Communicating Software Architecture using a Unified Single-View Visualization

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Abstract

Software is among the most complex human artifacts, and visualization is widely acknowledged as important to understanding software. In this paper, we consider the problem of understanding a software system's architecture through visualization. Whereas traditional visualizations use multiple stakeholder-specific views to present different kinds of task-specific information, we propose an additional visualization technique that unifies the presentation of various kinds of architecture-level information, thereby allowing a variety of stakeholders to quickly see and communicate current development, quality, and costs of a software system. For future empirical evaluation of multi-aspect, single-view architectural visualizations, we have implemented our idea in an existing visualization tool, Vizz3D. Our implementation includes techniques, such as the use of a city metaphor, that reduce visual complexity in order to support single-view visualizations of large-scale programs.

1. Introduction

Visualization techniques are widely considered to be important for understanding large-scale software systems [15]; yet knowing what to visualize and how to present information are themselves daunting issues. The challenges are many. First, there are several stakeholders in a software project—architects, developers, maintainers, managers—each asking different questions about the software. Answering a diverse set of questions will involve different abstraction levels, such as the architecture, the middle level structure [15], or the source code itself. Each question may require a distinct analysis; multiple analyses can generate huge volumes of data, which may be difficult to store, to manipulate, and to present. Having to manage multiple analyses, possibly through multiple visualizations (views), places a significant cognitive burden on any individual stakeholder. Multiple views also tend to make it difficult for separate stakeholders to communicate on subtle issues about a software architecture. These challenges make it hard for multiple stakeholders to reach a common understanding or consensus about the project.

Different stakeholders often interact around questions about the software system's architecture. For example, developers and project managers need to know where to make improvements, *e.g.*, "which components do we have to modify in order to improve the performance or security of our system?" Project managers need to know how to allocate team members to each part of the system and answer questions such as, "can we meet the next deadline?" Additionally, both managers and vendors are interested in development hot spots (frequently modified components), which may indicate areas of high system maintenance cost. Designers and maintainers are more interested in the overall structure of the system; this knowledge helps them to identify reusable components, for instance.

We are investigating a visualization technique designed to help all stakeholders collectively understand and better communicate the architecture of a large-scale software system. Our particular technique represents the structure of the system using a graph-based model, following common convention [15], and we augment this model with a number of static and dynamic analyses. Our specific choices of model and analyses help stakeholders answer a wide range of questions about the overall design, quality, and costs in development and maintenance (Section 2).

The central design goal of our approach is to visualize multiple task- (or stakeholder-) specific aspects of a software architecture using just a *single* view (Section 3), *cf.* Figure 1, to communicate problems, decisions and solutions between stakeholders. In contrast, existing approaches (Section 6) primarily rely on multiple views when visualizing multiple aspects of a system [1, 17, 30, 31]. Although multi-view approaches can be very effective, users may also have considerable difficulty managing and navigating through dif-

