



highlighting, where items selected in one view are highlighted in all others. In linked navigation, movement in one view triggers movement in the others.

There are many kinds of multiple-view approaches. In what is usually called simply the *multiple-view* approach, the same data is shown in several views, each of which has a different visual encoding that shows certain aspects of the dataset most clearly. The power of linked highlighting across multiple visual encodings is that items that fall in a contiguous region in one view are often distributed very differently in the other views. In the *small-multiples* approach, each view has the same visual encoding for different datasets, usually with shared axes between frames so that comparison of spatial position between them is meaningful. Side-by-side comparison with small multiples is an alternative to the visual clutter of superimposing all the data in the same view, and to the human memory limitations of remembering previously seen frames in an animation that changes over time.

The *overview-and-detail* approach is to have the same data and the same visual encoding in two views, where the only difference between them is the level of zooming. In most cases, the overview uses much less display space than the detail view. The combination of overview and detail views is common outside of visualization in many tools ranging from mapping software to photo editing. With a *detail-on-demand* approach, another view shows more information about some selected item, either as a popup window near the cursor or in a permanent window in another part of the display.

Determining the most appropriate spatial position of the views themselves with respect to each other can be as significant a problem as determining the spatial position of marks within a single view. In some systems, the location of the views is arbitrary and left up to the window system or the user. Aligning the views allows precise comparison between them, either vertically, horizontally, or with an array for both directions. Just as items can be sorted within a view, views can be sorted within a display, typically with respect to a derived variable measuring some aspect of the entire view as opposed to an individual item within it.

Figure 26.16 shows a visualization of census data that uses many views. In addition to geographic information, the demographic information for each county includes population, density, gender, median age, percent change since 1990, and proportions of major ethnic groups. The visual encodings used include geographic, scatterplot, parallel coordinate, tabular, and matrix views. The same color encoding is used across all the views, with a legend in the bottom middle. The scatterplot matrix shows linked highlighting across all views, where the blue items are close together in some views and scattered in others. The map in the upper-left corner is an overview for the large detail map in the center. The tabular views allow direct sorting by and selection within a dimension of interest.

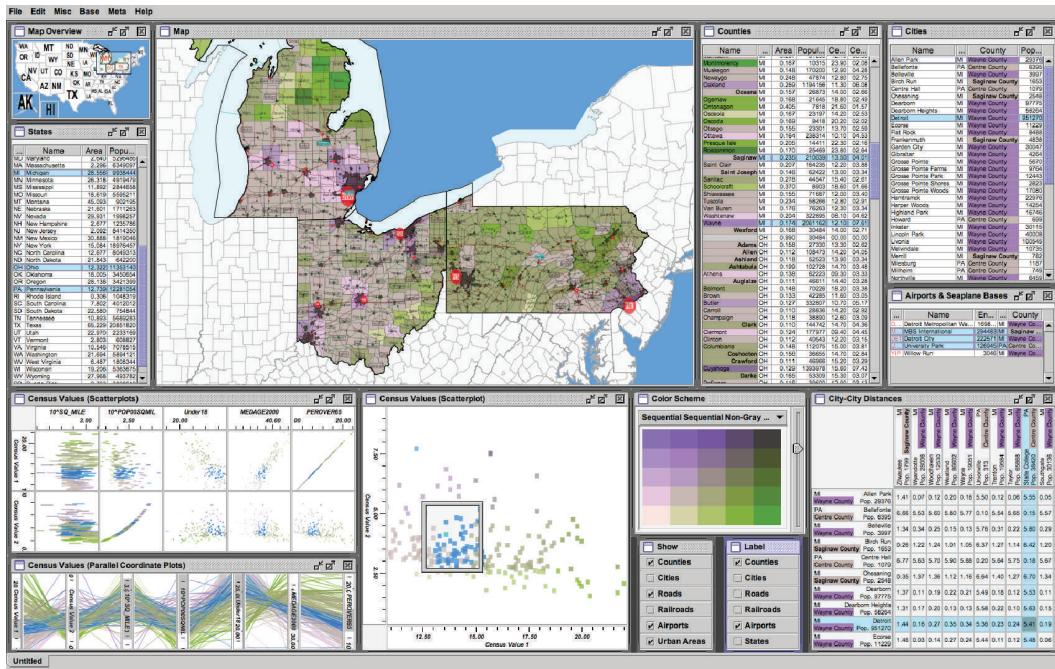


Figure 26.16. The Improvise toolkit was used to create this multiple-view visualization. *Image courtesy Chris Weaver.*

