Visualization techniques for program comprehension

A literature review

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Abstract

Understanding software is becoming more complex as programs are getting ever bigger. Many believe that the key to this problem is better visualization. The objective of this document is to provide an as thorough as possible overview of this field. This is the starting point for further research and development in this critical area. Over 140 papers and nearly as many tools were reviewed for this purpose. This document presents the most relevant and significant ones. Further work will be required to identify the most promising approaches to include visualization in current research projects.

Résumé

Comprendre un logiciel devient de plus en plus complexe à mesure que les programmes deviennent de plus en plus gros. Plusieurs croient que la clé de ce problème réside dans une meilleure visualisation. L'objectif de ce document est de fournir une vue aussi complète que possible de ce domaine. Ceci est le point de départ pour la recherche et le développement dans ce secteur critique. Plus de 140 documents et presque autant d'outils ont été examinés dans ce but. Ce document présente les plus pertinents et les plus importants. Des recherches supplémentaires seront requises pour déterminer les approches les plus prometteuses pour inclure la visualisation dans les projets de recherche courants.

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Executive Summary

The objective of this document is to provide an as thorough as possible overview of the techniques of program visualization and comprehension, as it is today. Over 140 documents and nearly as many tools were reviewed for this purpose. Only the most promising or significant ones are presented in this document. One thing is certain, this domain of research is quite active. There are way too many prototypes and tools to try them all. Candidates that show promises and warrant more investigation are SHriMP, Graphviz, aiSee, and Walrus.

The different aspects and criteria to take into account when comparing and trying to choose a visualization are presented. By refining these aspects and criteria, future work will try to come up with the best combination of tools possible. The goal is to speed up the process of understanding large software systems.

This work is relevant to the Canadian Forces for many reasons. First of all, military systems are becoming ever more complex while the need for interoperability keeps increasing. Getting systems to interoperate within a reasonable time frame depends on the speed at which the analyst can understand the programs. Good software visualization and comprehension techniques and tools will help force developers to maximize their development and maintenance effort, thereby decreasing the response time for critical operations. Furthermore, from a security standpoint, it is imperative to understand new software threats as fast as possible. The same tool can be used to decrease the time required to understand a threat and develop countermeasures. The tool could further be used by DND's many developers and contractors to speed up the development and maintenance of any software system. For example, when replacing a system by another in a system of systems, such a tool could greatly reduce the time needed. Another example where this can be useful is in the acquisition process for new software. Comparing different alternatives requires a basic understanding of the potential systems. An appropriate visualization and comprehension tool would greatly improve this process.

Finally, this work could potentially lead to collaboration between DRDC, universities, and the industry.

François Lemieux, Martin Salois; 2006; Visualization techniques for program comprehension; DRDC Valcartier TM 2005-535; Defence R & D Canada – Valcartier.

Sommaire

L’objectif de ce document est de fournir une vue aussi complète que possible des techniques de la visualisation et de compréhension de programme, tel qu’elles sont à ce jour. Plus de 140 documents et presque autant d’outils ont été examinés dans ce but. Seuls les plus pertinents et les plus importants sont présentés dans ce document. Une chose est sûre, ce domaine de recherche est très actif. Il y a beaucoup trop de prototypes et d’outils pour les essayer tous. Les candidats ayant du potentiel sont SHriMP, Graphviz, aiSee et Walrus.

Les différents aspects et critères à considérer quand vient le temps de comparer et de choisir une visualisation sont présentés. En améliorant ces aspects et ces critères, de futurs travaux essaieront de trouver la meilleure combinaison d’outils possible. Le but étant d’accélérer le processus de compréhension d’un grand système logiciel.

Ces travaux sont pertinents pour les Forces canadiennes pour plusieurs raisons. Premièrement, les systèmes militaires sont de plus en plus complexes alors que le besoin en interfonctionnement ne fait qu’augmenter. Réussir à faire interopérer les systèmes dans un temps raisonnable dépend de la rapidité avec laquelle l’analyste peut comprendre les programmes. Un bon outil de visualisation et compréhension logicielle aidera les ingénieurs des Forces à maximiser leurs efforts de développement et de maintenance, réduisant ainsi leur temps de réponse pour les opérations critiques. De plus, d’un point de vue de sécurité, il est impératif de comprendre les nouvelles menaces logicielles le plus rapidement possible. Le même outil peut être utilisé pour diminuer le temps requis pour comprendre la menace et développer des contre-mesures. L’outil peut aussi être utilisé par les nombreux développeurs et contracteurs du MDN pour accélérer le développement et la maintenance de n’importe quel système logiciel. Par exemple, lorsque vient le temps de remplacer un système par un autre dans un système de systèmes, un tel outil pourrait grandement réduire le temps requis. Un autre exemple où cet outil pourrait être utile est dans le processus d’acquisition d’un nouveau logiciel. Comparer les différentes alternatives requiert une compréhension de base des systèmes potentiels. Un outil de visualisation de compréhension approprié améliorerait grandement ce processus.

Finalement, ces travaux offrent un potentiel de collaboration entre RDDC, les universités et l’industrie.

François Lemieux, Martin Salois; 2006; Les techniques de visualisation pour la compréhension de programme; DRDC Valcartier TM 2005-535; R & D pour la défense Canada – Valcartier.

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1 Introduction

It is generally accepted that software development and maintenance is difficult and costly. Programs are becoming ever more complex and harder to understand. Some reasons for this include, but are not limited to:

- Increase in functionalities — millions of lines of code is common
- Evolution of the requirements as the program is used — systems must frequently be modified to meet these changing requirements
- High turnover rate in development and support personnel

As a result, complex software is rarely understood completely by the developers and even less so by the maintainers. Moreover, it is a very time-consuming and arduous task to understand complex system behaviors from source code. An example is the replacement of a system by another in a system of systems. Any tool that can speed up the understanding of the existing systems can greatly reduce the time and the cost associated with this task.

The field of software engineering has approached those problems in a number of ways. One key solution that has emerged is software visualization. This field of research seeks to make programs and algorithms easier to understand using various visualization techniques and cognitive approaches.

The main objective of this document is to provide a concise overview of the most significant aspects of software visualization and program comprehension. It is the result of a thorough survey of the literature on the subject, and even loosely-related subjects. Over 140 papers were read and classified and nearly as many tools were reviewed. Only the most relevant and significant ones were kept and are discussed in this document.

It is very difficult to classify the field of software visualization and program comprehension in clear-cut categories. This document tries to separate the techniques (Section 3) from the actual software systems that try to implement them (Section 4). This is followed by a discussion on how to evaluate these systems to find the best fit for the need (Section 5). But first, the remainder of this section gives the essential references and active groups in this field and the next section gives an introduction to software visualization and its terminology.

1.1 Essential References

Stasko et al [1] provide an excellent and comprehensive overview of software visualization. This book integrates knowledge, suggests principles, provides perspectives, and points out some ways for the future. The web page of Stasko's class on software visualization also contains an extensive list of references.

Another good source of information on software visualization is [2]. This is the first book that discusses software visualization from the perspective of software engineering.

1.2 Active Research Groups

Here is a list of the most important active research groups in the field:

Computer-Human Interaction and Software Engineering (CHISEL)

University of Victoria, Canada

> From the site: "Our primary objectives are to develop tools that support people in performing complex cognitive tasks. Our projects benefit from the collaborative approach taken within our group and with other researchers. As a group we operate by using collaboration, creative thinking, exploiting our synergies, and applying innovative research techniques."

Program Comprehension Research Group

Research Institute in Software Evolution, University of Durham, U.K.

> From the site: "The interests of the group are varied but we are all working towards one goal: improving the maintainability of software through researching issues of program comprehension."

AT&T Visualization Research Group

New Jersey, U.S.A.

> Their main research areas are: visual data mining, algorithms for graphics, computational geometry and optimization, and graph (network) visualization. The Graphviz project has been a cornerstone of their research for more than 10 years (see Subsection 4.1).

Visualisation Research Group

University of Durham, U.K.

> From the site: "We are investigating software and information visualization, from an original basis of visualization for program understanding. This has involved research into metaphors, animation, system evolution, 3-D representations, components, and dynamic monitoring of running systems. The current main focus is on providing suitable visualizations of complex data in distributed and dynamic software environments."

The Information Interfaces Group

GVU Center at Georgia Tech, U.S.A.

This is an HCI research group. From the site: “The group develops ways to help people understand information via user interface design, information visualization, peripheral awareness techniques, and software agency. They seek to utilize computing technologies to help people make sense, make better judgments, and learn from all the information available to them.”

2 An Introduction to Software Visualization

This section provides an overall introduction to software visualization. It starts with an overview of the concepts that rule software visualization as it seems to be understood today. Next, a very brief recapitulation of the history of this young domain, or rather where to find this information, is presented. Finally, a brief discussion on taxonomies in this discipline follows.

2.1 Terminology

It appears there is no consensus in the literature for an accepted definition of the overarching forms of software visualization. Each project *visualizes* a specific kind of information. Different sources put emphasis on different concepts in their definitions. However, a good starting point can be found in [3], in which the authors divide the field as shown in Figure 1.

Before giving any definitions, let us look at what the word *visualization* means when it refers to as *software visualization*.

Because visualization contains the root “visual”, a majority of people believes that visualization only deals with making pictures. Indeed, the common and most popular definition of “visual” only refers to images that people can see with their eyes. In the context of computer programs, however, Grant [4] says that “visual means visible on a computer display and visualization is communicating data with graphics.” Another point of view suggests the conveyance of mental images [5]: “The power or process of forming a mental picture or vision of something not actually present to the sight”. McCormick et al put the emphasis on the process of communication: “The study of mechanisms in computers and in humans which allow them in convert to perceive, use, and communicate visual information” (cited in [4]).

These last two definitions are the most interesting. They propose that a visualization can be the result of any combination of the human senses. This is a much broader definition.

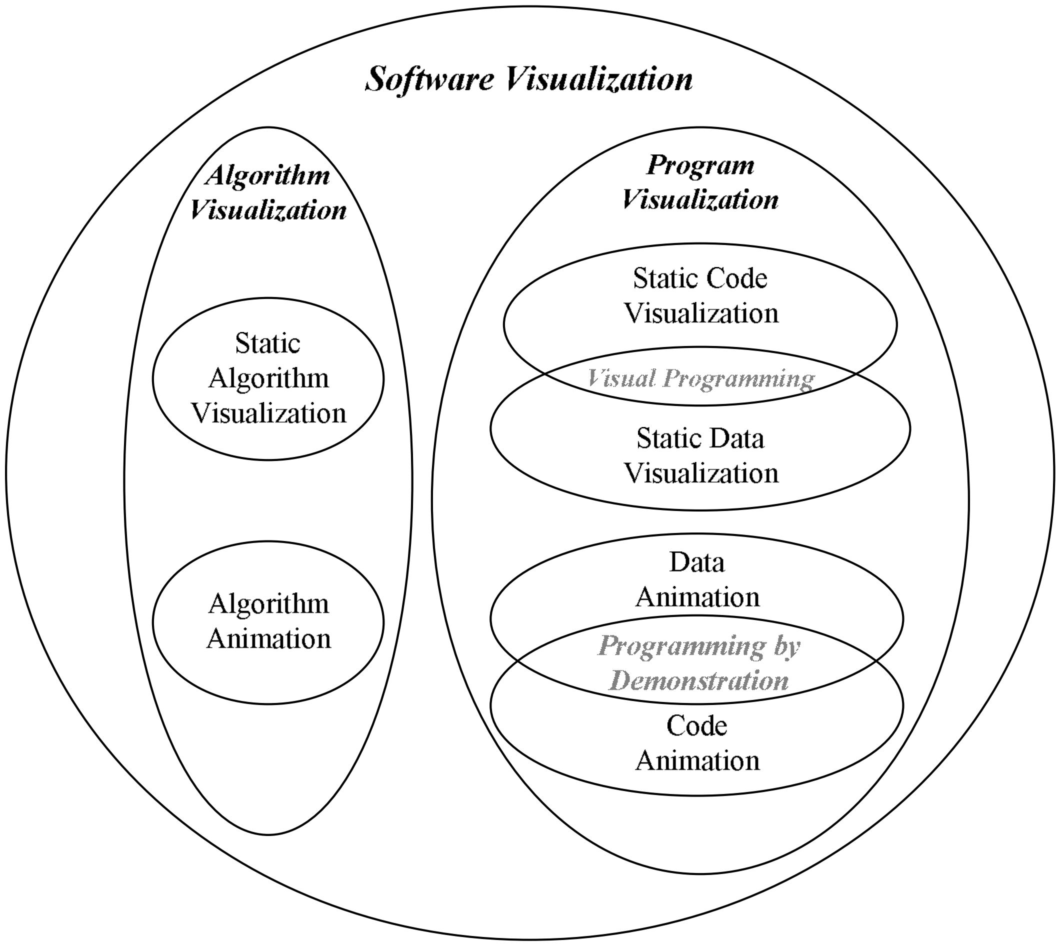


Figure 1: *Venn diagram showing the relationships between the various forms of software visualization [3]*

There does not seem to be a formal definition of *software visualization* either. The most well-known defines it as “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” [5]. Going back to Figure 1, it can be seen that it encompasses all of this. The next subsections explain the concepts of this Venn diagram in more detail. Note, however, that *visual programming* and *programming by demonstration* are special cases, as described below.

2.1.1 Program Visualization

Myers [6] defines program visualization as “the program is specified in a conventional, textual manner, and the graphics is used to illustrate some aspect of the program or its run-time execution." Gómez Henríquez [7] proposes a simpler definition: "program visualization is the art of giving programs another aspect than that of their source code." Price et al [3] suggest that Myers's definition implies a connection with the program (lower level) as opposed to the algorithm (higher-level). Therefore, they prefer a simpler definition. They define *program visualization* to be "the visualization of actual program code or data structures in either static or dynamic forms". This is clearly shown in their Venn diagram (Figure 1). There is no consensus for definitions of these concepts in the literature. Each project defines them in their own context. Doing so in the current project will be the subject of later work. Consequently, concise examples are given instead to illustrate the first level of this Venn diagram:

Static code visualization This might include some kind of graphical layouts illustrating subroutine-call graph or control-flow graphs.

Static data visualization This might appear as a "boxes and arrows" diagram of linked list of data structures showing the content.

Data animation This might show the same diagram as the previous case with the content of the boxes and the arrows changing dynamically as the program is running.

Code animation This could simply highlight lines of code in the IDE as they are being executed.

They also put two hard-to-place categories within program visualization (see Figure 1): *visual programming* and *programming by demonstration* (sometimes called *programming by example*). According to them, they are not really subsets of program visualization. They merely have a partial overlap. It seems they put them there for lack of a better place. Here is a description of these two categories:

Visual programming This seeks to make programs easier to specify by using a graphical notation. A graphical notation is often associated with the notion of *visual languages*. This notion has been well defined by Schmucker (1996), as cited in [8]: "[A visual language is one in which] a pictorial, iconic or graphical syntax (as opposed to a textual syntax) is used as primary means of expressing the logic of the program being written." This precludes the simple use of a graphical skeleton with textual flesh and GUI development tools. The graphics are used to create the program itself. Visual programming is a field in its own right and a quantity of books and papers on this subject can be found such as [9, 10, 11, 12]. This will not be further discussed in this document.

Programming by demonstration This is related to visual programming and it is defined as the specification of a program with user demonstrated examples.

The idea is that users may not have the advanced programming skills required to construct a program. Cypher [13] provides an excellent survey of this subject. This will not be further discussed in this document either.

2.1.2 Algorithm Visualization

Algorithm visualization is different from data and code visualization because it shows abstractly how the program operates. The visualization may not correspond directly to the data in the program, and changes in the visualization might not correspond to specific pieces of code. Price et al [3] define *algorithm visualization* as "the visualization of the higher-level abstractions which describe software." This category also has the dimensions of static and dynamic visualizations (see Figure 1):

Static algorithm visualization This category covers the static aspect. If often consists of a snapshot, or a trace, of one execution of the algorithm.

