CARTOGRAPHIC GENERALIZATION IN A DIGITAL ENVIRONMENT: WHEN AND HOW TO GENERALIZE

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ABSTRACT

A key aspect of the mapping process—cartographic generalization—plays a vital role in assessing the overall utility of both computer-assisted map production systems and geographic information systems. Within the digital environment, a significant, if not the dominant, control on the graphic output is the role and effect of cartographic generalization. Unfortunately, there exists a paucity of research that addresses digital generalization in a holistic manner, looking at the interrelationships between the conditions that indicate a need for its application, the objectives or goals of the process, as well as the specific spatial and attribute transformations required to effect the changes. Given the necessary conditions for generalization in the digital domain, the display of both vector and raster data is, in part, a direct result of the application of such transformations, of their interactions between one another, and of the specific tolerances required.

How then should cartographic generalization be embodied in a *digital* environment? This paper will address that question by presenting a logical framework of the digital generalization process which includes: a consideration of the intrinsic objectives of **why** we generalize; an assessment of the situations which indicate **when** to generalize; and an understanding of **how** to generalize using spatial and attribute transformations. In a recent publication, the authors examined the first of these three components. This paper focuses on the latter two areas: to examine the underlying conditions or situations when we need to generalize, and the spatial and attribute transformations that are employed to effect the changes.

INTRODUCTION

To fully understand the role that cartographic generalization plays in the digital environment, a comprehensive understanding of the generalization process first becomes necessary. As illustrated in Figure 1, this process includes a consideration of the intrinsic objectives of **why** we generalize, an assessment of the situations which indicate **when** to generalize, and an understanding of **how** to generalize using spatial and attribute transformations. In a recent publication, the authors presented the **why** component of generalization by formulating objectives of the digital generalization process (McMaster and Shea, 1988). The discussion that

follows will focus exclusively on the latter two considerations—an assessment of the degree and type of generalization and an understanding of the primary types of spatial and attribute operations.
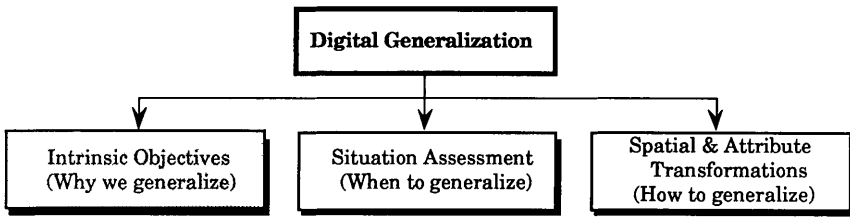

Figure 1. Decomposition of the digital generalization process into three components: **why, when,** and **how** we generalize. The **why** component was discussed in a previous paper and will not be covered here.

SITUATION ASSESSMENT IN GENERALIZATION: WHEN TO GENERALIZE

The situations in which generalization would be required ideally arise 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, p.242). As indicated in Figure 2, the **when** of generalization can be viewed from three vantage points: (1) **conditions** under which generalization procedures would be invoked; (2) **measures** by which that determination was made; and (3) **controls** of the generalization techniques employed to accomplish the change.
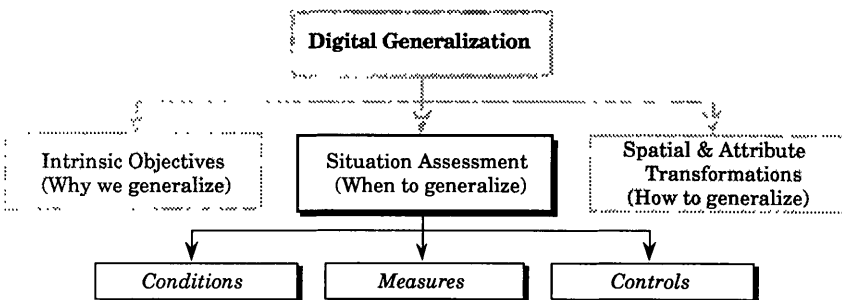

Figure 2. Decomposition of the **when** aspect of the generalization process into three components: *Conditions, Measures,* and *Controls.*

Conditions for Generalization

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

Congestion: refers to the problem where too many features have been positioned in a limited geographical space; that is, feature density is too high.

Coalescence: a condition where features will touch as a result of either of two factors: (1) the separating distance is smaller than the resolution of the output device (e.g. pen

width, CRT resolution); or (2) the features will touch as a result of the symbolization process.

