Map Generalization: Making Rules for Knowledge Representation

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Longman
Scientific &
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Longman Scientific & Technical,
Longman Group UK
Longman House, Burnt Mill, Harlow,
Essex CM20 2JE, England
and Associated Companies throughout the world.

Copublished in the United States with
John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158

First published 1991

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British Library Cataloguing in Publication Data
Map generalization: Making rules for
knowledge representation.
I. Buttenfield, Barbara P.
II. McMaster, Robert B.
526.028

ISBN 0–582–08062–2

Library of Congress Cataloging-in-Publication Data
Map generalization : making rules for knowledge representation /
editors, Barbara P. Buttenfield, Robert B. McMaster ; foreword by
Herbert Freeman.
p. cm.
Articles based on papers delivered at a symposium held during
April 1990 in Syracuse, N.Y.
Includes bibliographical references and index.
ISBN 0–470–21803–7
1. Cartography—Congresses. I. Buttenfield, Barbara Pfeil.
II. McMaster, Robert Brainerd.
GA101.2.M36 1991
526—dc20 91–22294
CIP

Set in Times 10/12 point by Columns of Reading.

Printed and bound in Great Britain at the Bath Press, Avon.

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A rule for describing line feature geometry

Barbara P. Buttenfield

Introduction

A continuing challenge for automating the cartographic process relates to using data from a digital cartographic database for representation at multiple map scales. The challenge involves feature simplification, and specifically the determination of feature details that must either be retained or omitted for appropriate graphic representation. The digital database is often produced for multiple purposes, including mapping at multiple scales; it is increasingly rare that a base map is digitized for mapping at a single scale. A related problem is that tolerance values selected for simplifying base map information must be modified as feature geometry varies within the digital file to ensure both accuracy and recognizability of graphic details on a generalized map. At present, decisions about where to adjust tolerance values are made manually, and form an expensive bottleneck to map production for government and commercial organizations.

This chapter explores a method for generating base map features at many scales from a single digital file, and presents a rule by which to determine those scales at which line feature geometry might be expected to change in map representation. The research has application to automating map simplification, incorporating numeric guidelines into digital files about what magnitude and variation in geometric detail should be preserved as the digital file is simplified for representation at reduced map scales.

Derivation of rules to guide the mapping process has been of long-standing interest to cartographers, primarily for reasons of consistency and quality control. The National Map Accuracy Standard was established in 1947 (Thompson 1979) to ensure horizontal and vertical control on USGS topographic maps. The Radical Law (Töpfer and Pillewizer 1966) provided numeric guidelines by which to determine how much detail to retain during map compilation and reduction. This is one of the earliest published rules formalized for map reduction and simplification. The inclusion of coefficients in the formula to control for map purpose and for dimensionality of treated features attests to the recognition that the appearance of map features depends upon both feature type and map purpose. But because a map surface is not homogeneous in the amount or type of detail it contains, the rule cannot be applied with mechanical uniformity.

For example, a topographic sheet may contain very dense settlement features within an urban area, with rectangular street patterns composed of (uniformly) rectangular geometry. It might be logical to apply a single rule to simplify the street pattern. Another part of the same sheet may lie beyond the confines of the urban area, and contain few settlement features, but perhaps include a drainage channel, or transportation network, or agricultural areas. Here, there may be very few features displaying rectangular patterns, or even uniformity. Coefficients for the Radical Law that are appropriate for one part of the map are not likely to provide appropriate simplification for every part of the map. In every case, the geometry of the map symbols must reflect the geographical structure of the landscape, and vary accordingly during map simplification.

One might argue that the solution to this problem is to simplify first the point features, then the line features, and so on. It can be shown, however, that the problem will arise even when treating line features (for example) in isolation. In digital form, cartographic lines are bundled as features that are not always tied to geographical or geometric uniformity. For example, the outline of the USA may be stored in a small-scale database as a single entity and incorporate both natural (coastline) and artificial (arcs of latitude) portions. Another example is provided by a digitally stored contour line that may contain very different amounts and types of crenulation and geometry as the terrain it crosses varies in bedrock hardness and composition.

The cartographic challenge is to apply simplification operators (rules) that accommodate the geographical and geometric changes occurring along the extent of the base map file. At one level, rules may involve changing the simplification or smoothing algorithm. At a different level, rules may involve changing tolerance values to preserve various geometric characteristics (e.g. line length). In a similar fashion, automating decisions about where to modify either the algorithm or the tolerance value must be based upon recognition of where the feature details can be seen to change in size or density. This creates problems for simplification of base map details, particularly for naturally occurring linear features.

The purpose of this research is to evaluate automatic methods to describe line feature geometry as it varies with map scale. This requires formalized description (knowledge) of the amount and type of details that occur along the extent of the digital file, and knowledge as to the scale at which the feature representation should change. In Chapter 5, three types of knowledge are discussed, including geometric, procedural, and structural (Armstrong 1991); it is the geometric knowledge which is the focus here. This chapter presents a method by which to determine changes in geometry, and demonstrates its application for several small examples.

The need to accommodate scale dependence in geographical depiction has been argued in previous literature, as geographical line features vary in appearance with changing scale of map representation (Mandelbrot 1986; Buttenfield 1984; Mark and Aronson 1984; Carpenter 1981; Goodchild 1980). It will be shown here that such features vary in their graphical geometry as well. Information identifying the type of geometric change and the specific map scales at which that change becomes visually evident can be utilized during map simplification to choose tolerance values that preserve both realism and accuracy of the feature as it is represented at multiple scales. The information can be collected as a formalized rule that can be stored in a digital coordinate file and used by a knowledge-based generalization system.

The rule presented in this chapter is termed a **structure signature**. It is a method of hierarchic subdivision and geometric measurement of a digital line feature. It provides formalized description of the line feature's geometric characteristics at successively finer levels of resolution, to accommodate the issue of scale dependence. The rule will be applied to demonstrate distinctions in three different geometric characteristics common to line features on maps, and to justify the need to break digital line files into smaller pieces to preserve uniform geometry during map simplification. Determination of changes in geometry may be inferred statistically, although the shape of the probability density function on which inferences are based may be non-standard.

It is important to note at the outset that while the following discussion will be expressed primarily in terms of vector coordinates and a vector-based solution, a similar argument (and solution) might be proposed within a raster environment with negligible modifications in analytical geometry. Many existing cartographic data sets (USGS DLG–E, National Ocean Survey (NOS) World Vector Shorelines, and Census Topologically Integrated Geographic Encoding and Reference (TIGER) files, for example) are currently formatted as vector strings or (as in the case of TIGER data) vector links between topological nodes. Many large GIS packages (e.g. ARC/INFO, System9, TYDAC) store feature data in vector form; thus the vector solution seems relevant. Where feasible in the discussion below, examples and references to raster processing will be incorporated into the discussion.

