Visualizing Software Changes

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Abstract

A key problem in software engineering is changing the code. We present a sequence of visualizations and visual metaphors designed to help engineers understand and manage the software change process. The principal metaphors are matrix views, cityscapes, bar and pie charts, data sheets and networks. Linked by selection mechanisms, multiple views are combined to form *perspectives* that both enable discovery of high-level structure in software change data and allow effective access to details of those data. Use of the views and perspectives is illustrated in two important contexts: understanding software change by exploration of software change data and management of software development. Our approach complements existing visualizations of software structure and software execution.

1 Introduction

A fundamental problem in software engineering for large systems is changing the code, to add new functionality, accommodate new hardware, support new operating environments and fulfill

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increased user expectations. In an ideal world, software architecture would anticipate and facilitate future changes. In reality, the architecture is imperfect, and incorporates compromises forced by time, cost, and knowledge constraints. As a consequence, an immense burden falls on the change process, which becomes complex, costly, hard to manage and difficult even to understand.

Data on software changes are typically stored in version management databases. A compelling opportunity, then, is to use these data to enable understanding and management of the change process. There are problems in using these data, however. The scale, complexity (see §2.3), and data handling issues are daunting: custom scripts and tools must be created to extract the data and domain specific manipulation are required to put them in proper form for analysis (Mockus, *et al.*, 1999). The next problem, after the data are extracted, cleaned, manipulated, and warehoused, is to perform effective analyses. Analyzing software data with conventional statistical and business intelligence tools is frustrating because of scale, data complexity, and because the tools are generic and lack software engineering domain knowledge.

To overcome this problem we have developed a number of visualization tools that both facilitate rapid exploration of high-level structure in software change data and also serve as a powerful visual interface to the data details. In this paper we describe these tools, and illustrate their application to two key problems. The first problem is *Understanding Software Change*, especially for exploratory analysis. Formal statistical analyses and reporting tools are appropriate for "assumptive-based" analyses where the tool confirms or refutes assumptions. Exploratory visual analysis is appropriate for discovery problems where the exact analysis questions are unknown. The second problem is *Management of Software Development*, for which precise, quantitative results of formal analyses may be less important than the rapid, qualitative understanding of the current status of a development project that visualizations afford.

The remainder of the paper is organized as follows. The setting for our research, the software change process and the data are summarized in §2. Abstractions and principles underlying the visualizations are articulated in §3, where the visual metaphors — *views* — that we employ are described. Applications of the visualizations to the two problems identified above are presented in §4 (Understanding Software Change) and §5 (Management of Software Development). We conclude, in §6, with a discussion and evaluation of the tools.

2 Software Changes and Data

Our definition of a change to software is data-driven: a change is any alteration to the software recorded in the change history database. With some simplification, changes fall naturally into three main classes (An, Gustafson & Melton, 1987; Swanson, 1976). *Adaptive* changes add new functionality to a system (for example, caller ID in a telephone switch), or adapt the software to new or changed hardware, or to other alterations in its environment. *Corrective* changes fix faults in the software. *Perfective* changes (also called "re-engineering") are intended to improve the developers' ability to maintain the software (in particular, to make additional changes in the future) but do not by themselves alter functionality or fix faults.

2.1 Setting

The tools presented here were developed in the context of an uncommonly rich data set: the entire change history of a large, fifteen-year old real-time software system for telephone switches. Currently, the system comprises 100,000,000 (numbers are approximate) lines of source code (in C/C++, the proprietary state description language SDL, and other languages) and 100,000,000 lines of header and make files, organized into some 50 major subsystems and 5,000 modules. For our purposes, a *module* is a directory in the source code file system, so that a code module is a collection of several files. Each release of the system consists of some 20,000,000 lines of code. More than 10,000 software developers have participated in the project over the last fifteen years.

The need for visualization is especially acute for projects of this magnitude, but our visual tools are broadly and widely applicable within the software development process. Although the original ideas were conceived in the context of large scale software production, they are equally useful for smaller department-sized projects: in §5 we illustrate their use for daily management of a 25-person development organization building a 250,000 line software system aimed at business intelligence.

2.2 The Change Process

The changes to the source code follow a well-defined, institutionalized process, whose main, hierarchical components are:

Features (for example, call waiting or credit card billing) are the fundamental requirements unit by which the system is extended.

Initial Modification Requests (IMRs) are the high-level design information by means of which the changes that implement a feature are transmitted to the development organization. Typically there are hundreds of IMRs per feature.

Modification Requests (MRs) translate IMRs into the low-level design information representing the work to be done to each module; thus there are multiple MRs per IMR. Described differently, an IMR is a problem, while an associated MR is all or part of the solution to the problem. The supervisor responsible for an IMR distributes the work to developers as MRs.

The developer to whom an MR is assigned "opens" the MR, makes the required modifications to the code, checks whether the changes are satisfactory (within a limited context, i.e., without a full system build), and then submits the MR. Code inspections and integration and system tests follow.

Deltas are editing changes to individual files in order to complete an MR. A file is "checked out" by a developer, edited and then "checked in."

2.3 Change Data

Data pertaining to the change history of the code itself reside in a version management system (similar to SCCS (Rochkind, 1975)), which tracks changes at the feature, IMR, MR and delta levels. Within the version management system, the structure of the change data is as follows (see Figure 1):

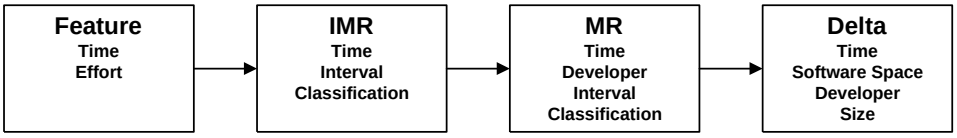

Figure 1: The Software Change Process and Associated Data. The hierarchy of the process flows from left to right. Software space, size, and interval can be defined at higher levels by aggregation. (For example, the size of a feature is the sum of the sizes of the associated deltas.)

Feature. In addition to descriptions, data for features include time and effort estimates that are inferred using methodology described in Graves & Mockus (1998, 2001).

IMR. Each IMR has an extensive record (89 fields in all) containing priority, date opened and closed, and the point in the development process when it was initiated (requirements, design, coding, testing, field operation).

MR. Each MR has a parent IMR, dates and affected files, and an abstract — English text describing the change and the reasons for it. There is no explicit format on how and what information is entered for the abstract field; however, its purpose is to allow other developers to understand what change was made and why.

Delta. The data for each delta list the parent MR and the date and time when the change was submitted to the version management system as well as numbers of lines added, deleted, and unmodified by that change.

This level of detail preserves the capability to build earlier versions of the software, which is necessary to serve customers with older versions.

Conceptually, the fundamental components of the change data are:

Time: The date when a change was made.
Software Space: Which files were changed, and which lines were added and deleted.
Developer: The engineer who made the change.
Type of the change, either adaptive, corrective or perfective.
Size: How many modules, files, and lines were affected.
Effort: How many developer-hours were required to perform the change.
Interval: How long the change took, in calendar time.

Figure 1 indicates the form and level of aggregation at which the version management database contains these components. The “change type” data have problematic aspects discussed in Eick, *et al.* (2001).

3 Principal Visualization Metaphors

A fundamental problem in visualizing software changes — and in information visualization generally (Card, Mackinlay & Shneiderman, 1999) — is to choose effective visual representations (metaphors) for data that are not inherently physical. The goal is an insightful rather than a faithful

depiction of the data. As noted in §1, visualizations are especially effective if they both facilitate rapid exploration of high-level structure in software change data *and* serve as effective interfaces to the data details.

For purposes of visualization, the components of software change data listed in §2.3 can be grouped into two categories. The first — *Dimensions* — are the attributes associated with the software development process. Our assumption is that for the purpose of understanding changes the dimensions, which include time, change type, software space, and developer identification, are independent entities that cannot be controlled. The dimensions are frequently, but not necessarily, categorical. The second category — *Measures* — includes variables such as size, effort, interval, and number of faults. Measures are the responses that the development organization wishes to understand and control. The most useful measures are usually additive.

The goal of an analysis is usually to understand the relationships between the dimensions and measures. The views we present show one or more measures as functions of one or more dimensions. In some cases, such as correlating interval with size, the value of one or more measures is used to filter the view of another. In others, such as correlating fault density with developer, the filtering occurs on the dimensions.