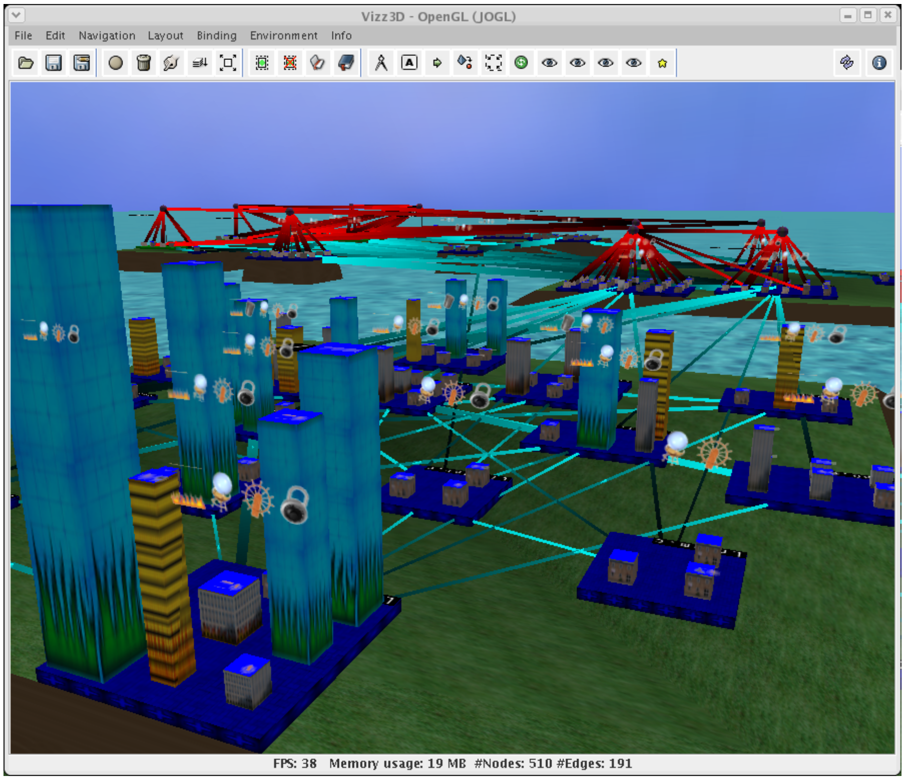


Figure 1. Architectural Program Visualization of a C++ Program.

ferent views [27, 28, 32]. In our current research, we are particularly interested in whether these difficulties can be overcome by judicious rendering within a single view.

To help answer this question, we have implemented a single-view visualization tool (Section 4). We use a metaphor based on cities that provides users with an intuitive physical interpretation of the system. In addition, we use a layout algorithm that permits the system to be rendered consistently each time the visualization is performed. That is, the layout is designed to be insensitive to small structural changes, thereby helping users remember and navigate in the visualization. Our specific implementation supports C and C++ programs, extending our earlier work for Java programs [20, 34].

Our overall approach allows multiple stakeholders to see and communicate about the same view, which facilitates the collective understanding and discussion of the system's architecture (Section 5).

2. Visualizing Architectures

There are roughly three levels of program visualization, based on the level of abstraction [15, 26]: *source code level*, *middle level*, and *architecture level*. This section explains what we mean by architecture level, and describes our specific model of the program and analyses in detail.

On the source code level, typical visualization tools include program and aspect editors. Advanced tools may integrate program editors with online debuggers and profilers. Source-level visualizations are very "low-level," as they relate directly to the underlying software artifact, and are primarily of interest to developers and maintainers.

On the middle level, visualizations are problem-specific. Developers and code maintainers have specific problems to solve, and they usually apply tailored algorithms and visualizations to the program to better understand both the problem and the program. Typical middle level visualizations include sequence diagrams, abstract syntax tree (AST) representations, dominance tree visualizations, concept lattices, control and data flow graphs.

The aim of architecture-level visualization is to rapidly summarize and communicate the architecture and design decisions of the overall software system. Architectural visualization is naturally more abstract than source- or middle-level visualizations, and therefore better suited to visualizations in the large. Abstract visualizations of software architectures combined with metrics can help different stakeholders to answer many questions about a software system.

For instance, project managers might use the visualizations to understand the aspects of a project that are most expensive, code designers can communicate current implementation deviations from original design plans, and code maintainers may use the visualizations to better understand unknown software systems [7].

Common examples of architectural visualizations are function call graphs, hierarchy graphs, and directory structures. There are many ways to present these graphs, such as UML diagrams, graph browsers, and component/connector graph drawings. Many tools support these visualizations [12, 26, 31][1]. However, to the best of our knowledge, no tool exists that supports the visualization and communication of software architecture between different software development and maintenance stakeholders.

2.1. A graph-based program model

To support communication among various stakeholders through a single-view architecture visualization, a program model combining different aspects of a program (important to different stakeholders) is needed. We have merged several tools (Section 4) to retrieve the following architectural program models of C/C++ applications:

- A *Function Call* graph represents the call relationship between different (C/C++) functions.
- A *Class Call* graph shows the interaction structure between (C++) classes.
- A *Class Contains* graph holds information about classes and their functions.
- A *Class Inheritance* graph represents the inheritance structure of an (C++) application.
- A *File Call* graph shows the call structure between source files.
- A *File Contains* graph shows functions in relation to their files. In C/C++, related functions may be implemented in (multiple) source as well as header files. The C++ specification does not enforce a standard implementation style. As a result, File Contains and Class Contains graphs are most likely to be viewed together.
- A *Directory Contains* graph represents the relationship between files and their corresponding directories.

Our graph-based program model is a union of the graphs implemented and described above. Table 1 shows examples of how various stakeholders might communicate software architecture through a particular set of graph types.

[1]We consider only graph-based tools and visualization approaches.

