Software Visualization in Prolog

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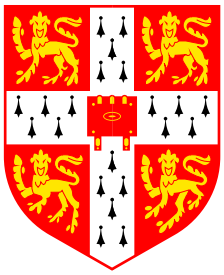

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Declaration

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This dissertation is approximately 44 000 words long, excluding appendices.

Acknowledgments

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Abstract

Software visualization (SV) uses computer graphics to communicate the structure and behaviour of complex software and algorithms. One of the important issues in this field is how to specify SV, because existing systems are very cumbersome to specify and implement, which limits their effectiveness and hinders SV from being integrated into professional software development tools.

In this dissertation the visualization process is decomposed into a series of formal mappings, which provides a formal foundation, and allows separate aspects of visualization to be specified independently. The first mapping specifies the information content of each view. The second mapping specifies a graphical representation of the information, and a third mapping specifies the graphical components that make up the graphical representation. By combining different mappings, completely different views can be generated.

The approach has been implemented in Prolog to provide a very high level specification language for information visualization, and a knowledge engineering environment that allows data queries to tailor the information in a view. The output is generated by a graphical constraint solver that assembles the graphical components into a scene.

This system provides a framework for SV called Vmax. Source code and run-time data are analyzed by Prolog to provide access to information about the program structure and run-time data for a wide range of highly interconnected browsable views. Different views and means of visualization can be selected from menus. An automatic legend describes each view, and can be interactively modified to customize how data is presented. A text window for editing source code is synchronized with the graphical view. Vmax is a complete Java development environment and end user SV system.

Vmax compares favourably to existing SV systems in many taxonometric criteria, including automation, scope, information content, graphical output form, specification, tailorability, navigation, granularity and elision control. The performance and scalability of the new approach is very reasonable.

We conclude that Prolog provides a formal and high level specification language that is suitable for specifying all aspects of a SV system.

Contents

Chapter 1

Introduction

Computer software has revolutionized the way we work, and the software industry is worth trillions of dollars world wide. Software systems are the most complex artificial objects ever constructed, and managing their complexity is difficult. Software is also very difficult to write, understand and debug. In response, software tools are rapidly evolving to create software more quickly and reliably.

One approach to the problems of comprehension and complexity is through computer graphics and visualization. This is *software visualization* (SV), which encompasses all applications of graphics to software development, including static program visualization, visual programming (manipulating graphical representations of code), and visualization of run-time behaviour.

The rationale for SV is that programmers and managers need to understand a software system, often long after it was written, for debugging and updating. It is widely accepted that code maintenance is the most expensive part of software engineering [94]. Even small algorithms can be difficult to understand, debug, or communicate to students. Computer graphics offers a powerful means of communicating that information through visualization.

The Year 2000 Bug highlights the need for SV. A programmer trying to debug poorly documented legacy code would wish to know not just the overall structure of the program, but the dependencies of the various functions in the system, which variables stored dates, and even which functions or statements apply date calculations. Using SV, a program analysis would determine this information and display it in graphical form.

Although development tools have provided enormous productivity gains, their degree of visualization is still very limited, and visual programming has not proved as successful as was initially hoped [107]. The recent advances in software development tools have come from improved user interfaces and graphical support, and SV could improve that productivity further.

In spite of the obvious benefits, there are considerable technical difficulties to overcome. The main problem preventing SV from being used in professional development tools is its inflexibility and high set up costs. A system for automatic SV is needed to make SV accessible to programmers. At the same time it should be flexible enough to provide the desired information is the desired format. In general, SV systems are either automatic or flexible - they are not both [64].

The aim of a SV system is to provide useful information about a program to a user. Programmers need many different types of information, so complete systems should visualize all aspects of software, including the program structure, low level details, high level overviews and run-time data. Most SV systems are very specific, and have a very limited scope. In addition they have a very poor range of granularity, and do not view the program on many different levels of detail. The elision control of most SV systems is very poor, and there are no facilities for filtering away irrelevant information, or for the user to specify what is or isn't of interest.

Existing SV tools or development environments have a very limited number of views of program objects or output data. In fact, there are dozens of different ways of representing every program object, each conveying different information, or using different visualization techniques.

Many SV systems only have fixed output, and changing the output requires manual programming, which hinders end users from tailoring their views. The mapping from data to graphical form is fixed by programming or specification languages in SV systems, but techniques for allowing users to change this mapping interactively would allow end users to customize the views themselves.

Interaction with SV systems is also very limited. Most views are not interactive so the objects in the view cannot be interacted with. For example it might be useful to display information about objects beneath the mouse cursor, or to provide a graphical display of whatever lies beneath the mouse cursor. It might also be useful to display an automatic legend of each view because views containing many different types of graphical structures can be confusing. Better navigation techniques would allow programmers to browse software and find information more quickly.

There is little theory that underpins SV. Current approaches do not use any theoretical basis, and are implemented *ad hoc*. Work should be done on the formalization of information display, which might lead to more principled methods for designing SV systems.

The specification techniques for SV systems are very awkward. SV systems are specified at a very low level, and they are therefore cumbersome to use. Work on specification languages is needed to provide high level specification and scripting of SV, which would make SV much easier to implement, and provide much more powerful systems.

In spite of these technical difficulties, SV systems provide valuable insights into the workings of complex software for many different kinds of computer language and task. The challenge SV presents is to provide a system which is very broad in scope, very flexible in its output, has dozens of different types of view, is completely automatic, can be interactively customized, and can be specified at a high level.

1.1 Aims

Price *et al.* [79] identify many of these difficulties and outline directions for future work. The aim of this work is to produce a SV system that addresses some of these problems by achieving the following aims:

1. Have a broad scope, visualizing all aspects of computer software. Previous systems are too limited in their scope. Aspects to include are:

   - Program structure.
   - Object orientation.
   - Methods.
   - Run-time data.
   - Results from program analysis, such as method calls, variable uses and cross references.

2. Provide a high level specification method. This should specify the following aspects of SV:

   - View content - what a view is showing. This must provide a generic query mechanism.
   - Graphical abstraction - how the contents of the view are rendered.
   - Interaction - how to interact with items in the view.

   The specification methods of existing systems are very awkward to use, and do not specify either view content or interaction.

3. Provide dozens of different views of the program and run-time data. Previous systems provide only a small number of views because of the difficulties in setting up new views.

4. Base the implementation on a theoretical foundation. Existing SV systems are not based on formal models.

5. Provide a rich and varied graphical output. This offers a more powerful and interesting means of expression.

6. Provide flexibility in graphical representation. Users should be able to interactively change the way data is represented.

7. Provide a legend that describes the contents of the view. This is necessary if the graphical representation is so flexible, and useful for users unfamiliar with the system. No other systems provide an automatic legend.

8. Provide navigation by browsing to program objects in the scene. Provide a preview window that graphically displays the object beneath the mouse cursor, and graphical bookmarks that store views for later retrieval. Such an interface would provide an easy means to access data.

9. Provide a text editing window that is synchronized with graphical views of the source code. This would provide code browsing and a complete development environment.

1.2 Work Done

These aims have been met by redesigning the visualization engine that sits at the core of the SV system to generate the views.

A specification method for information visualization has been developed by decomposing the visualization process into a series of relations that can be specified in Prolog. This provides a formal foundation to information visualization, and therefore to SV. The formal model is called a *semantic model* because the information content of a view, or its semantics, is always defined explicitly. The model also incorporates a formal model of interaction with visualizations.

This method has been shown to be practical by implementing a general purpose information visualization tool, *Semantic Visualization Tool* (SVT), using this approach. SVT can in principle be used for for any type of visualization, and it is specified entirely in Prolog. It provides a method for interfacing any knowledge based environment in Prolog to any graphical output algorithm.

SVT abstracts the information content of a view from its graphical representation. The mapping from the information content to the graphical representation is dynamic, so that different mappings can be selected from a menu to render the information differently. The mapping can be queried, so that a legend can automatically describe what is in the view. The mapping can be completely tailored by the user by interacting with the legend to change the way individual items are graphically represented.

SVT provides a browser interface so that any item in a view is navigated to by clicking on it. Alternative queries of the current object being viewed can be selected from a menu, and alternative methods of visualizing the current information can also be selected from a menu. A preview window automatically provides a graphical display of the object beneath the mouse cursor, and a bookmark window provides five thumbnail views that can be used to store and retrieve views.

SVT provides a framework for SV. A system called *Vmax* has been implemented to browse Java source code and Java run-time data. Vmax is specified in Prolog, and uses Prolog to analyze source code and run-time data and store the program database. Views defined in Vmax can query the program database to provide any information about the program.

SVT provides Vmax with a specification language that allows all aspects of SV to be specified at a high level. SVT also automatically manages navigation and the legend, and provides graphical algorithms to display the output.

Vmax has a text editor to edit source code, and provides a complete development environment with integrated end-user SV. Vmax can be extended by loading users' Prolog. Vmax also visu-

alizes Prolog, and can edit Prolog as a visual language, so that users can write their own queries visually to provide new views.

Prolog can specify other types of visualization, such as directory browsing and graphical user interfaces. SVT and Vmax were implemented to investigate whether using Prolog is a realistic approach to SV, and how such a system would be designed.

1.3 Results

SVT and Vmax provide a comprehensive SV environment. Because the approach is generic, the system has a very broad scope and a very wide range of graphical output form. Figure 1.1 shows a range of sample output.

On a modern desktop PC, the performance of Vmax is quite reasonable, making it suitable for visualizing projects of around 100 000 lines of code. The code input rate is about 6 300 lines of Java per second. The time to generate views is typically under half a second. The final system has 151 different types of view, or 70 if alternative visualizations are discounted. These include 44 views for Java source code, 7 views for Java run-time, 8 views for Prolog, 6 views for directories and one view for help.

A taxonometric classification of Vmax has been made using the taxonomy of Price *et al.* [79], given in Table 6.1. It shows the new approach to compare favourably to previous systems in many criteria including automation, scope, information content, graphical output form, specification, tailorability, navigation, granularity and elision control.

An empirical study of usability and usefulness of the system lies beyond the scope of this work. It is intended only to demonstrate new techniques, and there are no standard methods for empirical evaluation of SV systems. The system is easy to use due to its browser interface and degree of automation, but this has not been confirmed by usability studies.

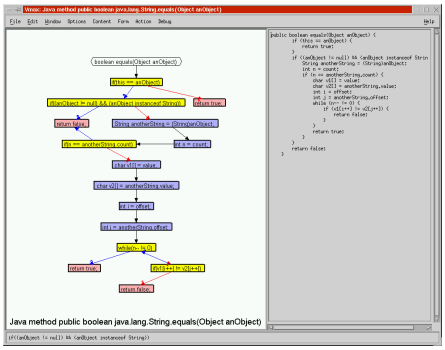
The reader is invited to download Vmax.[1]

1.4 Contribution

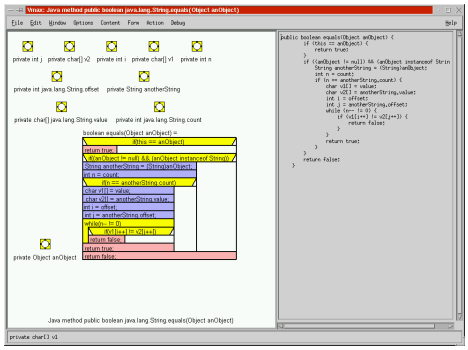
The work demonstrates a number of new techniques that can be applied to SV.

- It has been demonstrated that the programming language Prolog can be used to specify all aspects of SV.
- A SV system has been constructed that compares favourably to existing systems in many taxonometric criteria, including scope, information content, graphical output form, specification, tailorability, navigation, granularity and elision control.
- A semantic model of information visualization provides a link between visualization, first order logic, and knowledge engineering. Visualization systems and knowledge engineering systems can be integrated.
- A general purpose information visualization tool has been implemented that can be specified entirely in Prolog.
- A dynamic mapping between the information content of a view and the graphical form of a view has been implemented. This can be queried to provide an automatic legend, and modified by the user. Different mappings can be selected to tailor the output.
- A type system for information artefacts [38] and graphical artefacts has been implemented.
- Visual languages can be specified in Prolog.
- New methods of interaction have been demonstrated, including a browser interface to navigate around a program database, a legend, and a preview window.

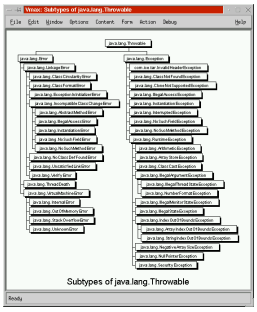
[1] URL: *http://www.cl.cam.ac.uk/Research/Rainbow/vmax*



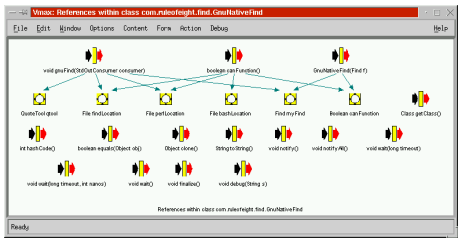
(a) Method control flow.



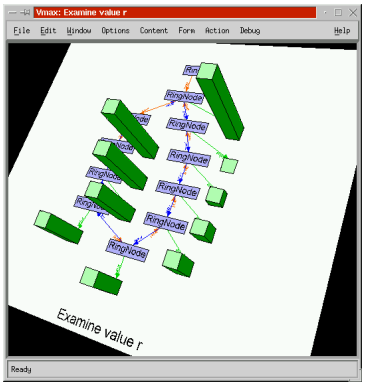
(b) Method block structure.



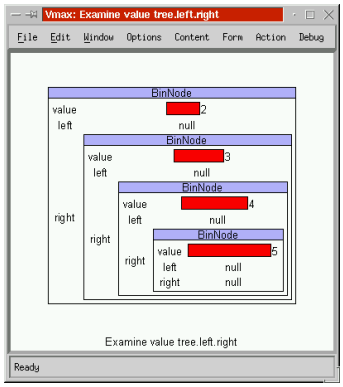
(c) Class hierarchy.



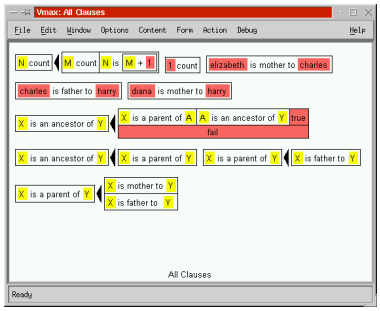
(d) Cross referencing.



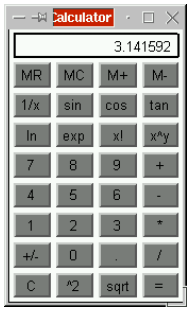
(e) Run-time data in a graph.



(f) Run-time data in a table.



(g) Prolog visualization.



(h) GUI specification.

Figure 1.1. The scope and output of Vmax.

- New visualizations for program objects, including coloured Nassi Shneiderman Diagrams [72], have been developed.

1.5 Notation and Typography

- Text that is written in a slanted font refers to Prolog or C++ source code. e.g. *virtual void On_reset_size();*
- Text inset in a Courier font is a larger example of Prolog or C++ source code. e.g.

```
// This is C++ source code
```

- Prolog atoms and functors begin with a lowercase letter. e.g. *charles* or *parent(charles, harry).*
- Prolog compound terms are written as a functor followed by a comma-delimited list of arguments in round brackets. e.g. *parent(charles, harry).*
- Prolog lists are written in square brackets. e.g. *[1, 2, 3].*
- Prolog variables begin with an uppercase letter. e.g. *X*, *Id* and *Object4.* The variable ' _ ' is unbound.
- Prolog predicates or compound terms may written as *Functor/Arity*. e.g. *parent(Parent, Child)* would be written *parent/2. parent/2* is understood to be distinct from *parent/3.*
- Prolog modules are written as *Module:Predicate.* e.g. *java:method(Method).* Often the module prefix is omitted.

1.6 Dissertation Overview

Chapter 2 describes the previous work in the field, from SV systems and visual programming, to the state of the art in commercial systems. The taxonomies of SV [79, 84] and visual programming [71] provide important reference points for future work, and have motivated much of this work.

Chapter 3 describes a formal model of information visualization, and how visualization can be specified in Prolog. This is the theory that underlies the rest of the work. Chapter 4 describes how the model and specification techniques described in Chapter 3 can be implemented in practice. A generic visualization tool, Semantic Visualization Tool, is developed that can be used to visualize any kind of data, including the structured and relational data in computer software.

Chapter 5 describes Vmax, a tool for software visualization, that is the main product of this work. Chapter 6 presents the results and evaluation of this work and discusses where Vmax fits in to the taxonomies of SV. The conclusions are in Chapter 7.

The appendices contain documentation for SVT and Vmax, and further examples to illustrate the specification techniques.

Chapter 2

Previous Work

Although computer programming is traditionally a textual discipline, the use of graphical illustrations of software has always played a useful role in software development and writing computer programs. Illustrations are used to plan and document software, although the idea of using illustrations to create programs (visual programming) has been around for a long time [99], as well as automated utilities to document and browse finished software. Visual techniques are now commonplace in software development, particularly in the design and generation of user interfaces, the construction of skeleton applications, and the navigation of source code.

This survey describes the issues and areas of research within software visualization, a number of systems - both commercial and research - that use software visualization techniques, and a number of taxonomies for describing and comparing software visualization systems. The survey concludes with research problems that need to be solved for software visualization to deliver real demonstrable gains to software developers.

2.1 Basic Definitions

There is no universal consensus in the literature for the definitions of broad terms such as *visual*, *visualization*, *visual programming*, *software visualization*, *program visualization* and *algorithm animation*. Although the concepts themselves are fairly clear, different sources place emphasis on different concepts in forming their definitions.

The Concise Oxford Dictionary [100] defines *visual* as "of, concerned with, or used in, seeing," and *visualize* as "make visible, esp. to the mind (thing not visible to the eye); make visible to the eye." Price *et al.* [79] prefer the definition "the power or process of forming a mental picture or vision of something not actually present in sight" from the Oxford English Dictionary [92], with the emphasis that visualization is a mental process rather than just the task of vision, and can therefore include all of the senses. This contrasts with the definition given by McCormick *et al.* [66] as "the study of mechanisms in computers and in humans which allow them in convert to perceive, use, and communicate visual information," with the emphasis clearly on the process of communication. These definitions are not mutually exclusive because visual communication precedes the cognitive model. In this text, visual is taken to mean "visible", and visualization to mean "conversion to visible form," even though this excludes the other senses. In the context of computers, visual means "visible on a computer display," and visualization is "communicating data with graphics." This specifically includes all graphical forms, as well as text, which is of course visible. These definitions are more straightforward than those offered by Price *et al.* or McCormick *et al.*

Myers [71] defines *visual programming* (VP) as "any system that allows the user to specify a program in a two-(or more)-dimensional fashion," and specifically excludes textual languages (which he considers to be one-dimensional), picture definition languages and drawing packages.

Price *et al.* define VP as "the use of visual techniques to specify a program in the first place." Price's definition is better because textual languages are visual and have a two-dimensional rendering – Myers confuses the display with the internal representation of the textual language.

Myers distinguishes *program visualization* (PV) from VP as "the program [being] specified in a conventional, textual manner, and the graphics is used to illustrate some aspect of the program or its run-time execution." Price *et al.* prefer the term *software visualization* (SV) to encompass *algorithm animation* (animating the operations of an algorithm), *code visualization* (a visual form of the program code) and *data visualization* (a visual form of the program data) and defines it to be "the use of the crafts of typography, graphic design, animation and cinematography with modern human-computer interaction technology to facilitate both the human understanding and effective use of computer software."

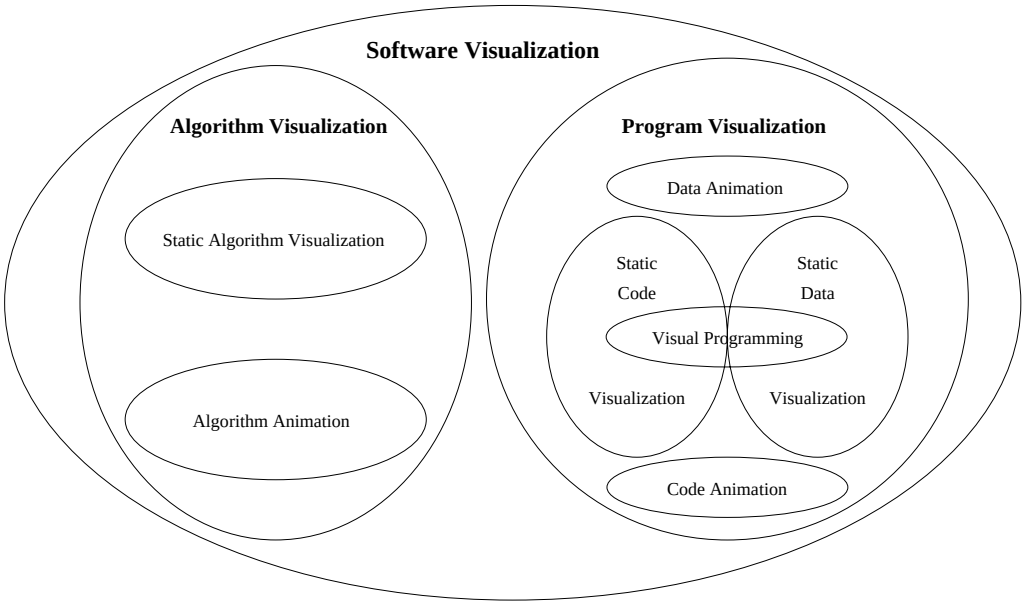


Figure 2.1. Venn Diagram showing relationships between the various fields of software visualization (reproduced from [79]).

Myers excludes VP from PV while Price *et al.* include it. Price *et al.* classify the SV fields and nomenclature according to Figure 2.1, although they concede that their classification is an oversimplification because these fields are strongly interrelated.

Sometimes products such as Delphi or Visual Basic are regarded as VP, because visual techniques are being used to create software. But these are not VP systems because textual programming is still necessary - navigation and the design of the user interfaces is visual, but that is not considered to be programming.

The above fields all use *visual languages* which Myers defines as "all systems that [use] graphics, including VP and PV systems," and *visual programming languages* (VPLs) are visual languages used for programming. The definitions given by Myers [71] are probably the *de facto* standard, but are by no means definitive.

2.2 Benefits of Software Visualization

Visual representations seek, if not always successfully, to assist software development. By providing representations of software that are in some way superior to text, programmers can understand complex software systems more easily, thus decreasing development and debugging effort and improving documentation and code reuse. Given that software is a trillion dollar industry, even small gains should be considered important.

There are many claims of the benefits of the visual environments for software development

and programming. Blackwell [10] looks at the benefits computer scientists perceive of visual programming, which also apply to software visualization. He analyzes these claims in detail, and finds a general consensus among computer scientists, although some claims are indeed controversial or counter empirical evidence.

Blackwell found that while few of these claims could be absolute, most had a logical basis or some supporting evidence, but the claims of superlativism, of being natural and intuitive, of utilizing more fully human cognitive resources, and of increased information content were unsound. However there are still many potential advantages of using imagery over text, including increased productivity, concretizing abstract concepts, program structure being more easily conveyed pictorially, assisting the programmer's mental model of software, and resemblance to the real world thus utilizing our instinctive manipulative skills [90].

There is some notable opposition to visual languages, which is reasonable in the absence of much empirical evidence supporting visual programming. Brooks [14] states that "A favorite subject for Ph.D. dissertations in software engineering is graphical, or visual, programming - the application of computer graphics to software design. Nothing even convincing, much less exciting, has yet emerged from such efforts. I am persuaded that nothing will." This argument should not be taken too seriously because it was written before windowing systems, he only considers flow chart techniques, and confuses superimposed views with multiple views. Brooks also claims that limited size of display renders visual programs unscalable, although this argument collapses when one considers multiple views. Scaling is indeed a problem in visual languages [17], but the problem has been overcome in textual languages. O'Brien [73] states "...beware the claims of visual programming. Drawing lines between objects becomes bafflingly web-like. Purely visual programming is not yet and may never be viable." This argument is also flawed because structured networks (such as those used in LabVIEW [104] or ProGraph [19, 77]) is just one visual representation of code. The empirical evidence supporting visual programming languages is discussed at length by Whitley [107].

These arguments are directed at the practicalities of VP where the text in the system has been replaced entirely by diagrams, rather than at SV. Visual programming has many weaknesses that need to be overcome, including lack of scalability [17], that visual representations are not as compact as textual ones [71], awkwardness to edit in visual notation, when text and keyboards can be faster [36], or that purely visual programming systems are no better than traditional ones for large projects. The emphasis of current research is to tackle these problems.

In fact Brooks [13] is entirely in favour of using diagrams to assist software development, and has "enthusiasm for using diagrams as thought and design aids." Brooks also concedes that multiple diagrams are required for different aspects of software, and that some aspects are more suitable for visualization than others. It is the awkwardness of visual representation at the lowest level (code) that seems to be impeding visual programming. Removing text entirely may indeed not be desirable or practical, but visual support for software development has proved to be very useful.

2.3 Taxonomies of Software Visualization

The most comprehensive taxonomy of SV is provided by Price *et al.* [79]. Myers's taxonomy [71] precedes Price's, and offers taxonomies for VP as well as PV. Roman and Cox [84] offer a simpler and less comprehensive taxonomy of PV. Taxonomies serve to classify, quantify and describe types of SV and visualization systems, assist in finding weaknesses and areas of research, and offer ways of comparing and evaluating SV systems.

The taxonomies also discuss and classify various SV systems. Price *et al.* classify and compare in detail twelve systems: Sorting out Sorting [3], Balsa [16], Zeus [15], TANGO [95], ANIM [8], Pascal Genie (from Chariot Software Group), UWPI [42], SEE [4], TPM [12], Pavane [86], LogoMedia [25] and CenterLine ObjectCenter [93]. Price *et al.* then construct a taxonomy based upon a tree structure, where each leaf in the taxonomy offers a different and orthogonal classification criterion. The complete taxonomy is shown in Figure 2.2.

Price *et al.* justify their first level classification by a generalized model of the software vi-

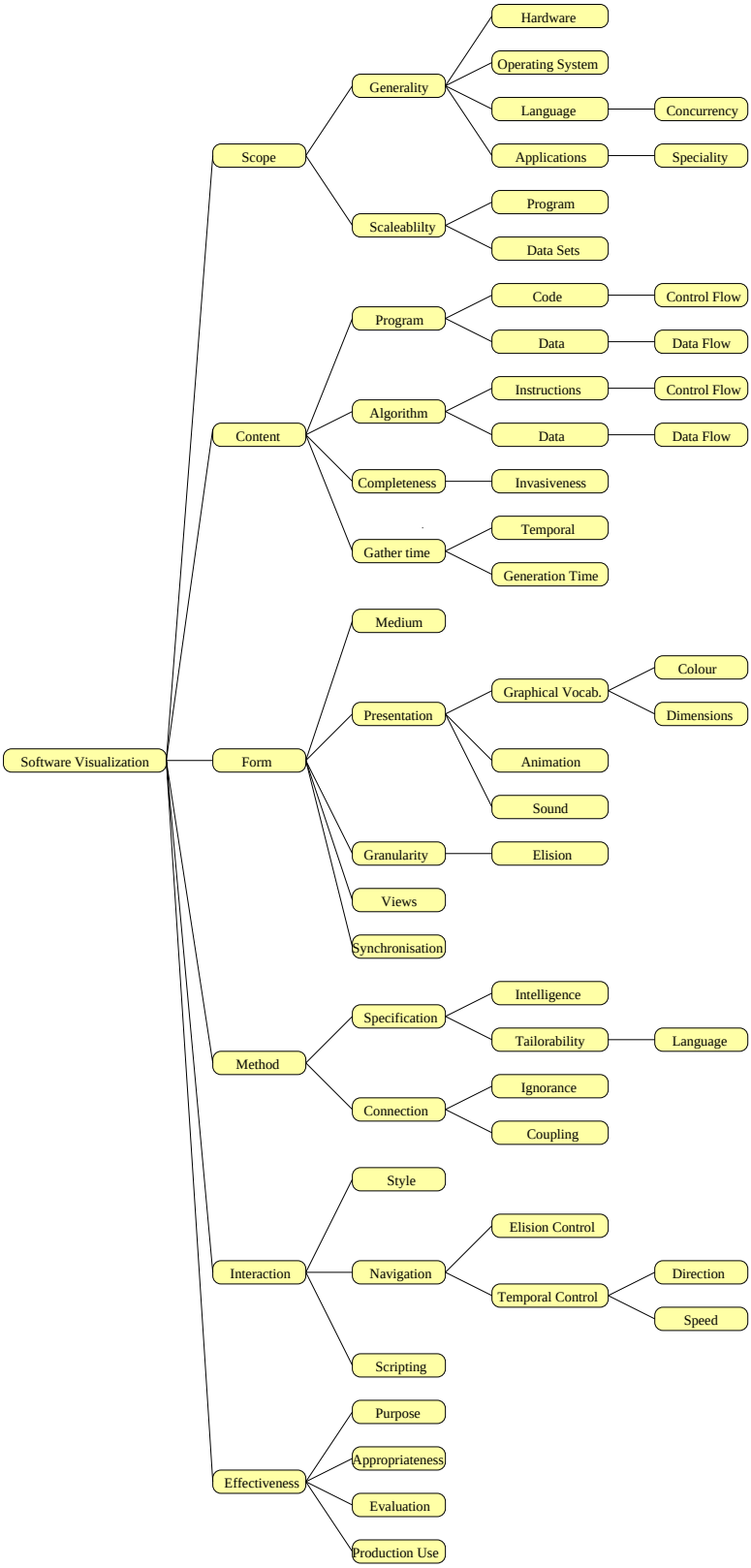


Figure 2.2. Price *et al.*'s taxonomy of software visualization.

sualization process. *Scope* relates to the source program and the input domain of the software visualizer. *Content* describes the particular aspect of the software that is visualized. *Form* describes the output of the system. *Method* describes how the implementation is specified and how the SV system works. *Interaction* describes how the user can interact with the view or the SV system to control, navigate, or modify the visualization. *Effectiveness* offers evaluation criteria for SV systems. By making their taxonomy tree structured they allow their taxonomy to be extended as the field evolves.

Roman and Cox offer a related taxonomy, shown in Figure 2.3.

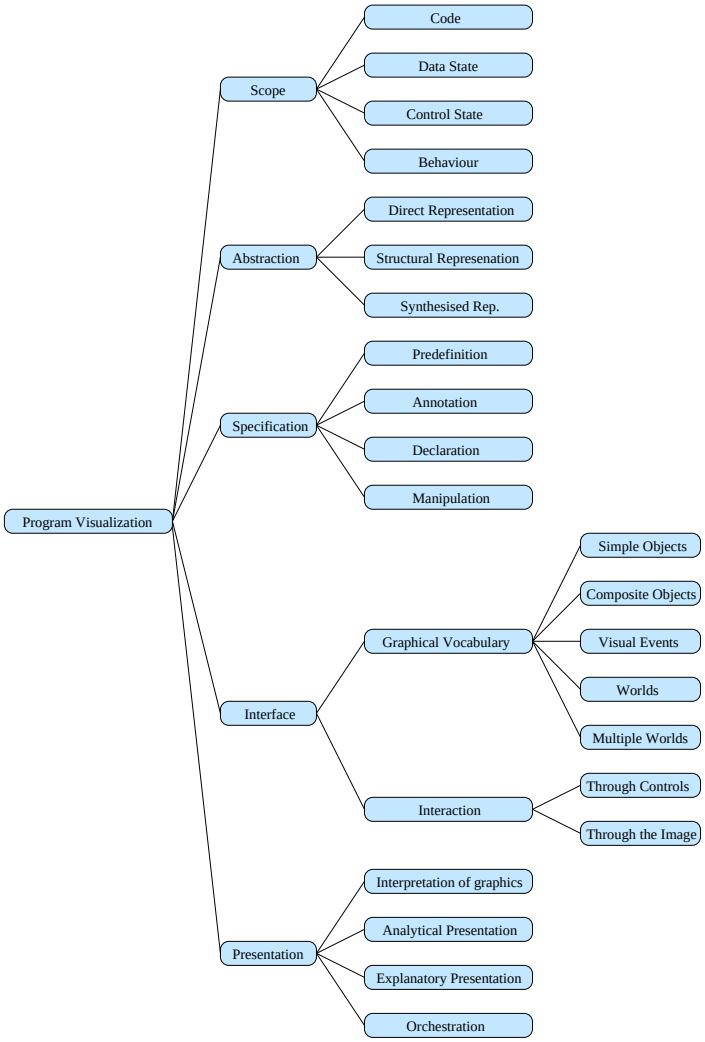


Figure 2.3. Roman and Cox's taxonomy of program visualization.

Roman and Cox's "Scope" category contains Price's "Scope" and "Content" categories. By "Abstraction", Roman and Cox mean the degree to which the code has been transformed. This overlaps Price's "Content" and "Form" categories. Roman and Cox's "Specification" category is contained within Price's "Method" category. Roman and Cox's "Interface" category describes both rendering and interaction, so contains Price's "Form" and "Interaction" categories. Roman and Cox's "Presentation" category denotes the semantics of the visualization, and is contained within Price's "Form" category. Roman and Cox's taxonomy is awkward here because it separates "Graphical vocabulary" and "Presentation." Roman and Cox do not consider "Effectiveness" and purpose in their taxonomy, when this is surely one of the most important facts about a SV system.

Myers [71] offers three different taxonomies, for programming systems, program visualization systems, and language specification technique. He classifies programming systems using

three orthogonal criteria, giving eight categories. The criteria are: visual vs. textual programming, example based vs. not example based, and interpreted vs. compiled. The taxonomy for PV systems uses a 2x3 grid, with static vs. dynamic on one axis, and code visualization, data visualization and algorithm visualization on the other. A programming system may belong to more than one category. The taxonomy by specification technique lists 14 different methods of language specification, and examples of visual languages belonging to each category. Myers' taxonomies are forerunners to Price *et al.*'s, which is far more comprehensive and more applicable to SV.

2.4 Software Visualization Systems

A range of SV systems are presented in this section. Unfortunately a comprehensive survey is beyond the scope of this work. There are hundreds of programming systems using visual techniques, which are roughly divided into development tools utilizing visual techniques, visual programming systems, and software visualization systems.

2.4.1 Development Tools

Almost every professional development tool uses visual techniques to assist application development. These visual development tools represent the state of the art commercially, and offer "rapid application development" compared with text-only environments. These tools form a basis for more advanced SV, and the visual representations, navigation techniques and human computer interaction issues in these systems are directly relevant to SV. Better SV techniques are likely to be incorporated into development systems as the sophistication of these tools grows.

A survey in *Personal Computer World* [76] reviews the leading visual development tools for the desktop market, where the leading platform is Microsoft Windows 95/NT. The products under review are Delphi 2.0, Optima++ 1.5, Power Objects, PowerBuilder 5.0, VisualAge Basic, Visual Basic 4.0, Visual C++ 4.2, Visual FoxPro 5.0, Java Workshop, Visual J++, Visual InterDev, Visual Basic 5.0, C++ Builder and Visual Café. Most offer database connectivity, object orientation, application builders, visual design, visual navigation and embedded help systems. The programming languages Java, C++, Pascal, FoxPro and Basic are used. Visual aspects of these systems include

- A graphical user interface.
- A windowed environment.
- Dialog boxes, tool-bars and pull-down menus.
- What-you-see-is-what-you-get (WYSIWYG) form designers.
- WYSIWYG graphical user interface design (menus, dialog boxes and graphical resources).
- Visual browsing of program resources (including graphical resources and program libraries).
- Code navigation using visual browsers of procedures and classes.
- Code navigation between code and GUI events.
- Visual modification of the properties of some types of program object and resources.
- Dialog box based skeleton code creation for components and applications.

There are only three visual notations used, each supporting interaction:

- Direct representation (of graphical resources, forms, menus, dialog boxes and source code).

- Nested list representation for hierarchical structures (such as procedures, classes, methods, help and graphical resources).
- Table or dialog box representation for program object properties.

Here we see a success of visual languages in designing spatial things (graphical user interfaces) spatially. These products do not however provide visual support for the programming itself, and merely insert code templates which the programmers need to flesh out themselves. While clearly useful, there are only a very limited number of application views, using only the nested list notation and are used just for code navigation. But even these techniques offer greater ease in building large high quality applications. Figure 2.4 shows a screen shot of Microsoft Visual Basic.

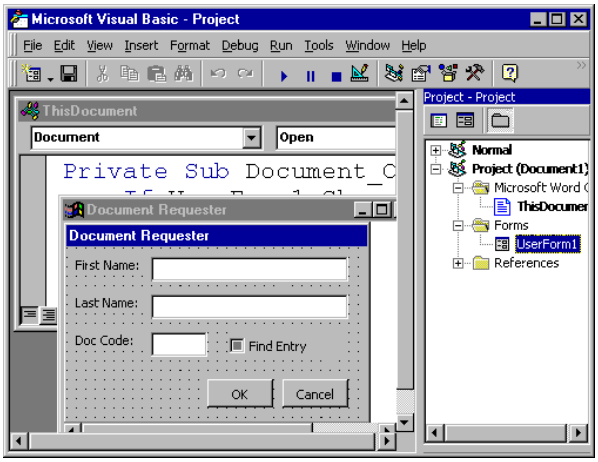


Figure 2.4. Microsoft Visual Basic 5.0, showing dialog box design and the project navigation tree.

Genitor

Genitor (from Genitor Corp.[1]) goes further than ordinary development environments because it offers a suite of tools for automatic navigation, project management and documentation. Its class editor, shown in Figure 2.5, provides a navigation tree that visualizes the method structure, and can be manipulated (via menus and drag and drop) to change the program objects.

While Genitor has access to a great deal of data about the program, its graphical output is very limited. A navigation tree shows only the structure of the file, and other interrelationships are not illustrated, but accessed through navigation. Its views are hard coded using just lists and a nested list view.

Source Code Analyzers

Source Navigator (from Cygnus Software[2]) is a development tool for C++, Java and COBOL that provides tree and graph views of the system. It shows the class hierarchy, cross references between classes, symbols used in the source code in a tree, and a graph of header file inclusion. It can manage projects in excess of 100 000 lines of source code.

CC Rider (from Western Wares[3]) uses a source code analyzer to view the structure of C++ programs. It can show class hierarchies, class ancestries, function call trees, class nesting, header file inclusion, symbols and program statistics. It can be used to navigate to parts of the source code, and provide detailed information about program objects.

[1]URL: *http://www.genitor.com*
[2]URL: *http://www.cygnus.com*
[3]URL: *http://www.westernwares.com*

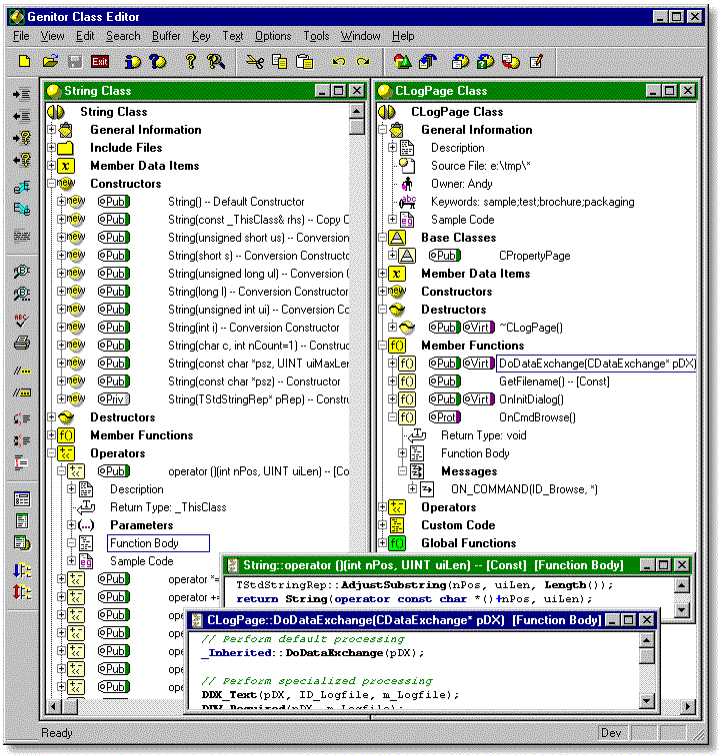


Figure 2.5. Genitor's class editor.

SNiFF+ (from Take Five Software[4]) has source code analyzers for C, C++, Java, Fortran, Assembler, Python, Tcl, Perl and Bash. It provides project and documentation management, views of class hierarchies, class browsing and include browsing, and source code navigation. Projects in excess of a million lines of code can be analyzed.

In these systems, the views are fixed, the information they provide is limited, their output vocabulary is limited, and they have no support for run-time information. However they offer a great improvement over text-only programming.

Tau

Tau [70] is a collection of tools to navigate and profile C++ source code, and incorporates class browsing and displays detailed run-time profile information visually. Views include

- File and class display. This provides list boxes to browse methods and classes in source code.
- Call graph extended display. Shows the calls made between functions as a graph.
- Class hierarchy browser. Shows the class hierarchy, and a window lists class members.
- Routine and data access profile display. Displays run-time usage of data.
- Speedup and parallel execution extrapolation display. Shows graphs of the performance of parallel C++.

Tau's visualization is too limited to classify it as a SV system. Tau is implemented manually - there is no easy way of extending the views or the system, and its output form is limited to numerical graphs and a class hierarchy.

[4]URL: *http://www.takefive.com*

2.4.2 Visual Programming Systems

Visual programming systems consist of a visual editor to construct visual programs in a visual programming language, and a means of executing the visual programs. In Price *et al.*'s definition [79], SV encompasses VP because VP is a specialization of SV that allows interactive modification of the program. VP systems use many visual programming languages (VPLs), visual representations of software, and techniques to interact with visualizations to modify the program.

Visual programming languages have existed since 1966 [99], and there are now hundreds of VPLs in existence. VPLs are becoming as prolific as textual languages, although there is not the same tool support (such as Lex and Yacc [2]) for visual programming [36], making it considerably more difficult to implement visual programming languages than a textual ones [71], and only a small number are commercially viable. VPLs that have had particular commercial importance include LabVIEW [104], ProGraph [19, 77], VisualAge (from IBM), Visual AppBuilder (from Novell), AVS (from Advanced Visual Systems) and AppWare (from Novell). Visual languages are more successful as end user languages for specific applications than as general purpose programming tools.

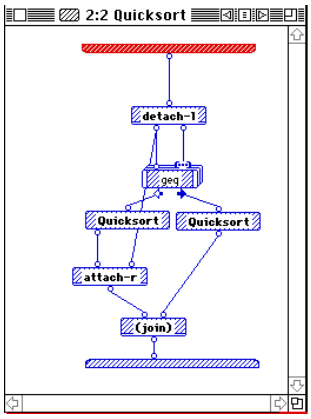


Figure 2.6. The quicksort algorithm written in ProGraph.

ProGraph, originally described by Pietryowski [77], is one of the most successful and widely used VPLs. Figure 2.6 shows an example of a ProGraph program.

It is plausible to suggest that visual languages might one day supersede the textual programming paradigm. At present practical issues such as scalability [17] and tools [36, 65, 71] need to be solved to make visual programming a viable alternative to textual programming.

2.4.3 Code Visualization Systems

Code visualization provides graphical information about the source code of a program. It includes high level overviews, program structure, and source code itself. It is different to visual programming in that code visualization systems do not necessarily modify graphical representations of code.

SEE

SEE [4] is a source code pretty printer that goes much further than syntax colouring. Syntax colouring is often used in text editors which identify the lexemes present in the source text and colour them according to their type (for example reserved words or comments). Syntax colouring gives demonstrable benefits to programmers, resulting in fewer syntax and typing errors, and faster comprehension of the source code [4].

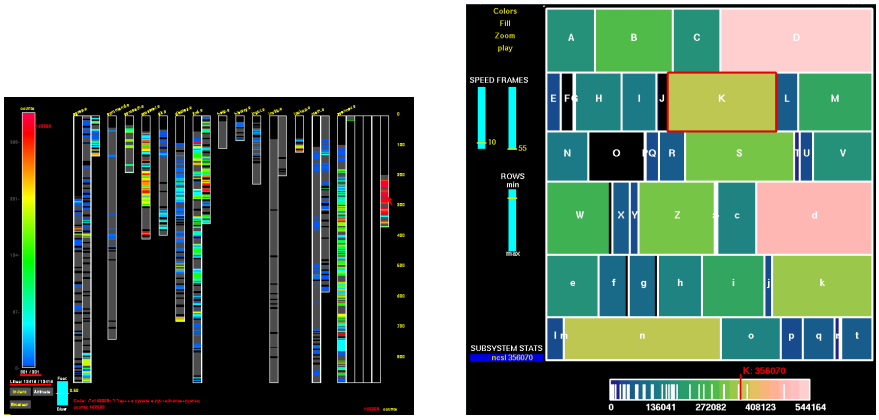
SEE converts source code into the style of a technical manual for automatic documentation. Type-faces, bold and italic emphasis, font size and shading are used to display the source text,

with one procedure per page, and procedure parameters clearly laid out in a table. Cross references to other procedures are generated automatically. There are other source formatting utilities available, including *vgrind* (in BSD Unix) and WEB (part of the TEX typesetting system).

SEE is very limited in its output - its output format is fixed, and it does not make extensive use of graphics.

SeeSoft and SeeSys

SeeSoft [29] by AT&T Bell Labs is a SV system that produces line-oriented software statistics of the source code in a software project. Each line of source code is represented by a single horizontal bar, contained in a vertical bar representing each source file. Modification statistics are compiled for each line of source code, which are then displayed using a coloured scale (continuous or discrete) showing update frequency, or time of last update. Files can be grouped according to function, and Figure 2.7(a) shows the screen layout.



(a) SeeSoft. (b) SeeSys.

Figure 2.7. Line oriented software statistics.

The display is interactive, allowing users to drag small windows over each source file to display actual source code, and change the colour scale. This visualization technique is sometimes referred to as a *mural* [49], where a long display is compressed in one dimension so that it may be contained within the screen, and a superimposed slider then magnifies the region of interest. Murals obey Shneiderman's "visual information seeking mantra: overview first, zoom and filter, then details-on-demand." [91]

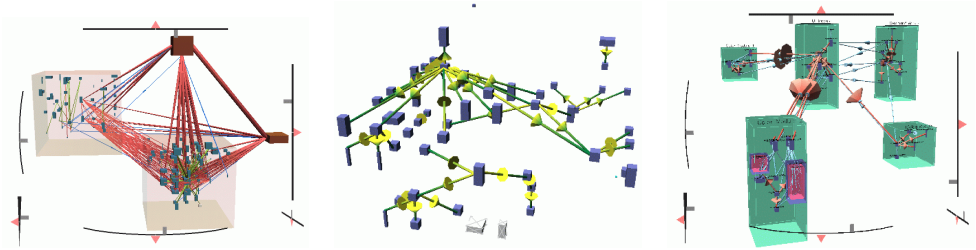
Baker and Eick [5] attempt to solve the problem of screen size and scalability by developing a system called SeeSys to visualize software systems using line-oriented software statistics. Instead of using fixed width bars with lengths proportional to the number of lines of code, the screen is divided into rectangular regions as shown in Figure 2.7(b) with rectangle areas proportional to the lines of code. The system can visualize files, directories and subsystems, and there is a zoom facility to zoom in on any subsystem. Additional information is presented to the user as the mouse moves over the visualization.

The output of SeeSoft and SeeSys is inflexible, so that the output data and format it fixed. There is also only one type of information available: the modification history of each line of source code, and the size and modification history of each source file. Nevertheless they provide a useful browsing and overview facility.

Graph Visualizer 3D

Graph Visualizer 3D (GV3D) [32, 105] is a tool to create three-dimensional visualizations of networks, and in particular of computer software and object-oriented code. Figure 2.8 shows

visualizations it can produce. By itself, GV3D is just a graphical output library that can be interfaced to analysis tools.



(a) Calls. (b) Class hierarchy. (c) Modules.

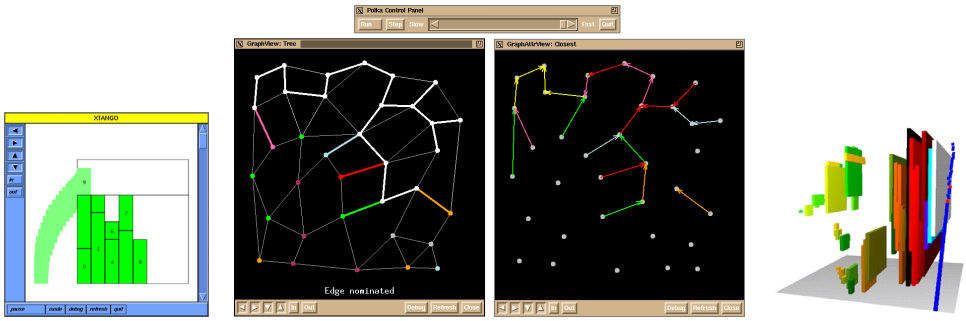
Figure 2.8. Renderings of almost 6 million lines of code by Graph Visualizer 3D.

2.4.4 Algorithm Animation Systems

Algorithm animation systems illustrate the principles of an algorithm by illustrating its operations on a data structure. Sometimes the animations don't relate to a real program at all, but are simply animation scripts. Of special interest is how the underlying program is connected to the output graphics, which is often no more complicated than embedded calls to a specialized graphics library.

Tango and Polka

Tango [95] is an algorithm animation system by J. Stasko at the Georgia Institute of Technology that can create smooth animations using smooth path transitions between execution steps. Animations are designed using trajectories and changes in size, colour and visibility. The source code is annotated to generate abstract data events, and under execution the data events map to animation events to generate the animation. Animation calls and visualization setup are written in C and inserted into the source program. There are user controls to pause, control speed and pan the display, and the visualizations are 2 and $2\frac{1}{2}$ dimensional, animated in real time. Figure 2.9(a) shows XTango - Tango for X-Windows that visualizes animation scripts generated from a running program.



(a) Bin packing in XTango. (b) Minimum spanning subtree in Polka. (c) Quicksort in Polka-3D.

Figure 2.9. Visualizations produced by Tango and its derivatives.

Tango has now been superseded by Polka [96], which is well suited for colourful smooth animations of parallel programs. Animation calls are made from a running algorithm that call a

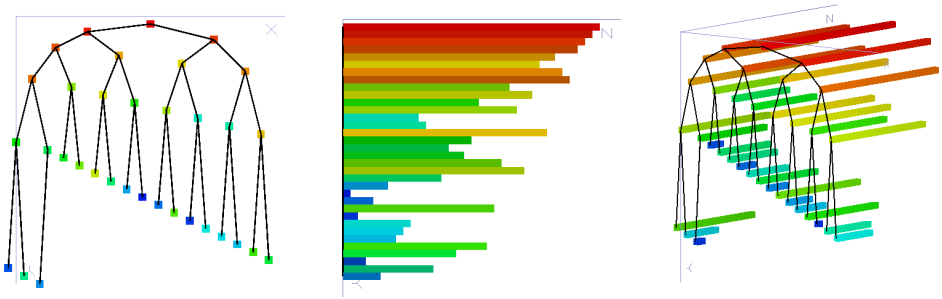
C++ library to effect animation events in a display. Objects are created that can be moved around the scene. Samba is a front end to Polka that accepts animation directives from a text file. Polka supports 2-D and $2\frac{1}{2}$-D visualizations, shown in Figure 2.9(b), but Polka-3D produces full 3-D visualizations shown in (c).

Several visualization systems have been built upon Polka, including PARADE [97] to visualize parallel and distributed systems, ConchViz to visualize the execution of cluster and message-passing environments. PVaniM visualizes and animates data from a Parallel Virtual Machine, which sends communication and user event statistics back to a monitor for visualization. There are other visualizers for parallel processes, including XPVM, Xab, PVMTrace and Pablo [57].

The main drawback with Polka is that it offers little more than an animation library in C++. Because the animator must manually write all of the animation calls, it is very time consuming to create animations in Polka. A degree of expertise is required to learn the library.

Balsa and Zeus

Zeus [15] by DEC SRC is written in Modula-3, and is based upon an algorithm animation system called Balsa [16]. Balsa itself was used as a teaching aid for algorithms using algorithm animation, and provided a windowed graphical display, panning, zooming and allowed users to view the execution of several algorithms running simultaneously, and can provide synchronized multiple views of the same algorithm. The user is able to set the graphical display of data items, and a source window with pretty-printed text is also available. Balsa works by inserting interesting event points into the source code (also known as *annotating* the source code), which generate visualization scripts that can be replayed.



(a) (b) (c)

Figure 2.10. Output from the Zeus algorithm animation system.

Zeus supports synchronized multiple configurable views. Zeus can run in a multi-threaded, multi-processor environment, making it suitable for visualizing parallel programs, some sound extensions have been incorporated into Zeus, and Zeus now supports 3-D. Figure 2.10 shows Zeus in operation.

Zeus uses Modula-3's class hierarchy to define views of an algorithm. Each running algorithm generates animation events, which call the animation library to provide output to the user. The effort of setting up new animations is high because the algorithm must be implemented within the Zeus framework, and hence does not correspond to real-world programs. The programmer must manually insert calls to Balsa and Zeus to perform the animation actions, requiring *a priori* detailed knowledge of the algorithm.

Pavane

Pavane [84, 86] is a visualization system that is capable of visualizing the run-time behaviour of parallel and massively parallel architectures. Parallel, distributed and concurrent execution is a very common subject of visualization because concurrent execution is so difficult to understand.

The implementation consists of five modules that can be distributed across a network, providing a parser to an intermediate language, a run-time execution monitor, visualization utilities, a renderer and a viewer. This architecture allows remote and distributed visualization. Visualizations in Pavane are specified in a declarative style [85], where a mapping is defined between the data space and objects in the visual space. This gives a powerful degree of abstraction of the visualization from the data. Smooth animation can also be defined. Its output is shown in Figure 2.11.

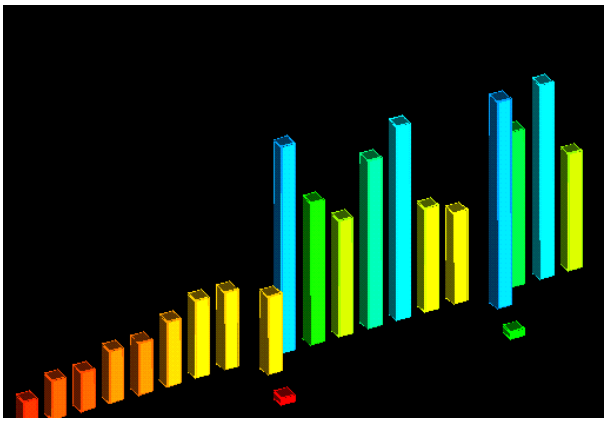


Figure 2.11. An animation of sorting by Pavane.

Pavane visualizations are very complicated to set up. The target program in C is manually annotated by inserting a number of calls that initialize Pavane and declare the data to watch (via the *VisualMonitor()* function). Event points are inserted into the source code by calling *VisualUpdate()* which tells Pavane to update the visualization with the new state.

A file containing *visualization rules* declares how to produce the visualization. Only numerical values and arrays can be passed to these rules. Each rule declares objects in the scene, and their screen coordinates depend on the values obtained from the C state. Expressions map the input data to coordinates in the scene. The syntax of these visualization rules is very complex. Once the system has been set up, quite powerful visualizations are possible.

The main problem with Pavane is the manual effort and complexity in defining new visualizations. Its specification language is very cumbersome and low level.

Leonardo

Leonardo [20] is an algorithm animation system that provides a logic programming language called *Alpha* to define graphics corresponding to data of a program executing in a virtual machine. Leonardo claims to be much easier to use than Pavane [85], and its virtual machine can be stepped forwards as well as backwards. An output from Leonardo is shown in Figure 2.12.

Declarations in Alpha are embedded in the object program within /** and **/, for example

```
int g[MAX_NODES][MAX_NODES];

/**
        Graph(Out 1);
        Node(Out N, 1) For InRange(N, 0, gNumNodes-1);
        Arc(X,Y,1) If g[X][Y]==1;
**/
```

Alpha declarations are simply logical predicates. It is similar to Prolog, but has a much more awkward syntax and has to define parameters as either inputs or outputs, and lacks unification and compound terms. Variables can only be integer types. Expressions from the target language can be embedded into Alpha directly. Whenever an Alpha predicate is called, expressions in the

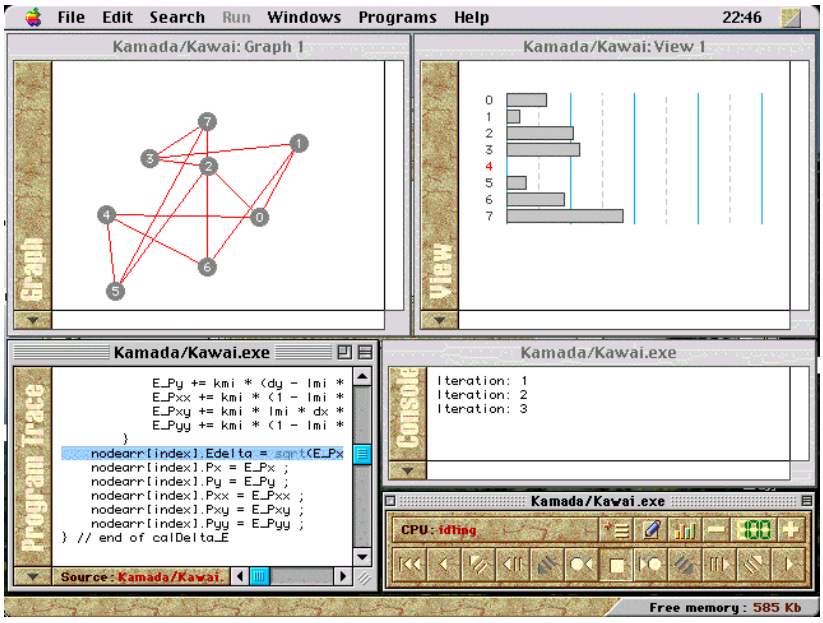


Figure 2.12. The Leonardo animation system.

target language are evaluated according the the current state of the the virtual machine. Thus the view is always synchronized with the virtual machine.