Of the components of change listed in §2.3, only time has an apparent physical representation. While structured (for example, as a network defined by links between modules, as in Figure 11) software space is not intrinsically physical. Software space and developer can, as categorical variables, index matrix and landscape views effectively (§3.1). Size, effort and interval, as numerical variables, can be mapped onto several visual attributes, such as color, size or shape.

We now describe the five visual metaphors used in this paper: matrix views (§3.1), cityscape views (§3.2), bar and pie charts (§3.3), data sheets (§3.4), and network views that relate changes to software structure (§3.5). We then describe combinations of metaphors called perspectives (§3.6), and interactive features of the metaphors and dynamic direct manipulation operations (§3.7). Each visual component, or *view* for short, embodies a visual metaphor or representation of the data. In our implementation, the views are dynamic and function both as visual displays and as an environment for visual analysis. Obviously the five visual tools that we consider do not exhaust all possibilities; instead they are examples chosen to show the power of visualization in specific settings and the metaphors that we have found most useful in our analyses. Nor do the components exist in isolation from one another: especially in §5, *perspectives* (§3.6) — multiple, linked views of different aspects of the change data, using a different visual metaphor for each — are central.

3.1 Matrix Views

Matrix views (Bertin, 1981) are effective for displaying one or more responses as a function of two categorical indices. The view itself, as in Figure 2, is a two-dimensional grid with rows corresponding to one index and columns to the other. Cell (i, j) contains a glyph depicting the values of one or more (usually numerical) responses when the row index is i and column index is j. The responses are encoded as visual attributes — size, color, shape, and texture — of the glyph.

In Figure 2, the indices are developers (rows) and software space (columns correspond to modules — subdirectories in the source code tree containing files with related functionality) and two responses are shown: size of changes, which is mapped onto the width of the bar in each cell, and

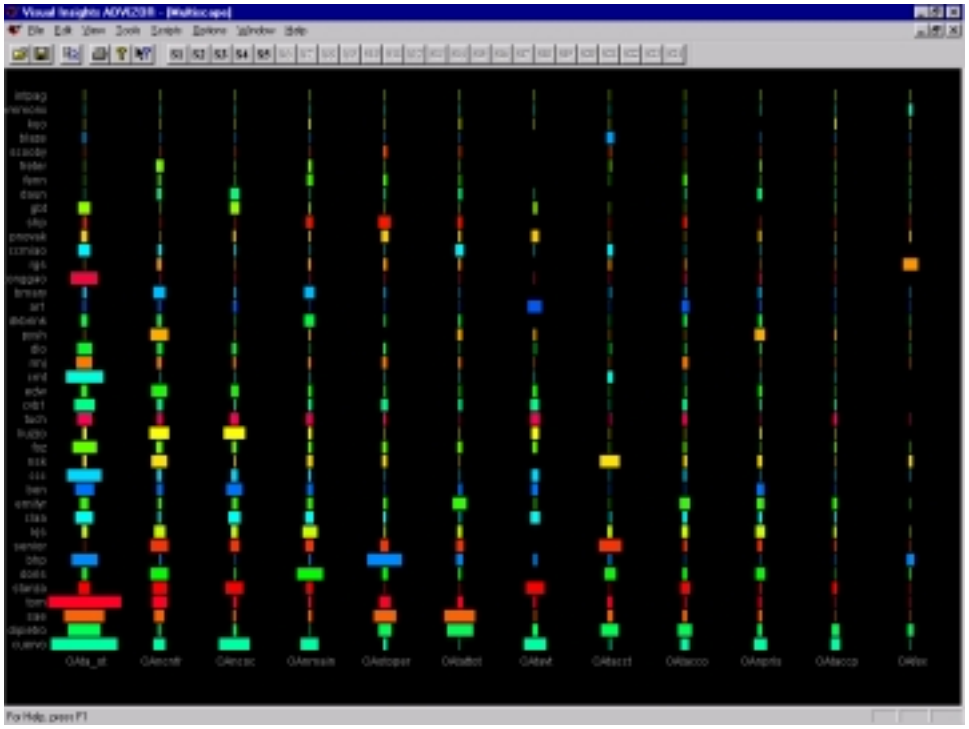

Figure 2: Example of a Matrix View showing change patterns for the top developers. *Indices:* Rows represent developers, columns are software space, at the level of aggregation of modules. *Responses:* bar width encodes module size, bar color encodes developer.

developer, which is redundantly mapped onto color.

Figures 9 and 10 contain additional examples of matrix views. In the former, as is sometimes useful for numerical responses, marginal information is displayed along the edges of the matrix view.

A strength of matrix displays is that many cells are visible; also, there is no overplotting. A single image can present the information contained in thousands or tens of thousands of cells. On a high-performance, 1280×1024 resolution monitor, cells of 10×10 pixels are easily seen. In extreme cases, cells as small as a few pixels or perhaps even a single pixel may work. Pan–and–zoom capabilities needed to deal with matrix views that are too big to fit on the screen are intuitive and implemented easily. In simple cases, the view can be scrolled in the same way as a spreadsheet, but sophisticated controls are also available, which more effectively maintain *focus+context* (Card, Mackinlay & Shneiderman (1999)).

In matrix (and cityscape) views, the structure of software space is irrelevant to creating the view: because there is no natural order to modules, the columns (say) of the view can be arranged in any order. The price of this ease, however, is that these views cannot effectively relate structure to other variables.

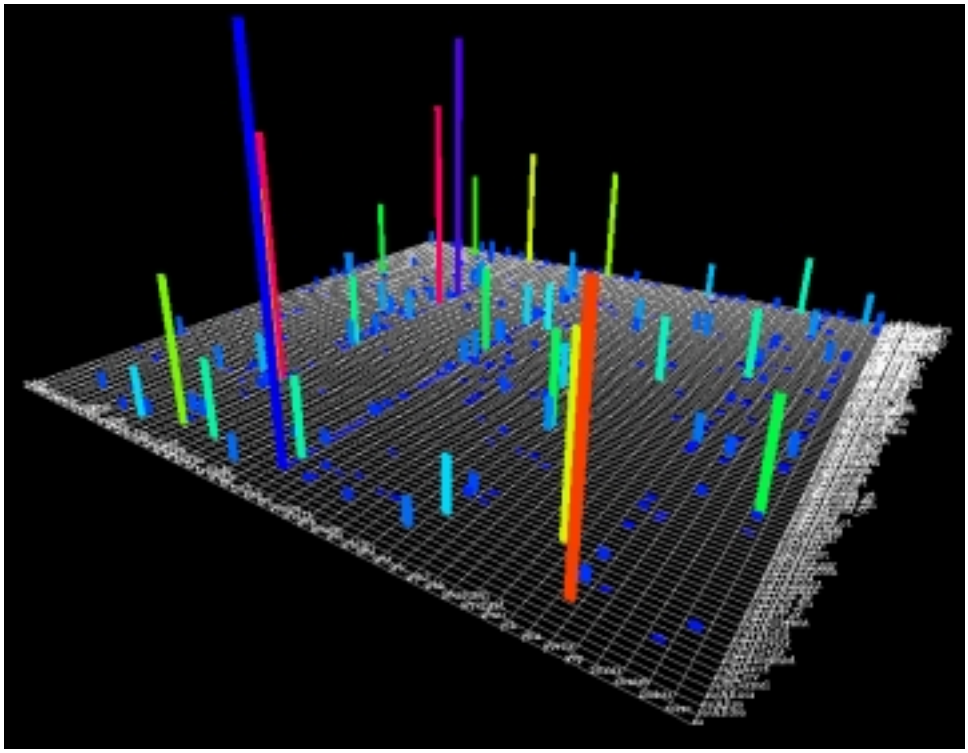

Figure 3: Example of a Cityscape View. *Indices:* Rows represent developers, columns are software space, at the level of aggregation of modules. *Responses:* Bar color and bar height both (redundantly) encode total number of changes.

3.2 Cityscape Views

Cityscapes (Hill & Hollan, 1991), or three-dimensional bar charts, are three-dimensional extensions of matrix views. There are two indices and one or more responses. Attributes that encode the response variables are, typically, the height and color of the vertical towers comprising the cityscape. In some implementations, the walls of the view are used to display additional information.

The cityscape view in Figure 3, which has the same indices as the matrix view in Figure 2, uses the heights of vertical towers to encode the number of changes made by each developer to different modules of the code. Color (redundantly but effectively) encodes the number of changes. Figure 10 contains an additional illustration of a cityscape visualization.

