Framing Guidelines for Multi-Scale Map Design Using Databases at Multiple Resolutions

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ABSTRACT: This paper extends European research on generating cartographic base maps at multiple scales from a single detailed database. Similar to the European work, we emphasize reference maps. In contrast to the Europeans’ focus on data generalization, we emphasize changes to the map display, including symbol design or symbol modification. We also work from databases compiled at multiple resolutions rather than constructing all representations from a single high-resolution database. We report results demonstrating how symbol change combined with selection and elimination of subsets of features can produce maps through almost the entire range of map scales spanning 1:10,000 to 1:5,000,000. We demonstrate a method of establishing specific map display scales at which symbol modification should be imposed. We present a prototype decision tool called ScaleMaster that can guide multi-scale map design across a small or large range of data resolutions, display scales, and map purposes.

Introduction

Mapmaking at scales between those that correspond to available database resolutions can involve changes to the display (such as symbol changes), changes to feature geometry (data generalization), or both. These modifications are referred to (respectively) as cartographic generalization and statistical or model generalization by Brassel and Weibel (1988) and later by Weibel (1995). Changes to display and geometry are in some instances co-dependent, meaning that modifications of one type can impact subsequent changes to the other. We argue that in previous literature, changes to geometry have overshadowed display change for mapping at multiple scales; and in some situations, this increases the mapmaking workload. Cartographic managers intending to balance or optimize the workload are thus faced with a variety of decisions, including:

• Which compiled-data resolution will be used for maps at any given display scale;
• At what point(s) in a multi-scale progression will symbols be changed;
• At what point(s) in a multi-scale progression will data geometry be modified to suit smaller scale presentation; and
• At what point(s) in a multi-scale progression must new data compilations be introduced.

From a data processing standpoint, symbol modification is often less intensive than geometry modification, and thus changing symbols can reduce overall workloads for the map designer. Figure 1 shows a simplified example of a few coastal features by Brassel and Weibel (1988) and later by Weibel (1995). Changes to display and geometry are in some instances co-dependent, meaning that modifications of one type can impact subsequent changes to the other. We argue that in previous literature, changes to geometry have overshadowed display change for mapping at multiple scales; and in some situations, this increases the mapmaking workload. Cartographic managers intending to balance or optimize the workload are thus faced with a variety of decisions, including:

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data generalization, especially when the target mapping scales show levels of detail that are similar to the resolution of compiled data. We demonstrate a method of establishing specific display scales at which display modification should be imposed. We also prototype a decision tool called ScaleMaster for multi-scale map design across a small or large range of data resolutions, display scales, and map purposes.

**Background and Related Literature**

The process of modifying details in spatial data has been a subject of longstanding interest in many disciplines, judging by publications in Cartography, GIScience, and Computer Science literature. Data reduction through generalization can effect varying and sometimes dramatic changes in line length, local coordinate density, topology, and other properties, thus most algorithms are designed to preserve one or more of these characteristics (Cromley and Campbell 1990; Buttenfield 2002). The guiding principles driving this body of work are to reduce visual clutter while preserving clarity and logical consistency. We review the work on generalization to show that the solutions offered to preserve clarity and reduce clutter through changes in symbol design and selection (Brewer 1995; Slocum et al. 1995) have been largely ignored in the multi-resolution mapping literature.

Published reports that describe and evaluate algorithms for cartographic generalization date back forty years at least, with early work focused on simplistic coordinate reduction of linear features and polygon boundaries. Subsequently, the emphasis shifted to “... address the interdependent generalization of related features (i.e., the elements of a topographic map)” (Weibel 1991, p. 172). In the past decade, generalization work has
formalized knowledge-based rules (Kilpelainen 1997), context-sensitive algorithms (Jones et al. 1995; Burghardt and Cecconi 2003), data modeling (Buttenfield 1995; Ruas and Lagrange 1995), and software agents (Galanda and Weibel 2002). It is important to note that the majority of recent work in cartographic generalization has taken place in Europe. Chronologic overviews can be found in Brassel and Weibel (1988), Buttenfield and McMaster (1991), McMaster and Shea (1992), Meng (1997), Weibel and Dutton (1999), and Mackaness et al. forthcoming.