Algorithm animation This category covers the dynamic aspect. The goal is to communicate how an algorithm works by graphically or aurally depicting its fundamental operations. It might show the data as lines of varying heights or the swap of two items as a smooth animation.

2.1.3 Other Definitions

These other terms require a definition to correctly understand this document. These definitions come from [3]:

Programmer "The person who wrote the program/algorithm being visualized."

Visualizer Also called an animator, this is "the person who specifies the visualization." This is the person who decides what to see and how to see it.

User Also called the viewer, this is "the person who views the resulting visualization and possibly navigates through it." The maintainer of a system is an example.

2.2 A Brief History

Software visualization is a discipline as old as computer science. However, it emerged as an independent field around the middle of the 1980s. In these early times, software visualization development was mainly oriented towards the visualization of an algorithm's dynamic behavior. Afterwards, its scope was widened to deal with other aspects of the programs. Static and dynamic visualizations of source code or the display of quantitative information about parallel executions are both examples that came later.

Software visualization is considered as a discipline of commercial interest since the mid 1990s only.

Very few papers deal with the historic aspect overall. Two good sources about the software visualization research and development are [5] and [14]. The last one sketches out in more detail the early history of software visualization.

2.3 Taxonomy

Many researchers have come up with valid taxonomies to help classify, quantify, and describe the different types of software visualization. Roman and Cox [15] offer a simple taxonomy. Myers [6] proposes two taxonomies, one for visual programming and one for program visualization.

The most comprehensive taxonomy is provided by Price et al [5]. They construct a taxonomy based upon a tree structure where each leaf provides a different and orthogonal classification criterion. The first level of their taxonomy contains six categories:

A: Scope What is the range of programs that the software visualization system may take as input for visualization? Scope relates to the source program and the specific intent of the software visualizer.

B: Content What subset of information about the software is visualized by the software visualization system? Content describes the particular aspects of the software that is visualized.

C: Form What are the characteristics of the output of the system (the visualization)? Form is concerned with how the fundamental characteristics of the system are directly related to what can be displayed.

D: Method How the implementation is specified and how the system works? A method consists of the fundamental features of the visualization system which the visualizer uses to create a visualization.

E: Interaction How does the user of the software visualization system interact with it and control it? Interaction is of fundamental importance in order to provide a system that is both easy to use and quick to learn.

```
sub_401000      proc near
arg_0           = dword ptr  8

55                push    ebp
8B EC             mov     ebp, esp
68 D8 80 40 00    push    offset aHelloHowOldAre
E8 7C 00 00 00    call    _printf    ;"Hello, how old are you? "
83 C4 04          add     esp, 4
8B 45 08          mov     eax, [ebp+arg_0]
50                push    eax
68 F4 80 40 00    push    offset aD       ; "%d"
E8 54 00 00 00    call    _scanf
83 C4 08          add     esp, 8
5D                pop     ebp
C3                retn

sub_401000      endp
```

Figure 2: *Binary versus assembly*

F: Effectiveness How well does the system communicate information to the user? Effectiveness is a highly subjective measure and is made up of many factors that are still investigated.

Refer to the paper for more detail. An interesting point is that this framework can be extended to follow the evolution in the field.

3 Techniques

Computer programs are conventionally represented in textual form. The reason for this may simply be historical. The machine code of the earliest computers was composed entirely of sequences of 0s and 1s. Modern computers are still using this today. Unfortunately, this low level language is understood by extremely few people. The left column of Figure 2 depicts a typical example. Note that binary is usually expressed in hexadecimal to save space.

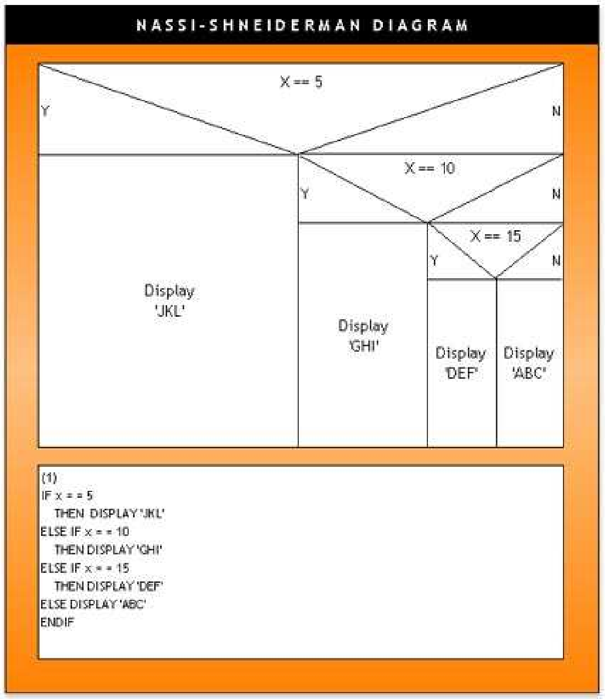
Of course, programmers quickly came up with a better way of representing these 0s and 1s using English mnemonics. This is known as the assembly language and it is simply a direct translation, as shown on the right of Figure 2. The assembly language is still used today for very low-level programming. In fact, all computer programs are still a sequence of 0s and 1s that one can examine in assembly.

```
/*This is a wonderful program*/
#include <stdio.h>

void input(int *ageP)
{
   printf("Hello, how old are you? ");
   scanf("%d", ageP);
}

void output(int age)
{
   printf("You are %d years old! Wow! That’s very old!", age);
}

int main(int argc, char* argv[])
{
   int age;
   input(&age);
   output(age);
   return 0;
}
```

Figure 3: *Improvement of a program’s source code appearance*

However, it was not long before someone came up with an even better way of programming: the high-level programming languages. Basic, C/C++, and Java are just some examples of such languages that are used today. An example of a C program is shown in Figure 3. Although not specific to C, notice the use of colors, fonts, spacing, and indentation. These simple devices from the printing and publishing industry came up later. Based on syntax and layout rules, they have been shown to significantly enhance the readability and understandability of the code. Nowadays, modern programming environments also use other elements such as collapsible items, pictures, and animated tracking (e.g. debugging.)

Furthermore, considerable efforts have been devoted to the field of *effective program appearance*. Also called *enhanced program appearance* or *effective program representation*, these techniques try to enhance the construction of programs to facilitate their reading, comprehension, and effective use. Baecker and Marcus [16] suggest that enduring programs should be made perceptually and cognitively more accessible and more usable. They demonstrate this in the SEE visual compiler prototype.



```
(1)
IF x = = 5
   THEN  DISPLAY 'JKL'
ELSE IF x = = 10
   THEN DISPLAY 'GHI'
ELSE IF x = = 15
   THEN DISPLAY 'DEF'
ELSE DISPLAY 'ABC'
ENDIF
```

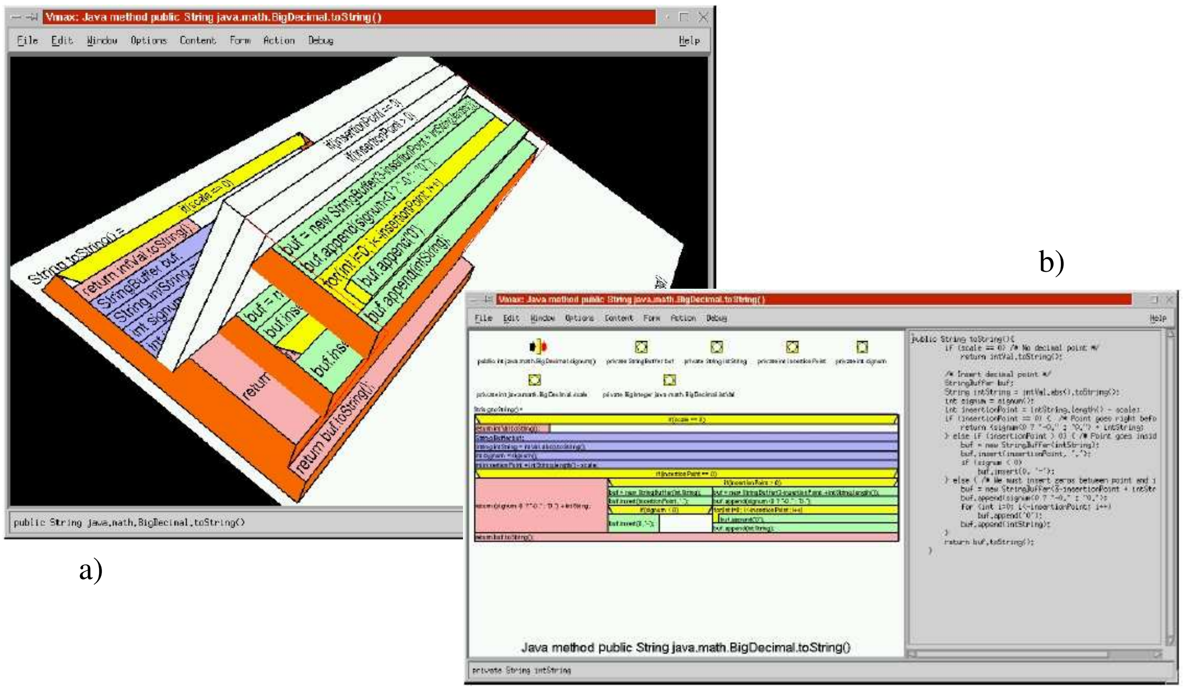
Figure 4: *Nassi-Shneiderman structured flowchart technique [17]*

Despite all of these improvements, textual representation turns out to be a very limited way of visualizing a program. Just imagine the case of large programs that are composed of millions of lines of code. Another example, where this is especially true, is the case of program discovery and comprehension. Trying to understand one's own code is difficult enough when it becomes that large, just imagine trying to understand someone else's! Therefore, practitioners and researchers continually strive to find better visualization techniques.

Many such techniques have been developed over time to try to visualize both structural and behavioral software information. The rest of this section outlines the most significant techniques.

3.1 The Nassi-Shneiderman Diagram

Many alternative ways of converting program text into a graphical form have been experimented in the 1970s. One relevant technique has been developed by Nassi and Shneiderman [18] to counter the unstructured nature of standard flowcharts. Shown in Figure 4, the basic structure of a Nassi-Shneiderman diagram is a rectangle that is subdivided in smaller rectangles that represent instructions. A conditional instruction is separated by two triangles representing the alternatives (yes/no.) Every-


Vmax: Java method public String java.math.BigDecimal.toString()
File Edit Window Options Content Form Action Debug Help
public String java.math.BigDecimal.toString()
a)
b)
Java method public String java.math.BigDecimal.toString()
private String intString

```
public String toString(){
        if (scale == 0) /* No decimal point */
            return intVal.toString();

        /* Insert decimal point */
        StringBuffer buf;
        String intString = intVal.abs().toString();
        int signum = signum();
        int insertionPoint = intString.length() - scale;
        if (insertionPoint == 0) {  /* Point goes right befo
            return (signum<0 ? "-0." : "0.") + intString;
        } else if (insertionPoint > 0) { /* Point goes insid
            buf = new StringBuffer(intString);
            buf.insert(insertionPoint, '.');
            if (signum < 0)
                buf.insert(0, '-');
        } else { /* We must insert zeros between point and i
            buf = new StringBuffer(3-insertionPoint + intStr
            buf.append(signum<0 ? "-0." : "0.");
            for (int i=0; i<-insertionPoint; i++)
                buf.append('0');
            buf.append(intString);
        }
        return buf.toString();
    }
```

Figure 5: *The Nassi-Shneiderman technique extended for Java code [4]*
a) 3-D block structure of a Java method
b) Colors add expressiveness

thing under the "yes" gets executed if the condition is true and vice versa. The flow of "time" is represented by going down the rectangle.

Although many people doubt the usefulness of this technique, it has nevertheless been extended recently to visualize Java programs [4]. Two examples are shown in Figure 5.

3.2 Graph Layouts

Displaying a graph consisting of nodes and arcs is one of the most common representations in software visualization. Nodes represent block of instructions and arcs indicate the flow. An arc can be directed. This means that it can be traversed only in one direction (it has an "arrow").

Where to put each node for maximum readability and effectiveness is what is called the *graph layout*. Graph layouts are informative. That is, they can be of great aid to visualizing various software engineering graphs and diagrams. Relevant examples include data structures (compiler data structures in particular), data flow diagrams,

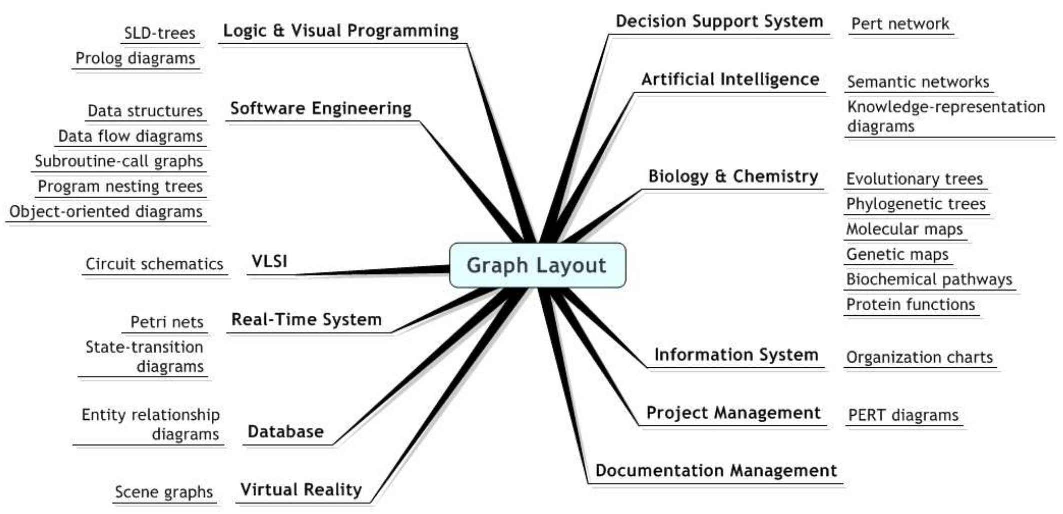


Figure 6: *Mindmap of application areas for graph layout*

subroutine-call graphs, program nesting trees, and object-oriented class hierarchies (e.g. UML diagrams). Graph layouts also have many other application areas, some of which are shown in Figure 6.

There are many techniques as to how to layout a graph. Such techniques are also commonly referred to as *layout heuristics*, *graph drawing techniques*, or *graph drawing algorithms*. All of these are traditionally considered under a branch of graph theory named graph drawing. Providing all the details is out of the scope of this document. However, the interested reader can refer to [19]. It contains an exhaustive survey on the subject.

Up to now, researchers have come up with four effective families of layout techniques. These are:

- Tree layout
- Hierarchical layout of directed graphs
- Orthogonal layout of planar and general graphs
- Force-based layout

Most techniques use a two-dimensional display but some have tried to project 3-D images in 2-D.