By comparison with matrix views, cityscapes are more compelling, but at the expense of decreased scalability. Using 3D towers to encode information requires more pixels per cell than a matrix view. Occlusion is another problem: tall towers toward the front of the cityscape obscure smaller ones toward the rear. These problems can be overcome to some extent by rotating, thresholding, or using other interactive techniques, but these techniques are not as intuitive as for matrix views.

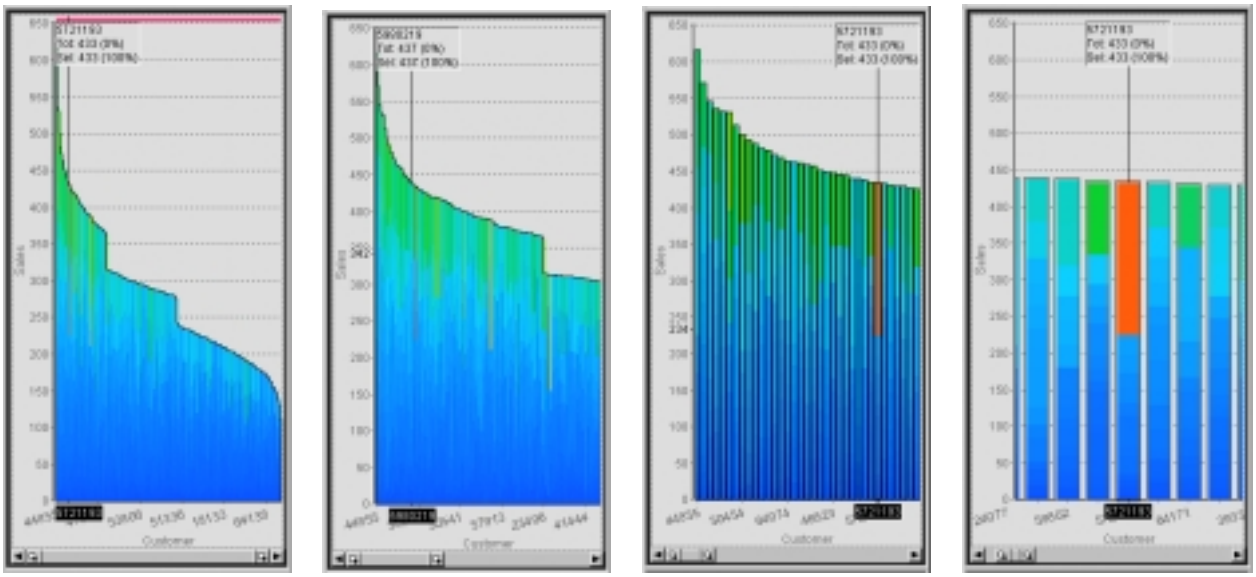

Figure 4: Bar chart scalability is increased by using levels of rendering detail, a red over-plotting indicator long the top (left), and a 1,000–to–1 zoombar along the bottom.

3.3 Bar and Pie Charts

Simple views such as *bar charts* and *pie charts* complement the richer, more complicated matrices and cityscapes. Although the visual metaphors embodied in bars and pies are well-known, in our implementation we have extended bars and pies in two important ways.

First, bar charts incorporate new mechanisms for *scalability*: by exploiting direct manipulation and interactivity, it is possible to visualize bar charts with thousands of bars. Such data volumes render static bar charts unusable. As shown in Figure 4, we increased bar chart scalability by using three techniques:

1. A zoombar supporting a 1000–to–1 dynamic range enables users easily to scroll and zoom into interesting regions.

2. The rendering of the bars varies according to the scale. At maximum zoom the bars are drawn as separate entities that are individually distinguishable. As the user zooms out, the bars are drawn with progressively less detail and eventually become single pixel vertical lines.

3. An overplotting mark indicates that more than one bar is represented by each vertical lines.

In addition, both bar and pie charts are color-coded using *color stacking*. For example, if the bars are showing MRs by programmer, and color is tied to MR severity, the colors for each severity will be stacked with each programmer's bar, as in Figure 12. This allows easy comparison of different severities across programmers.

Bars and pies are most effective as selectors linked to other views in a perspective (see below). As implemented in ADVIZOR™, bar charts scale effectively to indices with large numbers of values. Pie charts do not scale well under any circumstances.

3.4 Data Sheets

A data sheet is a scrollable text visualization (Eick, 1994; Eick, *et al.*, 1997b) providing direct access to individual data elements, such as IMRs, MRs or deltas. Although a sheet is fundamentally a simple multi-column textual display that can be sorted on the basis of any column, there is one crucial, interactive extension. To deal with scale, as the user zooms out to show more data elements, the text font size shrinks, eventually collapsing into tiny horizontal bars, with the bar length tied to the string width for text variables or encoding the value of numerical variables. (Table Lens (Inxight, 1999) has similar capabilities.)

As useful as data sheets are as visualizations in their own right, they are even more useful in providing immediate access to details of the data, which is especially effective when they are linked to other views.

3.5 Network Views

Although it is complex, software space does have structure. First, there is hierarchical structure (subsystems, modules, files) defined by the architecture of the code. Additional structure is associated with program states, function calls and shared variables. Still other structure may be associated with the change process itself, with modules or files linked, for example, by a history of common changes.

DataConstellations (Wills, 1999) is a visual tool for showing the structure of software space, using a network metaphor. Nodes represent software units (typically, modules), and visual attributes encode measures of association between nodes. In Figure 11 (see §4.6 for discussion), association corresponds to modules' having been changed together in the past (Eick, *et al.*, 2001). Interactive capabilities, including pan, zoom, and filtering, are available.

The strength of network views is that they can reveal high-level structure that is impossible to discern by other means (because the structure is too complex or too complicated to describe). Three principal, related weaknesses are lack of scalability, inability to display multiple link characteristics and overplotting (Ware & Frank, 1996). Scalability is a consequence of the fact that accessible, comprehensible graphs require many empty pixels. Link attributes other than width and color have not yet been used effectively. (Length conveys node associations.) Network layout algorithms (Fruchterman & Reingold, 1991; Gansner, *et al.*, 1993; Munzner, 1997) attempt to locate strongly associated nodes near one another, which helps minimize link overplotting, but the problem remains severe. Techniques employing metaphors for underlying structure in the network (Lamping & Rao, 1994; Munzner, 1997; Robertson, *et al.*, 1993; Schaffer, *et al.*, 1996) are avenues for future exploration.

3.6 Perspectives

As discussed above, each kind of view has strengths and weaknesses. Some (particularly matrix, cityscape and network views) support discovery of high-level structure in software change data, but are less effective as interfaces to the details. Data sheets, by their very nature, provide immediate access to details, but do not convey high-level structure very well. Bar and pie charts are primarily tools to explore and summarize the data, and are also effective selectors.

To exploit the complementary capabilities of different views, we construct *perspectives*, in which multiple views of the same software change data are displayed simultaneously, each using a different visualization strategy. More important, the views in a perspective are *linked*: selection operations (see §3.3) in one view are realized in the others as well. This allows the views that summarize or access details to act as filters for the views that enable understanding of high-level structure.

Figure 6, which contains linked bar and pie charts, is a simple, illustrative example. §4 and 5 present multiple applications of perspectives in the contexts of understanding software change and managing software development.

As described in Eick (2000), all views in a perspective are linked in five ways: by *color, focus, selection, labeling* and *exclusion*. Focus, selection, and exclusion, described below in §3.7, involve a case-based selection and linking model (Eick & Wills, 1995). In case-based linking systems based on a data table model, there is a state vector that represents the state of every row in the data table. Interactive operations such as recoloring, selection, exclusion, and labeling manipulate the states corresponding to various rows. State change events are propagated to the views using a publish-and-subscribe event handling mechanism. Each of the views then redraws itself using the refreshed state.

In our implementation any of the views may be combined into a perspective and are automatically linked. The perspectives are defined using an XML-based repository and created using proprietary authoring tools. See §6.2 for a brief description of our implementation. Our authoring environment supports data access, perspective creation, *ad hoc* reporting, and many of the other functions that are commonly available with business intelligence software. Our experience is that even novices can author, save, and reuse perspectives that they create.

3.7 Direct Manipulations

Software engineering data volumes overwhelm conventional visualization tools. To increase the scalability our views are interactive and support a common set of direct manipulations. There are two classes of direct manipulation operations: linked manipulations that propagate among the views and view-specific operations that affect only the current view. The linked manipulations include:

Focus: mousing over any graphical item causes it to become the focus item. By convention, the views dynamically label the focus item for easy identification.

Selection: users may select a set of graphical items by sweeping out a rectangle. Following Microsoft's desktop, the selected items are drawn in color and the unselected in gray.