Another thread of relevant literature has focused on database support for multi-scale data management and flexible zooming through many scales and for many map purposes (see, for example, Jones et al. 2000). Many European authors work within contexts of a national mapping agency producing databases containing linked multiple representations of detailed, high-resolution objects. These databases are referred to as multi-resolution or multi-representation databases (MRDB) (Kilpelainen 1997; Spaccapietra et al. 2000). Updates to these detailed objects autonomously propagate to all resolutions, reducing the work involved in updating maps (Stoter et al. 2004; Bobzien et al. 2005). Objects are linked through all resolutions to accomplish efficient updates, so the approach emphasizes object-level rather than scale-level representations. Some researchers approach object-level generalization and update using representation stamps (Balley et al. 2004). “The concept of multiple representations includes both the various representations stored in the database and also those that can be derived from existing representations” (Kilpelainen 1997, p.14), either by display change (symbol redesign) or geometry change (generalization of detail).

Managing decisions to create consistently high-quality products must be balanced against data processing workloads. This is especially important for on-demand and on-the-fly multi-scale mapping for the web (Torun et al. 2000; Cecconi and Gallanda 2002; Cecconi et al. 2002), mobile devices (Harrie et al. 2002; Hampe et al. 2004), and in-car navigation (Li and Ho 2004; Ulugtekin et al. 2004), in addition to multi-scale database management (Timpf 1998; Jones et al. 2000; Zlatanov et al. 2004). Related innovations include adaptive zooming (Cecconi and Gallanda 2002; Harrie et al. 2002; Hampe et al. 2004), online progressive vector transmission (Buttenfield 1999; Paiva et al. 2004; Zhou et al. 2004; van Oosterom et al. 2006), update propagation across multiple resolutions or representations (Dunkars 2004; Haunert and Sester 2004; Bobzien et al. 2005), and other interactive cartographic applications.

In multi-resolution work, symbolization is typically pre-established, perhaps based on the national look of a topographic series. Thus adjustment of symbols is not always discussed as a generalization operation. However, these authors do discuss it. Bédard and Bernier (2002) explicitly involve variation in visual variables in their discussion of multiple representations and their proposed VUEL (view element) concept for managing geometric, semantic, and graphic multiplicities. Rayson (1999) proposes a method of aggregating point symbols into stacks for military map display while zooming. Torun et al. (2000) discuss selection decisions for web mapping at scales roughly between 1:15K and 1:80K. They develop hierarchies of feature codes and eliminate progressively larger numbers of feature code groups at smaller map scales. Their classing-based method sets thresholds at which groups of features are removed from a map display, with class visibility becoming more exclusive in displays at smaller scales. They acknowledge the interaction between generalization constraints (e.g., graphical limits of output media and reading conditions) and symbol choices for feature classes.

Arnold and Wright (2005) focus on the interaction between feature updates and production of multiple cartographic representations from a single detailed database. They emphasize that mapmakers may have varied purposes (such as producing tourist, road atlas, or electoral maps) as they move from raw data to high-quality finished presentations. They contrast these more customized mapping goals to mapping that conforms to a standard design for a predefined scale range. They acknowledge the roles of four types of cartographic processing—selection, elimination, symbolization, and reclassification—that other authors tend to de-emphasize or pass over in discussion of generalization. They explicitly include the influence of symbolization in their workflow diagrams; they position symbolization as an influencing factor that affects cartographic and analytical representations for products derived from a multi-scale multi-purpose database (for example, see Figure 14 in Arnold and Wright, p. 415).

Cecconi et al. (2002) position symbolization at the beginning of a generalization process. For example, in road network mapping, symbolization precedes all other processes: selection, morphing, weeding, smoothing, rendering, and displacement. These other generalization processes would be re-run if symbols are adjusted in response to an unsatisfactorily generalized cartographic representa-
Cecconi et al. (2002) propose methods for adaptive zooming in web mapping that mix LoDs ("Level of Detail" databases pre-computed from existing databases) with on-the-fly generalization of Swiss topographic data. They explain how the two approaches are combined using diagrams, and examples of their figures are reprinted here.