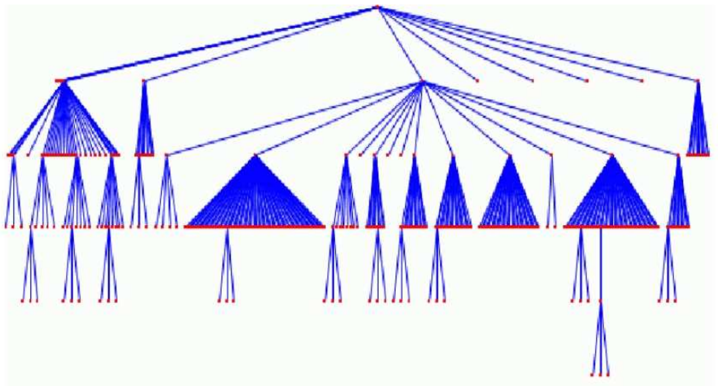


Figure 7: *Classical top-down tree layout [21]*

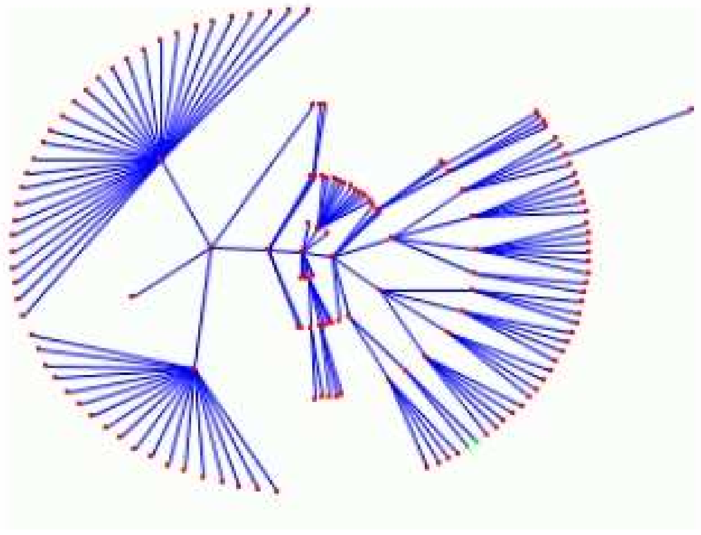


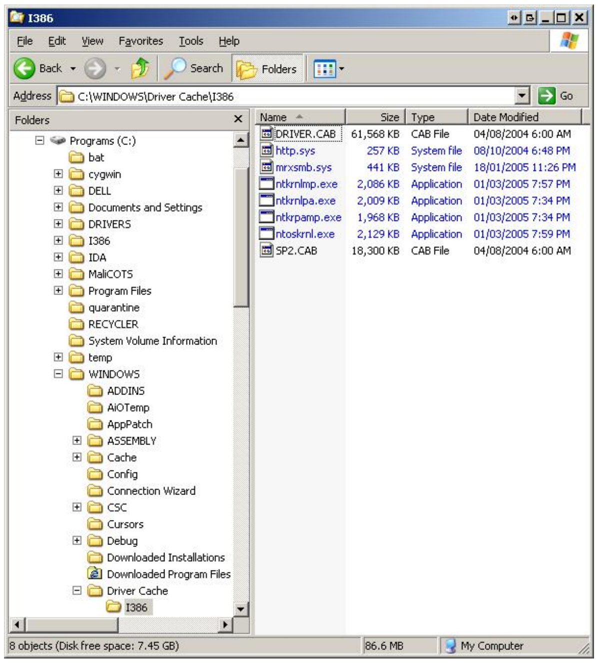
Figure 8: *Radial view of tree layout [20]*

3.2.1 Tree Layouts

A tree layout positions children nodes below their common ancestor. There are several alternatives to drawing trees. The algorithm given by Reingold and Tilford is probably the best-known [20]. It can be adapted to produce top-down (see Figure 7) as well as left-to-right tree structures. This same structure could be positioned differently by placing nodes on concentric circles according to their depth in the tree (see Figure 8).

Most users are familiar with a tree layout as they are very often used to describe the file hierarchy on computer systems (Figure 9).

A cone tree is a variation that displays hierarchical information in 3-D (Figure 10).


I386
File Edit View Favorites Tools Help
Back Search Folders
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Folders

- Programs (C:)
  - bat
  - cygwin
  - DELL
  - Documents and Settings
  - DRIVERS
  - I386
  - IDA
  - MaliCOTS
  - Program Files
  - quarantine
  - RECYCLER
  - System Volume Information
  - temp
  - WINDOWS
    - ADDINS
    - AiOTemp
    - AppPatch
    - ASSEMBLY
    - Cache
    - Config
    - Connection Wizard
    - CSC
    - Cursors
    - Debug
    - Downloaded Installations
    - Downloaded Program Files
    - Driver Cache
      - I386

Name	Size	Type	Date Modified
DRIVER.CAB	61,568 KB	CAB File	04/08/2004 6:00 AM
http.sys	257 KB	System file	08/10/2004 6:48 PM
mrxsmb.sys	441 KB	System file	18/01/2005 11:26 PM
ntkrnlmp.exe	2,086 KB	Application	01/03/2005 7:57 PM
ntkrnlpa.exe	2,009 KB	Application	01/03/2005 7:34 PM
ntkrpamp.exe	1,968 KB	Application	01/03/2005 7:34 PM
ntoskrnl.exe	2,129 KB	Application	01/03/2005 7:59 PM
SP2.CAB	18,300 KB	CAB File	04/08/2004 6:00 AM

8 objects (Disk free space: 7.45 GB) 86.6 MB My Computer

Figure 9: *A Microsoft Windows tree-view of the directory structure*

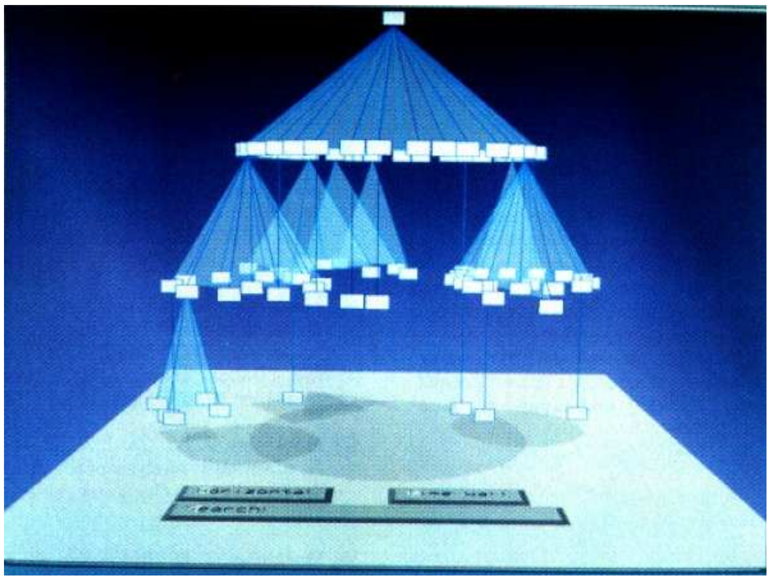


Figure 10: *The cone tree: A 3-D layout technique [22]*

This solution was developed to maximize the effective use of available screen space and enable a visualization of the whole structure.

3.2.2 Hierarchical Layouts

A hierarchical layout can be used to represent a directed graph. It emphasizes the dependence between objects by assigning nodes to a discrete level, so that the edges are directed somewhat uniformly from top to bottom. Such directed graphs are usually drawn with Sugiyama's algorithm [23] or one of its numerous variations or improvements. These techniques are perhaps the most common methods of visualizing a software structure.

In Figure 11, a node in the graph represents a function and an edge represents a call between functions. Function call graphs may be animated as a visual representation of how a program executes and color-coded to show "hot spots" [24].

The work of [25] on visualization for software engineering involves extending the call graph to three dimensions. A sample 3-D call graph is shown in Figure 12. In this technique, the selected file is shown in front with a fully expanded layout while the other files are shown as tags and/or in a more compressed layout. Hexagonal boxes represent collapsed files.

3.2.3 Orthogonal Layouts

An orthogonal layout has edges running horizontally or vertically. These edges are constrained to 90-degree bends to reduce the number of edge crossovers and the area covered by the graph. This type of layout has been well studied and practical techniques have been discovered [26]. The best results have been achieved on orthogonal drawings of planar graphs, as illustrated by the layout of a UML class diagram in Figure 13.

3.2.4 Force-based Layouts

There are many possibilities to apply force-based models to a graph layout. Two especially interesting techniques, spring embedder [28] and simulated annealing, have attracted more attention in the literature. The latter has its origin in the area of statistical mechanisms but it has been mostly applied to circuit schematic layouts. It will not be further discussed in this document.

The general idea behind the spring embedder technique is that two nodes with dependencies are more attracted to each other than two nodes without. A link becomes a spring between two nodes that can extend or compress depending on the forces in

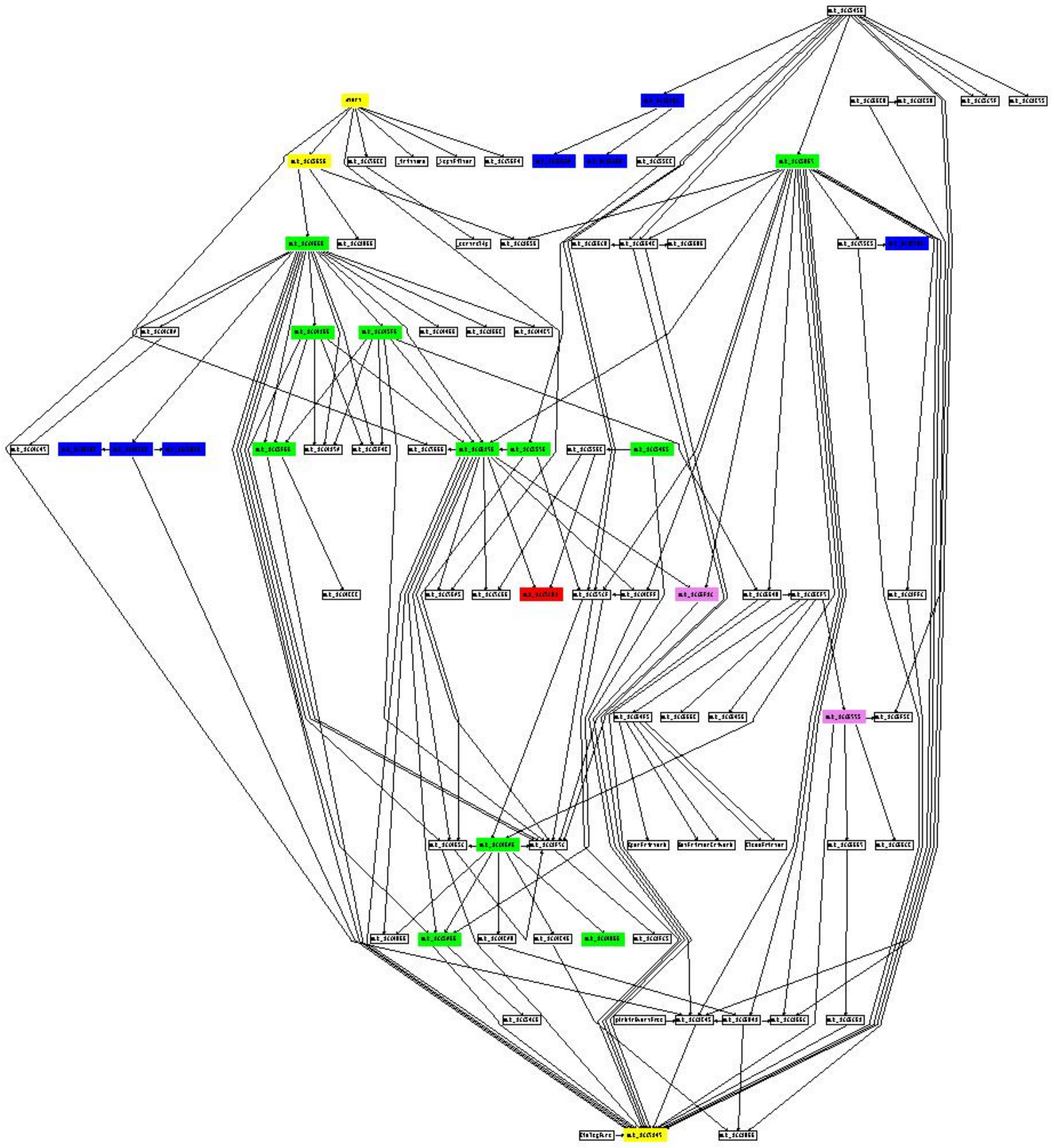


Figure 11: *The call graph layout is a natural representation of software structures*

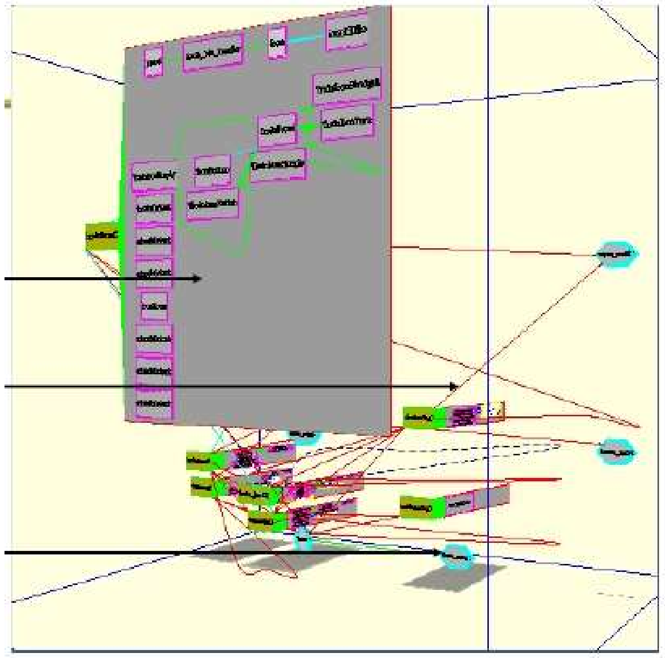


Figure 12: *Sample 3-D call graph layout [25]*

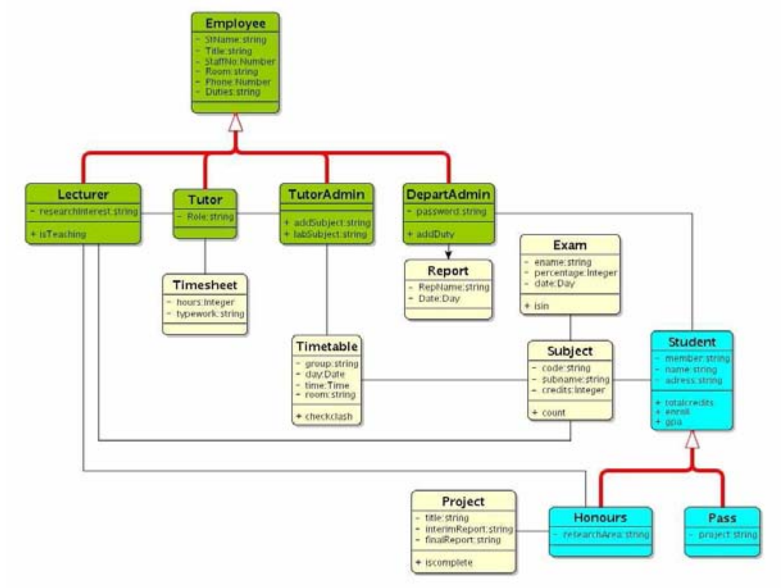


Figure 13: *Orthogonal layout of UML class diagram [27]*

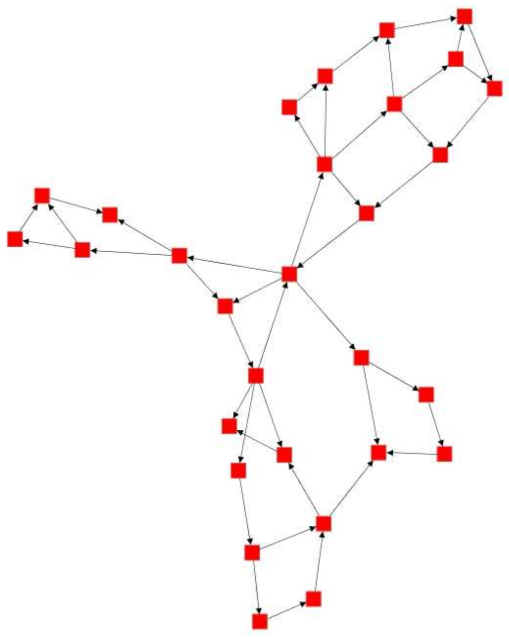


Figure 14: *Spring Layout of a control-flow graph [27]*

play. The optimum layout is achieved when the forces have been minimized. It is a question of balance.