Exclusion: unselected items may be eliminated from the views using the exclusion or filtering operation. By progressively selecting and excluding users may *drill-down* on subsets of the data.

Labeling: selected items may be labeled.

Recoloring: the views support multiple color scales that may be interactively remapped.

The non-linked manipulations include viewport manipulations such as zooming, scaling, panning.

4 Understanding Software Change

In this section, we show how the visualizations described in §3 function as tools to understand software change by exploring software change data. The setting for such exploration is one of research, in which the visualizations fulfill two principal functions. First, they are interfaces to the data, allowing exploration, browsing, filtering and drill–down in ways that other methods, such as SQL queries to the version management database, simply do not.

Second, the visualizations support the formulation of interesting questions about the software change process, as well as hypotheses about the change process, that would not be posed otherwise. The answers to such questions may be derived in a variety of ways, including additional exploration and formal statistical analyses (e.g., as in Eick, *et al.* (2001) or Graves, *et al.* (2000)).

As noted in §2.1, our database is the entire, fifteen year change history of a large, real-time software system for telephone switches. Because of the limitations involved in presenting views non-interactively on paper, in this section we restrict attention to changes to one subsystem of the software, which is involved with operator interaction with the switch. This subsystem, created in 1984, has been changed 150,850 times (deltas) by 549 programmers. As shown in the bar chart in Figure 6, tiny amounts of initial development occurred in 1984 and 1985, jumping to approximately 7,000 changes in 1986, becoming nearly 16,000 changes in 1990, and decreasing to just over 6,000 changes by 1998. Data for 1999 are for only part of the year.

4.1 Basic Statistics of Changes

The perspective shown in Figure 5 investigates the structure of changes — specifically, of IMRs. Recall that an IMR describes a problem and has associated to it a set of MRs that solve the problem. For the subsystem under study, Figure 5 shows the number of deltas per IMR, the associated release, number of developers active on the IMR, the number of lines added and the number of lines deleted. The color coding distinguishes these different items for each IMR. In Figure 5, only the 14 IMRs with the largest numbers of deltas are selected, but both the bar chart and the data sheet can accommodate all 16,062 IMRs for this subsystem.

In the bar chart, the user is touching (with the mouse) the blue bar corresponding to IMR 543977, which has an unusually large number of deltas (563) associated with it. The linked data sheet then shows other detail for that IMR.

4.2 Changes Indexed by Time

Figure 6 is a perspective emphasizing changes as a function of time. It contains a bar chart showing changes by year, a pie chart showing changes by file type and year, and three data sheets listing (1) Deltas, including parent feature and IMR; (2) Module properties, namely, module size and aggregated change sizes (lines added and deleted); and (3) The same module-indexed data as in (2), but sorted by the total number of changes. The colors, which are common to all views, encode the years of changes.

The primary purpose of this perspective is to pose and answer questions regarding the historical pattern of effort and types of files changed. The data sheets give access to details of the data, by

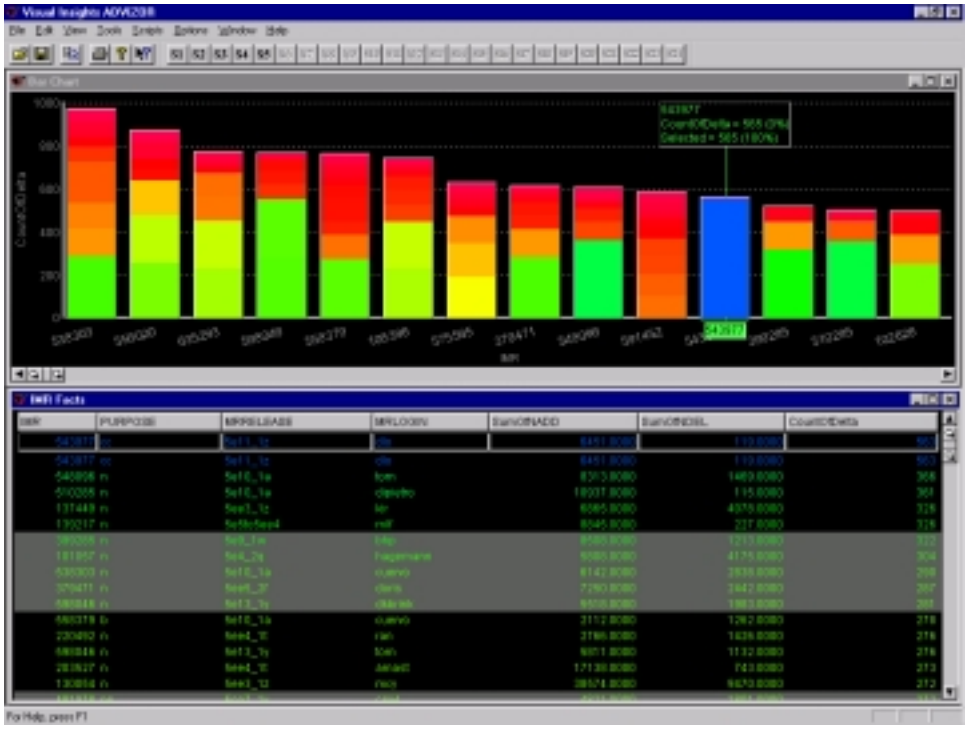

Figure 5: Perspective Showing Deltas Indexed by IMR, zoomed in on the fourteen IMRs with the most deltas. Colors show various IMR characteristics. *Bar chart:* number of deltas per IMR and number of lines added and deleted, differentiated by color. *Data sheet:* details for individual IMRs. Discussed in §4.1.

both change and module. One can see in the bar chart in Figure 6, for example, a significant decline in the annual number of changes in recent years.

The pie chart, in which wedges display numbers of changes by file type, shows that just over one-half of the changes have been to C language code, with just over an 1/8 to `sdl` (state description language) files, and just under one-eighth to `md` (make files). The colors, representing year in the bar chart, allow one to see that changes to `sd` files occur relatively more recently than those to other types of files.

The top data sheet serves mainly as a selector, enabling specific deltas to be mapped onto time, size, file type and other characteristics of changes. The bottom two data sheets (which contain the same data, but sorted differently) show that the most frequently changed subsystem is `hdr`. This not surprising, since `hdr` contains (global) header files that define cross-module interfaces.

4.3 Changes Indexed by Developer

The perspective in Figure 7 investigates the question “Who wrote the code?” The two data sheets contain the same information (the one on the left is a compressed version of the one on the right), indexed by developer: number of changes, total number of lines added and total number of lines deleted. Both are sorted by the number of changes, which is mapped onto color. Although Figure

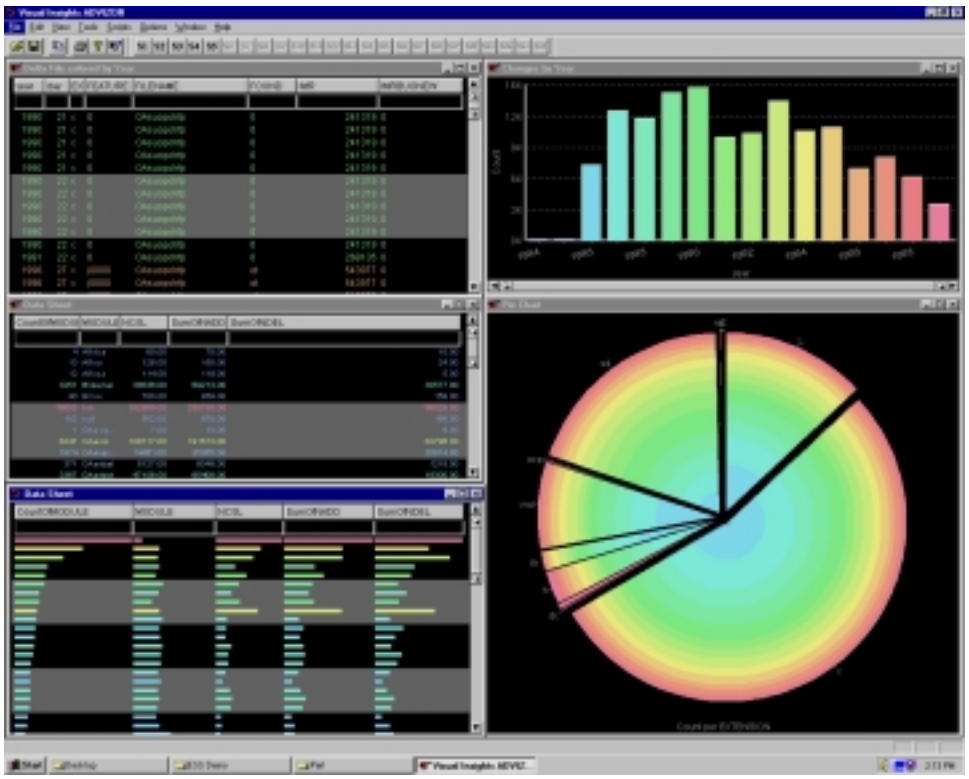

Figure 6: Perspective Showing Changes Indexed by Time. Color encodes year. *Bar chart:* numbers of changes by year. *Pie chart:* numbers of changes by file type. *Data sheets:* individual deltas (top) and changes aggregated by module (middle) and subsystem (bottom). The bottom data sheet shows the conversion of numerical values in a data sheet to bars, as described in §3.4. Discussed in §4.2.