Conflict: a situation in which the spatial representation of a feature is in conflict with its background. An example here could be illustrated when a road bisects two portions of an urban park. A conflict could arise during the generalization process if it is necessary to combine the two park segments across the existing road. A situation exists that must be resolved either through symbol alteration, displacement, or deletion.

Complication: relates to an ambiguity in performance of generalization techniques; that is, the results of the generalization are dependent on many factors, for example: complexity of spatial data, selection of iteration technique, and selection of tolerance levels.

Inconsistency: refers to a set of generalization decisions applied non-uniformly across a given map. Here, there would be a bias in the generalization between the mapped elements. Inconsistency is not always an undesireable condition.

Imperceptibility: a situation 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).

It is the presence of the above stated 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 graphic. One might question how this determination is made. Is it something that is computed by an algorithm, or must the we rely upon operator intervention? 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 also be highly subjective.

How, then, can we begin to assess the state of the condition if the quantification of those 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 be based entirely from outside a map product viewpoint. That is, to 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 **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).

Measures Which Indicate a Need for Generalization

Conditional measures can be assessed by examining some very basic geometric properties of the inter- and intra-feature relationships. Some of these 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.

Density Measures. These measures are evaluated by using multi-features 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 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 say 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 association with a common, but dissimilar area feature.

Length and Sinuosity Measures. These operate on 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. Examples include: 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 isomorphism—that is, the structural kinship between the stimulus pattern and the expression it conveys (Arnheim, 1974). Common examples of this includes closure, continuation, proximity, similarity, common fate, and figure ground (Wertheimer, 1958).

Abstract Measures. The more *conceptual* evaluations of the spatial distributions can be examined with abstract measures. Possible abstract measures include: homogeneity, neighborliness, symmetry, repetition, recurrence, and complexity.

Many of the above classes of measures can be easily developed for examination in a digital domain, however the Gestalt and Abstract Measures aren't as easily computed. 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 need first 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.

Controls on How to Apply Generalization Functionality.

In order to obtain unbiased generalizations, three things need to be determined: (1) the order in which to apply the generalization operators; (2) which algorithms are employed by those operators; and (3) the input parameters required to obtain a given result at a given scale.

An important constituent of the decision-making process is the availability and sophistication of the generalization **operators**, as well as the **algorithms** employed by those operators. The generalization process is accomplished through a variety of these operators—each attacking specific problems—each of which can employ a variety of algorithms. To illustrate, the linear simplification *operator* would access *algorithms* such as those developed by Douglas—as reported by Douglas and Peucker (1973)—and Lang (1969). Concomitantly, there may be permutations, combinations, and iterations of operators, each employing permutations, combinations, and iterations of algorithms. The algorithms may, in turn, be controlled by multiple, maybe even interacting, **parameters**.

> *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: (1) the importance of the individual features (this is, of course, related to the map purpose and intended audience); (2) the complexity of feature relationships both in an inter- and intra-feature sense; (3) the presence and resulting influence of map clutter on the communicative efficiency of the map; (4) the need to vary generalization amount, type, or order on different features; and (5) the availability and robustness of generalization operators and computer algorithms.

> *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.

> *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. Other than some very basic guidelines on the selection of weights for smoothing routines, practically no empirical work exists for other generalization routines.

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 IN GENERALIZATION: HOW TO GENERALIZE

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** of generalization is most commonly thought of as the operators which perform generalization, and results from an application of generalization techniques that have either arisen out of the emulation of the manual cartographer, or based solely on more mathematical efforts. Twelve categories of generalization operators exist to effect the required data changes (Figure 3).
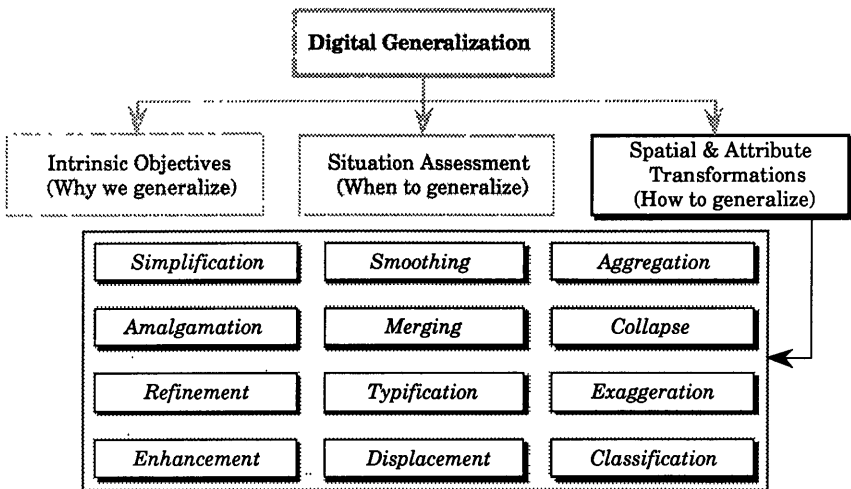