Preservation of details during line simplification

In map simplification, algorithms are applied to digital files to remove unwanted detail, to select or emphasize particular items, or to clarify by removing visual clutter. Most simplification algorithms incorporate some mechanism to control the amount of detail that is removed; for example, in an 'n^{th} point' algorithm, the *n* refers to a numeric threshold (a tolerance value) determining that *1/n* points will be eliminated systematically or randomly (Tobler 1966). Tolerance values can take many forms. They provide the width of corridors within which coordinates are eliminated (Deveau 1985; Douglas and Peucker 1973), or the number of coordinates to be considered for conversion to a straight line segment (Lang 1969). As argued above, tolerance values must be modified where it becomes evident that feature geometry has changed. Van Horn (1985) presents an example of the Virginia coastline, demonstrating problems with application of constant tolerance values. Manual tolerance value modification is accomplished intuitively, by visual inspection and reliance upon geographical familiarity with the map feature. Two cartographers will probably simplify the same line feature in nearly the same way, and vary their manual simplification in similar localities. But it will be rare that the identical coordinate location will be marked for transition in manual simplification.

In computer simplification, different solutions may result from the starting bias of a particular algorithm; this is particularly true of the family of 'corridor' tolerancing routines just discussed (Deveau 1985; Opheim 1982; Reumann and Witkam 1974; Ramer 1972). Inconsistent treatment of the same geographical feature in various digital map products can lead to incompatibility of adjacent map coverages, or of data products generated at multiple scales, and compound problems of inter-agency data transfer. The decision of how to choose simplification algorithms or how to select tolerance thresholds that guide their operation is neither well understood (McMaster 1987) nor readily formalized. Visual appearance and accurate positioning of a feature must be preserved, and appearance may vary across a range of map scales. Then, too, variations in size and frequency of detail will occur along the extent of the file, as geomorphology and terrain vary.

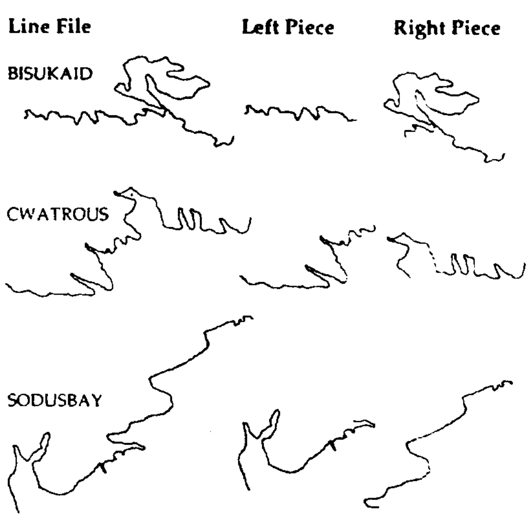

Fig. 9.1 Lines sampled from the McMaster (1983) data set

For example, in Fig. 9.1, the line BISUKAID (1499 points) is a 1 : 62 500 feature whose details differ in amplitude along its extent. The left piece shows smaller crenulations and a more unidirectional trend than the right piece, whose geometry approaches a space-filling curve. The cusps by which the left piece is defined may be eliminated by a simplification algorithm designed to generalize coarser angular details within the right piece. The line CWATROUS (875 points) is a 1 : 62 500 contour extending across differing bedrock material. The left piece exhibits sharp angularity, indicating softer bedrock and more localized downcutting, while the harder bedrock beneath the right half is apparently more resistant to local erosion. Graphically speaking, the details do not differ in size so much as in angularity for this line feature. SODUSBAY (1213 points) represents a coastline (1 : 62 500) and exhibits wave deposition and erosion along its extent. The left piece is characterized by higher frequency or density of detail. (All three line features are drawn from the McMaster 1983 data set.) The research question to be posed in this chapter concerns whether the geometric distinctions (amplitude, angularity, and density) of detail can be identified by formalized descriptions, and whether the formalized descriptions can be implemented as rules for knowledge-based simplification.

Knowledge-based simplification requires that the amount and type of detail in the digital file are defined before the algorithm begins to operate, and that expectations of the amount and type of details that should be retained or eliminated at the reduced scale are also defined. The current cartographic practice is to design algorithms with variable tolerance values that may be modified until the resulting simplification 'looks about right'. For large files containing many features of non-uniform geometry, the current practice is to assign initial tolerance values and then to monitor the progress of the algorithm through a large coordinate file, halting its operation to modify the tolerance threshold.

Returning to the lines in Fig. 9.1, the tolerance value needed to eliminate large amplitude details along the right piece of the BISUKAID file would probably eliminate too much of the smaller amplitude detail along the left piece. Breaking out pieces of the line with different amplitudes of detail and applying different tolerance values to each piece will preserve both the large and small amplitudes during simplification. For a small example such as this, of course, the decision of where to break the line can be accomplished by visual inspection. For large-volume mapping (i.e. coordinate files of 50 000 points or more) this type of manual intervention is inefficient, expensive, and will probably produce inconsistent results during simplification.

Formal description of the geometry contained within a digital file is complicated by the necessity to accommodate scale dependence. Natural features such as coastlines and river channels can be seen to vary in appearance depending upon the scale at which their representation is digitally encoded. One might argue that this is because the geographical feature is continuous, while the digital encoding methods for map representation are discrete. As pointed out by several researchers (Richardson 1961; Steinhaus 1954, 1960; Volkov 1949; Shokalsky 1930), geometric parameters of geographical features obtained by repeated measures using smaller and smaller units of measure do not always converge, and map representations at differing scales must therefore be in some respects unique.

From the context of satellite remote sensing, an example is revised from Buttenfield (1985). If the length of the Puget Sound coastline is measured on a LANDSAT image by counting pixels, its length will tally at some (rough) multiple of 79 m, assuming that image pixels are 79 m on a side. Features of the coastline smaller than 79 m will not be resolved, and thus escape measure. A thematic mapper (TM) image (resolution 30 m pixels) will incorporate some of these features, and the coastline will not be identical to the LANDSAT representation. Its length will be roughly equivalent to the length of the 79 m representation plus the length of all additional features resolved by the TM encoding. A Système Probatoire d'Observation de la Terre (SPOT) image of Puget Sound (10 m resolution) will incorporate still more features. Adding the length of these to the coastline measure will increase the length once again. This process will continue, through resolutions collected by high-altitude and low-altitude raster imaging, down to actual geodetic traverse measuring straight-line distance between selected points. Thus the length and consequently the details of the Puget Sound coast will continue to vary with changes in the scale of their (data capture and) measurement.