26.7 Data Reduction

The visual encoding techniques that we have discussed so far show all of the items in a dataset. However, many datasets are so large that showing everything simultaneously would result in so much visual clutter that the visual representation would be difficult or impossible for a viewer to understand. The main strategies to reduce the amount of data shown are overviews and aggregation, filtering and navigation, the focus+context techniques, and dimensionality reduction.

26.7.1 Overviews and Aggregation

With tiny datasets, a visual encoding can easily show all data dimensions for all items. For datasets of medium size, an overview that shows information about all items can be constructed by showing less detail for each item. Many datasets have internal or derivable structure at multiple scales. In these cases, a multiscale visual representation can provide many levels of overview, rather than just a single



level. Overviews are typically used as a starting point to give users clues about where to drill down to inspect in more detail.

For larger datasets, creating an overview requires some kind of visual summarization. One approach to data reduction is to use an *aggregate* representation where a single visual mark in the overview explicitly represents many items.

The challenge of aggregation is to avoid eliminating the interesting signals in the dataset in the process of summarization. In the cartographic literature, the problem of creating maps at different scales while retaining the important distinguishing characteristics has been extensively studied under the name of *cartographic generalization* (Slocum, McMaster, Kessler, & Howard, 2008).

26.7.2 Filtering and Navigation

Another approach to data reduction is to *filter* the data, showing only a subset of the items. Filtering is often carried out by directly selecting ranges of interest in one or more of the data dimensions.

Navigation is a specific kind of filtering based on spatial position, where changing the viewpoint changes the visible set of items. Both geometric and non-geometric zooming are used in visualization. With geometric zooming, the camera position in 2D or 3D space can be changed with standard computer graphics controls. In a realistic scene, items should be drawn at a size that depends on their distance from the camera, and only their apparent size changes based on that distance. However, in a visual encoding of an abstract space, nongeometric zooming can be useful. In *semantic zooming*, the visual appearance of an object changes dramatically based on the number of pixels available to draw it. For instance, an abstract visual representation of a text file could change from a tiny color-coded box with no label to a medium-sized box containing only the filename as a text label to a large rectangle containing a multi-line summary of the file contents. In realistic scenes, objects that are sufficiently far away from the camera are not visible in the images, for example, after they subtend less than one pixel of screen area. With *guaranteed visibility*, one of the original or derived data dimensions is used as a measure of importance, and objects of sufficient importance must have some kind of representation visible in the image plane at all times.

26.7.3 Focus+Context

Focus+context techniques are another approach to data reduction. A subset of the dataset items are interactively chosen by the user to be the focus and are drawn



in detail. The visual encoding also includes information about some or all of the rest of the dataset shown for context, integrated into the same view that shows the focus items. Many of these techniques use carefully chosen distortion to combine magnified focus regions and minified context regions into a unified view.

One common interaction metaphor is a moveable fisheye lens. Hyperbolic geometry provides an elegant mathematical framework for a single radial lens that affects all objects in the view. Another interaction metaphor is to use multiple lenses of different shapes and magnification levels that affect only local regions. Stretch and squish navigation uses the interaction metaphor of a rubber sheet where stretching one region squishes the rest, as shown in Figure 26.17. The borders of the sheet stay fixed so that all items are within the viewport, although many items may be compressed to subpixel size. The fisheye metaphor is not limited to a geometric lens used after spatial layout; it can be used directly on structured data, such as a hierarchical document where some sections are collapsed while others are left expanded.

These distortion-based approaches are another example of nonliteral navigation in the same spirit as nongeometric zooming. When navigating within a large and unfamiliar dataset with realistic camera motion, users can become disori-



Figure 26.17. The TreeJuxtaposer system features stretch and squish navigation and guaranteed visibility of regions marked with colors (Munzner, Guimbretière, Tasiran, Zhang, & Zhou, 2003).

