Mastering Map Scale:
Formalizing Guidelines for Multi-Scale Map Design

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Abstract
This paper extends European research on balancing the cartographic production workload. We emphasize the role of changes to the map display (such as symbol design or modification) in contrast to existing workload discussions that focus on changes to feature geometry. 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 scales. 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 be constructed for multi-scale map design across a small or large range of data resolutions, display scales, and map purposes.

1. 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. Cartographic managers 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 map symbols be changed;
- At what point(s) in a multi-scale progression must new data compilations be introduced; and
- What are the most efficient ways to set up and manage cartographic workloads.

From a processing standpoint, symbol modification is often less intensive than modifying data geometry, and thus changing symbol designs can reduce overall workloads for multi-resolution data modeling.

The European community has emphasized the need to develop efficient workloads for scale changing and for generalization operations (for example, Cecconi et al. 2002; Bobzien et al. 2005) since many are computationally intensive or require tedious manual refinement. We extend the European research by emphasizing that changes to symbol design are often incorporated without other 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 symbol modification should be imposed. We prototype a decision tool called ScaleMaster for multi-scale map design across a small or large range of data resolution, display scales, and map purposes.

2. 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. The guiding principles underlying this body of work are to reduce visual clutter while preserving logical consistency. 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).

Published reports that describe and evaluate algorithms for cartographic generalization date back forty years at least, with early work focusing 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, 172). In the past decade, generalization work has formalized knowledge-based rules (Kilpelainen 2000), 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 2003; Regnauld, 2003). 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), and Weibel and Dutton (1999).

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 (NMA) 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, 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 at 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; Zlatanova et al. 2004). Related innovations include adaptive zooming (Cecconi and Gallanda; Harrie et al.; Hampe et al.), online progressive vector transmission (Buttenfield 1999; Paiva et al. 2004; Zhou et al. 2004), 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. Bédard and Bernier (2002) more 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 to stacks for military map display while zooming. Among the authors who examine multiple scale representations, a subset systematically approach map production or analysis through the entire range of scales using databases at selected scales (or resolutions). Four key papers are discussed below: Arnold and Wright (2005) emphasize map production workflows, Cecconi et al. (2002) improve on-the-fly generalization performance, Torun et al. (2000) use classing calculations to decide which features to omit through a range of scales, and Lilburne et al. (2004) propose a method for matching database resolution to problem characteristics.

Arnold and Wright (2005) focus on the interaction between feature updates and production of multiple cartographic representations from a single detailed database. Their work has a more applied perspective than many database-focused papers. 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 on cartographic and analytical processing of a multi-scale multi-purpose database envisioned in their workflow diagrams. 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).

In contrast, Cecconi et al. (2002) position symbolization at the beginning of a generalization process. For example, in their Figure 5 that describes the generalization process for 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 representation.

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 (see their Figure 2[1]). (Structurally, their diagram is very similar to the ScaleMaster concept.) For example, a representation at 1:100K, generalized from an LoD at 1:25K, includes individual buildings, while representations at scales smaller than 1:150K would be prepared from a 1:200K LoD showing homogeneously colored urban areas (rather than buildings). A limit of applicability for the two LoDs is set at 1:150K. Maps are prepared at scales larger than an LoD's intended scale (for example, 1:150K is derived from 1:200K), going against the cartographic convention of always compiling from larger scales. We agree that this contravention will be necessary to implement map production across continuous ranges of scales from a small number of anchor databases.

Cecconi et al. (2002) expand this approach by delineating three scale ranges that summarize scale limits for appropriate processing. These bands are separated by vertical dashed lines through the diagram in their Figure 3a[1] which sketches levels of generalization complexity for a road network example. The preprocessed LoDs are shown as thick bars marking points along the complexity curve. Selection and simplification operators are applied throughout the complete range 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

[1] See Figures 2 & 3 in Cecconi et al. (2002) at http://www.isprs.org/commission4/proceedings02/pdfpapers/138.pdf

process and they suggest adjusting to smaller symbols if the other operations do not resolve conflicts.

Torun et al. (2000) also write on dynamic generalization for web mapping. The authors discuss selection decisions for mapping for scales roughly between 1:15K and 1:80K. They cumulate feature frequency through hierarchies of feature codes and eliminate progressively larger numbers of feature code groups at smaller map scales. They acknowledge that graphical limits of output media and reading conditions influence symbology choices for feature classes.