Geometric parameters as simple as line length have demonstrated capabilities for crude geomorphic distinctions (Buttenfield 1989), and one would expect that other parameters in addition to line length will serve to refine these distinctions. The formalized description of scale-dependent geometry may be thought of as a set of rules by which the geomorphic logic is preserved during map generalization; the set is comprised of a group of descriptions governing specific geometric parameters. The rules should be encoded into the digital files in a form directly available to the simplification algorithm. An example follows to demonstrate the utility of geometric parameters in a mapping context.

The cartographic importance of parametric description

With decreasing scale, the map representation of a large river narrows from an areal strip to a single line. The parallel indentations of a mapped fjord behave somewhat differently, however. At first, the two sides become more closely spaced, remaining proportional to the scaled width of the fjord. At a certain scale the fjord disappears altogether from the map representation. Rules for depicting fjords and rivers differ in this respect, and cartographers take this into account in deciding at what scale the graphic metamorphosis takes place. Intuitively speaking, two lines can be said to have different

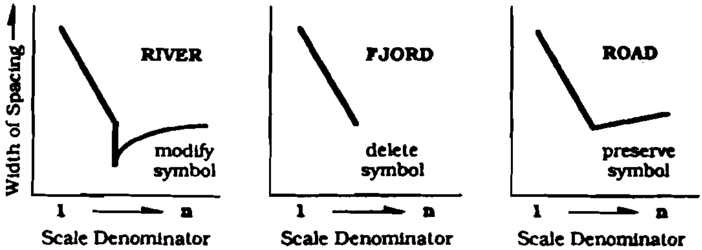

Fig. 9.2 The 'width of spacing' parameter provides a comparison of the relationship between size in graphic and geographical space across a progression from large-scale maps (left side of graphs) to small-scale maps (right side of graphs). The parameter distinguishes scale-dependent behaviour for three types of map features

geometries if they behave differently at different scales. Behaviour in this case refers to the digital values which geometric parameters take on as the representation is depicted at various scales. In differentiating fjord from river in this example, one may differentiate 'width of spacing' between roughly parallel lines bounding the areal strip of river bed or fjorded valley.

It is possible to plot hypothetical spacings for categories of line features at various scales in order to provide a graphic comparison of the relationship between size in graphic and geographical space. Three categories of lines are shown in Fig. 9.2, each of which is symbolized by a double line. The x-axis represents the denominator of the representative fraction, implying larger-scale representations on the left-hand side (e.g. 1 : 50 000) and smaller scale (e.g. 1 : 1 000 000) on the right. The y-axis represents the relationship between line spacing on the map and the actual width of the geographical feature. Negative-sloping lines on the graph indicate that as the scale denominator increases, map spacing decreases in proportion to geographical width. Positive slopes indicate that map spacing is becoming disproportionate to geographical width.

At large scales the river symbol width is proportional to actual width of the geographical feature it represents. With scale reduction, the river width on the map should decrease in linear proportion to the scale change. This kind of generalization is similar to the measurement of river channel width using aerial photography taken at increasing altitudes. Notice that the limits of resolution for the riverbank width will vary for a single channel. For example, the banks of the mouth of the Columbia River will be resolved at much smaller scales than will the headwaters. Thus a single entity in the database may require a variety of cartographic treatments along its extent.

Below the limits of resolution, the river should most appropriately be symbolized by a single line. The relationship between plotted line width and actual geographical width will change suddenly with the single line depiction, as shown by the vertical jog in the plot. The single line may be more narrow than the feature which it represents at the particular scale.

With further reduction (and especially if pen width is kept constant) the relationship between graphic and geographical width will rebound somewhat, and then approach some equilibrium at which the cartographer decides to remove the feature from the map. The map scale at which the feature is deleted will be a function of the importance of the river to the particular map purpose.

Line spacing for fjords differs from rivers in cartographic treatment, although at the largest scales the two symbols are treated in similar fashion. With decreasing scale, the width of the symbol is decreased proportionately. At the limits of resolution, however, both lines of the fjord symbol will be removed: by cartographic convention, fjord geometry is not defined by a single line. The convention is reflected by the abrupt termination of the plot.

The third plot stands in juxtaposition to the first two to exemplify cultural features. For fjords and rivers, the double line symbol is irregular at larger scales, reflecting irregularities of terrain. For parallel lines symbolizing a road or highway, the sides of the line symbol will be more regular, to reflect civil engineering standardized specifications of road width, radius of curvature, etc. At larger scales, of course, line spacing remains proportional to its geographical counterpart. At the limits of resolution, the double line representation may be preserved, as with interstate highway symbols on a road map. With further decrease in scale, the symbol is neither deleted nor modified. Line spacing will eventually become 'larger than life' as the map feature becomes disproportionately wider than the geographical road.

An important aspect of all three plots is that each one contains an identifiable jog or elbow. In a topographic mapping situation, one can identify quite specifically the scale at which the jog will occur. Limits of resolution are defined as half the National Map Accuracy Standard, or 0.01 inch (0.3 mm) (1/100 inch) at scale. According to this rule the jog should occur at the scale for which river width, road width, or fjord width reaches 0.01 inch (0.3 mm) on the map. For a 1 : 62 500 quadrangle, fjorded valleys smaller than about 50 feet (15.2 m) across should not be represented. At 1 : 125 000 the threshold is doubled. The resulting effect on rivers, for example, will be symbolization of all channels less than 100 feet (30.5 m) wide by a single line. Muller (1990) has also described evidence of such jogs, which he terms cusps, for settlement features generalized on Dutch topographic map series. One goal of formalizing scale-dependent descriptions is to identify specific scales at which cusps are expected to occur, for these are the levels of resolution at which the form of the map feature can be expected to metamorphose during generalization. For scale ranges between the cusps, one can speculate that the map features will change in some proportion to the scale change.

This example describes a relationship between three hypothetical features and their graphic representations at progressive scales in terms of a parameter relating line spacing on the map to geographical width of the feature. The cartographic application demonstrates how parametric rules may be used to predict the structure of map representations for the category called 'river' on topographic maps. The advantage of using parametric rules relates to the flexibility with which slight modifications can be implemented. For example, the cartographic simplification of a freely meandering stream will differ somewhat from the cartographic treatment of a tightly constrained stream channel in preserving the periodicity of meanders. One would expect the rule for rivers will be similar but not equivalent for all classes of rivers, although this remains to be demonstrated.

One is reminded of the techniques applied in a remote sensing training exercise to build a spectral signature for grass or asphalt and then apply it to distinguish land cover types on a satellite image. The spectral signature describes the reflectance pattern for a given type of land cover. This description is then compared with the image to delineate areas having similar patterns of reflectance, and to distinguish between dissimilar land covers. The spectral signature provides rules for expected reflectance across a range of wavelengths. In analogy, the line spacing plots described in this chapter may be thought of as a structure signature providing rules for the expected feature geometry represented across a range of map scales (Buttenfield 1984, 1986, 1987).