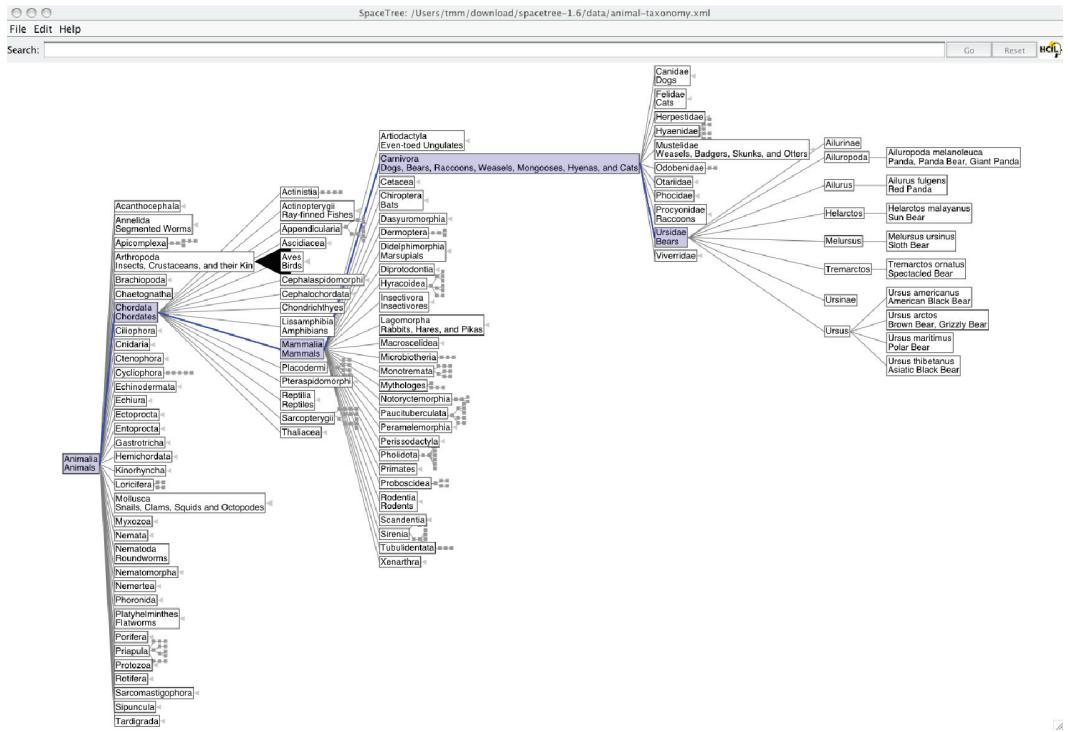


Figure 26.18. The SpaceTree system shows the path between the root and the interactively chosen focus node to provide context (Grosjean, Plaisant, & Bederson, 2002).

ented at high zoom levels when they can see only a small local region. These approaches are designed to provide more contextual information than a single undistorted view, in hopes that people can stay oriented if landmarks remain recognizable. However, these kinds of distortion can still be confusing or difficult to follow for users. The costs and benefits of distortion, as opposed to multiple views or a single realistic view, are not yet fully understood. Standard 3D perspective is a particularly familiar kind of distortion and was explicitly used as a form of focus+context in early visualization work. However, as the costs of 3D spatial layout discussed in Section 26.4 became more understood, this approach became less popular.

Other approaches to providing context around focus items do not require distortion. For instance, the SpaceTree system shown in Figure 26.18 elides most nodes in the tree, showing the path between the interactively chosen focus node and the root of the tree for context.



26.7.4 Dimensionality Reduction

The data reduction approaches covered so far reduce the number of items to draw. When there are many data dimensions, *dimensionality reduction* can also be effective.

With *slicing*, a single value is chosen from the dimension to eliminate, and only the items matching that value for the dimension are extracted to include in the lower-dimensional slice. Slicing is particularly useful with 3D spatial data, for example when inspecting slices through a CT scan of a human head at different heights along the skull. Slicing can be used to eliminate multiple dimensions at once.

With *projection*, no information about the eliminated dimensions is retained; the values for those dimensions are simply dropped, and all items are still shown. A familiar form of projection is the standard graphics perspective transformation which projects from 3D to 2D, losing information about depth along the way. In mathematical visualization, the structure of higher-dimensional geometric objects can be shown by projecting from 4D to 3D before the standard projection to the image plane and using color to encode information from the projected-away dimension. This technique is sometimes called *dimensional filtering* when it is used for nonspatial data.