Graphical components in the scene are declared directly as predicates, so for example the *Arc/3* predicate declares the presence of arcs in the scene. This approach has been proposed as a general purpose logic-based framework for visualization [23, 24]. Components of a scene in Alpha are "pulled" from the predicates by querying them. The predicates specify screen coordinates directly.

The alternative "push" style of imperative languages is

```
void draw() {
  Window(_W);
  for(int RecID=0; RecID < num; RecID++)
      Rectangle(_W, RecID, 10+RecID*20, 10, 15, a[RecID]),
      RectangleColor(_W, RecID, a[RecID]<50 ? DARKGREY : LIGHTGREY);
  Line(_W, _L, 5, 10, 10+num*20, 10);
}
```

The same functionality in Alpha is specified in [23] as

```
/**
  Window(Out _W);
  Rectangle(_W, Out RecID, Out X, Out Y, Out L, Out H)
        For RecID:InRange(RecID,0,num-1)
        Assign  X=10+RecID*20   Y=10
                L=15            H=a[RecID];
  RectangleColor(_W, RecID, Out DARKGREY)
        If a[RecID]<50;
  Line(_W, Out _L,
        Out 5, Out 10, Out 10+num*20, Out 10);
**/
```

As can be seen, the Alpha program is actually longer and more obscure than the imperative language! In the above example, the *draw()* function could be called automatically every time the data state changes. Nevertheless as a graphics language, Alpha is very expressive, and provides abstraction between the data and the view. Alpha is still low level because there is a low degree

of abstraction between the output of Alpha and the graphics on the screen. The Alpha script must be reprogrammed to change the output.

Eliot

Eliot [61] extends Polka [96] to make it automatic to use. Algorithms written in C are compiled in C++ to overload the C operators to invoke visualization events. For example, each type of program object such as an array or integer, is created as an Eliot class, and any attempt to make assignments to the data calls the overloaded operator which updates the display. The user can choose the graphical representation of the run time data from a menu, and display different outputs in different windows.

Eliot is much simpler to use than any of the other systems in this section because it is completely automatic, and the user's intervention with the source code is minimal. It also has much greater potential for intelligence, and can be used in conjunction with the standard Polka calls. Unfortunately Eliot still requires some modification of the source code, and its output is not as flexible as animation systems that program their animation explicitly. Eliot can only visualize integers, reals, characters, arrays and binary trees. Visualizing other structures would require special implementation. Eliot can only show the current data state.

2.4.5 Run-time Visualization Systems

Run-time visualization displays what is happening in a program as it is running. This can monitor code (including program statements, threads or object usage), and data. Data visualization differs from algorithm animation in its purpose and degree of abstraction. Data visualization reveals real data in running systems for analysis, while algorithm animation is mainly used for teaching. Algorithms and algorithm animation are more abstracted from the underlying program.

The University of Washington Program Illustrator

The University of Washington Program Illustrator (UWPI) [42] offers a source level run-time debugger of Pascal programs (allowing single instruction steps in the source code) that provides an automatic visualization of the data in the program. A *layout strategist* written in Lisp applies AI techniques to determine the best way to render the program data, and displays the current data state graphically in a window.

According to Price *et al.* [79], "UWPI is the best example to date of automatic SV with any kind of intelligence." But UWPI can only illustrate small programs involving sorting and graphs, and only possesses a shallow understanding of numerical program data.

GROOVE

GROOVE [89], from the Georgia Institute of Technology, illustrates the run-time behaviour of object-oriented systems using animation, so that programmers can better understand the class hierarchy and relationships. Figure 2.13 shows GROOVE.

GROOVE animations are created by manually creating visual objects in the scene from function calls. Therefore while GROOVE is flexible in its output, there is a degree of effort to create visualizations, and the system is only suitable for small programs.

Look!

Look! (from Objective Software Technology [5]) is a commercial product that allows visual display of the run-time behaviour of C++ systems. It is claimed that this allows programmers to understand the system much more quickly, find bugs much faster, reduce redundant object behaviour, and improve the overall code quality. Programmers can view references between classes, the

[5] URL: *http://www.objectivesoft.com*

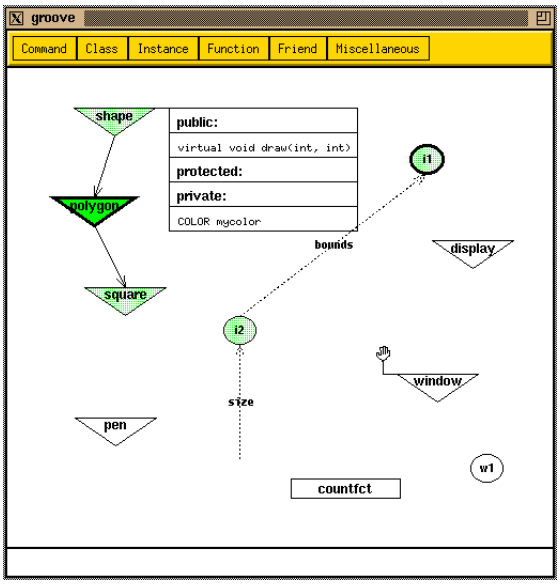


Figure 2.13. Screen-shot of GROOVE showing an object-oriented design.

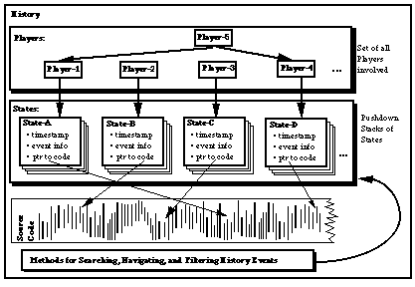
class hierarchy, object creation and deletion events and concurrent threads. Each view shows the current method acting on the objects.

Look! views are hard coded, and actually provide just four different visualizations: class references, class hierarchy, object creation and code clustering. While the system is automatic, it is dedicated to just these views and cannot be extended by the user. The views themselves show only object names and method invocations.

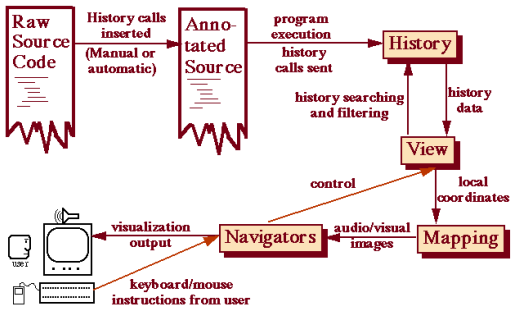
2.4.6 Architectures

Viz

Viz [26, 27] is a framework developed at Open University in which run-time SV systems may be built. Viz uses *players*, which can be any program object such as a variable, a function or a code block, to generate history events, shown in Figure 2.14(a).



(a) Acquiring and filtering history data.



(b) The architecture of Viz.

Figure 2.14. Viz.

The system architecture is shown in Figure 2.14(b), and consists of histories, views (individual visualization windows), mappings (translation from view information into graphical output) and navigators (to manipulate and move between views).

Viz itself provides only a framework for implementation, and does not provide a specification language.

Vogue

Vogue [51] is a 3-D visualization system that has been applied to parallel/concurrent programming, object orientation and software engineering. Systems built using Vogue include VisuaLinda [55], Integrating Version Control and Module Management [54], Fractal Views [52, 56] and Bottom-up Program Visualization [53].

Vogue's primary operation is to extrude an array of 2-D networks into a 3-D image. The argument is made that more information can be fitted onto the screen, and the evolution of a system can be viewed in a static diagram. However Vogue is an architecture that provides only nodes and links that must be created manually in the source code. Its output capabilities are very limited, using just colour, shapes and lines to communicate information. Vogue is actually just an output library, and is not an end user system because a considerable programming effort is required to generate visualizations.

2.5 Specification

2.5.1 Visual Language Theory

Visual language theory [65] explores formalisms for structuring the visual domain, and how graphical structure relates to the semantics of visual languages. From a theoretical standpoint, a visual language is "a set of diagrams which are valid 'sentences' in that language, where a diagram is a collection of 'symbols' in a two or three dimensional space." [65] One of the main issues in visual language theory is defining membership of visual languages. The main methods for specifying visual languages are graph grammars, attributed multiset grammars, logical formalisms and algebraic formalisms.

The main drawback with visual language theory is that it deals with interpretation, not view generation. This is useless for visualization, where the task is to generate the diagram in the first place. One grammar that is generative is given by Grant [36], where the grammar defines the geometric transformations of objects that are contained in one another.

In its broadest sense, parsing images is a vision problem. In visual language theory, diagrams are used where the symbolic constituents of the diagram are known. Such a pre-processing stage is analogous to lexical analysis. Parsing diagrams is more costly than parsing text, because of the unordered nature of the constituents of a diagram, and because geometric conditions must be tested.

Visual Grammars

The two main types of grammar are graph grammars and attributed multiset grammars. Graph grammars [81] regard the view as a set of interconnected symbols. Graphical rewrite rules specified in the grammar transform the graph of the image structure.

Attributed multiset grammars consist of rewrite rules on collections of symbols with attributes. One of the most general and powerful types of attributed multiset grammar are *Constraint Multiset Grammars* [65]. Geometric constraints on the attributes are tagged to the grammar rules. Such grammars can be implemented in Prolog, by using constraint logic programming [48] to specify the geometric constraints.

Semantics of Diagrams

The semantics of diagrams can be described by logical or algebraic formalisms. As well as using logic to reason about geometry, *description logics* [28] can be used to assign meaning to the

structure of the diagram. Description logics are less powerful than full first order logic, and are therefore more tractable.

Algebraic specification [103] maps the application domain into typed abstract data structures. An image is mapped into a data type, representing concepts or semantics. Algebraic rules define a functional mappings between the domains.

2.5.2 Numerical Data

Numerical data has particular significance in scientific visualization, and has uses in software visualization. Numerical-only methods are insufficient for heterogeneous visualization and visual languages. Hibbard *et al.* [43] develop a *scalar mapping technique* for mapping numerical data in a program to continuous quantities in a display, including time. A system called VIS-AD implements a specification language that defines data structures (of numbers), and mappings between elements in the data structures to graphical display coordinates. For example

```
map earth_location to xz_plane;
map temperature to y_axis;
```

In later work by Hibbard *et al.* [44], a *lattice model* describes the relationship between data and display. They concede that their technique is "inadequate for complex information processing" such as recursive data structures, and they foresee "considerable technical difficulties" to manage such data.

2.5.3 Specification Languages for SV

SV systems fall into three categories: those that are not extensible at all, those which are extended in the native programming language, and those that provide their own language for specification. Only Pavane, Leonardo, VIS-AD and Samba fall into the last category. Samba is merely a sequence of visualization and animation directives.

Both Pavane and Leonardo use a declarative specification to map live run-time data to graphical objects. The drawback with both systems is that they only provide a direct mapping to graphical objects on the screen. Thus they are both very low level approaches. Another problem they have is that they lack encapsulation, for example to define libraries of objects, and the mapping from the data to the graphics is fixed. A change in the mapping can require significant reprogramming. The implementations of Pavane and Leonardo are very different however.

VIS-AD also provides a declarative specification for mapping data to the screen, but is restricted to simple numerical data structures.

In spite of their limited success, declarative specification languages offer significant advantages over imperative programming methods [20]. For example they offer a higher degree of abstraction between the data and the graphics, the languages are specialized to the task, and are potentially easier to use.

2.6 Information Visualization

The wider field of information visualization looks at techniques for expressing all types of information in a visual form. Visualization has proved an extremely important use of computers, where the information they store needs to be output, and often visualization communicates information far more effectively that textual data. Visualization has applications in virtually every field, including business, science, finance, management, databases, information retrieval and software engineering.

2.6.1 Perception

The study of visualization examines what information to visualize, what visual representations to use (i.e. what visual languages to use), and how the visualization is created. The study of choosing visual representation lies largely in psychology, which regards visualization as a mental process, and performs experiments on human subjects to find metrics for human responses and the effectiveness of various types of notation. Creating the visualization is essentially the problem of computer graphics, and includes rendering, graph drawing and spatial constraint solving.

Psychological factors are rarely applied to SV, mainly because it of the absence of techniques to empirically measure the effectiveness of SV systems [79]. This does pose problems for objective and meaningful comparison between systems. Much of the SV literature completely disregards psychological factors, and merely regards visualization as a conversion from a program to a graphical representation, for example [84]. Psychological experiments must be performed under very controlled conditions, and software visualization is too large a domain to measure directly. The result is that psychology has so far offered few concrete ideas to SV that could not be derived using intuition, and indeed visualizations and visual languages can, and generally are, devised on an *ad hoc* basis, and are only informally evaluated.

There are psychology studies that can contribute to creating more effective visualizations. Rogowitz *et al.* [82] look at how we can exploit preattentive perception and colour/luminance mappings to create visualizations that can be searched more quickly and convey continuous or discreet data with greater veridicality. Perceived brightness is proportional to a *power* of luminance (hence gamma correction), so where luminance is used to convey continuous data, a corrective power should be applied, and examine other stimuli for conveying continuous information. Perceived colour varies discretely with hue (wavelength), so this should be exploited for discrete data, but compensated for in continuous data. Experiments in preattentive vision show how we can subconsciously pick out certain features of images (e.g. coloured spots), which can be exploited when searching large datasets in constant time, versus a linear searching time for attentive (conscious) searching. Preattentive effects can also disrupt the interpretation process by distracting the subject from the important features, and should be exploited to attract or direct attention to the important features of the visualization quickly.

Rogowitz and Treinish [83] propose a visualization system that considers perceptual rules to devise a visual representation for data. They argue that this is required because traditional visualizers may introduce unwanted artefacts into the image that obfuscate the meaning of the visualization, as described in [82]. They also claim that visualization is easier to implement and produces better and more meaningful representations when visualization rules (based upon perception) are used to generate visualizations, than high-level tools or direct coding. Current SV systems use high level tools and direct coding, which produce inflexible visualizations and offer little guidance on the effectiveness of the visualization.

2.6.2 Representations

Some systems use a three dimensional representation. There are advantages in using the third dimension, including added realism and tangibility of program objects, increased information density, and an extra quantitative axis. Shneiderman [90] argues that programmers think of their code as structural and tangible, and that direct manipulation of abstract objects in the computer using a visual paradigm would be the easiest and most natural way to interact with a computer. The 3-D approach adds reality and tangibility to the program objects, thus concretizing the software more effectively for the programmer. However there is evidence that making objects more realistic makes it more difficult for users to extract the information (or abstract the semantics) that the symbol conveys [63]. There is also evidence that 3-D visualizations can convey between “1.6 and 3.0” times more information than an equivalent 2-D view, and users are able to understand complex relationships better when presented in 3-D [105].

Lohse *et al.* [63] derive a classification of various basic types of visual representation, by asking subjects to sort a set of sixty images of a full range of visual representations. By performing statistical tests they compiled a taxonomy to grade each of the images according to the high level

properties of spatiality, temporality, comprehensibility, level of abstraction, continuity, attractiveness, subdivision, numerical level, dynamic vs. static and information rich vs. information poor. It emerged that there are eleven major clusters of representations: graphs, tables, graphical tables, time charts, networks, structure diagrams, process diagrams, maps, cartograms, icons and pictures. The work offers many ideas and visual representations - or combinations of them - that could be applied to SV, and gives the principle characteristics of each representation.

Tufte [101] details methods for scientific visualization of quantitative information. He gives a comprehensive collection of hundreds of graphical representations, with critique. This book offers a rich source of ideas and much more useful rule-of-thumb approaches for effective visualization than attempting to rationalize visualization on a formal basis. Many visualizations of software are quantitative.

Bertin [9] wrote one of the first texts on the *semiotics* or meaning of graphical representations. This is an informal treatment of diagrams. Bertin regards "order, form and proportion" to be the building blocks of any graphical representation. Bertin mainly considers visualizing numerical tables. Green and Benyon [38] regard "entities, attributes and relationships" as the fundamental components of information display, and discuss, again informally, the relationship between graphical properties (*graphical artefacts*), and the semantic properties (*information artefacts*) conveyed by the display.

2.6.3 Architectures

The AVE system [34] implements a flexible mapping from data to diagram using a data-driven approach, where the data itself determines how it is to be visualized, and AVE is particularly applicable to semantic networks [28] where the database contains heterogeneous data. The data relations are mapped onto graphical relations on the screen, such as interconnection or adjacency, by analyzing the structure of the data. Queries select subgraphs of the database, which are subject to structural analysis. Graphical relations are then assigned to the data relations using a ranking system, and the diagram is generated to render the data with the assigned graphical structure. Figure 2.15(a) shows the graphical representations it chooses for the various data structures, and Figure 2.15(b) shows the overall architecture.

The drawback with AVE is that the ranking system is hard coded and it has only a limited number of different layout techniques to apply.

2.6.4 Graphical Layout

Graph layout remains a difficult area of computer science. It is well known that optimizing graph layouts is generally NP-hard, and in particular minimizing edge crossings is NP-complete [33], so much work has been done in developing heuristics for graph drawing. Graph drawing is an important tool for SV, where relational data may be presented in a node-and-link fashion. There are many ways to present graphs, including using polylines, straight lines, as orthogonal drawings, as rooted trees, as free trees, in planar form, in 3-D, as convex, as gridded, as directed, as undirected, as hierarchical etcetera. A comprehensive survey of graph theory and methods is given by Battista *et al.* [6]

2.7 Research Directions

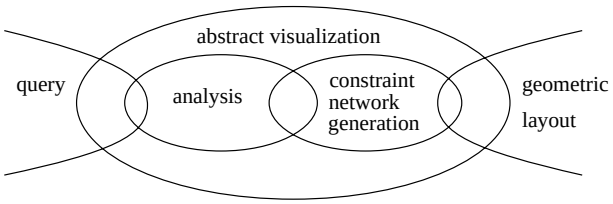
Both Myers [71] and Price *et al.* [79] identify several deficiencies in current systems that should be addressed in future research. The reason SV systems are not more successfully applied is because of these difficulties.

Both Price *et al.* and Myers say that formal specification of SV and VP systems is limited, and although theoretical work has been done in visual languages, it has so far proved to be impractical for SV.

Without the foundations for specification, and without formal data representation, it is difficult to provide specification for scripting. Scripting facilities for SV systems are extremely low level,

Relation type	Relational properties	Graphical relations
unqualified	directed	arrow
symmetric	symmetric	line
acyclic	acyclic	arrow
tree	tree	arrow
irreflexive order	irreflexive, asymmetric, transitive	arrow+relative position, arrow
irreflexive tree order	irreflexive, asymmetrical, transitive, tree	inclusion*, arrow+relative position, arrow
strict discrete linear order*	asymmetrical, transitive, completely connected, discrete domain	equidistant positions, brightness, saturation, arrow
strict continuous linear order	asymmetrical, transitive, completely connected, continuous domain	fixed distance, size*, brightness, saturation, arrow
bipartite	bipartite	attribute, arrow
unique mapping	functional	single attribute, grouping*, arrow

(a) Mapping data to graphical structure.



(b) Architecture (reproduced from [34]).

Figure 2.15. The AVE visualization system.

often consisting of in-line C code, and the data representation and management is usually *ad hoc*. This means that it is cumbersome to add views to systems, so SV systems tend to have a very limited number of views. The lack of views leads to fixed granularity, poor elision control, and poor or no navigation. Work is therefore needed to make SV easier to specify and implement.

The comparative difficulty of specification extends to layout, interaction (if possible at all), and navigation which are all manually coded. It makes it more difficult to change the graphical representation once the view has been implemented. Intelligence and flexibility are required, because a representation that is appropriate for 10 elements is unlikely to be appropriate for 100 000. AVE [34] and Rogowitz and Treinish [83] suggest ways to correct this. Work is needed to improve the tailorability and flexibility of SV systems.

It can be very time consuming to set up visualizations and add new views, to the point where the cost of setting up the view outweighs the insight gained from the visualization, particularly if the insight is difficult to gain because the data is represented inappropriately. Standard empirical evaluation methods for SV do not exist because the programming task is difficult to quantify. Hence evidence of worth is lacking for many SV systems. SV systems must be made easier and more automatic to use.

Scaling up systems to tackle large applications is a problem for many systems, caused by lack of proper data management to handle large data sets effectively, poor view granularity, poor elision control, poor automation, and poor flexibility in graphical representation. Hence most of the visualization systems presented here only display small quantities of data. Work is needed to manage large data sets and control elision more effectively.

2.8 Conclusions

Software visualization is an emerging field, and is becoming increasingly important in understanding, documenting, debugging and constructing software. The great success of visual tech-

niques in professional development tools has greatly cut application development time and improved application quality, and is set to continue as more techniques move from experimental systems into commercial ones. As software complexity grows, more powerful techniques must be devised to maintain large software systems.

The trend is that software development is becoming more visual, although visual programming languages are still inadequate to replace text entirely in most circumstances. Like visual programming languages, software visualization systems must demonstrate their benefits before they will gain widespread acceptance. Work must be done to find applicable formalisms for both visual languages and software visualization to allow progress. Software visualization is currently impeded by lack of high level specification, which could provide solutions for many problems, including view specification, quantity of views, graphical mapping flexibility, granularity, elision control, navigation, scalability and automation.

Chapter 3

A Model of Information Visualization

Software visualization presents unique challenges because the data presented is so heterogeneous and the graphical output can be so varied. What kind of theory could underlie such an open ended task? Current theories of visualization or visual languages do not adequately model the semantics of graphics, or are too limited, so existing implementations are not based on formal approaches.

The work in this chapter presents such a theoretical model that formally models the relationship between graphics and its semantics. It is named a *semantic* model because in this model, the semantics of graphical views are always explicit. This in turn leads to a decoupling of the information content in a view, and its graphical representation, and allows arbitrary queries to determine the content of a view.

An important aspect of any theory is its applicability, and the purpose of this theory is to provide an extremely concise and high level specification method. This will be used as the core of a visualization engine that is described in Chapter 4. Chapter 5 applies these specification techniques to software visualization.

3.1 Introduction

Software visualization is laborious to implement because the current tools are not sufficiently automatic and flexible, and lack effective scripting [79]. Computer software contains very relational, structured and heterogeneous data, and visualization tools are ill-equipped to manipulate this kind of data because theory on visualization and has not been fully developed to handle arbitrary data structures.

In this chapter a theory of visualization is developed that forms the basis of a generic visualization tool that will be used to visualize software. Foundations are a necessary first step, and provide a common language, a framework for implementation, and the capability for formal reasoning.

While there are many automatic tools for numerical and scientific visualization, heterogeneous data visualization has proved to be much more difficult to model and specify [44]. Existing approaches to heterogeneous data visualization rely on low level programming using imperative languages. Even declarative specification approaches such as Pavane [86] and Leonardo [20] explicitly specify graphical positions on the screen, and deal only with numerical quantities. The benefits of declarative or logic specification languages are not fully realized when such a low level approach is used, and logic languages such as Prolog are inferior to imperative languages for implementing general graphical algorithms because of their slow speed and lack of efficient data structures.

In this chapter these basic declarative approaches are improved. Instead of directly mapping

numerical data to screen coordinates, the visualization process is further subdivided as shown in Figure 3.1.

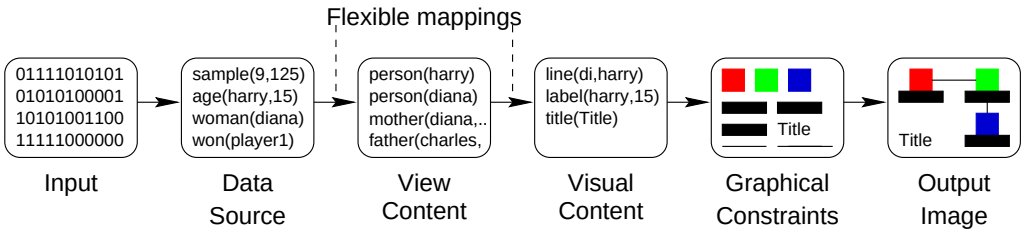


Figure 3.1. A semantic model of visualization.

The output is generated from a set of *graphical constraints*, which include spatial associations such as adjacency, containment or connections, attributes such as colours, and objects such as polygons and text. This is a much more high level approach to specification, and is completely generic.

Deriving the graphical constraints for a view is split into several steps. The first step is data gathering from the *input* shown in Figure 3.1, to provide a *data source* in some database. The information content in a view, or *view content*, is acquired by issuing a query to the database to construct a set of data. A one-to-one mapping maps the information content to a graphical representation, or *visual content*. A third mapping defines the graphical constraints that compose each visual in the visual content. We define a *visual* to be a set of graphical constraints that represents some meaningful graphical notation.

There are many advantages with this approach:

- Screen coordinates do not need to be specified, but are derived automatically by layout algorithms. Previous systems have only provided direct mapping to the display, and are therefore less flexible in their graphical output.
- It is possible to change the mapping from view content to visual content without redefining the views. It also makes it possible to provide multiple graphical representations for the same data. Previous systems have only provided a fixed mapping, which must be edited in text to change the view.
- These mappings can be fully formalized, and embedded in first order logic. It is possible to reason about heterogeneous data visualization. Previous systems do not base their specification on a formal model of visualization.
- These mappings can be specified straightforwardly in Prolog. This means that there is no need to devise a new language, and is therefore much easier to implement and will run much faster.
- Because Prolog is *introspective* (it can query its own program) and *dynamic* (it can modify itself), these mappings can be queried and modified by the user at run time. Other systems offer fixed visualization behaviour, and cannot display an automatic legend describing the view. The fact that the mapping between view content and visual content is a bijection permits this.
- It is possible to pose arbitrary queries to a knowledge database. Previous systems restrict this to run-time data.
- Visuals are specified independently of the view data, and can be reused. This is a big problem for previous systems which effectively have to start from scratch each time a new view is created.
- Multiple views can be defined independently and used within the same system. By labeling each view and visualization mapping, directives such as "visualize *function(Fn)* using *coloured_nassi_shneiderman_diagram*" can be issued. Support for multiple view definitions in other systems is much more limited.

- Arbitrary data structures can be passed through the visualization pipeline. Previous systems deal only with numbers, which is too limited.
- It is possible to interact with objects in the view, because they are assigned identifiers of objects in the database. Interaction is also specified formally. It isn't possible to specify interaction in other declarative systems.

3.2 Representing Data

Data gathering is an essential first step in any visualization system. Therefore it is necessary to formalize the notion of the data from which to visualize. Previous approaches [23, 44, 86] restrict this domain to numbers - this domain must be extended to encompass all types of data.

The approach we shall use is to regard this data as a set of propositions that can be computed to be true. Such a notion has little meaning in an imperative language, but in logic programming it is the set of propositions that can be proven from the inference rules of the logic program. The canonical form of logic programming is the programming language *Prolog*, although there are many other logic programming languages. We shall restrict ourselves to the core language.

Using Prolog has several advantages for data representation. First of all it is a very high level language for expressing relationships and inferences between data, and can express high level rules very naturally. Prolog is a good meta-language, so it is suitable for representing and reasoning about computer languages which are entirely rule-based. The work described in Chapter 5 shows that all aspects of computer languages can be modeled in Prolog.

A Prolog program constitutes a set of logical inferences in first order logic.[1] In other words Prolog is itself a formal notation, which removes the need to develop further notation in this chapter. Formal treatment of Prolog and first order logic is well established and is treated elsewhere [80].

A common application of Prolog is in knowledge engineering and automated reasoning [62]. Visualization has potential uses for displaying the results of automated reasoning, while automated reasoning adds flexibility to derive new knowledge (*implicit knowledge*) for presentation in a visualization system. Information visualization is the presentation of knowledge, so it is natural to integrate knowledge engineering into visualization.

Prolog is *Turing powerful*, so it can compute everything that a language such as C++ can, although the language has different applications. Prolog can perform any perform any kind of data manipulation. The following examples illustrate Prolog's approach to data representation.

Example 1. *Suppose sea-bed data is visualized, and at each discrete sample point lies the sea depth and its temperature. The predicate*

```
sea_depth(X, Y, Depth)
```

would convey the depth of the sea at the specified location, while

```
sea_temperature(X, Y, Temperature)
```

would convey the temperature at each location. Data would be added to these predicates from an external source. A query such as

```
?- sea_depth(X, Y, D), D>10, D<12.
```

would return all locations where the depth was between 10 and 12 metres.

Example 2. *Suppose wiring of a house is visualized. The predicate*

```
socket(Socket)
```

[1] Pure Prolog implements first order logic. *ISO Prolog* [1] contains features such as *cuts* that can break the logic, but are a practical necessity to prevent unwanted backtracking.

would identify the sockets, while the predicate

```
location(Socket, Location)
```

would identify the location of each socket, perhaps by a description or a set of co-ordinates. Wires could be indicated by

```
wire(Socket1, Socket2, Type)
```

to indicate the existence of the wires between sockets, with Type being live, neutral or earth.

Example 3. *Suppose the liveness of variables was visualized over a function. Variables could be represented as*

```
variable(Variable)
```

and statements by

```
statement(Statement)
```

and liveness could be indicated by

```
live(Variable, Statement)
```

The query

```
?- live(V, s).
```

would return which variables were live for a particular statement s, while

```
?- live(v, S), live(V, S).
```

would return which variables are concurrently live with variable v.

3.3 Specifying View Content

When the data has been gathered it is ready to be viewed. A query is issued to the knowledge database to extract the information to display. This is a set of terms called the view content, which is shown in Figure 3.1. In this way, every datum in the view is represented by one term. If T is the set of terms (defined in Appendix A), the view content C is

Definition 1 (View content). *Let $T_C \subseteq T$ be the set of terms that represent view content. Let $C \subseteq T_C$ be the the view content.*

Example 4. *The view content C for a small family tree could be the set*

```
[ person(charles), person(diana), person(elizabeth),
  person(harry), mother(elizabeth, charles),
  father(charles,harry), mother(diana, harry) ]
```

In a system with multiple views, each view is identified by a *view context*, which is represented by a term.

Definition 2 (View context). *Let $T_X \subseteq T$ be the set of terms that are view contexts. Let $x \in T_X$ be a view context.*

Example 5. *The view of the entire family tree could have the view context family_tree. The view showing just the ancestors of harry could have view context ancestors(harry).*

The view content C is specified by a *relation* between the view context x and C.

Definition 3 (View relation). *A view relation $\xrightarrow{Q}$ is a relation between T_X and T_C.*

The view relation defines which terms are in the view content for a particular view context. Relations are used instead of functions because they are more general, can be 'one-to-many', are bi-directional, and can be expressed in first order logic. The relation $\xrightarrow{Q}$ could be regarded as the *query* that determines the data in the view content.

All Prolog predicates can be regarded as relations between terms. The Prolog predicate is used as an indicator function which finds all members of the relation that match its arguments. This means that Prolog can be used to define the view relation, and a binary predicate

```
view_content(ViewContext, ViewContent)
```

specifies the binary relation between the view context and the view content. The first parameter specifies the view context, and the second view content for the view context. This is a 'one-to-many' relation. Clauses are added to the *view_content/2* predicate to add data to the view content.

Because Prolog is Turing powerful, and because terms can represent arbitrary data, any computable mapping from data source to the view content can be implemented. This method of specifying view content is therefore completely generic.

The view contexts T_X and view content T_C are implementation defined.

Example 6. *The family tree could be declared by the view relation*

```
view_content(family_tree, mother(X, Y)) :-
        parent_of(X, Y), woman(X).

view_content(family_tree, father(X, Y)) :-
        parent_of(X, Y), man(X).

view_content(family_tree, person(X)) :- man(X).

view_content(family_tree, person(X)) :- woman(X).
```

if the predicates woman/1, man/1 and parent_of/2 are defined. The view context is family_tree, which has in its view content the term mother(X,Y) to denote that X is mother to Y, father(X,Y) to denote that X is a father to Y, and person(X) to denote that X is a person.

ancestor_of/2, the transitive closure of parent_of/2, can be defined as

```
ancestor_of(X, Y) :- parent_of(X, Y).
ancestor_of(X, Y) :- parent_of(X, Z), ancestor_of(Z, Y).
```

Then the view context descendents(P) containing just the descendents of P could be defined

```
view_content(descendents(P), person(X)) :-
        P=X; ancestor_of(P, X).

view_content(descendents(P), mother(X, Y)) :-
        ancestor_of(P, Y), parent_of(X, Y), woman(X).

view_content(descendents(P), father(X, Y)) :-
        ancestor_of(P, Y), parent_of(X, Y), man(X).
```

Example 7. *The view relation*

```
view_content(wiring, socket(Socket, Location)) :-
        socket(Socket), location(Socket, Location).
view_content(wiring, wire(S1, S2, Type)) :-
        wire(S1, S2, Type).
```

has view context wiring, with the view content socket(Socket, Location) giving a socket with location, and wire(S1, S2, Type) denoting a wire between two sockets of the specified type.

Example 8. *The view relation sea_temperatures*

```
view_content(sea_temperatures, temperature_point(X, Y, Temp)) :-
        sea_temperature(X, Y, Temp).
```

gives the sea bed temperatures, while the view relation temperature_range(Min, Max)

```
view_content(temperature_range(Min, Max), inside_range(X, Y)) :-
        sea_temperature(X, Y, Temp), Min=<Temp, Max>=Temp.
view_content(temperature_range(Min, Max), outside_range(X, Y)) :-
        sea_temperature(X, Y, Temp), (Temp<Min; Temp>Max).
```

returns the sets of points inside and outside the given range $[Min, Max]$.

Example 9. *The view relation*

```
view_content(conjunction(A, B), C) :-
        view_content(A, C),
        view_content(B, C).
```

gives the intersection of A and B with view context conjunction(A,B), while the view relation disjunction(A,B), defined

```
view_content(disjunction(A, B), C) :- view_content(A, C).
view_content(disjunction(A, B), C) :- view_content(B, C).
```

gives the union of A and B.

3.4 Specifying Visual Content

The graphical description of the view, or visual content, is a set of terms describing the graphical structure of the view. It is derived from the view content by a mapping as shown in Figure 3.1. Each term in the visual content represents one graphical property of the display. The visual content is defined

Definition 4 (Visual Content). *Let* $T_V \subseteq T$ *be the set of terms that represent visuals. Let* $V \subseteq T_V$ *be the visual content.*

A mapping is specified from the view content C to the visual content V. This mapping is called a *visualization relation*, and can be regarded as the visual language that defines the protocol for communication.

Definition 5 (Visualization relation). *The visualization relation* $\xrightarrow{V}$ *is a relation between* T_C *and* T_V.

The visualization relation maps members of C to members of V. If $\xrightarrow{V}$ is a bijection then there is an unambiguous one-to-one correspondence between data and its graphical representation. The visualization would then be complete (every datum is mapped to something visible) and unambiguous (no two data are mapped to the same representation). If a user can see all of the visuals V in the image, i.e. they are not too small and indistinguishable, then he/she can invert $\xrightarrow{V}$ to recover its meaning C.

If the user knows the query $\xrightarrow{Q}$ he/she can deduce from his/her knowledge of C which propositions must be true or false. The approach works is because the structure of the image always matches the structure of the view content.

Multiple visualization relations can be provided for the same view. This gives flexibility in changing the graphical representation for a particular view. This would be useful if for example different users had particular preferences for colours or the way things were presented, if different graphical forms better suited a data set, or if different visualization relations emphasized or de-emphasized different parts of the view content. Because different visualization relations can coexist, each has a *visualization context* to identify it.

Definition 6 (Visualization context). *Let $v \in T$ be a visualization context. Let $\xrightarrow{V}_v$ be the visualization relation for visualization context v.*

The visualization context can be changed to select different visualization relations. This relation can be implemented by the Prolog predicate

```
visual_content(ViewContent, VisualizationContext, VisualContent)
```

The first argument specifies the member of the view content. The second argument specifies the visualization context. The third argument specifies the visual content. For a given visualization context, this predicates implements a binary relation between C and V.

The set of available visuals, T_V, is implementation defined.

Example 10. *The visualization relation with visualization context v*

```
visual_content(married(X, Y), v, next_to(X, Y)).
visual_content(mother(X, Y),  v, line(X, Y, green)).
visual_content(father(X, Y),  v, line(X, Y, blue)).
```

represents married(X,Y) by next_to(X,Y), mother(X,Y) by line(X,Y,green) and father(X,Y) by line(X,Y,blue).

Example 11. *The visualization relations v1 and v2 declare two different views of the house wiring.*

```
visual_content(socket(S, L),        v1, socket_drawing(S, L)).
visual_content(wire(A, B, live),    v1, graph_edge(A, B, black)).
visual_content(wire(A, B, neutral), v1, graph_edge(A, B, red)).
visual_content(wire(A, B, earth),   v1, graph_edge(A, B, green)).

visual_content(socket(S, L),        v2, icon(S, L, socket)).
visual_content(wire(A, B, live),    v2, tree_edge(A, B, brown)).
visual_content(wire(A, B, neutral), v2, tree_edge(A, B, blue)).
visual_content(wire(A, B, earth),   v2, tree_edge(A, B, green)).
```

The alternative forms are selected by changing the visualization context.

Example 12. *What is wrong with the following visualization relations?*

```
visual_content(man(X),   v, box(X)).
visual_content(woman(X), v, box(X)).

visual_content(ship(S, Name), w, ship_icon(S)).
```

Visualization relation v is not injective, so two different types of view content can map to the same visual. Both man(X) and woman(X) are represented by the same visual. Thus a user seeing a box(X) would not be able to tell whether it represented a man(X) or a woman(X).

Visualization relation w loses information by another means. It does not convey the name of the ship, Name, to ship_icon/1. A visual type system (described in Section 3.5) can prevent such information loss.

Example 13. *Given*

```
person(A) :- man(A).
person(A) :- woman(A).

view_content(c, person(X)) :- alive(X), person(A).
view_content(c, married(X, Y)) :- married(X, Y).
view_content(c, children(X, Y)) :-
        married(X, Y), child(X, C), child(Y, C).

visual_content(person(X),      v, circle(X, red)).
visual_content(married(X, Y),  v, line(X, Y)).
visual_content(children(X, Y), v, line_colour(X, Y, green)).
```

in view context c and visualization relation v, what can a user deduce from a green line interconnecting two red circles?

From seeing the view it is deduced that the visual content V must be

```
[ circle(A,red), circle(B,red), line(A,B),
  line_colour(A,B,green) ]
```

for some A and B to account for the image on the screen.[2] *Inverting the visualization relation v, the view content must be*

```
[ person(A), person(B), married(A,B), children(A,B) ]
```

From the rules and the view relation it can be deduced that for some A, B and C,

```
alive(A), person(A), (man(A); woman(A)),
alive(B), person(B), (man(B); woman(B)),
married(A, B), child(A, C), child(B, C).
```

3.5 A Visual Type System

Restrictions can be placed on $\xrightarrow{V}$ to ensure that the visualization relation is valid. Nonsensical mappings could be a relationship being mapped to a size attribute, or a string mapped to a colour. The resulting image would be invalid due to these errors, called *visualization errors*.

To help prevent such errors, a type system can ensure that members of the view content are only represented by suitable visuals. The visualization relation should only map content to visuals of the same *type* as the content. The type system is optional, but it has a secondary function of allowing users to modify the legend of a diagram by selecting type-compatible visuals, as described in Section 4.8.2.

By itself the type system cannot guarantee the integrity of the output, because the structure of the data may be unsuitable for the specified visualization method. For example a relationship in the view content may be represented by visual containment, but if the relationships in the view content do not form a tree then a visual object could be contained in two others and an error occurs. Another visualization relation that better suited the data would be required.

Each member in T_C is assigned a type by the type relation $:_C$, and each member in T_V is assigned a type by the type relation $:_V$.

Definition 7 (Content types). *Let T_T be the terms that represent types. The type relation $:_C$ is a relation between T_C and T_T.*

Definition 8 (Visual types). *The type relation $:_V$ is a relation between T_V and T_T.*

View content c may be mapped onto a visual g only if they have the same type. Formally,

[2] *A* and *B* cannot be the identical, otherwise this set would reduce to *[circle(A,red), line(A,A), line_colour(A,A,green)]*, which was not observed.

$$c \xrightarrow{V}_v g \implies \exists t \in T_T.\ c :_C t \wedge g :_V t \tag{3.1}$$

This ensures that information is not lost from the content when it is rendered, and that the visual representation of the content is suitable. The type relations can be implemented in Prolog with the predicates *content_type/2* (for $:_C$) and *visual_type/2* (for $:_V$)

```
content_type(Content, Type)
visual_type(Visual, Type)
```

which indicate the type of the visuals or content. The format of the type term *Type* is completely unrestricted.

Each datum can be characterized by the number of references it makes to other entities. These references (and hence the number of references) are preserved between the view content and the visual content. Data that makes no references to other entities is called an *entity*, data with a single reference is an *attribute*, and data with two or more references is called a *relationship*. The correspondence between content types and visual types is given in Table 3.1.

References	Content type	Visual type
0	entity	visual object
1	attribute	visual attribute
≥ 2	relationship	visual association

Table 3.1. The correspondence between information and its display.

Examples of visual objects include text, shapes, polygons, pictograms and icons. Examples of visual attributes include colours, transparency, font, size, changes in form and thickness. Examples of visual associations include containment, adjacency, relative position, connecting lines and layout. This list is not exhaustive and is implementation defined. These visuals form a *graphical vocabulary* with which the data in the view content is communicated to the user.

Any kind of data can be composed into a network of entities, attributes and relationships. The correspondence between the view content and the visual content is maintained because the type system ensures that entities in the view content must be mapped to visual objects in the visual content, attributes map to visual attributes and relationships map to visual associations. This correspondence is informally observed by Green and Benyon [38] who decompose graphic displays into entities, attributes and relationships between graphical objects. Bertin [9] regards order, form and proportion as fundamental to visualization, which are loosely observed as examples of attributes, entities and associations.

Extra information may be conveyed by a visual. For example a labeled icon could convey a text label, while a height bar could convey numerical data. The type of this data would be conveyed in the type of the visual.

The types assigned to visuals and content, T_T, are implementation defined. The particular type representation used in the following examples, and Vmax, forms a list of properties of the type. An entity in represented as *+Id*, and a reference as *-Id.* Strings have type *str(S)* and numbers have type *num(S)*. Thus any type containing a *+Id* is an object, one *-Id* is an attribute, and two or more *-Id* is an association.

Example 14. *Some examples of content types:*

Content	*Meaning*	*Type*
man(M)	*a man M*	*[+M]*
height(P, H)	*P has height H*	*[-P, num(H)]*
is_tall(P)	*P is tall*	*[-P]*
socket(S, Loc)	*a wall socket*	*[+S, str(Loc)]*
wire(A, B, Type)	*a wire*	*[-A, -B]*

Example 15. *Some examples of visual types:*

Visual	*Description*	*Type*
box(X)	*a box*	*[+X]*
circle(X, Colour)	*a coloured circle*	*[+X]*
labeled_icon(X, D, Type)	*a labeled icon*	*[+X, str(D)]*
line(X, Y, Colour)	*a coloured line*	*[-A, -B]*
highlight(X)	*highlighting*	*[-X]*
object_size(X, Size)	*object's size*	*[-X, num(Size)]*

Example 16. *The types for highlight(X) and is_tall(X) are declared*

```
visual_type(highlight(X), [-X]).
content_type(is_tall(X), [-X]).
```

3.6 Specifying Graphical Constraints

The visual content V is a high level graphical description of the view, that is mapped to a set of low level graphical constraints G that drive a graphical constraint solver. The graphical constraints are shown in Figure 3.1. The set of graphical constraints completely defines the output image.

Definition 9 (Graphical constraints). *Let $T_G \subseteq T$ be the set of terms that represent graphical constraints. Let $G \subseteq T_G$ be the graphical constraints of the view.*

Each visual in V is mapped to a set of graphical constraints that compose the visual.

Definition 10 (Visuals). *Let $\xrightarrow{G}$ be a relation between T_V and T_G.*

$\xrightarrow{G}$ is implemented in Prolog by the predicate *visual_primitive/2.*

```
visual_primitive(Visual, Constraint)
```

implements the relation $\xrightarrow{G}$ and defines the graphical constraints *Constraint* for a visual *Visual.* Clauses can be added to this predicate to define new visuals in the visualization system.

Example 17. *A labeled icon could be declared*

```
visual_primitive(labeled_icon(Id, Text, Icon), Primitive) :-
        Primitive = icon(icon(Id), Icon);
        Primitive = string(text(Id), Text);
        Primitive = v_stack(Id, icon(Id), text(Id)).
```

The object that is defined has an identifier Id, and has an icon of type Icon with identifier icon(Id), and a string of Text with identifier text(Id). v_stack(Id, icon(Id), text(Id)) specifies that the icon should be placed above the text.

Each graphical constraint has identifiers that reference other constraints for structuring the image.

Example 18. *A coloured line visual could be declared*

```
visual_primitive(line(From, To, Colour), Primitive) :-
        Primitive = edge(edge(From, To), From, To);
        Primitive = colour(edge(From, To), Colour).
```

The line between two objects with identifiers From and To is given the identifier edge(From, To).

Section 4.6 describes even more succinct specifications for the visuals in Examples 17 and 18. Section 4.6.1 describes how more complex visual objects may be specified using a set of geometric constraints. The set of graphical constraints G is next solved out and rendered as an image I.

Definition 11 (Image). *Let I be the output image. I is a function of G, $I(G)$.*

I could be regarded as a set of coloured pixels, a colour function over $\mathbf{R}^2$, or a subset of $\mathbf{R}^2$ or $\mathbf{R}^3$, where $\mathbf{R}$ denotes the set of real numbers.

$I(G)$ is implemented by a constraint solver and renderer that assembles the graphical constraints into an image. The implementation could use any layout or rendering algorithms, which will not be the subject of formal analysis.

The set T_G of graphical constraints is implementation defined. The graphical constraints provided by SVT are given in Section B.6.

3.7 Generating Views

The whole visualization process is the combined relation $\xrightarrow{Q}\xrightarrow{V}_v\xrightarrow{G}$, which is a relation between the view context x and the set of graphical constraints G that represent the image. $\xrightarrow{Q}\xrightarrow{V}_v$ is the relation between the view context x and the set of visuals V that describes the image. $\xrightarrow{V}_v\xrightarrow{G}$ is the relation between the view content C and the graphical constraints G.

Figure 3.2 illustrates how the relation $\xrightarrow{Q}\xrightarrow{V}_v\xrightarrow{G}$ derives the graphical constraints for the view context *family_tree*. The resulting relation is shown in Figure 3.3.

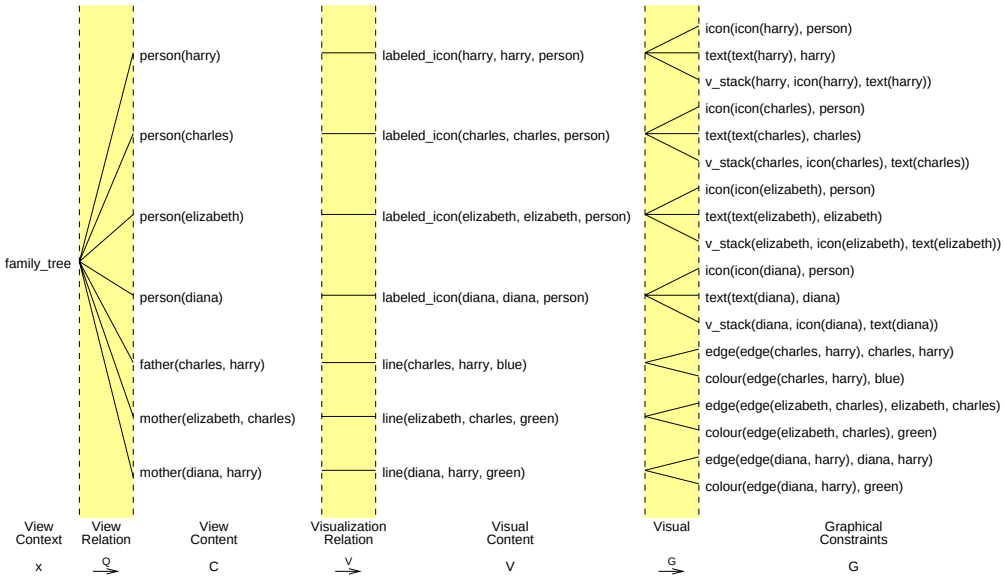


Figure 3.2. A graphical representation of the relations (shaded) showing how graphical constraints are derived from the view context.

The graphical constraints *Constraint* for a view context *ViewContext* and visualization context *VisContext* can be acquired by issuing the query

```
?- view_content(ViewContext, Content),
   visual_content(Content, VisContext, Visual),
   visual_primitive(Visual, Constraint).
```

The graphical constraints on the right hand side of Figure 3.2 or 3.3 are passed to a graphical constraint solver as described in Section 4.5. Figure 3.4 shows the final output.

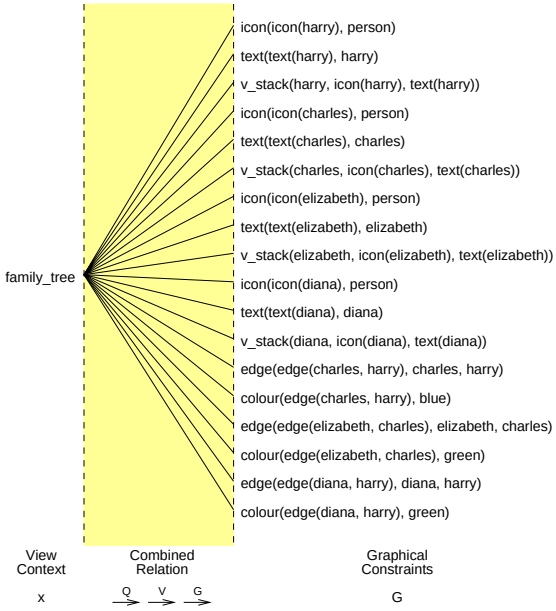


Figure 3.3. The combined relation $\xrightarrow{Q} \xrightarrow{V}_v \xrightarrow{G}$

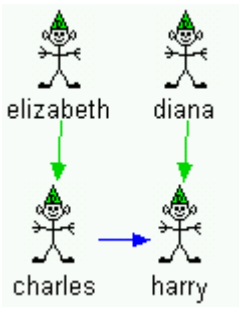


Figure 3.4. The family tree output by SVT.

3.8 Specifying Interaction

When the image has been generated the user can interact directly with the objects in the image, for example with a mouse. The user input is an *action*. The system's response is the *reaction*. An action followed by a reaction is called an *interaction*. This simple model can be used as a basis for specification.

3.8.1 Actions

Interaction is modeled as a relation between actions and reactions, called an *action relation*. Each action and each reaction is represented by a single term.

Definition 12 (Action relation). *Let $T_A \subseteq T$ be the set of terms that denote actions. Let $T_R \subseteq T$ be the set of terms that denote reactions. A relation $\xrightarrow{A}$ between T_A and T_R is called an action relation.*

It may be necessary to have more than one action relation. For example different types of view may have different interactive behaviour, or different users may have different preferences for interaction. Therefore each action relation has a term called an *action context* to identify it.

Definition 13 (Action context). *Let $a \in T$ be an action context. Then $\xrightarrow{A}_a$ is the action relation with action context a.*

The predicate *action/3*,

```
action(Action, ActionContext, Reaction)
```

implements the binary relation $\xrightarrow{A}_a$ between *Action* and *Reaction*, for a given action context *ActionContext*. Interactive behaviour is implemented by adding clauses to the predicate *action/3*.

Every time a user input occurs (such as a mouse move), the predicate *action/3* is called to determine the reaction. The graphical objects in the view contain identifiers (specified in the graphical constraints) that are used to identify objects beneath the mouse cursor.

Example 19. *The following actions are used in SVT:*

Action	*Description*
click(Object, Buttons, Times)	*The mouse has been clicked Times times over object Object, with the mouse buttons Buttons.*
drag(From, To, Buttons)	*A mouse drag from object From to an object To, with mouse buttons Buttons.*
key(Object, Key)	*A key Key has been pressed over object Object.*
linger(Object)	*The mouse has stopped over object Object.*
menu(Menu, Text)	*The menu Menu has item Text selected.*
move(Object, Buttons)	*The mouse has been moved over object Object, with mouse buttons Buttons.*

Example 20. *The action relation*

```
action(click(Person, [on, _, _, _], _), a,
        navigate_to(personal_details(Person))) :-
        person(Person).
```

declares that the reaction to a mouse press with the left mouse button over a person Person in action context a is navigate_to(personal_details(Person)). The underscores are wild-cards, or unnamed variables.

Example 21. *The action relation*

```
action(menu(actions(File), 'Delete file'), a,
        delete_file(File)) :-
        file(File).
```

declares that the reaction to the menu selection in action context a is delete_file(File), if File is a file.

3.8.2 Reactions

Reactions execute the system's response, in Prolog. To allow different implementations of reactions, each implementation is given a *reaction context* to identify it.

Definition 14 (Reaction context). *Let $T_{RC} \subseteq T$ be the set of reaction contexts. Let $r \in T_{RC}$ be the reaction context.*

Definition 15 (Reaction relation). *Let $\xrightarrow{R}$ be a relation between T_R and T_{RC}.*

The reaction relation implements the response in Prolog. The predicate *reaction/2*

```
reaction(Reaction, ReactionContext)
```

is used, where *Reaction* is the term denoting the reaction, and *ReactionContext* is the reaction context. Reactions are implemented by adding rules to the *reaction/2* predicate that have side-effects to perform the required task. The reaction term from *action/3* is passed immediately to *reaction/2* for execution. Interaction is the combined relation $\xrightarrow{A}_a \xrightarrow{R}$.

The action and reaction contexts, and terms denoting actions and reactions, T_A and T_R, are implementation defined. The action terms used by SVT are given in Section B.7.

Example 22. *The reaction relation*

```
reaction(navigate_to(ViewContext), r) :-
        new_view_context(ViewContext).
```

implements a reaction to navigate_to(ViewContext) in reaction context r, that changes the view context and redraws the view.

Example 23. *The reaction relation*

```
reaction(delete_file(File), r) :-
        filename(File, Filename),
        system_call(['rm ', Filename]).
```

implements a reaction to delete_file(File) in reaction context r.

Example 24. *The reaction relation*

```
reaction(Reaction, call) :- call(Reaction).
```

executes the reaction term as a predicate.

3.9 Chapter Summary

Visualization can be thought of as a mapping from the object to be visualized (the view context) to the image on the screen. From a generic model of visualization, this mapping can be decomposed into a series of relations, $\xrightarrow{Q}$, $\xrightarrow{V}_v$ and $\xrightarrow{G}$ that model different stages in the visualization process. These are formal mappings in first order logic.

The advantages of this are twofold. Firstly a theoretical foundation has been laid that reveals certain properties of visualization, such as the stages of visualization and the decomposition of graphical communication in terms of objects, attributes and relationships, and their correspondence to a semantic network. It is possible to prove what a user can and cannot deduce from a view, and theoretical work on the types of visual entities also follows from this work.

Most importantly however are the practical implications. It shows how knowledge-based systems implemented in Prolog can be interfaced to a visualization system, and suggests that Prolog's strengths in knowledge engineering make it a suitable front end for information visualization. Knowledge-based queries can be formulated directly in Prolog, to filter away unwanted data depending on the context or interests of the user. Prolog provides a very concise specification language for all stages of visualization. All specifications are directly executable in Prolog. As well as being completely generic, this method is very flexible. Any part of the visualization process can be modified by changing either the view or the visualization relation. Navigation is achieved by changing the view context, and there is no limit to the number of views that can be defined. The graphical representation of data can be changed simply by changing visualization context.

Interaction is modeled as a relation $\xrightarrow{A}$ between user actions and system reactions. The interactive behaviour is specified directly in Prolog.

The next chapter describes an implementation of this formal model in a visualization system.

Chapter 4

Semantic Visualization Tool

Semantic Visualization Tool (SVT) is a visualization tool that implements the semantic model of visualization described in Chapter 3. It is intended to be general purpose, allowing any kind of data to be presented in any format, although its strengths lie in presenting semantic networks. The most unusual aspect of this tool is the Prolog engine used for querying the scene data.

SVT is in essence a graphical constraint solver sitting on top of Prolog. Queries issued to Prolog return a large set of graphical constraints that are constructed into a scene graph and rendered. SVT provides a graphical user interface, a 3-D model viewer and an integrated text editor. Its architecture allows its presentation capabilities to be extended through extensive C++ and Prolog application programmer interfaces. The entire system is specified using Prolog, and pre-compiled Prolog files are dynamically loaded into the system to provide visualizations for the user.

Although SVT is completely generic, its primary aim is to visualize the kind of data present in program databases and program run-time information. Because this data and its presentation is so varied, a tool with maximum flexibility has been implemented. Vmax is a visualizing text editor built on top of SVT which provides graphical views of the program database and run-time information, and is described fully in Chapter 5.

4.1 Introduction

The theoretical model presented in Chapter 3 leaves much scope in its implementation. This chapter presents one possible implementation, to demonstrate the validity of the model and to provide a platform for software visualization which is the aim of this dissertation.

SVT provides the capability to script visualization in Prolog. The actual visualization application is written in Prolog and optionally also in C++. The architecture allows C code to be called from Prolog. At start-up, SVT loads the Prolog files that contain the specifications for view relations, visualization relations, interactive behaviour, and rules for querying and processing the input data.

This chapter deals with the final stages in the visualization process given in Figure 3.1. It is assumed that the data gathering and the view and visualization relations have been specified, so that SVT can simply issue a query to Prolog to return the graphical constraints that compose a scene.