Figure 14 shows the result of applying this technique to visualize a simple control call graph.

The spring layout method has attracted a lot of interest from researchers. For example, Frick et al [29] have presented new heuristics to improve this technique for a vast array of models. Others have developed new and more complex algorithms to represent large hierarchical graphs in 2-D and 3-D [30].

3.2.5 Others

Other layout techniques have been investigated to find better configurations. The goal is to find the most intuitive representation for a given problem set. For example:

Hyperbolic layout One of the newest forms of layouts, it has been developed to improve the visualization of and interaction with large graphs (mainly trees). These techniques can be implemented in either 2-D or 3-D. They provide a distorted view of the graph structure (see Figure 15).

Layout of cluster graphs This is part of the *abstraction* and *reduction* techniques

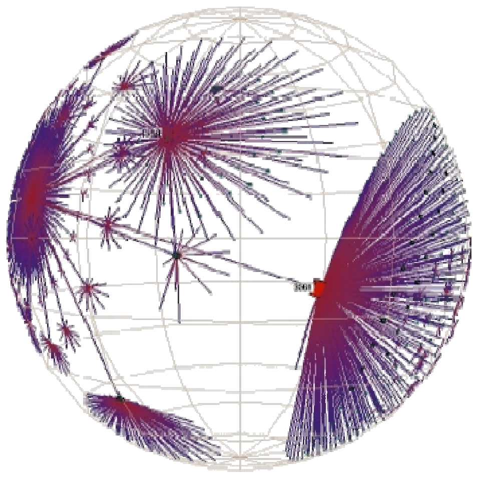
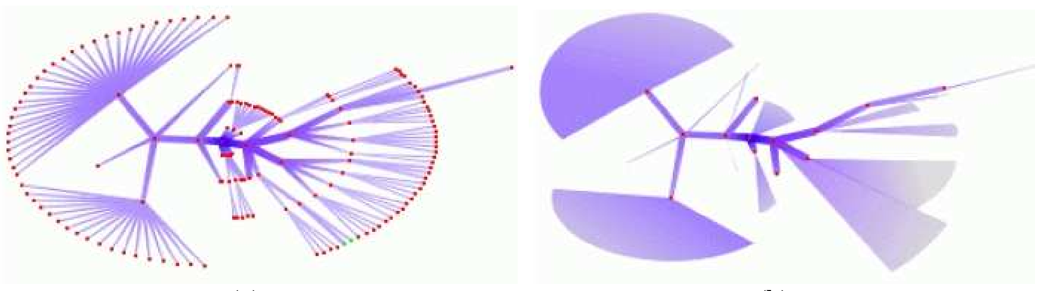


Figure 15: *Hyperbolic layout of 3,000 nodes connected by 10,000 edges [31]*



(a) (b)

Figure 16: *Clustering technique applied to a tree graph [20]*
a) full nodes in the background
b) grouping nodes under a super-node representation

that have been applied to reduce the visual complexity of a graph (see Figure 16). Clustering techniques are gaining momentum and should receive a lot of attention in the future.

Nested Graph Hierarchy This is an augmentation to the graph concept. A node can contain a nested graph and this can go on to arbitrary depth. This forms a hierarchically organized inclusion tree of graphs (see Figure 17).

Symmetric layout This technique attempts to find groups of symmetrical patterns in a graph by applying transformations that do not modify the information conveyed by the graph (Figure 18).

A general problem with most of the current graph layout techniques is that they are only applicable to relatively small graphs. In general, it is almost impossible

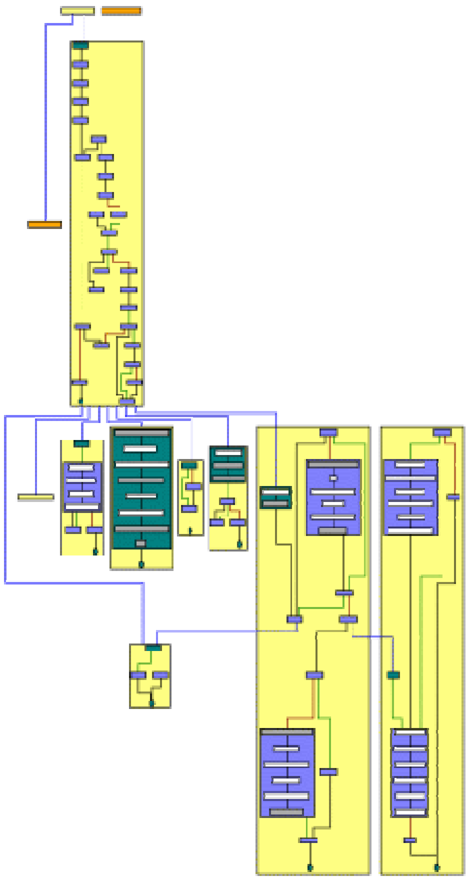


Figure 17: *A combined call and control-flow graph [32]*

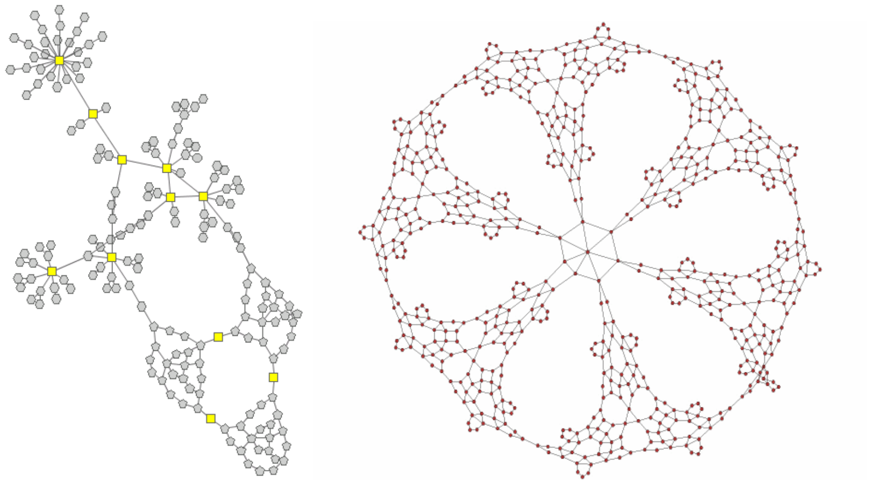


Figure 18: *Examples of Symmetric Layout [33]*

to create a graph with thousands of nodes and keep its planarity or try to minimize edge crossings.

Often the most obvious and practical solution is simply to layout a spanning tree for the graph. A spanning tree is a complex mathematical technique that segments a large graph in smaller ones. It will not be discussed in more detail here. A long list of algorithms to compute spanning trees for graphs can be found, both for the directed and undirected cases. See [34] for examples.

3.3 Space-filling

Space-filling techniques are designed to present the maximum amount of structured information in the minimum amount of space. There are two main techniques in this category:

- Tree-map
- Sunburst

3.3.1 Tree-maps

Tree-maps were first developed by Ben Shneiderman at the Human-Computer Interaction Laboratory (HCIL) of the University of Maryland during the 1990s [35]. A tree-map is a 2-D space-filing visualization technique in which each node is a rectangle whose area is proportional to a given metric for the corresponding software component (e.g. number of lines of code, number of descendants). Another metric can be used to calculate the order in which the boxes are drawn (e.g. alphabetical order, number of relationships, etc.) Colors can be used to add another dimension of information. This type of layout allows a quick visual comparison between different node attributes. An example is shown in Figure 19.

A group at Lulea University of Technology in Sweden developed a 3-D Tree-map for file browsing that shows the depth in the tree as the height of the box (Figure 20). Their study showed benefits for the 3-D layout for the task of identifying the deepest directory [37].

3.3.2 Sunburst

The SunBurst technique [38] is an alternative space-filling visualization that uses a radial layout instead of the usual rectangular one. In SunBurst, items in a hierarchy are laid out radially, with the top of the hierarchy at the center and deeper leaves farther away from the center. The radial angle of an item and its color correspond

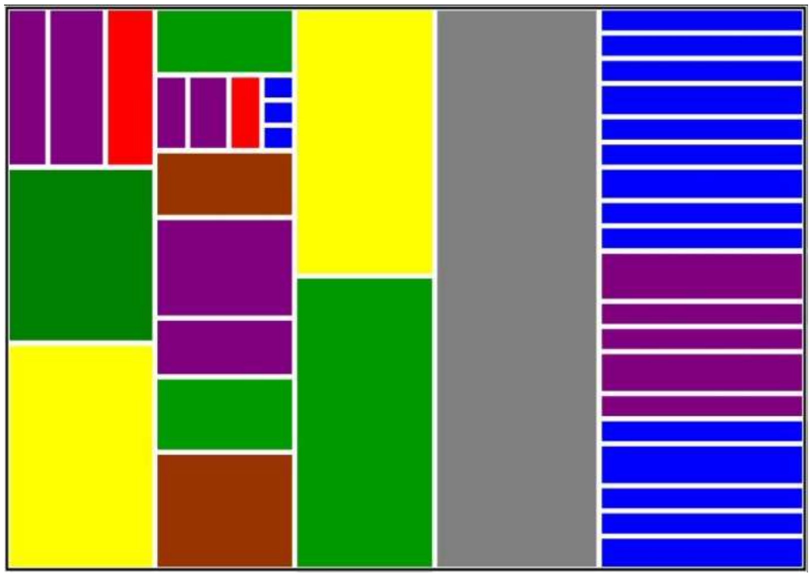


Figure 19: *Tree-map: A 2-D space-filling visualization technique (adapted from [36])*

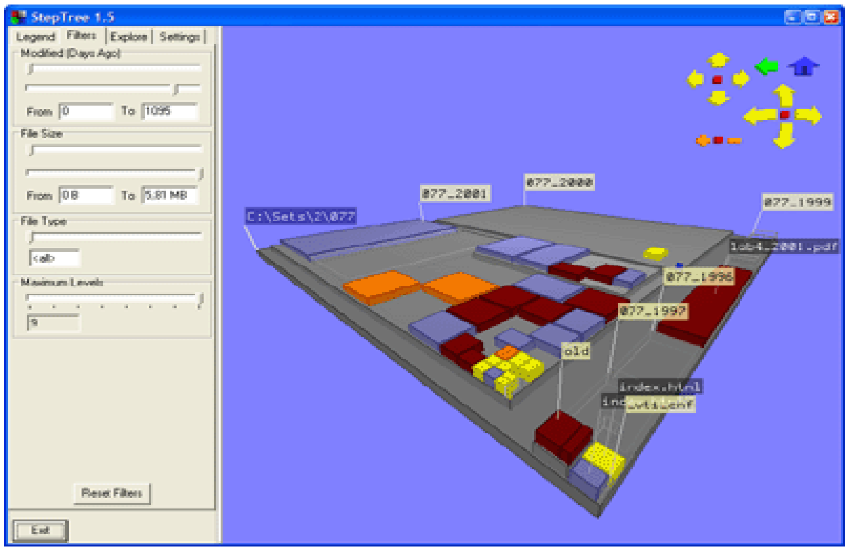


Figure 20: *StepTree: Extending tree-map to 3-D [37]*

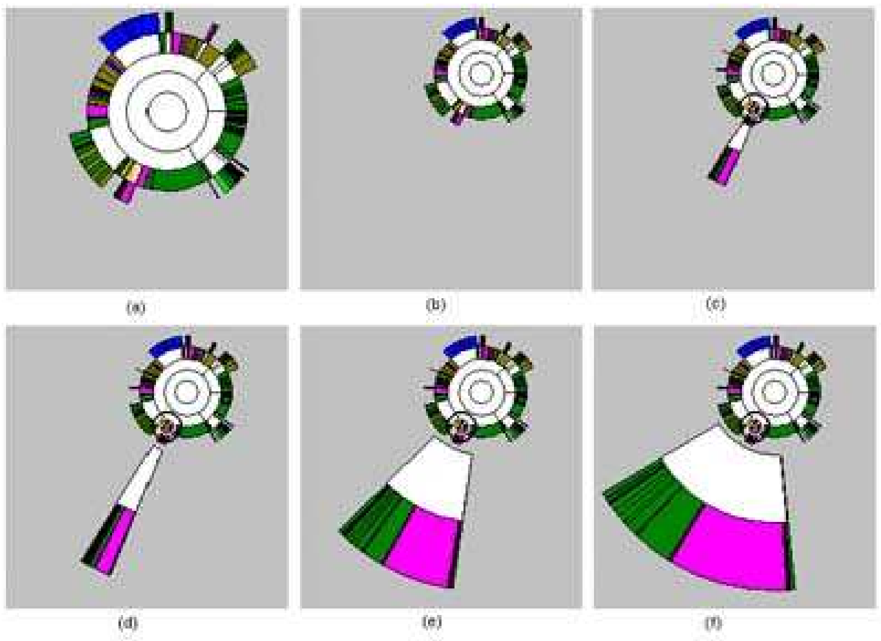


Figure 21: *Sequence of frames from the SunBurst visualization technique [38]*

to specific metrics. For instance, in visualizing a file system, the angle may correspond to the file or directory size and the color may correspond to the file type. An example is shown in Figure 21.

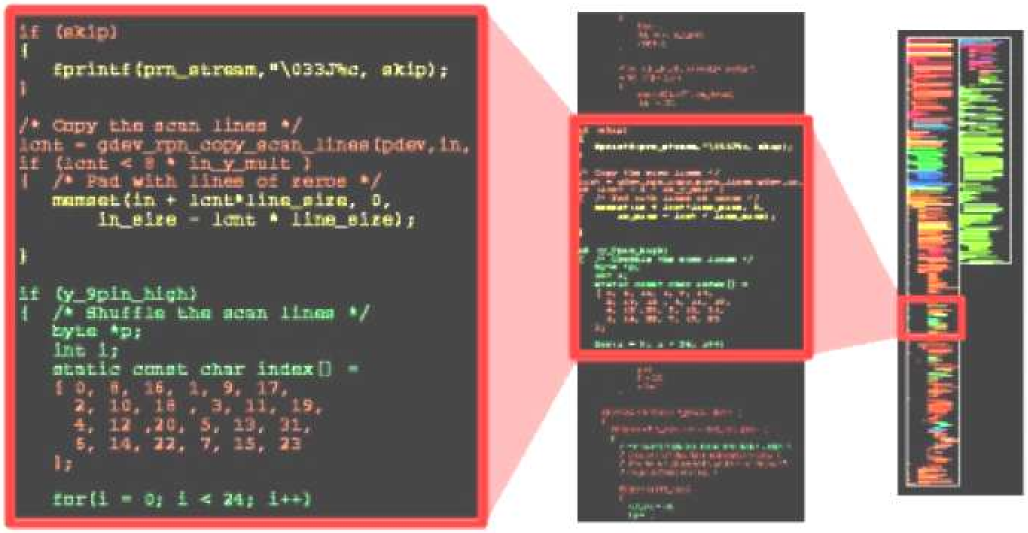
3.4 Information Murals

An *information mural* is a graphical representation of a large information space that fits entirely within a view. The miniature representation is drawn using anti-aliasing rules, intensity shading, and varying pixel size or color. It is generally useful for visualizing trends and patterns in the overall distribution of information. This approach follows Shneiderman's visual information seeking mantra: "overview first, zoom and filter, then details-on-demand" [4, cited]. There are two main techniques in this category:

- Line and pixel representation
- Execution mural

3.4.1 Line and Pixel Representations

Ball and Eick [24] developed a scalable technique for visualizing program text, text properties, and relationships. In the first version, named *line representation*, the



```
if (skip)
{
   fprintf(prn_stream,"\033J%c, skip);
}

/* Copy the scan lines */
lcnt = gdev_rpn_copy_scan_lines(pdev,in,
if (lcnt < 8 * in_y_mult )
{  /* Pad with lines of zeros */
   memset(in + lcnt*line_size, 0,
        in_size - lcnt * line_size);

}

if (y_9pin_high)
{  /* Shuffle the scan lines */
   byte *p;
   int i;
   static const char index[] =
   { 0, 8, 16, 1, 9, 17,
     2, 10, 18 , 3, 11, 19,
     4, 12 ,20, 5, 13, 21,
     6, 14, 22, 7, 15, 23
   };

   for(i = 0; i < 24; i++)
```

(a) (b) (c)

Figure 22: *Line representation using different scaling of color-coded program text [24]*

a) full text representation
b) smaller fonts
c) each line of text is reduced to a row of pixels

technique reduces each line of the program text to a single row of pixels, where length and indentation correspond to the original code (Figure 22).