Torun et al. (2000) describe a classing-based method to set thresholds at which groups of features are removed from a map display. Their Figure 2[2] illustrates the results of the procedure using a series of road types ordered by Dutch Topography Service Tdn codes, with higher numbers for minor features (2000 is a highway code and 3600 is a cycling path code). The features are classed using regular classification methods (equal intervals and natural breaks) common in statistical mapping with class visibility becoming more exclusive in displays at smaller scales. For example, with natural breaks classing applied to scales smaller than 1:40K, symbol visibility is turned off beginning with a category of walking paths and extending through more minor features (with higher code numbers). In contrast, feature codes for secondary roads and higher are set invisible at scales smaller than 1:80K.

Lilburne et al. (2004) do not focus on map display but present a closely related problem of selecting data scales to suit analysis problems in ecology and related domains. They focus on scale dependence in each part of a three-part framework composed of data, application model, and problem domain elements. They name their process Scale Matcher (so we are perhaps following their naming lead with ScaleMaster). They discuss the scale limitations of spatial models and databases for problem solving and examine issues of compatibility between data derived from different scales. They use an additional trio of extent, accuracy, and precision for both spatial and attribute characteristics to elaborate their framework and arrive at ratings for mismatched or unknown matches (failures) and compatible or acceptable matches (scale issues may also be flagged as ignored). They recommend that model results include measures for both imprecision and accuracy. They conclude with a case study on nitrate contamination of an aquifer involving issues of scale compatibility between a leaching model and available spatial data.

In the next section we report on an exercise that helped us think about how existing U.S. databases may be used for mapping through a continuous range of scales.

3. 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 data sets 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 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. The students did not attempt to include labels on these maps, which would also have affected symbol design. Other than selection and elimination decisions, they did not augment the designs with additional generalization operations (such as simplification,

[2] See Figure 2 in Torun et al. (2000) at http://kartoweb.itc.nl/kobben/publications/ISPRSamsterdam.pdf

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 symbol modifications were then integrated into a reference map displayed at many scales. A selection of mapped examples illustrate the experiment (Figures 1 to 4) and are 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.

Figure 1. A selection of symbol decisions within the ScaleMaster project at 1:15K. The Table of Contents (TOC) to the left has the road layers group expanded to show eight road_arcs layers, each associated with different symbol sets and selections used for the exercise. Each map subset in Figures 1 to 4 is shown at 50% of the on-screen size (increased from 72 to 144 ppi).

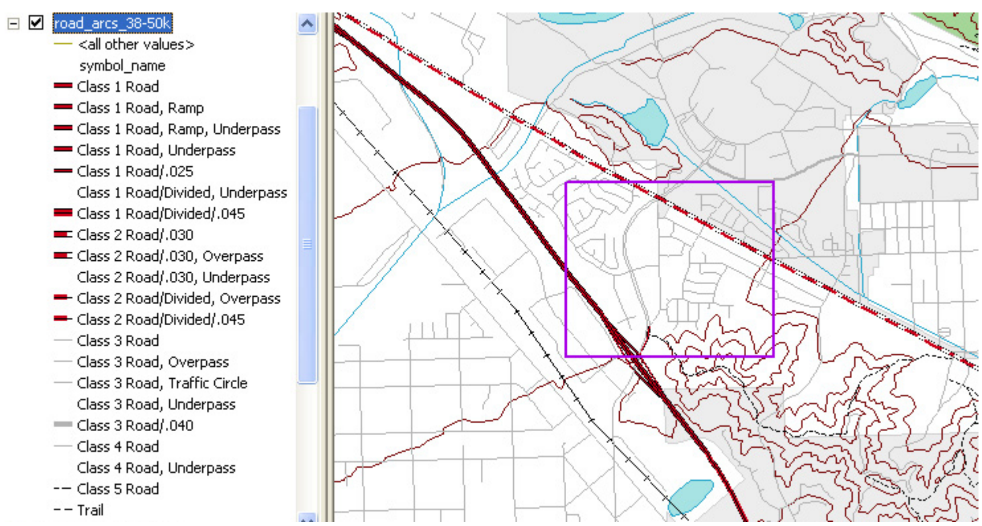

Figure 2. A selection of symbol decisions within the ScaleMaster project at 1:40K. The road symbols for 38K-50K are shown in the TOC.

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 the maps with layers contributed by all students viewed together. 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, replaced these with a thinner version of the symbols from 1:38K to 1:50K, and then changed to a single black line at smaller scales. The map subsets in Figures 1 to 4 also show changes in contour intervals and omission of building markers at smaller scales.