The graphical constraints returned from the query form the nodes of a scene graph. A scene graph is a data structure of nodes and links that stores the graphical structure of the scene [106].

Much of SVT is supporting architecture that provides a graphical user interface between the user and the visualization. In addition SVT provides a number of algorithms for graphical layout that assign 3-D coordinates to the objects in the scene graph. When the graphical components have been assigned coordinates, the scene graph is rendered.

4.2 Architecture

SVT is implemented in C++ and integrates OpenGL [50] to provide 3-D graphical output, SICStus Prolog 3.7 [59], and Motif 1.2 [41] for the graphical user interface. Each of these components provide C interfaces for compilation into a single executable file. The architecture of SVT is shown in Figure 4.1.

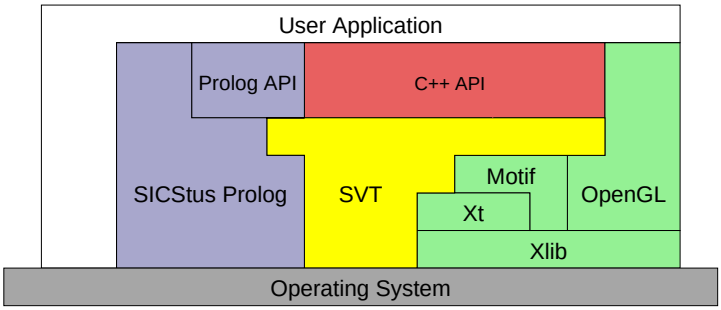


Figure 4.1. The architecture of SVT.

The structure of SVT in Figure 4.2 implements the semantic model shown in Figure 3.1. The colours match Figure 4.1.

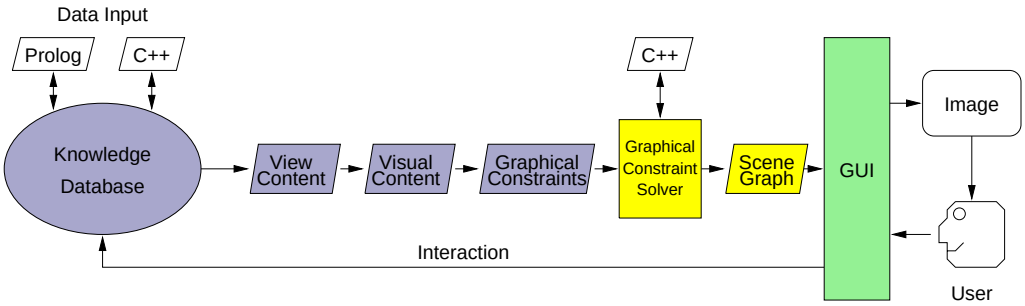


Figure 4.2. The structure of SVT.

4.3 Running SVT

SVT is an executable file *svt*, that runs the Prolog file specified on its command line. Additional command-line arguments are passed to the Prolog program. For example running

```
svt myvis arg1 arg2
```

from a UNIX shell would run the pre-compiled Prolog bytecode *myvis.ql* in SVT. The arguments *arg1* and *arg2* are passed as input to *myvis.*

The loaded Prolog files contain data interfaces, rules for reasoning about the data, and define the view, visualization, action and reaction relations, to completely define the behaviour of SVT.

A main viewing window is created by calling

```
create_viewer(ViewContext, VisualContext,
              ActionContext, ReactionContext)
```

with view context *ViewContext,* visualization context *VisualContext,* action context *ActionContext* and reaction context *ReactionContext.* This window consists of a main view area, a text area, pull-down menus and a status bar, shown in Figure 4.3.

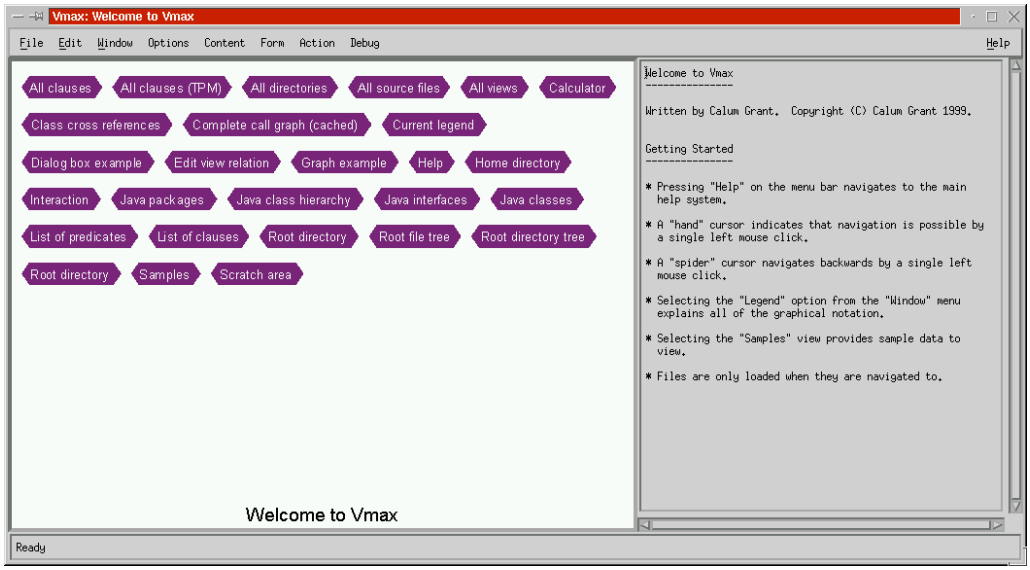


Figure 4.3. The main viewing window.

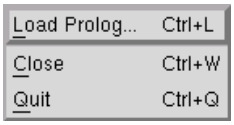


Figure 4.4. The *File* pulldown menu.

Additional Prolog files can be loaded by the *Load Prolog* option on the *File* pulldown menu, shown in Figure 4.4. The *Close* option closes the current window, and the *Quit* option exits the program.

4.4 View Manipulation

One of the main issues in visualization is to present exactly what the user wants, but it is often the case that too much information is presented to the user, called *information overload* [7]. *Information filtering* is necessary to remove the unwanted information while leaving the required information. While the view relations filter data semantically, viewpoint control can filter data spatially, and such spatial filtering has common applications in information murals [49], lensing techniques [87] and rubber sheets [88].

The screen has a finite size and hence has a theoretical upper limit on the amount of information it can convey.[1] In the cases where the data is simply too large to be fitted in a window, the feature size of the output is automatically reduced such that the whole view still fits in the window. An example is shown in Figure 4.5. This approach provides an initial overview of the whole data, even though detailed information may be lost, and this approach follows Shneiderman's "visual information seeking mantra: overview first, zoom and filter, then details on demand." [91]

A user may have an area of interest, or in the 3-D case, a volume of interest. There are many different techniques for scrolling and zooming to select such an area of interest [40], but the method used here is the one used Open Inventor [106]. The controls are given in Table 4.1.

Such controls are a standard method for manipulating 3-D models. This method also works for 2-D models, which provides single mouse movements for continuous movement of the image to any magnification and position over the scene. While rotation is necessary for viewing 3-

[1] A loose upper bound is the amount of video RAM.

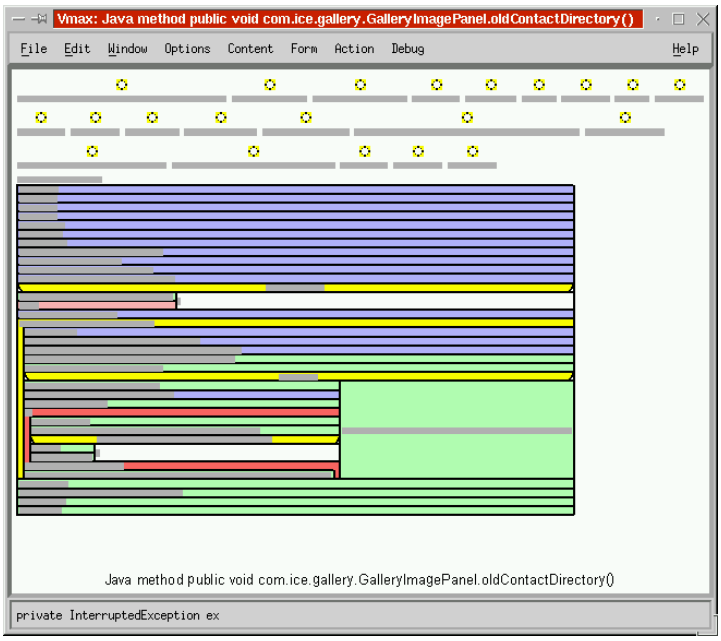


Figure 4.5. A complex view is shrunk to fit in the viewing area.

User input	Viewpoint movement
<ctrl> + mouse button 1	pan in direction of mouse move
<ctrl> + mouse button 2	rotate the view with the mouse movement, a fast movement spins it
<ctrl> + mouse button 3	zoom in or out with vertical mouse movement

Table 4.1. The controls for viewpoint manipulation.

D models, this feature is less useful for 2-D, and can be ignored by the user to maintain an orthogonal viewing direction to the scene. Examples of viewpoint manipulation are shown in Figure 4.6.

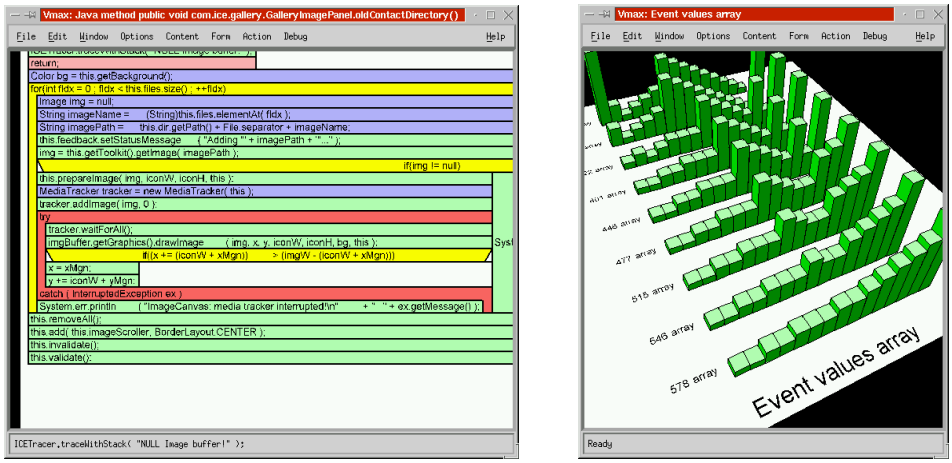
The *Window* menu is shown in Figure 4.7. The option *Reset viewpoint* moves the viewpoint back to the overview of the scene. If the content of the view has changed and the view needs to be refreshed, the option *Refresh view* will update the view. The drawing speed options affect the quality of the rendering, because it may be necessary to decrease the rendering quality to increase the rendering speed for smooth viewpoint control on slow hardware.

The *Legend* option creates a window to show the legend explaining the symbols present in the current visualization, and is described fully in Section 4.8. The *Zoom* option creates a window that shows a graphical view of the object beneath the mouse cursor, as described in Section 4.10.

The *Create new viewer* option creates a new viewing window containing the initial view, while *Duplicate* creates a new viewing window with the same content as the existing one. SVT manages multiple viewing windows. Toggling the *View window* option hides or reveals the graphical view, while toggling the *Text window* option hides or reveals the text window.

4.5 Generating Visualizations

Each view is generated by issuing a query to Prolog that returns the graphical constraints for a particular view context and visualization context. These constraints are structured into a scene graph, laid out and rendered.



(a) Pan and zoom of Figure 4.5.

(b) Rotation.

Figure 4.6. Examples of viewpoint manipulation.

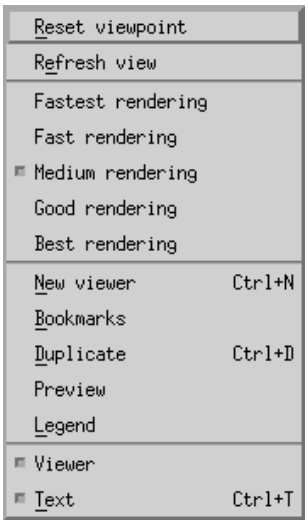


Figure 4.7. The *Window* menu.

4.5.1 Acquiring the Visual Primitives

Each view stores a record of its current view context, visualization context, action context and reaction context. To generate a view, the Prolog query

```
?- get_constraint(ViewContext,
                  VisualizationContext,
                  Constraint).
```

is issued to return the graphical constraints *Constraint* for its current view content *ViewContext* and visualization context *VisualizationContext.* All queries are issued through the C interface, and the textual representation is shown only for illustration.

The *get_constraint/3* predicate is implemented as

```
get_constraint(ViewContext, VisContext, Constraint) :-
        view_content(ViewContext, Content),
        visual_content(Content, VisContext, Visual),
        visual_primitive(Visual, Constraint).
```

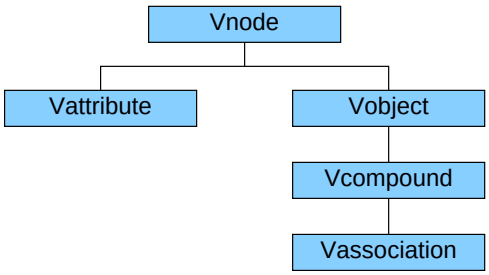


Figure 4.8. The base classes of graphical constraints.

and implements the relation $\xrightarrow{Q}\xrightarrow{V}_{v}\xrightarrow{G}$ described in Section 3.7.

4.5.2 Generating the Scene Graph

Each graphical constraint *Constraint* is a term that represents one node of a scene graph. The nodes in the scene graph are instances of the base classes shown in Figure 4.8. Thus each type of node is either a visual object or an attribute, and visual objects may be composite or binary associations. This base class hierarchy implements the basic graphical types in Section 3.5, which are objects, attributes and associations.

Vobject refers to all constraints that can be rendered on the screen, *Vcompound* refers to all constraints that compose sub-objects, *Vassociation* is an association between two visual objects, and *Vattribute* is an attribute applied to visual objects. This base class hierarchy covers all graphical entities, attributes and associations that can make up an image. The C++ header file *svtvisual.h* implementing this class hierarchy is included in Section B.9.1. The complete class hierarchy of visuals provided by SVT is shown in Figure 4.9.

As a naming convention, the graphical constraint's functor has the same name as the class of the object with a prepended 'V'. Thus the constraint *string(1234, 'Peter')* instantiates a class *Vstring* with identifier *1234* and string *'Peter'*. The functor's arguments are passed directly to the object's constructor for initialization. The complete list of graphical constraints provided by SVT is given in Section B.6.

This class hierarchy is designed to be completely extensible to incorporate any method of graphical output. A C++ file can extend one of the classes of Figure 4.9, and declare a handler to instantiate the new graphical constraint for inclusion in the scene graph.

Once the graphical constraints have been instantiated, they are structured into a graph. The objects must be *cross-referenced*, which means creating C++ pointers between the nodes in the scene graph. Each *Vobject* contains a term called its *identifier*, each *Vattribute* contains a term identifying the object to which it applies, and each *Vassociation* contains two terms identifying the objects that it associates.

Cross-referencing is implemented using a hash table. Each *Vobject* inserts its identifier and address into the hash table. Each *Vattribute* looks up the address of its object from the hash table. Each *Vassociation* looks up the addresses of the objects it associates from the hash table. It follows that the cost of cross-referencing is linear with the number of graphical constraints in the scene.

4.5.3 Structuring The Scene Graph

The cross-referenced nodes form a scene graph. A *Vwindow* object is created at the root node of the scene graph, and every object in this graph except the root node will have pointer to its parent. Any objects that do not have parents are automatically added to the *Vwindow* to ensure that the scene graph is connected.

Before each node is cross referenced, the node is initialized by calling its *On_initialize()* method. After each node has been cross referenced further initialization is done by calling the

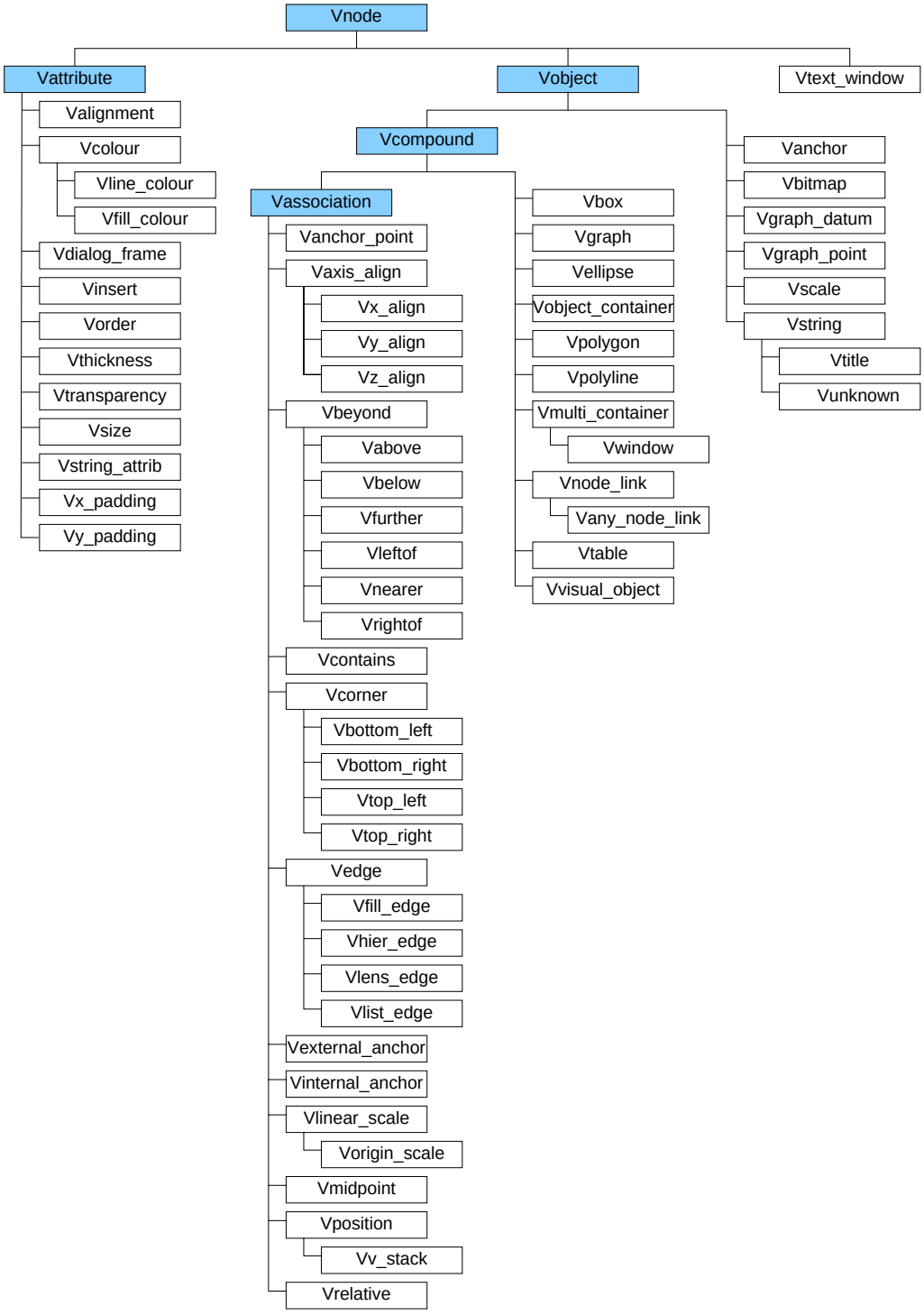


Figure 4.9. SVT's complete class hierarchy of graphical constraints.

node's *On_structure()* method. These functions are declared

```
virtual void On_initialize();
virtual void On_structure();
```

Additional structuring finds subgraphs connected by the *Vedge* association.

4.5.4 Graphical Layout

Each *Vobject* has the following virtual methods for graphical layout

```
virtual void On_reset_size();
virtual void On_set_size(double *new_size);
virtual void On_set_position(double *new_position);
virtual void On_draw();
```

that are called in that order. Each object determines its *natural size* expressed in pixel units as a 3-D bounding box. *On_reset_size()* sets the size of the visual object to its natural size, and if it is a composite object, it will first call *On_reset_size()* of its child members. The *Vobject* has pointers to all of its attributes and associations so that it can determine how it should be laid out. The *On_reset_size()* method of the *Vwindow* object is called to initialize the entire scene.

On_set_size() is called for each object to change its size, particularly to shrink it to fit the view in the viewing window. The *On_set_size()* method of the *Vwindow* object is called to ensure that the whole view fits in the viewing window, and composite objects call *On_set_size()* for each of their child objects.

On_set_position() is called for each object to position it correctly within the view. Composite objects set the position of their children. Finally *On_draw()* renders the object on the screen using OpenGL. Each object stores its own coordinates.

4.5.5 Graphical Layout Algorithms

The architecture allows any kind of layout algorithm to be applied to the scene graph. Some of the layout algorithms used in SVT are described here. None of these algorithms are particularly sophisticated, but they show how different algorithms can be applied to the scene graph.

Graph Layout

There are many types of graph layout algorithm [6], and the one chosen here is based upon the shortest path from a root vertex, as first described by Sugiyama *et al.* [98], mainly because of its speed and simplicity. A root vertex is selected, and preference is given to the vertex with the least number of edges leading towards it. Then the undirected unweighted distance to each other vertex in the graph is computed using a breadth-first search. Each vertex is assigned to a layer equal to its distance from the root vertex, so that the root vertex is on layer zero. This ensures that adjacent vertices appear on adjacent layers, or on the same layer. Finally an ordering of vertices on each layer minimizes the number of edge crossings. This algorithm works reasonably for sparse graphs and is shown in Figure 4.10.

Multi-container Layout

A multi-container is a composite visual object that lays out its children in rows as shown in Figure 4.11.

This algorithm resets the sizes of its children, and finds the optimum width of the container such that the aspect ratio is close to an ideal value. This width is found by interval bisection. The ordering of the children is not changed because their order may convey information.

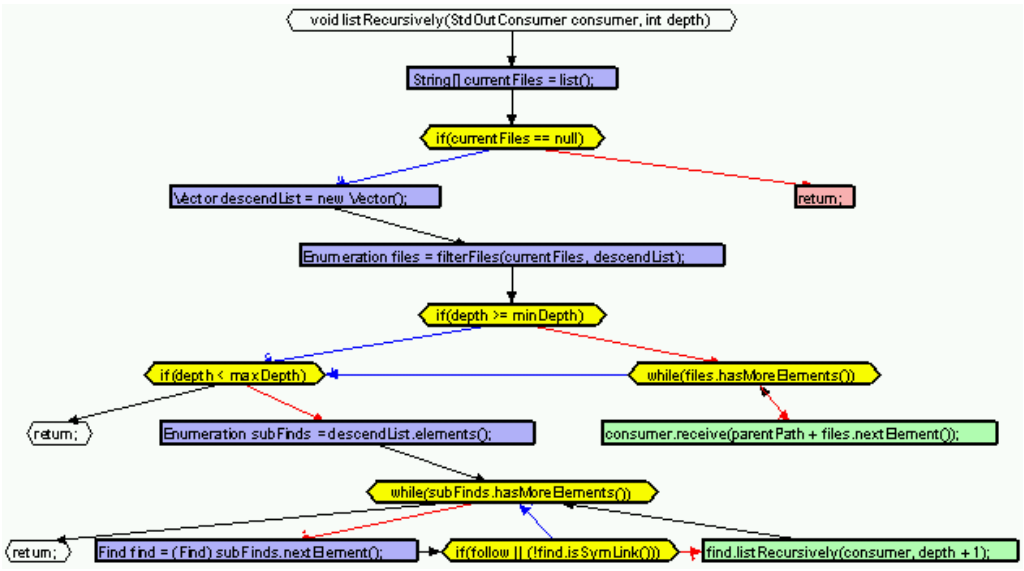


Figure 4.10. Graph layout.

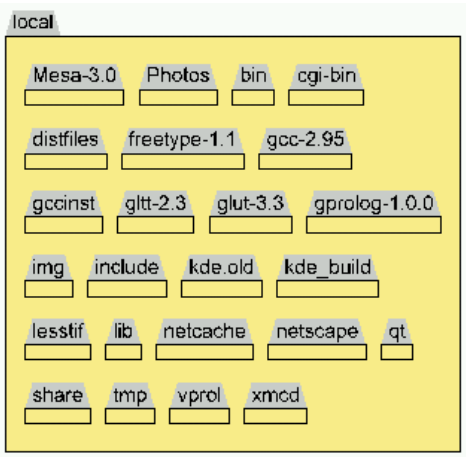


Figure 4.11. A multi-container.

Fish-eye Lens

A *fish-eye* lens "is a very wide angle lens that shows places nearby in detail while also showing remote regions in successively less detail." [87] A simple fish-eye lens has been implemented that shows a tree with the base of the tree with the highest detail. The root vertex is placed in the centre of the graph, and children are placed in concentric rings around the centre. The sizes of the children are reduced exponentially with distance from the root so that they fit into the graph without overlapping. A fish-eye lens is shown in Figure 4.12.

The algorithm works by assigning each vertex a sector of the circle and a depth d from the root vertex. Each vertex divides its sector equally between its children. The magnification of each vertex is given by

$$\alpha^{d-1} \tag{4.1}$$

and its distance from the centre by

$$R.(1-\beta^{d}) \tag{4.2}$$

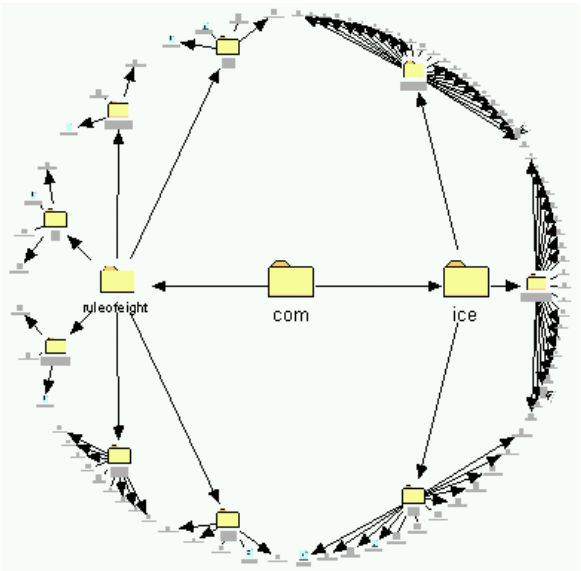


Figure 4.12. A fish-eye lens.

where d is the distance from the root node, R is the radius of the fish-eye lens, α is the decay constant for the size, and β is the radius ratio. In this implementation, α was chosen to be 0.5 and β was 0.4. In the case where the size of the vertices exceed their sector size, their radii are reduced to prevent overlap.

Hierarchical List Layout

A *hierarchical list* is a hybrid of a hierarchy shown in Figure 4.13(a) and a nested list shown in Figure 4.13(b), and is shown in Figure 4.13(c). It aims to achieve a better aspect ratio (ratio width to height) than either the hierarchy or list alone. Perhaps a better aspect ratio can make better use of the screen real-estate and fit more data onto the screen, as both the hierarchy and the list can make poor use of space.

The algorithm works from the leaf vertices up by summing the widths and the heights of a vertex's subtrees. If the total width exceeds the total height, then the list layout is used, otherwise the hierarchy layout is used. More sophisticated versions of this algorithm could do an even better job of packing trees into a small space.

4.6 Expanding the Graphical Vocabulary

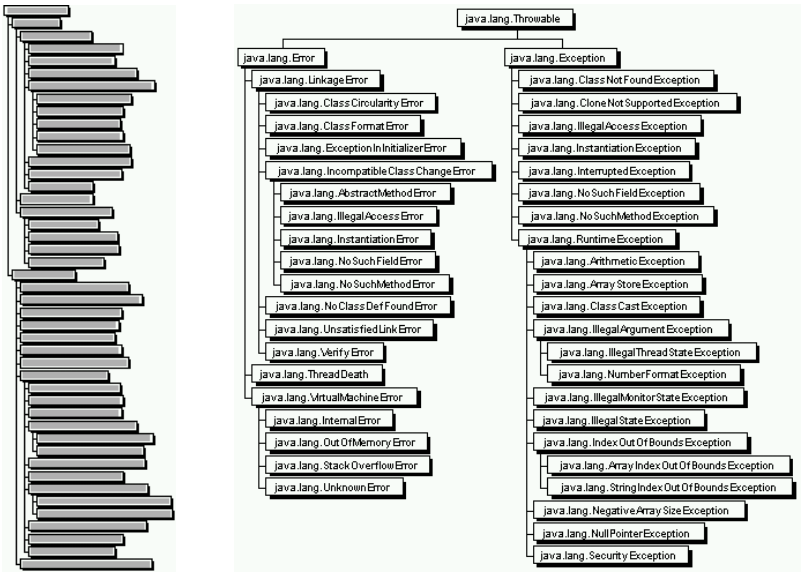
The set of visuals T_V forms a graphical vocabulary with which to communicate information. A large graphical vocabulary means a more varied graphical output (which is visually more interesting) and can be used to mimic other notations. This can be implemented in several ways in SVT. The first is through the C++ interface which can define new graphical constraints by using OpenGL directly to output graphics. The second is to add clauses to the *visual_primitive/2* predicate that composes graphical constraints into visuals, thereby augmenting T_V. This is still a low level approach but is much more convenient than programming in C++.

A more high level approach is to specify the composition of visuals directly by

```
visual_component(Visual, Component)
```

where *Visual* is the new visual being declared, and *Component* is a visual that is already declared. Visuals can be defined in terms of other visuals, and it is straightforward to augment and combine existing visuals. *visual_component/2* is called from *visual_primitive/2* by

(a) A hierarchy.



(b) A nested list. (c) A hierarchical list.

Figure 4.13. Tree layout.

```
visual_primitive(Visual, Primitive) :-
     visual_component(Visual, Component),
     visual_primitive(Component, Primitive).
```

and in particular lists of visual components can be declared by

```
visual_component([H|T], H).
visual_component([H|T], T).
```

This means that the specifications for a labeled icon

```
visual_primitive(labeled_icon(Id, Label, Type), Primitive) :-
        Primitive = icon(icon(Id), Type);
        Primitive = text(text(Id), Label);
        Primitive = v_stack(Id, icon(Id), text(Id)).

visual_primitive(labeled_icon(Id,Label,Type), Primitive) :-
        visual_primitive(icon(icon(Id), Type), Primitive);
        visual_primitive(text(text(Id),Label), Primitive);
        visual_primitive(v_stack(Id, icon(Id), text(Id)),
                         Primitive).

visual_component(labeled_icon(Id, Label, Type), Component) :-
        Component = icon(icon(Id), Type);
        Component = text(text(Id), Label);
        Component = v_stack(Id, icon(Id), text(Id)).

visual_component(labeled_icon(Id, Label, Type),
        [
```

```
        icon(icon(Id), Type),
        text(text(Id), Label),
        v_stack(Id, icon(Id), text(Id))
        ]).
```

are all equivalent. The latter offers the most succinct method of specification, and therefore all the visuals provided by SVT have been defined using only *visual_component/2* and *object_component/3* (described in Section 4.6.1). In this example

```
visual_component(coloured_line(A, B, Colour),
        [
        line(A, B),
        line_colour(A, B, Colour)
        ]).

visual_component(red_line(A,B), coloured_line(A,B,red)).
```

the visual *red_line/2* is defined in terms the visual *coloured_line/3* which is itself composite. No additional Prolog is required to use the visuals *labeled_icon/3*, *coloured_line/3* and *red_line/2*.

4.6.1 Specifying Visual Objects

Visual objects are graphical entities on the screen. They are effectively pictograms that communicate entities and data in the view content. Visual objects can also communicate textual and numerical information, and combine other visual objects. It is the way visual objects combine that is particularly difficult [36], as illustrated in Figure 4.14, but this complex behaviour is necessary to implement visual languages.

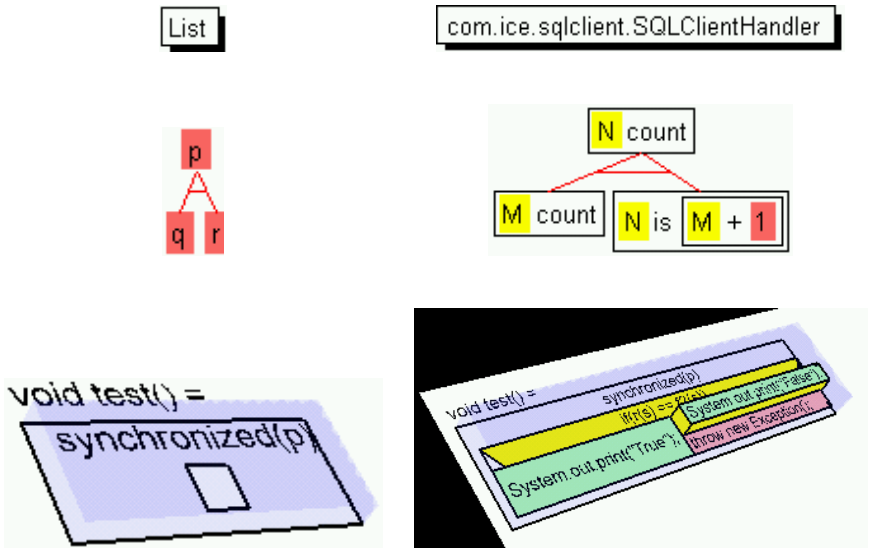


Figure 4.14. Visual objects adapt their layout in response to other visual objects.

Such behaviour could of course be programmed directly through the C++ interface, but SVT provides a means of specifying this expansion behaviour in Prolog. Each visual object consists of a set of *anchors* that are points in space[2], and graphical components (such as lines and polygons) attached to these anchors. These object components are specified with the *object_component/3* predicate, which specifies the components *Component* of an object with visual *Visual* and identifier *Identifier*.

[2]Anchors could be points in space-time, for animation, but this possibility has not been explored.

```
object_component(Visual, Identifier, Component)
```

Figure 4.15 shows the anchors and graphical components of a box with a shadow.

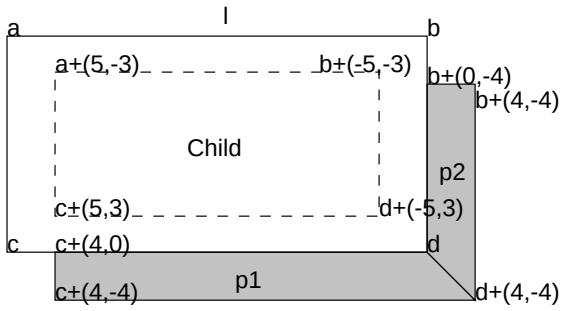


Figure 4.15. The anchors and graphical components of a box with a shadow.

The complete specification for this visual object is

```
object_component(shadow_box(Box, Child), Box,
        [
        contain(Child, a+(5,-3), b+(-5,-3), c+(5,3), d+(-5,3)),
        l=line([a,b,d,c,a]),
        p1=polygon([c+(4,0), d, d+(4,-4), c+(4,-4)]),
        p2=polygon([b+(0,-4), b+(4,-4), d+(4,-4), d])
        ]).
```

The name of the visual is *shadow_box(Box, Child)*, where *Box* is the identifier of the visual object, and *Child* is the identifier of the object that is inserted into it. The second argument to *object_component/3* specifies the identifier of the visual object, in this case *Box*. The third argument specifies the components of the object.

Object components (such as *l=line([a,b,d,c,a])*) are translated into graphical constraints by the *component_primitive/3* predicate that defines how object components map to graphical constraints. *component_primitive/3* is called from

```
visual_primitive(Visual, Primitive) :-
        object_component(Visual, Id, Component),
        component_primitive(Component, Id, Primitive).
```

The complete list of object components provided by SVT is given in Section B.5. The visual *shadow_box/2* can be used like any other visual. For example

```
visual_component(text_shadow(Id, Text),
        [
        text(text(Id), Text),
        shadow_box(Id, text(Id))
        ]).
```

creates a visual *text_shadow/2* which displays text within a shadowed box. A coloured background can be added to *shadow_box/2* by

```
object_component(shadow_box_colour(Box, Colour), Box,
        [
        p=polygon([a,b,d,c]),
        p=colour(Colour)
        ]).

visual_component(shadow_box_colour(Box, Child, Colour),
        [
```

```
        shadow_box(Box, Child),
        shadow_box_colour(Box, Colour)
        ]).

visual_component(blue_text_box(Box, Text),
        [
        text_box(Box, Text),
        shadow_box_colour(Box, paleblue)
        ]).
```

to define the new visuals *shadow_box_colour/2*, *shadow_box_colour/3* and *blue_text_box/2*.

In the *shadow_box/2* example, the identifiers for the object components are *p1* and *p2* for the polygons, and *a*, *b*, *c* and *d* for the anchors. The predicate *component_primitive/3* combines these names with the identifier of the object, so the polygons have identifiers *vc(Box, p1)* and *vc(Box, p2)* and the anchors have identifiers *anchor(Box, a)*, *anchor(Box, b)*, *anchor(Box, c)* and *anchor(Box, d)*.

This subtlety is necessary to allow the cross referencing described in Section 4.5.2 to work correctly. Otherwise the name *a* would be a global identifier in the scene and two different *shadow_box*es would share the same anchor and the output would be incorrect. Name mangling puts anchors and object components in different name spaces, and component identifiers only have scope within the visual object. Note that in the definition of *shadow_box_colour/2*, the anchors *a*, *b*, *c* and *d* are in the same name space as *shadow_box/2* because they refer to the same object. Figure 4.16 shows the name expansion for two different instances of a *shadow_box/2* with identifiers *123* and *312*.

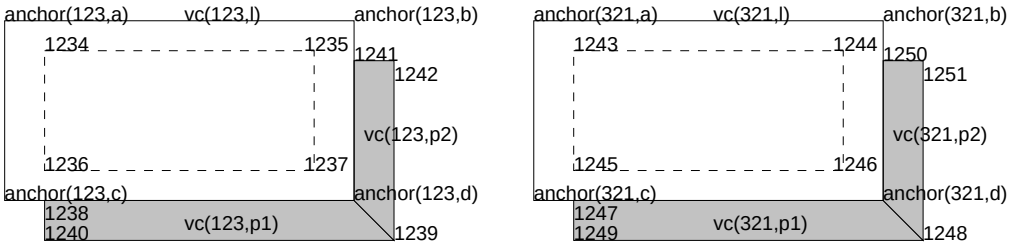


Figure 4.16. Object component name expansion to prevent name clashes.

Anchor Expressions

The appearance of a visual object is governed by the way its anchors are positioned. Anchor coordinates cannot be absolute because they must move to accommodate child objects, such as in the *shadow_box/2* example, and must move with the position of the visual object.

SVT implements a very general approach to positioning anchors, by declaring anchors and imposing arbitrary constraints on them. Such geometric constraints can be very difficult to solve, and is a separate topic [58]. Completely arbitrary constraints are in general insoluble.

These constraints are specified in *anchor expressions* in the object components. *contain(Child, a+(5,-3), b+(-5,-3), c+(5,3), d+(-5,3))* contains the anchor expressions *a+(5,-3)*, *b+(-5,-3)*, *c+(5,3)* and *d+(-5,3)*. These anchor expressions specify the four corners of the container (top-left, top-right, bottom-left and bottom-right respectively) and also give some positional constraints.

An anchor expression is a term that specifies an anchor, and also constraints on that anchor. It is a notation that is intended to give a direct and concise method of specifying the position of graphical components in a visual object. Anchor expressions are converted into graphical constraints in the same way as other object components. An anchor expression may be of the form

- *Anchor*
  The identifier of an anchor. This expression creates the graphical constraint *anchor(anchor-(Object, Anchor))*.

- *Anchor + Offset*
  An offset from a named anchor. This expression creates the graphical constraints *anchor(NewAnchor), offset(NewAnchor, Anchor, Offset). Offset* is a 2-D or 3-D vector of numbers.

- *Anchor2 = Anchor1 + Offset*
  An offset between two named anchors, creating the graphical constraints *offset(anchor(Object, Anchor2), anchor(Object, Anchor1)).*

- *midpoint(Anchor1, Anchor2)*
  A midpoint between two named anchors, creating the graphical constraints *anchor(NewAnchor), midpoint(NewAnchor, anchor(Object, Anchor1)), midpoint(NewAnchor, anchor(Object, Anchor2)).*

- *Anchor3 = midpoint(Anchor1, Anchor2)*
  A named midpoint between two named anchors, creating the graphical constraints *midpoint(anchor(Object, Anchor3), anchor(Object, Anchor1)), midpoint(anchor(Object, Anchor3), anchor(Object, Anchor2)).*

Additional constraints may be imposed on anchors depending on the context in which anchor expressions are used. For example if an anchor is specified as the corner of a container, then it is aligned with the other corners of the container. Anchor expressions appear within specifications for polygons, text and containers, but can also appear as object components. Some constraints can only be specified as object components, such as

- *xalign(Anchor1, Anchor2), yalign(Anchor1, Anchor2), zalign(Anchor1, Anchor2)*
  Constrains the given axis to be aligned in both anchors. Generates the graphical constraint *axis_align(anchor(Object,Anchor1), anchor(Object, Anchor2), N)* where *N* is 0, 1 or 2.

Laying out Visual Objects

The constraints on the anchors must be solved to give screen coordinates for the anchors and hence for the graphical primitives. When a visual object receives an *On_reset_size()* call it must assign relative coordinates to all of its anchors to find their extrema and the size of the visual object.

The visual object can traverse the scene graph to determine the set of constraints that it needs to solve. Such constraints form a set of linear inequalities. Solving such linear systems is well established - an example of such an algorithm can be found in [11]. Even some non-linear geometric constraints can be solved, and algorithms for solving these types of constraint can be found in [58]. The point to emphasize is that any system of constraints can be specified in Prolog and implemented in C++.

A simple local propagation solver is implemented in SVT. The anchors form a network of values that are connected by constraints. The basic constraint types are

$$x = y + c \qquad x \geq y + c \qquad x = my + nz \tag{4.3}$$

where x, y and z are floating point variables and c, m and n are fixed values. The constraint network is constructed for the three coordinate values in each anchor in the visual object.

Each anchor expression of the form *A = B + (x,y,z)* generates the constraints

$$A_1 = B_1 + x \qquad A_2 = B_2 + y \qquad A_3 = B_3 + z$$

where the suffix indicates the axis (1, 2 or 3). Each constraint of the form *xalign(A,B)*, *yalign(A,B)* or *zalign(A,B)* generates one of the constraints

$$A_1 = B_1 \qquad A_2 = B_2 \qquad A_3 = B_3$$

Each midpoint expression of the form *A = midpoint(B,C)* generates the constraints

$$A_1 = \frac{1}{2}B_1 + \frac{1}{2}C_1 \qquad A_2 = \frac{1}{2}B_2 + \frac{1}{2}C_2 \qquad A_3 = \frac{1}{2}B_3 + \frac{1}{2}C_3$$

Each containment component of the form *contain(Child,A,B,C,D)* where the dimensions of *Child* are (x, y, z) generates the constraints

$$\begin{array}{llllllll} A_2 & \geq & C_2 + y & B_1 & \geq & A_1 + x & C_1 = A_1 & D_1 = B_1 \\ & & & B_2 & = & A_2 & C_3 = A_3 & D_2 = C_2 \\ & & & B_3 & = & A_3 & & D_3 = A_3 \end{array}$$

Each containment component of the form *contain(Child,A,B,C,D,E,F,G,H)* where the dimensions of *Child* are (x, y, z) generates the constraints

$$\begin{array}{llllllll} A_2 & \geq & C_2 + y & C_1 & = & A_1 & E_1 = A_1 & G_1 = E_1 \\ & & & C_3 & = & A_3 & E_2 = A_2 & G_2 = C_2 \\ & & & & & & E_3 \geq A_3 + z & G_3 = E_3 \end{array}$$

$$\begin{array}{llllllll} B_1 & \geq & A_1 + x & D_1 & = & B_1 & F_1 = B_1 & H_1 = F_1 \\ B_2 & = & A_2 & D_2 & = & C_2 & F_2 = E_2 & H_2 = G_2 \\ B_3 & = & A_3 & D_3 & = & A_3 & F_3 = E_3 & H_3 = E_3 \end{array}$$

The constraint network in the *shadow_box/2* example is shown in Figure 4.17. Each anchor has been assigned a letter, and the number of constraints between anchors is shown.

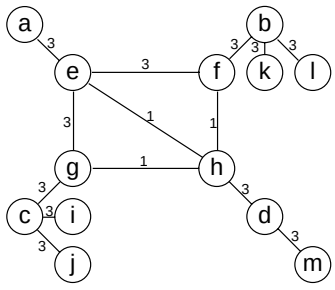


Figure 4.17. The constraint network for the shadow box.

The object component *contain(Child, a+(5,-3), b+(-5,-3), c+(5,3), d+(-5,3))* generates the following constraints for the anchor expressions

$$\begin{array}{llllllll} e_1 & = & a_1 + 5 & f_1 & = & b_1 + (-5) & g_1 = c_1 + 5 & h_1 = d_1 + (-5) \\ e_2 & = & a_2 + (-3) & f_2 & = & b_2 + (-3) & g_2 = c_2 + 3 & h_2 = d_2 + 3 \\ e_3 & = & a_3 + 0 & f_3 & = & b_3 + 0 & g_3 = c_3 + 0 & h_3 = d_3 + 0 \end{array}$$

and the following constraints for the container

$$\begin{array}{llllllll} e_2 & \geq & g_2 + y & f_1 & \geq & e_1 + x & g_1 = e_2 & h_1 = f_1 \\ & & & f_2 & = & e_2 & g_3 = e_3 & h_2 = g_2 \\ & & & f_3 & = & e_3 & & h_3 = e_3 \end{array}$$

where the dimensions of the contained object are (x, y, z). The remaining anchor expressions in the definition of *shadow_box/2* generate the following constraints:

$$\begin{array}{lllllllllllll} i_1 & = & c_1 + 4 & j_1 & = & c_1 + 4 & m_1 & = & d_1 + 4 & k_1 & = & b_1 + 0 \\ i_2 & = & c_2 + 0 & j_2 & = & c_2 + (-4) & m_2 & = & d_2 + (-4) & k_2 & = & b_2 + (-4) \\ i_3 & = & c_3 + 0 & j_3 & = & c_3 + 0 & m_3 & = & d_3 + 0 & k_3 & = & b_3 + 0 \end{array}$$

$$\begin{array}{lll} l_1 & = & b_1 + 4 \\ l_2 & = & b_2 + (-4) \\ l_3 & = & b_3 + 0 \end{array}$$

The constraints are implemented by the class hierarchy shown in Figure 4.18. Each graphical component that adds anchor constraints contains the constraints as member variables so the constraint network is constructed automatically when the scene graph is created. For example the class *Voffset* contains three *OffsetConstraint*s, one for each axis.

Figure 4.18. A class hierarchy to implement constraint satisfaction by value propagation.

Initially, all constraint values are set to *NaN*, a special floating point value used to indicate that the value has not been set. Then an anchor in the visual object is selected arbitrarily, and the *SatisfyConstraints()* method is called for each of its three axes.

SatisfyConstraints() applies each constraint attached to the value in turn. If the values attached to that constraint are changed, then *SatisfyConstraints()* is called for the changed value. In this way the network of constraints is traversed until every constraint is satisfied. Each constraint ensures that its values are monotonically increasing, which prevents instability of the algorithm, and a tolerance must be used to account for numerical rounding errors.

It is possible for constraints to be unsatisfiable, such as $y = x + 3$ and $x = y + (-4)$. This algorithm will not detect such inconsistencies, but a maximum iteration count can ensure that the algorithm terminates. Each time a constraint is applied, a counter is decremented, and if it reaches zero, the algorithm terminates, a warning message is printed, and the current incomplete solution is used.

There are many more advanced types of constraint system [47], but even these simple constraints can express very varied visual languages. The architecture of SVT would allow more advanced geometric constraints to augment these basic ones.

4.7 Interaction

While viewpoint manipulation is implemented in C++, interaction with the data is specified entirely in Prolog. User input events such as mouse moves and key presses are passed through the GUI to SVT. SVT receives the screen coordinates of mouse inputs and interrogates the scene graph to determine the objects beneath the mouse cursor that the user was intending to interact with.

The result is an *action term* that encodes the user's input. This encodes a high level description of the action such as a mouse move over a particular object, rather than low level screen coordinates. The action terms that SVT generates are:

- *click(Object, Buttons, Times)* - The mouse has been clicked over object *Object*, with the mouse buttons *Buttons*, *Times* times. *Buttons* is the term *[Left, Middle, Right, Shift]*,

where *Left* is the left mouse button, *Middle* is the middle mouse button, *Right* is the right mouse button, and *Shift* is the shift key, which are either *on* or *off*.

- *drag(From, To, Buttons)* - A mouse drag from object *From* to object *To*, with the mouse buttons *Buttons*.
- *key(Object, Key)* - A key *Key* has been pressed with the mouse cursor over object *Object*.
- *linger(Object)* - The mouse cursor is resting over an object *Object*.
- *menu(MenuContext, MenuText)* - An item from a menu *MenuContext* with menu text *MenuText* has been selected.
- *move(Object, Buttons)* - The mouse cursor has moved over an object *Object*, with mouse buttons *Buttons*.

4.7.1 Disambiguating Actions

It will often be the case that there is more than one object beneath the mouse cursor, perhaps because the objects are nested, or because the 'line of sight' beneath the mouse cursor intersects several objects. These two cases are illustrated in Figure 4.19.

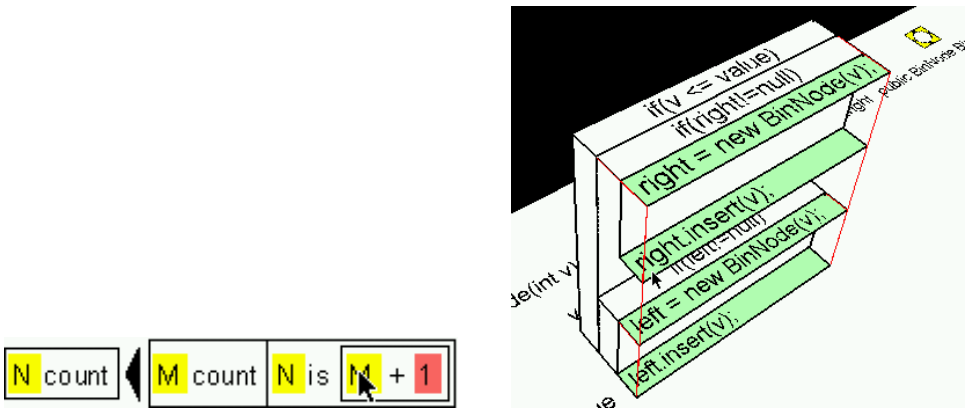


Figure 4.19. Ambiguous mouse input. The mouse cursor indicates more than one object, so the system must decide which the user intended.

The rule for selecting actions is to allow only one visual object to be subject to interaction, so the user's input generates just a single action term. When objects are nested, the innermost object in the nesting is given precedence. The *action/3* predicate is queried to determine if an action exists for that object. If not, its containing object is queried until an object with an action is found.

In the 3-D case, the mouse position will indicate a line intersecting the scene, rather than just a single point as in the 2-D case. The *camera position* indicates the view frustum and is stored as a position vector, and three orthogonal unit vectors forming a coordinate frame for the viewer. The mouse position is indicated by a vector perpendicular to the plane of the viewer extending along the z-axis of the viewer. This line is transformed from the viewer's coordinate frame to the scene graph's coordinate frame, and objects in the scene graph are tested for intersection with this line. The geometry for such transformations can be found in [31].

In general a bounding-box intersection test with the line is all that is needed. By calculating the distance from the object to the viewer, precedence of actions can be given to objects that are nearest the viewer. Not every visual object in the scene needs to be tested. Because objects are often nested, child objects need only be tested if the line intersects their parent object.

Once the correct action is found, its reaction is executed by the *reaction/2* predicate.

4.7.2 Menus

The predicate *action/3* can also specify menus. Each menu has a term to identify it, called a *menu context*. The action term is of the form

```
menu(MenuContext, Description)
```

where *MenuContext* is the name of the menu, and *Description* is the text that appears in the menu. For example a menu indicating actions on an object could be specified

```
action(menu(actions(File), 'Compress file'), svt
        compress(File)) :-
        file(File).
action(menu(actions(File), ['Delete ', Name]), svt,
        delete_file(File)) :-
        (file(File) ; directory(File)),
        identifier(File,Name).
action(menu(actions(Class), 'Make all members public'),
        svt,
        to_public(Class)) :-
        java:class(Class).
action(menu(actions(_), seperator), svt, []).
action(menu(actions(_), 'Exit SVT'), svt, exit).
```

specifies the menu *actions(Object)* in an action context *svt*. This menu is automatically customized depending on what object is conveyed in the menu context. Menu contexts do not have to be parameterized. The order items appear in the menu matches the order in which they are declared. The special description *seperator* is not displayed verbatim in the menu, but inserts a horizontal divider for aesthetic purposes. More complex menu structures such as sub-menus could in principle be declared in a similar way. Another example of a menu specification is given in Section C.5.1.

Menus can be created as either 'pop-up' or 'pull-down'. The former is displayed at the mouse cursor position, while the latter is invoked from the menu bar. A pop-up menu is created by calling

```
popup_menu(MenuContext)
```

which pops up the given menu, typically from the *reaction/2* predicate. Pull-down menus are declared

```
pulldown_menu(MenuContext, Description)
```

which declares that the menu *MenuContext* with label *Description* should be put on the menu-bar.

When an action is selected from a menu, its corresponding reaction is executed.

4.7.3 Navigation

In SVT, navigation is achieved by changing the view context. This is done using the *new_view_context/1* predicate or the *new_view/2* predicate which also changes the visualization context.

```
new_view_context(NewViewContext)
new_view(NewViewContext, NewVisualContext)
```

The new contexts are passed to the current viewer which deletes the old scene, and constructs a new scene as described in Section 4.5. *new_view_context/1* or *new_view/2* are typically called from *reaction/2* as a response to a user input.

SVT provides an action context *svt* that navigates to an object by clicking on it, just as in World Wide Web browsing. A click on the background of the view navigates backwards, which is can also be done from the Action menu. The mouse cursor changes to indicate the different types of navigation.

Each object declares which view contexts are applicable to it using the *view/3* predicate.

```
view(Object, ViewContext, Description)
```

declares that the view context *ViewContext* can be used to visualize object *Object*, and *Description* is a textual description of the view. For example

```
view(Directory, file_view(Directory), 'Files in directory') :-
        directory(Directory).

view(Directory, directory_tree(Directory),
        'Sub-directory tree') :-
        directory(Directory).

view(Class, inherited_members(Class),
        ['Class members inherited in ', Name]) :-
        java:class(Class), identifier(Class,Name).

view([], all_picture_files, 'Picture files').
```

declares two view contexts for a directory, one for a Java class and one that is not associated with an object. When there are multiple views of an object, the first declaration is used, forming the default view context for that object. Where possible, the current view context is reused so that the target view is of the same type as the original. Navigation is implemented[3] by

```
action(click(Object, [on,off,off,off], 1), svt,
        navigate_to(ViewContext)) :-
        view_context(Object, ViewContext, _).
reaction(navigate_to(ViewContext), svt) :-
        new_view_context(ViewContext), !.
```

Another way to change the view context is through the *Content* menu. The menu *navigate(Object)* displays all the view contexts that can be used to visualize a particular object *Object*. The user then selects a view context from this menu and the system navigates to it. The Content menu is declared

```
action(menu(navigate(Object), Description), svt,
        navigate_to(ViewContext)) :-
        view(Object, ViewContext, Description).

action(menu(navigate(_), seperator), svt, []).

action(menu(navigate(_), 'Home'), svt, navigate_to(home)).
```

When the user presses the right-hand mouse button on an object in the scene, the Content menu is displayed to navigate to any view of that object. The Content menu on the menu bar selects a different view of the current object. A Content menu for a class is shown in Figure 4.20. The option *Home* goes to the initial view shown in Figure 4.3.

4.7.4 Selecting Graphical Form

The visualization contexts *VisualContext* that can be used with a view context *ViewContext* are declared

[3] Additional checks are present to ensure that the given object has been correctly loaded.

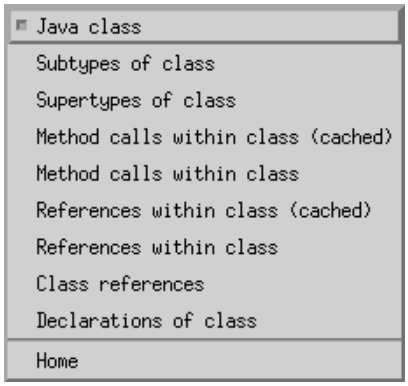


Figure 4.20. A *Content* menu, used to change the information displayed about an object.

```
visual_context(ViewContext, VisualContext)
```

The *Form* menu on the menu-bar changes the visualization context, and is shown in Figure 4.21. The description for each menu item is declared by the predicate *visual_context_description/2*, and the menu is declared

```
pulldown_menu(form(ViewContext), 'Form') :-
        current_view_context(ViewContext).

action(menu(form(ViewContext), Text), svt,
        set_vis_context(VisualContext)) :-
        visual_context(ViewContext, VisualContext),
        visual_context_description(VisualContext, Text).

reaction(set_vis_context(VisualContext), svt) :-
        new_visual_context(VisualContext).
```

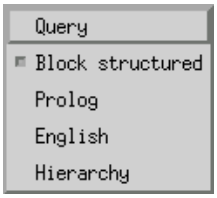


Figure 4.21. A *Form* menu, used to change the visualization context.

