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# On Geometry and Transformation in Map-Like Information Visualization

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**Abstract.** A number of visualization techniques have been put forward that implement a map metaphor to display abstract, non-georeferenced information. This paper refers to these as *map-like information visualizations* that are distinguished from other information visualization approaches in a number of ways. It interprets some of the principles underlying these techniques within a framework informed by geographic information science (GIScience). Recent geographic efforts in this research area have linked ideas about the nature of geographic information to cognitive schemata proposed by cognitive linguists. This paper draws on the arguments that have emerged from those efforts regarding the nature and usefulness of geographic metaphors. It proposes to discuss particular projection techniques, like multidimensional scaling or self-organizing maps, with reference to the geometric primitives they employ. These primitives will drive the choice of geometric and symbolic transformations that are necessary to achieve a particular visualization. Designers of map-like visualizations are thus challenged to seriously consider the implications of particular computational techniques and the consequences of symbolization choices.

## 1 Introduction

Two-dimensional representations have become a pervasive theme in the development of visual exploration and retrieval tools for digital libraries. Many of the proposed visualizations are decidedly "map-like", exhibiting graphic elements and design characteristics of traditional maps. What makes a visualization of abstract information, such as a document corpus, *map-like*? Like traditional maps, such visualizations are constructed from geometric primitives that then become associated with certain map symbols and displayed on a flat display surface. Traditional geographic maps as well as map-like information visualizations are the result of some form of projection of a higher-dimensional configuration into a two-dimensional display space. However, map-like visualizations are not maps in the traditional sense, because they depict abstract information spaces, instead of geographic space.

What sets these visualizations apart from other information visualization techniques? General information visualization techniques include three-dimensional displays. Map-like visualizations are typically restricted to two-dimensional displays, with the possible exception of landscape visualizations. The latter type is often referred to as 2.5-dimensional. Since these landscape visualizations are constructed by interpolation or extrusion of numeric attributes from a two-dimensional geometric configuration, they are still dependent upon the particular characteristics of the two-dimensional techniques discussed in this paper.

Map-like visualizations are distinguished from other two-dimensional visualizations by how coordinate axes are defined. It is different from all those methods in which two dominant variables of a data set are directly mapped to the two axes. While map-like visualizations are in agreement with those methods regarding the primacy of location for human observers [1, 2], they do not exhibit such clear association between each axis and one of the input variables. They do also not give preferential treatment to any particular axis. Classic tree layouts, for example of dendrograms created through hierarchical clustering, are not considered to be map-like, due to the direct mapping of cluster distances onto one axis. Axes in map-like visualizations are defined very differently, compelling Shneiderman et al. [3] to refer to them as “non-meaningful.” Indeed, by far the most frequently asked first question of users confronted with such visualizations is: ”What do the axes mean?” The two axes are not meaningless, but rather they reflect aspects of *all* the input dimensions (i.e., variables) in a complex manner, the particulars of which are determined by the employed projection technique. It is exactly this underlying mix of input variables that gives these visualizations the potential to portray high-dimensional information spaces in a map-like form.

## 2 Relationship to Other Work

By its very nature, research in information visualization crosses the boundaries of individual disciplines. Researchers in this rather young area do however emerge from distinct, established academic disciplines and this is necessarily reflected in the particular approaches that are being pursued. A look at dominant publication outlets confirms that the core of the information visualization research community consists of computer scientists. They have put forward most of the individual techniques as well as overarching taxonomies. Of particular relevance to this paper are efforts to develop taxonomies of visualizations [4-8].

Geography and cartography have a long history of information visualization activities, if we were to include *geographically referenced information*, which is typically visualized in the form of maps. Geographic and cartographic interest in the provision of visual representations for *abstract information* is a more recent phenomenon. A particularly influential guiding principle of those efforts has been Waldo Tobler’s *First Law of Geography*, published in a 1970 paper, according to which everything is related to everything else, but closer things are more closely related [9]. It was a logical predecessor to Tobler’s later observation, in 1979, of the parallels between multidimensional scaling and the surveying technique of trilateration [10].