They generalized this technique to increase the information density by a factor of ten. Figure 23 illustrates the principle. Each column represents a single file. Each line of code uses color-coded pixels ordered from left to right in rows within the columns. That way, it is possible to visualize over a million lines of code on a standard high-resolution monitor (e.g. 1280x1024).

Different applications of this technique have been shown to be helpful in visualizing code version history, differences between releases, and static properties of code. It is also useful for code profiling, program slicing, and identifying hot spots in program execution (e.g. bottlenecks).

3.4.2 Execution Murals

Jerding and Stasko [40] go beyond Ball and Eick's representation with a technique called *execution mural*. This technique provides a quick insight into various phases of the execution of object-oriented programs. Figure 24 illustrates this technique.

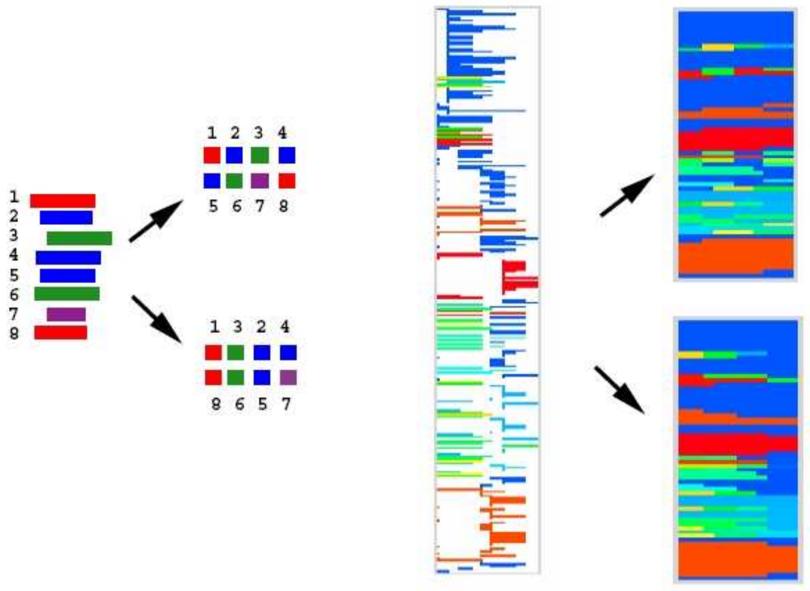


Figure 23: *The principle of pixel representation technique [24]*

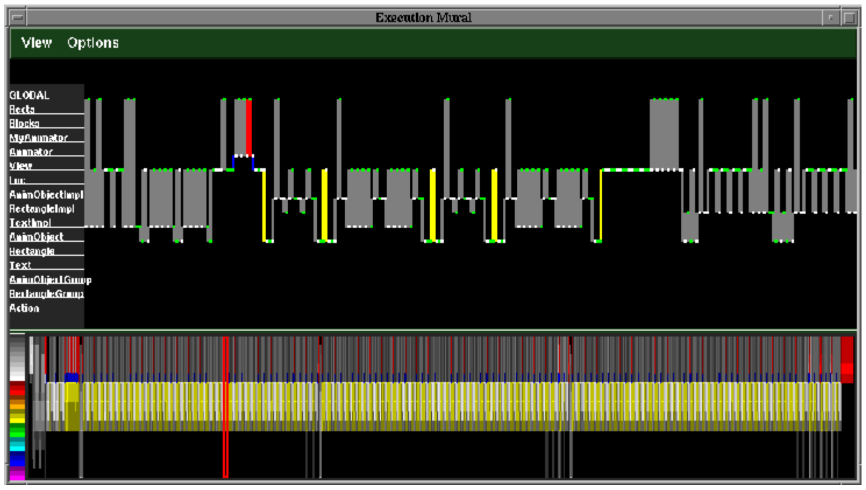


Figure 24: *Execution mural view of message traces from an object-oriented program [39]*

The upper portion of the view is the focus area where a subset of the messages can be examined in detail. The bottom portion is a navigational area that includes a mural of the entire message trace and a navigation rectangle that indicates where the focus area fits within the entire execution.

3.5 Interaction and Navigation

Many approaches have incorporated interaction and navigation techniques to enhance information visualization. Many believe that, in visualization systems, navigational techniques are as important as the visual aspect itself. There are three main aspects to interaction and navigation:

- Scrolling or panning
- Focus and context views
- Multiple views

3.5.1 Scrolling or Panning

The simplest technique is to provide a mechanism for scrolling or panning through a detailed visualization display. For example, the ubiquitous scrollbar provides two important cues to the user:

Size It gives a quick idea of how much is visible out of the entire information space.

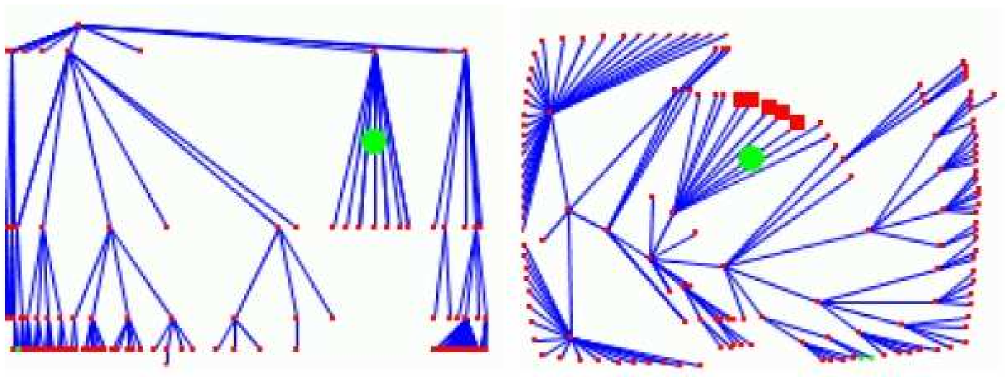
Position It gives a quick idea of where the visible area is with respect to everything else.

Scrollbars, however, do not provide semantic information about the content. As described below, adding zooming to a single view allows the user to shift from a very detailed display to a more global overview.

3.5.2 Focus and Context Views

When drawing a map to help a lost friend, one does not draw a picture-perfect map. One indicates the landmarks, such as a bridge or a large building. This is the context. Then one draws more detail around the precise area of interest. This is the focus.

This idea is used in visualization systems with techniques such as the *fish-eye* view. Generally, these are known as different lens that the user can apply to look at the representation with a different focus and/or a different context [20].



(a) (b)

Figure 25: *Fish-eye views [20]*
a) cartesian fish-eye
b) polar fish-eye

In the fish-eye view, the focus of the information is displayed in great detail while the rest of the information has less. For example, the rest of the information may be smaller or contain less information. The main advantage is that all of the information is still there and fits in a single view. The user is relieved from having to shift back and forth from a detailed view to a separate global view. Animation may be used to allow interactive real-time updates when the area of focus changes. Figures 25 and 26 give two examples to illustrate this. The left part of the first figure is a normal view while the right part focuses on the green dot. In the second figure, the "Game Play" subsystem is magnified but one can see where it fits within the rest of the system in the background.

A number of other focus and context techniques have been proposed. Some of them are:

Perspective wall of information Here, the focus is a detailed section of the information space in 2-D. The remaining information is shown around it in a 3-D perspective (Figure 27) [42].

Magic lens A magic lens is a movable lens that can filter the information underneath using different criteria. For example, it can simply zoom the view or it can display what is under the upper layer (e.g. the content of a closed box) [43].

Table lens This technique is a special lens specifically tailored to look at large tables [44].

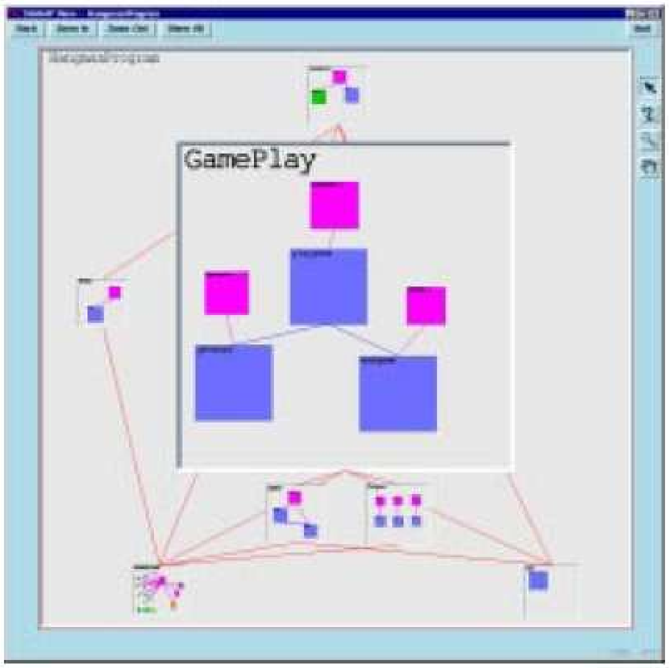


Figure 26: *SHriMP's fisheye view [41]*

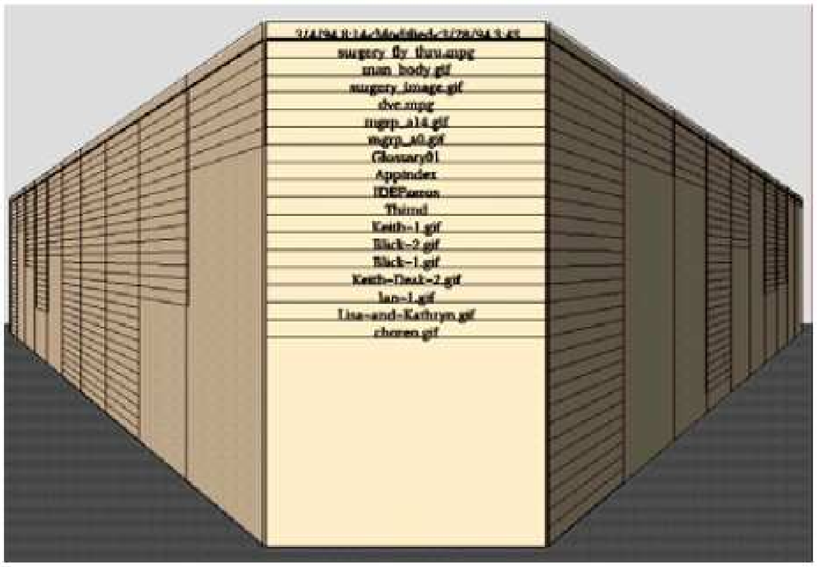


Figure 27: *The perspective wall of information technique [42]*

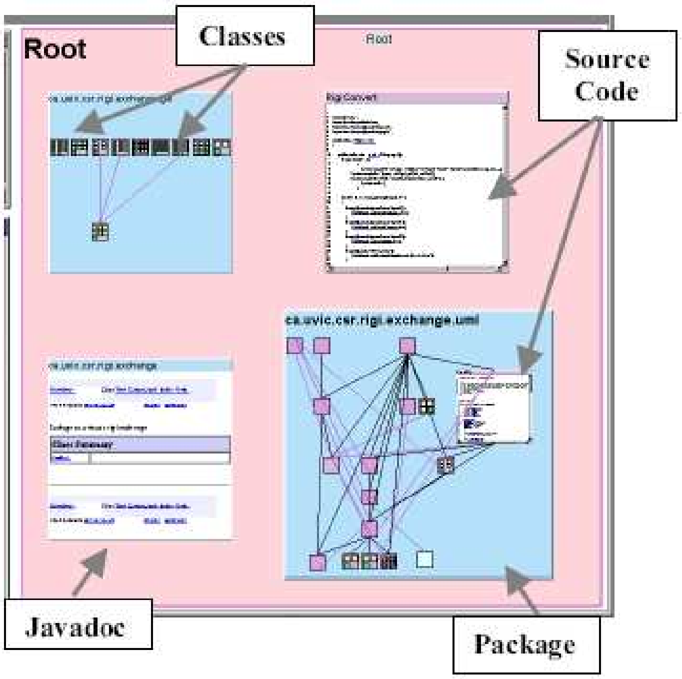


Figure 28: *SHriMP's multiple views of a Java Program [45]*

Although combining all of these techniques into other visualizations can be worthwhile, focus and context views often suffer from a performance problem. Indeed, every time the focus changes, the size and position of each element may change. This involves refreshing the visualization many times per second. Thus, the performance can drop considerably when dealing with large graphs.

3.5.3 Multiple Views

A third alternative is to separate the detailed view from the global view. A navigational or map window shows a miniature version of the entire information space along with some sort of "you are here" indicator. For software visualization, an example might be to allow the user to interact with various representations of the information in separate areas of the screen.

For example, the execution mural technique seen in subsection 3.4.2 uses a multiple-view mechanism to increase the navigation capabilities. Designed to speed program comprehension, the SHriMP tool uses multiple views of software architecture (Figure 28). More detail about SHriMP is given in subsection 4.6.

3.6 Animation

A software visualization animation is simply a series of operations that illustrate the behavior of a program. It displays the transitions between different states of the program. It can either concentrate on the data and its structure (e.g. data flow) or on the behavior of the program (e.g. control flow.)

Animating visual displays has mostly been investigated in the area of algorithm visualization. Brown [46] presents a taxonomy that may be used to analyze algorithm animation displays in detail. He also gives an overview of algorithm animation techniques [47].

Multiple algorithm animation techniques have been reported in the literature:

Multiple views It is generally more effective to use several views to illustrate the various aspects of even a simple algorithm.

State cues They reflect the dynamic behavior of an algorithm. Animators can show changes in the state of data structures by changing their graphical representation on the screen. State cues link different views together by representing specific abstractions the same way in every view.

Static historic A static view of an algorithm's history lets the user focus on the crucial events, i.e., the places where significant changes occur in time.

Continuous versus discrete transitions The graphical representation of a change to a data structure can either be incremental (smooth and continuous) or discrete. The link between the changes can be more difficult to "see" if the changes are discrete. Stasko [48] concentrates on smooth transitions.

Multiple algorithms Being able to run several algorithms simultaneously lets the user compare and contrast them easily.

Input data selection The choice of input data strongly influences the message conveyed by an animation. Different techniques take into account the amount of data and their implementation patterns.