4.7.5 Modifying the Action Relation

Interactive behaviour can be displayed and modified by selecting the *Interaction* view, which has view context *actions(ActionContext)* for an action context *ActionContext.* This allows a more user-friendly specification of the action relation and provides information to the user about the interactive behaviour. This view is shown in Figure 4.22.

Selecting the *Add action* option on the Action menu adds a new entry to the table. Clicking on the action text pops up a menu showing the different types of action that are available, shown in Figure 4.23(a), and selecting one changes the action relation and updates the view. *Delete action* removes the entry from the table. Clicking on the reaction text pops up a menu showing the different types of reaction that are available, shown in Figure 4.23(b), and selecting one changes the action relation and updates the view. These modifications are not currently saved for future use.

Options are declared in the Actions menu by

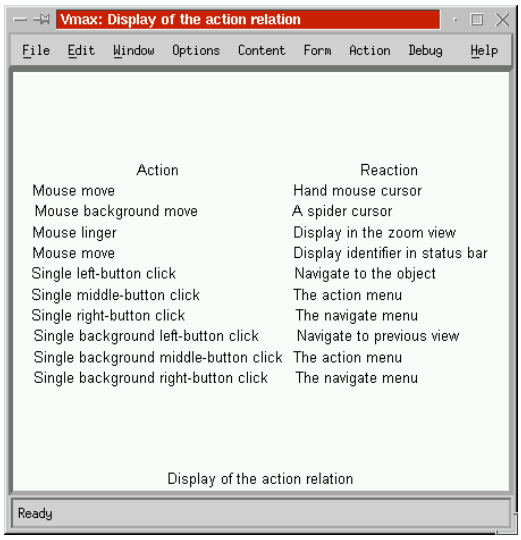
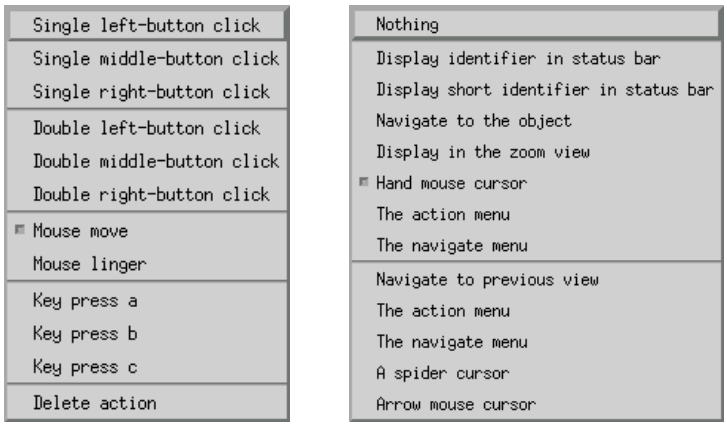


Figure 4.22. The *Actions* view for displaying and modifying the action relation.



(a) The *Actions* menu.

(b) The *Reactions* menu.

Figure 4.23. The pop-up menus to change interactive behaviour.

```
action_menu(Object, Action, ActionText)
```

where *Object* is the object being acted upon, *Action* is the action term, and *ActionText* is the text appearing in the actions menu. *Object* could also be a pair of objects such as *[A,B]* for a drag action. Reactions are declared in the Reactions menu by

```
reaction_menu(Object, Reaction, ReactionText)
```

where *Reaction* is the reaction term, and *ReactionText* is the text that appears in the menu. The condition on the action is declared by

```
user_action(Reaction)
```

The dynamic predicate

```
user_action(Action, ActionContext, Reaction)
```

stores this mapping for the action context *ActionContext.* The user defined actions are implemented by the clause

```
action(Action, ActionContext, Reaction) :-
        user_action(Action, ActionContext, Reaction),
        user_action(Reaction).
```

For example

```
action_menu([X], click(X, [off, on, off], 1),
        'Single middle-button click').
reaction_menu([X], delete_file(X), 'Delete file').
user_action(delete_file(X)) :- file(X).

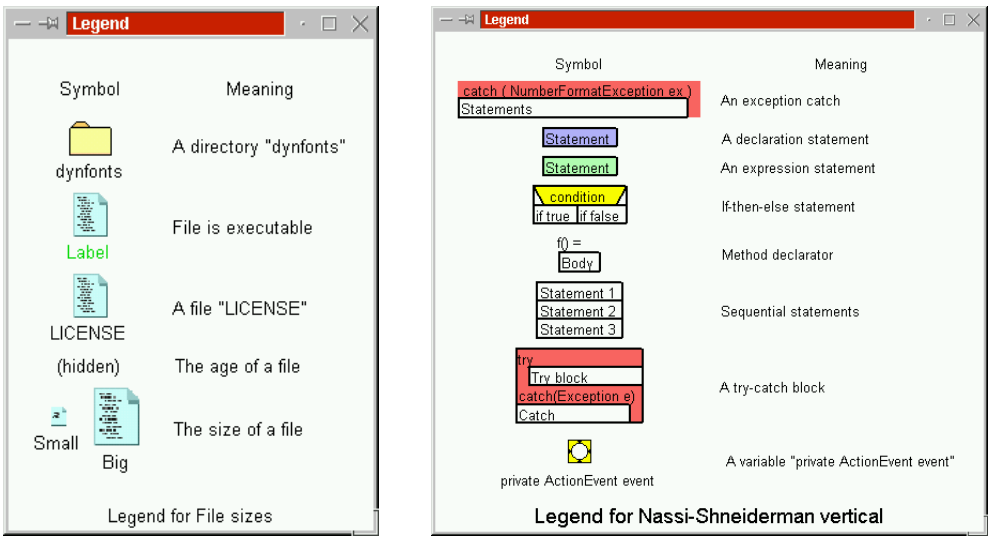
user_action(click(X, [on, off, off], 1), svt, navigate_to(X)).
user_action(naviagate_to(X)) :- view_context(X, _, _), !.
```

adds a single middle-button click action, a *delete file* reaction, and specifies navigation behaviour for a left-mouse click. In the case where multiple actions are declared for an object, all the actions are executed.

4.8 The Legend

Graphical communication can only be effective if the user is able to interpret the image. Because the graphical output can be so varied, even for the same data, there is great potential for confusion with notation, rendering the visualizations useless.

To help prevent this, a *legend* is provided by SVT to explain all of the graphical notation in a view. This is a window giving an example of each symbol, and a textual description of what it denotes. Examples are shown in Figure 4.24.



(a) A legend for a directory.

(b) A legend for a method.

Figure 4.24. Legends explaining the symbols in a view.

The legend communicates the visualization relation to the user. Whenever the view context or visualization context is changed, the legend automatically updates itself to the new view. The legend is displayed when the user selects the *Legend* option from the *View* pull-down menu. When multiple main windows are being used, the window with the most recent change updates the legend. The legend can also be resized and deleted via the window manager.

4.8.1 Displaying the Legend

The legend is generated like any other view, and has the view context *legend(ViewContext, VisualContext)*, where *ViewContext* and *VisualContext* are the view and visualization contexts of the main view. This view queries the view content using

```
?- view_content(ViewContext, Content).
```

to determine the content *Content* of the object view. It then forms a set of terms with distinct functors, which prevents duplication of symbols in the legend. The descriptive text for each entry in the legend is declared

```
content(Content, Type, Description)
```

which specifies the type *Type* and descriptive text *Description* for view content *Content*. The legend queries this predicate to determine the text in the legend entry.

The graphical symbol that appears in the legend is declared

```
visual(Visual, Type, Description, SymbolId, SymbolVisual)
```

This specifies that when the visual *Visual* is displayed in the legend, the symbol is *SymbolVisual* for an identifier *SymbolId*. The type of the visual is *Type*. The graphical symbol *SymbolVisual* that depicts the view content *Content* is retrieved by

```
?- visual_content(Content, VisualContext, Visual),
   visual(Visual, _, _, SymbolId, SymbolVisual).
```

Once the view content and its accompanying symbol have been declared using the *content/3* and *visual/5* predicates, they are automatically displayed in the legend whenever they are used.

Example 25. *The content type file/2 is declared.*

```
content(file(File, Text), [+Id, str(Text)],
        ['A file named ', Text]).
```

The visual labeled_icon/3 is declared

```
visual(labeled_icon(Id, Text, Icon), [+Id, str(Text)],
        ['A labeled icon of a ', Icon],
        Symbol, labeled_icon(Symbol, Text, Icon)) :-
        icon(Icon).
```

4.8.2 Modifying the Visualization Relation

The second function of the legend allows the user to edit the visualization relation to dynamically modify how information is graphically represented. The legend has an action context that displays a pop-up menu when an entry in the menu is clicked on by the mouse. This menu displays a list of alternative graphical forms for the data, and the current graphical representation is indicated in the menu, as shown in Figure 4.25.

Selecting an option from this menu changes the visualization relation to use the selected graphical form. Both the visualization relation and the legend are updated to reflect the changes. Figure 4.26 shows an example of changing a visualization relation.

The menu of alternative graphical forms is found by determining the type *Type* of content *Content*, and finding compatible visuals with the same type. The query

```
?- content(Content, Type, _),
   visual(Visual, Type, Description, _, _).
```

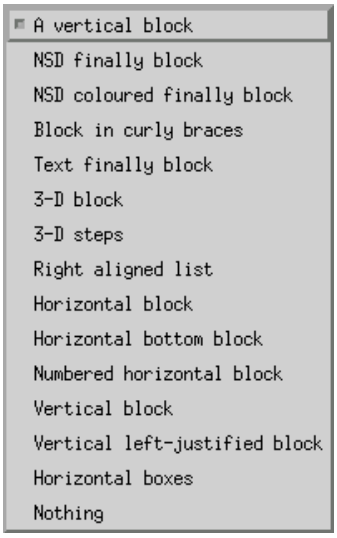


Figure 4.25. A menu providing alternative graphical forms.

is used to build the menu. Selecting a visual *NewVisual* from this menu modifies *visual_content/3* by

```
?- retract(visual_content(Content, VisualContext, OldVisual)),
   assert(visual_content(Content, VisualContext, NewVisual)).
```

The predicates *content_type/2* and *visual_type/2* described in Section 3.5 are defined

```
content_type(Content, Type) :- content(Content, Type, _).
visual_type(Visual, Type) :- visual(Visual, Type, _, _, _).
```

4.9 The Bookmarks

Selecting the *Bookmarks* option from the *View* menu creates a row of five small windows as shown in Figure 4.27.

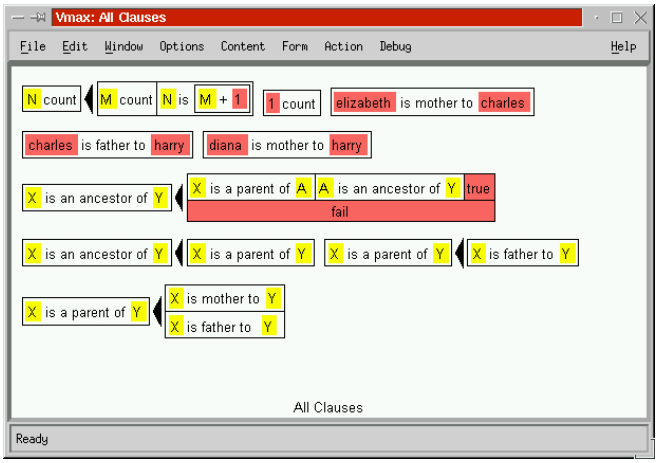
These windows can be used as place-holders or *bookmarks* to store views for later retrieval, and show a miniature version of the stored view. A single left mouse click on the bookmark will retrieve it to the main viewing window. A right mouse click will pop up the menu shown in Figure 4.28.

The *Bookmark* option sets the view and visualization context of the bookmark to those of the main view. The *Retrieve* option sets the view context and visualization context of the main view to those of the bookmark. The *Swap* option exchanges the view and visualization contexts of the bookmark and the main view. The *Refresh* option updates the bookmarked view if data has changed.

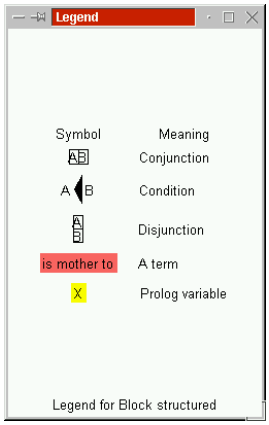
4.10 The Preview Window

Selecting the *Preview* option from the *View* window makes a *Preview* window appear, as shown in Figure 4.29.

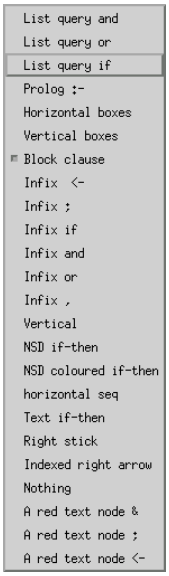
This window can be used to display any view, and SVT's default action context provides a preview function that displays the object beneath the mouse cursor. This gives a preview of what navigating to that object would show, without the user having to commit to the navigation or having to press any mouse buttons. The preview window is declared



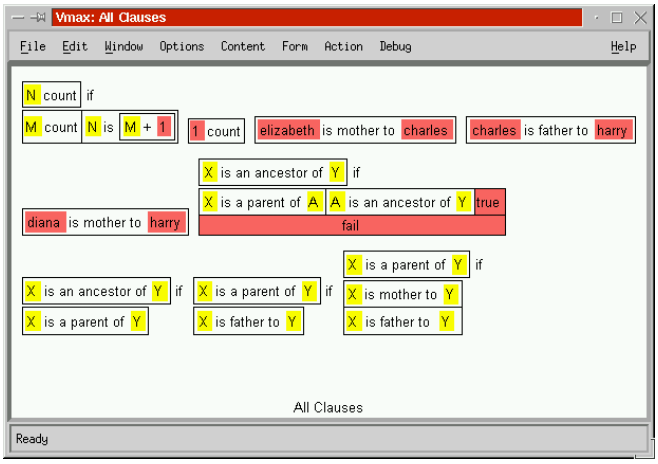
(a) The initial view.



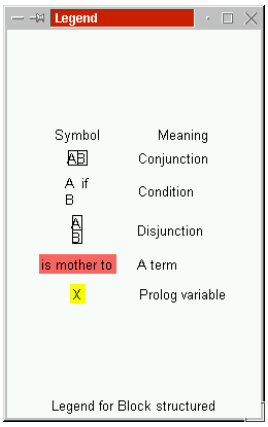
(b) The initial legend.



(c) Change the visualization relation.



(d) The new view.



(e) The new legend.

Figure 4.26. Changing the visualization relation from the legend.

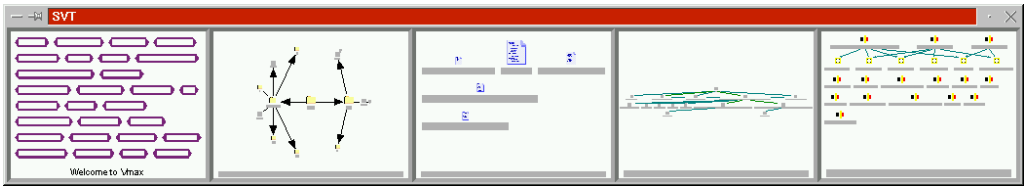


Figure 4.27. A row of bookmarks.

Figure 4.28. The *Bookmarks* menu.

```
action(linger(Obj), svt, zoom_context(ViewContext)) :-
        view(Obj, ViewContext, _).
reaction(zoom_context(ViewContext), svt) :-
        visual_context(ViewContext, VisualContext), !,
        new_zoom_view(ViewContext, VisualContext).
```

Naturally this behaviour can be altered to display something completely different in the preview window. Another means of identifying the object beneath the mouse cursor is to look in the status bar. When the mouse cursor is moved over a visual object *X*, if it has a textual description *Text* provided by the predicate *long_identifier(X, Text)*, then that text is shown in the status bar by calling the predicate *set_status_text(Text)*.

```
action(move(X), svt, display_text(Text)) :-
        long_identifier(X, Text).
reaction(display_text(Text), svt) :- set_status_text(Text).
```

4.11 Chapter Summary

SVT is an implementation of the formal model of visualization described in Chapter 3. It is a general-purpose visualization workbench that is specified using compiled Prolog. It provides multiple windows for 3-D output, and incorporates a 3-D model viewer and a window for editing text. The executable is built around Prolog, Motif and OpenGL, and runs under UNIX.

Each view issues a query to Prolog to return the graphical constraints that compose the scene. These constraints are cross-referenced to create a scene graph. Graphical layout algorithms traverse the scene graph to assign 3-D coordinates to the objects in the scene. These algorithms are held in virtual methods of the nodes of the scene graph, and are invoked to reset, structure, size, resize, position and render each object. SVT implements a range of graphical output which can be extended by deriving new classes from the constraint hierarchy.

The graphical vocabulary can be expanded to provide more varied graphical output. New visuals can be defined as combinations of existing visuals, and visual objects can be defined in terms of graphical components and anchors. Anchor expressions provide a concise means of specifying constraints that allow objects to be resized correctly. Visual objects are laid out by satisfying the set of constraints created by the object components and the anchor expressions.

Interaction is specified entirely in Prolog using the simple model described in Chapter 3. Care must be taken to interact with the intended object, which is taken to be the innermost object in a nesting. Menus are also specified using this method, and can be completely customized by the data. Navigation is achieved by changing the view context, which can be done by clicking on an object with a view context, from a pull-down menu or from a pop-up menu. The visualization

Figure 4.29. The *Preview* window.

context is also changed from a pull-down menu. There is a view to display and edit the current action relation.

The legend window automatically describes all the visual notation in the view, and can also be used to modify the visualization relation from a pop-up menu. A bookmarks view provides thumbnails for storing views for later retrieval, and a preview view automatically displays the object beneath the mouse cursor.

SVT provides the capability to specify a visualization environment at a high level, and interface it to a knowledge database. SVT can only provide the scripting and flexibility because it uses Prolog to define the behaviour of the system. By itself, SVT does not provide any visualizations, these must still be supplied by an application written in Prolog, and optionally C++. Chapter 5 describes one such system that is used to visualize software.

Chapter 5

A Tool for Software Visualization

This chapter describes Vmax, a programmers' text editor built on SVT, that provides software visualization. Vmax provides a browser window for visualizing the filing system, Java source code, run-time data, and can edit Prolog graphically. Vmax deals with all levels of granularity, from high level program structures to visualizing source code. SVT's architecture allows arbitrary queries of a program database for very specialized views, providing an information-rich environment for the programmer.

The aim of implementing Vmax is to investigate how software visualization can be specified and scripted within the environment provided by SVT. The system demonstrates how to specify SV, alternative views of the same data, browsing, a broad scope showing all levels of granularity, selectively hiding information, and increases the number of graphical views available to programmers.

5.1 Introduction

Vmax is a text editor with graphical views for visualization and browsing. The graphical views can visualize almost every program object in a variety of formats, and most objects in the views can be navigated to by a single mouse click. Run-time data can also be gathered, displayed and animated. Vmax merely provides the data to visualize, but SVT provides the framework for visualization and navigation.

The visualization windows can contain any views generated by SVT, and display views of the filing system, the program database, Java source code and run-time information. The visualization window provides a navigation and browsing facility, by providing many different views of the program database, including views of individual methods or variables. Views are set up to link to related views, so for example a view of a Java method has links to the variables it references, and the functions it calls. It is possible with a single mouse action to navigate to the class that defines the variable, other methods that reference the variable, methods that call the current method, the reachable functions, or any number of user defined views.

In designing Vmax, the aim was to anticipate what information a programmer needs at any given time, to provide no more and no less, to anticipate where a programmer wants to navigate and to minimize the effort required to get there. SVT is very flexible in specifying its behaviour, so can be tailored heavily to suit this kind of environment.

The views and interactive behaviour of Vmax merely illustrate the possibilities of visualization and navigation, but no investigation has been done here of programmers' needs. This would require questionnaires, timed completion tasks and detailed measurement of programmers' activities, which is beyond the scope of this work. Vmax produces activity logs that would facilitate such a study. Vmax should however offer benefits over ordinary textual programming, but there is no empirical evidence to support this. Because Vmax provides all of the functionality of a textual programming environment, it should certainly do no worse than a text editor.

Vmax stores information as facts in Prolog's internal database. This means that the data is not persistent and needs to be reloaded between sessions. Directories and source code are loaded on demand, when the user attempts to visualize them. Lex and Yacc [2] are used to lexically analyze and parse input files, and the parse tree is passed to Prolog for analysis. This constructs the program database which is stored in dynamic Prolog predicates.

Each entity in the program database is assigned a unique identifier, so for example any file, directory, method, variable, class, or statement are all represented by unique integers. *uid(Id)* returns a new identifier *Id* which is guaranteed not to clash with any other identifier. *uid/1* is implemented as a counter which returns a different integer each time it is called. Representing entities by unique integers gives efficient storage and indexing.

Run-time data is gathered by adding *trace points* to the Java source code, which inserts a call to output a value to a *trace file*. The *Reflection* package *java.lang.reflect* analyzes the structure of the value to output its contents. Trace calls can be added to the source code simply by dragging a variable to the point in the source code where the trace should occur. The generated trace file is read in and visualized.

Java source code can be visualized as a visual programming language, either as a control flow diagram or as a Nassi-Shneiderman Diagram [72]. Even expressions can be visualized. Prolog can also be visualized as a visual language, and even be used to define views in a more user-friendly manner.

Vmax provides 70 view contexts, 133 visuals, and includes 151 different views (if the different visualization relations for each view context are counted). These views can be extended by users' Prolog, as can the analysis routines to provide further useful information for the programmer.

5.2 Architecture

Vmax extends SVT's predicates with many of its own for software visualization. Some of these are implemented in C++. There are predicates for lexical analysis using Lex, parsing using Yacc [2], parsing directories, parsing run-time data, analyzing Java, analyzing run-time data, and visualizing Prolog. Many views and visuals have been defined. Its architecture is shown in Figure 5.1.

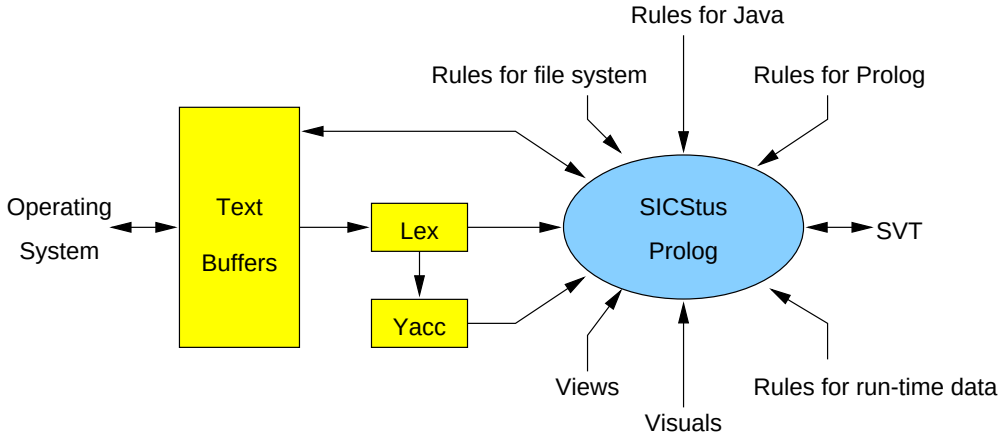


Figure 5.1. The architecture of Vmax.

5.3 Text Processing

Text processing is a significant part of Vmax, because it needs to parse directories, source code, run-time trace files, and allow the user to edit parts of files. To enable this, a data structure of *text nodes* and *text buffers* has been implemented as part of SVT. Text buffers store text files in a single array of text, and text nodes are nodes in the parse tree of a text file.

A text node stores pointers to a segment of text as offsets into a text buffer, so each text node represents a block of text. The address of this text node can be passed to Prolog, which can query its contents or display it in the editing window. Figure 5.2 shows a data structure of text nodes and text buffers.

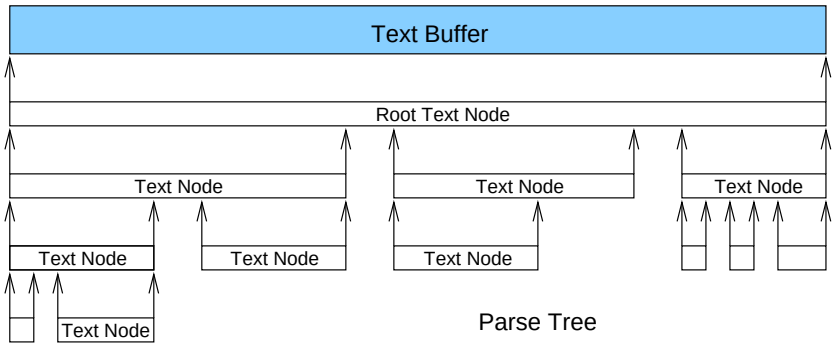


Figure 5.2. A data structure of text nodes in a text buffer.

If a text node's buffer is tagged as read-only, then so is its text in the editing window. When text is edited, text moves in the buffer, and so the text nodes must move their pointers to new positions. This is done by traversing the parse tree, and can be implemented more efficiently if text nodes store text offsets *relative* to their parents' offsets.

A text buffer can pipe the input or output of a shell command into the text buffer, or load and save files. File text buffers have an associated filename. Each text buffer can also have an associated lexical analyzer and parser. An instruction to execute the lexical analyzer (in Lex) or parser (in Yacc) on that text buffer will invoke the correct one, since there are multiple lexical analyzers and parsers compiled into Vmax. It is even feasible to parse a single text node, allowing local updates to the parse tree.

A complete list of operations Prolog can perform on text is given in Section B.2.5. A text file is loaded by calling

```
create_file_buffer(Filename, Buffer, TextNode, Type)
```

which creates a file buffer for file *Filename* and type *Type*, and returns the address of the buffer *Buffer* and text node (of the whole file) *TextNode*. The characters *CharList* in a text node *TextNode* can be retrieved by calling

```
lexeme_string_list(TextNode, CharList)
```

A lexical analysis can be performed by calling

```
lex_buffer(Buffer, Lexemes)
```

which returns the list of lexemes *Lexemes* for the buffer *Buffer*, using its lexical analyzer. The buffer can be parsed by calling

```
parse_buffer(Buffer, Tree)
```

which returns the whole parse tree *Tree* as a large term conveying all of the text nodes in the parse tree for buffer *Buffer*. A slight drawback of this method is that a data structure has been constructed for the entire parse tree, which is slow. Perhaps the parser should construct Prolog terms instead of text nodes.

Prolog can itself parse using *definite clause grammars* (DCGs) [75] that can replace the Yacc parser. Parsing with a DCG is slower because it executes in Prolog and not C.

5.4 Directory Visualization

Vmax can visualize the computer's filing system. It reads in directories off disk and stores the directory data in Prolog's knowledge database. The predicate *ensure_directory_loaded(Path)* loads the given directory into the knowledge database. It executes the command *ls -Lal* and pipes the output into a text buffer. This buffer is then parsed, using a simple DCG that describes the format of a directory listing. The DCG reads in the directory data and puts it into the database.

Each file and directory in the filing system is assigned a unique identifier. Each file or directory also has a path, which is represented as a list, so that for example */usr/bin/netscape* would be represented as *[netscape, bin, usr]*. The predicate *path_id(Path, Identifier)* determines the unique identifier *Identifier* for each path *Path*.

A complete listing of the filing system predicates is given in Section B.3.1. Each file is stored as a *file(Identifier)* and each directory as *directory(Identifier)*. If a file is a member of a directory, then *member(Directory, File)* stores that file *File* is a member of the directory *Directory*. The *contains/2* predicate gives the transitive closure of the *member/2* predicate.

The file *File*'s name *Name* is stored in *filename(File, Name)*, and its full path *Path* in *file_path-(File, Path)*. The flags *readable(File)*, *writable(File)* and *executable(File)* store information about the status of the file. *file_fullname(File, FullName)* gives the full filename *FullName* of the file or directory, and *file_extension(File, Extension)* returns the file extension *Extension* (e.g. *txt*) of the file. *file_barename(File, BareName)* gives the filename without its extension. *file_timestamp(File, TimeStamp)* gives the file's creation date *TimeStamp*, and *file_age(File, Age)* gives the age *Age* of the file in seconds.

The above predicates provide enough information for a complete file browser. The default directory view is shown in Figure 5.3.

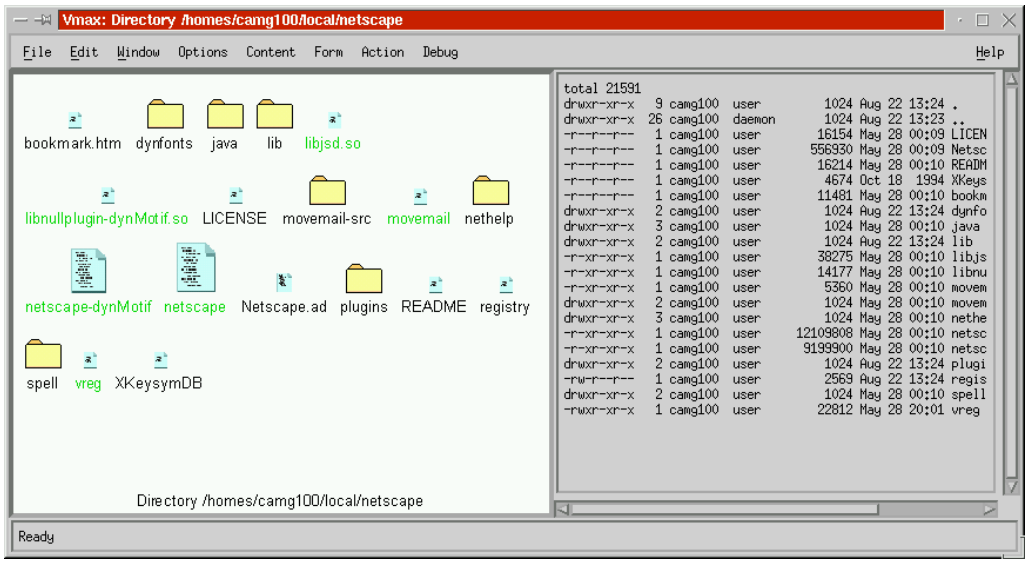


Figure 5.3. A view showing the contents of a directory.

The information in this view includes the directory name, the files, their names, their sizes, their ages, and the type of the file. If the text window is open, the directory is listed there. This is a lot of information to present, so the visualization relation can select what to display and present it in different ways. The view is declared

```
view(Dir, directory_view(Dir), 'Directory contents') :-
        directory(Dir).

view_content(directory_view(Dir), title(['Directory ', Name])) :-
        long_identifier(Dir, Name).
```

```
view_content(directory_view(Dir), text(Text)) :-
        text_node(Dir, Text).

view_content(directory_view(Dir), file(File, Name)) :-
        member(Dir, File), file(File), identifier(File, Name).

view_content(directory_view(Dir), directory(File, Name)) :-
        member(Dir, File), directory(File), identifier(File, Name).

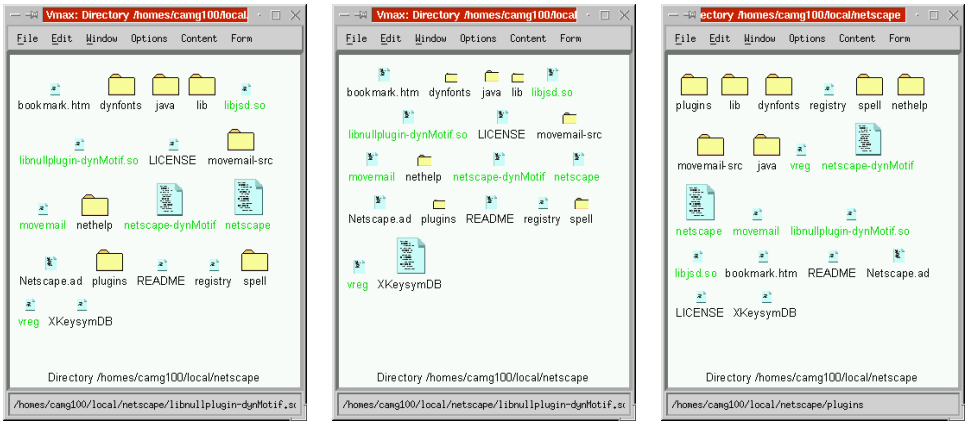
view_content(directory_view(Dir), file_size(File, Size)) :-
        member(Dir, File), file_size(File, Size)).

view_content(directory_view(Dir), file_age(File, Age)) :-
        member(Dir, File), file_age(File, Age).

view_content(directory_view(Dir), executable(File)) :-
        member(Dir, File), executable(File).

view_content(directory_view(Dir), source_code(File)) :-
        member(Dir, File), source_code(File).
```

Three different visualizations of this view are shown in Figure 5.4.



(a) File sizes. (b) File ages. (c) Files by age.

Figure 5.4. Alternative views of a directory.

Using SVT's default action context, a single left mouse button click on an object in the scene navigates to it, selecting the default view for that object. Moving the mouse cursor over an object displays its identifier in the status bar, and if the Preview window is open, the file or directory beneath the mouse cursor is displayed in it. Directories are automatically read in as navigation proceeds.

Figure 5.5. The Content menu for a directory.

Figure 5.6. View showing just Java files in a directory.

The other views of a directory are selected from its Content menu shown in Figure 5.5. The list of Java files in a directory is shown in Figure 5.6. This view is declared

```
view(Dir, java_dir(Dir), 'Java files in directory') :-
        directory(Dir).

view_content(java_dir(Dir), title(['Java files under ', Name])) :-
        long_identifier(Dir,Name).

view_content(java_dir(Dir), class(File, Name)) :-
        member(Dir, File),
        java_source_code(File),
        short_identifier(File, Name).

view_content(java_dir(Dir), directory(File, Name)) :-
        member(Dir, File),
        directory(File),
        identifier(File, Name).
```

Directories are structured in trees, which can be displayed in a number of ways. The basic directory tree is specified

```
view(Dir, dir_tree(Dir), 'Directory tree') :- directory(Dir).

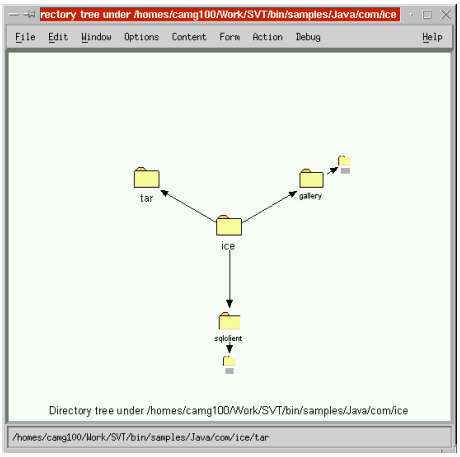
view_content(dir_tree(Root),
        title(['Directory tree under ', Name])) :-
        long_identifier(Root, Name).

view_content(dir_tree(Root), directory(Dir)) :-
        self_or_contains(Root, Dir).

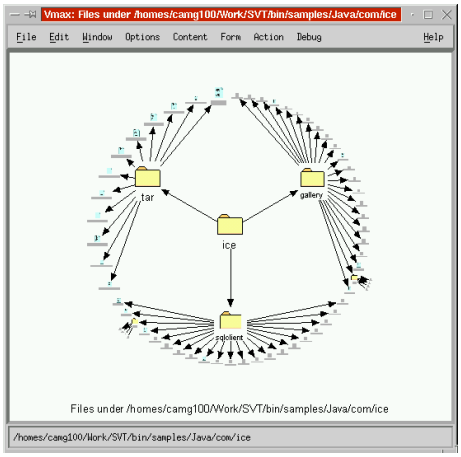
view_content(dir_tree(Root), contains(Dir1, Dir2)) :-
        self_or_contains(Root, Dir1),
        directory(Dir1), member(Dir1, Dir2), directory(Dir2).

self_or_contains(Self, Self).
self_or_contains(Self, Child) :- contains(Self, Child).
```

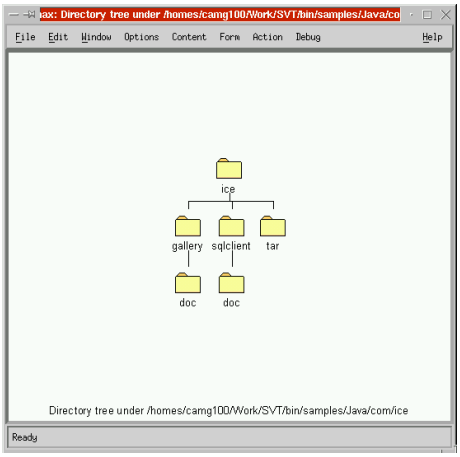
A basic directory tree is shown in Figure 5.7(a). Directory trees can also show files, as shown in Figure 5.7(b), and the hierarchy can be represented in different ways, as shown by Figure 5.7. Drag and drop has been implemented to move files and directories.



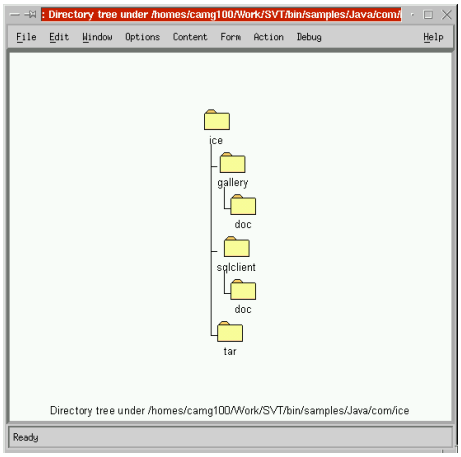
(a) Fish-eye directories.



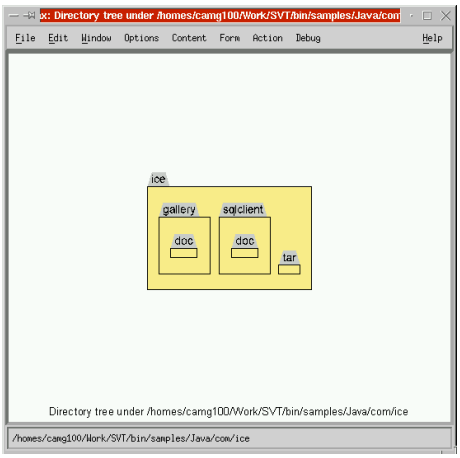
(b) Fish-eye files.



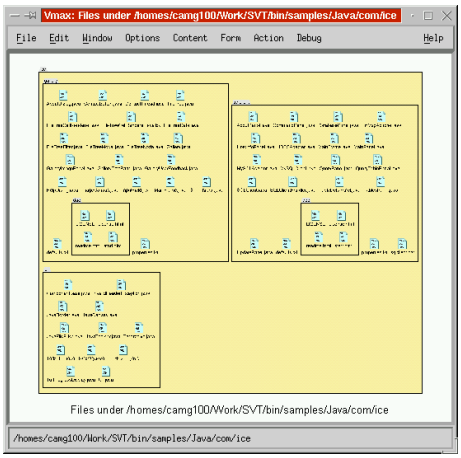
(c) Hierarchy directories.



(d) List directories.



(e) Contained directories.



(f) Contained files.

Figure 5.7. Some different views of a directory tree.

5.4.1 MIME Types

A MIME type is a "multipurpose internet mail extension," used for declaring the content of a file. MIME types can be implemented straightforwardly in Prolog, by

```
mime_extension(Type, Extension)
```

to declare that a particular MIME type *Type* has the filename extension *Extension.* Subtyping of MIME types is declared

```
mime_subtype(SuperType, SubType)
```

for MIME types *SuperType* and *SubType.* Applications to handle MIME types are declared

```
mime_application(Type, Description, Application)
```

where *Description* describes the application and *Application* is the location of the executable. MIME types provide relevant application programs for a file, which appear automatically on the Action menu of a file as shown in Figure 5.8. Selecting an application executes it with the given file.

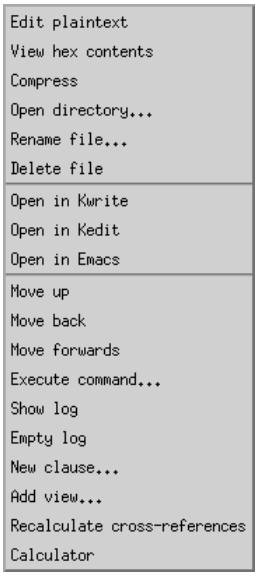


Figure 5.8. MIME types add applications to the Action menu of a file.

5.5 Analyzing Java Source Code

5.5.1 Constructing the Program Database

Before Java can be visualized it must be read in to Prolog's knowledge database. This is achieved by parsing Java source code and analyzing the parse tree using language rules from the Java Language Specification [35]. These rules can be expressed quite naturally in Prolog. Program analysis itself is well understood, forming the basis of all compilers.

Java source code is loaded on demand, and the program database (the database that stores information about the program) is stored in dynamic predicates in memory and is therefore not persistent. The program database could be stored externally to make it persistent, but that would have been slower and slightly more laborious to implement.

The predicate *ensure_java_loaded(File)* is invoked to load the given file *File.* This predicate is called from *ensure_fresh/1* when an attempt is make to navigate to a Java source file, or from the

Load all Java files option is selected from the Action menu of a directory. *ensure_java_loaded/1* loads the given file into a text buffer, and invokes Lex and Yacc to return the parse tree of the Java file.[1] The Lex and Yacc scripts for the Java syntax can be derived from the LALR(1) grammar in the Java Language Specification [35]. Alternatively a compiler front end could be interfaced directly to Prolog.

The parse tree is in the form *node(Type, TextNode,* C_1*,* C_2*, ...* C_n*)* where *Type* is an integer identifying the node, *TextNode* is the address of the text node, and $C_1 ... C_n$ are terms of the same form. Leaf nodes of the form *node(Type, TextNode)* represent lexemes.

This parse tree is analyzed by pattern matching the parse tree with the production rules present in the Java grammar. For example this code excerpt

```
program_file(node(118,_,P,I,T), File) :-
        package_statement(P,File,Package),
        import_statements(I,File),
        type_declarations(T,locale(Package,File,[],[])).
```

matches one possible structure of the root node. There is a clause for each production rule in the Java grammar. The predicates that traverse the parse tree also store information about the Java file in Prolog's database – this part of of Prolog's database could be called the program database. The predicate *java:program_file(Tree, File)* adds the Java file *File* to the program database given its parse tree *Tree*. The file's buffer *Buffer* is stored *java:buffer(File, Buffer)*. Note that the predicates relating to Java have been put in the separate module *java*.

The first part of a Java file is its package declaration and its import declarations. The predicate *java:package(File, Package)* stored the file's package *Package*, as a list of names. The predicate *java:import_declaration(File, Id, Import)* stores that the file imports the package *Import*, so for example *java.util.Hashtable* would be represented *['Hashtable', 'util', 'java']*. *Id* is the unique identifier of the import statement. The predicate *java:import_all_declaration(File, Id, Import)* stores that the file imports all classes from the package *Import*.

Class and interface declarations form the body of the Java file. Each declaration *Declaration* in the file is stored as *member(File, Declaration)*, and *java:declaration(Declaration, ClassType, Modifiers, Extends, Interfaces, ClassHeader)*. *ClassType* is the type of the class, either a *class* or an *interface*. *Modifiers* is a term representing the modifiers specified for the declaration, of the form *modifiers(Abstract, Final, Access, Static, Transient, Volatile, Native, Synchronized)*. *Extends* is the name of the class this declaration extends. *Interfaces* is a list of the names of the declarations this class implements. *ClassHeader* is the text node of the class header. Additionally *text_node(Declaration, Text)* stores the text node of the entire declaration.

Each declaration's members *Member* are stored in the *member(Declaration, Member)* predicate. The type of the member is indicated by the *java:variable(Member)* and the *java:method(Member)* predicates, to determine whether the member is a field or a method.

Variables are stored as *java:variable(Variable, Type, Modifiers)*, where *Variable* is the identifier of the variable, *Type* is a term denoting its type, and *Modifiers* is a term describing the modifiers applied to the variable. If a variable is a parameter to a method, then this fact is stored *java:parameter(Variable)*. If a variable has an initializer, then this value is stored *java:initializer(Variable, Expression)*, where *Expression* is a term denoting the expression that initializes the variable.

Methods are stored *java:method(Method, Type, Modifiers, Parameters, Throws, BlockStmt, Statements)*, where *Type* is the return type of the method, *Modifiers* are the modifiers of the method, *Parameters* is the list of parameters of the method, which is a list of variable identifiers. *Throws* is a list of class names that the method can throw, *BlockStmt* is the block of statements *Statements* that make up the method body.

Constructors are treated as methods, but the predicate *java:constructor(Method)* indicates that the method is really a constructor. Static initializers to classes are declared *java:static_initializer(Id, Block, Statements)* and non-static initializers as *java:nonstatic_initializer(Id, Block, Statements)*, where *Block* is a block of statements *Statements*.

[1] The first version of Vmax visualized C++. Its grammar is not LALR(1), so a DCG was used.

Statements are stored *java:statement(Statement)*, where *Statement* is the unique identifier of the statement. Each block *Block* of statements is stored *java:block(Block, Statements)*, where *Statements* is a list of statement identifiers. A block statement is stored *java:block_statement(Statement, Block, Statements)*, where *Block* is the block of statements *Statements* that make up the block statement. An expression statement is stored *java:expression_statement(Statement, Expression)*, where *Expression* is the term representing the expression. A conditional statement is stored *java:conditional_statement(Statement, Condition, CText, Then, Else)*, where *Condition* is a term representing the condition expression, *CText* is the text node of the condition, *Then* is the identifier of the *then* statement, and *Else* is the identifier of the *else* statement. A *while* statement is stored *java:while_statement(Statement, Condition, CText, Body)*, where *Body* is the statement of the body of the loop. The other types of statement are stored *java:break_statement/1*, *java:break_statement/2*, *java:case_statement/3*, *java:conditional_statement/4*, *java:continue_statement/1*, *java:continue_statement/2*, *java:declaration_statement/2*, *java:default_statement/1*, *java:do_while_statement/4*, *java:empty_statement/1*, *java:for_statement/8*, *java:labelled_statement/2*, *java:return_statement/1*, *java:return_statement/2*, *java:synchronized_statement/4*, *java:throw_statement/2* and *java:try_statement/6* – these predicates are documented in Section B.3.2.

Expressions in statements or declarations are represented by terms. Prefix, postfix and infix operators *Operator* are represented by *prefix(Operator, E)*, *postfix(Operator, E)* and *infix(Operator, A, B)* respectively on expressions *A*, *B* and *E*. A conditional is represented by *conditional(Cond, A, B)* for a condition expression *Cond*. Cast expressions are represented *cast(Type, Expr)*, where *Type* is the type of the cast. Qualified names are represented as *qualified_name(Name)*, where *Name* is a list of atoms. Literals are represented by *literal(String)*, where *String* is the characters in the literal. Method calls are represented *method_call(Method, Parameters)*, where *Method* is an expression specifying the method, and *Parameters* is a (possibly empty) list of expressions. A member access is represented *field_access(Expr, Field)*, where *Field* is the name of the member. A class instantiation is represented *new_class(Type, Parameters)*, where *Type* is the class to be instantiated, and *Parameters* is the list of expressions. An array instantiation is represented *new_array(Type, DimExprs, Dims)*, where *Type* is the type for instantiation, with a list of dimension expressions *DimExprs* of *Dims* dimensions.

Types in expressions or variables are also represented by terms. A primitive type is represented *primitive(P)*, where *P* is one of the primitive types such as *boolean* or *double*. A named type is of the form *named(Name, File)*, where *Name* is a list of identifiers (for example *java.util.Hashtable* would be *['Hashtable', 'util', 'java']*), and *File* is the file that the type appears in. The file is important, because different names may refer to different classes depending upon the file they are in. An array of a type is of the form *array(Type)*, where *Type* is a type term. Array types can be nested.

The Java source code can be rescanned using the *java:rescan_file(File)* predicate to rescan the file *File*. This traverses the program database and calls *retract/1* to remove the data from the database. Updating the program database is necessary in an editing environment where the source code can change.

5.5.2 Analyzing the Program Database

Vmax adds a number of predicates for deriving various types of information about the program, which augment the program database to provide information for visualization. The rules used to implement these follow from the Java Language Specification [35].

The predicate *java:direct_supertype/2* finds the immediate supertype of a class, *java:supertype/2* finds any supertype of a class, *java:direct_subtype/2* finds a class's immediate subtypes, and *java:subtype/2* finds all subtypes of a class. *java:direct_superinterface/2* finds the interfaces that a class implements, while *java:superinterface/2* finds all interfaces that a class implements. The predicate *java:class_member(Class, Member)* gives class members *Member* of a class, including those inherited from supertypes. *java:class_method(Class, Method)* gives the methods *Method* belonging to a class, including those inherited from supertypes.

The predicates *java:is_abstract/1*, *java:is_native/1*, *java:is_private/1*, *java:is_protected/1* and *java:is_public/1* return information about the status of members and methods.

The predicate *java:contains_statement(Statement1, Statement2)* returns all statements *Statement2* that are contained within the (possibly compound) statement *Statement1*. The predicate *java:method_contains_statement(Method, Statement)* uses this to return the statements *Statement* contained within a method *Method*. *java:statement_entry_point/2* returns the entry point (first statement executed) within a compound statement, *java:statement_exit_point/2* returns the last statement executed, and there may be more than one, for example due to branching. *java:method_entry_point/2* gives the first statement executed in a method, and *java:method_exit_point/3* gives the last statement, and again there may be multiple solutions available by backtracking. The predicate *java:statement_follows(Method, Statement1, Statement2, Transition)* returns all pairs of sequentially executed statements *Statement1* and *Statement2* in a method, the transition type *Transition* being *case(X)*, *default*, *else*, *for*, *sequence*, *then* and *while*, to indicate the different circumstances in which the statements follow. Exception handling is not indicated by this predicate.

The predicate *java:sub_expression(Expr1, Expr2)* returns the sub-expressions *Expr2* of an expression *Expr1*. *java:sub_expression_decl(Statement, Decls1, Expr, Decls2)* returns the sub-expressions *Expr* of a statement *Statement*, and a list of declarations *Decls2* that apply to the sub-expression. The predicate *java:method_sub_expression(Method, Expr, Context)* uses this to find the sub-expressions of a method, and returns the context *Context* in which the expression used, which includes the local declarations and the class. The predicate *java:expression_reference(Expr, Context, Variable)* returns variables *Variable* referenced by the expression, and *java:expression_calls(Expr, Context, Method2)* returns the method *Method2* called by the given expression. Even though *Method2* may be overridden, this predicate does not check this possibility. *java:expression_type(Expr, Context, Type)* returns the type of an expression. *java:find_declaration(Type, Class)* gives the class *Class* of a type, if it exists. The predicate *java:method_calls(Method1, Method2)* returns the methods *Method2* that may be called by method *Method1*. *java:reachable(Method1, Method2, Prev, Visited)* returns all methods *Method2* that are reachable from *Method1*, where *Prev* is the calling method of *Method2*, and *Visited* is a list of methods the search algorithm has been before, to ensure termination.

The complete list of predicates for Java source code is given in Section B.3.2. These predicates merely scratch the surface of algorithms that can provide meaningful information about a program. Unfortunately there are no short-cuts in their implementation, but direct access to the program database, and the ability to add new predicates that build on old ones, mean that Prolog is a suitable meta-language for programs. Prolog is suited to analyzing Java source code because its data structures (expressions, types, parse trees) are all trees which can be represented straightforwardly as Prolog terms, Prolog has its own internal database which acts as the program database, and because Java's language rules can be expressed as Prolog clauses.

5.6 Java Visualization

5.6.1 Visualizing Files, Classes and Packages

Clicking on Java source code file will load and navigate to that file. The default view for a file shows the main class (or interface) in the file, shown in Figure 5.9.

Another view of a file shows the overall structure of the file, shown in Figure 5.10, which puts the whole text file in the editing window. Each of the items in Figure 5.10 can be navigated to, so for example, clicking on the package navigates to the package, clicking on the import declarations navigates to the classes indicated, and clicking on a class navigates to that class.

The class view shows the class members and methods, excluding those inherited from supertypes and interfaces and includes information about the members, such as whether they are public, native or abstract. Each symbol in the view can be navigated to. The sizes of the methods are indicated. The text of the class appears in the editing window. This view is declared

```
view(Decl, java_decl(Decl), 'Class contents') :-
        java:declaration(Decl).
```

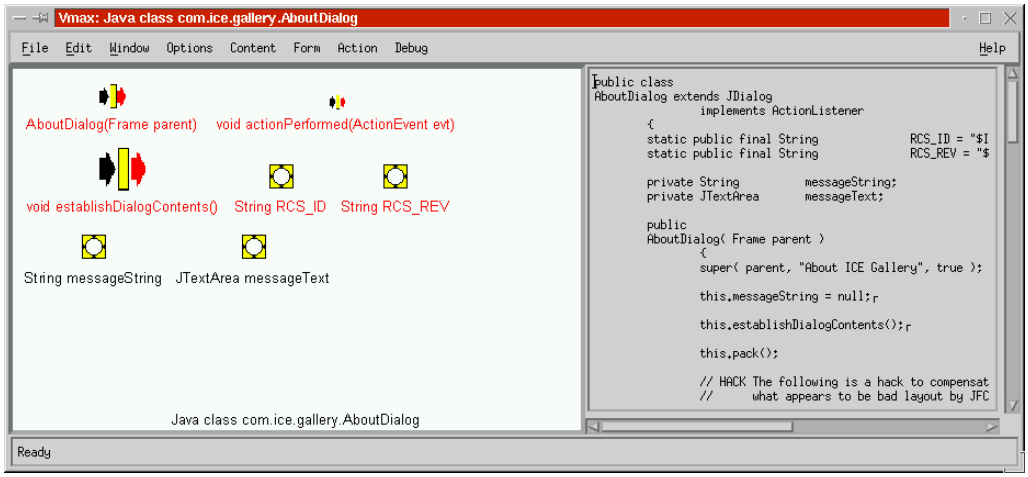


Figure 5.9. The main class of a file.

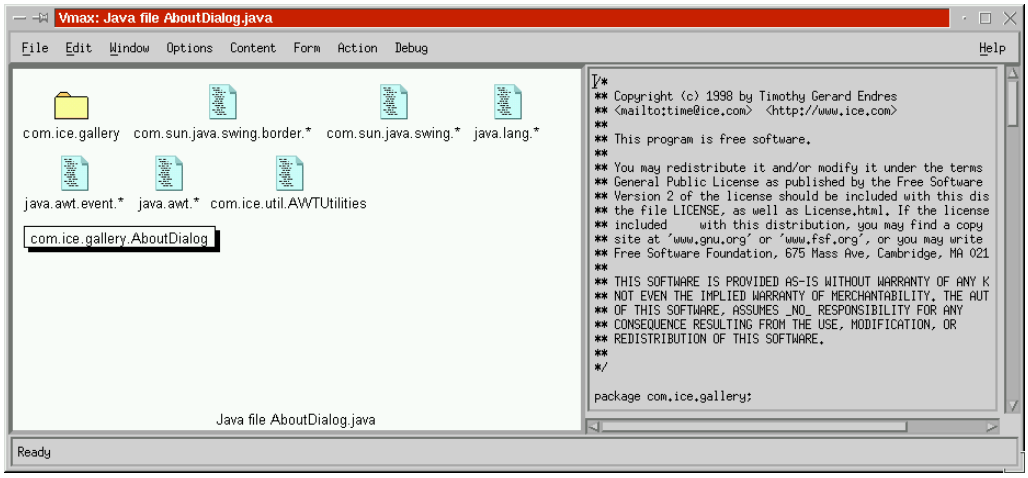


Figure 5.10. The overview of a Java file.

```
visual_context(java_decl(Decl), class).

view_content(java_decl(Decl),
        title(['Java ', Type, ' ', Name]) ) :-
        java:declaration(Decl, Type, _, _, _, _),
        long_identifier(Decl, Name).

view_content(java_decl(Decl), text(T)) :- text_node(Decl, T).

view_content(java_decl(Decl), variable(Var, Name)) :-
        member(Decl, Var),
        java:variable(Var),
        identifier(Var, Name).

view_content(java_decl(Decl), method(Method, Name)) :-
        member(Decl, Method),
        java:method(Method),
        identifier(Method, Name).

view_content(java_decl(Decl), native(Method)) :-
        member(Decl, Method),
        java:is_native(Method).

view_content(java_decl(Decl), abstract(Method)) :-
        member(Decl, Method),
        java:is_abstract(Method).

view_content(java_decl(Decl), public(Member)) :-
        member(Decl, Member),
        java:is_public(Member).
```

The alternative views of a class are selected from its Content menu shown in Figure 5.11.

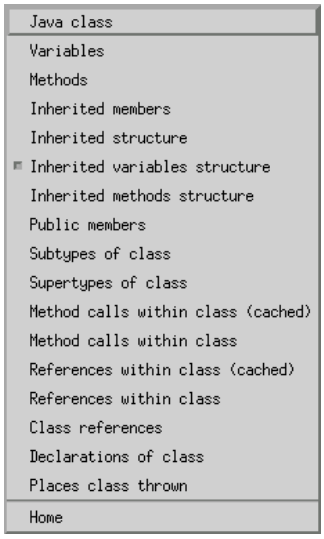


Figure 5.11. The Content menu for a class or interface.

The view of a class including all of its inherited members is shown in Figure 5.12. Variations of this view show only methods, variables or public inherited members (Figure 5.13). Figure 5.14 shows the supertypes and superinterfaces of a class, and these views are combined to show members in supertypes in Figure 5.15.

A view showing the subtypes of a class is shown in Figure 5.16, and a view giving the implementations for an interface is shown in Figure 5.17. There are views showing all type declarations

(Figure 5.18) and all interfaces (Figure 5.19). The complete class hierarchy is shown in Figure 5.20.

As mentioned previously, each item in these views can be navigated to by clicking on it, and navigating to a particular view for that object is achieved by right-clicking on the object to pop up its Content menu.