In some datasets, there may be interesting hidden structure in a much lower-dimensional space than the number of original data dimensions. For instance, sometimes directly measuring the independent variables of interest is difficult or

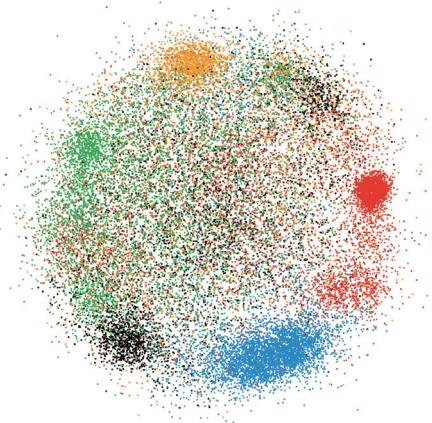


Figure 26.19. Dimensionality reduction with the Glimmer multidimensional scaling approach shows clusters in a document dataset (Ingram, Munzner, & Olano, 2009), © 2009 IEEE.



impossible, but a large set of dependent or indirect variables is available. The goal is to find a small set of dimensions that faithfully represent most of the structure or variance in the dataset. These dimensions may be the original ones, or synthesized new ones that are linear or nonlinear combinations of the originals. Principal component analysis is a fast, widely used linear method. Many nonlinear approaches have been proposed, including multidimensional scaling (MDS). These methods are usually used to determine whether there are large-scale clusters in the dataset; the fine-grained structure in the lower-dimensional plots is usually not reliable because information is lost in the reduction. Figure 26.19 shows document collection in a single scatterplot. When the true dimensionality of the dataset is far higher than two, a matrix of scatterplots showing pairs of synthetic dimensions may be necessary.

26.8 Examples

We conclude this chapter with several examples of visualizing specific types of data using the techniques discussed above.

26.8.1 Tables

Tabular data is extremely common, as all spreadsheet users know. The goal in visualization is to encode this information through easily perceivable visual channels rather than forcing people to read through it as numbers and text. Figure 26.20 shows the Table Lens, a focus+context approach where quantitative values are encoded as the length of one-pixel high lines in the context regions, and shown as numbers in the focus regions. Each dimension of the dataset is shown as a column, and the rows of items can be resorted according to the values in that column with a single click in its header.

The traditional Cartesian approach of a scatterplot, where items are plotted as dots with respect to perpendicular axes, is only usable for two and three dimensions of data. Many tables contain far more than three dimensions of data, and the number of additional dimensions that can be encoded using other visual channels is limited. Parallel coordinates are an approach for visualizing more dimensions at once using spatial position, where the axes are parallel rather than perpendicular and an n -dimensional item is shown as a polyline that crosses each of the n axes once (Inselberg & Dimsdale, 1990; Wegman, 1990). Figure 26.21 shows an eight-dimensional dataset of 230,000 items at multiple levels of detail (Fua, Ward, & Rundensteiner, 1999), from a high-level view at the top to finer detail