Colors The right use of colors can enhance and complement all of the above techniques. It is usually applied in five distinct ways:

- Encode the state of data structures
- Highlight activity
- Tie views together
- Emphasize patterns
- Make the history visible

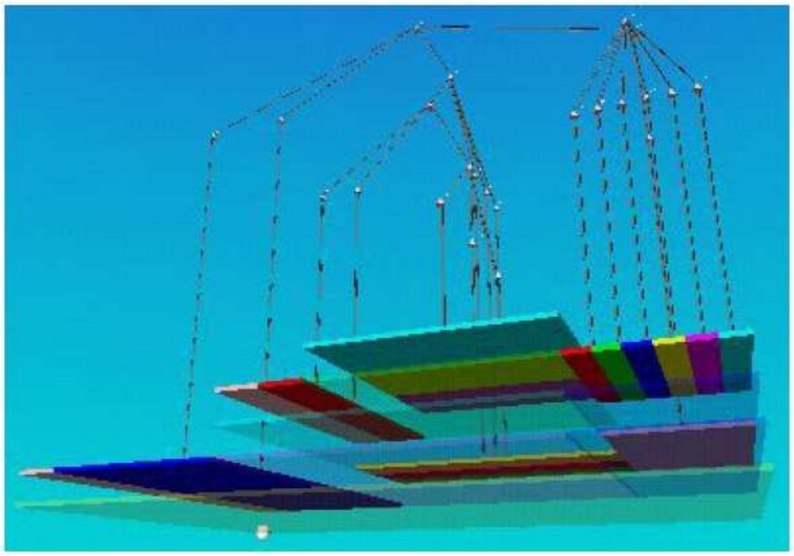


Figure 29: Variation on a conventional tree-map, implemented in VRML [49]

3.7 Virtual Environments

More recent works show promises with techniques that use virtual environments as a basis for visualization. This approach is being considered to overcome the problem that a very large amount of information needs to be displayed on a very small screen.

Churcher et al [49] have experimented with virtual environments by implementing the tree-map metaphor in a Virtual Reality Modelling Language (VRML). The view shown in Figure 29 is useful to emphasize the relationship between a weighted tree-map (lower part) and its original structure (upper part).

Knight and Munro [50, 51] have investigated an innovative solution to the problem of visualizing Java code. In this 3-D virtual word called *Software World*, the code is represented as buildings and districts in a city environment. Higher levels of detail are shown in a map-like style using techniques that fit a large amount of information into a finite space. They believe that using an urban environment takes advantage of the user's natural perception. The world has different visualization levels:

World The software system as a whole

Country A package within the system/world

City A file from the software system

District A class contained within the specific file/city

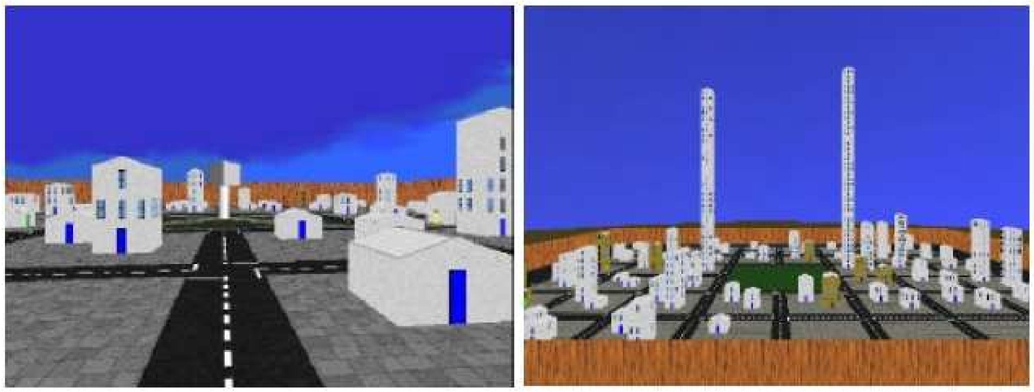


Figure 30: *Visualization of Java code within a Software World [51]*

Building A method within a class/district

Figure 30 shows two examples of a java system as a world.

Young and Munro [52] present a non standard visualization of a call graph structures within a virtual reality environment. Called *CallStax*, their technique is different in that it represents the paths through the graph rather than the graph as a network. As shown in Figure 31, CallStax uses the extra dimension to maximize the amount of information and interactivity through this environment.

3.8 Auralization

The main idea behind auralization is to convert changes in the program state into sounds. Very few experiences on auralization have been published until now. Francioni et al [53] were among the first researchers to use non-speech audio for software visualization. Other applications can be found in [54]. One experience uses audio in algorithm animations to:

- Reinforce visuals
- Convey patterns
- Replace visuals
- Signal exceptional conditions

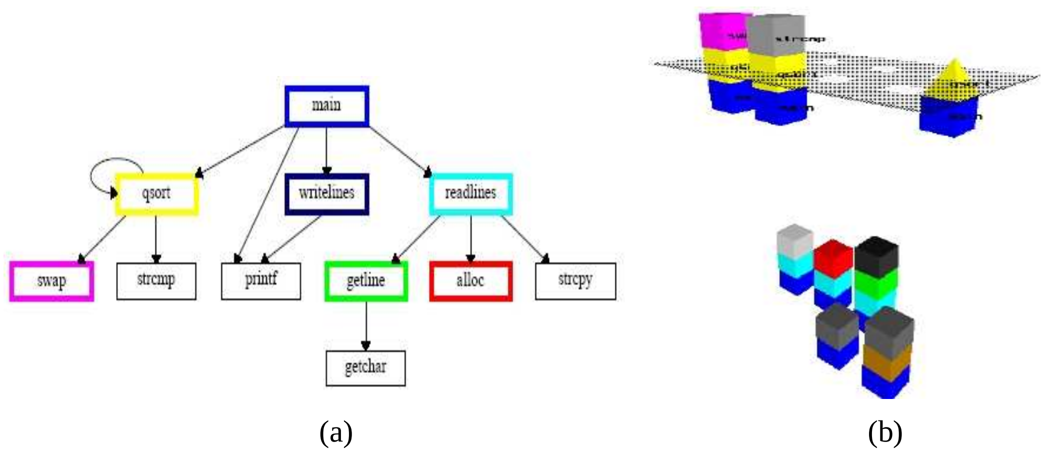


Figure 31: *The CallStax technique [52]*
a) standard 2-D call graph
b) visualization using the Superscape VR package

4 Systems

Two aspects should be considered when looking at computer software in practice.

On the one hand, a maintainer gathers the required information using static and dynamic analysis. In static analysis, the program is not executed. Only "static" information is used, such as source code and file dependencies. In dynamic analysis, the information is gathered by running the program and monitoring its behavior.

On the other hand, current visualization techniques can also convey information using static and dynamic methods. In this case, *static* means the information is non-temporal while *dynamic* means that the information displayed graphically changes as the program executes.

Combining these two aspects yields Table 1. All boxes in this table share the common goal of transforming information into meaningful and useful visualizations.

As previously stated, different techniques have been developed to visualize information. These techniques are a key component in a visualization system. They make software visible through the display of programs, program artifacts, and program behavior.

To achieve this goal, many different environments, hundreds of tools (including toolkits), and procedure libraries were created around the world. In this document, a set of programs and tools that regroups different techniques to look at software is called a software visualization system. In the literature, such a system is sometimes

Table 1: *Mapping between gathering information techniques and visualization techniques*

		Visualization techniques	
		Static (S_v)	Dynamic(D_v)
Information gathering techniques	Static (S_i)	Visualizing non-temporal information	Animating static information
	Dynamic (D_i)	Visualizing a snapshot or trace of program execution	Visualizing an animation of program execution

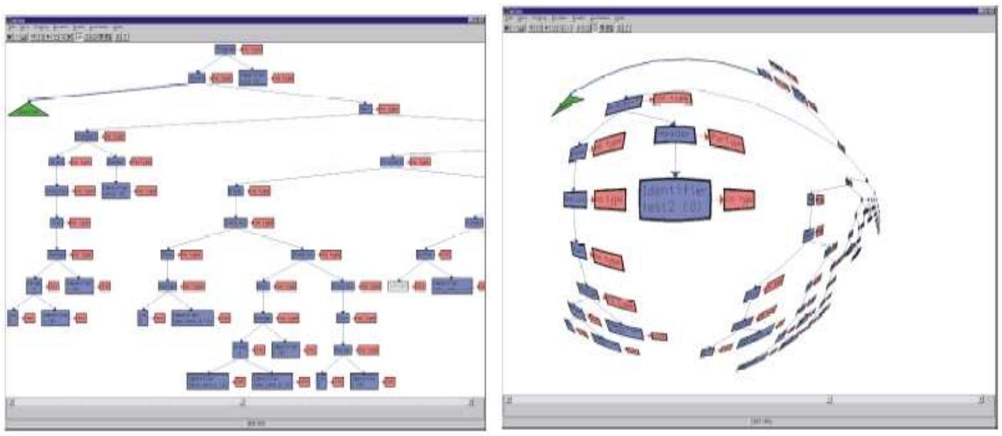
referred to as a tool, an environment, or a library.

It is very difficult to find a comprehensive overview of these systems that includes every commercial, free, and prototype systems. A few references on multiple systems with succinct descriptions exist [20, 55, 56, 57]. Additionally, very few studies have tried to classify these systems according to the type of analysis. For example, a classification according to the level of metric information that is gathered. Low-level information consists of program properties (e.g. source code, number of lines, etc.), while high-level consists of abstracted data (e.g. algorithms, classes, etc.) Myers [6] has used this approach to classify around twenty visualization systems according to whether they illustrate code/data/algorithms or convey static or dynamic information. Others claim that the key point of a suitable classification framework must take into account the level of interaction with the user in the specific context usage. More recently, Tilley and Huang [58] have proposed a task-oriented classification with three distinct classes: static, interactive, and editable. According to them, this type of classification will ultimately map common activities of program comprehension to specific forms of software visualization.

Consequently, it is very difficult to produce a summary of all the systems that have been developed. Given the quantity of systems, it would be next to impossible to test them all and have something significant to say about each one. However, many have been tested for the current projects. The rest of this section presents some relevant systems in more detail. These systems were chosen as being representative and illustrate many of the techniques previously presented. A technical note will be published shortly as an addendum to this document. It will list all tools, environments, libraries, systems, etc. that were found, along with their fact sheet.

4.1 Graph Visualization Systems

These systems use graphical representations for the navigation and analysis of software information. Although dynamic graph layouts seem more appropriate in the



(a) (b)

Figure 32: *aiSee graph visualization [32]*
a) normal view
b) fish-eye view

context of program comprehension, the majority of current graph layout systems employ static layout algorithms (batch).

A well-known tool is called aiSee [32] and has already been shown (Figure 32). aiSee automatically calculates a customizable layout of graphs specified in GDL. This layout can be interactively explored, printed, or exported in various formats. Users can choose from a variety of 15 layout algorithms (or visualization techniques). aiSee can animate a series of transformations and provide smooth transitions. The interface, however, is quite outdated.

Graphviz [59] is an open source graph visualization toolkit that includes practical tools and libraries to manipulate graphs and their representation. It includes stream and event interfaces for graph operations, high quality static and dynamic layout algorithms, and the ability to handle sizable graphs. Components of this toolkit have been used in tools supporting most aspects of software engineering such as Acacia (Reverse Engineering), Xray (Debugging), LOTOS (Specification), and Improvise (Process).

Walrus [60] is a tool to interactively visualize large directed trees in a three-dimensional space. It is technically possible to display a graph containing a million nodes. In practice, however, Walrus is suited for moderately-sized graphs with a few tens of thousand of nodes and links. Walrus computes its layout based on a user-supplied spanning tree and uses 3-D hyperbolic geometry to display graphs under a fisheye-like distortion (see Figure 33). This allows the user to examine the fine details of a small area while always having a view of the whole graph available as a frame of

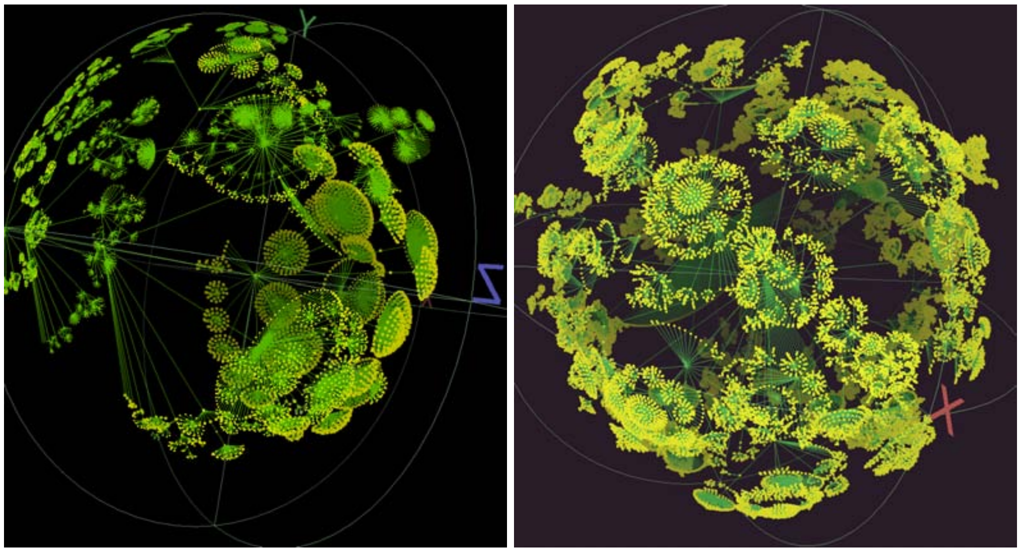


Figure 33: *Walrus tool for visualizing large directed graphs in a 3-D space [60]*
a) Graph containing 18,474 nodes and 18,473 links
b) Graph containing 535,102 nodes and 601,678 links

reference.

4.2 Tree-map Systems

The first generation of Tree-map systems has also been developed at HCIL. Tree-Viz™ is implemented on the Macintosh platform while the Windows version is called WinSurfer™.

The SeeSys software interactive visualization tool, developed by Baker and Eick [61, 62], is another concrete application of Tree-maps. It can visualize files, directories, and subsystems. It also provides a facility to zoom in on any subsystem. Figure 34 shows a screenshot in which rectangular areas are proportional to the number of lines of code. SeeSys presents additional information to the user as the mouse hovers on top of the visualization.

Dynamic queries have been added in more recent implementations of tree-maps. It allows a rapid and reversible selection of attribute values that creates shrinking subtree structures and encourages data exploration. Micro Logic Corp sells a commercial product for Microsoft Windows named DiskMapper [63]. ILOG includes the tree-map technique into their concept software Discovery [64]. It allows the user to visualize any hierarchy. For example, a directory of 50,000 files colored

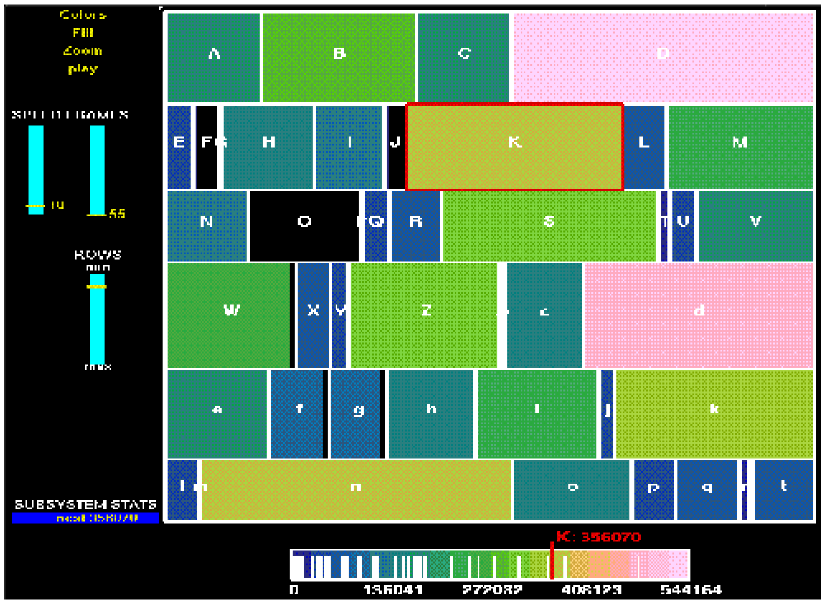


Figure 34: *Interactive SeeSys system embodying the tree-Map technique [62]*

according to their type.