Other researchers have considered the signature concept in categorizing information at multiple scale (Pike 1988). Varying forms of the concept are referred to by similar names, for example 'fingerprint' (Witkin 1986). The parametric approach and the reduction of continuous data to discrete geometric measurement are common to all, although parameters vary from one implementation to another. In any implementation, a set of parameters (rather than a single measure) will probably be required to capture the full complexity of geographical details. Some parameters will best distinguish certain kinds of features, but not others. It is not the purpose of this research to compare between parametric signature methods, but rather to explore the application of a particular method, the structure signature, to the description of topographic line features. Extensions to line simplification and tolerance value modification will be proposed subsequently.

A parametric rule for scale-based description

The parameters

Five parameters will be incorporated into the structure signature. Each is based on a geometric measurement, for example line length, or zero-crossings (Thapa 1988) of a coordinate string across some sort of anchor line. Measurements are repeated for subdivisions of the line using the Douglas reduction algorithm (Douglas and Peucker 1973). As the line is subdivided, each section is stored in a striptree data structure (Ballard 1981). Measures are made for each strip, and summarized across the tree. This procedure and the parametric measures are refined from Buttenfield (1986, 1989) and Jasinski (1990).

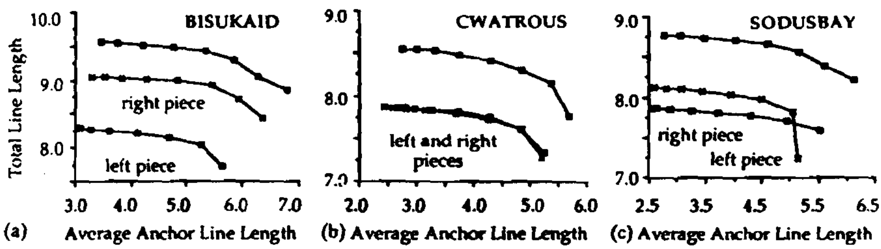

Fig. 9.3 Richardson line length plots provide clearest distinctions between features whose details vary in amplitude, as in the case of BISUKAID. The lack of differentiation for plots of CWATROUS and SODUSBAY indicates that angularity and density of detail are not so clearly distinguished by this parameter

The first parameter (shown in Fig. 9.3) relates the decrease of average strip length at finer levels of resolution to the increase in total line length. This measure was first reported by Richardson (1961), and is the basis for Mandelbrot's (1967) subsequent derivation of fractal dimension. The Richardson plots are used here instead of the fractal *D* value, which has been criticized by a number of cartographic researchers for problems of instability (see Clarke 1990 for a good summary of this work). Buttenfield (1989) modified Richardson's original procedure by relaxing his assumption of linearity. Instead of fitting a linear regression model to the set of measured lengths, she found that merely connecting points in the graph discloses values of average anchor line length at which the rate of increasing total line length changes suddenly. These sudden changes identify cusps, as predicted in the line spacing example above, and were also discovered by Muller (1990).

The resolution (average anchor line length) at which both pieces of the CWATROUS graph (Fig. 9.3(b)) change slope is just under 5.0 units, whereas for the left piece of SODUSBAY (Fig. 9.3(c)) a marked cusp is apparent at a resolution of just over 5.0 units. One should expect that cusps will occur at different resolutions for different line features. This kind of information justifies the avoidance of single tolerance thresholds applied uniformly to simplify all features on a map coverage, for clearly a tolerance value that is sensitive to (that is, eliminates) details smaller than 5.0 units will simplify both the CWATROUS pieces, but have no visible effect upon the SODUSBAY file. A small increase in the tolerance value will generate a very different looking simplification of the map as a whole. Knowledge about the type and amount of details contained in specific features can be used to computational advantage (that is, avoiding the computation time when applying a tolerance value that will have no visible effect) as well as to select a tolerance value that will reduce details more uniformly across the map surface.

While the Richardson line length parameter can provide knowledge about the amount of detail contained in a line feature, other geometric distinctions

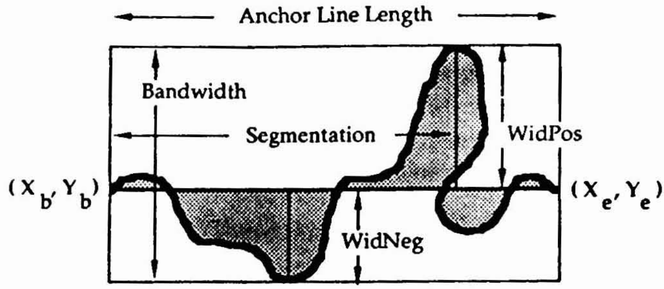

Fig. 9.4 Parameters for a structure signature include the measurements displayed here. The MBR is the rectangle bounding the line segment. Anchor line length is the length of the MBR, and bandwidth is the width. Segmentation is the distance from the beginning coordinate to the location on the anchor line where the maximum deviation occurs. Error variance is the discrete approximation of the shaded area. Concurrence is a count of the number of times the coordinate string crosses the anchor line

are not made clear. One can see in comparing Richardson plots for the pieces of BISUKAID that the line length parameter distinguishes readily between variations in amplitude of detail, although it is not providing clear separations for the changes in angularity found in the CWATROUS file. The varying density of detail evident in the pieces of the SODUSBAY line is evident at finer levels of resolution, where denser (high frequency) details increase overall line length. However, the distinction between line pieces is not as apparent for frequency of detail as for amplitude. Robust distinction between the line files probably requires combining the Richardson line length parameter with other parameters in the structure signature.

In Fig. 9.4, the original coordinate string for a line (or piece of a line) is shown to crenulate around a straight line connecting endpoints of the string. The first computation (anchor line length) measures Euclidean distance between the beginning and ending coordinates of the string.

$$\text{Length} = \sqrt{[(X_b - X_e)^2 + (Y_b - Y_e)^2]} \qquad [9.1]$$

This measure is used to standardize two parameters describing the minimum bounding rectangle (MBR) surrounding the coordinates for each piece of the line as it is subdivided. With further subdivisions, the anchor line length for a line piece will more closely approximate the length of the coordinate string within the MBR. The implication, of course, is that the anchor line provides the most simplified representation of the original coordinate string, which justifies its use to standardize both MBR parameters. The first of these, labelled 'bandwidth', measures the maximum perpendicular deviation of any coordinate in the original string on either side of the anchor line. Deviations are summed to compute the width of the MBR. The bandwidth label is used in the same context as Peucker's (1975) appellation.

$$\text{Bandwidth} = \frac{(\text{WidPos} + \text{WidNeg})}{\text{Length}} \quad [9.2]$$

