they are symbolized, where previously in an unsymbolized format there were not in juxtaposition. As is the case above, the road and railroad, although physically close, do not really begin to coalesce until after the 50% reduction has taken place. To maintain some degree of visual separation, these two features have been displaced from one another. As is evident in the above figure, without the displacement the two feature collide in map space and become unintelligible. With displacement, however, each feature can be clearly located.

[1] classification, and
[2] symbolization.

Each of these attribute transformation processes are highlighted below.

Classification. One of the principal constituents of the generalization process that is often cited is that of data classification (Muller 1983). Here, we are concerned with the grouping together of objects into categories of features sharing identical or similar attribution. This process is used for a specific purpose and usually involves the agglomeration of data values into groups based upon their proximity to other values along a number line (Dent 1985). The classification process is often necessary because of the impracticability of symbolizing and mapping each individual value.

Symbolization. Robinson defines the symbolization process as "... the assignment of various kinds of marks to the summarizations resulting from classification and to the essential characteristics, comparative significances, and relative positions resulting from simplification." (Robinson et al., 1984, 131) As Robinson points out, the symbolization process makes generalization visible, and is a critical process in preparing the map. In order to represent real–world features on a map, and make those representations meaningful, the graphic depiction of features are systematically adjusted through changes in the primary graphic elements of *hue, value, size, shape, spacing, orientation,* and *location* (Robinson et al., 1984). These elements, together with the classes of symbols, constitute the fundamental elements of all graphics. Bertin (1983) has documented a similar list which he refers to as *visual variables,* though his definitions differ in several aspects.

As an element of the generalization process, symbolization consists at two levels: (1) as a change in scale of measurement from the original data set; or (2) as a change in the data type. Scale of measurement refers to the classic organization of measurement theory which involves four nested levels or scales of measurement: nominal, ordinal, interval, and ratio (Taylor 1977). Here, *Nominal* scales are based on a categorization of attributes and indicates only if an object does or does not belong in a particular class or group. Also called a categorical scale, this classification reflects only qualitative differences. *Ordinal* scales rank the objects along a number line. Although the ranks may be identified by numbers, they only reflect comparative differences. *Interval* scales have the basic characteristic that the objects are ranked not only in terms of some property but also the differences or intervals between objects in terms of that property are known. Scale values here are defined in terms of an arbitrary origin. Finally, *Ratio* scales are identical to the interval scales except that they possess a natural origin from which the ranked data can be compared. This gives an intrinsic meaning to the numerical expression itself. As these measurement scales are nested, the generalization of measurement scales can only occur from ratio to interval, ordinal, or nominal; from interval to ordinal or nominal; or from ordinal to nominal. Generalization in the opposite direction is not possible.

The process of generalization by symbolization also occurs with respect to data type changes. Data sets can exist in one of four fundamental geometric categories: point, linear, areal, or volumetric. Representation of these data types on the map occur in one or more of four categories of symbols: points, lines, areas, and volumes. Changes in dimensionality between a feature and its map representation allows a cartographer to generalize map features in the interest of map legibility, or merely to make map symbols more compact at reduced map scales (Muehrcke 1986).

Generalization by symbolization, therefore, is accomplished by changing either the scale of measurement or the type of the data, or both. A decision on the level of generalization for each of these two elements, coupled with the selection of the primary graphic elements used to encode the data set, is the essence of cartographic symbolization. The success or failure of a map depends fundamentally on this process (Robinson et al. 1984).

Characteristics of Spatial and Attribute Transformations

The spatial and attribute transformations discussed in this chapter are not all equally applicable to the four fundamental geometric categories (point, linear, areal, or volumetric), nor are they fundamentally equal in their preservation of dimensionality, or their need for a concomitant symbolism change after their application. Table 3.1 summarizes these characteristics.

Conceptual Model in Summary

This chapter has observed the digital generalization process through a decomposition of its main components. These include a consideration of (a) the intrinsic objectives of **why** we generalize, (b) an assessment of the situations which indicate **when** to generalize, and (c) an understanding of **how** to generalize using spatial and attribute transformations (see Figure 3.22). The philosophical objectives of why generalize was considered in an overall framework that focused on three types of elements (theoretical, application-specific, and computational). Six theoretical elements (including reducing complexity, maintaining spatial accuracy, maintaining attribute accuracy, maintaining aesthetic quality, maintaining a logical hierarchy, and consistently applying generalization rules), three application-specific elements (map purpose and intended audience, appropriate scale, and retention of clarity), and three computational elements (cost effectiveness of algorithms, maximum data reduction, and minimum memory/disk storage requirements) were outlined.