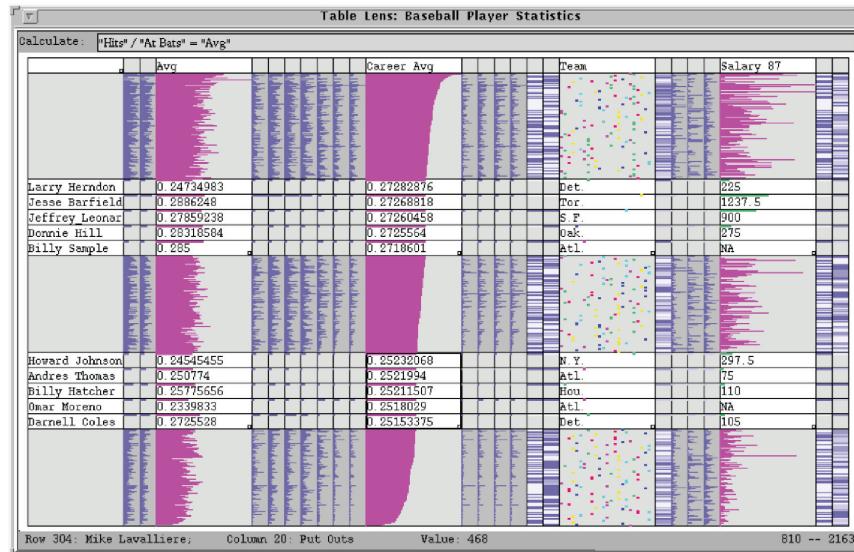


Figure 26.20. The Table Lens provides focus+context interaction with tabular data, immediately reorderable by the values in each dimension column. *Image courtesy Stuart Card (Rao & Card, 1994), © 1994 ACM, Inc. Included here by permission.*

at the bottom. With hierarchical parallel coordinates, the items are clustered and an entire cluster of items is represented by a band of varying width and opacity, where the mean is in the middle and width at each axis depends on the values of the items in the cluster in that dimension. The coloring of each band is based on the proximity between clusters according to a similarity metric.

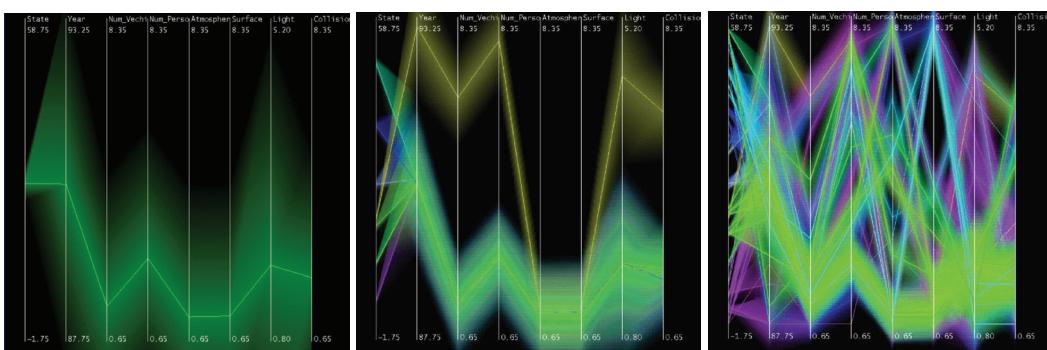


Figure 26.21. Hierarchical parallel coordinates show high-dimensional data at multiple levels of detail. *Image courtesy Matt Ward (Fua et al., 1999), © 1999 IEEE.*

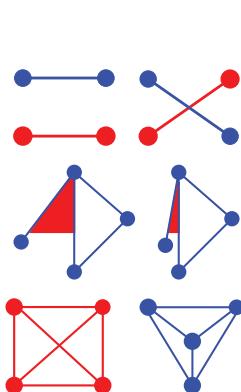


Figure 26.22. Graph layout aesthetic criteria. Top: Edge crossings should be minimized. Middle: Angular resolution should be maximized. Bottom: Symmetry is maximized on the left, whereas crossings are minimized on the right, showing the conflict between the individually NP-hard criteria.

26.8.2 Graphs

The field of graph drawing is concerned with finding a spatial position for the nodes in a graph in 2D or 3D space and routing the edges between these nodes (Di Battista, Eades, Tamassia, & Tollis, 1999). In many cases the edge-routing problem is simplified by using only straight edges, or by only allowing right-angle bends for the class of *orthogonal* layouts, but some approaches handle true curves. If the graph has directed edges, a layered approach can be used to show hierarchical structure through the horizontal or vertical spatial ordering of nodes, as shown in Figure 26.2.

A suite of aesthetic criteria operationalize human judgments about readable graphs as metrics that can be computed on a proposed layout (Ware, Purchase, Colpys, & McGill, 2002). Figure 26.22 shows some examples. Some metrics should be minimized, such as the number of edge crossings, the total area of the layout, and the number of right-angle bends or curves. Others should be maximized, such as the angular resolution or symmetry. The problem is difficult because most of these criteria are individually NP-hard, and moreover they are mutually incompatible (Brandenburg, 1988).