Figure 3. Decomposition of the **how** aspect of the generalization process into twelve operators: simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, typification, exaggeration, enhancement, displacement, and classification.

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 graphic. Data sources for map production and GIS applications are typically of variable scales, resolution, accuracy—and each of these factors contribute to the method in which cartographic information is presented at map scale. The information that is contained within the graphic 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, both individually and collectively. As a result, the graphic depiction of the features changes to suit the scale-specific needs. Below, each of these

transformation processes or generalization operators are reviewed. Figure 4 provides a concise graphic depicting examples of each in a format employed by Lichtner (1979).

Simplification. 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 the least 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 considerations 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, 1987).

Smoothing. 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 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).

Aggregation. There are many instances when the number or density of like point features within a region prohibits each from being portrayed and symbolized individually within the graphic. 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. 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.*

Merging. 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. 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. 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 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. Though the overall initial features are thinned out, the general pattern of the features is maintained with those features that are chosen by showing them in their correct locations. Excellent examples of this can be found in the Swiss Society of Cartography (1977). This refinement process retains the general characteristics of the features at a greatly reduced complexity.

Typification. In a similar respect to the refinement process when similar features are either too numerous or too small to show to scale, the typification process uses a representative pattern of the symbols, augmented by an appropriate explanatory note (Lichtner, 1979). Here again the features are thinned out, however in this instance, the general pattern of the features is maintained with the features shown in *approximate* locations.

Exaggeration. The shapes and sizes of features may need to be exaggerated to meet the specific requirements of a map. For example, inlets need to be opened and streams need to be widened if the map must depict important navigational information for shipping. The amplification of environmental features on the map is an important part of the cartographic abstraction process (Muehrcke, 1986). The exaggeration process does tend to lead to features which are in conflict and thereby require displacement (Caldwell, 1984).

Enhancement. 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 (e.g. 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. 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 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: (1) shifting the features from their true locations (displacement); (2) modifying the features (by symbol alteration or interruption); or (3) or deleting them entirely from the graphic.

Classification. One of the principle constituents of the generalization process that is often cited is that of data classification (Muller, 1983; Robinson, et al., 1978). 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 placed into groups based upon their numerical proximity to other values along a number array (Dent, 1985). The classification process is often necessary because of the impracticability of symbolizing and mapping each individual value.

Spatial and Attribute Transformations (Generalization Operators)	Representation in the Original Map	Representation in the Generalized Map	
	At Scale of the Original Map		At 50% Scale
Simplification			
Smoothing			
Aggregation	Pueblo Ruins Miguel Ruins	Ruins	Ruins
Amalgamation			
Merge			
Collapse	Lake	Lake	Lake
Refinement			
Typification			
Exaggeration	Bay Inlet	Bay Inlet	Bay Inlet
Enhancement			
Displacement			
Classification	1,2,3,4,5,6,7,8,9,10,11,12, 13,14,15,16,17,18,19,20	1-5, 6-10, 11-15, 16-20	Not Applicable

Figure 4. Sample spatial and attribute transformations of cartographic generalization.

SUMMARY

This paper has observed the digital generalization process through a decomposition of its main components. These include a consideration of the intrinsic objectives of **why** we generalize; an assessment of the situations which indicate **when** to generalize, and an understanding of **how** to generalize using spatial and attribute transformations. This paper specifically 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 was considered in an overall framework that focused on three types of drivers (conditions, measures, and controls). Six conditions (including congestion, coalescence, conflict, complication, inconsistency, and imperceptibility), seven types of measures (density, distribution, length and sinuosity, shape, distance, gestalt, and abstract), and three 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 (simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, typification, exaggeration, enhancement, displacement, and classification). The ideas presented here, combined with those concepts covered in a previous publication—relating to the first of the three components—effectively serves to detail a sizable measure of the digital generalization process.

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