In the formula, 'WidPos' and 'WidNeg' represent deviations on either side of the anchor line (the positive side is on the same side of the anchor line as the origin of the coordinate space) (Bartsch 1974: 263) and are illustrated in Fig. 9.4. 'Length' represents anchor line length, as computed in the first equation. The bandwidth parameter additionally provides a measure of the cross-sectional symmetry of the line feature, for equal deviations on both sides of the anchor line indicate a feature with symmetric amplitudes of detail. This measure should therefore provide good distinctions between line pieces exhibiting differing amplitudes of detail, as in the case of BISUKAID.

$$\text{Segmentation} = \frac{\sqrt{[(X_b - x)^2 + (Y_b - y)^2]}}{\text{Length}} \quad [9.3]$$

The second MBR parameter is called segmentation and is defined as the location along the anchor line where the next subdivision will occur, that is, the location of the coordinate (x, y) which lies at the maximum perpendicular distance from the anchor line. Distance is measured from the beginning coordinate of the anchor line (X_b, Y_b). Segmentation is standardized to the anchor line length to eliminate bias of measurement units. For example, a segmentation value of 0.25 indicates that the maximum deviation occurs ¼ of the way down the anchor line. Interpretation of this parameter may indicate ranges of self-similar geometry. If the segmentation value is preserved across several levels of resolution, that would imply that the line details (at least the maximum deviation) are occurring again and again at the same (relative) location along the line.

Two other parameters describe the path of the coordinate string within the MBR. Error variance is computed in the format of any standardized deviation, as the sum of the squared deviations of distances between coordinates in the original string and the anchor line. McMaster (1986) computes a very similar measure to reflect areal displacement.

$$\text{Error variance} = \sqrt{\left[\frac{\Sigma\,(\text{Distance})^2 - \dfrac{\Sigma\,(\text{Distance})^2}{\text{No. of coordinates}}}{\text{No. of coordinates} - 1}\right]} \quad [9.4]$$

The error variance parameter is illustrated in Fig. 9.4 as the shaded area. Error variance is a discrete approximation of the total discrepancy between the anchor line (the most simplified representation of the line) and the original coordinate string). Error variance is standardized by the number of coordinates in the string, and is reported logarithmically. The formula for distance is expressed in the usual format for directed distance from a straight line in the plane, using the generalized coefficients (A, B, C) for the anchor line equation (Bartsch 1974: 261). Distance of any coordinate (x, y) from the anchor line is given by

$$\text{Distance} = \frac{Ax + By + C}{\text{Length}} \qquad [9.5]$$

The slope of the anchor line will affect the sign of the coefficients A, B, and C, and therefore of the distance value. Positive distance values indicate deviations lying on the same side of the anchor line as the origin of the coordinate space, and negative values indicate deviations on the opposite side of the anchor line. Maximum positive and negative values of the distance computation produce the WidPos and WidNeg values used to measure bandwidth above.

Concurrence, the fifth parameter, is also measured using the distance computation. It is defined as a count of the number of times the distance value changes sign (from positive to negative values) going in sequence along the coordinate string. This indicates the number of times the original string crosses the anchor line, or how closely the anchor line concurs with the original coordinates' path. Concurrence is standardized by the number of coordinates in the string, to give a count of actual crossings as a proportion of the potential number of crossings. This allows the concurrence to vary between 0 and 1, in similar fashion to a correlation coefficient. An arc of a circle will have a value of zero, for example, and the value for a coordinate string in which coordinates alternate back and forth in zigzag fashion about the anchor line will approach 1.0. In Fig. 9.4, the coordinate string crosses the anchor line four times (endpoints are excluded). Thapa (1988) applies a similar measure (referred to as 'zero crossings', to indicate the change in signed values), although he measures the parameter for only a single level of resolution and does not standardize his values.

Incorporating the parameters into the rule

The generation of the structure signature rule involves measuring and summarizing five parameters of a line (Richardson line length, bandwidth, segmentation, error variance, and concurrence) at successively finer levels of resolution. For a digital file, this means measuring the line as a whole, by constructing the anchor line and MBR, then computing (anchor line) length and width of the MBR, concurrence, segmentation and error variance. The line must be subdivided in some consistent fashion and the procedure of measurement repeated, to simulate finer levels of resolution. Subdivision may proceed by means of breaking the line file in two equal-sized portions (in half), or into two randomly sized portions, or by some substantive criteria (for example, choosing as a breakpoint the coordinate marking first-order geodetic control, or the location of a city, major shipping port, or prominent landmark). In this research, the goal is to retain recognizability of the line feature as it is represented at many levels of resolution; thus the line subdivision must be designed to account in some way for preservation of details important for line recognition.

This is accomplished by application of Douglas and Peucker's (1973) line simplification algorithm. Its application in this research is not incidental, for several reasons. First, the line reduction routine has been shown (Kelley 1977) to identify coordinates of maximum angular change, which Attneave (1954) identifies as a major priority for shape recognition. Additionally, the Douglas routine identifies an almost identical set of coordinates as those selected by visual inspection to be critical for recognition of the line in its simplified form (White 1985). The algorithm's selection of these critical points (as Marino 1979 has referred to them) generates simplifications that mimic those generated by manual generalization, and retains details critical for map reader recognition. Finally, the Douglas algorithm can be applied in hierarchic fashion (Douglas and Peucker 1973) to subdivide a line file automatically, while retaining the line's critical shape information overall.

The line files used in this project (BISUKAID, CWATROUS, and SODUSBAY) were subdivided in the following manner. First, points were selected randomly to initialize eight pieces without introducing cartographers' bias. This action might be considered analogous to the identification of certain points in a coordinate file that must be preserved, such as city locations, points where hydrographic channels intersect, map sheet edges, and other constraints beyond the cartographer's control. The five parameters were measured for this (random) subdivision, and stored in a striptree data structure. Each piece was next subdivided using the Douglas algorithm, to produce 16 pieces, which were measured and stored. The 16 were subdivided again using the Douglas-Peucker algorithm to produce 32 pieces. Any given piece of the line within which the maximum deviation fell below 0.0005 inch (0.0127 mm) was not further subdivided, as this is half the resolution at which the lines were originally digitized. When 90 per cent of the line pieces reached the limits of tolerance, the subdivision procedure was terminated.

A final step in generating the structure signatures involves summarizing the measured parameters for each level of resolution. A logical choice summarizes by computing a mean and variance for each measured parameter, as it can be argued that the subdivision process (by any method) is a sampling procedure. Many different line pieces could result from using different subdivision methods. Thus the particular set of line pieces resulting from any particular subdivision is one sample representing the line broken into finer and finer pieces. Use of the first and second moment statistics also provides a good check on the homogeneity of line measurements, that is, the magnitude of the variance may indicate lack of uniform geometry within the line file as a whole. This point will be returned to later in the chapter.