Many approaches to node-link graph drawing use force-directed placement, motivated by the intuitive physical metaphor of spring forces at the edges drawing together repelling particles at the nodes. Although naive approaches have high time complexity and are prone to being caught in local minima, much work has gone into developing more sophisticated algorithms such as GEM (Frick, Ludwig, & Mehldau, 1994) or IPsep-CoLa (Dwyer, Koren, & Marriott, 2006). Figure 26.23 shows an interactive system using the r -PolyLog energy model, where

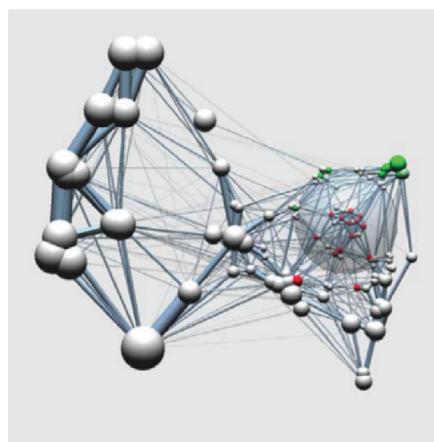


Figure 26.23. Force-directed placement showing a clustered graph with both geometric and semantic fisheye. *Image courtesy Jarke van Wijk* (van Ham & van Wijk, 2004), © 2004 IEEE.

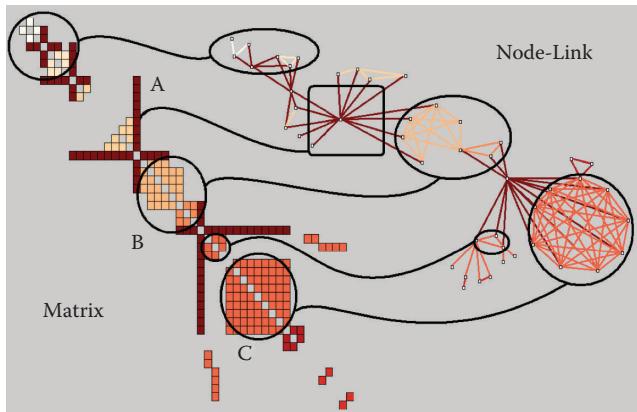


Figure 26.24. Graphs can be shown with either matrix or node-link views. *Image courtesy Jean-Daniel Fekete (Henry & Fekete, 2006), © 2006 IEEE.*

a focus+context view of the clustered graph is created with both geometric and semantic fisheye (van Ham & van Wijk, 2004).

Graphs can also be visually encoded by showing the adjacency matrix, where all vertices are placed along each axis and the cell between two vertices is colored if there is an edge between them. The MatrixExplorer system uses linked multiple views to help social science researchers visually analyze social networks with both matrix and node-link representations (Henry & Fekete, 2006). Figure 26.24 shows the different visual patterns created by the same graph structure in these two views: A represents an actor connecting several communities; B is a community; and C is a clique, or a complete sub-graph. Matrix views do not suffer from cluttered edge crossings, but many tasks including path following are more difficult with this approach.

26.8.3 Trees

Trees are a special case of graphs so common that a great deal of visualization research has been devoted to them. A straightforward algorithm to lay out trees in the two-dimensional plane works well for small trees (Reingold & Tilford, 1981), while a more complex but scalable approach runs in linear time (Buchheim, Jünger, & Leipert, 2002). Figures 26.17 and 26.18 also show trees with different approaches to spatial layout, but all four of these methods visually encode the relationship between parent and child nodes by drawing a link connecting them.