4.3 Information Mural Systems

Techniques from information murals can be integrated to create a software visualization system. By adding panning and zooming capabilities, such a system can be stand-alone or part of a global view with more detailed informational displays.

SeeSoft [24] is a system that produces line-oriented software metrics out of source code. Figure 35a is a view of 48,913 lines of C code spread across 68 files. It uses the pixel representation technique (Subsection 3.4.1). Colors indicate the nested level, pink being the highest.

Another example from SeeSoft is showcasing the hot spots of a program execution (see Figure 35b). Here, the color of each line represents the number of times the line was executed. Red represents high execution frequency while blue is low. Lines that were not executed in this run are shown in grey. Finally, white represents lines that are not executable, such as declarations, comments, and static arrays.

Proof-of-concept information mural systems are being developed to support program comprehension during design recovery, validation, and reengineering tasks. Figures 36 and 37 show two examples of applications built using the optimized mural technique detailed in [39]. In this technique, the lines of a source code file map to a single row of pixels in the miniature representation.

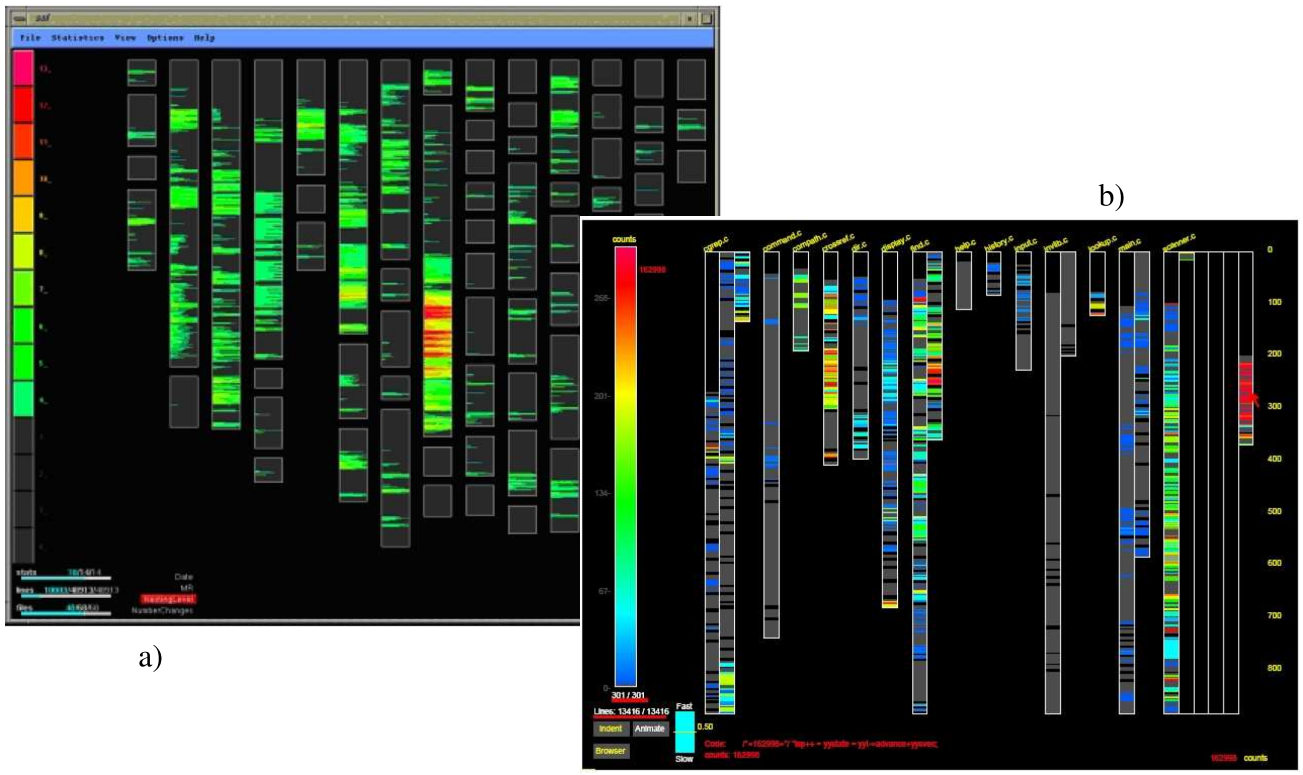


Figure 35: *SeeSoft [24]*
a) Static properties of a C program
b) Hot spots in program execution

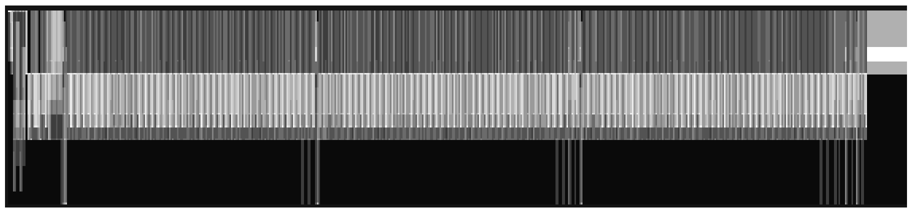


Figure 36: *Mural of object-oriented message trace (over 50,000 messages) [39]*

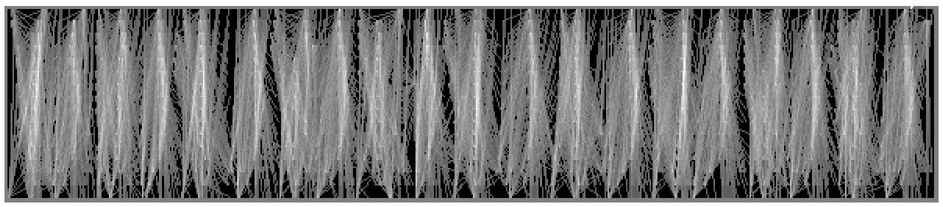


Figure 37: *Mural of parallel message trace (executing on 16 processors) [39]*

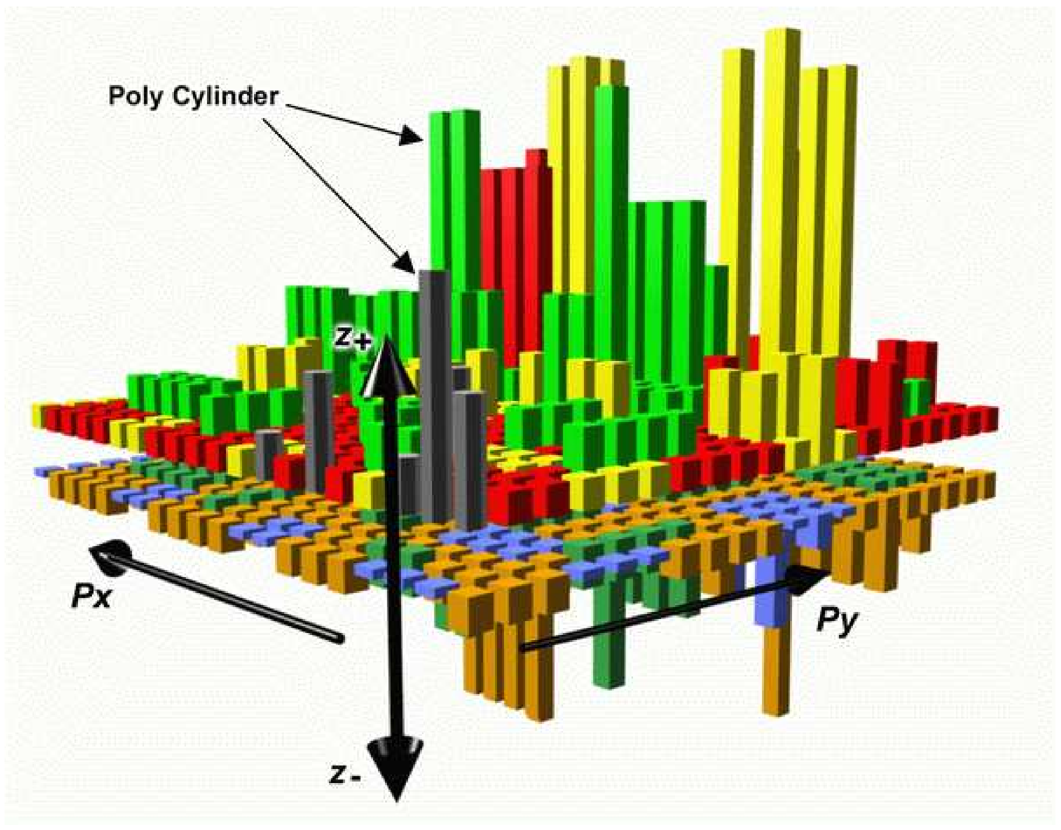


Figure 38: *Elements of the sv3D visualization framework [65]*

Marcus et al [65] also extend the SeeSoft metaphor with their sv3D software visualization framework. This solution builds new information murals using the third dimension, texture, and an abstraction mechanism. Sv3D currently uses containers, poly cylinders, height, depth, color, and position. An example mural is shown in Figure 38.

sv3D also provides support for user tasks by introducing new manipulation techniques and interfaces. Figure 39 is one example supporting a number of filtering methods. They also mention that multiple applications of sv3D to support software evolution and comprehension are being investigated.

4.4 Algorithm Animation Systems

Algorithm animation systems display the inner working of an algorithm by illustrating its operations as data structures. Many in the literature think that most of these systems are only academic experiments without practical value. Nevertheless, here are some examples.

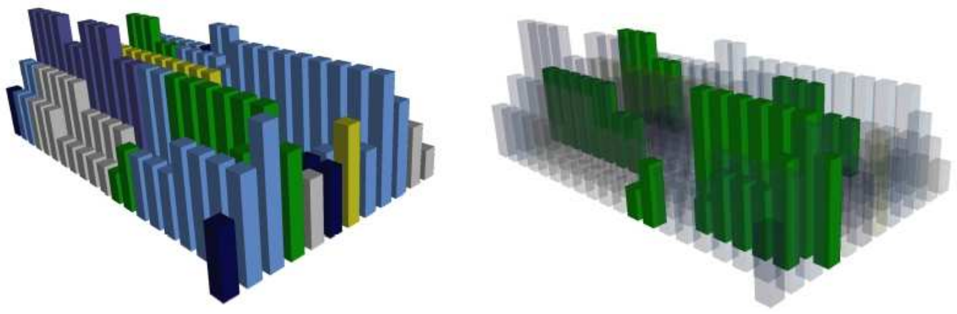
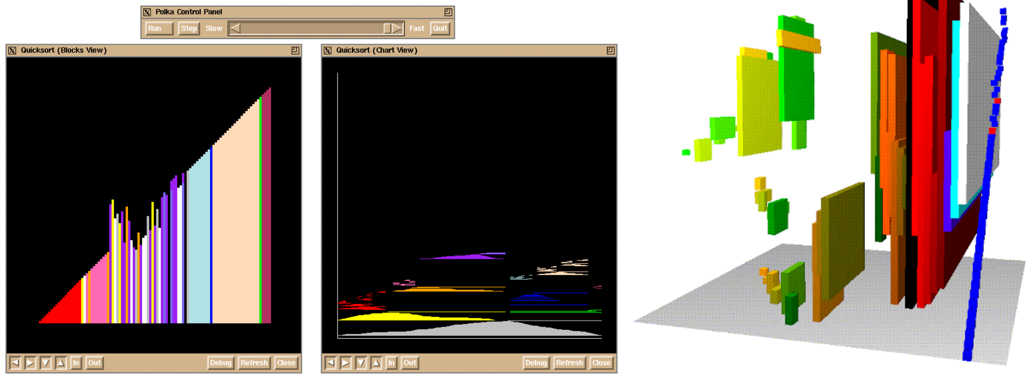


Figure 39: *sv3D directly supports user interaction by eliminating occlusion using transparency control [65]*



(a) (b)

Figure 40: *Visualizations produced by the Polka algorithm animation system [68]*
a) 2-D parallel quick sort
b) full 3-D quick sort

Polka [66] is an animation system that is particularly well suited to building animations algorithms (Figure 40). It can be used to animate programs, computations, and parallel computations. Polka supports colors, real-time, smooth animations, 2-D and 2.5-D, and even full 3-D visualization (Figure 40b). Polka provides its own high-level abstractions to make animation creation easier and faster than many other systems. Users do not have to be graphics experts to develop their own animations. Polka also includes an interactive front-end called Samba [67]. It can be used to generate animations from program that can generate ASCII.

Zeus [69] is a system to view and interact with an animation. It is based on the same principles as BALSA-I, which was the first widely known algorithm animation system. BALSA-I was developed by Marc Brown and Robert Sedgewick at the Brown

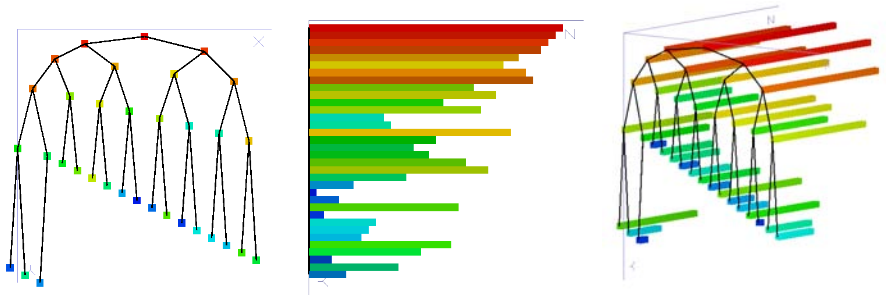


***Figure 41:** Output from Zeus algorithm animation system [70]*

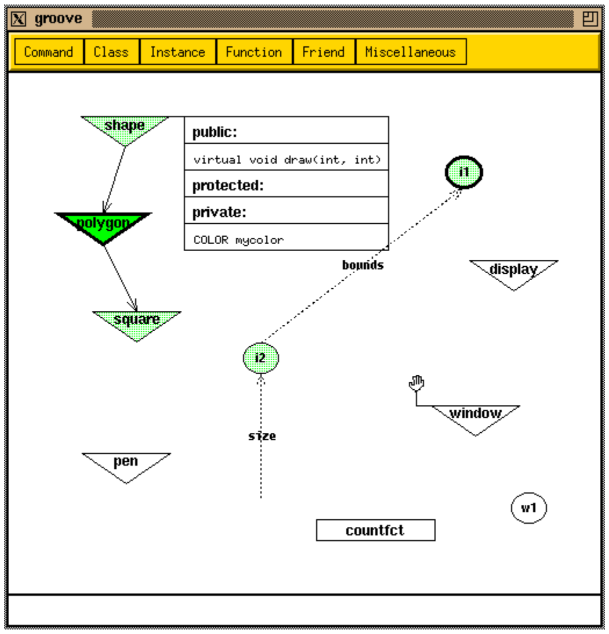
University in 1984. Both Zeus and BALSA-I use the concept of annotating algorithms with interesting events. They allow the creation of multiple views that are updated when they receive events. Figure 41 shows Zeus in operation. Setting up a new animation is a heavy task because the algorithm must be implemented within the Zeus framework. The programmer must manually insert calls to perform the animation actions. This requires an a priori detailed knowledge of the algorithm.

4.5 Run-time Visualization Systems

Run-time visualization systems display the dynamic execution of a program for the purpose of debugging, profiling, and understanding the program's behavior. Run-time visualization differs from algorithm animation in its purpose and degree of abstraction. The former monitors the real production code and reveals real data for analysis, while the latter is an abstraction built to understand the algorithms involved. For example, run-time visualization can be used to display program statements, threads, and object usage.