The intention in summarizing parameters for any level of resolution is to incorporate the measurements for all of the pieces, including pieces whose details have been previously resolved. Parameters for line pieces whose details had reached the resolution limits at a previous level of subdivision were incorporated into the summaries for subsequent subdivisions, so that summaries for any single level of resolution incorporated a complete representation of the line file. As discussed earlier in the chapter, it is reasonable to expect non-uniformity in the amount and type of detail occurring on a map. Likewise it is reasonable to find that details within a single feature will also vary, as geometry is not currently used as a criterion for breaking out features in a digital file. Therefore, one can predict that any striptree formed by this procedure will be sparse in some locations. Further discussion of structure signatures may be found in Buttenfield (1984, 1986) and Jasinski (1990). The remainder of the chapter demonstrates a small implementation of the structure signature concept to show how it may be applied to distinguish geometric character.

Calibrating the structure signature rule

In order to formalize a rule for distinguishing between types of geometric variation, such as amplitude, angularity, and frequency of detail, one must calibrate the rule so that parameters measured for features of equivalent geometric character are (nearly) equivalent, and parameters for different geometric character are distinctive. This should hold true for differing features as well as for portions within a digital line file whose geometric character is non-uniform (not homogeneous). If portions of a line feature differ then the structure signatures for those portions should reflect those differences, if the signatures are to be considered useful rules for distinguishing between types of detail to be preserved during simplification.

To demonstrate, nine signatures have been constructed (see Figs 9.5–9.7), three for each of three features taken from the McMaster (1983) data set and shown previously in Fig. 9.1. These features display differences in geometry along their extent. The lines differ in one case in amplitude of detail, in another case in blockiness or angularity, and in a third case the variation in frequency of detail is the distinguishing factor. For the purposes of calibrating the structure signature rule, the line pieces have been arbitrarily broken on the basis of visual inspection. Once it has been shown that the signatures are distinctive, then the question of implementation becomes realistic. Without the 'proof of concept', the rule is difficult to validate.

It is important to realize during the following discussion of the structure signatures that comparisons are limited to pieces of a single line file, not between them. For BISUKAID, comparisons on the basis of amplitude of detail will be emphasized. Emphasis for CWATROUS and SODUSBAY will be based on angularity and frequency of detail, respectively. The digital files were broken into the pieces already displayed in Fig. 9.1, and structure signatures generated for the entire file and for each piece.

Each column of the figure represents a structure signature, including the parameters measuring the MBR and the parameters describing the path of

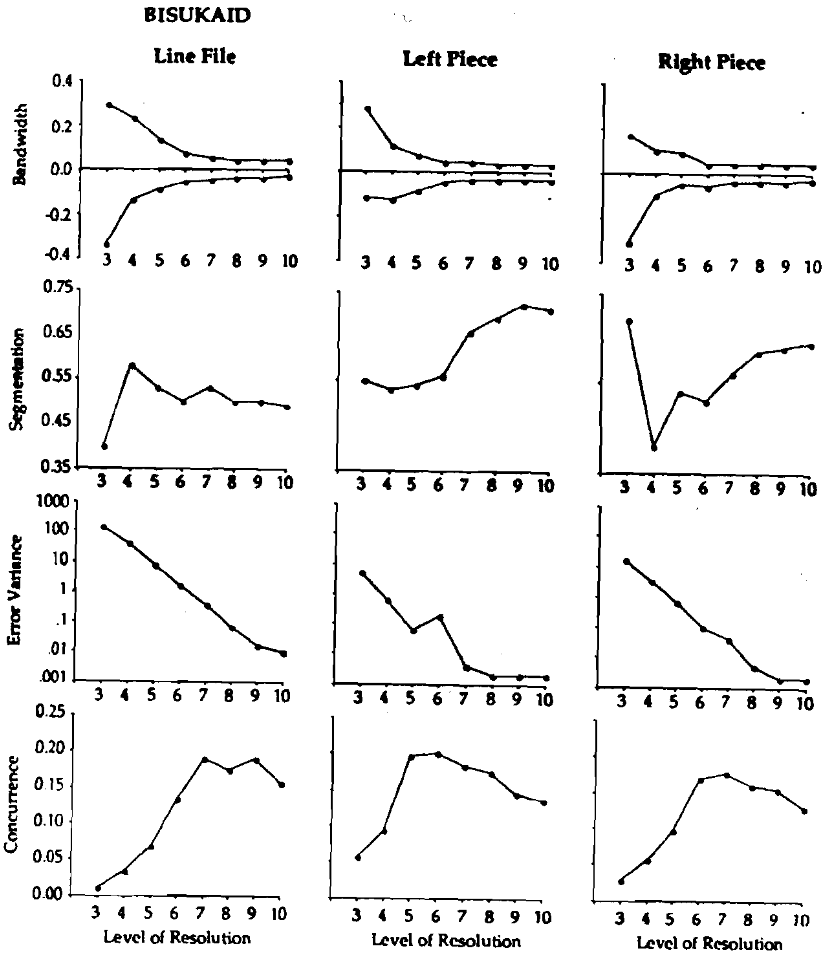

Fig. 9.5 Structure signatures showing differences in amplitude of detail

the coordinate strings within the MBR. Along the x-axis of each plot, tick marks represent levels of resolution at which the parameters were measured. For level 3, the line was subdivided into 8 pieces (2^3), for level 4, into 16 pieces (2^4), and so on, using the Douglas-Peucker routine. Due to the differential details along each line, and the fact that not all of the line files contain 1024 points to begin with, the striptree will become somewhat sparse at finer levels of resolution; however, at least 90 per cent of the nodes are filled at every level, as described above. Signature parameters for the entire line are graphed in the leftmost column, and signatures for the two pieces are displayed in the centre and rightmost columns, respectively.

As expected, some parameters seem to be more effective than others for distinguishing differences in amplitude, blockiness, and frequency of detail. Several parameter graphs display scale-dependent cusps referred to earlier in the chapter, identifying levels of resolution where geometry of the lines changes suddenly. Other line files may display geometric characteristics not considered here. For example, one could study periodicity of details along the coastline of Cape Hatteras and North Carolina, or variations in sinuosity along the British Columbia coastline. This underscores the need for refinement of the signature parameters and for the possible incorporation of additional parameters. The parameters presented here are not intended to be encyclopaedic. Development of additional parameters and refinement of those presented in this chapter form a topic for further research.