7 does not convey it directly, the display has been filtered interactively to show only the top 10% of the programmers, measured by number of changes.

The data sheets corroborate the 80%–20% rule (twenty percent of the programmers make 80 percent of the changes). In this case, the rule is closer to 90%–10%: the top 50 of 549 programmers made the majority of the changes. The two most active programmers, *prog1* (actual developer names have been masked) and *prog2*, made 5,416 and 5,377 changes (together, 7% of the changes), respectively, adding or deleting 112,580 and 138,494 lines of code. The third most active programmer, *prog3*, made (only) 3,336 changes.

The bar chart shows number of lines added, indexed by developer, with color continuing to represent the number of changes. That number of changes and lines added are positively but not perfectly correlated is clear from this view; a statistical analysis could be performed to quantify the correlation, or for comparison to other subsystems.

Figure 7: Perspective Showing Changes Indexed by Developer. *Data sheets:* Numbers of changes, lines added and lines deleted. *Bar chart:* Number of lines added, indexed by developer. Discussed in §4.3.

4.4 Size of Changes Indexed by Release

Figure 8 is a perspective containing two bar charts that show the size of changes indexed by release. In both charts, each release corresponds to two bars, one showing lines added, the other showing lines deleted. Releases are ordered by time in the lower chart, with color encoding release number (and, indirectly, time). Major releases — measured by size — are clearly distinguishable from minor ones. The upper bar chart uses the same colors as the lower one, but in it releases are ordered according to lines of code added or deleted, providing an effective selector to focus on details of the data.

4.5 Activity Indexed by Developer and Software Space

Here we address a variant of the question in §4.3: "Who changed which parts of the code?" (That is, who worked in which parts of software space?). Figure 9 contains a matrix view showing the number of changes indexed by developer (horizontal axis) and module (vertical axis), in this case the most informative unit of granularity of software space. Developers are sorted by total number of changes, shown as a histogram beneath the matrix view. The two bar charts illustrate different forms of drill–down access to details of the data. That on the left focuses on a few selected

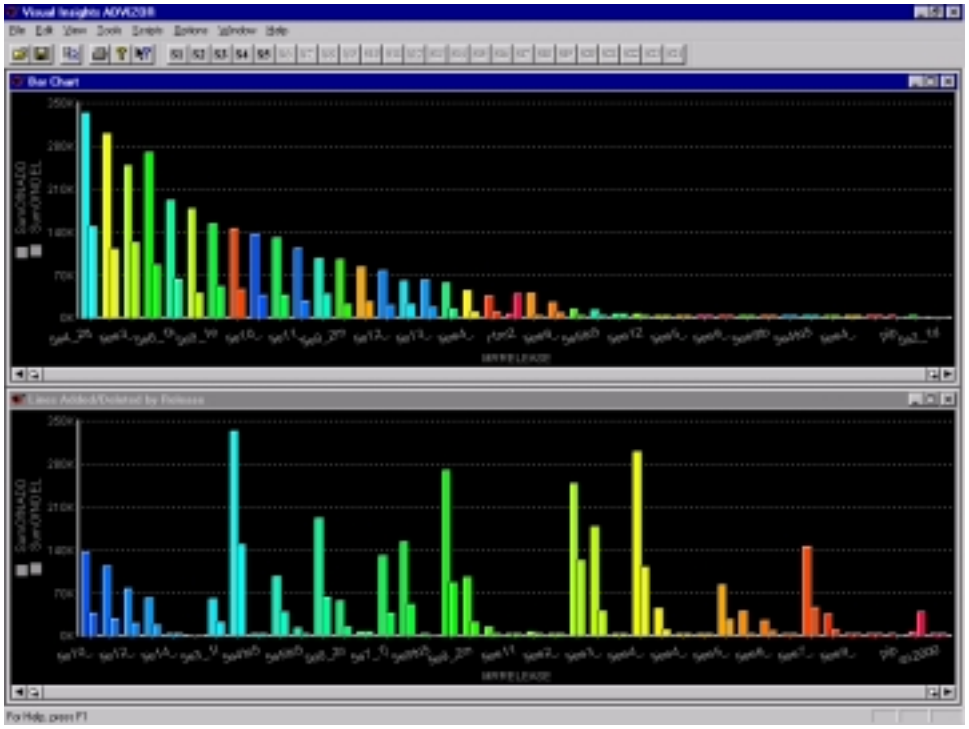

Figure 8: Size of Changes Indexed by Release. *Top:* Changes sorted by size (number of lines of code added or deleted). *Bottom:* Changes sorted by release number. Color encodes release number. Discussed in §4.3.

developers, that on the right shows the activity over software space for the most active developer.

The perspective in Figure 10 has similar goals. All views in this perspective are colored by developer, affording easy matching of corresponding data in different views. The bar charts index changes by module and developer separately, in effect showing marginal statistics from the matrix and cityscape views, and also allowing filtering by either module or developer. This allows one, for example, to identify the programmers who worked on particular modules or to determine where particular programmers worked.

The matrix view, in which rows represent developers and columns represent modules, encodes number of changes as the width of the bars in each cell, while the cityscape view encodes the number of changes as the height of the tube. The large red tube in the cityscape and the large red bar in the matrix view each represent the same 778 changes.

4.6 The Span of Changes

The *span* of a change — the number of software units involved (depending on resolution, files or modules) — was introduced in Eick, *et al.* (2001) as a measure of the increasing difficulty to change legacy software over time. There are three primary reasons to expect that changes touching more files will be more difficult to accomplish. First is the necessity to gain or access expertise about unfamiliar files from other developers; this is especially vexing in large-scale software, where each

Figure 9: Number of Changes Indexed by Developer and Module. *Matrix view:* changes by developer (columns) and module (rows). *Left bar chart:* Total number of changes for selected developers. *Right bar chart:* Number of changes by module for a single developer. Discussed in §4.5.

developer has only localized knowledge of the code. Second is the breakdown of encapsulation and modularity: changes spanning multiple files are more likely to modify interfaces. Third is the size: touching multiple files increases the size of changes.

In particular, an increase in span over time represents increasing difficulty to change the code, as well as deterioration of its original modular architecture. Figure 11 uses DataConstellations (§3.5) to display software space structured by means of IMR linkages. In this view, nodes correspond to files. The strength of the relationship between two files is a (normalized) measure of the frequency with which both are changed as part of the same IMR:

$$\text{Strength}(i,j) = \frac{N_{i,j}}{\sqrt{N_i N_j}}, \tag{1}$$

where $N_{i,j}$ is the number of IMRs under which files i and j were both changed, and N_i is the number under which i was changed.

Changes over time can be shown by animating the view in Figure 11 or with multiple views corresponding to different time periods (Eick (1998a)).