Figure 2 shows a representation at 1:100K, generalized from an LoD at 1:25K, which includes individual buildings. For some data layers, the 1:25K LoD would serve as a source for mapping down to 1:200K. However, the authors state that Swiss cartographic convention breaks the representation of individual buildings at 1:150K. Building representations at scales smaller than 1:150K would be prepared from a 1:200K LoD showing homogeneously colored urban areas (rather than buildings). For some types of data then, feature data are pulled from an LoD source compiled at a smaller scale than the demanded map scale (for example, a 1:150K building representation is derived from 1:200K LoD data), going against the cartographic convention of always deriving from larger compilation scales. We agree that this contravention will be necessary to implement map production across continuous ranges of scales, but typification and displacement are applied mostly through the middle range of scales (approximately 1:50K to 1:300K). Because additional operators are applied, the complexity curve arcs upward in this range. Similar diagrams are presented for buildings/settlements, railroads, rivers, and lakes and each has different operator limits and selected LoD scales. The authors implement symbolization at the beginning of the mapping process, and they suggest adjusting to smaller symbols if the other operations do not resolve conflicts.

In the next section we report on an exercise that helped us think about how display change (i.e., Brassel and Weibel’s 1988 “cartographic generalization”) may obviate the need for some types of geometry change. We said earlier that many types of display change will involve lower workloads than geometry change. We reiterate this argument using an empirical exercise in which we only change symbols and change feature selections to examine this aspect of workloads for multi-scale mapping. Our exercise uses existing U.S. databases for mapping through a continuous range of scales.

The ScaleMaster Exercise

Cindy Brewer worked through a scale exercise with seven graduate students at the Pennsylvania State University in the fall of 2004, in collaboration with Charlie Frye and Aileen Buckley at ESRI. Charlie and Aileen provided USGS DLG (Digital Line Graph) data sets for the Redlands, CA, area at anchor scales of 1:24,000, 1:100,000, and 1:2,000,000, along with style files for default topographic symbols. The graduate seminar project focused primarily on design change across a range of display scales. The stu-
students' goal was to produce topographic general-reference maps that could be read on 19-inch flat-panel screens, which were typically set at 72 ppi. On-screen display dictates coarse resolution and thus constrains symbol design. Figures 4 to 7 look coarse because they demonstrate what the maps looked like at 72 ppi as the students made design decisions. They are shown in the Figures at 50-percent reduction with no re-sampling, retaining the pixilated onscreen appearance. To print them from higher-resolution exports would not demonstrate the design challenge set for the students. The students did not attempt to include labels on these maps, which would also have affected symbol design. Other than selection decisions, they did not augment the designs with additional generalization operations (such as simplification, displacement, and collapse) that affect geometry, in order to focus the study on design (and complete the project in a half semester).

Each student studied a group of related features (such as hydrography) across the three anchor scales and through continuous scale change for the ScaleMaster exercise. Each student's map layers were then integrated into a reference map displayed at many scales. Students used multiple criteria as they made symbol modification and feature selection and elimination decisions. They examined the visual hierarchy among symbols and reduced size and contrast so that particular feature types were not more prominent than suitable for a topographic general-reference map. Likewise, features with related characteristics were designed with related symbol styles. For example, water body outlines and areas and stream lines were represented with the same hue. More contrast was added if symbols were set too similar at smaller scales. For example, a solid gray line for a power line caused it to look too similar to road symbols and required adding a pattern to the power line. Point symbol sizes and line widths were reduced to ease clutter among features. Area feature outlines were also removed, small features within a class were eliminated, and fewer feature classes were selected to reduced clutter. A selection of mapped examples illustrates the exercise (Figures 4 to 7) and is discussed in more detail below. The purple box in these Figures marks the same extent on each map to highlight the amount of scale change between these example displays.