Any discipline that wants to make scientific contributions outside its established territory needs to first clarify the nature of its domain of inquiry and define a set of core concepts. For geography, geographic space represents the core domain. Among its core concepts are location, region, distribution, spatial interaction, scale, and change [11]. How are these concepts relevant to map-like interfaces to abstract information? If *spatial metaphors* represent a useful basis for the design of user interfaces, then geographic concepts dealing with *space* should be given serious consideration. As for *metaphors*, the work of cognitive linguists [12, 13] has been particularly influential. Couclelis [14] convincingly links those metaphor notions with geographic concepts. She argues that there are three fundamental groups of questions that arise in this endeavor:

- questions regarding the *meaning of geographic concepts* in visual representations of abstract information,
- how geographic concepts can help to perform relevant *cognitive tasks*, and
- issues surrounding the particular concepts, tools, and methods for incorporating geographic concepts into a *visual presentation* of abstract information.

Fabrikant and Buttenfield [15] draw on lessons from geography, cognitive science, and human computer interaction (HCI) to distinguish three spatial frames of reference. These are grounded in geographic space, cognitive space, and Benediktine space [16], respectively. Each is associated with metaphors of distinct character, with consequences for the design of actual interfaces. Fabrikant's ongoing research extends much beyond previous empirical work by testing the relevance and usefulness of particular components of the geographic metaphor, such as distance or scale [17].

Skupin [18, 19] proposes to consider the relevance of cartography to information visualization beyond an appreciation of the map metaphor. This refers particularly to the principles underlying map projection techniques, to problems of graphic complexity, to the choice and positioning of labels, and to map design principles.

## 3 Geometric Configurations

Research and development efforts in information visualization have matured to a point at which the provision of meaningful taxonomies of the various techniques is a necessary step towards the creation of a coherent theoretical framework on which further progress will depend. A number of taxonomies have now been proposed. Some of these treat the information visualization field in its entirety [4, 5, 8]. Other taxonomies are devoted to specific groups of techniques. Examples are papers on graph visualization [6] and pixel-oriented techniques [7].

This paper proposes to distinguish projection techniques used for map-like information visualizations according to the geometric primitives they employ. Distinct techniques exist to project elements of a high-dimensional information space in order to create two-dimensional configurations made up of these basic geometric primitives, which are either zero-, one-, or two-dimensional. This proposed division of techniques derives from Couclelis' argument regarding the cognitive rationale behind use of the spatial metaphor [14]. She argues that experiential space is made up of certain elementary building blocks that correspond to the geometric primitives of mathematical space. *Places*, *ways*, and *regions* are fundamentally distinct experiential categories. If we are to make the map metaphor believable and useful, then we have to give serious consideration to how the corresponding geometric primitives of *points*, *lines*, and *areas* are created, transformed, and ultimately visualized.

### 3.1 Points

Zero-dimensional primitives are employed by such techniques as multidimensional scaling (MDS), principal components analysis (PCA), and spring models. Information space elements enter these methods as discrete units, typically in some form of vector space model [20], with only implicit representation of inter-document relationships. In the case of MDS, distance between documents is made explicit and computed as dissimilarity for each pair of documents. This method makes a fairly overt attempt to preserve distance relationships. In the case of nonmetric MDS, which is appropriate for non-Euclidean, nonmetric dissimilarity measures, this is based on the rank order of dissimilarities. This also helps to allow the bridging of large dimensional gaps between vector space and low-dimensional display space, since some contraction of unused vector space portions and expansion of dense portions can occur. However, MDS implementations typically do not convey these distortions to the user at all. Zero-dimensional configurations can be visualized in a straightforward manner, by linking point symbols and labels to the computed point locations.

Point configurations are useful for the creation of landscape visualizations. Feature attributes can be linked to point locations as elevations and interpolated to form a continuous surface [21]. While this can result in a visually attractive representation, the attribute to be interpolated as well as the interpolation function and parameters have to be chosen carefully. Existing proposals in this direction rarely consider how meaningful the mixture of continuous surfaces with discrete feature labels is [18], or how to visually represent uncertainty associated with different portions of an interpolated surface.