4.7 Dimensions of Software Change Visualization

The six examples of change visualizations are illustrative of the types of visualizations that have been useful in our exploration of software changes. The examples investigate change statistics,

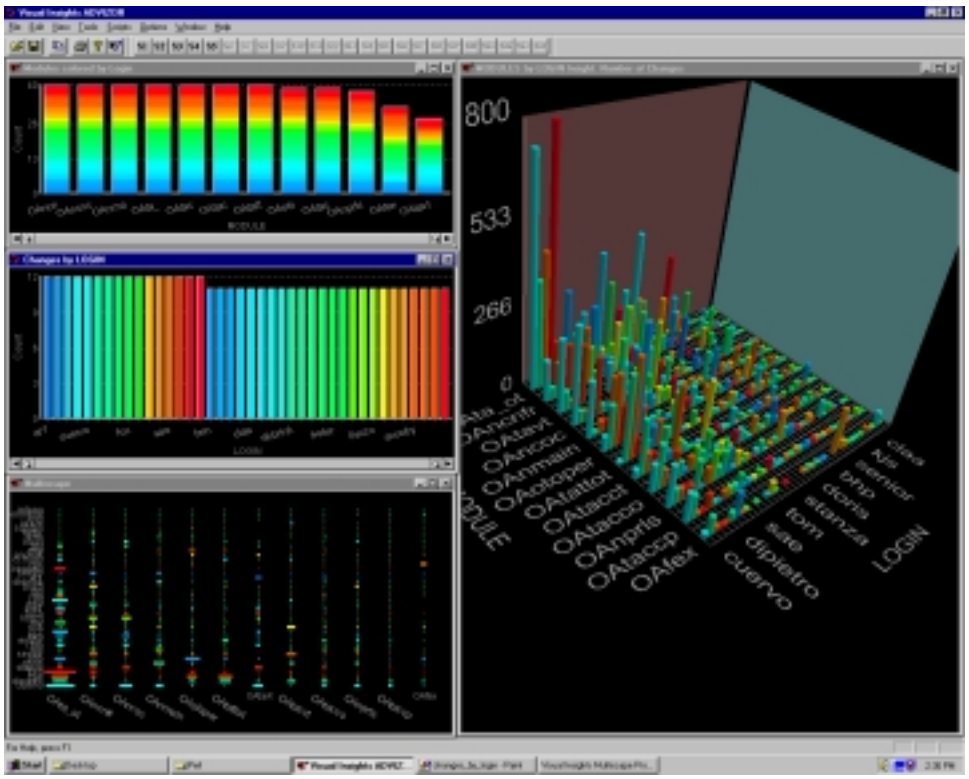

Figure 10: Number of Changes Indexed by Developer and Module. *Bar charts:* Changes by module (top) and by developer (bottom), with color encoding developer. *Matrix view* and *Cityscape view:* number of changes indexed by developer (columns) and module (rows). Discussed in §4.5.

change by time, by developer, by release, by code touched, and by change span. Although this is not a complete taxonomy, it is a starting point that we have found this to be a useful in our analyses of software systems. Our subjective results have also been confirmed and validated in sessions with the developers who wrote and maintained various subsystems in the code.

5 Management of Software Development

As evidenced by the number of late and canceled projects, software development management is not easy. In this section we present a set of perspectives illustrating the use of visualizations as part of software development management. As compared with understanding software change (§4), this setting is characterized by need for rapid analyses that guide management decision–making and support specific courses of action. The analyses may be less detailed or less formal than in the research setting of §4, and the conclusions are primarily qualitative.

Three issues will be addressed: MR status, MR severity and developer activity. The views presented here are derived from a single project to a new software product. Taken together, they constitute a case study on the role of visualization in software development management. As noted in §2.1, the setting here is relatively small: 25 developers and a 250,000-line code base.

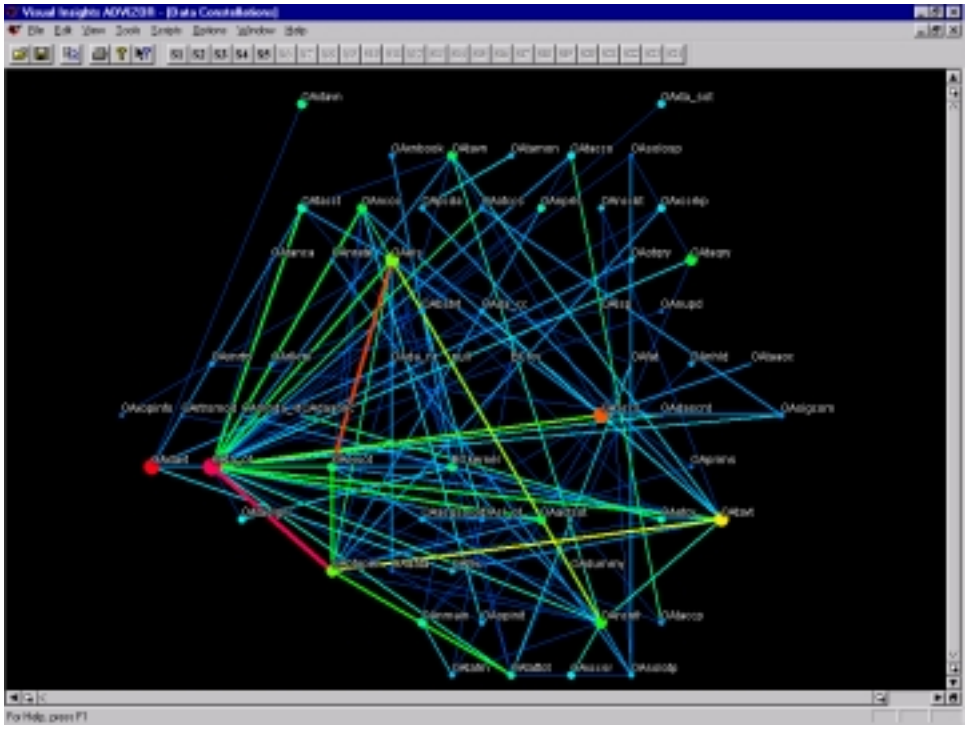

Figure 11: Relationships Between Files Based on IMR Linkages. Nodes are files, and linkage is defined by the relative frequency of files being changed as part of the same IMR. Link color shows the strength of this relationship, defined by equation (1). Discussed in §4.6.

The perspectives presented here are highly coherent. All contain the same five views: two bar charts showing MRs indexed by initiating developer and assigned developer (for repair), two pie charts showing MRs indexed by severity and status, and a scatterplot of MRs over time. The only difference is that they are applied to different sets of data. The data in some perspectives result from a selection operation in others.

5.1 MR Status

As described in §2.2, work flows into a development organization as IMRs describing problems, and is distributed to developers as a series of MRs solving (pieces of) those problems. At the beginning of work for a release, the majority of the MRs will be for new functionality. If work is progressing successfully, MRs should increasingly emphasize bug fixes and tiny enhancements addressing issues found by beta customers. An important challenge for development organizations is to keep track of MR activity, identify bottlenecks and find trouble areas.

The perspective shown in Figure 12 is an entry point in meeting these needs. It leads to the more focused perspectives, designed to address more specific questions presented in §5.2. The basic perspective shows MR counts indexed by *Creator* — the programmer or tester who discovered the problem and initiated the MR; the *Programmer* to whom the MR was assigned; *Severity* of the MR — `high`, `medium` or `low`; and the current *Status* of the MR — `submitted`, `under_review`,

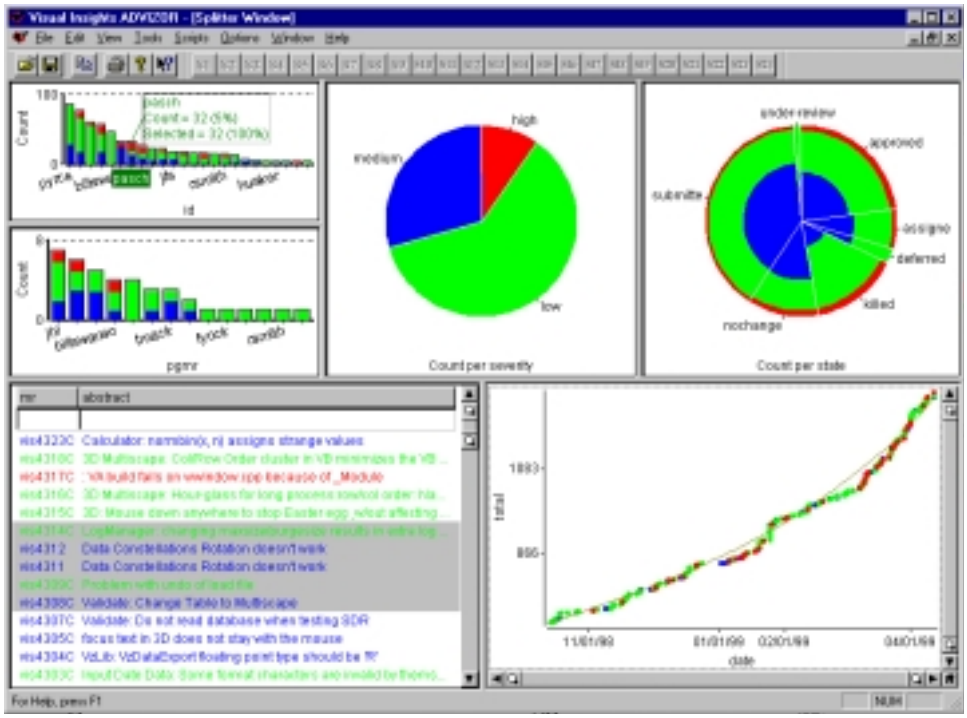

Figure 12: Perspective showing MRs Indexed in Multiple Ways. *Bar charts:* MRs indexed by creator (i.e. submitting programmer) (top) and assigned programmer (bottom). *Pie charts:* MRs indexed by severity (left) and status (right). *Data sheet:* MR abstract. *Scatterplot:* Cumulative number of MRs, indexed by time. Discussed in §5.1.