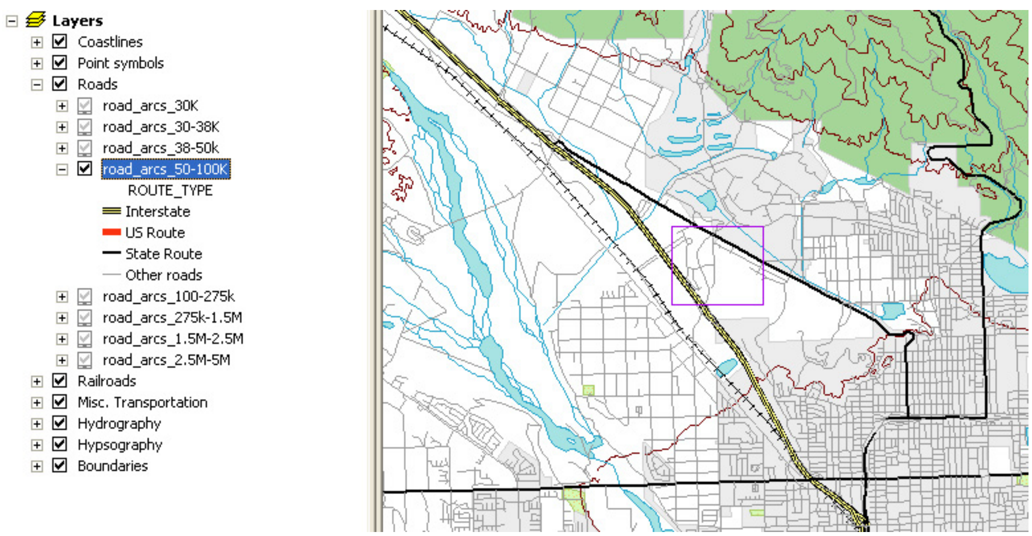

Figure 3. A selection of symbol decisions within the ScaleMaster project at 1:90K. The road symbols for 50K-100K are shown in the TOC.

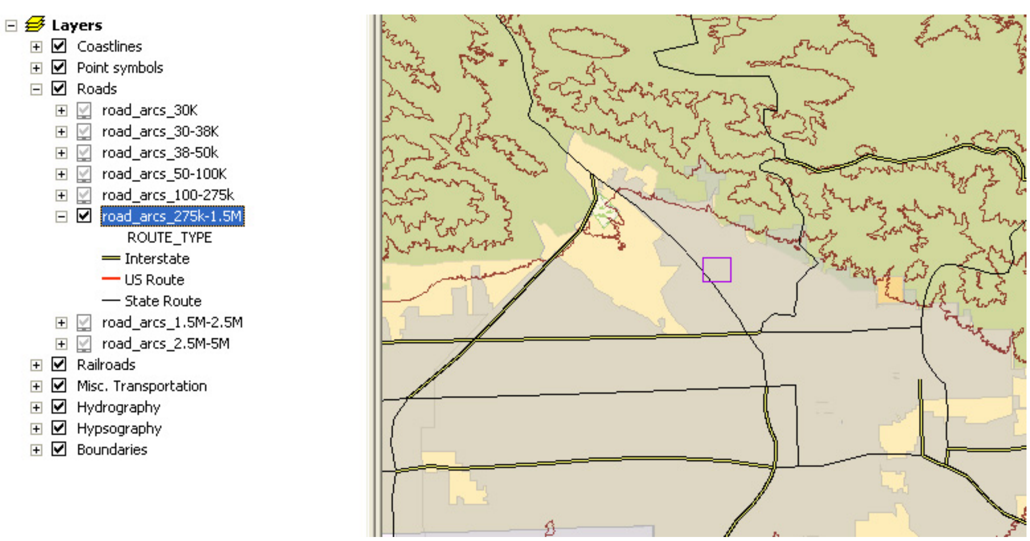

Figure 4. A selection of symbol decisions within the ScaleMaster project at 1:300K. The 1:300K map falls in a "scale gap" where DLG hydrography data were not suitable in the absence of generalization, so it is missing that layer.

Map designs were examined by typing in progressively smaller representative fractions for the display from a range 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 adjusted 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 a usable range of mapping scales for each feature group (hydrography, transportation, and so forth). These specifications formed the basis for creating the ScaleMaster tool (Figure 5). Feature groups are listed to the left and each is associated with student names on the right.