Students worked with their layers to decide scale ranges, selections, eliminations, and symbol changes. They copied their layers into a master ArcMap project. The group then gathered in class and critiqued the appearance of maps with layers contributed by all students viewed together in the master project. These were visual evaluations of the maps (rather than computed evaluations). Smaller scales often required omission of feature types when the display became too cluttered. For example, Steven Gardner used a wide red and white dash with a black casing for state routes set visible to 1:38K (Figure 4), replaced this symbol with a thinner version of the symbol from 1:38K to 1:50K (Figure 5), then changed to a single black line at scales smaller than 1:100K (Figure 6), and omitted selected state routes at scales smaller than 1:100K.
The map subsets in Figures 4 to 7 also show changes in contour intervals and omission of building markers at smaller scales. Map designs were examined by typing in progressively smaller representative fractions for the display from a range of 10K to 5M. For example, the instructor would type in a series of scales such as 13K, 20K, 45K, 150K, 300K, 600K, 1M, and 4M and the group would evaluate map appearance at each of these sampled scales. At the next class meeting the group would sample a different set of scales through the 10K to 5M range. The class criticized symbolization, commenting on symbols that overwhelmed others or were not sufficiently visible, were too cluttered, were too coarsely presented, and so forth. Then the students each went
back to editing their feature group by adjusting visibility ranges, eliminating subsets of features, and adjusting symbols to integrate better through all scales with the other students' designs. Students' decisions affected subsequent rounds of design checking, which prompted further adjustments, until the group was satisfied with the overall design. The focus was not on designing for the anchor scale and extrapolating from that design. Instead, the group was designing for the entire range of possible map scales.

Once the cycles of symbol redesign and class critique were complete, the exercise had established appropriate symbol designs within ranges of mapping scales for each feature group (hydrography, transportation, and so forth). These specifications formed the basis for creating the ScaleMaster tool (Figure 8). Feature groups are listed to the left,
Figure 8. ScaleMaster diagram prepared to describe symbol behavior for feature classes from three DLG databases for maps ranging from 1:10K to 1:5M. Maps were general-reference topographic-style maps without labels and viewed onscreen using desktop computer displays at 72 ppi.
and each is associated with student names on the right.

The final product each student delivered was a set of ArcMap layers with symbol styles and visibility ranges specified, and a sketch of a horizontal slice through the ScaleMaster diagram. Diagram compilation was organized in a fairly low-tech manner. The instructor handed out graph paper with scales marked on a logarithmic axis. Each student then drew the ranges through which each dataset was useful and marked key design-change break points. These individual lines across strips of the graph paper were then compiled into the composite ScaleMaster diagram. The format for this diagram is patterned after a diagram Charlie Frye presented during a research planning talk on multi-scale basemap data models in May 2003 at ESRI, and which developed into a core visual example for our research discussions.

Three hues are used for horizontal bars across the ScaleMaster diagram, each indicating a different anchor scale: blues for 1:24K, purples for 1:100K, and greens for 1:2M. The lightness series for each anchor scale marks scale ranges for particular symbol design settings. General descriptions of symbol changes are noted with letters at breaks along these bars. For example, at about 1:150K, letters a and c indicate that main rivers were selected from the 1:100K data and the color of lake outlines was lightened. Some bars stop with no further representations at smaller scales to indicate that students felt the feature should be eliminated to reduce clutter. For example, city polygons and railroad lines are no longer represented on maps past 1:300K.

In contrast to the gaps seen for hydrography and point features, the students pulled administrative boundaries “up-scale” from the 1:2M dataset. The straight lines and smooth curves of railroads also allowed students to use them at much larger scales than their 1:2M source would suggest. The green bars for railroads are far displaced from the 1:2M position on the diagram because rail lines were not included on the smaller scale maps, but the selection of lines offered in the 1:2M data was suitable through the 1:30K to 1:250K range. The ScaleMaster decisions were made in the context of a student exercise without strong requirements for map accuracy and completeness, but many mapmaking purposes share a reduced need for planimetric precision, especially for on-demand web contexts.

In addition to symbol design changes, students selected feature classes and removed some subclasses for the mapping exercise (for example, see notes a, b, and k in Figure 8). Thus selection and elimination were used along with symbol design for the map solutions, and we consider both to be display modifications. We acknowledge that some cartographers consider selection and elimination to be types of generalization. Our discussion has emphasized the distinction between display modifications and generalization methods that modify feature geometry. Feature geometry is not changed when removing entire feature classes or subclasses from the display. Thus, we consider selection and elimination of features to also be a design decision.