`approved`, `assigned`, `deferred`, `killed`, or `no_change`. In addition, the perspective contains a data sheet serving as a user interface to MR abstracts and a scatterplot of numbers of MRs as a function of time (augmented by a smooth fitted trend curve). As the following examples illustrate, this perspective functions both to show patterns within the MRs and as an interface to the details.

Basic Information. The *Creator* and *Assigned* bar charts in Figure 12 show who is initiating and fixing the MRs. For example, the perspective shows that three programmers currently are assigned more than five MRs, which may be cause for concern.

The *Severity* pie chart shows that approximately 1/8 of the MRs are high severity, a bit more than 1/4 are medium, and about 2/3 are low, suggesting that too many problems are accorded MR status that could have been dealt with otherwise. Possibly confirming this, the *Status* pie chart indicates that no action is taken in response to about 1/4 of the MRs — those whose status is `no_change` or `killed`. Not surprisingly, most `killed` MRs are of low severity. One positive message in the *Status* pie chart is that most MRs have been resolved (those in the `approved`, `deferred`, `killed`, `no_change` and `submitted` states).

The increasing slope (convexity) of the fitted line in the *MR Count* scatterplot indicates that new MRs are being discovered at an increasing rate. While the implications of this increase are unclear, it is unlikely to have been discovered without visualization tools.

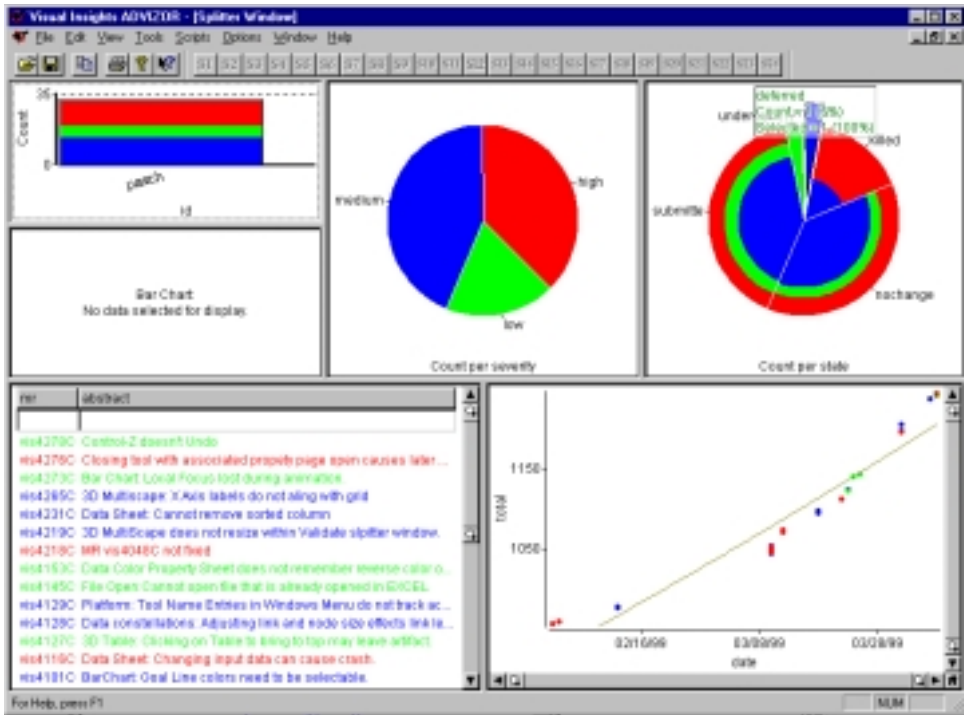

Figure 13: Perspective showing MRs Initiated by Programmer *pasch*. The views are the same as in Figure 12, but applied only to data for *pasch*. Discussed in §5.1.

Activities of One Developer. In Figure 12, programmer *pasch* (interactively labeled with the mouse in the upper bar chart) stands out. This person initiated 32 MRs, 5% of the total, but more important (as shown the large red bar) discovered an unusually high percentage of severe MRs. From the standpoint of understanding the skills of particular programmers, this is worth investigating.

Figure 13 focuses on *pasch*. It contains the same views as in Figure 12 — it was created by the selection operation shown there — but applied only to the data for *pasch*. Thus, the upper bar chart and the *Severity* pie chart contain the same information. The *Status* pie chart shows that this person has been assigned no MRs for repair. This is also reflected in the absence of the lower bar chart, which in Figure 12 displayed MRs assigned for repair. Clearly, *pasch* devotes significant effort to testing. To the extent that *pasch*'s activities may deviate from assigned duties or that *pasch*'s skills as a tester were not being exploited, this information is very valuable. The same pie chart also shows that all of the MRs discovered by *pasch* have been resolved, although one has been `deferred`. Using the data sheet to access the abstract for the deferred MR (not shown) allows a manager to confirm that `deferred` is the correct disposition.

The scatterplot in Figure 13 provides information about *pasch*'s work patterns. Evidently *pasch* did preliminary testing in early February, worked on other activities during the second half of February and first week of March, and then tested aggressively during the second and third weeks of March.

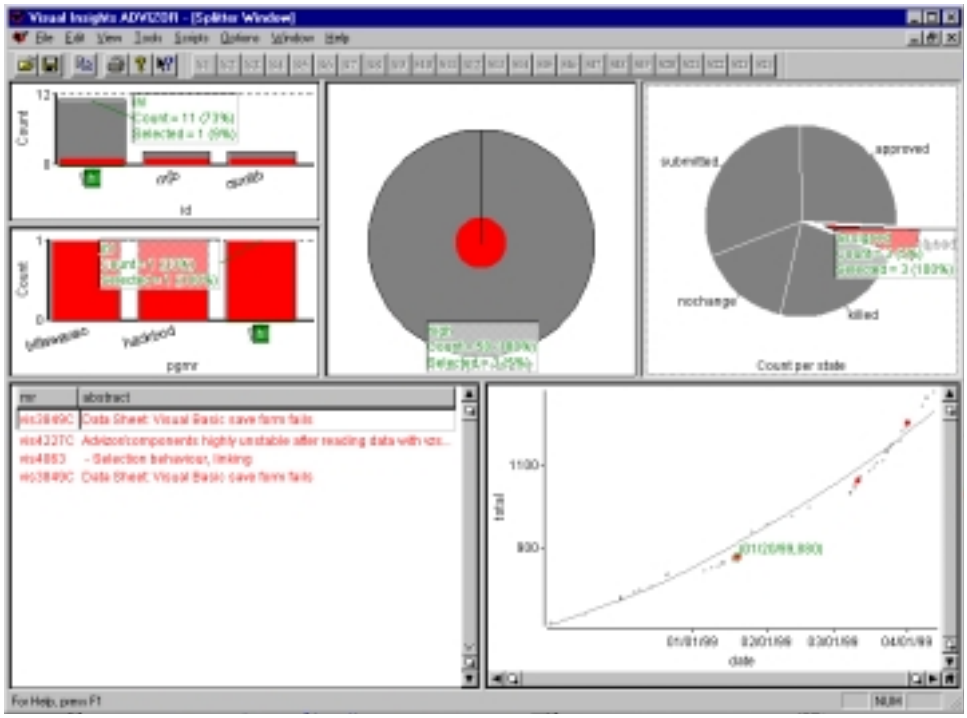

Figure 14: Perspective showing High-Severity, Open MRs. This filtered version of Figure 12 indicates that three are currently being worked. Discussed in §5.2.

5.2 High-Severity MRs

High-severity MRs represent critical problems in need of immediate attention. Key metrics for a development organization are the number of open high severity MRs, how long they have been open, who is working on them and why they have not been resolved.