### 3.2 Lines

Typical for one-dimensional configurations are graph layout methods. To this category belong tree graph methods, which are used to visualize hierarchies such as those obtained by hierarchical clustering procedures. Graph layout methods have also been developed for non-tree structures, such as the topological structure of hypermedia information spaces. Herman et al. [6] provide a comprehensive survey of graph visualization methods. Examples for map-like graph visualizations are H-tree layouts, balloon views, and hyperbolic views.

The added dimensionality of links between node locations provides graph visualizations with an opportunity to directly visualize distortions, since links themselves can be symbolized according to the degree of distortion. Methods like the hyperbolic tree make use of the added affordance of a linked representation in a different way, by introducing distortions to provide spatial context.

### 3.3 Areas

Elements of an information space could be represented in two-dimensional form as areas. In geographic representations, areas are often conceptualized as topologically disconnected entities (e.g., lakes or metropolitan areas) and visualized accordingly. In map-like information visualization it is far more common to create topologically connected areas. This typically amounts to the tessellation of a given display surface. The tree map method [22] is the prime example for such a tessellation-based area representation. Tree maps are frequently used whenever hierarchically structured data, such as from the Open Directory Project, are encountered. Tree maps provide a complete tessellation with areas of different sizes being assigned to leaves and nodes of the hierarchy. Variation of area sizes on tree maps is akin to what cartographers call cartograms, in which the size of geographic objects, such as individual countries, is changed to reflect some numeric attribute.

Less explicitly structured input data, such as high-dimensional vector spaces, can also be visualized with tree maps, after computation of a hierarchical clustering solution.

### 3.4 Fields

Geometric configurations based on points, lines and areas reflect a conceptualization of information spaces as consisting of discrete objects. Alternatively, one could interpret elements of a digital library as sample observations of an information *continuum*. Phenomena exhibiting continuous, gradual variation are commonly referred to as *fields*.

The most common information visualization technique implementing a field concept is the self-organizing map (SOM) method [23]. It creates a regular tessellation using uniform area units, akin to raster elements used in digital imagery and GIS. SOMs indeed behave similarly to standard raster data models, compared to the vector-like behavior of the object conceptualizations discussed in the previous sections. For example, how a SOM can be used very much depends on its resolution. A SOM with very fine resolution, i.e. a large number of neurons or nodes, will enable the creation of a detailed visual representation, including the eventual ability to distinguish individual documents [19]. On the other hand, using a coarse SOM amounts to a document classification.

The objective function of the classic Kohonen algorithm is similar to k-means clustering and attempts to preserve topological neighborhood relationships. Kohonen maps perform rather well at this, but at the cost of a pronounced contraction of those map areas that correspond to thinly populated portions of the high-dimensional information space.

### 3.5 Alternative Geometric Configurations

Researchers developing map-like interfaces have to consider that fundamental spatial relationships, such as proximity and neighborhood, are highly dependent on the specific method used to create the initial configuration. It is often possible to use alternative projection techniques, but the most fundamental differences are found when the employed geometric primitives are of a different dimensionality.

Consider as one example the task of visualizing a hypermedia network, such as a set of linked Web pages. One possibility would be to compute a distance matrix based on network distance, i.e. the number of hyperlinks that one would have to traverse to jump from one node to another. This distance matrix is fed to a MDS procedure. Connecting the resulting node locations with straight-line segments, according to the hyperlink structure, then finishes the depiction of the hypermedia network. Now imagine an alternative solution, in which a graph layout method is used to determine coordinate locations for nodes with explicit consideration of the link structure. Even though both results could eventually employ identical symbolization, i.e. identical point and line symbols, the two visualizations would be fundamentally different.

For another example, imagine that one would take the vector space model of a document corpus as input and create alternative visualizations using MDS and SOM. One approach would compute a similarity matrix and use MDS to derive points directly. The second approach would first train a Kohonen map and then find the set of neurons that best fit the input data set. The MDS configuration will provide explicit coordinates for each document, but will be less flexible when additional documents are to be mapped, because the geometric space between points is not explicitly defined in terms of the input feature space. Within the area tessellation of the Kohonen map the high-dimensional vector space of the training data set is represented in explicit chunks. Every portion of the trained SOM is thus explicitly associated with a portion of the information continuum. That makes it very easy to map out documents that were not part of the SOM’s training data set. The chunking of vector space comes at a price though. Depending on the coarseness of the grid of neurons, individual neurons can become associated with multiple documents, preventing the assignment of discrete document coordinates. Choosing a finer resolution SOM can counteract this. However, training a high-resolution SOM exacts a computational toll, much like the processing of high-resolution satellite imagery does.