As an aside, the term “ScaleMaster” grew from in-class conversations and procedures. The instructor named the master GIS project, to which each student contributed layers, ScaleMaster, and that filename grew to be the label for the whole exercise. Also, the class worked on the exercise immediately before the 2004 U.S. Presidential election and was watching the Votemaster web site (electoral-vote.com) which synthesized poll results and displayed predictions on a generalized cartogram. Thus mastering maps was on their minds. It is interesting to note that in an ecology modeling problem, Lilburne et al. (2004) present a framework called “Scale Matcher” for selecting data scales to suit ecology problems.

**Discussion—The Consequences of Scale Change**

The mapping process for the ScaleMaster exercise differed from designing a map at each anchor scale or at a particular intermediate scale. The emphasis was first on how each group of features “behaves” through all scales and how sensitive the features are to scale change. The student group systematically examined how the symbolized features in one layer worked together with other layers to produce maps at multiple scales. This was an iterative process that concluded with draft map designs for all scales and an overall understanding of how differently the feature groups behaved during scale change.

Behavior, in this context, means that symbol appearance and data geometry change across a range of map scales. Visual expectations of the Earth vary as one moves closer (Morrison and Morrison 1994), reflecting earth and atmospheric processes as they become detectable at specific resolutions. Cartographers are trained to design maps such that some processes appear more prominently when creating maps at a given scale.
For example, Buttenfield et al. (1991) inventoried European topographic maps to determine changes in symbol appearance and priorities for transportation, hydrography, and settlement features across a range of large (1:10K) to small (1:250K) scales. These authors determined that terrain and natural processes are more prominent on larger scale maps, while urban limits and transportation networks attain higher prominence on medium (1:100K) and smaller scale topographic maps. This also appears to be the logic underlying USGS topographic mapping symbols (Thompson 1988).

Furthermore, data sensitivities to scale are theme based. Mark (1991) argues that across a range of map scales, naturally occurring features (for example, terrain data and hydrography) will change more often in geometry and symbology than will cultural features (roads, land use). “More often” means that a larger number of critical breakpoints or thresholds can be defined along the progression of scale, where changes must be made either to symbols or geometry (or to both). In part, this is due to the nature of cultural features; for example, roads are built to a fixed radius of curvature, based on the turning radius of automobiles. However, it is also the case that certain naturally occurring surface processes (such as vegetation) will change less often across scales simply because they are dependent on, and surficial to, underlying coarser resolution processes (for example, soil type and moisture, water table depth, or local climate). Essentially, the resolution at which change in the dependent process becomes evident is a function of the resolution of the causative processes.

In this context, we can reflect on the utility of ScaleMaster as a tool to guide symbol redesign for multi-scale mapping. It is important to note that the patterns in this ScaleMaster outcome are specific to DLG data and to the three anchor scales (1:24K, 1:100K and 1:2M). They are also specific to modifying symbology and making feature selections and eliminations only (i.e., not to modifying feature geometry). A ScaleMaster tool built for other multi-scale anchor databases compiled by another National Mapping Agency would likely differ, as would a ScaleMaster tool constructed for types of maps other than reference base maps. It is difficult to predict which of these conditions would have the greatest impact, the anchor databases, scale changing operators, or the map purpose. Nonetheless, we offer a few initial reflections on the ScaleMaster tool and on the exercise.

One thought-provoking aspect of ScaleMaster is the widely varied ranges at which students found data to be useful. For example, the 1:24K data for hydrographic features and roads have fairly constrained ranges that extend up to about 1:50K. In contrast, the 1:24K parks, forests, and city boundaries are useful on maps well past 1:200K. Running vertically through the ScaleMaster stack at various scales suggests that a mapmaker may be pulling from multiple datasets to build a map at a custom scale. For example, the 1:70K vertical line intersects with parks, forests, and city polygons from the 1:24K data; hydrography, roads, point features, and contours from 1:100K data; and railroads from 1:2M.