It is possible to identify several distinctions in each of the structure signature examples (Figs 9.5–9.7), using some but not all of the signature parameters. In Fig. 9.5, for example, the bandwidth parameter provides good distinction for variations in amplitude of detail. For the right piece of BISUKAID, notice that the maximum negative deviation at level 4 is of a greater magnitude than at level 3. This is unusual, as one would expect smaller amplitude details to be resolved with finer resolution. Probably the larger deviation has to do with the closed shape apparent in the right piece; this geometry is obscured in the signature of the whole file, however.

In the segmentation graphs, one can see that for the line taken as a whole, there is an initial relocation of the maximum deviation, followed by a series of subdivisions occurring roughly about half-way along the anchor line. This implies longitudinal self-similarity, which is not borne out by signatures for the two pieces of the line file, both of whose subdivisions drift along the anchor line for this range of resolutions. It is apparent that non-uniformity of geometric character can be obscured when treating large sections of a cartographic file as a single item.

The cusp in error variance at level 6 for the left piece of BISUKAID indicates an increase in the sum of the squared deviations of the coordinate string from its anchor line. The small amplitude crenulations evident in the left piece appear to be about the same size and of a constant frequency, and level 6 identifies a scale at which they are first becoming resolved. To simplify BISUKAID to this scale, a tolerance value should be chosen that is sensitive to this amplitude of detail. Suitable values for a tolerance threshold can be determined from the y-axis of the bandwidth graph, which displays the average maximum deviation (roughly 0.4–0.6 inch (10–15 mm) on either side of the anchor line) found at this level. Additional information can be computed using the Richardson line length parameters, to determine a resolution (average anchor line length) which will produce a given total line length.

Concurrence has been defined as a ratio between the actual number of anchor line crossings and the number of coordinates in the strip. The ratio can rise even if the number of crossings stays the same, since fewer coordinates will be contained as the subdivision process isolates smaller pieces of the line. It is the level at which sudden slope changes occur that is of interest in this parameter. A cusp from positive to negative slope always indicates a drop in the number of anchor line crossings. At fine resolutions,

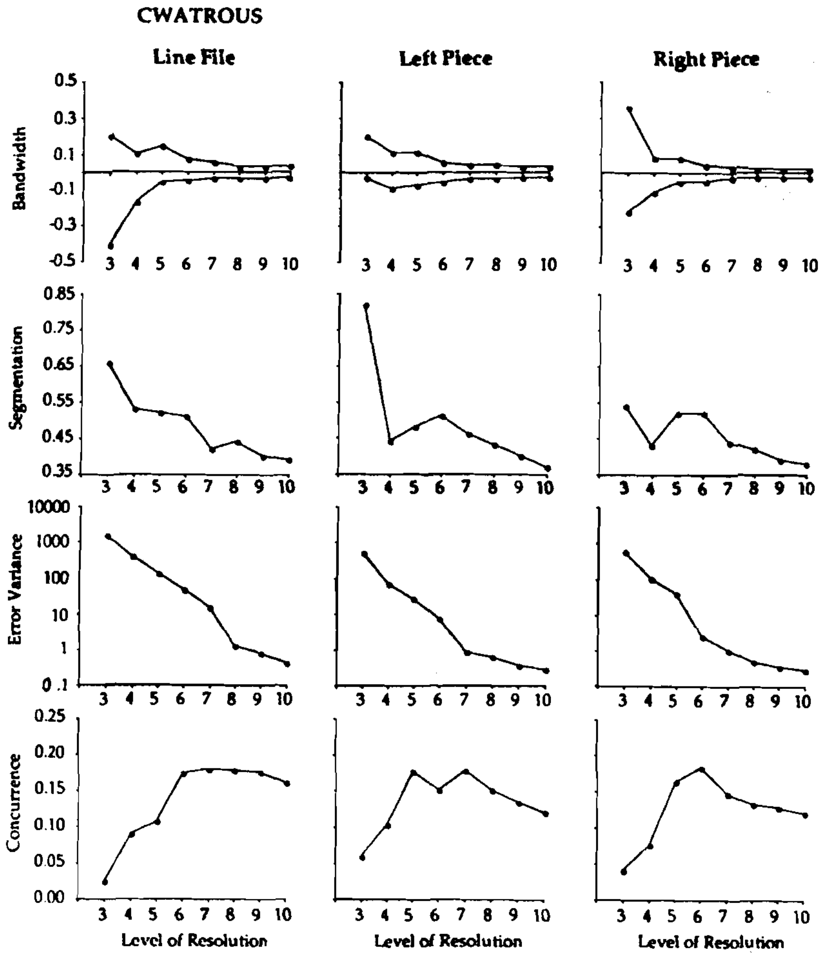

Fig. 9.6 Structure signatures showing differences in angularity of detail

this implies that details in the coordinate string have been largely resolved. For BISUKAID, this occurs at level 7 for the line taken as a whole, but at level 5 for the left piece (smaller amplitude details) and at level 6 for the large amplitude details of the right piece.

For CWATROUS (Fig. 9.6), the line pieces do not differ in amplitude of detail so much as in angularity. Bandwidth for the line taken as a whole and for the right piece display a similar steep drop during early subdivisions, and the smaller magnitude deviations evident in the graph for the left piece are masked by this pattern. Segmentation provides the most distinctive parameters. For the line as a whole, the horizontal slope across levels 4–6 indicates that segmentation is occurring at roughly the same location along the anchor line, implying statistical if not precise self-similarity for the parameter in this range of resolution. Segmentation for the right piece of the