This chapter additionally addressed the latter two components of the generalization process—that is, the **when**, and **how** of generalization—by formulation of a set of assessments which could be developed to indicate a need for, and control the application of, specific generalization operations. A systematic organization of these primitive processes—in the form of operators, algorithms, or tolerances—can help to form a complete approach to digital generalization. The question of when to generalize

TABLE 3.1 SPATIAL AND ATTRIBUTE TRANSFORMATION CHARACTERISTICS

Spatial and Attribute Transformations	Applicable Data Types*	Symbolism Change?	Dimension Preserved?	Dependent on Other Operators?	Change in Scale of Measure?	Change in Data Type?
Simplification	L,A,V	No	Yes	Yes	Yes	Yes
Smoothing	L,A,V	No	Yes	Yes	Yes	Yes
Aggregation	P	Yes	No	Yes	Yes	Yes
Amalgamation	A	No	Yes	Yes	Yes	Yes
Merging	L	Yes	No	No	Yes	Yes
Collapse	L,A	Yes	No	Yes	Yes	Yes
Refinement	P,L,A,V	Yes	Yes	No	Yes	Yes
Exaggeration	L,A	No	Yes	Yes	Yes	Yes
Enhancement	L,A	No	Yes	Yes	Yes	Yes
Displacement	P,L,A	No	Yes	Yes	Yes	Yes
Classification	P,L,A,V	N/A	N/A	Yes	Yes	Yes
Symbolization	P,L,A,V	N/A	N/A	Yes	Yes	Yes

*Note: P=Point, L=Line, A=Area, V=Volume; N/A= Not Applicable

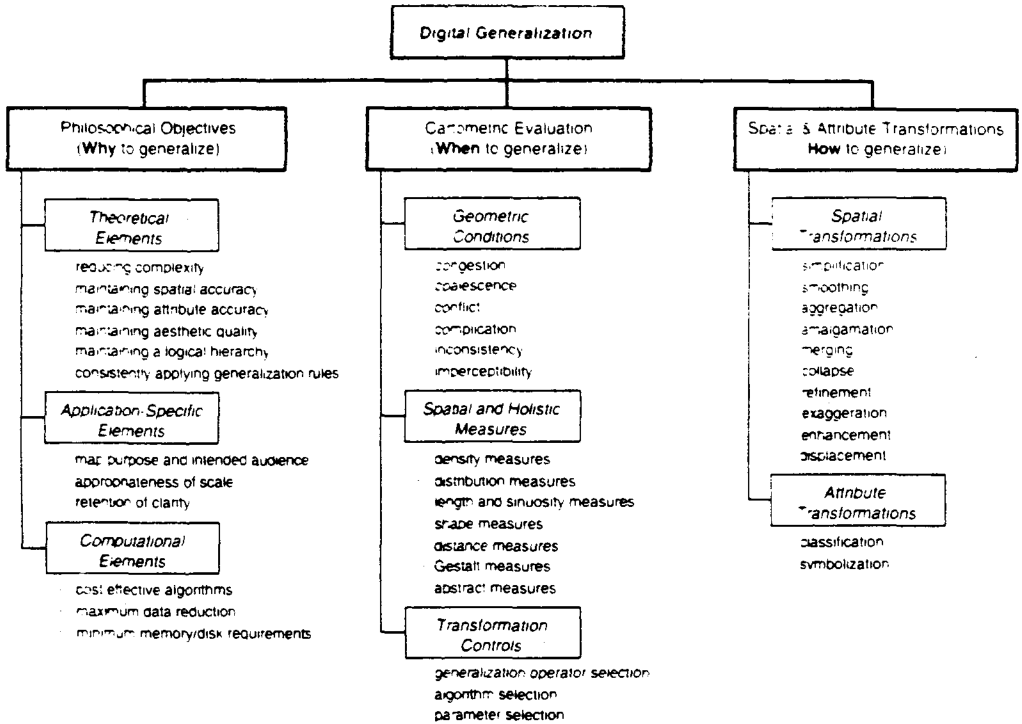

FIGURE 3.22 A DIGITAL GENERALIZATION MODEL. The digital generalization process can be decomposed into three critical components: **why**, **when**, and **how** to generalize. Each of these are, in turn, further decomposed into identifiable elements.

was considered in an overall framework that focused on three types of drivers (geometric conditions, spatial and holistic measures, and transformation controls). Six geometric conditions (including congestion, coalescence, conflict, complication, inconsistency, and imperceptibility), seven types of spatial and holistic measures (density, distribution, length and sinuosity, shape, distance, Gestalt, and abstract), and three transformation controls (generalization operator selection, algorithm selection, and parameter selection) were outlined.

The application of how to generalize was considered in an overall context that focused on twelve types of operators. Specifically, this included the ten spatial transformations (simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, exaggeration, enhancement, and displacement), and the two attribute transformations (classification and symbolization).

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