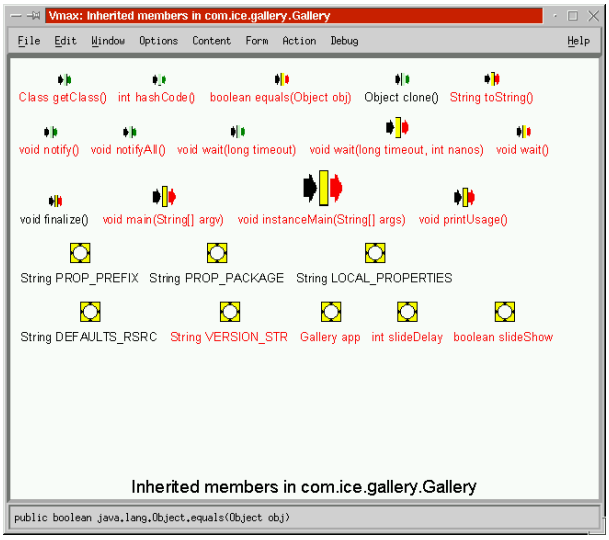


Figure 5.12. A class view including all inherited members and methods.

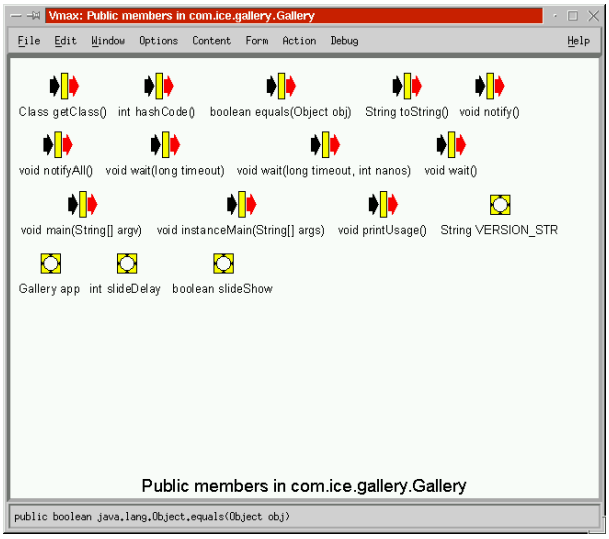


Figure 5.13. A class view of all public inherited members and methods.

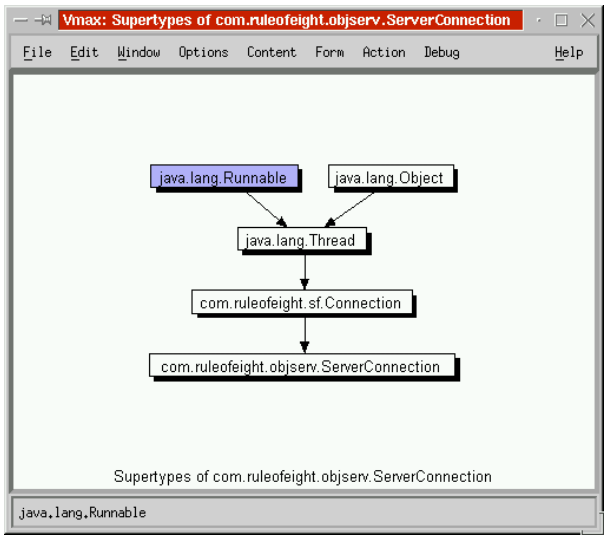
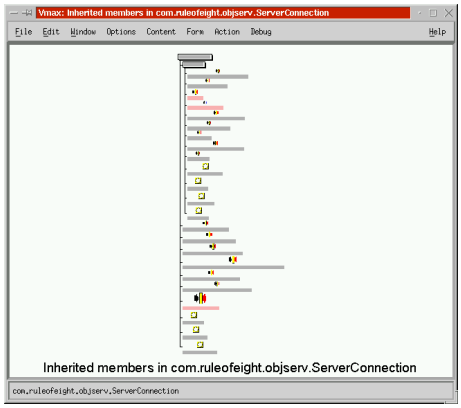
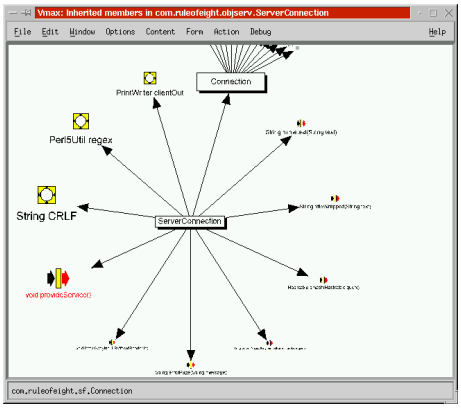


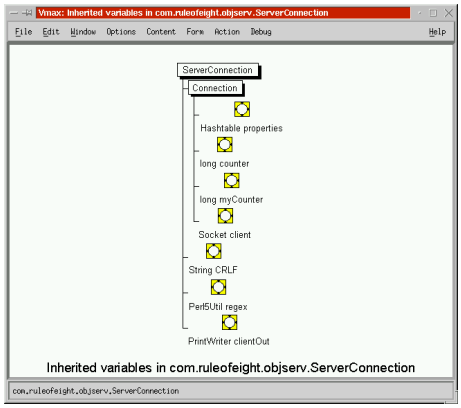
Figure 5.14. The supertypes and interfaces of a class.



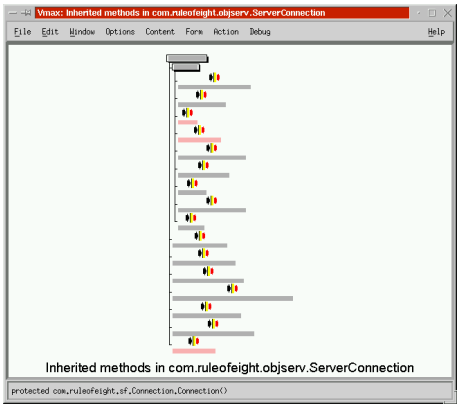
(a) All members.



(b) All members (fish-eye).



(c) Variables.



(d) Methods.

Figure 5.15. A class view giving members of supertypes.

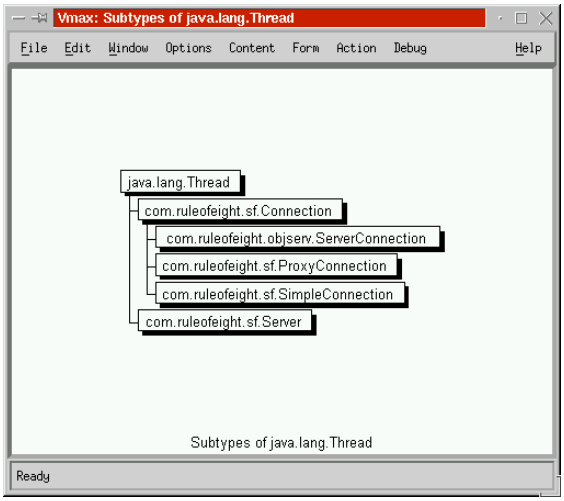


Figure 5.16. The subtypes of a class.

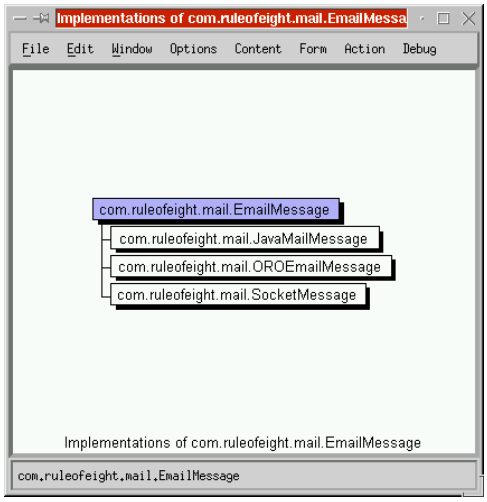


Figure 5.17. The implementations of an interface.

Figure 5.18. All classes and interfaces.

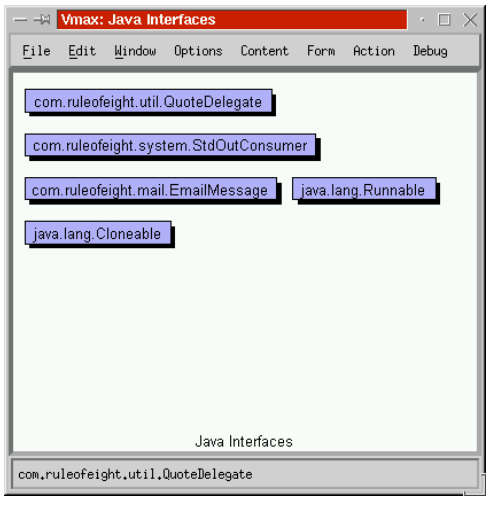


Figure 5.19. All interfaces.

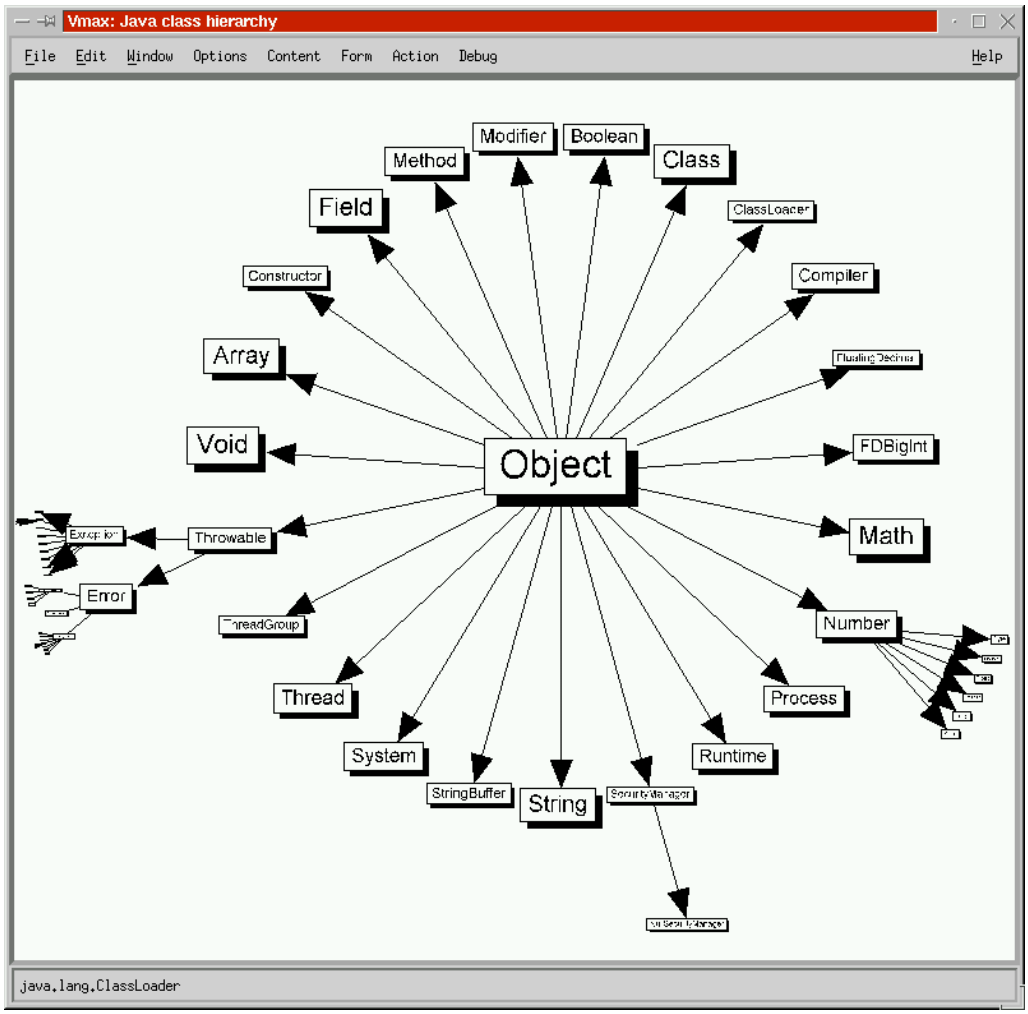


Figure 5.20. The whole class hierarchy.

5.6.2 Visualizing Cross-references

The information from program analysis in Section 5.5.2 is used to construct a variety of views to show how program objects relate to each other.

The class references view in Figure 5.21 shows which declaration types are present in the given class. The references between all classes is shown in Figure 5.22. This view can be restricted to a particular package. The *Declarations of class* view in Figure 5.23 gives all the places (in methods and classes) where the given class has been declared.

The *Places class thrown* view in Figure 5.24 gives all the methods where the class is thrown as an exception.

The reachable methods of a method in Figure 5.25 show all of the methods that are reachable from a given method. The *Calls to method* view shows all of the methods that may call the given method. The *Method calls within class* view of a class shows which methods call other methods within a class, in Figure 5.26. The complete call graph can be shown, but this is less useful because it is so large and the graphical layout algorithm has difficulty finding a good layout.

It is not possible to determine exactly which methods get called where. For example some sections of code are semantically "dead", and will never get executed. It is generally not possible to determine which method gets executed in a method invocation, because that method may be overridden by a subtype, and only methods that are *final* can be guaranteed not to be overridden. Further program analysis could restrict which methods might be called, but Vmax does not attempt this. The *Overriding methods* view shows the methods that override a given method, and the *Overridden methods* view shows all of the methods that have been overridden by a given method.

The *References of method* view in Figure 5.27 shows all of the methods and variables used by the method. The *References within class* view in Figure 5.28 show which class methods access which member variables. The *Reachable references* view of a method in Figure 5.29 combines the reachable methods with the method references to give a tree of all the variables that are reachable from the current method.

Clicking on any class member will navigate to it. Navigating to a variable will go to the type of the variable, if available, or to a view showing all of the methods where the variable is referenced.

Because method calls and variable references can be time-consuming to compute (especially for a view that has to scan the entire database), there is the option of precomputing cross-references from the Action menu. This constructs the dynamic predicates *cached_calls(M, M2)* and *cached_references(M, V)* which store which methods *M* use other methods *M2* or variables *V*. These behave exactly the same as method_calls/2 and *method_refs/2*, but are much faster.

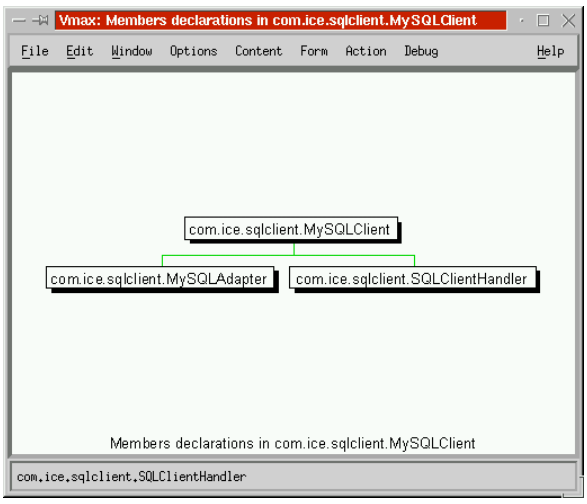


Figure 5.21. Classes contained within a class.

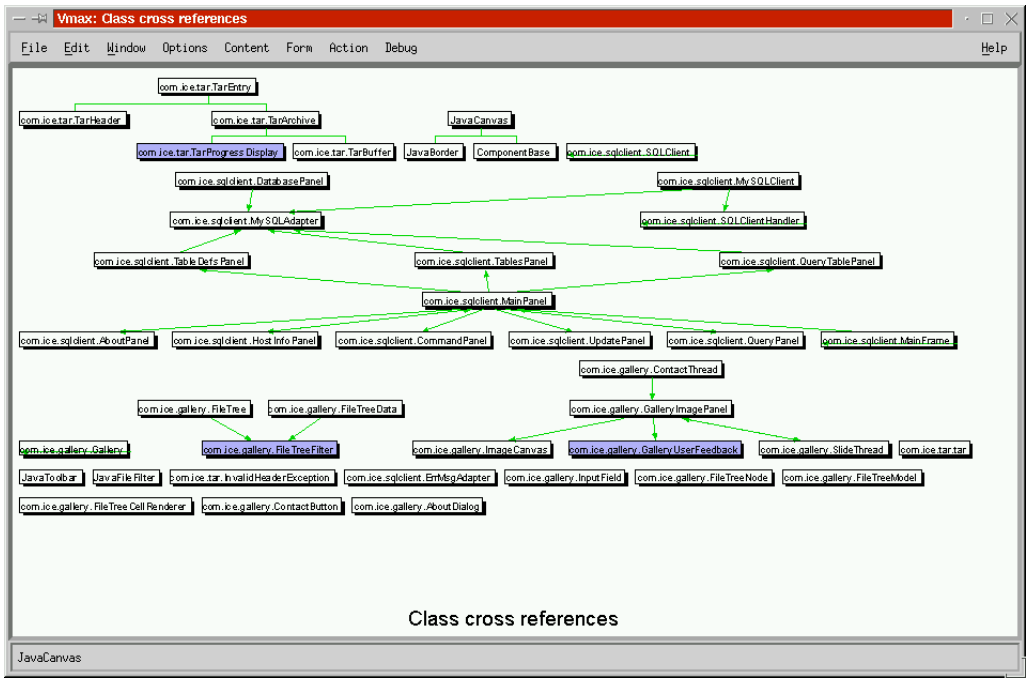


Figure 5.22. Membership of classes within others.

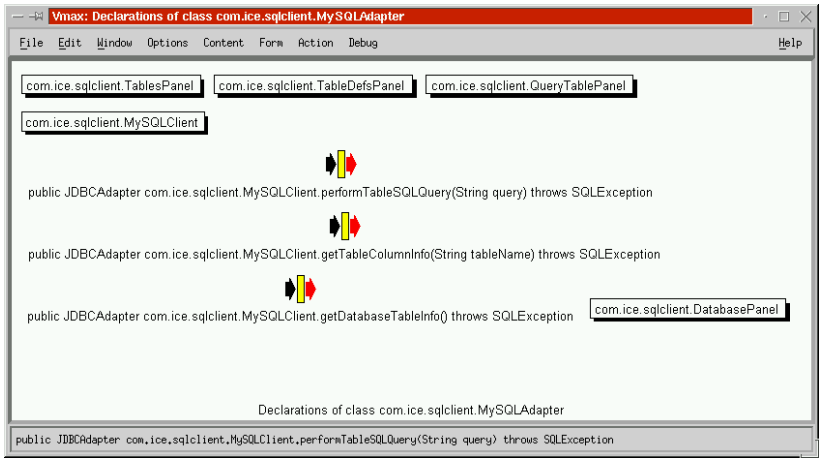


Figure 5.23. Places where a class is used.

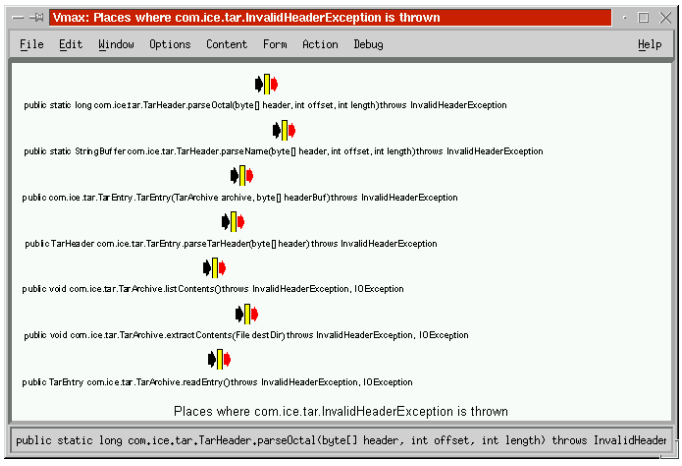


Figure 5.24. Methods where a class is thrown.

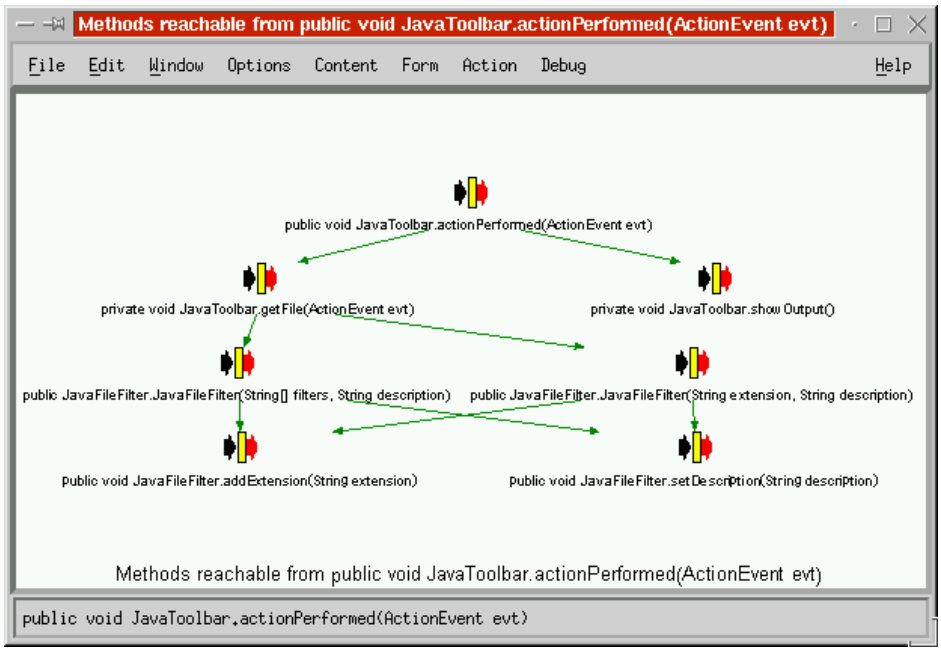


Figure 5.25. Reachable methods.

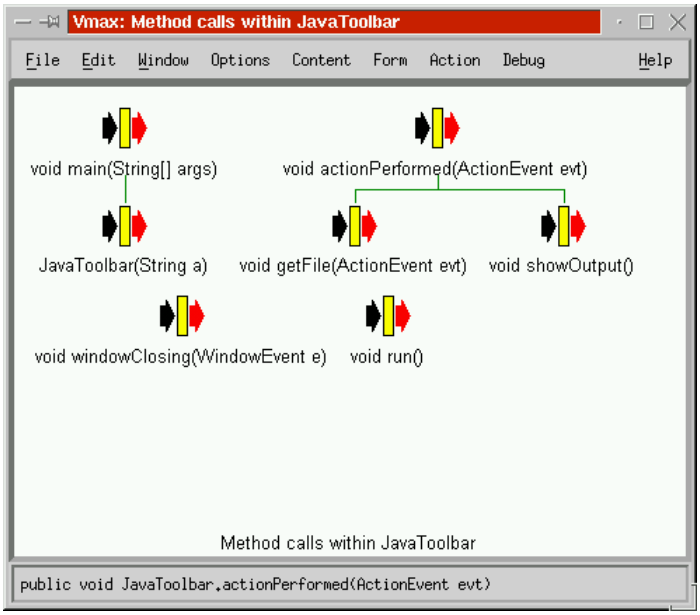


Figure 5.26. Method calls within a class.

Figure 5.27. Methods and variables used by a method.

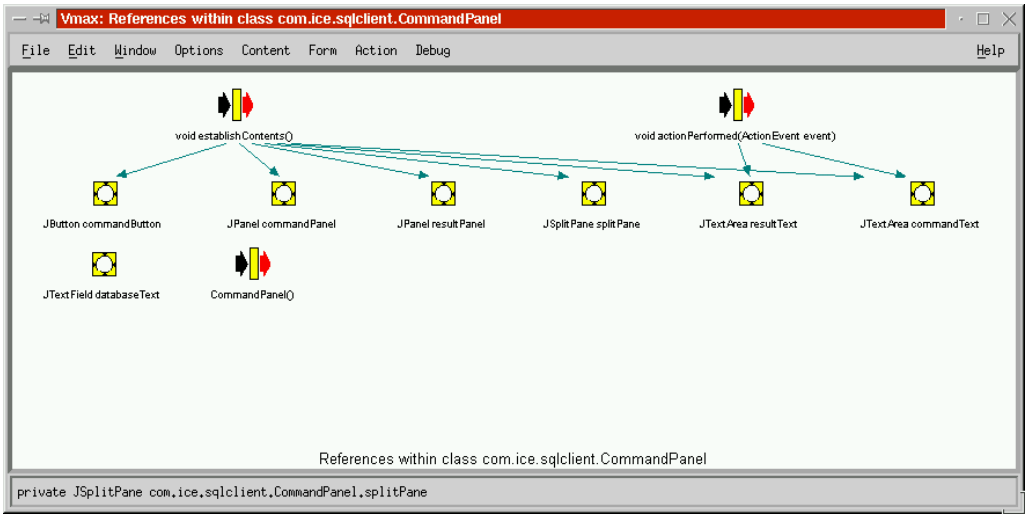


Figure 5.28. Variable usage within a class.

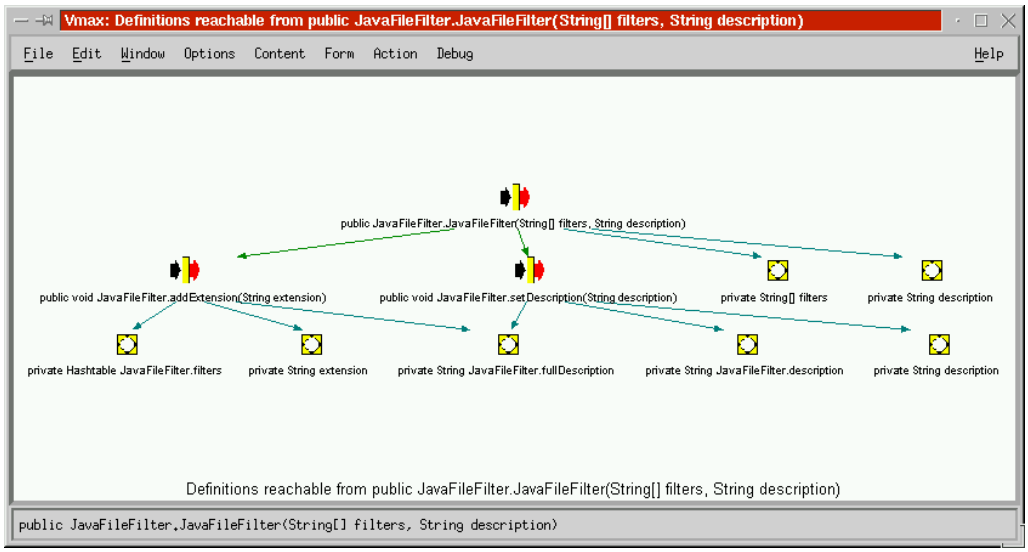


Figure 5.29. Variables and methods reachable from a method.

5.6.3 Visualizing Methods

Navigating to a method will give a graphical representation of the method body, as a *Nassi-Shneiderman Diagram* [72], which is an established graphical representation for block-structured code. Colour has been introduced to highlight the different types of statement. The basic method view is shown in Figure 5.30.

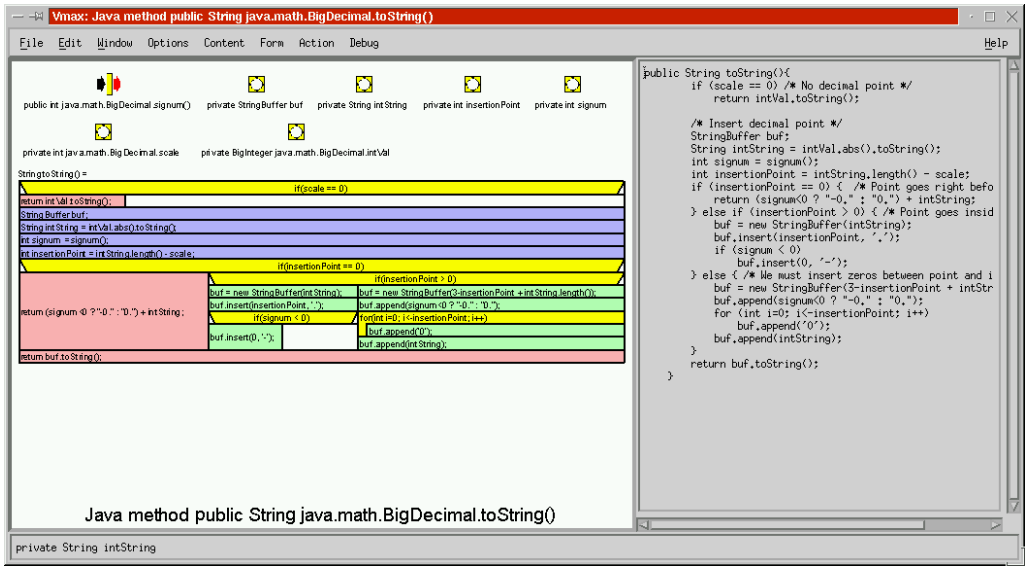


Figure 5.30. The default view of a method.

The view also contains all variables that the method references, and all methods that may be called, providing easy navigation to them. Different visualization relations for this view can give different forms of the code, and Figure 5.31 shows this and in particular the effect of adding colour to a Nassi-Shneiderman Diagram. The graphical structure of these diagrams is specified entirely using linear constraints described in Section 4.6.1.

It is even possible to modify the visualization relation in the Legend to turn one of these views into any other, and Figure 5.32 shows how text can be transformed into a coloured Nassi-Shneiderman Diagram. At each step, a different notation has been selected in the Legend, thus transforming the view.

There are some block constructs that Nassi and Shneiderman could not anticipate in 1973. A synchronized block is shown in Figure 5.33 and a try-catch-finally block is shown in Figure 5.34.[2] There are many other possible notations.

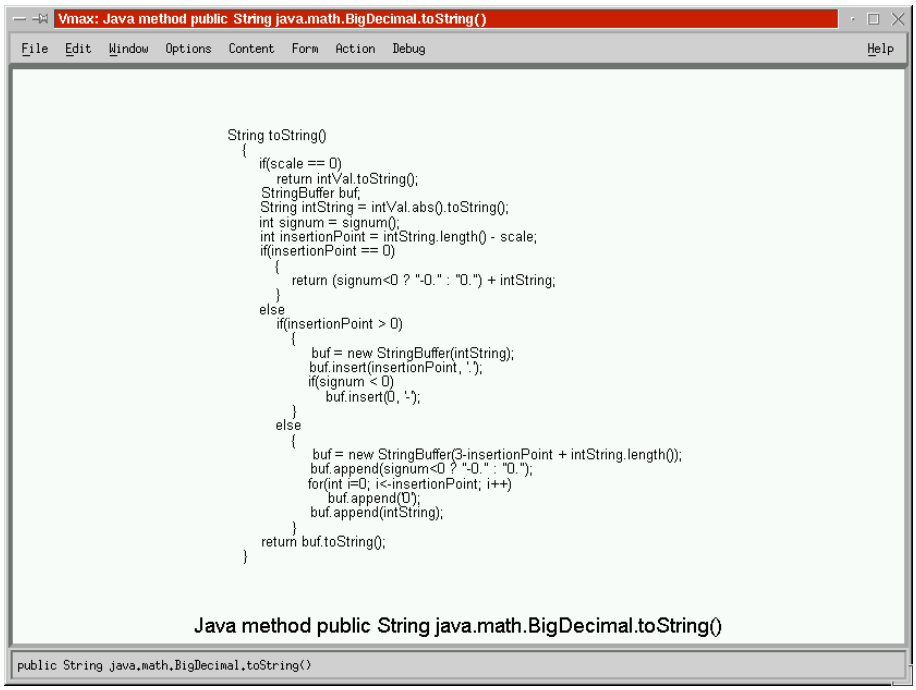
Switch statements with many options tend to make the diagram very wide, and this is shown in Figure 5.35(a). A modification to this notation to rectify this is shown in Figure 5.35(b), which also reflects Java's semantics that unless there is a break statement, case rules are executed sequentially.

Different method displays are obtained from the method's Content menu shown in Figure 5.36. Another means of representing the method code is through a flow graph. This shows control flow between statements in a method. Different types of transition (such as the branch of a condition) are labeled and indicated by different colours, as shown in Figure 5.37.

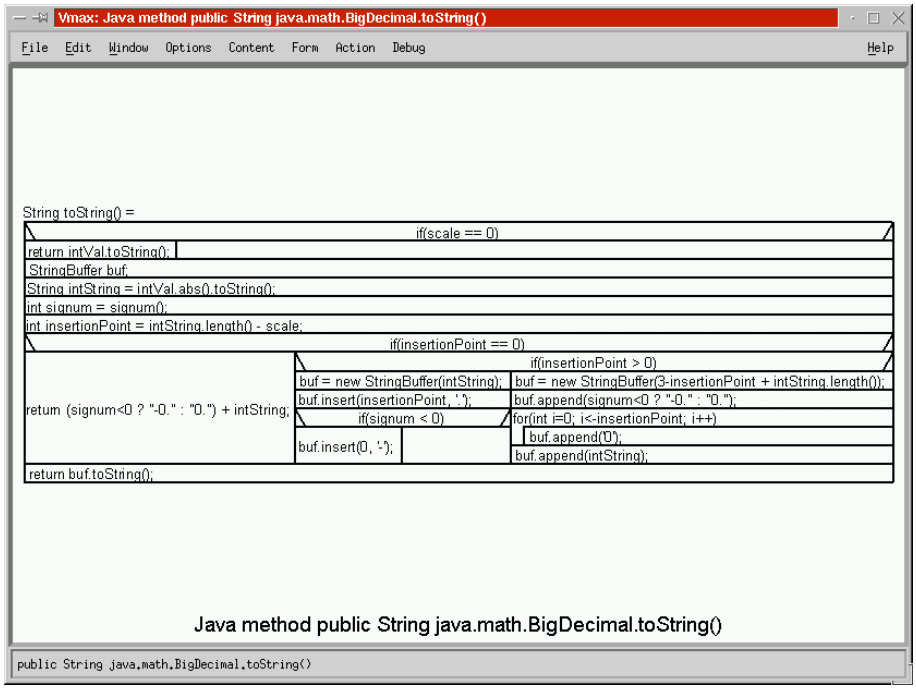
Exceptions present problems because potentially they can be thrown at any point during a try block, it is difficult to analyze which exceptions could be thrown at which points, which handler would handle it, and could obfuscate the flow chart. For these reasons they are not shown in the flow graphs. Synchronized blocks are also difficult to represent in a flow graph, and only the entry point of a synchronized block is indicated.

A final representation for a method extends Nassi-Shneiderman diagrams to visualize expressions within statements. An example is shown in Figure 5.38.

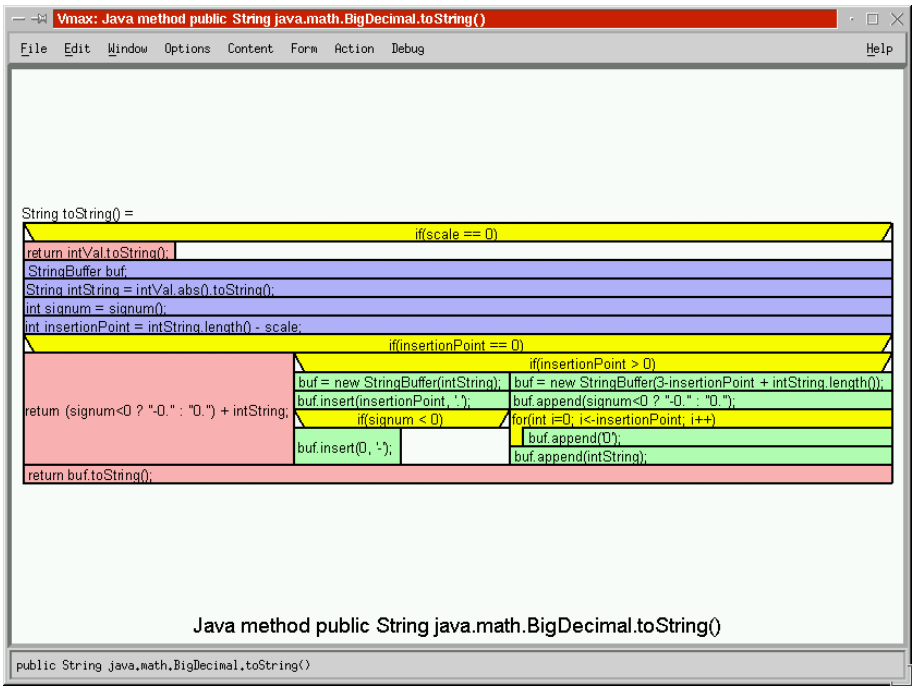
[2] Thanks to Alan Blackwell for suggesting these.



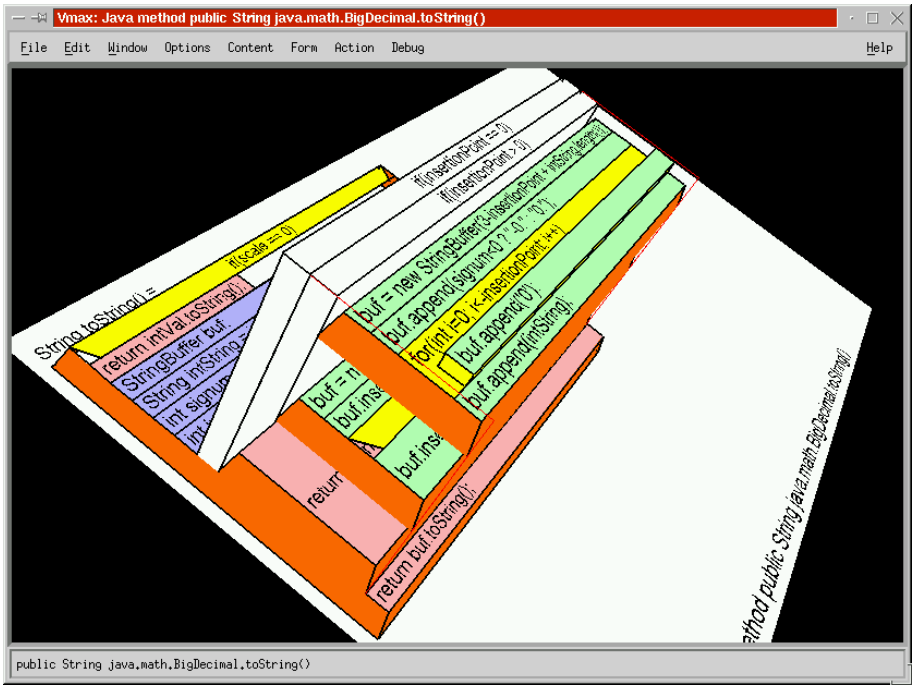
(a) Indented text.



(b) Nassi-Shneiderman Diagram.

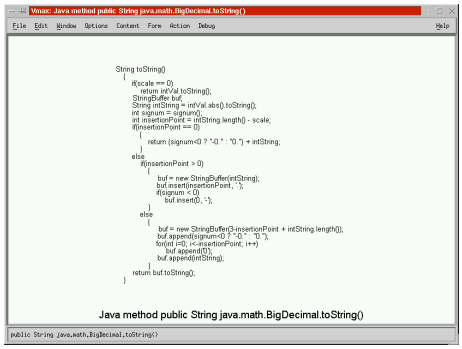


(c) Coloured Nassi-Shneiderman Diagram.

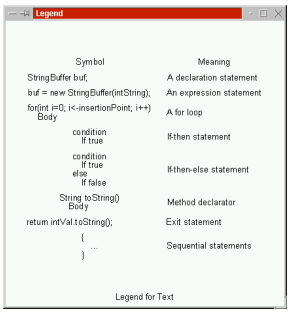


(d) 3-D block structure.

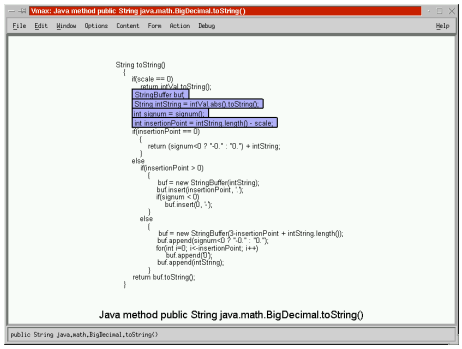
Figure 5.31. Different representations of block structured code.



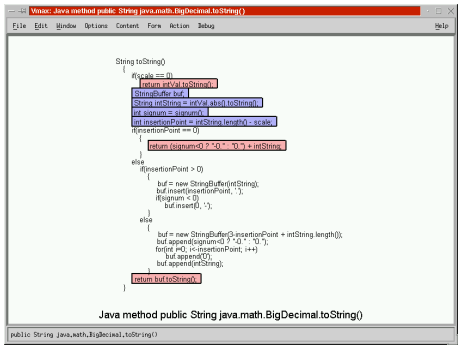
(a) The initial view.



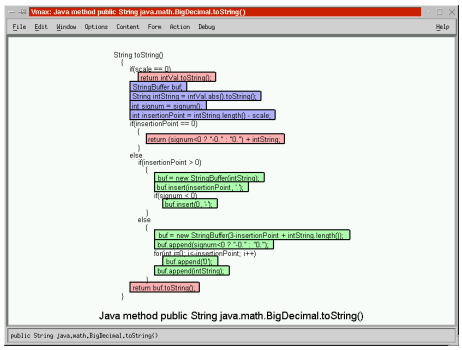
(b) The initial legend.



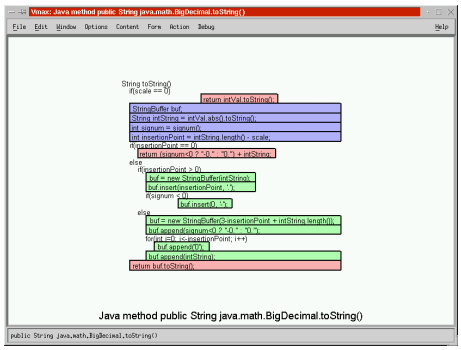
(c)



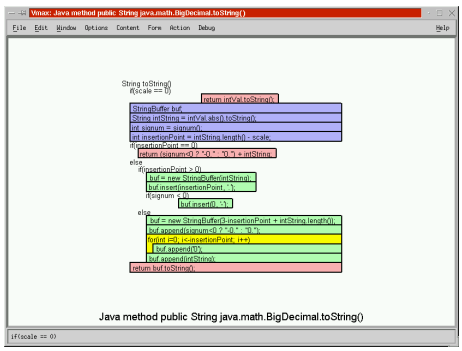
(d)



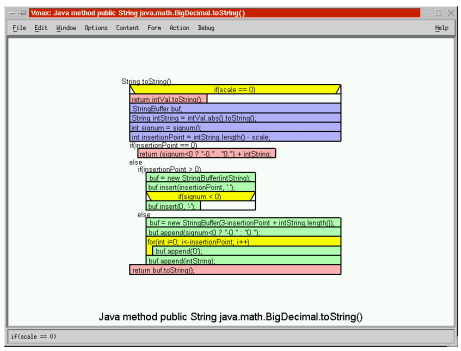
(e)



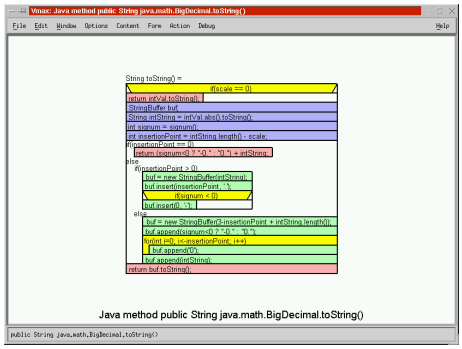
(f)



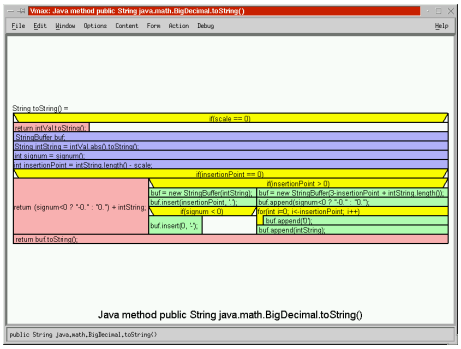
(g)



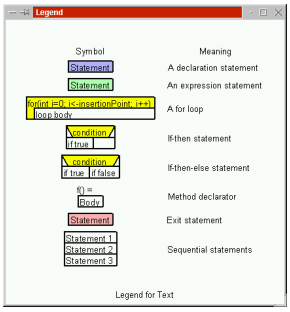
(h)



(i)

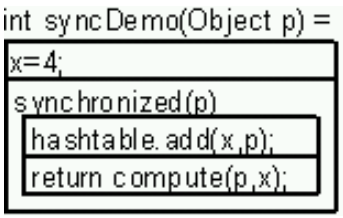


(j) The final view.

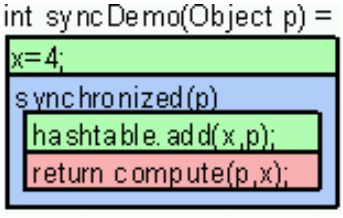


(k) The final legend.

Figure 5.32. A textual representation of code is transformed into a visual one by selecting different graphical forms in the legend.

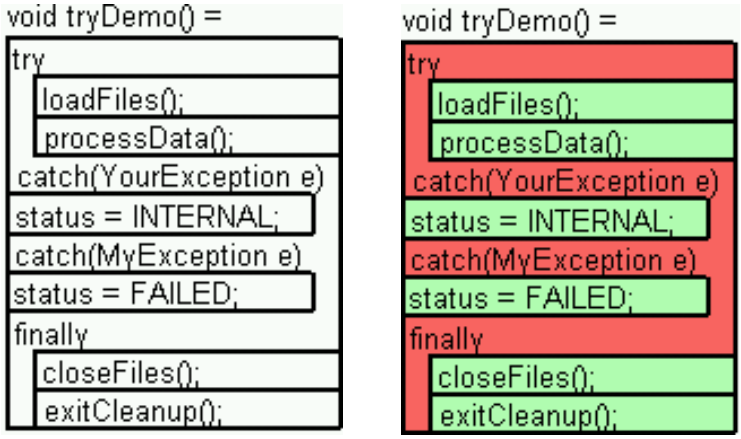


(a) Black and white.



(b) Colour.

Figure 5.33. A synchronized block.

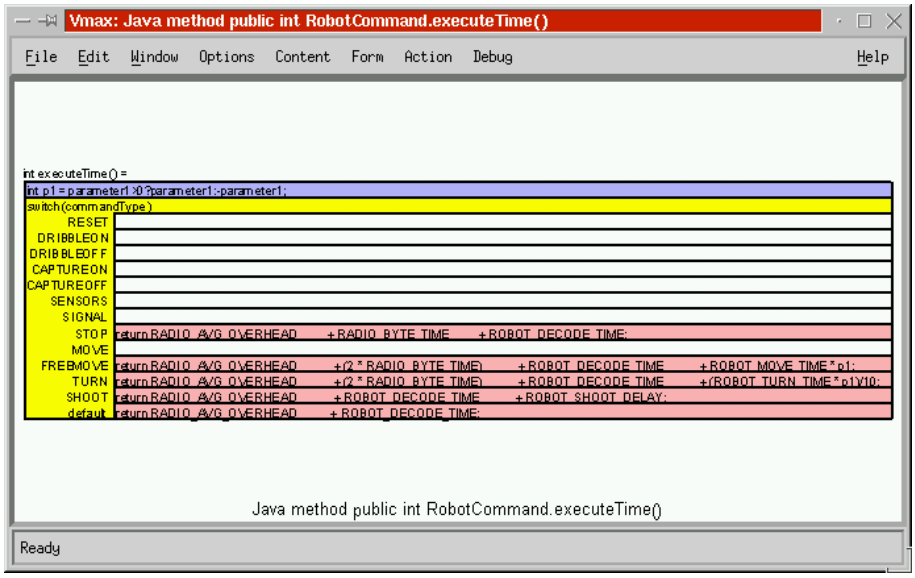


(a) Black and white.

(b) Colour.

Figure 5.34. A try-catch-finally block.

(a) Traditional horizontal switch statement layout.



(b) A vertical layout of a switch statement.

Figure 5.35. Alternative graphical forms of a switch statement.

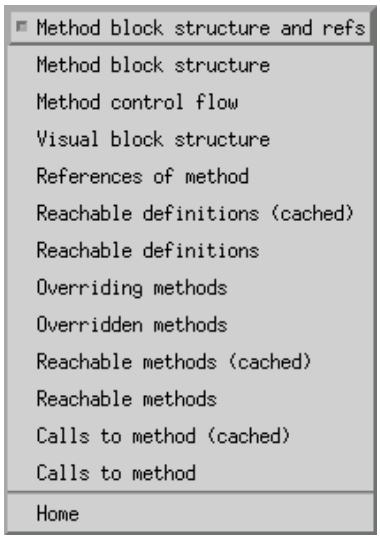
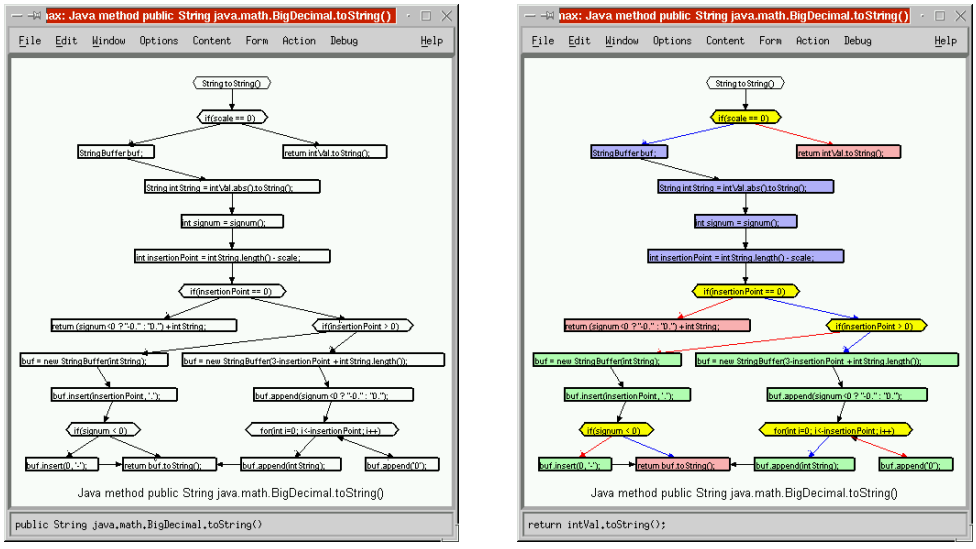


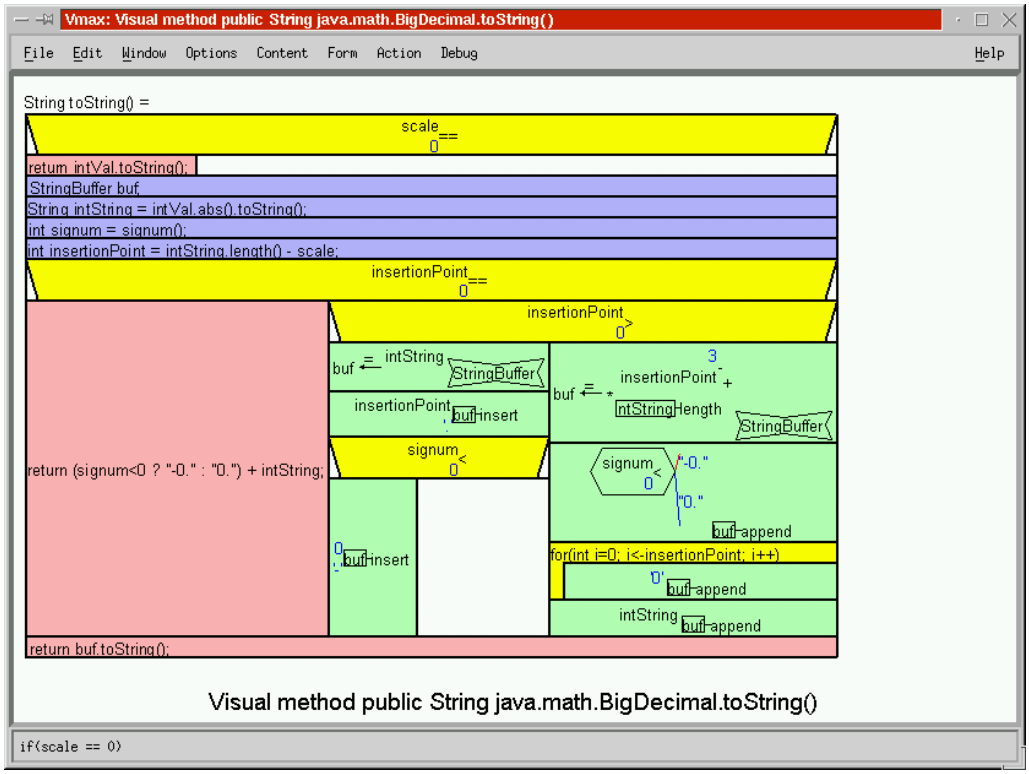
Figure 5.36. The Content menu for methods.



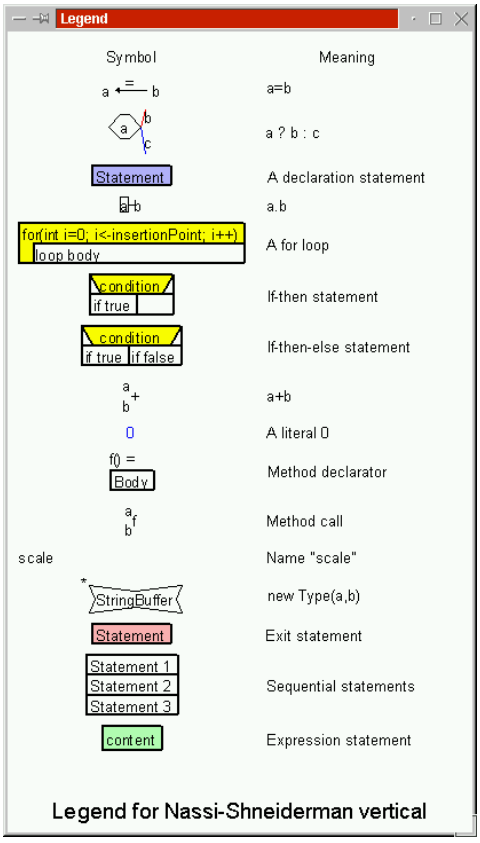
(a) Black and white.

(b) Colour.

Figure 5.37. Control flow within a method.



(a) The view.



(b) The legend.

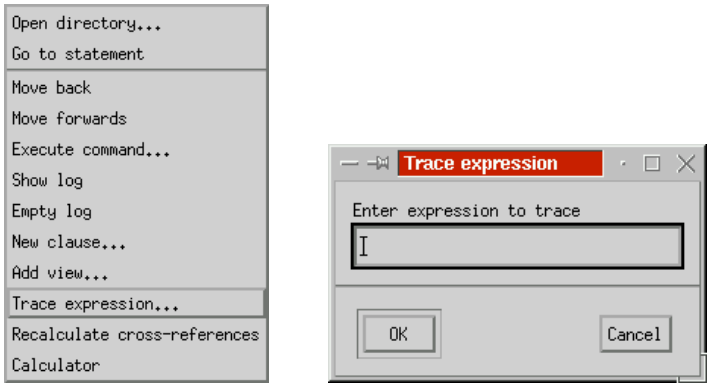
Figure 5.38. Nassi-Shneiderman Diagrams with colour and expression visualization.

5.7 Analyzing Run-time Data

Run-time data is gathered from a Java program by inserting *trace points* into the source code, and recompiling it. When the Java program executes, these *trace calls* output the run-time data to a *trace file*. Vmax reads this file and adds the data to Prolog's knowledge database for visualization.

5.7.1 Adding Trace Points

Trace calls can be inserted into the source code manually (simply by typing them), or automatically. The Action menu of a statement (obtained by clicking with the middle mouse button on the statement) has the option *Trace expression...* which pops up a dialog box prompting for the expression to trace at that statement. This is shown in Figure 5.39.



(a) A statement's Action menu. (b) The trace expression dialog box.

Figure 5.39. Tracing an expression by clicking on a statement.

The easiest way to trace a variable is to drag the variable to a statement, which will trace the variable at that statement. This has exactly the same effect as entering the name of the variable in the dialog box in Figure 5.39(b). The fully qualified name of the variable is used as the trace expression, to disambiguate it from other variables with the same name. Figure 5.40 illustrates this method, which works with both block structured and flow chart notations of the source code.

When a trace point is inserted, the fact

```
java:trace_point(EventNo, Expression, Statement)
```

is added to Prolog's database, where *EventNo* is a unique identifier, *Expression* is the trace expression text, and *Statement* is the identifier of the statement. The text *svt.trace.trace(EventNo, "Expression", Expression);* is inserted into the text buffer before the statement *Statement.* [3]

All the trace points in a Java file can be removed by selecting the *Remove trace points* option from the file's Action menu.

5.7.2 Generating the Trace File

After all of the trace points have been added, the program is recompiled and executed. When a *java.lang.Object* is passed to *svt.trace.trace()*, it uses the *Reflection* package *java.lang.reflect* to probe the contents of the object. This allows run-time querying of data types, including field names, types and values, and is used to extract all of the information about the object for output to the trace file. Unfortunately *java.lang.reflect* can only probe public members, which is a necessary security feature. If a compound object (derived from *java.lang.Object*) is encountered,

[3] This could change the semantics of the program, so ideally a more sophisticated method is required.