Figure 14, which is derived by filtering the perspective in Figure 12, focuses on open, high-severity MRs. It allows managers to see at once that there are only three open, high-severity MRs, assigned one each to programmers *billswanso*, *hackbod* and *jhl*. The oldest of these was initiated on January 20, and the most recent on April 1. (Views are based on data through April 28.) The oldest MR was both initiated by and assigned to *prog3*. This suggests that perhaps the long time to clear this defect results from the absence of a separate tester advocate.

Figure 15 contains the same perspective as Figure 14, but shows both open and closed severe MRs. The bar chart shows that no high-severity MRs have been deferred to the next release.

5.3 MR Quality

High numbers of `killed` and `no_change` MRs are an indication of poor MR quality. Unnecessary MRs waste the resources used to investigate them. Potential remedies include additional training for members of the testing organization.

Figure 16, derived from Figure 12 by filtering to include only system testers, investigates `killed` and `no_change` MRs. It reveals that all MRs initiated by the testers correspond-

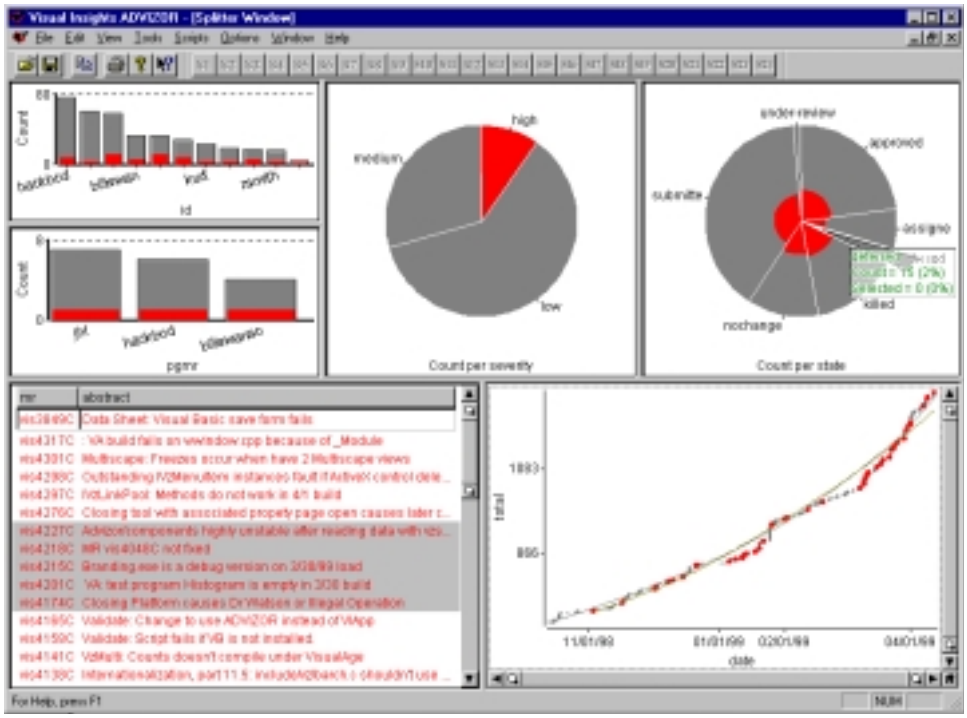

Figure 15: Perspective showing both Open and Resolved High-Severity MRs. The views are the same as in Figure 14, but data for both open and resolved severe MRs are displayed. Discussed in §5.2.

ing to the two leftmost bars — both new staff members — were resolved as either `killed` or `no_change`. Similarly, nearly two-thirds of MRs initiated by *pasch* were `killed` or `no_change`. Ordinarily, such high rates would be cause for concern and management attention. In this case, however, further investigation indicated that these three programmers were performing self tests and identifying problems, and then assigning MRs to themselves.

5.4 Scope of Examples

The example and issues covered in this section are the ones that a high-performance development team found useful in its daily operations. In a production environment with deadlines and other pressures research tools are only used if they provide significant value. For this organization the value provided was high enough that the tool became part of their everyday process.

There are undoubtedly other important issues and problems suitable for change-specific visualizations. It is interesting to note that the single perspective is used for all of the examples in this section. This perspective is actually functioning as an interactive “digital dashboard” that provides current project status.

Figure 16: Perspective Showing MRs Resolved as `killed` and `no_change`. Discussed in §5.3.

6 Discussion

6.1 Relation to Previous Research

This research builds on visualizations of software structure and previous research on software changes in three significant ways. First, it focuses on visualization of perhaps the most fundamental activity in software engineering — software change. Second, the research has created a suite of perspectives and visual tools for historical analysis of software change. Finally, we have extended visualization into operational aspects of software development.

There is a rich history of scientific visualization and visualization aimed at dynamic systems. Unfortunately, much of the research is not appropriate for visualizing software changes. Scientific visualization research tends to focus on issues involved with visualizing time-varying, large-scale, 3D scientific data. Software change data, however, is not 3D and the changes in time occur at discrete times.

Historically, some of the most exciting examples of software visualization have involved algorithm animation. One of the earliest examples was Baecker's videotape picturing sorting algorithms (Baecker, 1981). This work focused on helping programmers understand algorithms. Other significant early research efforts involving algorithm animations include Brown's examples (Brown, 1988) and Stasko's algorithm animation systems (Stasko, 1990). Our visualization focus, of course, is not on algorithm animation but rather on visualizing changes.

Another focus in software visualization has been on visualizing code itself. Baecker, *et al.*

provide techniques for efficiently typesetting programs (Baecker, *et al.*, 1990). A related approach to visualizing software text and line-oriented statistics such as age, developer and release involves SeeSoft™ and its many applications (Ball & Eick, 1996; Eick, 1998b,a; Eick, *et al.*, 1997a; Eick, Steffen & Sumner, 1992). The central metaphor used by SeeSoft is literal: lines of code are presented by lines of pixels that preserve file structure, length and indentation. Other attributes are mapped onto line color. Implicitly, these visualizations can display data associated with changes (age is an example), but they are not designed to visualize changes themselves. See Stasko, *et al.* (1998) for additional aspects of software visualization.

Although attention to software change and maintenance is long-standing, statistical analysis and visualization of change data (and of software metrics in general) on a large scale have occurred only recently. In an early paper, Ebert proposes several visual metaphors for understanding software metrics (Ebert, 1992).

In another stream of related work, the statistical analyses and models focused on *code decay* — decayed code is harder to change than it should or can be. This stream has elucidated particular aspects of software change data (Eick, *et al.*, 2001; Graves, *et al.*, 1997, 2000; Graves, 1999; Graves & Mockus, 1998; Staudenmayer, *et al.*, 1998), as well as pointed clearly to the need to visualize such data. In other examples (Eick, *et al.*, 2001; Graves, *et al.*, 2000), the visualizations are focused not on the software data themselves, but instead on the results of statistical analyses of the data, using DataConstellations (Wills, 1999) and SiZer (Chaudhuri & Marron, 1999).

6.2 Implementation

The views and perspectives presented in this paper are implemented via Visual Insights' ADVIZOR™ (Visual Insights, 1999b; Eick, 2000), which runs under Microsoft Windows. ADVIZOR™ is neither targeted nor restricted to software change data. The capabilities of ADVIZOR™ exploited here are to create multiple individual views (matrix and cityscape views, bar and pie charts, data sheets and network views), and to link these (via mouse-based selection operations) into perspectives. Perl and Visual Basic scripts were used to extract and manipulate data on subsystems from the version management database (Mockus, *et al.*, 1999). The perspectives described in §5 are in daily operational use. The concepts and questions underlying the views are, of course, quite generic, and transfer readily to other environments.

Perspectives are created using an authoring tool that provides data access, a visual programming environment, and supports customization via Visual Basic scripts. As with other enterprise software applications, there is a web-based, client-server deployment module.

The views themselves are written in C++ using a visualization library that we call Vz. This library is an object-oriented, platform-neutral class library focused on visualization. The library (1) Renders efficiently; (2) Contains fast graph layout and placement algorithms; (3) Supports view linking; (4) Contains statistical algorithms; (5) Provides 3D navigation; and (6) Uses a common "look-and-feel."

7 Conclusions

Numerous factors generate strong impetus to visualize software change data. Change is fundamental and inevitable in large software systems. The payoffs — intellectual and economic — from understanding change well and managing it effectively are significant. Data about software change are collected routinely, but are too massive and complex to be dealt with by formal analyses alone.

In the research reported in this paper, we have created a number of visualization concepts for software change data, and implemented them both individually and linked to form perspectives. The utility and value of these perspectives for exploring change data and for managing software development have been demonstrated using real data and real problems.

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