GROOVE [71] is a system that uses animation to illustrate the run-time behavior of an object-oriented system. With this system, programmers can better understand the class hierarchy and relationships. Figure 42 is a simple view from the GROOVE system. Triangles represent classes, circles represent instances, and rectangles represent functions. An animated arrow is an invocation (method call). Colors illustrate class hierarchies and relationships. A certain degree of effort is required to create visualizations. Thus, it would be difficult to use the system for anything but small programs.

University of Washington Program Illustrator (UWPI) [72] offers a source level run-time debugger for Pascal programs. It allows to single step source code instructions. It also provides an automatic visualization of the data in the program. A layout strategist module, written in Lisp, uses artificial intelligence techniques to



public:
virtual void draw(int, int)
protected:
private:
COLOR mycolor

Figure 42: *Screenshot of GROOVE showing an object-oriented design [71]*

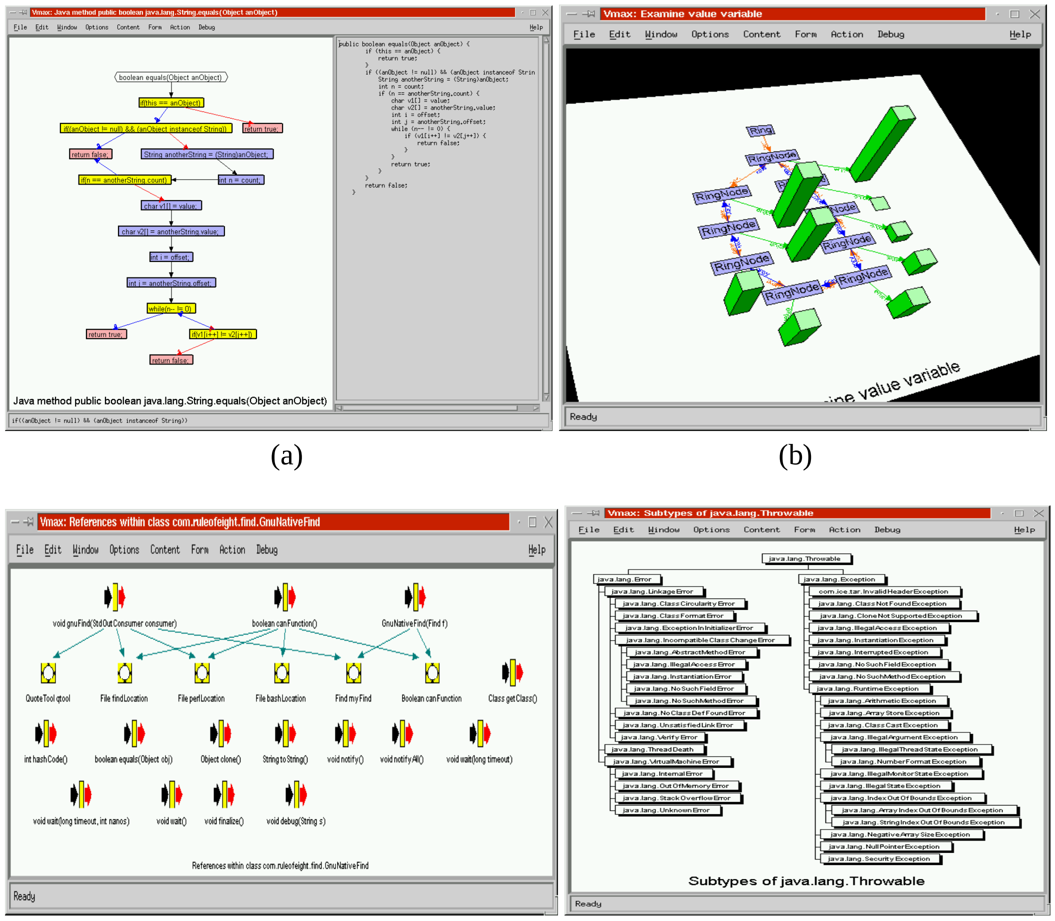
determine the best way to render the program's data. Finally, the current data state is displayed graphically.

4.6 Software Exploration Systems

The goal of a software exploration system is to help the user in forming a mental model of the complete program. To do so, it builds a graphical representation of the static software structure and/or its run-time behavior.

Vmax [4] provides information about the program structure and run-time data through a wide range of highly-interconnected and browsable views. Because the approach is generic, the system has a broad scope and can produce a wide range of graphical outputs. Figure 43 shows four sample outputs. Different views and visualizations can be selected. An automatic legend describes each view and can be interactively modified to customize how data is presented. An editable source code window is synchronized with the graphical view.

SHriMP (Simple Hierarchical Multi-Perspective) [73] is both an application and a technique. It is designed to enhance the visualization and exploration of software architectures. Because SHriMP is domain-independent, it can also be used to explore many other complex information spaces. An interesting application is the exploration of large software programs. Currently, there are three tools that are built around SHriMP:


Vmax: Java method public boolean java.lang.String.equals(Object anObject)
Java method public boolean java.lang.String.equals(Object anObject)
Vmax: Examine value variable
Vmax: References within class com.ruleofeight.find.GnuNativeFind
References within class com.ruleofeight.find.GnuNativeFind
Vmax: Subtypes of java.lang.Throwable
Subtypes of java.lang.Throwable
Ready

```
public boolean equals(Object anObject) {
        if (this == anObject) {
            return true;
        }
        if ((anObject != null) && (anObject instanceof Strin
            String anotherString = (String)anObject;
            int n = count;
            if (n == anotherString.count) {
                char v1[] = value;
                char v2[] = anotherString.value;
                int i = offset;
                int j = anotherString.offset;
                while (n-- != 0) {
                    if (v1[i++] != v2[j++]) {
                        return false;
                    }
                }
                return true;
            }
        }
        return false;
    }
```

(a) (b)

(c) (d)

Figure 43: *Different outputs of the Vmax system [4]*
a) method control flow b) run-time data in a graph
c) cross referencing d) class hierarchy

Stand-Alone SHriMP A stand-alone Java application that visualizes *graph-based* data formats such as GXL, RSF, XML, and XMI.

Creole An Eclipse plugin that lets the user explore Java code visually. It can show the code's structure and the links (references, accesses, etc.) between its different pieces (Figure 44).

Jambalaya A plugin created for the Protégé tool that uses SHriMP to visualize ontologies and knowledge bases. Protégé is "an ontology editor and a knowledge-base editor." It has been developed at Stanford University to allow a domain expert to build a knowledge base by creating and modifying reusable ontologies and problem-solving methods (Figure 45).

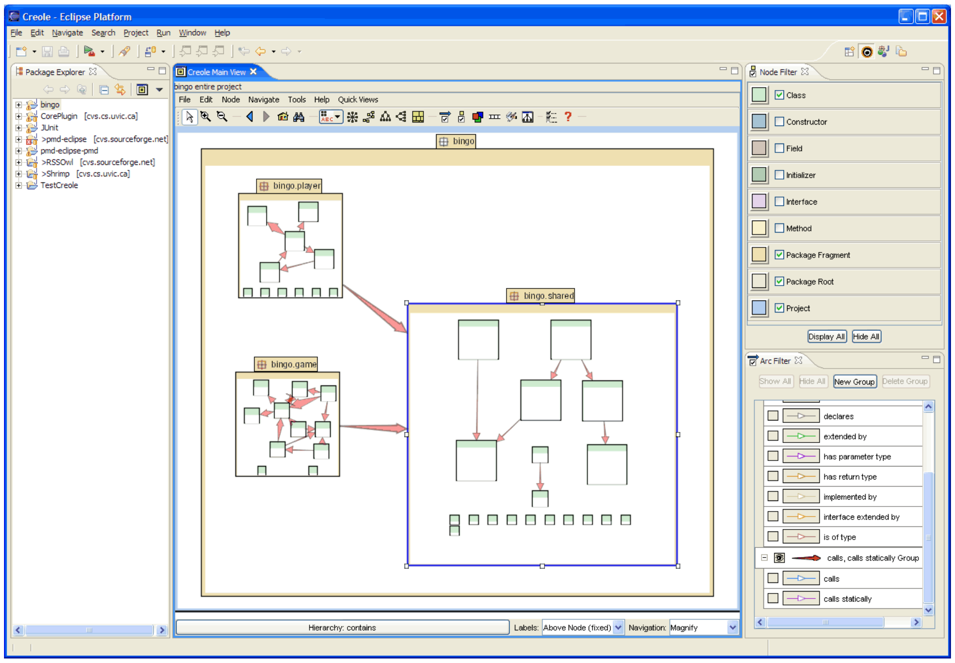


Figure 44: *Creole is an Eclipse plugin to explore Java code [73]*

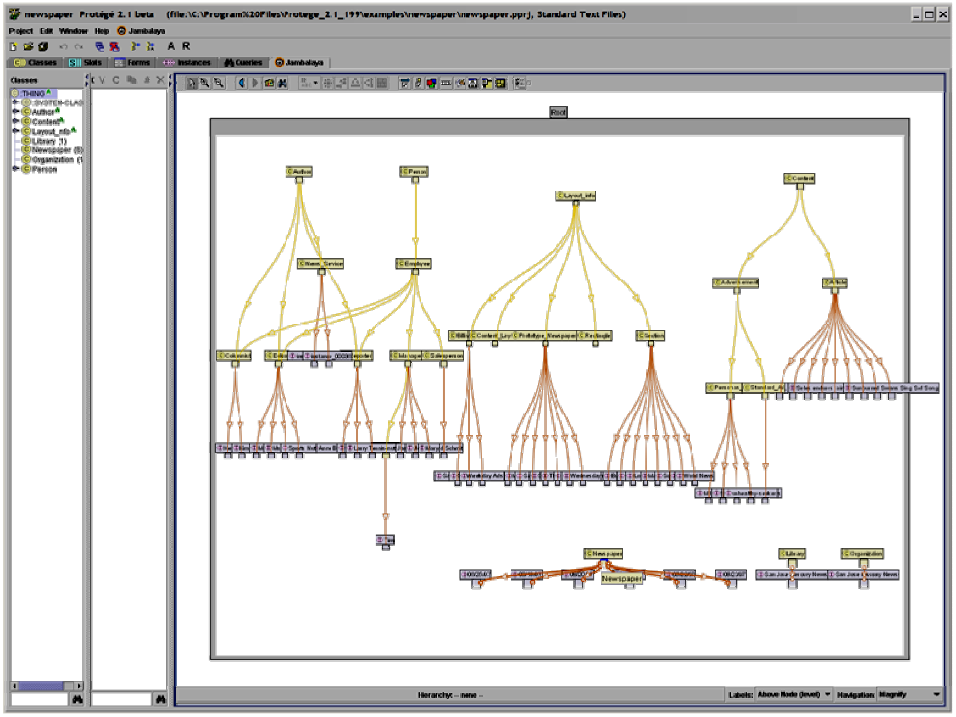


Figure 45: *Jambalaya is a Protégé plugin to visualize onthologies and knowledge bases [73]*

4.7 Auralization Systems

LogoMedia is a well-known system that supports user-defined code and data program auralization [74, 75]. With the help of control and data probes, it makes a specific sound just before a line is executed. These probes could be also inserted with a graphical editor.

There is not much research in this area. Software visualization concentrates almost exclusively on the visual sense. However, it is possible that human ears could be useful for certain things in software comprehension. . .

5 Evaluating a Software Visualization Systems

It is now obvious that many software visualization techniques are available. However, to what extent are they efficient and effective in assisting with software development and maintenance? Are there any methods to evaluate them quantitatively or qualitatively? These questions were not discussed much until the end of the 1990s. Experts in the field noticed that these tools were pretty slow in penetrating the software engineering market so they decided to find out why.

However, very few studies were published. Lately, there has been an upsurge in this area but many of the analyses were not performed using a formal approach. Others were purely qualitative and used existing taxonomies as a reference [76, 4, 77]. Still others were more quantitative and measured the impact of visualization systems on performing very specific tasks [77, 78]. It is therefore difficult to generalize a meaningful and generic method to evaluate a system.

It is worth looking more closely at some of these existing methods.

For example, Charland et al [79] recently conducted a qualitative study to observe and evaluate how commercial software comprehension tools can help architects in understanding large programs. They noticed that software comprehension tools generally do not provide the appropriate viewpoints, abstraction levels, and filters that are needed to understand a complex software architecture. The limit of existing systems is around 1,000 classes. More than that and the existing tools lose their usefulness.

Bassil and Keller [77] are one of the few to have performed a quantitative evaluation. They address various functional, practical, cognitive, and code analysis aspects that users might be looking for in a software visualization tool.

Buchsbaum et al [78] have conducted work of a more industrial nature. They examined the effectiveness of visualization techniques as an aid to software infrastructure comprehension. Their results help to formulate the general requirements for software visualization and program comprehension tools.

Storey [80] also reports on many studies on this subject. From these studies, the essential characteristics that contribute to the efficiency of a visualization can be extracted. These four, mutually non exclusive, aspects are:

Cognitive aspect It seems imperative that how a system is used should suit a particular comprehension strategy. This strategy should be based on a formal cognitive model and should be tailored for the specific characteristics of the maintainer, program, and tasks to perform.

Output aspect This concerns the characteristics of the system that are directly related to what can be displayed. Software visualizations can be very large and complex, both spatially and temporally. Thus, the choice of an appropriate metaphor and it representation model is imperative.

Interaction aspect Tools are often not easy to install, learn, and use. Hence, this adds an additional cognitive overhead to the user. This could be alleviated by providing good navigation facilities and meaningful orientation cues. Presenting the information in an order that contributes to software comprehension is also a must. In the future, interacting with ever more complex software will unconditionally require facilities for advanced navigation through large information spaces.

Computation aspect This aspect asks questions such as what is the primary target medium for the visualization system? How big is the screen? Nowadays, it is common to have two or more monitors. The graphical capabilities of standard desktops are getting ever more powerful. Hence, it is expected that virtual reality environments will soon become a popular target medium for software visualization systems.

This interpretation conforms to the classification model proposed by Price et al [5]. In fact, their taxonomy is one of the most formal, much more than the ones presented earlier. It would be inefficient to go into more detail in this overview.

6 Conclusion and Future Work

As seen in this document, much research has been performed in the last few years to enhance visualization techniques and tools. In theory, most of these systems are dedicated to complex program comprehension. However, very few of these systems provide a visualization that allows a useful mental model to be created in the mind of the user.

Over 140 papers and nearly as many tools were read, explored, and tested for this literature review. Only the most promising or significant ones are presented in this document. One thing is certain, this domain of research is quite active. There are way too many prototypes and tools to try them all. Candidates that show promises and warrant more investigation are SHriMP (Subsection 4.6), Graphviz [59], aiSee, and Walrus (the last three are discussed in Subsection 4.1).

A technical note will be published shortly as an addendum to this document. It will list all tools, environments, libraries, systems, etc. that were found, along with their fact sheet.

This literature review was conducted to try to find out as much as possible on available systems and techniques. Refining the aspects and criteria defined in Section 5, future work will try to come up with the best combination of tools possible. The goal is to speed up the process of understanding large software systems.

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List of Acronyms

ASCII	American Standard Code for Information Interchange
CHISEL	Computer-Human Interaction and Software Engineering
DND	Department of National Defence
DRDC	Defence Research & Development Canada
GDL	Graph Description Language
GUI	Graphical User Interface
GVU	Graphics, Visualization and Usability

GXL Graph eXchange Language

HCI human-computer interaction

HCIL Human-Computer Interaction Laboratory

IDE Integrated Development Environment

MDN Ministère de la Défense Nationale

RDDC Recherche et Développement pour la Défense Canada

RSF Rigi Standard Format

SHriMP Simple Hierarchical Multi-Perspective

U.K. United Kingdom

UML Unified Modeling Language

U.S.A. United States of America

UWPI University of Washington Program Illustrator

VRML Virtual Reality Modelling Language

XMI XML Metadata Interchange

XML Extensible Markup Language

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visualization technique, software understanding, program comprehension, software visualization, cognitive aid