The division of techniques according to the dimensionality of geometric primitives follows from cognitively useful distinctions in experiential space. Higher-level concepts, such as *region* or *scale*, derive from the more basic concepts. However, there may be fundamental differences of the degree to which individual techniques meaningfully support higher-level concepts. Consider the differences between Kohonen maps and treemaps. Using either method we could communicate the existence of *regions* via area fill color. To the human observer, the two map-like visualizations are then functionally identical. However, differences in the principles underlying the two techniques mean that regions are actually constructed in very different ways. Borders between regions will be defined more locally and strictly for tree maps and more holistically and fluidly for Kohonen maps. Related to this, the concept of *scale* will be embedded very differently in these two visualizations. How is this of concern to interface designers? Users expect map-like visualizations of non-geographic information to *function* like geographic maps, at basic and higher levels. Any mismatch between this expectation and the reality of an interface should be of concern and at the very least be communicated to the user.

## 4 Map Transformations

Some cartographers have long seen mapmaking as a sequence of transformations [10], similar to the visualization reference model proposed by Card et al. [24]. Understanding this transformational character of maps can help designers of map-like interfaces to more fully realize the potential of the geographic metaphor.

### 4.1 Transformations Between Geometric Configurations

The categorization of techniques presented in the previous section does not consider any particular method of symbolizing or otherwise transforming the geometric configuration that might occur *after* the projection. Transformations between different geometric arrangements are common in Geographic Information Systems (GIS) and easily modifiable to fit the needs of non-geographic visualization. For example, a point configuration obtained by MDS can be turned into a continuous surface representation through surface interpolation. If the goal is the delineation of point territories, then tessellation into Voronoi polygons is an easy choice. Use of geometric transformations can help to mitigate some of the problematic issues encountered with particular projection techniques. For example, one can derive individual document coordinates from a Kohonen map by randomly distributing document points inside their respective neurons. Depending on the coarseness of the neuron grid, this will result in the kind of solution typically obtained by MDS, but without the scalability problems of that method.

Error, uncertainty, and distortion characteristics of the original data set as well as of the original projection will of course propagate throughout all further processing and should be considered when visualizations are eventually created.

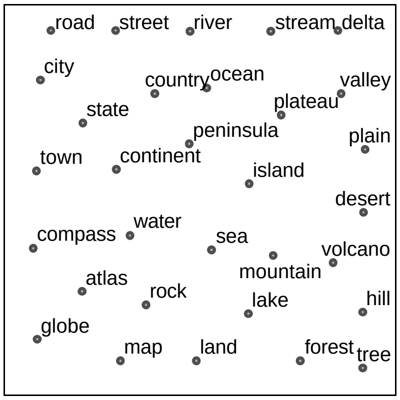


**Fig. 1.** Point Configuration Derived from Self-Organizing Map

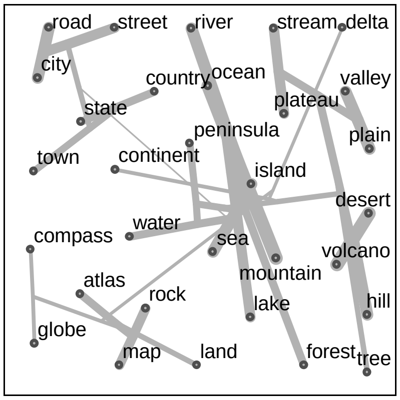
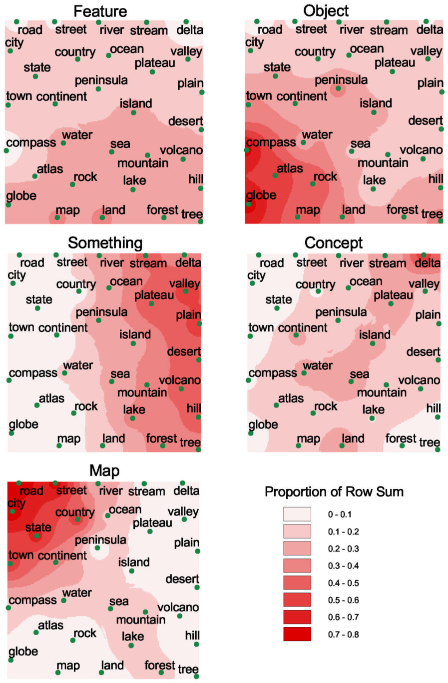