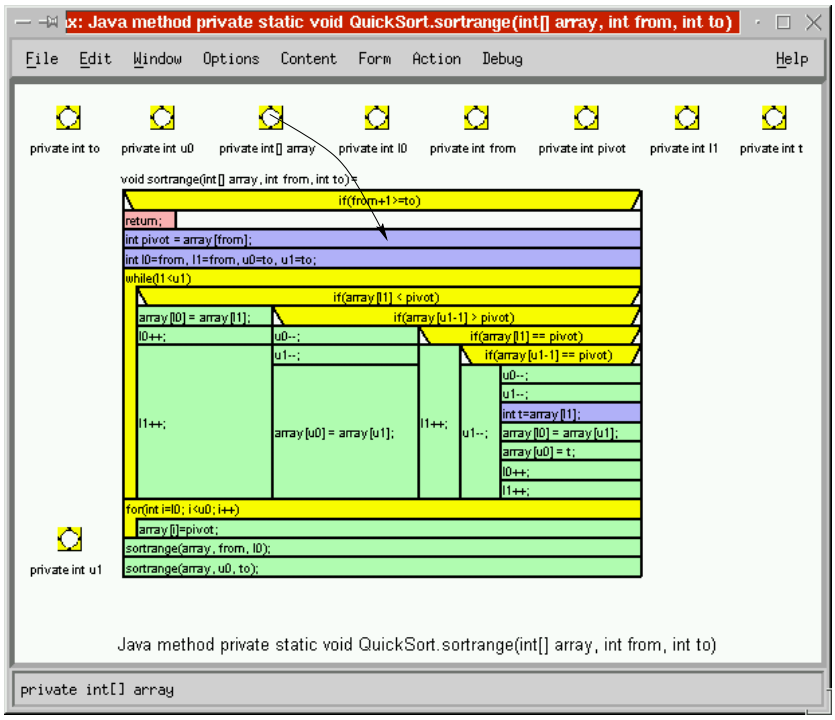


Figure 5.40. The variable is 'drag and dropped' onto the statement to automatically insert a trace of the variable in front of the statement.

then its members are traced recursively, but a hash table (*java.util.Hashtable*) stores the *Object*s that have already been encountered, to prevent the trace routine from entering infinite loops in cyclic data structures.

Each time *svt.trace.trace(Event, Name, Expression)* is called, it outputs

```
Event: eventno
Name: name
TimeStamp: time
```

to the trace file, where *eventno* is the event number *Event*, *name* is the name of the event, and the *time* is the time in milliseconds from the start of the program. The next output is *Expression.* An *int* is output

```
IntegerValue: value
```

where *value* is the value of the integer. A *float* or a *double* is output

```
FloatValue: value
```

where *value* is the value of the float. An array is output

```
ArrayLength: length
contents
```

Where *length* is the length of the array, and *contents* is *length* values that make up the array. A *null* object is output

```
Object: null
```

and a *java.lang.Object* is output

```
ClassName: class
ObjectNo: id
Fields: fields
members
```

where *class* is the name of the object's class, *id* is an integer assigned to the object, *fields* is the number of fields in the Object, and *members* are the members of the class. If the object has been output previously in the same event, then instead it is output

```
ObjectNo: id
```

The field members are output

```
FieldName: name
value
```

where *name* is the name of the field, and *value* is its value. Fields and array members may themselves be objects or arrays.

5.7.3 Reading the Trace File

A trace file is read by navigating to it. The *ensure_trace_loaded(File)* predicate is called which reads the file *File*. The trace file is read into a buffer, and a lexical analysis is performed on it using Lex. The lexemes are parsed using the DCG [75]

```
trace_file([])    --> "".
trace_file([H|T]) --> input(H), trace_file(T).

input(input(E,T,V))   --> event(E), time(T), value(V).
input(input(E,N,T,V)) --> event(E), name(N), time(T), value(V).
name(N)               --> "Name: ", string(N).
event(E)              --> "Event: ", integer(E).
time(T)               --> "TimeStamp: ", integer(T).

value(integer(I)) --> intvalue(I).
value(float(F))   --> floatvalue(F).
value(array(L))   --> array(L).
value(O)          --> object(O).

intvalue(I)   --> "IntegerValue: ", integer(I).
floatvalue(F) --> "FloatValue: ", float(F).
array(L)      --> "ArrayLength: ", integer(N), values(N, L).

values(0, [])    --> "".
values(N, [H|T]) --> {N>0, M is N-1}, value(H), values(M).

object(nullobject) --> "Object: ", "null".
object(object(Id)) --> "ObjectNo: ", integer(Id).
object(object(Id, Class, Fields)) -->
        "ClassName: ", string(Class),
        "ObjectNo: ", integer(Id),
        "Fields: ", integer(F), fields(F, Fields).

fields(0, [])    --> "".
fields(N, [H|T]) -->
        {N>0, M is N-1}, field(H), fields(M, T).

field(field(Name, Value)) -->
        "FieldName: ", string(Name), value(Value).
```

The implemented DCG reads lexemes slightly differently (using the *token/2* predicate), and also adds this data to Prolog's database by adding facts to the dynamic predicates *trace:event/5* and *trace:value/3*. Each input event is stored

```
trace:event(Input, File, EventNo, Time, Value)
```

where *Input* is a unique identifier for the input number, *File* is the identifier of the trace file, *EventNo* is the event identifier, *Time* is the time stamp of the event, and *Value* is the unique identifier of the input value. Each input value is stored

```
trace:value(Value, String, Term)
```

where *Value* is the unique identifier of the value, *String* is a string that describes the value (such as *myarray[5].x*), and *Term* is a term that stores the value. *Term* can be

- *array(Values)* - An array with a list of values *Values*.
- *float(Float)* - A *float* or *double* with value *Float*.
- *integer(Int)* - An integer with value *Int*.
- *null* - A null object.
- *object(Id, Class, Fields)* - An object with object id *Id*, class name *Class*, and fields *Fields*. *Fields* is a list of members of the form *field(FieldName, Value)*.
- *object(Id)* - An object with object id *Id*.

If changes are made to the source code, or trace points have been added or removed, then the program can be recompiled and executed to generate a new trace file. The option *Reload trace* on the trace file's Action menu purges the run-time data from the database and loads in the new trace file. Because the trace file is stored off line, it can be re-examined at any time.

5.8 Run-time Data Visualization

Clicking on a trace file navigates to it, which reads it in and analyzes it if necessary. The default view is shown in Figure 5.41, which gives event lines for each value traced. An *event line* is a line representing time on which marks have been indicated where the event occurs. Time is along the horizontal axis, and different events are on the vertical axis.

Each event line is labeled with the expression or variable that was traced. Every value in the trace file can be visualized by selecting the *All values* view of the trace file. This view is shown in Figure 5.42. The values in a single event line can be displayed by clicking on an event line, shown in Figure 5.43, with the time in the left column, input expression in the middle column, and the value in the right hand column. This event line can be animated as shown in Figure 5.44. The animation is implemented by

```
trace:animate_file(File) :-
        repeat,
        trace:input(_, File, _, _, Value),
        frame_rate(1.0),
        navigate_to(trace_value(Value)),
        user_interrupt.
```

where backtracking over the predicate will navigate to each value *Value* in the trace file *File*. A variation of this action animates groups of inputs, and another variation animates backwards. The *repeat* predicate loops the query, *frame_rate(1.0)* pauses to ensure an interval of one second between calls, and *user_interrupt* throws an exception when the user presses the *Escape* key, terminating the animation.

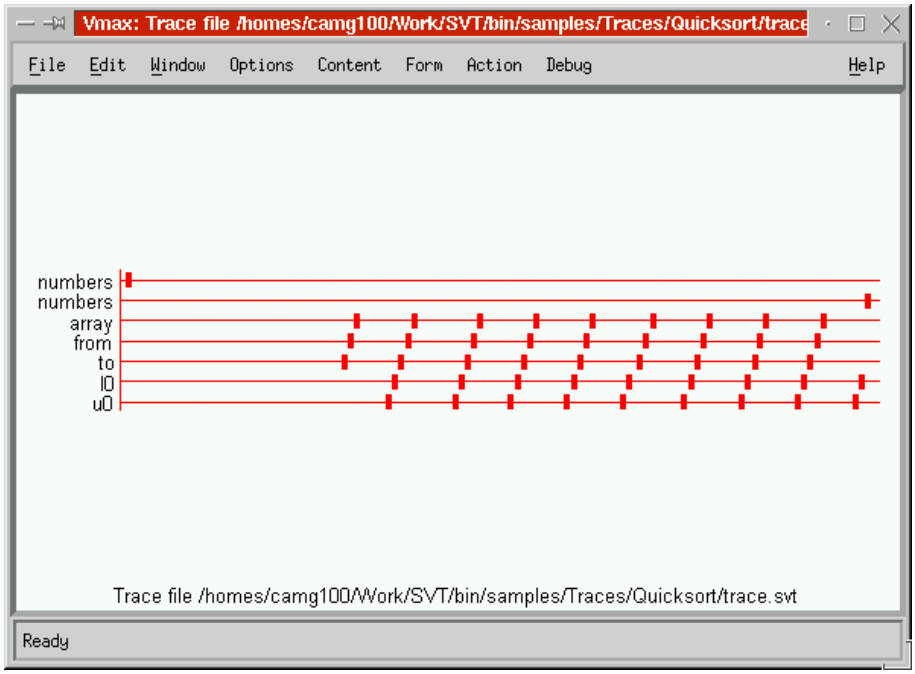


Figure 5.41. All the events in a trace file.

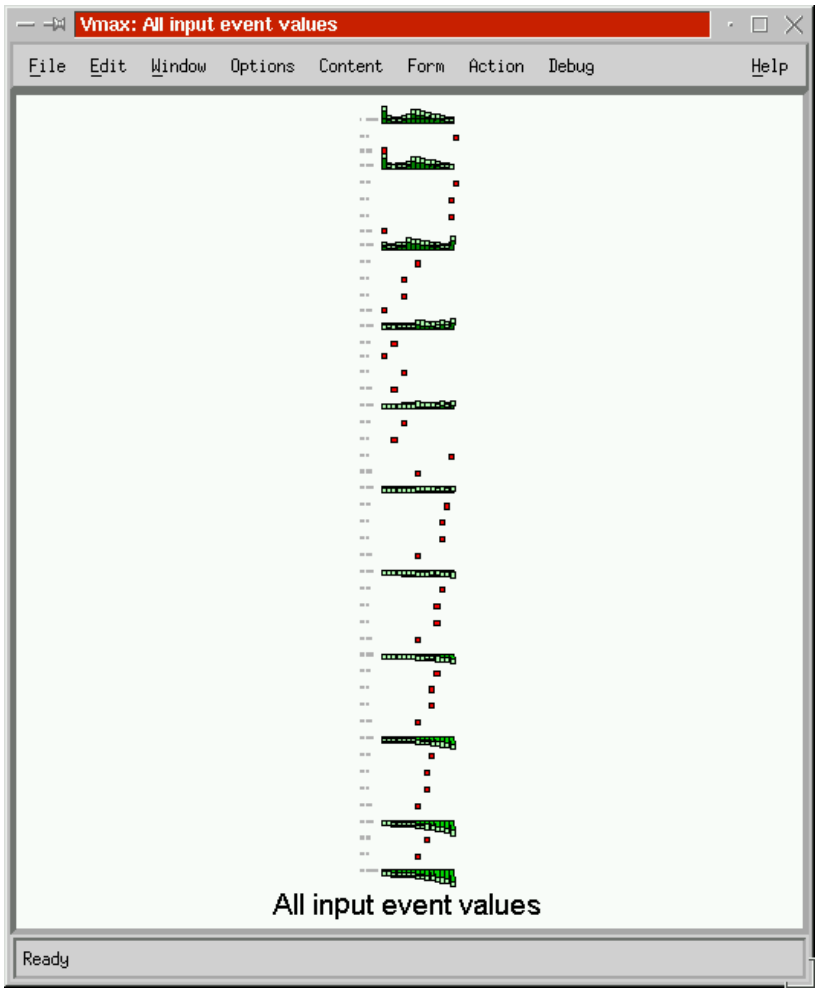


Figure 5.42. All values in a trace file.

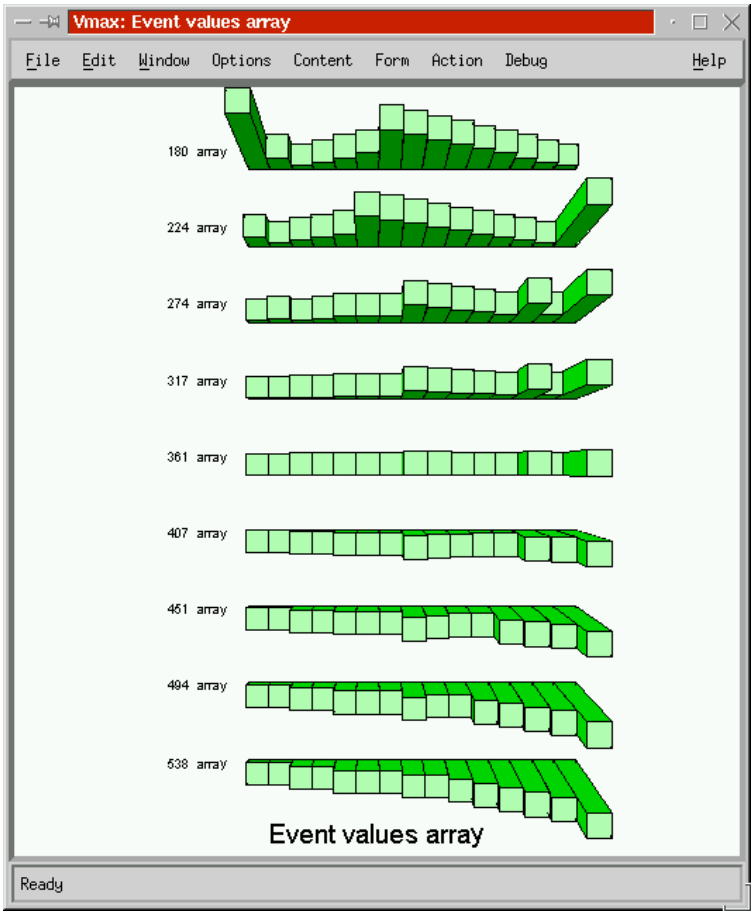
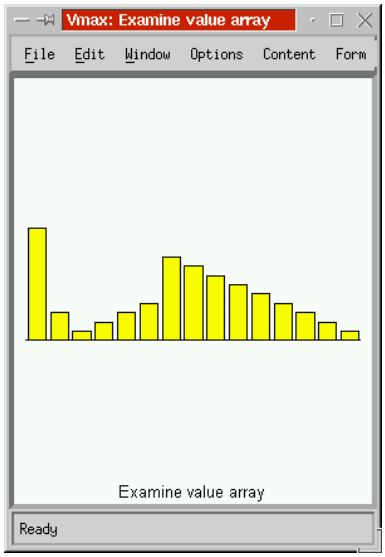
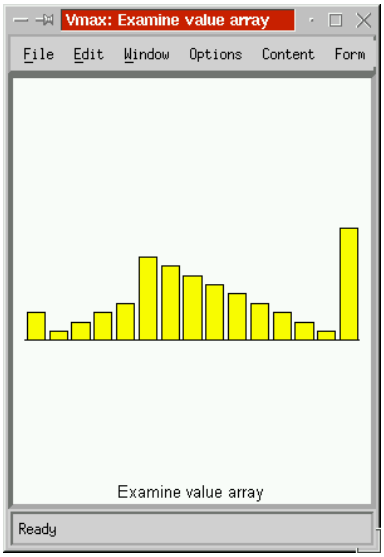


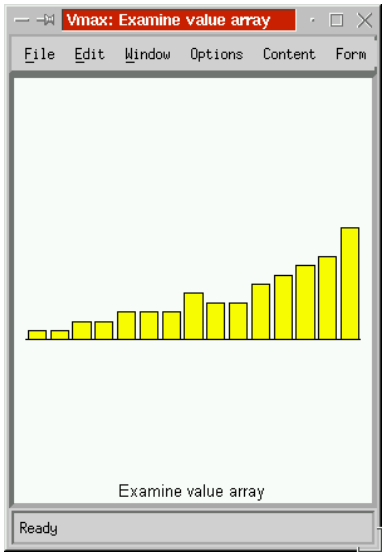
Figure 5.43. All the values in an event line.



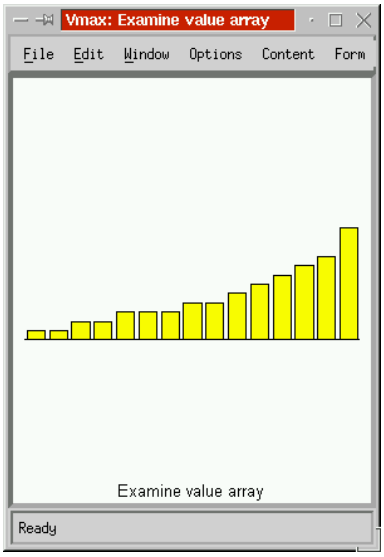
(a) Frame 1.



(b) Frame 2.



(c) Frame 8.



(d) Frame 9.

Figure 5.44. Animating an event line.

An individual input can be visualized by clicking on it in a view, or by clicking on its marker on the event line. Pressing the 'n' key or navigating to the *Next input* view of an input will navigate to the chronologically next input of the same event. Pressing the 'p' key or navigating to the *Previous input* view of an input will navigate to the previous input of the same event. The *Any next input* view displays the next input from any event, and *Any previous input* displays the previous input from any event. The *Next 5 inputs* view of an input will display the next five inputs from the same event, and the *Any next 5 inputs* will display the next five inputs from all events, shown in Figure 5.45.

The statement at which the trace occurred can be navigated to by selecting the *Go to statement* view of the event line.

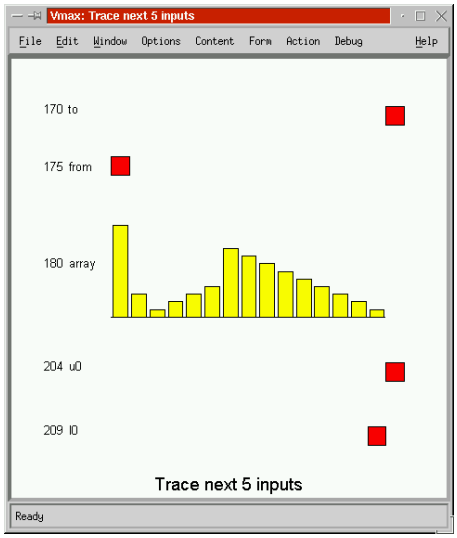


Figure 5.45. A sequence of five inputs.

5.8.1 Value Visualization

An individual value can be visualized by clicking on its input mark on an event line, or from a view. Clicking on a member of a compound structure navigates to the sub-structure indicated by the mouse. The correct name for each sub-structure (such as *array[5].x*) is automatically derived for the value and displayed in the title of the view. This name is automatically displayed in the status bar as the mouse moves over the view. The value view is specified

```
view(Value, trace_value(Value), 'Value') :-
        trace:value(Value, _, _).

view(Input, trace_value(Value), 'Value of input') :-
        trace:input(Input, _, _, _, Value).

visual_context(trace_value(Value), trace).

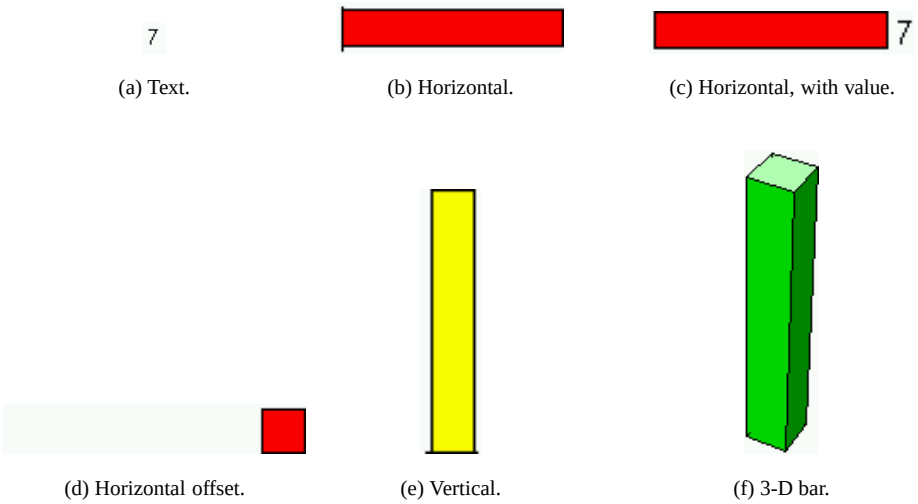
view_content(trace_value(Value), title(['Value ', Name]) ) :-
        identifier(Value, Name).

view_content(trace_value(Value), Content) :-
        trace:value_content(Value, Content).

trace:value_content(Value, Content) :-
        trace:value(Value, _, Term),
        (
                Term = array(Values),
```

```
            in_list(Value2, Values),
            trace:value_content(Value2, Term)
    ;
            Term = array(Values),
            Content = array(Value, Values)
    ;
            Term = integer(I),
            Content = integer(Value, I)
    ;
            Term = float(F),
            Content = float(Value, F)
    ;
            Term = null,
            Content = null(Value)
    ;
            Term = object(Value, Class, Fields),
            Content = object(Value, Class, Fields)
    ;
            Term = object(Value, Class, Fields),
            in_list(field(Name, Value2), Fields),
            trace:value_content(Value2, Content)
    ).
```

Integer and floating point values can be visualized as shown in Figure 5.46. Arrays can be visualized as shown in Figure 5.47, and structures as in Figure 5.48. The name of the structure and fields are displayed with the data itself. Very large data structures may clutter the view, so it is possible to show a structure to a certain depth, as shown in Figure 5.49. Browsing to members in the view would reveal more structure.



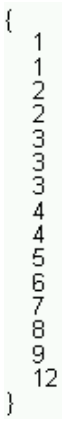
(a) Text. (b) Horizontal. (c) Horizontal, with value.

(d) Horizontal offset. (e) Vertical. (f) 3-D bar.

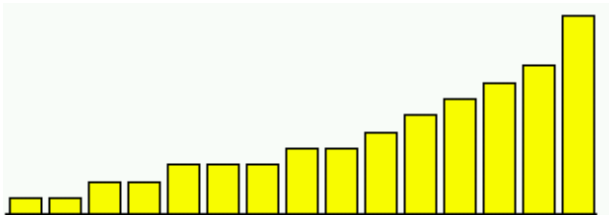
Figure 5.46. Different ways of visualizing integer and floating point values.

By using the legend, a textual representation of a value can be transformed into a graphical one, as shown in Figure 5.50. At each step, a different graphical notation is changed in the Legend, thus transforming the view.

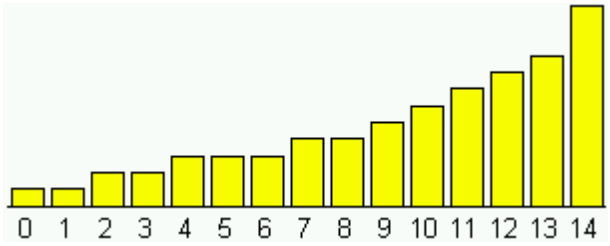
It should be clear that any combination of graphical representations can be combined to tailor the view. More visuals could be added, and specialized views can be declared in Prolog if the provided views prove inadequate.



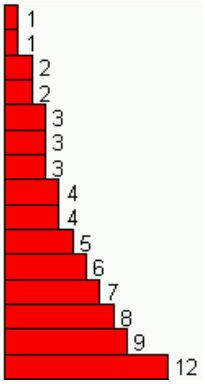
(a) Text.



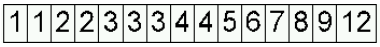
(b) Horizontal.



(c) Horizontal numbered.

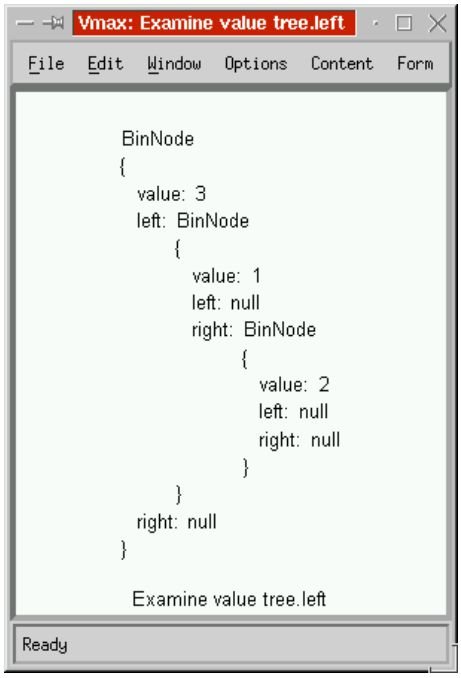


(d) Vertical.

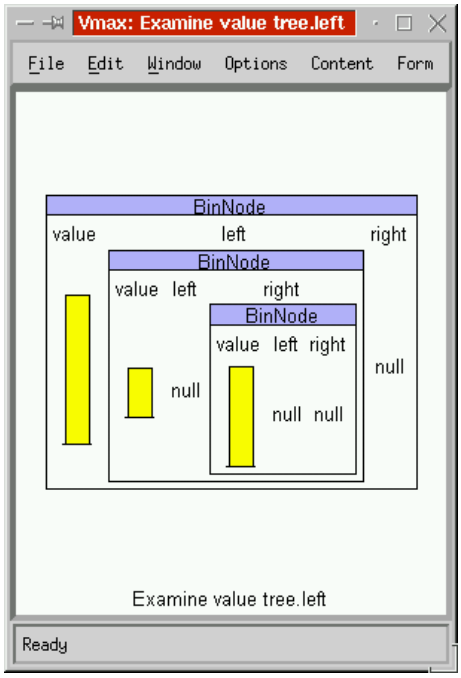


(e) Boxed.

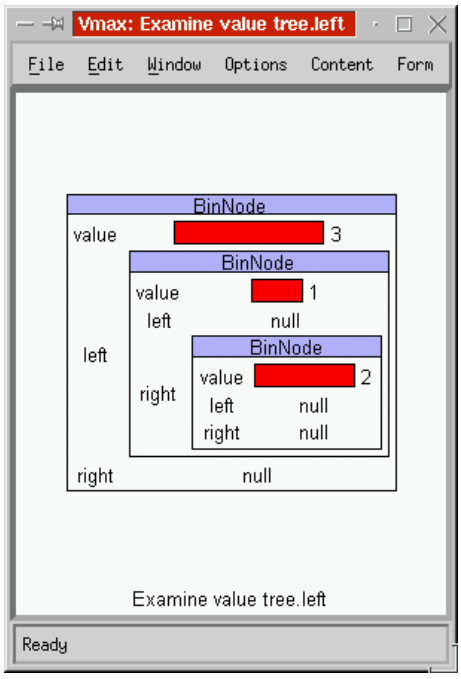
Figure 5.47. Different ways of visualizing arrays.



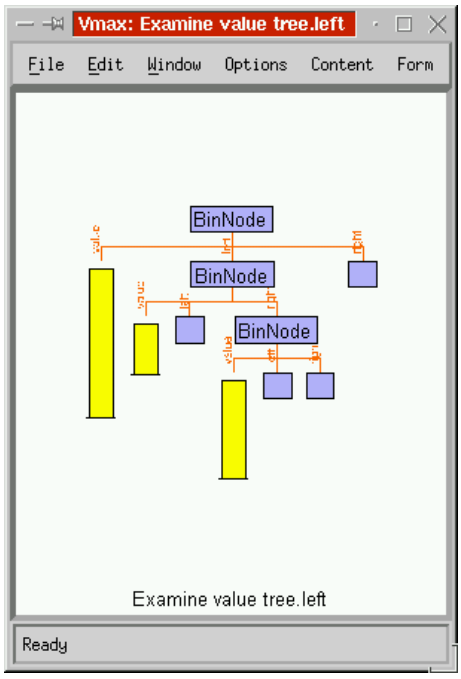
(a) Text.



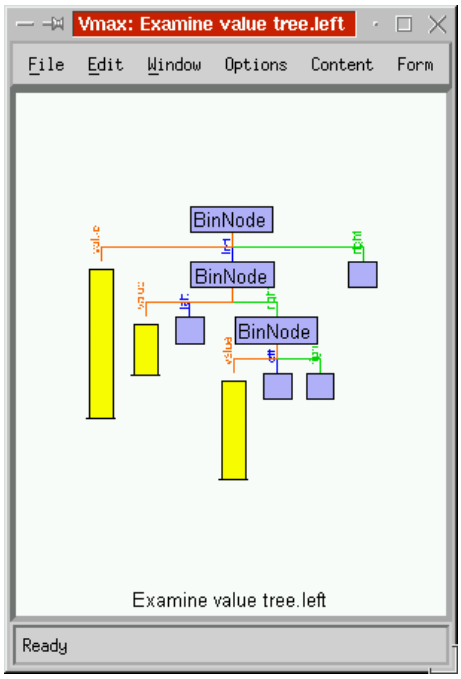
(b) Horizontal.



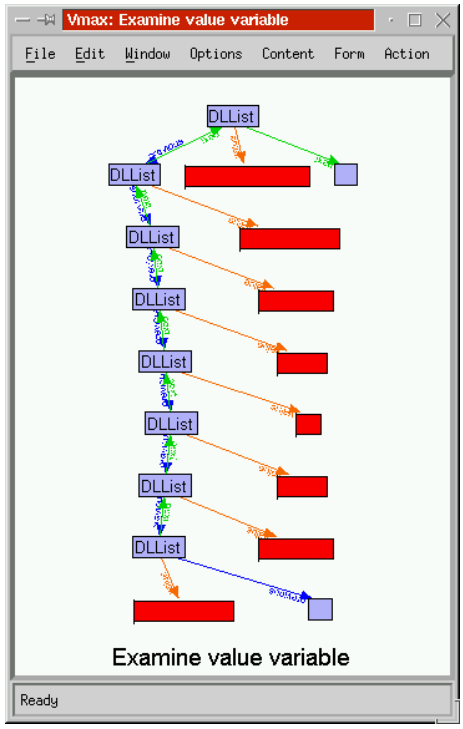
(c) Vertical.



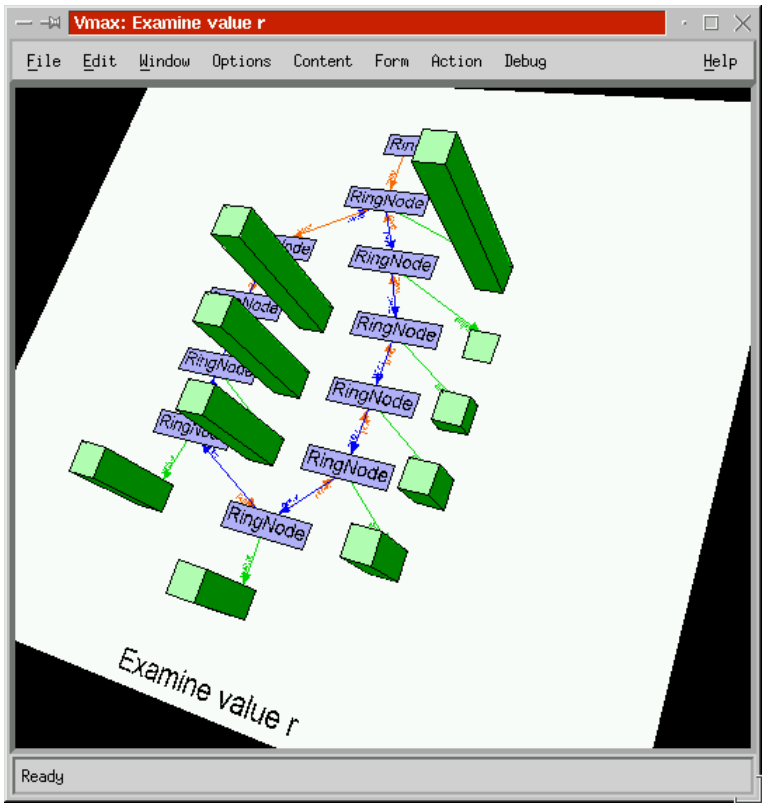
(d) Plain graph.



(e) Graph with coloured edges.

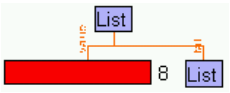


(f) A doubly linked list.

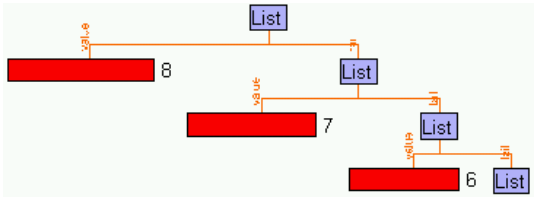


(g) A ring.

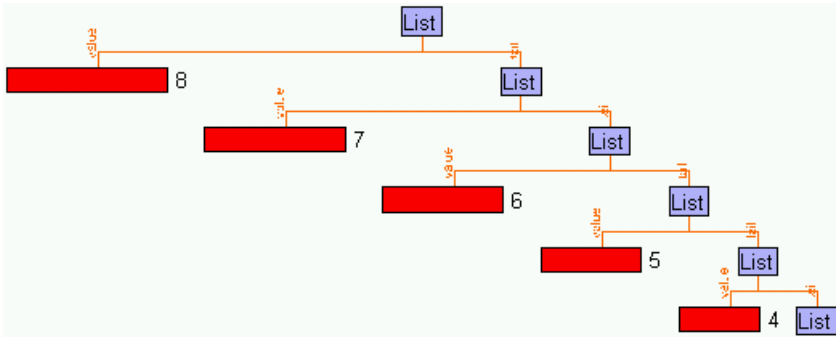
Figure 5.48. Different visualizations of structures.



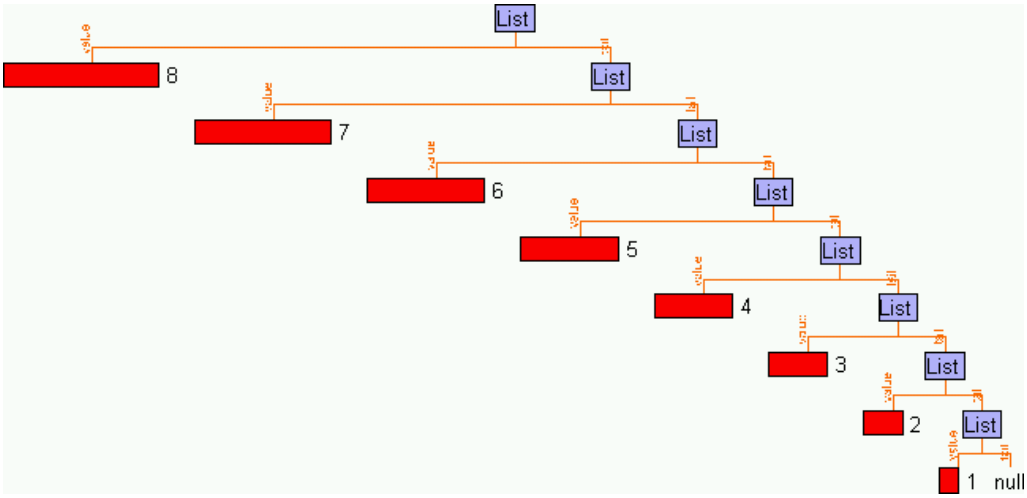
(a) Depth=1.



(b) Depth=3.

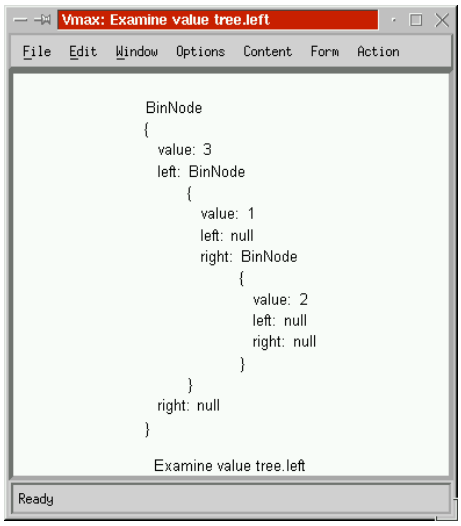


(c) Depth=5.

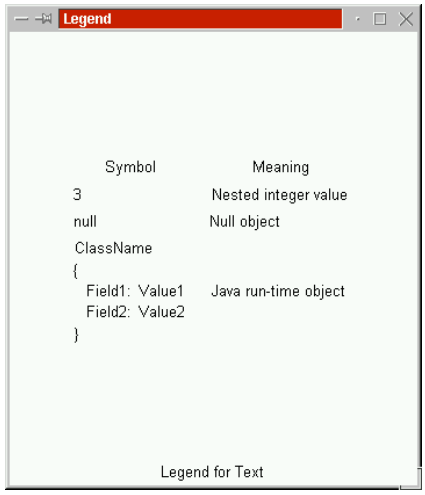


(d) The whole structure.

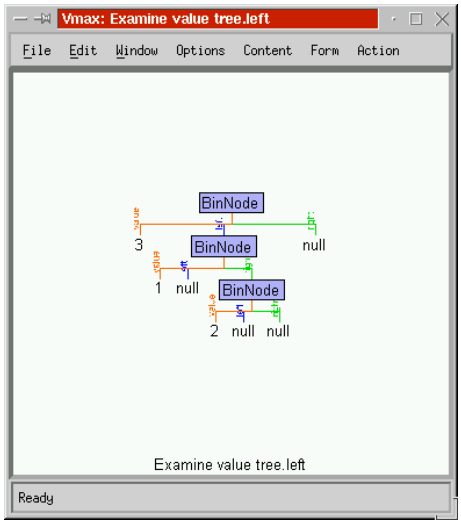
Figure 5.49. Visualizing a structure to a given depth.



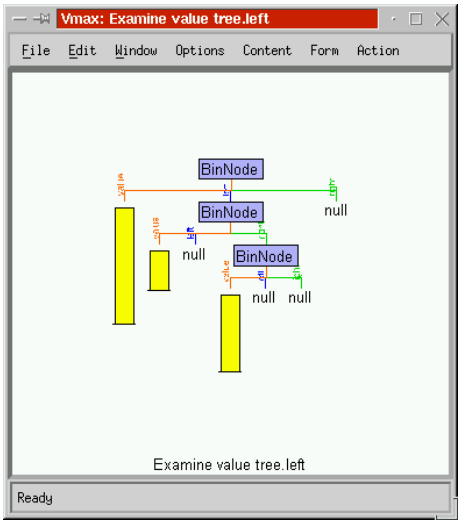
(a) The initial view.



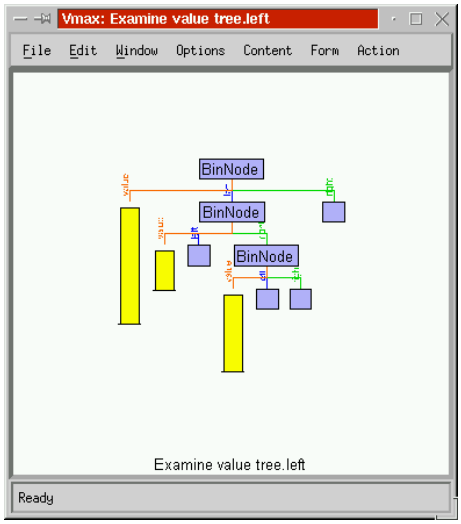
(b) The initial legend.



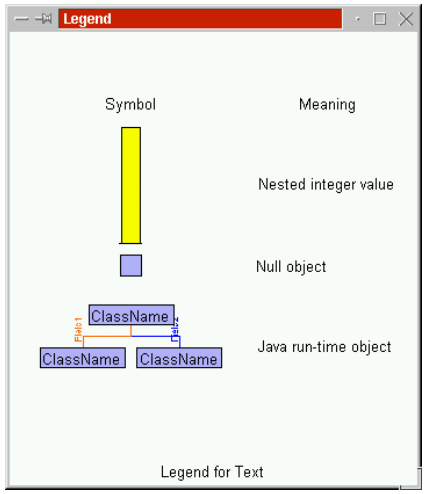
(c)



(d)



(e) The final view.



(f) The final legend.

Figure 5.50. Transforming a textual display of a value into a graphical display using the Legend.

5.9 Prolog Visualization

It is natural to ask what other languages Prolog and SVT are capable of analyzing and displaying. The answer is all languages, because Prolog is Turing powerful, and Prolog is no more tailored to Java than to any other language. However different programming languages require different structures and rules.

Vmax can display and edit Prolog as a visual language. This demonstrates SVT's potential for visual programming, and offers a possible solution to end user specification of visualization. Prolog clauses are stored

```
user_clause(ClauseId, Clause)
```

where *ClauseId* is a unique identifier for the clause, and *Clause* is the structure of the clause. There is no external textual representation of Prolog at present. The clauses that the user has defined can be viewed by the *Clauses* or *Predicates* view shown in Figure 5.51. All clauses can be visualized in the *All Clauses* view shown in Figure 5.52.

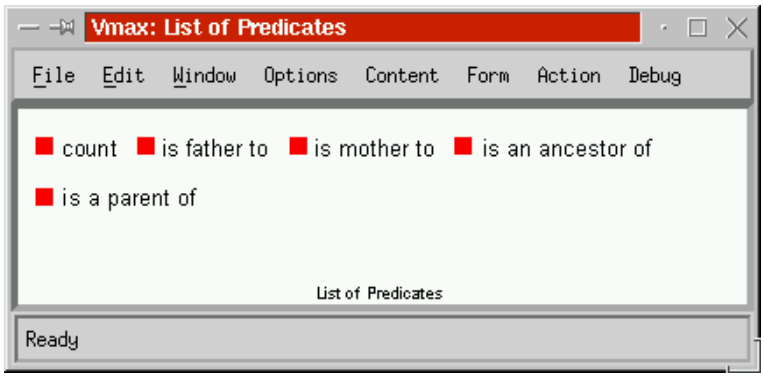


Figure 5.51. The user-defined predicates.

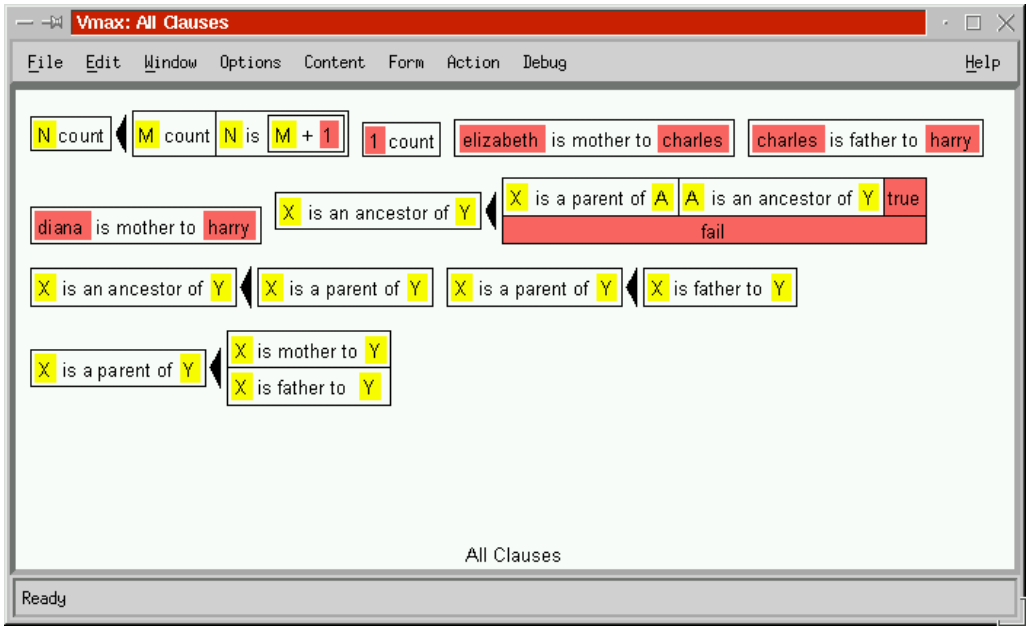
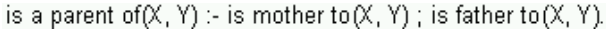


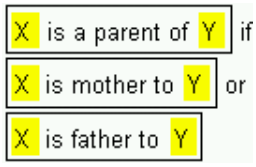
Figure 5.52. Visualizing all clauses simultaneously.

Clicking on one of the clauses navigates to it. The structure of the clause can be visualized in a number of ways, as shown in Figure 5.53. As before, the Legend can be edited to transform any one of these views into any other.

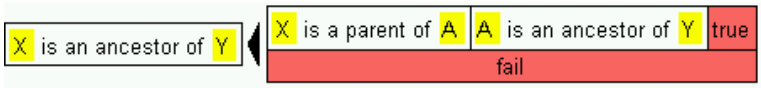


(a) Prolog.

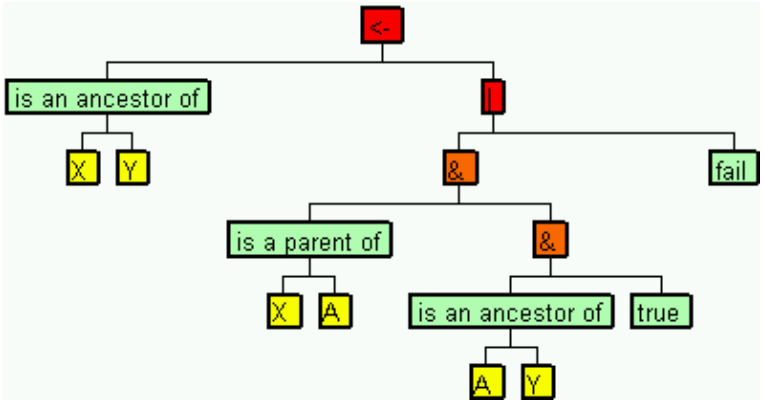
(b) English.



(c) Query.



(d) Block structure.



(e) Tree.

Figure 5.53. Different visualizations of a clause.

To display a clause, each sub-term of the clause is given an identifier *Id* of the form *sub-term(Parent, Position)* where *Parent* is the identifier of its parent term, and *Position* is the position of the sub-term in its parent compound term. Each term is represented in the view content as *term(Id, Functor, Args)*, where *Functor* is the name of the functor, and *Args* is a (possibly empty) list of identifiers that are the child terms of the compound. The terms *:-/2*, *,/2* and *;/2* are treated separately.

The block structured notation shown in Figure 5.53(d) is similar to VPL [60] and uses the horizontal axis for conjunction, and the vertical axis for disjunction. A different view similar to the Transparent Prolog Machine (TPM) [30] is shown in Figure 5.54. A red horizontal line indicates conjunction.

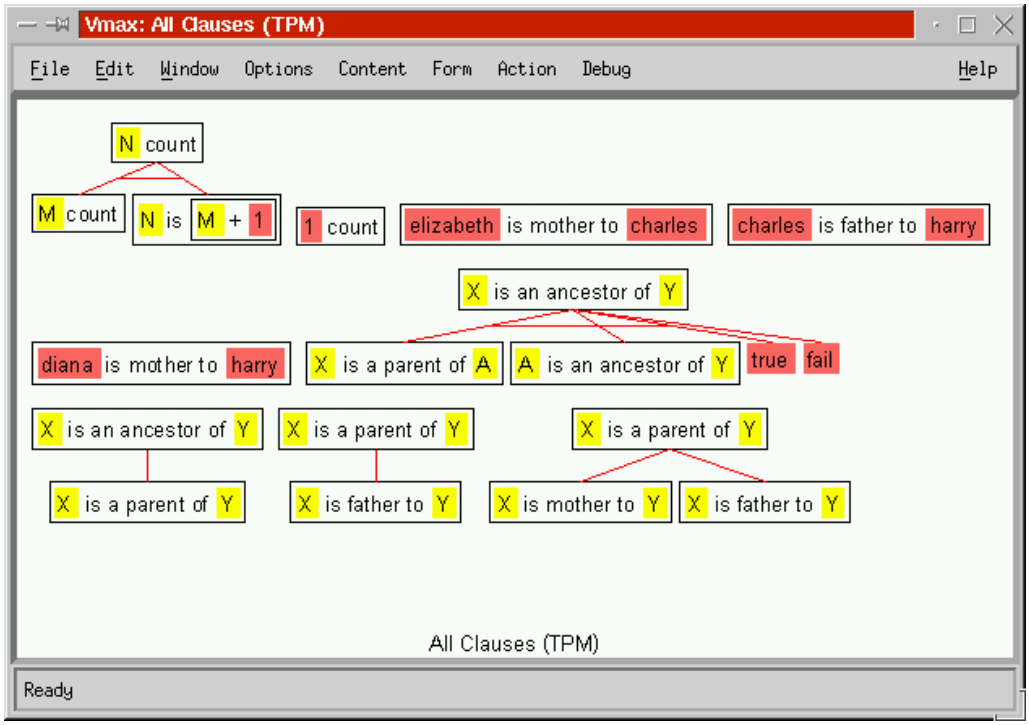


Figure 5.54. Visualizing predicates in the style of TPM.

5.9.1 Editing Prolog

Clauses can be edited in a number of ways. The *Add new clause* option on the action menu of the *Predicates* view adds a new user clause. Clicking on the clause navigates to it, and its *Clause* view shows just that clause, while its *Predicate* view shows all the clauses in its predicate. The *Delete clause* option on a clause's action menu removes the clause.

A right-mouse click on a term will pop up a menu giving alternative names for its functor or atom. Selecting an alternative from this list will change the functor and redisplay the view. The *Set functor...* option lets the user enter the name of the functor. This menu is shown in Figure 5.55, and the menu is defined by the *user_term/3* predicate. This list could get quite long, so maybe a system of sub-menus could be implemented to manage this.

A middle-mouse click on a term will pop up a menu giving operations on the term, as shown in Figure 5.56. The *Increase arity* option increases the arity of the compound term by one, and *Decrease arity* decreases the arity by one. A compound term with an arity of zero becomes an atom. *Cut*, *Copy*, *Paste*, *Delete* and *Duplicate* perform the described action on the term.

Dragging a term onto another will replace the destination with the source term of the drag, and this also works between windows. The effect of such a drag is shown in Figure 5.57. There is also a separate *Scratch terms* view which can be used to deposit terms temporarily by dragging

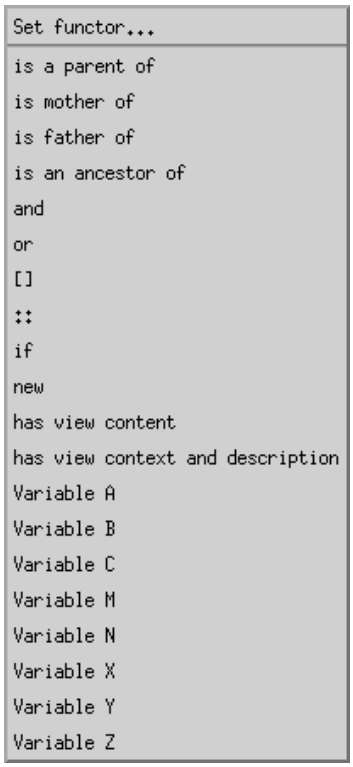
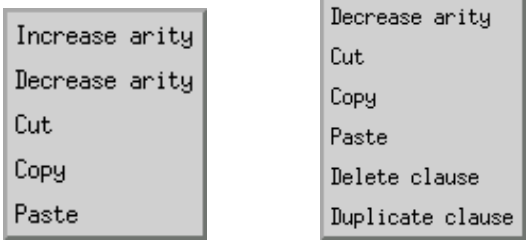


Figure 5.55. The menu to change the functor of a term.



(a) Actions on terms. (b) Actions on clauses.

Figure 5.56. Menus of operations on terms.

terms to the window. The dynamic clause *scratch_term(Id)* indicates those terms that belong in the scratch view, and these terms are not executable.

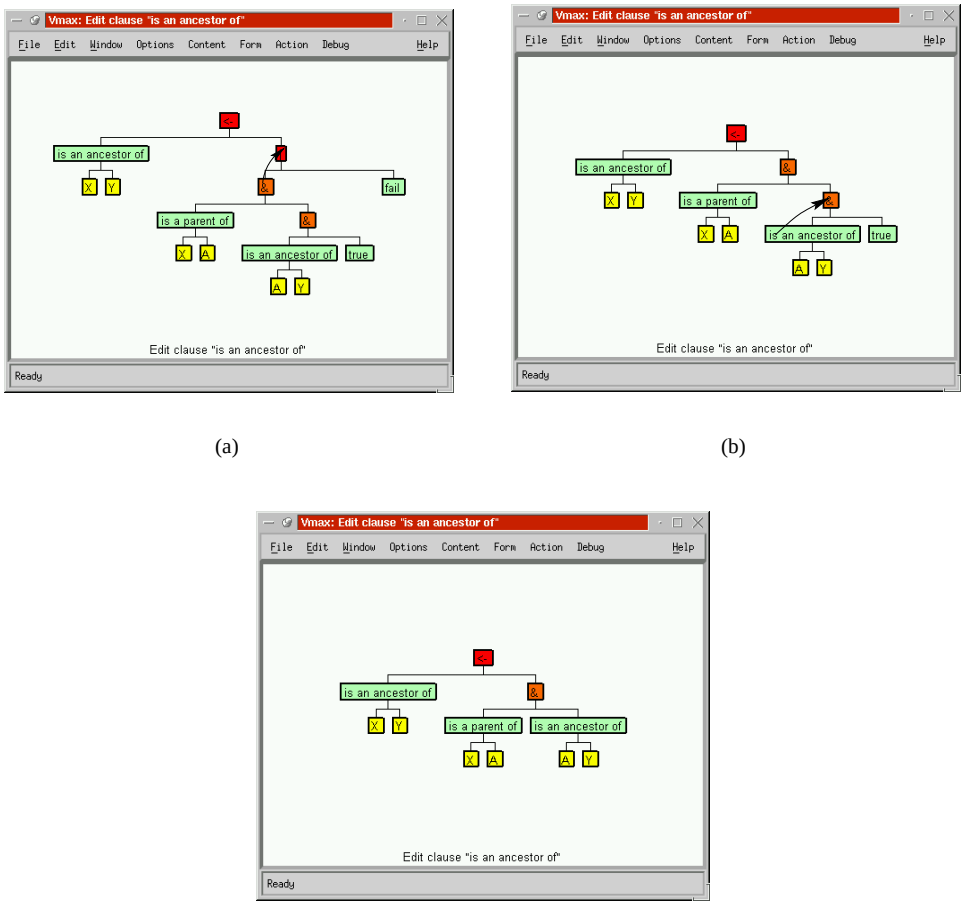


Figure 5.57. Direct manipulation of clauses.

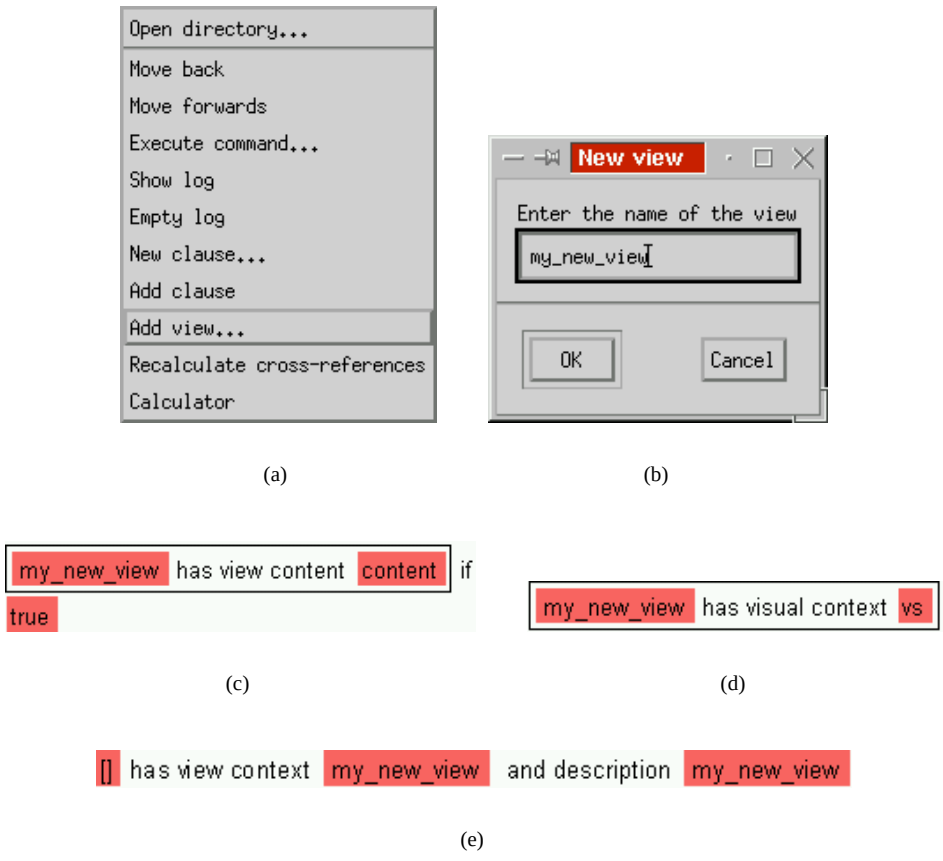
Since Prolog can be edited graphically, it should be possible to specify SVT entirely through this visual language. The proviso is that these dynamic changes to Prolog are not persistent because they do not write back to the source code. A better implementation would load and save textual representations of Prolog.

The *Add new view...* option on the action menu prompts the user for the name of the new view, creates skeleton clauses for the new view, and navigates to *Edit view relation* for the new view. This is shown in Figure 5.58.

5.10 The Help System

Pressing *Help* on the menu bar activates the help system. This navigates to the view *help(main)*. This view displays the help text in the text window, and indicates the sub-topics in the graphical window. Clicking to one of the help topics navigates to that help topic. In this way, SVT's views are used to display help.

The predicate *help_topic(Topic, SubTopic)* declares help sub-topics, and the predicate *help_topic(Topic, Title, Text)* declares the help text, where *Topic* is a term identifying the topic, *SubTopic* is the sub-topic, *Title* is the help topic title, and *Text* is the help text for the topic. The help topic for a particular view *ViewContext* could have the view context *help(ViewContext)*, providing



(a) (b)

(c) (d)

(e)

Figure 5.58. Creating a new view.

view specific help.