Another interesting aspect of the ScaleMaster outcome is a data gap across the ScaleMaster stack, roughly between 1:250K and 1:700K. Horizontal bars for some features do not cover this range because they are not ordinarily shown on reference maps at these scales (for example, surface streets, railroads, and miscellaneous transportation). Hydrography, however, should be shown, and the gaps in the ScaleMaster stack indicate that data in the anchor compilations (1:24K, 1:100K, and 1:2M) are not suitable within the range when map design proceeds by symbol modification. This is not a criticism of the National Mapping Agency that produced these data, rather it indicates that hydrography data require geometry change in addition to symbol redesign, or, alternatively, that maps in the range of 1:250K to 1:700K based on DLG anchor data would benefit from inclusion of an intermediate anchor database. Buttenfield and Hultgren (2005) undertook this exercise, embedding 1:250K VMAP data into this same DLG dataset, and integrating the two thesauri. A similar exercise was undertaken in Poland to fuse cartographic thesauri compiled at 1:50K and 1:250K (Gotlib and Olszewski 2006). Those authors report similar findings on discrepancies and redundancies between feature codes, and the impact of military versus civilian agency missions on semantics of the fused databases.

A third interesting aspect relates to scale sensitivities of the DLG data depicted in this ScaleMaster tool. Conventional wisdom is that anchor data can be suitably used for mapping across a range of scales roughly two to five times the anchor. Thus, 1:24K data could be reduced to 1:100K, 1:100K data could be reduced to 1:400K, and 1:2M data could be reduced well beyond 1:5M. Following this logic, the 1:24K anchor data should be most sensitive to scale change, requiring the most frequent symbol design breakpoints, and behaving suitably across the shortest scale range. Looking at the ScaleMaster, one can see that this is not
the case. Scale ranges for the 1:24K anchor data extend across a scale range of about 2x (40K), and these anchor data required few display changes beyond selection at the smallest scales. We interpret this to mean that avoiding geometry changes will severely limit the usable range of mapping scales for 1:24K DLG data. The 1:2M anchor data should be least sensitive and suitable for mapping across the longest scale range with fewest breakpoints. In the exercise this tends to be the case, with 1:2M data layers suitable across a 10x scale range (500K to 5M). It carries the most display revision breakpoints, which are in every case symbol redesign (not selection), implying that symbol redesign is adequate to “push” the display suitability for this smallest scale anchor database.

The scale sensitivity of the 1:100K anchor data should lie somewhere in between the large- and small-scale anchors but, curiously, it does not. This range of suitable mapping scales extends only to 1:150K, except for point features and urban area boundaries, at which selection and symbol redesign are mandated. Moreover, data must be pulled from both other anchor resolutions to fill in content on landcover and some transportation features. In these respects, the 1:100K anchor data appear to be the most sensitive to scale change, contrary to cartographic intuition.

Summary

We justify our argument that symbol modifications can offset the need for geometry change and extend the usable range of reference base-mapping scales (for a given set of anchor databases) by means of an empirical exercise using USGS DLG data across scales 1:10K to 1:5M. Our results support earlier reverse engineering of cartographic basemap symbols (Buttenfield et al. 1991; Paranteinen 1995; Edwardes and Mackaness 2000) showing that various cartographic layers behave differently with scale change. We report results demonstrating how symbol change and selection/elimination can produce maps through much of this scale range. We present a decision tool called ScaleMaster that can be constructed for multi-scale map design across a small or large range of data resolutions, display scales, and map purposes. The ScaleMaster tool that we introduce demonstrates a method of establishing specific map display scales at which display modifications should be imposed. In this case study, we examine a topographic basemap on-screen display. Further work is in progress examining differences between ScaleMaster diagrams produced for maps with different purposes from a larger database.

Formalizing and parameterizing the decisions that trained cartographers make about changing map scale effectively would benefit organizations seeking to maintain consistency of multi-scale design outcomes. This approach would guide systematic production of a minimum number of LoDs derived from larger scale data and identification of additional intermediate-scale data sets suited to an organization’s mapping needs. The approach also benefits organizations lacking a staff cartographer, and it may lead to an improved quality of map products.

The ScaleMaster concept informs decisions that support effective map production workloads. Incorporating symbol change into generalization activities extends the range of mappable scales for a given database, which can reduce the volume of data to be maintained in-house and reduce data processing workloads for map production. The goal is to transform cartographic data across scale ranges and only change symbols and data as much as is needed to preserve visual quality and still meet the map purpose, while maintaining the smallest-volume cartographic database. This approach generates an effective and efficient mapping workflow that can support all the map products created and distributed by an organization.

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