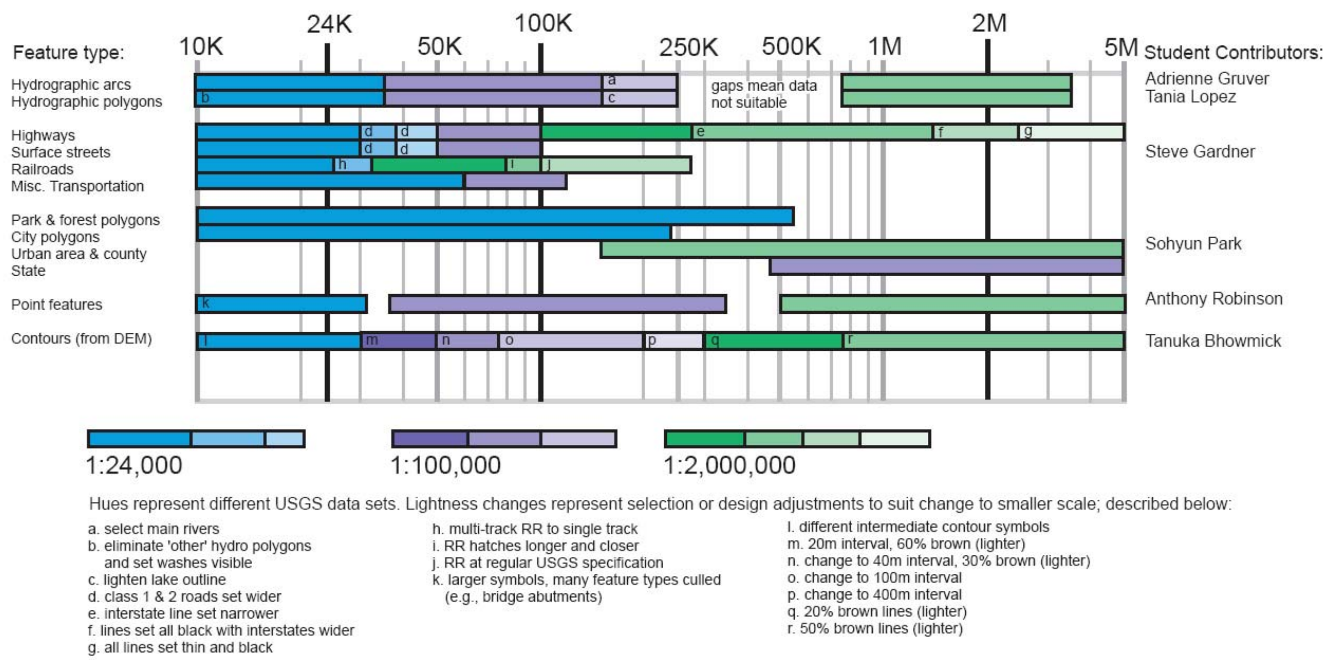

Figure 5. ScaleMaster diagram prepared to describe the symbol behavior for feature classes from three DLG databases for maps ranging from 1:10K to 1:5M. Maps were general-reference topographic-style maps without labels and viewed onscreen using desktop computer displays at 72ppi.

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 were 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 but many mapmaking purposes share this 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 5). Thus selection was used along with symbol design for the map solutions, and we consider both to be display modifications. We acknowledge that some cartographers consider selection to be a type 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 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 website (electoral-vote.com) which synthesized poll results and displayed predictions on a generalized cartogram. Thus master-ing maps was on their minds.

4. 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 "behave" through all scales and how sensitive they 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).

It is also important to note that the patterns in this ScaleMaster outcome are specific to DLG data, and to applying symbology alone. A ScaleMaster tool built for other multi-scale anchor databases 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 three conditions would have the greatest impact, the anchor database, the 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 250K and 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 NMA 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 – 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 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 2 to 5 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 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 very few symbol 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 – 5M). It carries the most symbol 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 scale 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 appears to be the most sensitive to scale change, contrary to cartographic intuition.

5. 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 empiric exercise mapping USGS DLG data across scales 1:10K to 1:5M. Our results support earlier reverse engineering of cartographic base map 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 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 symbol modification should be imposed.

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 datasets suited to an organization’s mapping needs. The approach also benefits organizations lacking a staff cartographer, and 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.

Acknowledgements

The graduate students who worked together to create ScaleMaster in Cynthia Brewer’s Cartography Seminar at Penn State were Tanuka Bhowmick, Steven Gardner, Adrienne Gruver, Tania del Mar López Marrero, Sohyun Park, Anthony Robinson, and Stephen Weaver. Charlie Frye and Aileen Buckley at ESRI supported the project with planning, discussion, data, and symbol files. The authors gratefully acknowledge funding by ESRI (Professional Services Agreements 2003B6345 and 2003B6346.

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