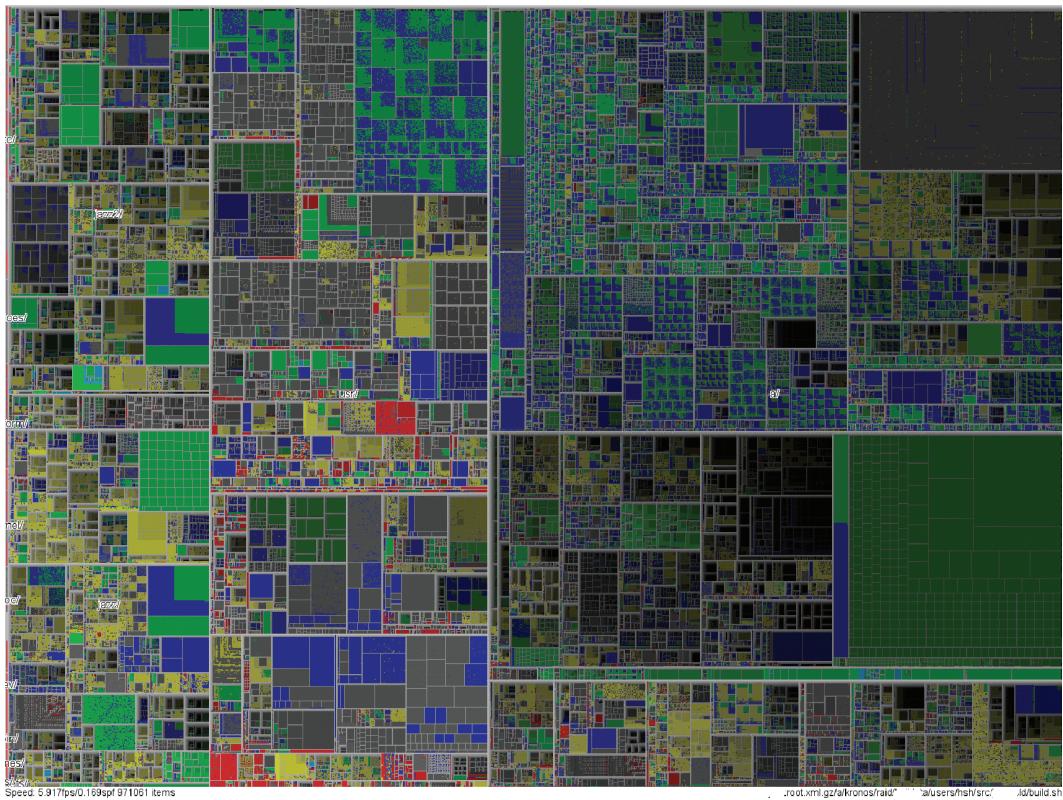


Figure 26.25. Treemap showing a filesystem of nearly one million files. *Image courtesy Jean-Daniel Fekete (Fekete & Plaisant, 2002), © 2002 IEEE.*

Treemaps use containment rather than connection to show the hierarchical relationship between parent and child nodes in a tree (B. Johnson & Shneiderman, 1991). That is, treemaps show child nodes nested within the outlines of the parent node. Figure 26.25 shows a hierarchical filesystem of nearly one million files, where file size is encoded by rectangle size and file type is encoded by color (Fekete & Plaisant, 2002). The size of nodes at the leaves of the tree can encode an additional data dimension, but the size of nodes in the interior does not show the value of that dimension; it is dictated by the cumulative size of their descendants. Although tasks such as understanding the topological structure of the tree or tracing paths through it are more difficult with treemaps than with node-link approaches, tasks that involve understanding an attribute tied to leaf nodes are well supported. Treemaps are space-filling representations that are usually more compact than node-link approaches.



26.8.4 Geographic

Many kinds of analysis such as epidemiology require understanding both geographic and nonspatial data. Figure 26.26 shows a tool for the visual analysis of a cancer demographics dataset that combines many of the ideas described in this chapter (MacEachren, Dai, Hardisty, Guo, & Lengerich, 2003). The top matrix of linked views features small multiples of three types of visual encodings: geographic maps showing Appalachian counties at the lower left, histograms across the diagonal of the matrix, and scatterplots on the upper right. The bottom 2×2 matrix, linking scatterplots with maps, includes the color legend for both. The discrete bivariate sequential colormap has lightness increasing sequentially for each of two complementary hues and is effective for color-deficient people.

26.8.5 Spatial Fields

Most nongeographic spatial data is modeled as a field, where there are one or more values associated with each point in 2D or 3D space. Scalar fields, for example CT or MRI medical imaging scans, are usually visualized by finding isosurfaces or using direct volume rendering. Vector fields, for example, flows in water or air, are often visualized using arrows, streamlines (McLoughlin, Laramee, Peikert, Post, & Chen, 2009), and *line integral convolution* (LIC) (Laramee et al., 2004). Tensor fields, such as those describing the anisotropic diffusion of molecules through the human brain, are particularly challenging to display (Kindlmann, Weinstein, & Hart, 2000).

Frequently Asked Questions

- What conferences and journals are good places to look for further information about visualization?