Graph	**Program Manager**	**Architect/ Designer**	**Developer**	**Maintainer/ Re-engineer**
Function Call		x	x	x
Class Call		x	x	x
Class Contains			x	x
Class Inheritance		x	x	x
File Call	x	x	x	x
File Contains			x	x
Directory Contains	x	x	x	x

Table 1. Correlation Graphs - Stakeholders

Table 1 only suggests what information might be of interest to each stakeholder. Of course, we might modify the table to reflect the interest, expertise, or task at hand. The key point in Table 1 is that a *unified* architectural visualization more flexibly supports and encourages interaction among stakeholders, compared to visualizing and communicating multiple stakeholder-specific representations in various notations.

2.2. Augmenting the model with analyses

There is more information of interest to various stakeholders than plain structural graphs can represent. For instance, when investigating a Directory Contains graph, a project manager would also like to understand the complexity of the files being viewed with respect to other metrics, such as size. The additional program information can either be shown in tables and be related to the views, or more preferably be integrated directly into the views themselves.

For our prototype, we have implemented a number of analyses, the results of which can be attached to our program model. We list examples below; though not all-inclusive, this list can be extended easily:

Run-Time Analyses. We collect run-time information about C/C++ applications using the *gprof* profiling tool.

- *Execution Time Analysis* profiles the time spent in functions, identifying performance "hot spots," or functions that execute for an exceptionally long time.
- *Execution Frequency Analysis* profiles the call frequency of functions to determine exceptionally frequently called functions.

Metric Analyses collect program information about single entities such as functions.

- *Lines of Code (LOC)* is measured for each function.
- *Unsafe Function Calls*. Certain aspects of C++ (*e.g.*, unchecked array access, raw pointers), can lead to low-level buffer overflows, page faults, and segmentation

faults. In this analysis, we detect calls to "unsafe" functions, such as `sprintf`, `scanf`, `strcpy`.

- *Global Variables*. We traverse the program's abstract syntax tree (AST) to check for public declared variables (within the scope of classes) and global variables (outside the scope of classes). It is considered a good programming style to avoid global variables.
- *New-Delete Analysis*. In C++, when deleting scalar entities, the scalar C++ *delete* statement should be used to ensure correct program behavior. Similarly, dynamically allocated arrays must be deleted with the *delete[]* statement. Our analysis is based on data-flow and control-flow information.
- *Cyclomatic Complexity (CC)* indicates how much effort is required to maintain a function. Our implementation of McCabe's Cyclomatic Complexity [19] counts the possible execution branches in a function for the following branching statements: if, for, while, do-while, and (switch-)case.
- *Arithmetic Complexity*. For each function, this analysis counts the number of arithmetic operations on float, int, float pointer, and int pointer types. Thus, functions and classes with large arithmetic operation counts can be detected. This is particularly important in scientific computing codes, since such functions should be the most robust and reliable pieces of the software.

Advanced Static Analyses help to recover various hidden aspects of software. In general, these analyses can not be interpreted alone; results indicate relations between entities.

- *Pattern Matching* is used to locate functional and non-functional properties of a software system, *e.g.*, MPI [22] calls in high performance computing. This approach is similar to visualizing aspects from aspect-oriented programming (AOP) [13].
- *Class Membership*. This analysis annotates each member function with its associated class and source file it is implemented in. It discovers fragmented member functions, *i.e.*, member functions declared in the same class but defined in different files. This analysis may uncover "bad" coding styles or refactoring efforts that were applied to split large source files.
- *Strongly Connected Components (SCC)*. We detect cyclic dependencies between functions, classes or files. In general, nodes in a cyclic dependency may be merged to reduce call dependencies, and hence to reduce the structural complexity of the system.

Repository Analyses retrieve information from a source-code repository such as CVS or SVN and attach it to the current program model. In our current implementation of C/C++ visualization, we have not attached this information yet. We base the need for such information on our previous studies visualizing Java repository information [20, 24] using VizzAnalyzer [35] and Kenyon [3].

- *Work Distribution* is an analysis that determines the specific developers that are working on a specific part of a software system. This information gives an idea about the progress of the maintenance or development team and can also assist to estimate time to completion.
- *Frequent Change*. Entities changed frequently result in higher maintenance efforts and costs. Thus, it is essential to determine frequently changed components.
- *Defect Dependencies* show how certain defects and their bug-fixes relate [4, 6]. Defect analyses may help to predict software project/maintenance costs.