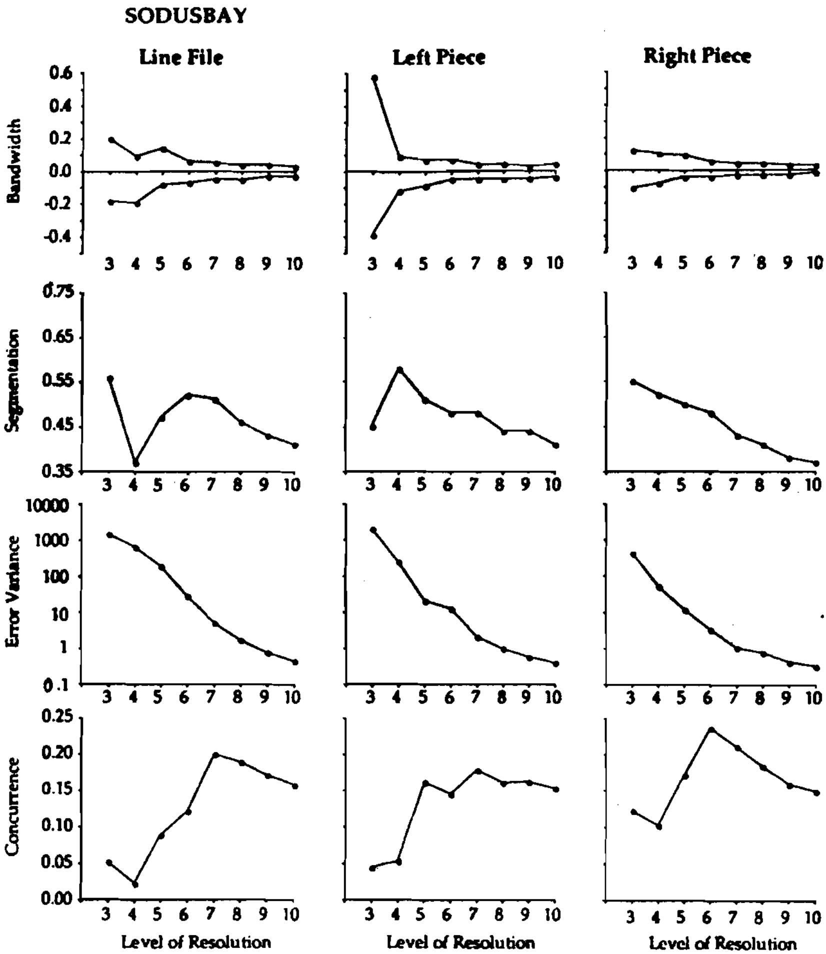

Fig. 9.7 Structure signature showing differences in frequency or density of detail

line displays self-similarity for two of these levels. Map representations generated within this range may appear nearly identical. The pattern of segmentation for the left piece is distinct, and oscillates back and forth along the anchor line. This characteristic is masked completely in the signature for the entire line.

Neither the error variance nor the concurrence graphs display clear differences, and this is logical, as the pieces of CWATROUS differ neither in the overall amount of deviation nor in the frequency of deviation from their anchor lines. Angularity is not so well described by these parameters as by segmentation. Kelley (1977) demonstrated that the Douglas-Peucker algorithm will tend to select coordinate locations of maximum angular change and will also control the selection of the segmentation point. One should expect that the pattern of segmentation will reflect substantial variations in angularity accordingly.

While differences can be seen for several parameters graphed in Fig. 9.7, differences in frequency of detail are expected to be most apparent in graphs of the concurrence parameter. The drop in concurrence at finer resolutions is apparent here as in Fig. 9.5 and 9.6, and again the cusp of change from positive to negative slope occurs at different levels. As a ratio of actual anchor line crossings to potential for crossings, concurrence is a probability measure. The left piece displays a high density of high-frequency details, and the cusp at level 4 where the positive slope suddenly increases indicates a rise in the number of crossings coupled with a drop in the average number of coordinates. For the right piece and line taken as a whole, the cusp at level 4 indicates an initial drop in concurrence; the lower frequency details display a periodic character whose phase may be synchronized with anchor line length at this resolution to form pieces of the line that are like arcs of circles.

Structure signatures for the pieces of the line can be seen to differ from the signatures for the lines taken as a whole. For some parameters, the differences are quite marked. Parameters for Richardson line length, bandwidth, and error variance appear best to distinguish differences in amplitude of detail. Angularity seems to be most clearly distinguished by segmentation, although this may be dependent upon subdivision by the Douglas-Peucker algorithm. If another subdivision procedure were applied, for example simply dividing the line pieces in half, the segmentation parameter would display a very different pattern, obscuring the angularity differences. Frequency of detail seems best distinguished by concurrence. Other parameters may improve the discriminating ability of the structure signature rule, or contribute to the distinction of other types of geometric characteristics.

As proposed in beginning this experiment, a robust rule describing feature geometry should take on unique values to indicate different geometric characteristics. This has been demonstrated. The counter-proposition, that descriptions of similar geometric characteristics should appear similar, has only been alluded to here. A more comprehensive calibration will require demonstration that the same feature collected from different data sources or by different methods (e.g. scanning and vector digitizing) will produce similar structure signatures. This is beyond the scope of the current chapter.

Implications for map generalization

One interesting aspect of the examination of line geometry using structure signatures is that geometric differences evident in signatures generated for pieces of a line are often masked when parameters are averaged for the line as a whole. This argues for generating structure signatures for line features of uniform geometry to ensure the parameters are not biased by heterogeneous amounts and types of detail. This begs the question of how to determine portions of a digital file containing uniform detail. It would be unfortunate if the generation of structure signatures required plotting the entire digital file and marking it manually, for of course this is the very obstacle one is trying to avoid by generating the signatures in the first place. There are at present no formalized rules that may be used to delineate sections of a file containing uniform detail.

Full implementation of such rules will require a certain amount of data exploration. For example, the determination of what is homogeneous geometry will probably differ for cultural features and naturally occurring features. Examples include highways, whose radii of curvature are constrained, and railroads, whose path across terrain is often constrained by gradient. For line features particularly, determination of serial trend may depend as much on map purpose or the map audience, as on geomorphology. Actual determination of geometric distinctions for a particular feature type will probably require some form of empiric evaluation or perceptual testing to preserve consistency in implementation. For now, its utility for automating map simplification must remain speculative.

The structure signature rule presented in this chapter can be implemented now, providing knowledge to automate cartographic line simplification. The structure signature's purpose is to determine scales at which the geometry of a line feature changes. Implementation requires that information be stored with the digital data on the amount and type of details that occur along the extent of the line. That is, line files should be tagged (as one tags coordinate strings with feature codes, for example) with the geometric characteristics that must be preserved within that string at particular map scales. This method can be applied when coordinate files are entered into a database, or as a form of preprocessing. Feature headers could take on form of a look-up table of mean and variance pairs for given parameters, where the look-up table values provide knowledge for selection of tolerance values to preserve specific geometric characteristics. It must be recognized that current simplification algorithms do not look for knowledge of this sort within the data files on which they operate, and thus full implementation of a knowledge-based simplification system will require more than simply adding information to file headers.

The work described in this chapter is intended to demonstrate that rules can be formalized to describe geometry that changes with scale, and to provide information about geometric characteristics that might be retained or eliminated during map simplification tasks. Procedures for generating a structure signature have been described and applied to small cartographic examples to demonstrate its utility for feature descriptions. Indications from this research have been discussed as to how the rule might be refined by modifying parameters. New geometric parameters may be developed to improve overall discriminating ability of the signatures. The structure signatures are presented as an example of a rule by which line feature geometry may be formalized, and applied to break digital lines automatically into pieces that are homogeneous in geometric character. Implementation of this concept has major implications for reduction of production costs and preservation of quality control in using a single digital line file to general maps at multiple scales.

Acknowledgements

This chapter reports research that is part of NCGIA Initiative 3, Multiple Representations and is supported in part by a grant from the National Science Foundation (SES 88-10917). Support by USGS National Mapping Division is also gratefully acknowledged. Comments by reviewers and by the Syracuse Symposium participants have clarified the writing.

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