**Fig. 2.** Ultrametric Tree Projected onto Point Configuration



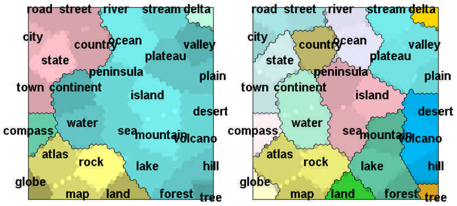


**Fig. 4.** Two Levels of a Hierarchical Classification of SOM Neurons Visualized on the SOM Geometry. Five- and Fifteen-Cluster Solutions Shown (from [25])

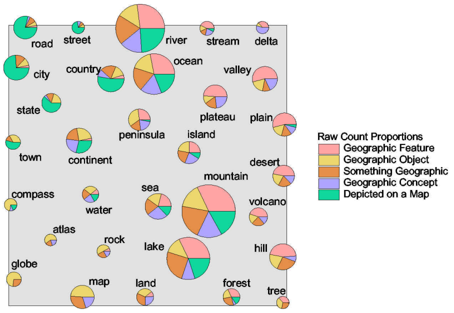


**Fig. 3.** Visualization of Five Input Variables as Interpolated Surface (from [25])

**Fig. 5.** Visualization of Five Input Variables as Pie Charts Associated with Point Locations

### 4.2 Alternative Visualizations from One Geometric Configuration

Cartographic representations are also transformational in the sense that a single geometric configuration could lead to a number of valid visualizations that might encode equivalent information, but are not equal. The data set underlying the visualizations shown here is a human subject test used to investigate aspects of geographic ontology [25]. Subjects were asked to list examples for geographic "things", with five variations in how the specific question was posed ("geographic feature," "geographic object," "geographic concept," "something geographic," and "something that could be portrayed on a map"). A vector space model is created from the responses consisting of 31 objects and five variables. Then a Kohonen map is computed as the basis for a series of transformations. In the first visualization, unique two-dimensional coordinates are displayed for each of the input objects (Figure 1). Then, a hierarchical clustering solution is computed for the original 31 objects and the resulting ultrametric tree is projected onto the point configuration (Figure 2). Line thickness corresponds to distance levels such that thicker lines connect points that are closer in feature space. Notice how similar feature space distances may correspond to very different 2-D distances (e.g., the *river-mountain* pair vs. the *road-city* pair). One could also use the point configuration to investigate the five input variables by producing five interpolated surfaces and displaying them in a form similar to Tufte's small multiples [26](Figure 3). In another approach, two levels of a hierarchical clustering solution of the five-dimensional SOM neurons are shown using the Viscovery SOMine software (Figure 4). Finally, a pie chart map is displayed, constructed from the relative proportion of subject responses for each term (Figure 5). All of the figures, with the exception of figure 4, were produced by combining a given SOM-derived point configuration and transforming it using statistical and geometric operators, and finished in standard GIS software.

## 5 Conclusions

Those attempting to produce useful map-like representations of abstract information are faced with a multitude of design decisions. There are a number of techniques available that will transform an information space into a low-dimensional geometric configuration. This paper argued that grouping these techniques according to the employed geometric primitives helps to understand their conceptual underpinnings, for example regarding the difference between object and field conceptualizations of an information domain. This helps to point toward the transformations that can turn two-dimensional configurations into a variety of geometric and topological structures. Add to this a choice among symbolization techniques and it becomes clear that the eventual appearance of a visualization does not have to be driven by the initial projection method. One implication of this is that similar symbolization techniques can be applied to the results of such diverse techniques as self-organizing maps, multidimensional scaling or pathfinder network scaling. Comparative studies of different visualization techniques with respect to issues of computation, perception, and comprehension should thus be much more feasible than the current lack of such studies suggests.

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