Table 2 lists stakeholders and these analyses in which they might be particularly interested.

Metric/Analysis	Project Manager	Architect/ Designer	Developer	Maintainer/ Re-engineer
Execution Time			x	x
Execution Frequency			x	x
Lines of Code	x	x	x	x
Unsafe Function Calls			x	x
Global Variables		x	x	x
New-Delete			x	x
Cyclomatic Complexity	x		x	x
Arithmetic Complexity			x	x
Pattern Matching		x	x	x
Class Membership			x	x
SCC		x	x	x
Work Distribution	x			
Frequent Change	x		x	x
Defect Dependencies	x			x

Table 2. Correlation Analyses - Stakeholders

Table 2 only suggests what is possible. For our prototype, we have implemented all of the analyses above (except pattern matching and the repository analyses). The analysis results are attached to our model graph. With the model graph at hand, the user can now view, interactively select (reduce) and communicate information of interest.

3. Practical Single-View Visualization

We believe that single-view visualizations are better than multi-view visualizations when communicating about software architecture. First, single-view illustrations avoid the difficulties when managing and navigating through different views [27, 28, 32]; secondly, they rapidly summarize a system because all information is available within that view; and thirdly, having one view helps different stakeholders to easily communicate different concerns within the same familiar picture. Single-view visualizations do not replace detailed stakeholder-specific visualizations. Rather, they unify different stakeholder-specific architectural visualizations to a common image that can easily be communicated, as is done in the engineering industry where task-specific blueprints are unified to be understood by architects, electricians, civil engineers, and others. As an example, Kruchten introduced (software) architectural blueprints in which a logical view describes classes and associations for end users and a development view describes modules and compilation dependencies for developers and managers [16]. Both views are essential. Nevertheless, we believe that a single unified view combining both the logical and development view could support the communication between end users, developers and managers. We plan to evaluate this hypothesis in future work.

To study the effects of single-view visualizations, we have developed a tool prototype, *cf.* Section 4. For our prototype to work effectively (*i.e.*, by reducing the cognitive overload for a viewer [28, 32]), we need to handle the inherent complexity of multiple architectural aspects within one view. Below, we describe complexity reduction techniques we have selected and implemented from literature:

- *Abstraction*. To cope with a flood of information, we need mechanisms for filtering, aggregating, or merging low-level details into higher-level properties [25, 36]. Abstraction techniques are part of Vizz3D [20].
- *Association with Source Code*. The architectural visualization should be easy to relate to the underlying software artifact [36]. Therefore, we have extended Vizz3D with the capability to interactively view the source code in association with any node of the architectural view. This feature associates architecture and source levels, *cf.* Section 2.
- *Metaphors*. Many graphic designs lack an intuitive interpretation, requiring that a user be trained to understand them. We can alleviate this problem by selecting metaphors that are familiar to the user, such as those found in the real world. Tangible metaphors improve understanding and social interaction [8]. We have chosen and implemented the city metaphor [14, 24], *cf.* Section 4.1, to increase program understandability.
- *Predictability*. Two different runs of a layout algorithm, involving the same graphs, should not lead to radically different visual representations. This property is also referred to as "preserving the mental map" of the user [23]. While force-directed layouts are usually not predictable, hierarchical algorithms improve the situation, but they do not scale particularly well. For improved predictability and scalability, we have implemented a combination of force-directed and hierachical layout within our tool, *cf.* Section 4.2.

The items above do not constitute an all-inclusive list of complexity reduction techniques or features a tool should support. There are several other techniques discussed in the literature [31, 36]. Some techniques were not chosen because of their minor impact. For instance, focus and context [9], in which a user focuses on a visual detail without losing the visual context, also aids program comprehension. However, as Storey, *et al.*, report in their user study, although focus and context (particularly fish-eye) views are thought to be useful, in practice they tend not to be used [32]. Moreover, it is not our primary goal to define a complete list, but rather to implement a reasonable number of techniques to support our goal to show that our single-view visualization can present all manners of architectural information.

4. Implementation: Vizz3D

Our prototype is based on Vizz3D [20, 34], a 3D information visualization system primarily developed for program visualization. Vizz3D is highly flexible and allows users to define and reassign layout algorithms and metaphors at run-time. Hence, visualizations can be configured on-line [20].