5.11 Chapter Summary

Vmax is a programmers' editor that integrates many areas of software visualization. As well as providing overviews of large program structures such as packages and classes, it also visualizes small scale structures such as methods and expressions in visual languages. Run-time data is also visualized, and due to the ability to edit the visualization relation, can be displayed in a virtually unlimited number of ways. The views are highly interconnected, and browser-style navigation makes it simple to select a desired view.

Vmax augments SVT with parsers for directories, Java source code and trace files, and provides predicates for reading in, analyzing and visualizing them. A structure of text nodes stores the parse tree, and each text node represents a block of text that can be edited in the text window. This structure adapts as editing proceeds.

Run-time data is acquired by inserting trace calls into Java source code, recompiling and executing it. Java's Reflection package is used to examine the structure of each run-time value it receives. This generates a file which is read and analyzed, and the results can be browsed, displayed in many different forms, and animated.

Prolog can be edited as a visual language, in several different graphical forms. This can be used to add new views as an alternative to textual specification.

Vmax demonstrates the potential SVT has to define and implement visualization systems. The implementation shows that Prolog is capable of specifying all aspects of SV, and that the browser environment SVT provides can be used effectively as an interface to information.

Chapter 6

Discussion

This chapter discusses where Vmax fits into the taxonomies of SV, which enable a comparative evaluation of Vmax with other systems. In many criteria, Vmax outperforms existing systems. Vmax's main contribution is in its tailorability, flexibility and automation, and it is shown that the underlying approach is sufficiently broad to cover all aspects of SV.

SVT and Vmax are not commercial products, and have not been evaluated as such. They are intended to demonstrate how Prolog can specify visualization. An empirical evaluation would be needed to demonstrate the effectiveness of Vmax, but that is beyond the scope of the work.

Because of the different approach of Vmax and SVT, there are many research directions that emerge from this work. The modular design allows components to be replaced without affecting the rest of the system. Further work is discussed, including the possibilities of voice, visual or interactive specification techniques, improved graphical constraint layout and interfacing SVT to commercial visualization and development systems.

6.1 Classifying Vmax

As well as outlining future directions, Price *et al.* [79] provide a framework for comparison and classification. This indicates whether Vmax has been successful in addressing the issues raised in the paper. The classification of Vmax in their taxonomy is given in Table 6.1.

A classification of $\star\star\star\star\star$ means that Vmax is particularly strong in that area, while $\star$ means that Vmax does not support the feature at all. As there are no objective metrics for measuring these criteria, they should be regarded as no more than a rough guide.

The taxonomy of Price *et al.* is used in favour of the taxonomy of Roman and Cox [84] because it is more comprehensive and more suited to comparative evaluation.

6.1.1 Scope

The scope of Vmax is very broad, because it is comprehensive in program and run-time visualization. No other systems combine both program and run-time visualization to the same degree. Systems using a declarative specification [20, 85] lack the power of data manipulation for managing and displaying program databases, and are restricted to numerical data. Where Vmax is deficient, it should be possible to extend Vmax's scope by adding more views (§4.4). (A.1)

Vmax's support for Java is much more extensive than it is for Prolog. (A.1.3) At present there is no specific support or view for concurrency, although the architecture time-stamps input events which would record concurrent behaviour (§5.7.2). The specification mechanism could cope with concurrency. (A.1.3.1) Because Prolog stores the complete program database (§5.5),

Category	Classification
A: Scope	
A.1 Generality	⋆⋆⋆⋆⋆
A.1.1 Hardware	any desktop PC
A.1.2 Operating System	Linux
A.1.3 Language	Java
A.1.3.1 Concurrency	⋆⋆⋆
A.1.4 Applications	any in language
A.1.4.1 Speciality	none
A.2 Scalability	⋆⋆⋆⋆
A.2.1 Program	⋆⋆⋆⋆ 6 320 lines/s, 115 000 lines
A.2.2 Data Set	⋆⋆⋆⋆ 19 500 lines/s
B: Content	
B.1 Program	⋆⋆⋆⋆⋆
B.1.1 Code	⋆⋆⋆⋆⋆
B.1.1.1 Control Flow	⋆⋆⋆⋆⋆
B.1.2 Data	⋆⋆⋆⋆⋆
B.1.2.1 Data Flow	⋆⋆
B.2 Algorithm	⋆⋆⋆⋆
B.2.1 Instructions	⋆⋆⋆⋆⋆
B.2.1.1 Control Flow	⋆⋆⋆
B.2.2 Data	⋆⋆⋆⋆⋆
B.2.2.1 Data Flow	⋆⋆
B.3 Fidelity and Completeness	⋆⋆⋆⋆⋆
B.3.1 Invasiveness	⋆⋆⋆⋆⋆
B.4 Data Gathering Time	compile- and run-time
B.4.1 Temporal Control Mapping	dynamic to static and dynamic
B.4.2 Visualization Generation Time	post-mortem
C: Form	
C.1 Medium	colour monitor
C.2 Presentation Style	
C.2.1 Graphical Vocabulary	points, lines, polygons, tables, graphs, position, size, enclosure, pictograms; plain text
C.2.1.1 Colour	⋆⋆⋆⋆⋆
C.2.1.2 Dimensions	⋆⋆⋆⋆
C.2.2 Animation	⋆⋆⋆
C.2.3 Sound	⋆
C.3 Granularity	⋆⋆⋆⋆⋆
C.3.1 Elision	⋆⋆⋆⋆⋆
C.4 Multiple Views	⋆⋆⋆⋆⋆
C.5 Program Synchronization	⋆
D: Method	
D.1 Visualization Specification Style	automatic
D.1.1 Intelligence	⋆⋆⋆⋆⋆
D.1.2 Tailorability	⋆⋆⋆⋆⋆
D.1.2.1 Customization Language	interactive or Prolog
D.2 Connection Technique	automatically annotated
D.2.1 Code Ignorance Allowed	⋆⋆
D.2.2 System-Code Coupling	⋆⋆
E: Interaction	
E.1 Style	browser, mouse, menus, direct manipulation
E.2 Navigation	⋆⋆⋆⋆⋆
E.2.1 Elision Control	⋆⋆⋆⋆⋆
E.2.2 Temporal Control	⋆⋆⋆⋆
E.2.2.1 Direction	⋆⋆⋆⋆⋆
E.2.2.2 Speed	⋆⋆⋆
E.3 Scripting Facilities	⋆⋆⋆⋆
F: Effectiveness	
F.1 Purpose	expert software development
F.2 Appropriateness and Clarity	⋆⋆⋆⋆⋆ ?
F.3 Empirical Evaluation	⋆
F.4 Production Use	⋆

Table 6.1. The classification of Vmax in Price, Baecker and Smalls' taxonomy [79].

and any type of run-time data (§5.7), Vmax can be used for any visualization task. (A.1.4) Vmax has no speciality because of its broad scope. (A.1.4.1)

Vmax is very scalable because its query mechanism filters away extraneous data that can clutter the views, and if views fill up their contents are shrunk (§4.4). The limitations are due to the size of the program database. This can fill up the physical memory and so the performance of Prolog degrades (§6.2.2). (A.2) Vmax can read 6 320 lines of Java per second as measured on a 400MHz Pentium PC with 128MB of memory. With this setup, a project of 115 000 lines of code has been visualized (§6.2.2). Vmax is inadequate for projects of several million lines of code, due mainly to the internal representation of the program database, and the comparatively slow execution speed of the Prolog analyzer. Program analysis in C or C++ would be much faster. (A.2.1)

Similar constraints are placed on the run-time data. 19 500 lines of run-time data are read per second. One line of run-time data is equivalent to one integer (§6.2.2). (A.2.2)

6.1.2 Content

The information content of the views is extensive due to the query mechanism that Prolog provides (§3.3), and the completeness of the program database (§5.5) and the run-time data (§5.7). (B.1) If the existing views prove to be deficient, a new view can be defined to augment the system. It provides code visualization at the statement level (§5.6.3). (B.1.1) The control flow between statements and between methods is shown completely (§5.6.3, §5.6.2). (B.1.1.1)

Vmax has complete access to the run-time data, displayable in a wide variety of formats. (B.1.2) Vmax is weak on data flow because Java is a control orientated language. The data flow within a method is not shown, although the information is available to compute it. The data dependencies between methods and variables are shown however (§5.6.2). (B.1.2.1)

Vmax cannot visualize algorithms, because it only has access to raw source code. However it can be structured into a flow chart which would help visualize the algorithm (§5.6.3). (B.2) Expressions in statements can also be visualized, if that is really desired (§5.6.3). (B.2.1)

The control flow is shown within a method and also between methods. However the actual control flow of an executing program is not displayable. Showing run-time control flow is not possible because analysis of run-time data is done off line (§5.7). A possibility would be to interface Prolog to the Java Virtual Machine Debug Interface [68] to perform live debugging. (B.2.1.1)

Prolog has complete access to the Java's parse tree, and can compute any information about the program because it is Turing powerful (§5.5). It does not have complete access to run-time data at all times, although any individual data can be completely monitored at trace points (§5.7). (B.3) Vmax affects the performance of the running program much less than systems where the view is synchronized with the data, because the viewer does not pause the program for animation and stepping (§5.7). (B.3.1)

Vmax gathers data about the program before and after it is run (§5.5, §5.7). (B.4) The run-time data can be stepped and animated, but static views of sequences of events can also be generated (§5.8). (B.4.1) Run-time visualization occurs after the program has been run (§5.8). (B.4.2)

6.1.3 Form

The output of Vmax is on a colour monitor. (C.1) The constraint hierarchy implements many different kinds of graphical component and layout algorithm, providing a wide range of output (§4.5, §B.6). There are limits in the capabilities of the graphical layout algorithms, but a range of visual languages have been implemented (§5.6.3, §5.9). (C.2.1)

Colour is used widely to convey information, and indeed any numerical quantity or attribute can be used to colour any graphical component, including bitmaps. (C.2.1.1) The views in Vmax do not generally make use of three dimensions. The algorithms for graph and container layout (§4.5.5) are two dimensional, but they could be adapted to produce 3-D layouts. The constraint-based object layout is fully three dimensional (§4.6.1), allowing 3-D objects, containment and

height bars (§5.8.1). (C.2.1.2)

The visualizations are static, and animation can only be shown as a sequence of frames (§5.8). Animation constraints could be added to the viewer so that the output in the view is animated. A modification to the view generator could automatically generate smooth paths between objects with the same identifier in sequential frames. More primitive approaches such as Tango [95] are more versatile because they allow animation to be programmed explicitly. (C.2.2)

Sound was not incorporated into Vmax because there have been no demonstrated benefits of using sound in program visualization [25]. Sound constraints could be provided that are generated from the information content of a view, or Prolog could call the sound library directly. Zeus [15] is stronger in this area because it has an interface to a sound library. (C.2.3)

Vmax's control over granularity is far more extensive than in previous systems. A range of granularity from individual expressions (§5.6.3) to whole class (§5.6.1) and package hierarchies (§5.4) can be viewed, while other systems are often limited to one task and one level of granularity [79]. (C.3) Vmax's elision control is also very advanced, because different views of the same object can hide or reveal data (§4.7.4), and the legend can be modified to hide or reveal information (§4.8.2). Elision is selected by the user. In many other systems, elision is achieved by editing text. (C.3.1)

Vmax has very good control over multiple views, because the user can create as many viewing windows as desired (§4.4), and display any kind of data there. The views in different windows cannot be synchronized however. (C.4)

The run-time data is not synchronized with the program because it is displayed off line (§5.8). It is not clear whether on-line or off-line viewing of run-time data is better, because on-line allows the data state of the program to be modified live, and asynchronous viewing requires more storage, but allows much better temporal control and allows static views of dynamic events (§5.8), such as in Vogue [51]. Asynchronous data display interrupts the running program much less. Vmax could be run in synchronous mode, by interfacing to a remote Java Virtual Machine via its debug interface [68]. (C.5)

6.1.4 Method

Views can be specified on many levels. Defining the information in a view is done via textual specification in Prolog (§3.3), and also using visual specification (§5.9). Choosing the presentation style of the view is done through pull-down menus (§4.7.4), and selecting the data to visualize is done via direct interaction with the view (§4.7.3, §5.7.1). (D.1)

The system displays many different types of intelligence. For example, it uses automatic layout (§4.5), automatically finds suitable views for an object (§4.7.3), automatically finds suitable visualization contexts for a view (§4.7.3), and automatically tailors menus to the data (§4.7.2). Potentially Prolog could analyze the data structure and decide itself how to display it. However users still need to choose the view and visualization context themselves. (D.1.1)

Almost every aspect of visualization (§3.3, §3.4) and interaction (§3.8, §4.7.2) can be specified in Prolog, making the system highly tailorable. Tailorability can be done by the user by changing the visualization relation (§4.7.4), modifying it using the Legend (§4.8.2), or editing the action relation (§4.7.5). (D.1.2)

A high degree of customization is possible just by selecting different views (§4.7.3) or graphical forms (§4.7.4), but the legend itself can be edited to customize output completely (§4.8.2). Graphical queries can be added that customize the information in a view (§5.9). Additional Prolog can be dynamically loaded that contains more view specifications (§4.4). Other declarative systems can only be customized by textual programming [20, 86]. (D.1.2.1)

Vmax is connected to the program via loading its source code (§5.5), loading its run-time data (§5.7.3) and automatic annotation by inserting trace points into the source code via drag and drop (§5.7.1). The connection technique is similar to Viz [27] where "players" are event lines in Vmax, "states" are input events, the "history" is the trace file, "view" is the view context, "filters" are the view relations, "mapping" is the visualization relation and "navigators" are the action relation. (D.2)

A user of Vmax needs to be familiar with Java in order to understand concepts such as inheritance, overloading, variable usage or function calls. The user also needs to understand the source code in order to know where trace points should be inserted. Prior understanding of the algorithm is necessary in many systems to create effective output, but systems such as Eliot [61] and Leonardo [20] do not require the selection of trace points. (D.2.1)

The visualization system is almost completely decoupled from the target system. There is only a small amount of code that is dynamically linked to the target system via Java's class loader, to output run-time data structures to a trace file (§5.7.2). (D.2.2)

6.1.5 Interaction

The interaction style is more advanced than in other systems because it uses a browser interface (§4.7.3). Interaction using the mouse and keyboard can be completely specified in Prolog (§3.8), or dynamically modified (§4.7.5), and can specify menus (§4.7.2) and direct manipulation (§5.9). (E.1)

Navigation is easy with a browser interface (§4.7.3), which is very important because there are 70 different types of view to choose from. (E.2) Other SV systems do not provide specification for interactive behaviour.

Elision control is high, as selecting different views of the same object from menus (§4.7.3) can filter out what is not of interest. Different visualization relations (§4.7.4) or editing the legend (§4.8.2) can also hide various types of information. Elision is manually controlled through menu selections. (E.2.1)

Temporal control is also quite good, because the program data can be stepped forwards or backwards, and animated forwards or backwards at any frame rate (§5.8). (E.2.2)

There is no facility to record and play back user inputs. Textual scripting is possible by executing sequences of Prolog commands (§4.3). (E.3)

6.1.6 Effectiveness

The purpose of Vmax is different to many SV packages because it is designed to be used on real programs, and not small examples for teaching. (F.1) This change of emphasis makes it imperative that views can be generated quickly and automatically.

The automatic legend describes each view, so therefore the views should be clear and self explanatory (§4.8). No other SV systems provide an automatic legend for each view. The views themselves have not been optimized to programmers' needs, but the system can be completely tailored to provide the most appropriate views (§3.3, §3.4) and interaction (§3.8). (F.2)

An empirical evaluation is beyond the scope of this work. Vmax is aimed at software developers, and measuring the performance of the whole development process is difficult. It is therefore not possible to say whether Vmax is effective in real situations, or whether Vmax is at all appropriate for the task. (F.3)

Vmax is new software and has not had a chance to be used in real projects. It is not quite of production quality, and lacks user manuals. The research aims were not to produce commercial software. (F.4)

6.2 Evaluating Vmax

Evaluation poses a particular problem for SV systems. There has been little empirical evaluation of the other systems described here [71, 79]. An empirical evaluation is beyond the scope of this work, so conclusions about Vmax's usability or the merits of adding graphics to a programming environment will not be made.

One approach is to evaluate the usability of the system using a 'cognitive dimensions' framework [37, 39]. This is a framework for discussion about programming environments, providing many different evaluation aspects and criteria. Often changes in one dimension will affect the

performance in others. However it is more focused on tasks of data manipulation and visual programming, while Vmax does not provide these functions. Cognitive dimensions can describe particular notations and environments, but Vmax uses a general approach that does not fix the notation or environment. From a cognitive dimensions perspective, the programming task is still textual. Cognitive dimensions only examines the user's perspective, and does not discuss the implementational aspects.

The approach we shall use is to compare Vmax's capabilities with existing systems, and Price *et al.*'s taxonomy [79] provides a suitable framework for such discussion. It is given in Section 6.1. This provides a means of comparison for particular aspects of the system, but does not provide an overall measure of its worth. The suitability of a particular tool is entirely task dependant.

6.2.1 Benefits

Although Vmax provides very flexible graphical output, and has very fine control over the information presented in its views, it has not been shown whether this is of benefit.

There are several studies that show that different notations perform better in different circumstances [107]. Green [37] argues "a notation is never absolutely good, therefore, but only in relation to certain tasks." Because programming is such a varied task, maximum flexibility in the graphical representation would be required for the visualization system to be effective, because specific notations may not be appropriate in all circumstances.

Information control, or elision, is an important aspect of information systems, and in particular SV systems because of the different kinds of programming task and areas of interest. So called "spaghetti-plate syndrome" [17] is a major problem for control oriented languages because of the visual complexity of the output. The Deutsch limit [67] places a limit on the information density of graphical displays. However there is also evidence that visual notations become more effective when the problem size grows [22, 78]. Whitley [107] poses the question "Given the range of information required in programming, can a VPL highlight enough of the important information to be of practical benefit?" The only way the trade-off between visual complexity and information completeness can be resolved is through elision control to selectively choose what to display by providing many different views.

The user interface uses graphical browsing techniques which have been shown to be a very easy, successful and effective means of information retrieval, and utilizes direct manipulation which is argued to be a natural interface to data [90].

Usability testing is beyond the scope of this work. There are no objective metrics for comparing the effectiveness of different SV systems [79], and there has been little empirical evaluation of the other systems described in this dissertation. So while there is indirect evidence that the facilities offered by Vmax are useful, and that it is easy to use, this has not been confirmed by user studies.

6.2.2 Performance

The performance figures shown in Table 6.2 were obtained on a 400MHz Pentium II PC with 128MB of RAM running Linux 2.2. They were measured by enabling a logging function in SVT that times these tasks.

Task	Speed
Code input rate	6 320 lines per second
Cross referencing	5 144 lines per second
View generation	900 constraints per second
Trace file input rate	19 503 lines per second

Table 6.2. The performance of Vmax.

The figure given for view generation depends on the constraints, and the amount of compu-

tation required to derive the view content. A typical view may contain 100 or more constraints, beyond which the view starts to get cluttered. These figures are of course approximate because they depend on hardware and the specific data used.

Vmax offers a responsive interface and is practical to be used for medium sized projects, of around 100 000 lines of code. Source code of 115 000 lines has been successfully visualized.

This performance could be significantly improved by a more efficient implementation. The performance was limited by Prolog's memory management, which filled up the computer's memory as more facts were added to its database, suggesting that specially written storage routines should be used for the program data.

6.2.3 Extensibility

Vmax is readily extensible by adding more views and program analyses in Prolog files and loading them on start up. The graphical output can be readily modified and extended by defining more visuals. New languages can be added by adding lexical analyzers and parsers to the executable, and the Prolog to analyze them, which could coexist with the existing source code analyzers.

6.3 Evaluating SVT

6.3.1 The Specification Language

Specifying SVT is very different to specifying other visualization systems because there is so much more to specify. There are views, view content, visual content, visualization contexts, visualization context descriptions, visuals, visual components, visual objects, menus, actions, reactions and content types to declare. This may seem very complicated, but it provides much more flexibility and automation for the end user.

When specifying one aspect of the system, the implementor does not need to be concerned about how the other aspects are specified. In particular, the view content is specified completely independently to the visual content, which is specified independently to the graphical constraints of the visuals. By subdividing the problem, each component is much simpler to specify, and can be reused.

The specification method SVT uses may be directly compared with Pavane [85] and Leonardo [20]. Leonardo uses a logic based language Alpha, but the resulting notation is more awkward than Prolog's, and can only manage integer values, not compound terms, so it would be useless for knowledge engineering. A strength of Alpha is that it can embed numerical expressions from the object language directly into it.

Pavane's declarative approach is more awkward than Alpha's. The languages are very similar in their usage, but Pavane offers an iterative style of programming, and generates graphical objects as tuples in a data-space. Pavane uses named parameters to pass attributes to the graphical objects it constructs. SVT uses parameter position to pass arguments to its visuals. Pavane's implementation actually translates Swarm based declarations into Prolog, although the implementor does not see this.

Both Alpha and Pavane construct low level geometric objects by specifying their graphical coordinates directly, which is little improvement over an ordinary graphics toolkit. Alpha can assign integers to objects in the scene. SVT works very differently by generating high level constraints on the output image, which are automatically structured. Constraints are necessary to combine different notations and to handle arbitrary graphical structures. Every object in the scene has a label which can be any Prolog term.

Because Alpha and Pavane use directly mapped objects to the screen, they provide no encapsulation of visual objects. Even something as simple as a red arc has to be programmed in two separate predicates in Alpha. In SVT, constraints can be composited arbitrarily, and are compositions of primitive graphical constraints, providing encapsulation and specification at a much higher level. While SVT provides three stages of visualization, Pavane and Alpha provide just one, thereby fixing their output.

Alpha and Pavane cannot specify interaction. The objects in their scenes do not have semantics, so there is no means of interacting with them. SVT can specify any interactive behaviour for any object or component in the scene.

The size of specification is small in SVT because SVT provides encapsulation via visuals, so only the bijection between the semantics and the visuals needs to be defined. By editing the legend, this bijection does not need to be specified at all. Alpha and Pavane require textual programming to change the graphical display, but this can be done by the end user through a GUI in SVT.

Both Alpha and Pavane can specify animation in their scenes. Animation in SVT is quite primitive, and is limited by the viewer, and not by the specification language.

6.3.2 Modularity

SVT and Vmax are modular in their design. The window manager is accessed through a well defined interface so that SVT can be used with any windowing system.

The layout constraint solver could be completely replaced by any layout mechanism that interfaces Prolog to OpenGL. The existing hierarchy could be extended with better layout algorithms. The 3-D graphics toolkit could be replaced, or the declarative language that is used to drive the constraint solver. Even C++ can drive the constraint solver directly, thus bypassing the need for Prolog to generate visualizations.

Other aspects of the data gathering such as the program database do not need to be managed by Prolog either, but could be stored using existing tools and accessed by Prolog.

6.3.3 Application Areas

Information Visualization

SV is a particularly challenging example of information visualization because of the size and complexity of the data structures, the wide range of possible output, and the highly heterogeneous nature of the data. Other applications are possible, provided that the data is interfaced to Prolog.

Visual Programming

Visualization is an intrinsic part of visual programming, because visual language systems need to generate diagrams to communicate the visual program. The constraint based output of SVT can specify visual languages, which relates the diagram to the language structure and semantics.

Vmax uses several graphical notations to represent programs in Prolog or Java. There is no facility to manipulate Java graphically, which distinguishes program visualization from visual programming.

The combination of visualization and interaction provides a complete specification of visual programming. SVT can emulate block-structured visual languages, but is more limited with node and link based programming. Extending SVT's layout capabilities would extend the possible visual language notations.

Graphical User Interface Specification

A graphical user interface (GUI) is essentially an interactive graphical view, and can therefore be specified in SVT. Visuals define the widgets in the GUI, which are generated automatically from the data in the view.

The dialog box in Figure 6.1 is specified

```
view_content(dialog, font_option(Font, Name, Status)) :-
        font_data(Font, Name), widget_data(Font, Status).
```

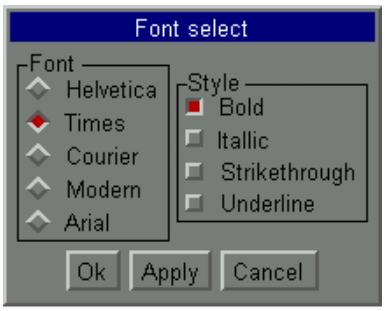


Figure 6.1. A dialog box specified in SVT.

```
view_content(dialog, style_option(Style, Name, Status)) :-
        style_data(Style, Name), widget_data(Style, Status).

visual_content([], dialog,
        [
        window(window, 'Font select', main),
        vertical(main, options, buttons),

        % Buttons
        button(yes_button, 'Ok'),
        button(no_button, 'Cancel'),
        button(apply_button, 'Apply'),
        horizontal(buttons, [yes_button,apply_button,no_button]),

        % Options
        vertical(fontlist),
        group(font_group, 'Font', fontlist),
        vertical(stylelist),
        group(style_group, 'Style', stylelist),
        horizontal(options, font_group, style_group)
        ]).

visual_content(font_option(Id,Text,Status), dialog,
        labeled_choice(Id,Text,Status,fontlist)).

visual_content(style_option(Id,Text,Status), dialog,
         labeled_selection(Id,Text,Status,stylelist)).

action(move(B,_), svt, indicate(action)) :-
        selector_button(B) ; choice_button(B,_).
action(click(B, _, _), svt, toggle_selector(B)) :-
        selector_button(B).
action(click(B, _, _), svt, Action) :- button(B,Action).
action(click(B, _, _), svt, choice_select(B,C)) :-
        choice_button(B,C).
```

The calculator in Figure 6.2 was created using similar methods. The calculator supports keyboard input. In comparing two calculator applications in Figure 6.3, the Tcl/Tk [74] implementation in Figure 6.3(a) (obtained as a Tclet from Scriptics [1]) was 127 lines, while the Prolog implementation in Figure 6.3(b) was 58 lines long.

[1] URL: *http://www.scriptics.com/products/tcltk/plugin/calculator.html*

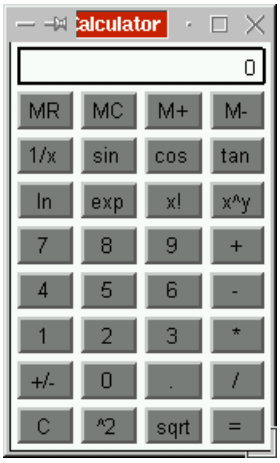
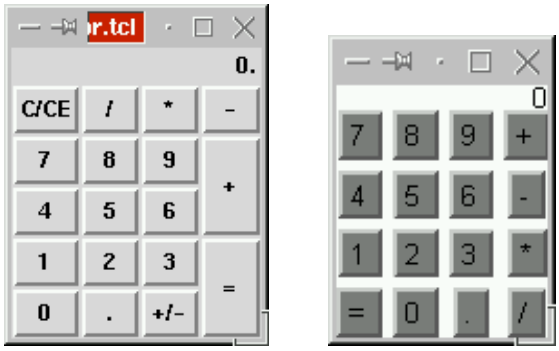


Figure 6.2. A fully functional scientific calculator specified in SVT.



(a) Tcl/Tk. (b) Prolog.

Figure 6.3. Similar calculators.

6.4 Commercial Relevance

Programming is difficult and time-consuming, and therefore expensive. Tools which make programming easier, more reliable and faster, reduce the cost of writing and maintaining programs, and are therefore important. Visualization is merely an extension of the existing trend of providing graphical environments in which to program, which provide graphical support for using the compiler, editing, navigating, modifying code, creating skeleton applications and creating user interfaces. Visualization can reduce the cognitive burden on the programmer, thereby improving productivity. These benefits are already being exploited in commercial programming products.

The approach used by SVT and Vmax could be used in commercial products. A stand-alone programming environment like Vmax could provide a working alternative to existing environments, and provide a much greater range of visualization. Otherwise an environment such as Microsoft Visual Studio could have an embedded Prolog interpreter linked to its project databases.

Stand-alone visualization tools could also be based upon, or augmented by, SVT's approach to visualization. Existing architectures such as IBM's Visualization DataExplorer[2] and AVS Express[3] could be interfaced to SVT, and provide access to both the data sources and the output display and scene graphs.

SVT and Vmax are not commercial products, but demonstrate the technical viability of implementing SV in a knowledge engineering environment.

6.5 Further Work

6.5.1 Measure Usability of Vmax

The usability of Vmax has not been formally measured, and therefore the benefits of using it have not been proven. Studies that compare the performance of users using a text-only system and those using a graphical system such as Vmax would answer this question. Unfortunately such broad studies are rarely conclusive, and may not relate to "real-world" tasks [45]. Vmax would have to be evaluated in real situations to measure the performance of users using the system.

Vmax generates output messages monitoring its activity which can be saved into a log file for future analysis. Changes in view context and visualization context are recorded and time-stamped. Navigation graphs between view contexts could reveal how users actually used the system, rather than what is possible. Usage statistics such as mean time between navigations, number of view contexts used, number of times the visualization relation is changed, use of bookmarks, use of preview window, use of the legend, or the way objects were visualized would provide evidence of worth for that feature. It would provide a workbench for measuring the psychology of programmers.

It would seem clear that a feature or view should be deemed "useful" if it is used regularly by a user. If a wide range of views was used, or views and navigation paths were taken that are not available in traditional programming systems, then the worth of Vmax is demonstrated. Questionnaires could also give supporting evidence.

6.5.2 Measure Programmers' Needs

No attempt has been made to optimize the graphical views and notations used in Vmax, which are only a first approximation of what might be useful. Discovering which notations programmers find most useful, what information programmers require, and how they wish to navigate, would lead to a configuration of Vmax that was more tailored to programmers' needs.

Choice of graphical notation can have a significant impact on user performance [37]. Comparative performance of various graphical notations can be measured, but care must be taken to

[2]URL: *http://www.ibm.com/dx*
[3]URL: *http://www.avs.com*

ensure that the experiments are not swamped by noise and become inconclusive [107]. The architecture of Vmax allows very different notations and views to be constructed relatively easily, so would be an appropriate test-bed for different notations.

A study of how users navigated through Vmax would indicate important navigation paths, and perhaps yield the kind of information programmers were interested in. Questionnaires asking programmers' needs could provide data on what information to provide.

6.5.3 Improve the Graphical Constraint Solver

There are limitations in the types of graphical output possible by SVT, because of limitations in the graphical constraint solver. It lacks many layout algorithms and its graph layout is quite primitive. It does not have strong support for numerical visualization, including producing many kinds of graph, or volumetric data. Even so, the graphical output it does produce is sufficiently powerful to implement various visual languages and notations.

The modular architecture allows any kind of graphical constraint solver to be used. The graphical constraints returned by Prolog can drive any constraint layout mechanism. The existing constraint solver can be extended through its C++ interface to augment the layout algorithms already present.

The geometric constraint solver used to lay out visual objects can only manage linear constraints, and is inadequate to solve more complicated geometric constraints, or find "optimal" solutions.

6.5.4 Animation

SVT was not originally designed to be an animation tool. Animation constraints could be provided that control animation in the scene, and the viewer could be reimplemented to provide animation. Paths of smooth motion such as those in Tango [95] could also be specified via constraints. Inter-frame animation could be implemented by automatically providing smooth path transitions between the same object in sequential views.

Positions within the scene could be specified using four dimensions, and linear interpolation between points in space-time could provide animation in the style of Pavane [85].

6.5.5 Sound

Program auralization [25] could potentially communicate more information than graphics alone. Perhaps sound could form part of the view. This could be specified by sound constraints generated from the information in the view. A sound constraint would not affect the graphical output, but would call a sound library. A visual could combine aural constraints with visual constraints.

Moving the mouse over an object could also generate sound. In this case the interaction with the object would result in a reaction that calls the sound library directly from Prolog.

6.5.6 Automatic Choice of Graphical Layout

The visualization relation must be specified manually by declaring how information is mapped to visuals. Systems such as AVE [34] are data driven, and determine a suitable mapping from the structure of the data. Such technology could be integrated into SVT, although it is not clear whether this feature would be useful. The visualization context could be selected automatically depending on the form of the data.

6.5.7 Improve the Graphical User Interface

The specification method for menus is fairly primitive, allowing only separators and bullet items. This could be made more sophisticated by adding sub-menus and implementing tool bars using

a similar specification technique. The viewing window does not have scroll bars, but these are also an effective method for viewpoint control. *Balloon help* could describe objects beneath the mouse, replacing the legend.

6.5.8 Investigate other Specification Languages

There are many variations of Prolog and other query-based languages that would be able to implement the semantic model of visualization. Prolog was chosen because of its established use, its formal basis, and its simplicity. If the core language is sufficient to express a visualization system, then any language which builds on Prolog is also sufficient. The differences in syntax between the dialects of Prolog would change the appearance of the specifications, but not change their meaning significantly.

Prolog itself provides a means of modifying its syntax using the *op/3* predicate. This example shows how new operators could replace *view_content/2* and *visual_content/3*:

```
family_tree -Q-> person(X)
        :- man(X); woman(X).

person(X) -V-> labeled_icon(X, X, person) using graph.
```

A possible use for SVT is in visualizing databases. Prolog can be interfaced to external databases, but it may make sense to implement the semantic model in the database language itself. The relationships between the the view context, the view content, the visual content and the graphical constraints might be expressible in a relational database language such as SQL [21]. Database languages are often imperative or functional, which lack backtracking capability, and the syntax of such queries may not be so user friendly. However Datalog [102] offers a language similar to Prolog that implements a relational model to access an underlying database.

6.5.9 Investigate Visual Specification Languages

The main problem with Prolog is that it is slightly too complicated to be used as an end-user language. Its execution model is quite difficult to understand, and most users are used to imperative programming styles. Thus only expert users would be able to add new views to the visualization system.

The visual languages Vmax provides to edit Prolog clauses are fully operational, albeit changes are not persistent. The benefit of this notation and means of editing over textual Prolog has not been demonstrated, and it is unclear whether users would find this approach, or any visual language, a more accessible means of specifying visualization.

A more comprehensive study of graphical notations and editing for specifying visualization queries may yield results on the merits of graphical specification, and yield notations that are particularly effective. Work in visual query languages [18] and end user queries could be used to specify the information content in views.

Visuals and visual objects could be designed by graphical tools instead of textual specification.

6.5.10 Natural Language Interface

Another approach to end-user specification is to use a natural language interface. Many natural language systems use Prolog, so it would be quite straightforward to embed a natural language interface into SVT. Queries such as “show the marital status of the salesmen who work in Ipswich who sold no speakers last month” could be converted into a clause for the view content. A command such as “show salesmen as circles” could change the visualization relation.

6.5.11 Formal Theory of Visualization

The semantic model in Chapter 3 is a fully formalized theory of visualization, based upon set theory. By formulating the relations in logic, the model is essentially an inverse of description logic [28] that is used to describe rather than generate the graphical properties of an image. The constraints form the basis of a constraint multiset grammar [65], and the scene graph relates to graph grammars [81]. The theoretical work in Chapter 3 could be reconciled with these other visual language formalisms.

6.5.12 Improve Program Analysis

There is much information about the source code that has not been analyzed. For example data flow in methods, or which methods get called in which circumstances, abstract interpretations of the data, or which values can be stored in which variables. Adding these analyses to Vmax would enhance the information presented to the programmer.

6.5.13 Visualize other Languages, such as C++

Vmax focuses on Java, but other programming languages could be visualized. There should be no difficulties in providing visualization for other languages, and to visualize many different languages simultaneously.

6.5.14 Data Persistence

SICStus Prolog provides predicates for persistent data storage in an external database. Vmax does not make use of it, and uses the non-persistent internal database. This means that large software systems have to be stored in main memory, which can be exhausted, and the data must be reloaded each time Vmax is run, which could be time consuming. It could be better to store the program database externally to avoid this.

A distributed client-server architecture could centralize this database, to have an entire workgroup cooperating in the same system. Views could be served as VRML over the internet, and navigation within the VRML viewer could connect to the server to request the new view.

6.5.15 Provide Visual Programming

Vmax provides visual programming for Prolog. The graphical notations for Java could also be manipulated, but that is beyond the scope of this work. Drag and drop techniques could rearrange source code at the statement level, and tool bars could automatically construct code for programming constructs or members of classes.

6.5.16 Interface to Compilers

Program analysis is performed by Prolog, which is a slower language than C or C++, and reimplements much of the work of existing compilers. Instead of performing program analysis itself, Prolog could interface to other tools that could return it information when requested. The program database could be stored externally in another tool.

6.5.17 Interface to the Java Virtual Machine Debug Interface

Run-time information is displayed off line. A graphical interface to the Java Virtual Machine Debug Interface [68] could provide access to live program information, which could browse the run-time data, and show the control flow through the program.

6.5.18 Improve Efficiency

There are many areas of SVT and Vmax that could be speeded up. For example there is a lot of dynamic memory allocation to construct each view. Such data could be constructed on a stack. An entire parse tree data structure is constructed during parsing, which is unnecessary.

6.6 Chapter Summary

A classification of Vmax in a taxonomy of SV systems [79] shows Vmax to be strong in many areas of SV, in spite of having such broad scope. The general specification technique has been shown to be appropriate for all aspects of SV. Unlike many other SV systems, Vmax is very scalable, and is practical to use in medium sized projects of 100 000 lines of code. All aspects of software can be visualized, and it is unusual for a system to be strong in both program and data visualization, or to offer any flexibility in program visualization. Its constraint based layout provides a much more flexible range of output. The query based mechanism provides good elision control and deals with all levels of granularity. The output of other systems is textually programmed, whereas Vmax can be modified by the end user. Interaction and navigation is much more advanced than in other systems. The legend describes each view so the views should be clear, but this has not been demonstrated in an empirical evaluation.

The specification strategy differs from other declarative systems such as Pavane [85] and Leonardo [20], because it uses three stages of visualization, and is based upon an established language with efficient implementations. Specifications in Vmax are reusable and provide encapsulation of graphical objects - this is not possible in the other approaches.

As well as improvements to the implementation, there are many avenues for further academic research. The modular design allows any component of the system to be replaced.

Chapter 7

Conclusions

This dissertation has described a new paradigm for specifying and implementing SV. A knowledge engineering environment stores and reasons about the data, and views are generated by querying the graphical constraints for a particular view and visualization method. By subdividing this query, every aspect of the visualization system can be specified.

The work is aimed at addressing problems with automation, flexibility, granularity, elision and specification, that have been very difficult to solve in existing systems. Its wide ranging scope makes it a strong alternative to other declarative and imperative implementations. However the added complexity has performance implications.

7.1 Vmax

Vmax is very different to use from other systems because of its user interface. The popularity of the browser interface indicates that this might be a good choice for software browsing. It is also very different because the number of views it provides is an order of magnitude greater than previous systems'. It is much more flexible and tailorable in its information content, the graphical display (changed from the Form menu or the Legend), and its interactive behaviour. Minimum user input is required to select the appropriate view.

But are these features useful? Without direct empirical measurements it is not possible to be certain. There is plenty of indirect evidence which suggests that alternative graphical representations are necessary for different tasks, and that the ability to filter out different kinds of information is necessary to avoid cluttering the display. Graphical browsers are widely used and effective, and without a legend views can be difficult to interpret. Price *et al.* [79] also cite problems with elision control, that Vmax solves because of its query mechanism, and granularity, which Vmax solves by its generic view generation mechanism.

The classification in Table 6.1 summarizes the strengths and weaknesses of Vmax.

7.1.1 Strengths of Vmax

- Broad scope and content. The data Vmax presents is far more wide ranging than in other SV systems.
- Good elision control. The user can control what to display or not to display.
- Granularity. The program can be viewed at many levels of detail.
- Tailorability. The view content and visual presentation can be changed to suit the user.
- Scalability. Quite large code bases and complex data structures can be visualized.

- Extensibility. It is comparatively easy to add new views to the system using the specification language.
- Automatic legend. Users can understand and modify the graphical representation.
- User interface. Navigation and browsing is achieved by single mouse clicks, graphical bookmarks and the preview window.
- Number of views. Vmax has 70 different types of view, which is an order of magnitude greater than in other systems.
- Automation. Minimum user input is required to select and view the data.
- Visual program structures are created automatically from source code.
- Integration into a complete development environment.
- Good temporal control over run-time data. It can be stepped and animated forwards and backwards.

7.1.2 Weaknesses of Vmax

- Limitations in program size. 115 000 lines of code is quite reasonable, but is not as good as some professional analysis tools.
- Limitations in input speed. The parser and program analysis is slower than some other source code analyzers written in C.
- Lack of synchronization with the running program.
- Lack of smooth data animation.

7.2 Implementing SV Systems

The work has highlighted several techniques that could be used in SV systems. The browser interface worked very well, and seems like a good interface for data exploration. The 3-D output could be used with good effect, particularly for numerical data structures, but was slightly less convincing for communicating program structures. With modern hardware and graphics libraries, there is little extra overhead in producing 3-D rather than 2-D output.

A wide range of graphical output is useful to tailor the output and enrich the graphical communication. A wide range of graphical layout algorithms is useful to deal with different types and structures of data. If users need to specify more advanced layout control, geometric constraints offer an approach.

Multiple views are already common, and proved to be necessary to retrieve different types of data without cluttering the view. Changing the view and visualization method from pull-down menus provided a convenient way of doing that. Graphical bookmarks and a preview window function well and are potentially useful. A legend to describe each view would reduce possible confusion over notation.

These functions do not necessarily have to be implemented in Prolog. For systems that do not require the flexibility and automation of Vmax, or the ability to pose queries, Prolog is not necessary. In this case, standard graphical output methods should be used.

SV systems that need to be highly tailored, provide many different views, and need to analyze and reason about programs could benefit from using Prolog as its visualization mechanism. In this case the specification techniques in Chapters 3 and 4 could be used. A constraint based layout mechanism is then needed to combine different graphical notations.

7.3 Specifying SV Systems

The way SV systems are specified is important to be able to construct systems quickly and effectively. A special purpose specification language and environment can potentially reduce the costs of implementation. An implementation is more likely to be error-free if the syntax of the language matches the semantics of the problem [94].

Previous systems have had only limited success with specification because they use a very low level approach. The declarative specification languages may be no better than C for graphical layout. Pavane [86] and Leonardo [20] are not *per se* better visualization systems than Polka [96] or Zeus [15]. In previous declarative systems, numbers from run-time data are used to specify the screen coordinates of graphical objects on the screen. This approach is too limited for code visualization and arbitrary data structures.

This work has made specification more powerful and flexible by subdividing the visualization process and generating high level graphical constraints. In this way, the specification is at a higher and more abstract level. In declaring a view, an implementor does not need to be concerned with the graphical representation, and vice versa. Also visual representations and view declarations can be reused rather than reimplemented. If the mapping between the view content and the visual content is a bijection, then a dynamic legend can be implemented.

It is also useful to specify interaction, because this adds more flexibility to the system, and can be used for many different things, such as bookmarks, menus, changes to the mouse cursor, data manipulation and navigation. The user interface can be completely tailored by the data.

Declarative specification methods are arguably more suitable than imperative languages, because visualization is data orientated and not sequential. A knowledge engineering environment may also help to represent heterogeneous data.

7.4 The Role of Prolog in Software Visualization

It has been demonstrated that Prolog can play a central role in information visualization and SV systems, and can specify every visual and interactive aspect of a SV system. But that does not necessarily make it superior to other approaches.

Prolog has certain characteristics that make it particularly suitable for SV. The other declarative SV systems base their implementations on logic languages [20, 86]. It provides an environment for knowledge engineering that manages the data and analysis part of SV, and it provides a query language for the contents of the views. This work has shown how these two functions can be combined.

For specialized systems with limited scope and fixed visualization behaviour, there is little advantage to be gained from the flexibility that Prolog provides. However it may be easier to implement such a system using a Prolog-based visualization tool like SVT. Systems that are knowledge orientated, require user queries, and offer multiple views and flexible visualizations, could use the specification environment that SVT provides.

Systems that focus on numerical and volumetric data would derive only limited benefit from Prolog. Existing techniques for numerical data are already very powerful.

Although the speed of Prolog is not as high as C, and some algorithms may be better implemented in C, it is not a choice between Prolog and C. Most Prologs have a C interface, so C and Prolog can work together to achieve the best of both worlds. Some Prologs, such as BinProlog [1] and GNU Prolog[2], will actually compile to native code which is linked into the executable.

The use of Prolog does not have to be restricted to SV. It provides a suitable meta-language for many other types of knowledge.

[1] URL: *http://www.binnetcorp.com*
[2] URL: *http://pauillac.inria.fr/~diaz/gnu-prolog*

7.4.1 Advantages of using Prolog as a Specification Language

- Prolog is a query language. Data queries can be formulated directly in the language. Previous declarative approaches to SV do not provide a database to query.
- Prolog is a good meta-language for reasoning about source code. Programming language rules can be expressed quite naturally in Prolog, which allows program structures to be queried.
- Specifications in Prolog are directly executable. There is no need to implement a language interpreter because existing ones can be used. Existing Prolog implementations are likely to be far more efficient than *ad hoc* declarative implementations.
- Prolog has good theoretical foundations. This allows formal reasoning using existing visual language theory.
- Prolog is Turing powerful.
- Prolog is already widely used in other applications.
- Unlike imperative languages, Prolog is a high level language good for knowledge engineering.
- Prolog has a built in mechanism for parsing text.
- Its untyped execution allows heterogeneous data to be passed through the visualization pipeline.
- Prolog is dynamic. The code can be modified at run time, for example to add new queries and change the visualization and action relations. New code can be loaded at run-time.
- Prolog is introspective. This means that it can query itself, for example to show the visualization relation in the legend. This is impossible in imperative languages.
- Any graphical output mechanism can be used.

As discussed in Section 6.5.8, these advantages are not necessarily peculiar to Prolog.

7.4.2 Disadvantages of Prolog

- Prolog is not very suited to applications programming because of its execution model and data handling. In fact Prolog is even used to implement parts of Microsoft Windows NT [46].
- Its execution speed is inferior to low level languages like C.
- There is overhead in providing a Prolog virtual machine and execution environment.
- Many sources of data are provided in C which must be converted into Prolog. However Prolog can access such data through a C interface.
- Large numerical data sets are more efficiently manipulated in C. But Prolog can call C functions for intensive computations.
- The output must be fed to a graphical constraint solver. The graphical constraint solver is slower and much trickier to implement than directly mapped graphics.

7.5 Information Visualization in SVT

SVT provides a very general framework for information visualization. By implementing a knowledge database in Prolog, and declaring the visualization environment at a high level, any type of information visualization can be implemented. SVT implements a complete graphical browsing environment for the data.

This approach provides an alternative to the traditional low level imperative programming method of implementing visualization. By using a more high level language to declare the visualization system directly, development times could be greatly reduced.

7.5.1 Formalizing Information Visualization

The underlying semantic model was demonstrated to be an effective method of expressing visualization. A very wide range of views have been expressed in the model. By ensuring that each visualization is decomposed into a bijection between the semantics and its representation (or syntax), the task of specification is simpified, and the mapping between the semantics and the graphical representation can be made flexible. The specification and implementation of SVT uses this formal model.

A formal theory of visual types was proposed, and was also shown to be an effective basis for implementation. It is due to this work that an interactive legend could be implemented. The model of interaction is also formal, and can even be used to express other formal models of interaction, such as CCS [69], given in Section C.5.2. There has been almost no previous work on the formal theory of SV.

7.6 Contribution

- A theoretical model of visualization has been devised that expresses the high level relationship between computer graphics and its underlying semantics. While other such models exist [44] they are not applicable to SV because they are restricted to numerical data.
- A general technique for specifying visualization, visual languages, interaction and SV in Prolog has been developed.
- A generic visualization tool has been implemented that uses the theoretical model and specification method.
- A link has been established between visualization and knowledge engineering.
- A SV system that is based upon this model and specification method has been implemented.
- Some new visualizations and visual languages, including the use of colour in Nassi-Shneiderman diagrams [72] have been developed.
- New methods of interaction, such as a browser-style interface and interactive modification of the legend have been demonstrated.
- The new techniques integrate SV with visual programming and text-based development environments.

7.7 Future Directions

There seems little doubt that the recent advances in software tools will continue. Graphics, visualization and interactive techniques look certain to play a role, as will greater reusability and automation of software creation. Programming languages are continually evolving to meet the

needs of the day, and the hardware on which they run. As methods of programming change, then so must the methods of visualization.

There are also many uncertainties, for example what will be the next major programming paradigm shift, the use of parallelism and formal methods, or even whether textual programming can be replaced entirely by natural language, visual, immersive, interactive or artificial intelligence systems. Maybe a combination of all of these technologies will play a role.

In software visualization, the goal must still be to serve the user, through power and usability. More information should be presented in more ways. But power and flexibility should not come at the expense of usability. *Automation* must make sure that the increased power and flexibility is accessible without unduly impeding the user. *Intelligence* is required to anticipate the correct data and graphics to output, and to make views adapt to the data and search criteria. *Interaction* with the views and the application could manipulate data and provide direct means of querying and navigation. *Specification* through graphical and interactive techniques would tailor visualization solutions with minimum effort. Finally *integration* of the different types of SV with other development tools would realize these potential benefits.

Vmax goes some way to tackling these issues, but much further work discussed in Section 6.5 is needed. SV based on knowledge engineering in Prolog provides a strong alternative to existing approaches, but can only complement rather than supersede existing work.

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Appendix A

Definitions

This appendix contains mathematical definitions that have not been included elsewhere.

Definition 16 (Atoms). *Let A be the set of atoms.*

An *atom* is an indivisible unit of information such as a name or a number, and the set A is infinite. For example *a, b, c, charles, harry, 3,* and *3.14* are all atoms.

Definition 17 (Terms). *The set of terms T is the smallest set closed under*

$$\frac{a \in A}{a \in T} \qquad \frac{f \in A \qquad t_1, \ldots, t_n \in T, n \geq 1}{f(t_1, \ldots, t_n) \in T}$$

For example *f(1), parent(node(123, 456)),* and *harry* are all terms.

Definition 18 (Relations). *If A and B are sets, then R is a relation between A and B if and only if $R \subseteq A \times B$. $aRb \iff (a, b) \in R$.*

Definition 19 (Composition of relations). *If R_1 is a relation between A and B, and R_2 is a relation between B and C, where A, B and C are sets, then $R_1 R_2$ is the relation between A and C defined by*

$$(a, c) \in R_1 R_2 \iff \exists b \in B.(a, b) \in R_1 \text{ and } (b, c) \in R_2$$

Note that relation composition is associative, because for relations R_1, R_2 and R_3, $(R_1 R_2) R_3 = R_1 (R_2 R_3)$.

Appendix B

Documentation

These notes provide a brief summary of the predicates and functions available to developers who wish to create visualizations using Semantic Visualization Tool, and to extend its capabilities. Only the publicly available predicates have been listed.

B.1 Running SVT

SVT is invoked

```
$ svt [options] [file] [arg1 arg2 ... argn]
```

where *file* contains the specification for the visualization system in fcompiled SICStus Prolog. Optional arguments *arg1 ... argn* are passed to Prolog and may be read by the *user_arguments/1* predicate. The optional *options* may include

- *-a argument* - Argument *argument* is passed to the Prolog program.
- *-l file* - Loads the fcompiled Prolog *file*. Files are loaded in the order they appear on the command line.
- *-p path* - Specifies the SVT directory. Otherwise this value is obtained from the environment variable *$SVT_PATH*.
- Xt options - To customize the appearance of the user interface.

B.2 SVT Predicate Summary

In addition to the built in Prolog predicates [59], SVT provides many predicates for visualization and interaction. Only the most important predicates are listed here. Vmax adds many more predicates for Java, file system browsing and run-time data structures. Predicates are either

- *[Extensible]* - These predicates are declared as *multifile* and are intended to be augmented by user code to implement the visualization system.
- *[Not extensible]* - These are predicates that provide functionality that would not normally be augmented by the user.
- *[Dynamic]* - These extensible predicates are declared as *dynamic* and may be modified at run-time to store data through the *assert/1* and *retract/1* predicates.

SICStus Prolog's module system is used to prevent name clashes. Unless otherwise specified, all SVT and Vmax predicates are in the module *svt*.

B.2.1 View Predicates

create_viewer(ViewContext, VisualContext, ActionContext, ReactionContext) [Not extensible] Creates a main viewing window with a text pane, status bar and pull-down menus. The initial view shown in the main viewing area has view context *ViewContext*, visualization context *VisualContext*, action context *ActionContext* and reaction context *ReactionContext.*

current_view_context(ViewContext) [Not extensible] Returns the view context of the current view in *ViewContext.*

navigate_as(Object, ViewContext) [Not extensible] Changes the current view context to visualize *Object*, or if that fails, use *ViewContext.*

navigate_to(ViewContext) [Not extensible] Changes the view context to *ViewContext.* This will also ensure that the contents of the view are current by calling *ensure_fresh/1.*

new_view(ViewContext, VisualContext) [Not extensible] Changes the view context to *ViewContext* and the visualization context to *VisualContext.* This is a direct call that does not ensure that data is loaded.

new_view_context(ViewContext) [Not extensible] Changes the view context to *ViewContext.* This is a direct call that does not ensure the validity of the view context or automatically loads data.

new_visual_context(VisualContext) [Not extensible] Changes the visualization context to *VisualContext*, and redraws the view.

new_zoom_view(ViewContext, VisualContext) [Not extensible] Changes the preview window to have view context *ViewContext* and visualization context *VisualContext.* The preview window is updated.

popup_frame(ViewContext, VisualContext, ActionContext, ReactionContext) [Not extensible] Creates a viewing window with no text pane, status bar or pull-down menus. The initial view shown in the main viewing area has view context *ViewContext*, visualization context *VisualContext*, action context *ActionContext* and reaction context *ReactionContext.*

refresh_view [Not extensible] Redisplays the current view, which is useful if the information content of the view is known to have changed.

retrieve_thumbnail_view [Not extensible] Sets the view and visualization context of the main viewer to the view and visualization context of the current (bookmark) view.

save_thumbnail_view [Not extensible] Sets the view and visualization context of the current (bookmark) view to the view and visualization context of the main viewer.

swap_thumbnail_view [Not extensible] Swaps the view and visualization contexts of the current (bookmark) view and the main viewer.

viewport_object(Object) [Not extensible] Returns the object *Object* being visualized.