The IEEE VisWeek conference comprises three subconferences: InfoVis (Information Visualization), Vis (Visualization), and VAST (Visual Analytics Science and Technology). There is also a European EuroVis conference and an Asian PacificVis venue. Relevant journals include IEEE TVCG (Transactions on Visualization and Computer Graphics) and Palgrave Information Visualization.

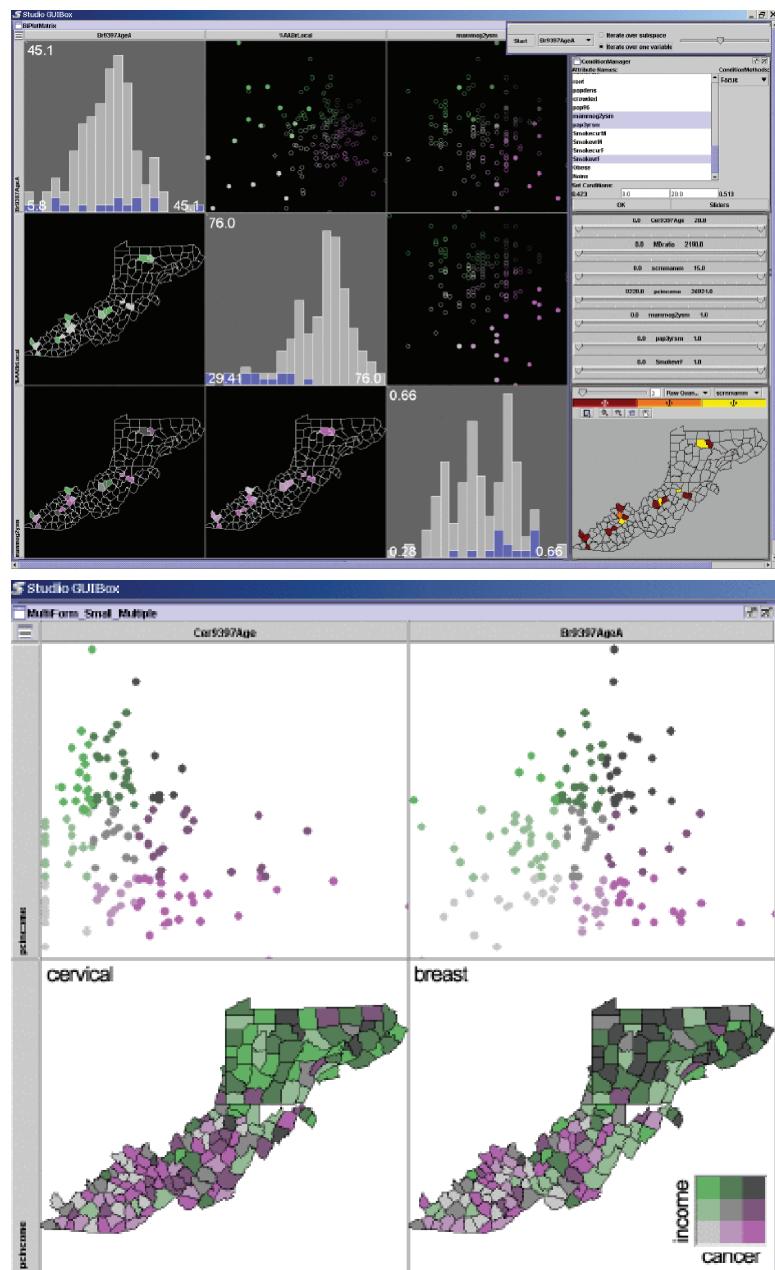


Figure 26.26. Two matrices of linked small multiples showing cancer demographic data (MacEachren et al., 2003), © 2003 IEEE.



- What software and toolkits are available for visualization?

The most popular toolkit for spatial data is `vtk`, a C/C++ codebase available at www.vtk.org. For abstract data, the Java-based `prefuse` (<http://www.prefuse.org>) and `Processing` (processing.org) toolkits are becoming widely used. The `ManyEyes` site from IBM Research (www.many-eyes.com) allows people to upload their own data, create interactive visualizations in a variety of formats, and carry on conversations about visual data analysis.

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Fundamentals of Computer Graphics

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