To reduce a user's cognitive load, Vizz3D has a variety of operations, such as the aggregation and filtering of nodes. In addition, users may at run-time filter all nodes and edges of certain types, thereby allowing the visualization of arbitrary combinations of the graphs defined in Section 2.1. For instance, a user may interactively select several types of edges to display; the resulting same image might then represent a Function Call graph, a Class Call graph, a File Contains graph, or all graphs simultaneously.

We have enhanced Vizz3D with the ability to view the corresponding source code when interactively selecting visual entities. In addition, to achieve predictable and consistent layouts and to provide an intuitive representation of our program model, we have configured our own layout and metaphor for Vizz3D. (Sections 4.1–4.2, below).

Our prototype works on real C and C++ applications [33]. To build our implementation, we have used, combined, and enhanced the following reverse engineering tools: ROSE [29], a C/C++ source-to-source code transformation tool used for program retrieval; ROSEVA, a program analyzer developed to create and merge the various graphs described above; VizzAnalyzer [35], a framework for reverse engineering tool integration, allowing us the rapid integration of various program analysis and visualization tools; and for language interoperability between C/C++ (ROSE and ROSEVA) and Java (VizzAnalyzer), we use Babel [2].

4.1. An intuitive city metaphor

Metaphors help users to better understand complex situations. For our architectural program visualization, we have chosen a city metaphor [14, 24]. Our metaphor comprises the following elements, *cf.* Figure 1[2]. *Buildings* represent functions. Building *textures* represent source code metrics; for instance, the (tall) blue colored buildings in Figure 1 indicate a $LOC > 200$. Similarly, other textures in this image indicate other thresholds. *Cities* (blue plates) indicate source files. *Pillars* (C++ only), shown perpendicular to cities in Figure 2, represent class definitions. The pillars are the foundation for *water towers* (spheres), representing header files. In this way, a header file can have multiple class definitions. Finally, (green) *landscapes*, which carry cities and water towers, represent directories. The water and sky in Figure 1 and 2 are optional aesthetic decorations. Note that the above is an example of one visual configuration; to determine the most effective configuration, cognitive studies must be conducted. Vizz3D merely allows different user defined mappings (from program model entities to visual entities). For more information see [20].

4.2. Computing consistent layouts

Our layout algorithm extends the force-directed algorithm of Huang and Eades [11] by combining it with a hierarchical algorithm. Because force-directed layout algorithms can in general be rather slow, we calculate the forces for coarse-grained nodes first, *i.e.*, for header files, source files, and directories. Figure 3 a) shows the layout of 36 files. The edges represent *Directory Contains* relationships. Files belonging to the same directory, representing components by design, are laid out close together. The size of a source file reflects the number of functions defined within it. Buildings are laid out compactly next to each other, *i.e.*, they are not part of the force-directed layout. The second step is to apply the landscapes (directory structure) for the cities (files), *cf.* Figure 3 b). The height of the landscape (y-axis) represents the depth of the directory path. Therefore, cities or files in a deeper directory structure are represented on a higher hierarchical level. As a result of the force-directed layout, directories containing subdirectories are laid out more closely. As subdirectories are on a higher hierarchical level, subdirectories produce “visual mountains”, similar to 3D tree-maps [5], where directory structures are represented to the user in a hierarchical way.

Our layout provides predictable visualizations (see Section 3) in that different runs of the system produce fairly similar landscapes. Together with our 3D city metaphor, familiar entities can quickly be rediscovered. The current layout predictability can even be improved if the initial random seed of our layout is kept constant across multiple runs.

[2]Directed edges are color interpolated from a light to a dark color.

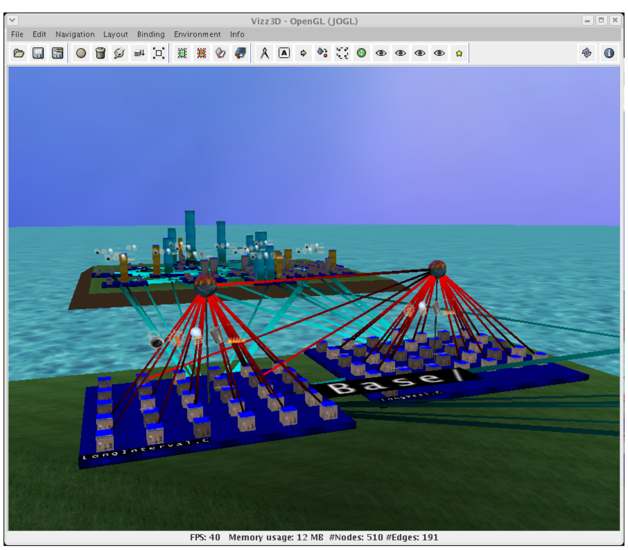


Figure 2. Architectural Visualization.