B.2.2 Visualization Predicates

add_component(Visual, Id, Component) [Extensible] This predicate can be used in place of *object_component/3* but is used to add object components to an existing object.

anchor_expression_id(Expression, Object, Id) [Not extensible] Returns an identifier *Id* for an anchor expression *Expression* in a visual object *Object.*

anchor_expression_primitive(Expression, Object, Id, Primitive) [Not extensible] Returns the graphical constraints *Primitive* of an anchor expression *Expression* in a visual object *Object* with anchor identifier *Id.*

object_component(Visual, Id, Component) [Extensible] Declares the object components for a visual object *Visual* with identifier *Id. Component* is typically a list of components.

object_primitive(Component, Id, Primitive) [Not extensible] Specifies the graphical constraints *Primitive* that an object component *Component* generates in a visual object with identifier *Id.*

view(Object, ViewContext, Description) [Extensible] Declares that the view context *ViewContext* can be used to visualize entity *Object*, and the view description is *Description.* If a visualization is not tied to a particular entity, then *Object* is the atom *[].*

view_content(ViewContext, ViewContent) [Extensible] Specifies the query $\xrightarrow{Q}$ that declares what the content *ViewContent* is for a particular view context *ViewContext.*

visual_component(Visual, Component) [Extensible] Declares that *Component* is a visual that is added to the view when the visual *Visual* is. *Component* may be a list of visuals.

visual_content(ViewContent, VisualizationContext, VisualContent) [Extensible] [Dynamic] Specifies the relation $\xrightarrow{V}$ that declares how view content *ViewContent* is mapped to visual content *VisualContent* for a particular visualization context *VisualizationContext.*

visual_context(ViewContext, VisualContext) [Extensible] Declares that the visualization context *VisualContext* is suitable for displaying the view context *ViewContext.*

visual_primitive(Visual, Primitive) [Not extensible] Specifies the graphical constraints *Primitive* that are generated by a visual *Visual.*

B.2.3 Legend Predicates

content(Content, Type, Description) [Extensible] The content term *Content* has type *Type* and description *Description.* This predicate can be used instead of *content_type/2* and *content_description/2.*

content_description(Content, Description) [Extensible] Declares that the information content *Content* has textual description *Description.* This text appears in the legend alongside the symbol.

content_type(Content, Type) [Extensible] Declares the type relation $:_C$ that assigns types *Type* to information content *Content.*

visual(Visual, Type, Description, SymbolId, Symbol) [Extensible] The visual term *Visual* has type *Type*, description *Description*, and has a symbol *Symbol* in the legend with object id *SymbolId. Symbol* is the visual that appears in the legend. This predicate combines *visual_description/2*, *visual_type/2* and *legend_symbol/2.*

visual_context_description(VisualContext, Description) [Extensible] Declares that the visualization context *VisualContext* has textual description *Description.* This text apperas in the *Form* pull-down menu that selects alternative visualization contexts for the data.

visual_description(Visual, Description) [Extensible] Declares that the visual *Visual* has textual description *Description.* This text appears in the pop-up menu that selects alternative graphical forms for the content.

visual_type(Visual, Type) [Extensible] Defines the type relation $:_V$ that assigns types *Type* for the visual *Visual.*

B.2.4 Interaction Predicates

action(ActionContext, Action, Reaction) [Extensible] Declares that in action context *Action-Context*, the user's input *Action* has response *Reaction.*

mouse_cursor(Cursor) [Not extensible] Changes the mouse cursor to *Cursor.* Valid cursors are *hand*, *normal*, *watch*, *zoomin* and *zoomout.*

popup_menu(Menu) [Not extensible] Posts a pop-up menu at the mouse cursor. *Menu* is the menu context identifying the menu to display.

popup_modal(Title, Message, Buttons, Result) [Not extensible] Pops up a *modal* dialog box (one that must be dismissed before this predicate returns) with title *Title*, message string *Message*, a list of strings *Buttons* giving a list of buttons. *Result* returns the button that was pressed, or 0 for cancel.

popup_text(Title, Prompt, Default, Result) [Not extensible] Pops up a *modal* dialog box prompting the user to enter text, which is returned in *Result. Title* is the title of the dialog box, *Prompt* is the explanatory text, and *Default* is the initial text. If the user hits the *Cancel* button, the unit atom *[]* is returned in *Result.*

pulldown_menu(MenuContext, Text) [Extensible] Declares a pull-down menu with menu bar text *Text* and menu context *MenuContext.*

reaction(ReactionContext, Reaction) [Extensible] This predicate implements responses to user input, and is called whenever a reaction *Reaction* needs to be executed in reaction context *ReactionContext.*

set_status_text(Text) [Not extensible] Changes the text in the status bar to *Text.*

B.2.5 Text Predicates

buffer(Object, Buffer) [Dynamic] Assigns the text buffer *Buffer* to entity *Object.*

create_file_buffer(Filename, Buffer, TextNode, Type) [Not extensible] Creates a text buffer *Buffer* and loads the file *Filename* into it. The text node of this file is *TextNode*, and the buffer is given an associated type *Type.*

delete_text_node(TextNode) [Not extensible] Deletes the text in the text node *TextNode* from its buffer.

insert_before(TextNode, Text) [Not extensible] Inserts the string *Text* immediately before the text node *TextNode* in the text node's buffer.

lex_buffer(Buffer, Lexemes) [Not extensible] Applies the buffer *Buffer*'s lexical analyser and returns a list of lexemes *Lexemes.* Each list member is a pointer to a text node.

lexeme_float(TextNode, Float) [Not extensible] Takes the address of a text node *TextNode* and returns the floating point number *Float* in the text.

lexeme_integer(TextNode, Integer) [Not extensible] Takes a text node *TextNode* and returns the integer *Integer* in the text.

lexeme_length(TextNode, Length) [Not extensible] Returns the length *Length* of a text node *TextNode.*

lexeme_string(TextNode, String) [Not extensible] Returns the contents of a text node *TextNode* as an atom.

lexeme_string_list(TextNode, String) [Not extensible] Returns the contents of a text node *TextNode* as a string of chars.

move_text_cursor_to(TextNode) [Not extensible] Moves the text cursor in the editing window to the given text node *TextNode.*

node_structure(TextNode, Type, Children) [Not extensible] Returns the type *Type* for a text node *TextNode*, and its list of child text nodes *Children.*

object_size(Object, Size) [Not extensible] Returns the size in bytes *Size* of an object *Object*'s text node.

parse_buffer(Buffer, TextNode) [Not extensible] Applies the buffer *Buffer*'s lexical analyser and parser and returns the text node *TextNode* that is the root of the parse tree.

parse_tree(Buffer, Tree) [Not extensible] Applies the buffer *Buffer*'s associated lexical analyser and parser and returns a term *Tree* describing the entire parse tree. The term *Tree* is of the form *node(Type, TextNode,* C_1*,* C_2*, ...,* C_n*)*, where *Type* is an integer, *TextNode* is the address of its text node, and $C_1, ..., C_n$ are subterms of the same format.

reload_buffer(Buffer, TextNode) [Not extensible] Re-reads the contents of the text buffer *Buffer* from the external source, typically the filing system, and returns the new text *TextNode.*

save_buffers [Not extensible] Ensures that all of the text buffers that have changed are written to disk. Use before running programs that could examine these files.

text_node(Object, TextNode) [Dynamic] Assigns the text node *TextNode* to an entity *Object.*

token(TextNode, Type) [Not extensible] Returns the type *Type* of a text node *TextNode.*

B.2.6 Miscellaneous Predicates

colour(Colour, (R, G, B)) [Extensible] Defines colour names *Colour* for use in object components and visuals.

contains(Root, Descendent) [Not extensible] This is the transitive closure of *member/2.*

contains(Root, Descendent, Depth) [Not extensible] The same as *contains/2* but only searches to a maximum depth of *Depth.*

current_time([Y,Mo,D,H,Mi,S]) [Not extensible] Returns the current time as year *Y*, month *Mo*, day of month *D*, hour *H*, minute *Mi* and second *S.*

darken(Colour1, Colour2) [Not extensible] Takes a colour *Colour1* and returns a colour *Colour2* that is darker.

ensure_fresh(Object) [Extensible] Makes sure that the given entity *Object* is loaded and is up to date. This predicate is called every time the view context is changed.

identifier(Object, Identifier) [Extensible] Declares that the entity *Object* has a textual identifier *Identifier.*

lighten(Colour1, Colour2) [Not extensible] Takes a colour *Colour1* and returns a colour *Colour2* that is lighter.

long_identifier(Object, Identifier) [Extensible] Declares that entity *Object* has a long textual identifier *Identifier.*

member(Parent, Child) [Extensible] [Dynamic] Declares a relationship between *Parent* and *Child.*

short_identifier(Object, Identifier) [Not extensible] Declares that entity *Object* has a short textual identifier *Identifier.*

system_call(Command) [Not extensible] Executes the shell command *Command*, and waits for the process to terminate before returning.

system_process(Command) [Not extensible] Executes the shell command *Command*, and does not wait for the process to terminate before returning.

timer_start [Not extensible] Resets the internal timer.

timer_stop(Time) [Not extensible] Returns the elapsed time *Time* (in seconds) since *timer_start/0*.

uid(UID) [Not extensible] Returns a unique identifier *UID*. This is extremely useful when dynamically declaring new entities with unique names. The returned *UID* is an integer so that it can be indexed efficiently. *uid/1* is implemented as a counter.

user_arguments(List) [Not extensible] Returns the list *List* of arguments passed to SVT when it was invoked.

B.3 Vmax Predicate Summary

B.3.1 Filing System

compressed(File) [Not extensible] File *File* is compressed.

directory(File) [Dynamic] File is a directory.

ensure_path_loaded(Path) [Not extensible] Reads in the directory specified by *Path*.

executable(File) [Dynamic] File is an executable file.

file(File) [Dynamic] File is a file.

file_age(File, Age) [Not extensible] Returns the age *Age* (in seconds) of a file *File*.

file_barename(File, BareName) [Not extensible] Returns the filename *BareName* without its file extension for a file *File*.

file_extension(File, Extension) [Not extensible] Returns the filename extension *Extension* for a file *File*.

file_fullname(File,Name) [Not extensible] File *File* has full name *Name*, for example */usr/bin/netscape*.

file_path(File, Path) [Dynamic] File *File* has path *Path*, which is a list of directories. For example */usr/bin/netscape* would have path *[netscape, bin, usr]*.

file_timestamp(File, [Y,Mo,D,H,Mi,S]) [Dynamic] returns the creation date of the file *File*, as year *Y*, month *Mo*, day of month *D*, hour *H*, minute *Mi* and second *S*.

filename_information(Path, Status) [Not extensible] Returns the type of file *Status* of a file *Path* in the filing system. This queries the operating system directly, and returns *0* if the file does not exist, *1* if it is a regular file, *2* if it's a symbolic link, and *3* if it's a directory.

get_list_from_path(Filename, List) [Not extensible] Determines the file's path *List* from its full filename *Filename*. For example */usr/bin/netscape* would return *[netscape, bin, usr]*.

header_file(File) [Not extensible] File *File* is a header file.

home_directory(Dir) [Not extensible] Directory *Dir* is the user's home directory.

home_directory_path(PathName) [Not extensible] Returns an atom *PathName* giving the user's home directory *$HOME*.

java_source_file(File) [Not extensible] File *File* is Java source code.

make_file_fullname(DirName, Filename, FullName) [Not extensible] Returns the complete file path *FullName* for a file *Filename* in directory *DirName.*

makefile(File) [Not extensible] File *File* is a makefile, as determined by its filename.

path_id(Path, Id) [Not extensible] Returns a unique identifier *Id* for a given path *Path.*

picture_file(File) [Not extensible] File *File* is graphics, as determined by its filename extension.

prolog_source(File) [Not extensible] File *File* is Prolog source code, with suffix *.pl.*

readable(File) [Dynamic] File *File* is readable.

root_directory(Dir) [Not extensible] Directory *Dir* is the root directory.

source_code(File) [Not extensible] File *File* contains source code. This is determined by the filename extension.

svt_path(PathName) [Not extensible] Returns an atom *PathName* containing the value of *$SVT-_PATH.*

writable(File) [Dynamic] File *File* is writable.

B.3.2 Java Source Code

These predicates are in the module *java.*

block(Block, Statements) [Dynamic] Block is a block of statements *Statements.*

block_statement(Statement, Block, Statements) [Dynamic] Statement is a block *Block* of statements *Statements.*

buffer(File, Buffer) [Dynamic] The java file *File* has buffer *Buffer.*

break_statement(Statement) [Dynamic] Statement is a *break* statement.

break_statement(Statement, Label) [Dynamic] Statement is a *break* statement to label *Label.*

cached_calls(Method1, Method2) [Dynamic] This is a precomputed version of *method_calls/2* that stores that *Method1* calls *Method2.*

cached_reference(Method, Variable) [Dynamic] This is a precomputed version of *method_refs/2* that stores that *Method1* references the variable *Variable.*

case_statement(Statement, Expression, Text) [Dynamic] Statement is a *case* statement with case *Expression* with text node *Text.*

class(Class) [Not extensible] Class is a Java class.

class_member(Class, Member) [Not extensible] Returns members *Member* which are members of the class *Class.* This includes members inherited from supertypes.

class_method(Class, Method) [Not extensible] Returns methods *Method* which are methods in the class *Class.* This includes methods inherited from supertypes.

class_path(Dir) [Not extensible] Returns the directory *Dir* of the Java source code. May return multiple solutions on backtracking.

conditional_statement(Statement, Condition, CText, Then) [Dynamic] Statement is an *if-then* statement with condition expression *Condition*, text node of the condition *CText*, and body statement *Then.*

conditional_statement(Statement, Condition, CText, Then, Else) [Dynamic] Statement is an *if-then-else* statement with condition expression *Condition*, text node of the condition *CText*, which takes the statement *Then* if true, and *False* if false.

constructor(Method) [Not extensible] Indicates that *Method* is a constructor.

contains_statement(Statement1, Statement2) [Not extensible] Statement *Statement1* contains statement *Statement2*, for example within a block.

continue_statement(Statement) [Dynamic] Statement is a *continue* statement.

continue_statement(Statement, Label) [Dynamic] Statement is a *continue* statement to label *Label.*

declaration(Declaration) [Not extensible] Declaration is a Java declaration - either a class or an interface. *member/2* gives the members of the declaration, and *identifier/2*, *short_identifier-/2* and *long_identifier/2* return descriptions of the declaration.

declaration(Declaration, ClassType, Modifiers, Extends, Interfaces, ClassHeader) [Dynamic] Declaration is a declaration of a *ClassType*, which is either *class* or *interface.* Its modifiers *modifiers* is the term are *modifiers(Abstract, Final, Access, Static, Transient, Volatile, Native, Synchronized). Extends* is the name of the class it extends, and *Interfaces* is a list of classes it interfaces. *ClassHeader* is the text node of the header of the class.

declaration_statement(Statement, Decls) [Dynamic] Statement is a declaration statement declaring the list of declarations *Decls.*

default_statement(Statement) [Dynamic] Statement is a *default* label.

direct_subinterface(Class, Interface) [Not extensible] Class or interface *Class* directly implements *Interface.*

direct_subtype(Supertype, Subtype) [Not extensible] Class *Subtype* extends class *Supertype.*

direct_superinterface(Interface, Class) [Not extensible] Class or interface *Class* directly implements *Interface.*

direct_supertype(Subtype, Supertype) [Not extensible] Class *Subtype* extends class *Supertype.*

do_while_statement(Statement, Condition, CText, Body) [Dynamic] Statement is a do-while statement with condition expression *Condition*, condition text node *CTerm*, and statement body *Body*.

empty_statement(Statement) [Dynamic] Statement is an empty statement.

expression_calls(Expression, Context, Method) [Not extensible] The expression *Expression* calls the method *Method* in context *Context.*

expression_reference(Expression, Context, Variable) [Not extensible] The expression *Expression* references the variable *Variable* in context *Context.*

expression_statement(Statement, Expression) [Dynamic] Statement is an expression statement with expression *Expression. Expression* is a term storing the structure of the expression.

expression_type(Expression, Context, Type) [Not extensible] The expression *Expression* has type *Type* in context *Context.*

find_declaration(Type, Declaration) [Not extensible] Finds the declaration (class or interface) *Declaration* that is referred to in a Java type *Type.* An array of a class will return the class.

find_variable(Name, Context, Variable) [Not extensible] Returns the variable *Variable* that the name *Name* refers to, when used in the context *Context. Context* contains the local declarations.

for_statement(Statement, Init, IText, Condition, CText, Incr, IncText, Body) [Dynamic] Statement is a *for* statement with initializer expression *Init* and text node *IText*, condition expression *Condition* and text node *CText*, incrementation expression *Incr* and text node *IncText*, and statement body *Body*.

has_name(Object, QualifiedName) [Dynamic] Variable, declaration or method *Object* has the fully qualified name *QualifiedName.* e.g. *java.lang.Object* would have qualified name *['Object', 'lang', 'java'].*

import_all_declaration(File, Id, Package) [Dynamic] Java file *File* imports all the declarations from package *Package.* e.g. *java.io* would have package *[io, java]. Id* is the identifier of the import statement.

import_declaration(File, Id, Declaration) [Dynamic] Java file *File* imports the declaration *Declaration.* e.g. *java.io.OutputStream* would have declaration *['OutputStream', 'io', 'java'].* *Id* is the identifier of the import statement.

initializer(Variable, Expression) [Dynamic] The variable *Variable* is initialized by the expression *Expression.*

interface(Interface) [Not extensible] Interface is a Java interface declaration.

is_abstract(Method) [Not extensible] Method is an abstract method. All method declarations in interfaces are considered to be abstract.

is_native(Method) [Not extensible] Method is a native method.

is_private(Member) [Not extensible] Class member (method or variable) *Member* is private (has private access.)

is_protected(Member) [Not extensible] Class member *Member* is protected.

is_public(Member) [Not extensible] Class member *Member* is public.

svt:java_source_file(File) [Not extensible] File is a file containing Java source code. This is determined solely by its file extension.

labelled_statement(Statement, Label) [Dynamic] Statement is a *label* statement with label *Label.*

make_qualified_name(List,Text) [Not extensible] Returns text *Text* for a qualfied name *List.* e.g. *['Object', 'lang', 'java']* returns *java.lang.Object.*

method(Method) [Not extensible] Method is a method, which may be abstract or native.

method(Method, Type, Modifiers, Params, Throws, BlockStmt, Statements) [Dynamic] Method is a method with return type *Type*, modifiers *Modifiers*, parameters *Params* as a list of variables, throws *Throws* as a list of class names, *BlockStmt* as the identifier of the block body, and *Statements* as the list of statements in the method body.

method_calls(Method1, Method2) [Not extensible] The method *Method1* calls the method *Method2.*

method_refs(Method, Variable) [Not extensible] Method *Method* references the variable *Variable.*

method_contains_statement(Method, Statement) [Not extensible] Java method *Method* contains the statement *Statement.*

method_entry_point(Method, Statement) [Not extensible] Statement *Statement* is the first executable statement in method *Method.*

method_sub_expression(Method, Expression, Context) [Not extensible] Method *Method* has a sub-expression *Expression* in context *Context*, which is the declarations that apply to the expression.

name_of(Name, QualifiedName, Object) [Dynamic] Object *Object* has fully qualified name *QualifiedName* and short name *Name.* This mirrors *has_name/2* but is indexed differently.

nonstatic_initializer(Id, Block, Statements) [Dynamic] The non-static initializer *Id* has a block *Block* of statements *Statements.*

package(File, Package) [Dynamic] Java file *File* is in package *Package.* e.g. package *java.lang* would be stored *[lang, java].*

package_declaration(Id) [Dynamic] Id is a package declaration.

parameter(Variable) [Dynamic] Indicates that the given variable is a parameter to a method.

program_file(ParseTree, File) [Not extensible] Performs the analysis of the parse tree *ParseTree* of the file *File.*

reachable(Method1, Method2, Prev, Visited) [Not extensible] Method2 is reachable from *Method1*, and *Prev* is the method that calls *Method2. Visited* is a list of methods already visited (to prevent looping), which is initially *[].*

return_statement(Statement) [Dynamic] Statement is a *return* statement with no return value.

return_statement(Statement, Expression) [Dynamic] Statement is a *return* statement that returns the expression *Expression.*

scan_directory(Directory) [Not extensible] Reads in all of the Java source files in a given directory *Directory.*

statement(Statement) [Dynamic] Statement is a Java statement.

statement_entry_point(Statement, EntryPoint) [Not extensible] Gives the statement entry point *EntryPoint*, the first statement executed, within a compound statement *Statement.*

statement_exit_point(Statement, ExitPoint) [Not extensible] Gives the statement exit point *ExitPoint*, the last statement executed, within a compound statement *Statement.* May give multiple exit points upon backtracking.

statement_follows(Method, Stmt1, Stmt2, Type) [Not extensible] In method *Method*, statement *Stmt1* is followed by statement *Stmt2* with transition type *Type. Type* may be one of *case(Label), default, else, for, for_exit, sequence, then, while, while_exit.*

statement_text(Statement,Text) [Dynamic] Java statement *Statement* has text *Text.*

static_initializer(Id, Block, Statements) [Dynamic] Static initializer *Id* has a block *Block* of statements *Statements.*

switch_statement(Statement, Condition, CText, Block, Statements) [Dynamic] Statement is a switch statement with condition expression *Condition*, condition text node *CText*, and a block *Block* of statements *Statements.*

sub_expression(Expression1, Expression2) [Not extensible] Finds a sub-expression *Expression2* of an expression *Expression1.*

sub_expression_decl(Statement, Decls, Expr, NewDecls) [Not extensible] Finds the sub-expression *Expr* nested within a statement *Statement*, and returns the list *NewDecls* of declarations that apply to that sub-expression.

subinterface(Interface,Class) [Not extensible] Class or interface *Class* directly or indirectly implements interface *Interface.*

subtype(Supertype, Subtype) [Not extensible] The transitive closure of *direct_subtype/2.* Java class *Subtype* is a subtype of *Supertype.*

superinterface(Class,Interface) [Not extensible] Class or interface *Class* directly or indirectly implements interface *Interface.*

supertype(Subtype, Supertype) [Not extensible] Java class *Supertype* is a supertype of *Subtype.*

synchronized_statement(Statement, Expression, Text, Body) [Dynamic] Statement is a *synchronized* statement, with lock *Expression*, text node *Text*, and statement body *Body*.

throw_statement(Statement, Expression) [Dynamic] Statement is a *throw* statement that throws the expression *Expression*.

try_statement(Statement, Block, Statements, Catches, FBlock, FStatements) [Dynamic] Statement is a *try-catches-finally* block, with main body *Block* of statements *Statements*, a list *Catches* of catch blocks of the form *catch(Text, Variable, CBlock, CStatements)*, and a finally block *FBlock* of statements *FStatements*.

variable(Variable) [Not extensible] Variable is a variable.

variable(Variable, Type, Modifiers) [Dynamic] Variable is a variable of type *Type* and modifiers *Modifiers*.

while_statement(Statement, Condition, CText, Body) [Dynamic] Statement is a while statement with condition expression *Condition*, condition text node *CTerm*, and statement body *Body*.

B.3.3 Java Run-time

java:add_tracepoint(Statement, Expression, TracePoint) [Not extensible] Adds a trace point *Expression* before a statement *Statement*, and returns the identifier of the trace point *TracePoint*.

trace:any_next_input(Input1, Input2) [Not extensible] Finds the next input event *Input2* after *Input1*.

trace:any_prev_input(Input1, Input2) [Not extensible] Finds the input event *Input2* immediately preceeding *Input1*.

ensure_trace_loaded(File) [Not extensible] Loads the contents of trace file *File*.

trace:event(Input, File, EventNo, Time, Value) [Dynamic] Input is an input event in a trace file *File*, with associated event number *EventNo*, that occurred at time *Time*, and whose value is *Value*.

trace:next_input(Input1, Input2) [Not extensible] Finds the next input event *Input2* after *Input1*, that has the same event number.

trace:prev_input(Input1, Input2) [Not extensible] Finds the input event *Input2* preceeding *Input1* on the same event line.

java:trace_point(EventNo, String, Statement) [Dynamic] EventNo is an event number that examines value *String*, at java statement *Statement*.

trace:value(Value, String, Term) [Dynamic] Value is a value in a trace file, that examines the variable *String*, and whose value is encoded in term *Term*. *Term* is

- *array(Values)* - An array with list of values *Values*.
- *float(Float)* - A *float* or *double* with value *Float*.
- *integer(Int)* - An *int* with value *Int*.
- *null* - A *null* object.
- *object(Id, Class, Fields)* - An object with object id *Id*, class name *Class*, and *Fields* is a list of members of the form *field(FieldName, Value)*.
- *object(Id)* - An object with object id *Id*.

B.3.4 Prolog Source Code

exec_clause(Clause) [Not extensible] Declares that the clause *Clause* is executable, i.e. not in the scratch area.

user_clause(Clause, Term) [Dynamic] Stores a clause *Clause* with the structure of the clause stored by the term *Term.*

user_term(Functor, Arity, Description) [Extensible] Defines a new term to go in the *Change functor* menu, with new functor *Functor*, new arity *Arity* and description *Description.*

user_view_content(ViewContext, Content) [Dynamic] A dynamic version of *view_content/2* that can be modified by the user at run-time.

user_view_context(Object, ViewContext, ViewDescription) [Dynamic] A dynamic version of *view/3* that can be modified by the user at run-time.

user_visual_context(ViewContext, VisualContext) [Dynamic] A dynamic version of *visual_context/2* that can be modified by the user at run-time.

scratch_term(Clause) [Dynamic] Declares that the clause *Clause* is in the scratch area.

B.4 Visuals Defined by SVT

This information is displayed by selecting *List visuals* from the *Debug* menu.

B.5 Visual Object Components Defined by SVT

[H|T] A list of object components.

P1=above(P2) Constrains the anchor *P1* to be above anchor *P2.*

alignment(Object, Align) Sets the alignment of the visual object *Object* to be *Align* within its container.

anchor(E) An anchor expression *E.*

P1=below(P2) Constrains the anchor *P1* to be below the anchor *P2.*

Id=colour(Colour) Attributes the colour *Colour* (as defined by the *colour/2* predicate or as *(R,G,B)*) to the object component *Id.*

contain(Object, A, B, C, D) Contains a sub-object *Object* with corners *A*, *B*, *C* and *D.*

Id=container(A, B, C, D) Creates an empty container *Id* with corners *A*, *B*, *C* and *D.*

Id=container(A, B, C, D, E, F, G, H) Creates an empty container *Id* with the corners of its bounding cuboid *A*, *B*, *C*, *D*, *E*, *F*, *G* and *H.*

insert(Container, Object) Inserts an object *Object* into an empty container.

P1=further(P2) Constrains the anchor *P1* to be further than anchor *P2.*

fillcontainer(Object) Sets the alignment of the visual object *Object* to fill its container.

P1=leftof(P2) Constrains the anchor *P1* to be left of anchor *P2.*

line(Points) Declares a sequence of line segments along the list of anchors *Points.*

Id=line(Points) Declares a sequence of line segments *Id* along the list of anchors *Points.*

P1=nearer(P2) Constrains the anchor *P1* to be nearer than anchor *P2.*

oscale(Scale, A, B, Value, Vector) Offsets the anchor *B* by r.*Vector* from *A*, where r is the weighting of the value *Value* in the scale *Scale*, taken from the origin.

polygon(Points) Creates a polygon whose vertices are given by the list of anchors *Points.* The polygon should not be self-intersecting, and the vertices should go clockwise or anti-clockwise.

Id=polygon(Points) Creates a polygon with identifier *Id* with list of vertices *Points.*

Id=multicontainer(A, B, C, D) Creates an empty container with corners *A*, *B*, *C* and *D*, into which multiple objects can be inserted.

P1=rightof(P2) Constrains the anchor *P1* to be right of anchor *P2.*

scale(Scale, A, B, Value, Vector) Offsets the anchor *B* by r.*Vector* from *A*, where r is the weighting of the value *Value* in the scale *Scale.*

text(Text, A, B, C, D) Declares a text component with string *Text* with corner anchors *A*, *B*, *C* and *D.*

Id=text(Text, A, B, C, D) Declares a text component with string *Text* and identifier *Id* with corner anchors *A*, *B*, *C* and *D.*

Id=thickness(Thickness) Attributes the thickness *Thickness* (in point values) to the line *Id.*

Id=transparency(Value) Attributes the transparency *Value* (between 0 and 1) to the object component *Id.*

xalign(P1, P2) Aligns two anchors *P1* and *P2* in the x axis.

yalign(P1, P2) Aligns two anchors *P1* and *P2* in the y axis.

zalign(P1, P2) Aligns two anchors *P1* and *P2* in the z axis.

B.6 Graphical Constraints Defined by SVT

alignment(Object, Align) Visual object *Object* is given alignment *Align*, which is read by containing objects such as tables. *Align* may be

- *bottom* - Object is aligned to the bottom of the container.
- *fill* - Object is expanded in both x and y axis to fill the container
- *left* - Object is aligned to the left of the container.
- *right* - Object is aligned to the right of the container.
- *top* - Object is aligned to the top of the container.
- *xfill* - Object is expanded in the x axis to fill the container.
- *yfill* - Object is expanded in the y axis to fill the container.

colour(Object, (R, G, B)) Attributes visual object *Object* with the RGB colour value *(R,G,B).*

contains(A, B) Specifies that visual object *A* contains visual object *B.*

fill_edge(Id, A, B) An edge between two visual objects *A* and *B.* This type of edge is laid out as a hierarchical list.

graph(Id, X, Y) A graph *Id* with axes labelled *X* and *Y.*

graph_point(Id, X, Y, Z) A sample point on a graph, with identifier *Id* at position *(X,Y,Z).*

hier_edge(Id, A, B) An edge between two visual objects *A* and *B*, that is laid out horizontally as a hierarchy.

icon(Id, Type) An icon *Id* with type *Type.*

insert(Object, Position, Child) Passes a child object *Child* to a visual object *Object* in position *Position.*

insertable_object(Object, Name) Declares an insertable object *Object* with name *Name.*

lens_edge(Id, A, B) An edge *Id* between two visual objects *A* and *B*, laid out as a fish-eye.

list_edge(Id, A, B) An edge *Id* between two visual objects *A* and *B*, laid out as a vertical list.

multi_container(Object) Creates a visual object *Object* which can contain any number of objects which are laid out in a 2-D palette, using the *contains/2* constraint.

order(Object, Order) Assigns an order *Order* to a visual object *Object*, which is used to present visual objects in a certain sequence.

scale(Id) Declares a scale *Id* in the view, for comparing numerical values.

size(Object, Scale, Value) Sets the size of the visual object *Scale* according to the value *Value* in scale *Scale.*

table(Id, Cols, Rows) Creates a table *Id* with *Cols* columns and *Rows* rows. If *Cols* is zero, then the table is filled from top to bottom and the number of columns is variable. If *Rows* is zero, then the table is filled from left to right and the number of rows is variable. Otherwise the table is filled left to right.

text_window(TextNode) Places the contents of the text node *TextNode* in the editing area of the viewer.

title(Title) Sets the title of the view to be the string *Title.*

v_stack(Id, A, B) Creates a new visual object *Id* that puts visual object *A* above visual object *B.*

B.7 Actions Defined by SVT

click(Object, Buttons, Times) The mouse has been clicked on object *Object*, with the mouse buttons *Buttons*, *Times* times. *Buttons* is the term *[Left, Middle, Right, Shift]*, where *Left* is the left mouse button, *Middle* is the middle mouse button, *Right* is the right mouse button, and *Shift* is the shift key, which are either *on* or *off.*

drag(From, To, Buttons) A mouse drag from object *From* to object *To*, with the mouse buttons *Buttons.*

key(Object, Key) A key *Key* has been pressed with the mouse cursor over object *Object.*

linger(Object) The mouse cursor is resting over an object *Object.*

menu(MenuContext, MenuText) An item from a menu *MenuContext* with menu text *MenuText* has been selected.

move(Object, Buttons) The mouse cursor has moved over an object *Object*, with mouse buttons *Buttons.*

B.8 Views Defined by Vmax

This information is displayed by selecting *List views* from the *Debug* menu.

B.9 The C++ Interface

B.9.1 Adding Graphical Constraints

The base classes *Vnode*, *Vobject*, *Vattribute*, *Vcompound* and *Vassociation* are declared in the file *svtvisual.h*, listed below. An instance of the class *SVT_declare_visual* should examine the Prolog term passed to the method *Declare_visual()*, and return a new instance of the specified class, or return *0* if no match is found. These handlers form a chain. The instantiated visual is automatically added to the scene graph.

The C++ code is linked to the SVT object files to produce a new executable with the new constraint.

The File *svt_visual.h*

```
// Defines classes for creating visual constraints in SVT
// Written by Calum Grant
// Copyright (C) Calum Grant 1998, 1999

#ifndef SVTVISUAL_H
#define SVTVISUAL_H

namespace SVT
{
  class Vnode
  {
  public:
    int p[5];  // Internal data

    Vnode();
    virtual ~Vnode();

    virtual void On_reset();
    virtual void On_structure();
  };


  class Vobject : public Vnode
  {
  public:
    double d[14];  // Internal data
    int    p[25];  // Internal data

    // Structure query:
    class Vassociation *First_assoc(int&) const;
    class Vassociation *Next_assoc(int&) const;
    class Vattribute   *First_attrib(int&) const;
    class Vattribute   *Next_attrib(int&) const;

    // Bounding box manipulation:
    void          Set_size(const double*);
    void          Set_position(const double*);
    const double* Get_size() const;
    const double* Get_min_pos() const;
    void          Get_max_pos(double*) const;

    Vobject(int);
    virtual ~Vobject();

    virtual void On_reset();
    virtual bool On_attribute(class Vattribute*);
```

```
  virtual void On_reset_size();
  virtual void On_set_size(const double*);
  virtual void On_set_position(const double*);
  virtual void On_draw() const;
};


class Vcompound : public Vobject
{
public:
  int p[2];  // Internal data

  Vobject *First_child(int&) const;
  Vobject *Next_child(int&) const;

  Vcompound(int);
  virtual ~Vcompound();

  virtual void On_reset();
  virtual void On_reset_size();
  virtual void On_set_size(const double*);
  virtual void On_set_position(const double*);
  virtual void On_draw() const;
};


class Vassociation : public Vcompound
{
public:
  int p[14];  // Internal data

  Vobject *From() const;
  Vobject *To() const;

  Vassociation(int id, int from, int to);
  virtual ~Vassociation();

  virtual void On_reset();
  virtual void On_structure();
};


class Vattribute : public Vnode
{
public:
  int p[13];  // Internal data

  Vobject *Object() const;

  Vattribute(int);
  virtual ~Vattribute();

  virtual void On_reset();
};


class SVT_declare_visual
{
public:
  SVT_declare_visual();
  virtual Vnode *Construct_visual(int)=0;
```

```
    SVT_declare_visual *next;
  };


  char  *StringTerm(int);           // Convert string terms to char*
  double FloatTerm(int);            // Convert float terms to double
  int    IntTerm(int);              // Convert int/float terms to int
  void   VectorTerm(int, double*);  // Convert (X,Y,Z) terms to double*
}

#endif
```

B.9.2 The Graphical User Interface

The functionality of SVT is completely independent of the type of graphical user interface. All communication with the graphical user interface is done through the classes *MainBase* and *ViewBase*, declared in the file *svt.h*. These are abtract base classes, and the actual interface is implemented in their derived classes. An interface for Motif 1.2 has been implemented.

The File *svt.h*

```
// GUI interface for SVT
// Written by Calum Grant
// Copyright (C) Calum Grant 1998

#ifndef SVT_H
#define SVT_H

namespace SVT
{
  enum SVT_cursor { SVT_ARROW, SVT_WAITING, SVT_ZOOMIN, SVT_ZOOMOUT,
        SVT_POINT };
  enum SVT_type { SVT_MAIN, SVT_THUMBNAIL, SVT_ZOOM, SVT_PLAN,
        SVT_LEGEND, SVT_POPUP };


  class ViewBase
  {
  public:
    class View *data;

  public:
    ViewBase();
    virtual ~ViewBase();

    void GL_draw();
    void Drawing_speed(int);
    void Input_event(int input, int d0, int d1, int d2);
    void Key_press(int key);
    void Mouse_move(int x, int y, int shift, int ctrl);
    void Mouse_pause(int x, int y);
    void Mouse_press(int x, int y, int l, int m, int r, int shift, int ctrl);
    void Mouse_release(int x, int y, int l, int m, int r, int shift, int ctrl);
    void Main_viewer();
    void Reset_view();
    void Editor_insert(int offset, char *text);
    void Editor_delete(int offset, int length);
    void Editor_update();
    void Resize_view();
    void Refresh_view();
```

```
    void Menu_select(int id, int item);
    void Popup_select(int);
    void Duplicate_view(ViewBase*);
    void Reset_viewpoint();
    void Background_process();
    void Help();

    // These functions are called by SVT:
    virtual int  Window_width()=0;
    virtual int  Window_height()=0;
    virtual void GL_redraw()=0;
    virtual void Mouse_cursor(SVT_cursor)=0;
    virtual void Pulldown_menu(char *title, int id, char**)=0;
    virtual void Inactivate_pulldown(int id)=0;
    virtual void Popup_menu(char**)=0;
    virtual void Status_text(const char*)=0;
    virtual void Set_text_window(const char*text, int size, bool ro)=0;
    virtual char* Get_text_window(int &length)=0;
    virtual void Set_text_position(int position)=0;
    virtual void Lock_editor()=0;
    virtual void Set_title(const char*)=0;
    virtual SVT_type Get_type()=0;
    virtual void Set_frame_size(int, int)=0;
    virtual void Destroy()=0;
    virtual void Start_background_process()=0;
    virtual void Stop_background_process()=0;
  };


  class MainBase
  {
    class Main *data;

  public:
    MainBase(const char*path=0);
    virtual ~MainBase();

    void Boot();
    int add_data(char*pred, int data);
    int remove_data(char*pred, int data);
    int load_prolog(char*filename);
    char *Boot_error();

  public: // These functions are called by SVT:
    virtual bool Break()=0;
    virtual ViewBase *Create_popup()=0;
    virtual ViewBase *Create_viewer()=0;
    virtual char *Get_string(const char *title,
        const char *prompt,
        const char *def)=0;
    virtual int Get_option(const char *title,
        const char *prompt,
        const char **buttonlist)=0;
    virtual char **Get_user_arguments(int&)=0;
  };
}

#endif
```

Appendix C

Further Examples

This appendix contains complete and fully functioning examples of the specification techniques. For reasons of conciseness, they were not be presented in full in the main body of this dissertation.

C.1 Views

All views (shown in Figure 4.3)

```
view([], views, 'All views').

visual_context(views, views).

view_content(views, title('Welcome to Vmax')).
view_content(views, view(navigate_to(C), D)) :-
        view_context([],C,D), D \== separator.
```

All Java interfaces (shown in Figure 5.17)

```
view([], java_interfaces,  'Java interfaces').

visual_context(java_interfaces, vs).

view_content(java_interfaces, title('Java Interfaces')).
view_content(java_interfaces, interface(I,T)) :-
        java:interface(I),
        long_identifier(I,T).
```

The Java class hierarchy (shown in Figure 5.20)

```
view([], java_classhier, 'Java class hierarchy').

visual_context(java_classhier, vs).
visual_context(java_classhier, fisheye).
visual_context(java_classhier, tree).

view_content(java_classhier, title('Java class hierarchy')).
view_content(java_classhier, class(Class,Name)) :-
        java:class(Class),
        short_identifier(Class,Name).
view_content(java_classhier, contains(Super,Sub)) :-
        java:class(Sub),
```

```
        java:direct_supertype(Sub,Super).
```

Complete call graph

```
view([], call_graph, 'Complete call graph (cached)').

visual_context(call_graph, vs).

view_content(call_graph, title('Complete call graph')).
view_content(call_graph, function(F,I)) :-
        java:method(F),
        long_identifier(F,I).
view_content(call_graph, calls(A,B)) :-
        java:method(A),
        java:cached_call(A,B).
```

Method calls within a class (shown in Figure 5.26)

```
view(C, cached_calls(C), 'Method calls within class (cached)') :-
        java:class(C).

visual_context(cached_calls(_), vs).

view_content(cached_calls(C), title(['Method calls within ',I])) :-
        long_identifier(C,I).
view_content(cached_calls(C), function(F,I)) :-
        java:class_method(C,F),
        identifier(F,I).
view_content(cached_calls(C), calls(A,B)) :-
        java:class_method(C,A),
        java:cached_call(A,B),
        java:class_method(C,B).
```

References to a variable

```
view(V, cached_variable_refs(V), 'References to variable (cached)') :-
        java:variable(V).

visual_context(cached_variable_refs(_), vs).

view_content(cached_variable_refs(V),
        title(['References to variable ',I])) :-
        long_identifier(V,I).
view_content(cached_variable_refs(V), function(M,I)) :-
        java:cached_reference(M,V),
        long_identifier(M,I).
```

C.2 Visualization Relations

The following example shows the visualization relations for block structured Prolog (shown in Figure 5.53).

```
% Query structured

visual_context_description(query, 'Query').
visual_content(tpm_predicate(Id,H,T), query, tpm_predicate(Id,H,T)).
visual_content(or_term(Id,A,B), query, query(Id,or,A,B)).
visual_content(and_term(Id,A,B), query, query(Id,and,A,B)).
```

```
visual_content(if_term(Id,A,B), query, query(Id,if,A,B)).
visual_content(term(Id,Text,List), query, pl_term(Id,Text,List)).
visual_content(variable_term(Id,Text), query, colour_text(Id,Text,yellow)).

% Block structured

visual_context_description(block, 'Block structured').
visual_content(tpm_predicate(Id,H,T), block, tpm_predicate(Id,H,T)).
visual_content(or_term(Id,A,B), block, pl_or(Id,A,B)).
visual_content(and_term(Id,A,B), block, pl_and(Id,A,B)).
%visual_content(if_term(Id,A,B), block, infix_text(Id, ' <- ', A,B)).
visual_content(if_term(Id,A,B), block, block_clause(Id,A,B)).
visual_content(term(Id,Text,List), block, pl_term(Id,Text,List)).
visual_content(variable_term(Id,Text), block, colour_text(Id,Text,yellow)).

% English

visual_context_description(prolog_english, 'English').
visual_content(tpm_predicate(Id,H,T), prolog_english, tpm_predicate(Id,H,T)).
visual_content(or_term(Id,A,B), prolog_english, infix_text(Id,'or',A,B)).
visual_content(and_term(Id,A,B), prolog_english, infix_text(Id,'and',A,B)).
visual_content(if_term(Id,A,B), prolog_english, infix_text(Id,'if', A,B)).
visual_content(term(Id,Text,List), prolog_english, pl_english(Id,Text,List)).
visual_content(variable_term(Id,Text), prolog_english, text(Id,Text)).

% Tree

visual_content(tpm_predicate(Id,H,T), tree, tpm_predicate(Id,H,T)).
visual_content(or_term(Id,A,B), tree, tree_node(Id,'|',[A,B], red)).
visual_content(and_term(Id,A,B), tree, tree_node(Id, '&',[A,B], orange)).
visual_content(if_term(Id,A,B), tree, tree_node(Id, '<-', [A,B], red)).
visual_content(term(Id,Text,List), tree, tree_node(Id,Text,List, palegreen)).
visual_content(variable_term(Id,Text), tree, tree_node(Id,Text,[],yellow)).

% Prolog

visual_context_description(prolog, 'Prolog').
visual_content(tpm_predicate(Id,H,T), prolog, tpm_predicate(Id,H,T)).
visual_content(or_term(Id,A,B), prolog, infix_text(Id,';',A,B)).
visual_content(and_term(Id,A,B), prolog, seq_text(Id,', ',A,B)).
visual_content(if_term(Id,A,B), prolog, pl_if(Id,A,B)).
visual_content(term(Id,Text,List), prolog, prolog_text(Id,Text,List)).
visual_content(variable_term(Id,Text), prolog, text(Id,Text)).
```

C.3 Visuals

A labeled edge in a hierarchy

```
visual(labeled_hier_edge(A,B,Text,Colour), [-A,-B,str(Text)],
        ['A ', colour, ' hierarchical edge labeled ', Text],
        Symbol,
        [
        container(Symbol),
        text(p(Symbol), 'A'),
        text(c(Symbol), 'B'),
        contains(Symbol, p(Symbol)),
        labeled_hier_edge(p(Symbol), c(Symbol), Text, Colour)
        ] ) :- Colour = red ; Colour = blue ; Colour=green.

visual_component(labeled_hier_edge(A,B,Text,Colour),
```

```
        [
        hier_edge_colour(A,B,Colour),
        edge_label(A,B,Text)
        ]).
```

A coloured if-then-else structure in a Nassi-Shneiderman Diagram

```
visual(nsd_coloured_if(Id,C,T,F), [+Id,-C,-T,-F],
        'NSD coloured if-then-else', Symbol,
        [
        nsd_coloured_if(Symbol, cond(Symbol), true(Symbol),
                false(Symbol)),
        nsd_statement(true(Symbol), 'if true'),
        nsd_statement(false(Symbol), 'if false'),
        string(cond(Symbol), condition)
        ]).

visual_component(nsd_coloured_if(If,Cond,True,False),
        [
        nsd_if(If,Cond,True,False),
        nsd_if_colour(If)
        ]).
```

C.4 Visual Objects

A labeled interconnecting arrow

```
visual(jvl_assign(Id,Text,L,R), [+Id,-L,-R,str(Text)], 'left arrow',
        Sym,
        [
        string(left(Sym), a),
        string(right(Sym), b),
        jvl_assign(Sym,Text,left(Sym),right(Sym))
        ]).

object_component(jvl_assign(Id,Text,L,R), Id,
        [
        text(Text, p,q,x1+(5,0),y1+(-5,0)),
        x=midpoint(c,d),
        y=midpoint(e,f),
        contain(L,a,c,b,d),
        contain(R,e,g,f,h),
        yalign(c,e),
        yalign(d,f),,
        line([x1=x+(4,0), y1=y+(-4,0)]),
        polygon([x1+(4,3), x1, x1+(4,-3)])
        ]).
```

An if-then-else structure in a Nassi-Shneiderman Diagram

```
visual(nsd_if(Id,C,T,F), [+Id,-C,-T,-F], 'NSD if-then-else', Symbol,
        [
        nsd_if(Symbol, cond(Symbol), true(Symbol), false(Symbol)),
        nsd_statement(true(Symbol), 'if true'),
        nsd_statement(false(Symbol), 'if false'),
        string(cond(Symbol), 'Condition')
        ]).

object_component(nsd_if(Object, Condition ,True ,False), Object,
```

```
        [
        cond=contain(Condition,a+(10,-2),b+(-10,-2),g+(10,2),h+(-10,2)),
        contain(True,g,e,c,f),
        fillcontainer(True),
        contain(False,e,h,f,d),
        fillcontainer(False),
        l1=line([g,a,b,h]),
        l1=thickness(2),
        l2=line([g+(10,0), a]),
        l2=thickness(2),
        l3=line([h+(-10,0), b]),
        l3=thickness(2)
        ]).
```

A labeled dialog selection button

```
visual_component(select(Id,Text,on),
        select(Id,Text,darkgrey,lightgrey,darkred)).

visual_component(select(Id,Text,off),
        select(Id,Text,lightgrey,darkgrey,grey)).

object_component(select(Id,Text,Top,Bottom,Face), Id,
        [
        t=text(Text,a,b,p4+(10,-2),c),
        p3=p4+(-10,0),
        p2=p4+(0,10),
        p1=p2+(-10,0),
        i1=p1+(2,-2),
        i2=p2+(-2,-2),
        i3=p3+(2,2),
        i4=p4+(-2,2),
        face=polygon([i1,i2,i4,i3]),
        face=colour(Face),
        l1=polygon([p1,p2,i2,i1]),
        l1=colour(Top),
        l2=polygon([p1,p3,i3,i1]),
        l2=colour(Top),
        d1=polygon([p3,p4,i4,i3]),
        d1=colour(Bottom),
        d2=polygon([p2,p4,i4,i2]),
        d2=colour(Bottom)
        ]).
```

C.5 Interaction

Interacting with the bookmarks

```
action(click(_, [on, off, off, off], 1), thumbnail, retrieve_view).
action(click(_, [off, off, on, off], 1), thumbnail, swap_menu).

reaction(swap_views, thumbnail) :- swap_thumbnail_view.
reaction(retrieve_view, thumbnail) :- retrieve_thumbnail_view.
reaction(save_view, thumbnail) :- save_thumbnail_view.
reaction(swap_menu, thumbnail) :- popup_menu(thumbnail).
reaction(refresh, thumbnail) :- refresh_view.
```

C.5.1 Menus

The bookmarks menu (shown in Figure 4.28)

```
action(menu(thumbnail, 'Bookmark'), thumbnail, save_view).
action(menu(thumbnail, 'Retrieve'), thumbnail, retrieve_view).
action(menu(thumbnail, 'Swap'), thumbnail, swap_views).
action(menu(thumbnail, 'Refresh'), thumbnail, refresh).
```

Menu to modify the structure of terms (shown in Figure 5.56)

```
action(menu(term_menu(Term), 'Increase arity'), svt, increase_arity(Term)).
action(menu(term_menu(Term), 'Decrease arity'), svt, decrease_arity(Term)).
action(menu(term_menu(Term), 'Cut'), svt, cut_term(Term)).
action(menu(term_menu(Term), 'Copy'), svt, copy_term(Term)).
action(menu(term_menu(Term), 'Paste'), svt, paste_term(Term)).
action(menu(term_menu(Clause), 'Delete clause'), svt,
        delete_clause(Clause)) :-
        user_clause(Clause).
action(menu(term_menu(Clause), 'Duplicate clause'), svt,
        duplicate_clause(Clause)) :-
        user_clause(Clause).
```

C.5.2 An Implementation of CCS

CCS [69] is a theoretical calculus of communicating systems. This example shows that formal models of interaction can be expressed within SVT's action/reaction model.

```
% Demo of CCS in action/reaction model.
% CCS terms are represented P1|P2|P3|... for concurrency,
% and [T1,T2,...] is a process.
% Transitions of +X and -X are reduced.
% The silent transition tau is automatically reduced.
% Restriction of a name X is marked nu(X).
% Renaming is marked [New/Old].
% [] accepts no reductions.

action(trans([tau|S],tau), ccs, S).

action(trans((A|B),T), ccs, (A1|B)) :- action(trans(A,T), ccs, A1).

action(trans((A|B),T), ccs, (A|B1)) :- action(trans(B,T), ccs, B1).

action(trans([+X|S],+X), ccs, S).

action(trans([-X|S],-X), ccs, S).

action(trans([H1|S],T), ccs, [H2|S]) :- action(trans(H1,T), ccs, H2).

action(trans([nu(X)|S0],T), ccs, [nu(X)|S]) :-
        action(trans(S0,T), ccs, S), restrict(X, T).

action(trans([[B/A]|S0],T), ccs, [[B/A]|S]) :-
        action(trans(S0,T0), ccs, S), rename(A, B, T0, T).

action(trans((A0|B0),tau), ccs, (A|B)) :-
        action(trans(A0,X), ccs, A),
        action(trans(B0,Y), ccs, B),
        neg(X,Y).
```

```
action(trans([write(X)|S],tau), ccs, S) :- write(X).

neg(+X, -X).
neg(-X, +X).

restrict(X, +X) :- !, fail.
restrict(X, -X) :- !, fail.
restrict(_, _).

rename(A, B, +A, +B) :- !.
rename(A, B, -A, -B) :- !.
rename(_, _, A, A).

reaction(S0, ccs) :- action(trans(S0,tau), ccs, S), reaction(S, ccs).
reaction(_, ccs).

:- Dispenser = (TeaDispenser | CoffeeDispenser),
   TeaDispenser = [-t,-p,-p,-p,+tea|TeaDispenser],
   CoffeeDispenser = [-c,-p,-p,+coffee|CoffeeDispenser],
   Person1 = [+c,+p,+p,-coffee,+drunk_coffee],
   Person2 = [+t,[p/coin],+coin,+coin,+coin,-tea,+drunk_tea],
   M1 = [-drunk_coffee, write('Drunk the coffee. ')|M1],
   M2 = [-drunk_tea, write('Drunk the tea. ')|M2],
   reaction((Dispenser | Person1 | Person1 | Person2 | M1 | M2), ccs).

% Output is: Drunk the tea. Drunk the coffee. Drunk the coffee.
```

C.6 A Scientific Calculator

This example gives the implementation of the scientific calculator in Figure 6.2.

```
% Calculator application implemented in SVT
% Written by Calum Grant

:- module(svt).

:- multifile view_content/2, view/3, action/3, reaction/2,
   object_component/3, visual_content/3, visual_component/2,
   visual_context/2, visual/5, visual_context_description/2.


popup_calculator :-
        popup_frame(calculator([0,'=',0,1,true,0]), calculator, svt, svt).


% Management of calculator state

calculator:evaluate(A, B, '+', A+B).
calculator:evaluate(A, B, '-', A-B).
calculator:evaluate(A, B, '*', A*B).
calculator:evaluate(A, B, '/', A/B).
calculator:evaluate(A, B, 'x^y', exp(A,B)).
calculator:evaluate(_, N, '=', N).

calculator:evaluate(A, '^2', A*A).
calculator:evaluate(A, sqrt, B) :- A>=0 -> B is sqrt(A); B is nan.
calculator:evaluate(A, sin, sin(A)).
calculator:evaluate(A, cos, cos(A)).
calculator:evaluate(A, tan, tan(A)).
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calculator:evaluate(A, '1/x', 1/A).
calculator:evaluate(A, ln, B) :- A>0 -> B is log(A); B is nan.
calculator:evaluate(A, exp, exp(A)).
calculator:evaluate(_, 'C', 0).
calculator:evaluate(A, 'x!', B) :-
        A>170 -> B is inf;
        A2 is truncate(A), A>=0 -> factorial(A2,B);
        B is nan.

calculator:memory(_, R, 'MC', 0, R).
calculator:memory(M, R, 'M+', M+R, R).
calculator:memory(M, R, 'M-', M-R, R).
calculator:memory(M, _, 'MR', M, M).

calculator:input(digitpress(D), [_,F,O,_,false,Mem],
        [R2,F2,O2,M2,I2,Mem2]) :-
        calculator:input(digitpress(D), [0,F,O,1,true,Mem],
        [R2,F2,O2,M2,I2,Mem2]).
calculator:input(functionpress('.'), [_,F,O,_,false,Mem],
        [0,F,O,0.1,true,Mem]).
calculator:input(digitpress(D), [R,F,O,M,true,Mem],
        [R2,F,O,M,true,Mem]) :-
        (M=1; M= -1), !, R2 is R*10 + M*D.
calculator:input(digitpress(D), [R,F,O,M,true,Mem],
        [R2,F,O,M2,true,Mem]) :-
        M2 is M * 0.1, R2 is R+D*M.
calculator:input(functionpress('.'), [R,F,O,M,true,Mem],
        [R,F,O,M2,true,Mem]) :-
        (M=1; M= -1), M2 is M*0.1.
calculator:input(functionpress('+/-'), [R,F,O,M,I,Mem],
        [R2,F,O,M2,I,Mem]) :-
        R2 is -R, M2 is -M.
calculator:input(functionpress(Fn), [R,F,O,M,_,Mem],
        [R2,Fn,R2,M,false,Mem]) :-
        calculator:evaluate(1,1,Fn,_), calculator:evaluate(O,R,F,R3),
        R2 is R3.
calculator:input(functionpress(Fn), [R,F,O,M,_,Mem],
        [R2,F,O,M,false,Mem]) :-
        calculator:evaluate(R,Fn,R3), R2 is R3.
calculator:input(functionpress(Fn), [R,F,O,M,_,Mem],
        [R2,F,O,M,false,M2]) :-
        calculator:memory(Mem,R,Fn,M3,R3), M2 is M3, R2 is R3.

digit(Atom, Digit) :- name(Atom, [N]), name('0', [Zero]), Digit is N-Zero,
        Digit<10, Digit>=0.

factorial(M, 1) :- M =< 1.
factorial(A, B) :- A > 1, N is A-1, factorial(N,X), B is A*X.


% Define the calculator buttons

calculator:digit(D, P) :-
        D=7, P=20; D=8, P=21; D=9, P=22;
        D=4, P=24; D=5, P=25; D=6, P=26;
        D=1, P=28; D=2, P=29; D=3, P=30;
        D=0, P=33.

calculator:function(F, P) :-
        F='MR',  P=1;  F='MC',  P=2;  F='M+',  P=3;
        F='M-',  P=4;  F='1/x', P=5;  F=sin,   P=6;
        F=cos,   P=7;  F=tan,   P=8;  F=ln,    P=9;
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        F=exp,   P=10; F='x!',  P=11; F='x^y', P=12;
        F='+',   P=23; F='-',   P=27; F='*',   P=31;
        F='/',   P=35; F='+/-', P=32; F='.',   P=34;
        F='C',   P=51; F='^2',  P=52; F='sqrt',P=53;
        F='=',   P=54.

calculator:button(calculator:digit(D), D, P)    :- calculator:digit(D, P).
calculator:button(calculator:function(F), F, P) :- calculator:function(F, P).


% Declare the calculator view

view([], calculator([0,'=',0,1,true,0]), 'Calculator').

visual_context(calculator(_), calculator).

view_content(calculator(_), calculator_button(Id, Text, Pos)) :-
        calculator:button(Id, Text, Pos).
view_content(calculator([R|_]), result(result, R)).


% Declare the visualization relation

visual_context_description(calculator, 'Calculator').
visual_content([], calculator, calculator).
visual_content(result(Id, Text), calculator, right_text(Id, Text)).
visual_content(calculator_button(Id, Text, Pos), calculator,
        calculator_button(Id, Text, Pos)).


% Declare visuals for the calculator

visual(right_text(Id,Text), [+Id, str(Text)], 'Right aligned text',
        Symbol, right_text(Symbol, Text)).

visual_component(right_text(Id, Text),
        [
        string(Id, Text),
        alignment(Id, right)
        ]).

visual_component(calculator,
        [
        title('Calculator'),
        border_line(border, calculator, 5),
        table(keypad, 4, 0),
        calculator(calculator, result, keypad)
        ]).

visual(calculator_button(Id, Str, Pos), [+Id, str(Str), num(Pos)],
        'Calculator button', Sym, button(Sym, Str)).

visual_component(calculator_button(Id, Text, Pos),
        [
        button(Id, Text),
        alignment(Id, fill),
        contains(keypad, Id),
        order(Id, Pos)
        ]).

object_component(calculator(Id, Result, Keypad), Id,
        [
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        contain(Result, p1+(4,-4), p2+(-4,-4), p3+(4,4), p4+(-4,4)),
        contain(Keypad, p3+(0,-5),p4+(0,-5), b3, b4),
        l = line([p1, p2, p4, p3, p1]),
        l = thickness(2)
        ]).

object_component(border_line(Id, Sub, S), Id,
        [
        contain(Sub, a+(S,-S), b+(-S,-S), c+(S,S), d+(-S,S)),
        line([a, b, d, c, a])
        ]).


% Interaction with the calculator

% Define the mouse cursor changes

action(move(calculator:digit(_), _),    svt, indicate(action)).
action(move(calculator:function(_), _), svt, indicate(action)).

action(click(calculator:digit(D), _,_),   svt, digitpress(D)).
action(click(calculator:function(F),_,_), svt, functionpress(F)).
action(key(_, K), svt, digitpress(D)) :-
        digit(K,D),
        current_view_context(calculator(_)).
action(key(_, K), svt, functionpress(F)) :-
        current_view_context(calculator(_)),
        calculator:key(K,F).
action(key(_, K), svt, functionpress(K)) :-
        current_view_context(calculator(_)).


% Define the key bindings

calculator:key('\r', '=').
calculator:key(' ',  'C').
calculator:key('c',  'C').
calculator:key('^',  'x^y').
calculator:key('!',  'x!').

reaction(functionpress(Fun), svt) :-
        Fn=functionpress(Fun),
        current_view_context(calculator([R,F,O,M,I,Mem])),
        calculator:input(Fn, [R,F,O,M,I,Mem], [R2,F2,O2,M2,I2,Mem2]),
        set_view_context(calculator([R2,F2,O2,M2,I2,Mem2])),
        R2 \== R,
        refresh_object(result(result, R2)),
        restructure_view.

reaction(digitpress(Fun), svt) :-
        Fn=digitpress(Fun),
        current_view_context(calculator([R,F,O,M,I,Mem])),
        calculator:input(Fn, [R,F,O,M,I,Mem], [R2,F2,O2,M2,I2,Mem2]),
        set_view_context(calculator([R2,F2,O2,M2,I2,Mem2])),
        R2 \== R,
        refresh_object(result(result, R2)),
        restructure_view.


% Make the calculator appear in the action menu

action(menu(action(_), 'Calculator'), svt, calculator_popup).
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reaction(calculator_popup, svt) :- popup_calculator.


% Create a calculator

:- popup_calculator.
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