4.3. Representing analysis results

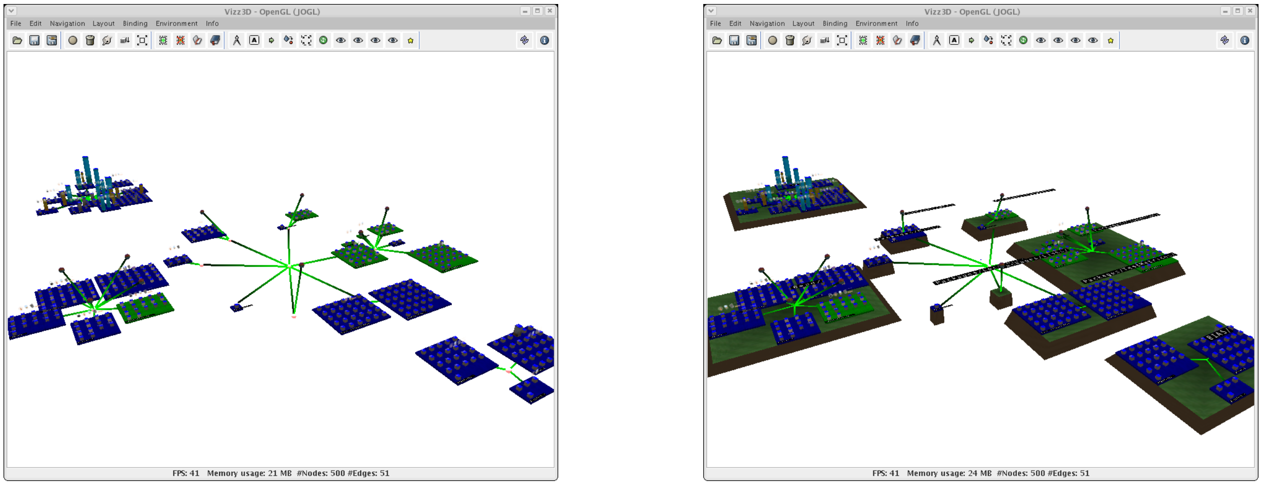
Our single-view restriction means that all analysis results are displayed in one view, raising immediate concerns about information overload. To overcome this problem, we display metrics either with 2D *icons* [27] within our 3D scene (*i.e.*, 2D icons are shown on top of each building and above each city to convey information), or we use visual properties such as height, width, depth, and texture, among others. Analysis results may also be represented by color; this means, however, that only one analysis at a time can be represented. For instance, all strongly connected components are colored red (the top roof of a building).

5. Application Examples

We envision a variety of scenarios in which our single-view architectural visualization would be particularly useful. We outline several such scenarios in this section, emphasizing the ways in which our approach can facilitate collaboration and discussion among stakeholders.

5.1. Quality Assessment

Project managers and developers can easily assess various aspects of a software system’s quality in our one-view vi-



(a) (b)

Figure 3. (a) layout algorithm between files (b) adding the directory structure

sualization. For instance, consider Figure 1, which combines a *File Call-*, *Class Inheritance-*, *Class Contains-*, *File Contains-* and *Directory Contains* graph. In addition, this figure shows software complexity information (fire texture), global variables (globe icon), oversized functions (blue buildings), unsafe functions (lock icon), and run-time information (the width and depth represents run-time information).

By interactively examining Figure 1, developers can communicate concerns, such as global variables, new-delete deviations, or unsafe functions, to managers, and help the managers understand where and why additional time must be spent to improve those components. Similarly, complex areas of the system, as indicated by cyclomatic or arithmetic complexity, can be easily illustrated via the common metaphor. Developers of all skill levels can use this kind of visualization to detect and communicate concerns, and they may do so over a variety of communication media, such as teleconferencing or virtual reality displays.

We anticipate that single-view collaboration will help stakeholders detect code quality problems earlier, make meetings more effective, and reduce project costs in general.

5.2. Componentization

Once a software system becomes large, it is essential to decomponentize it, *i.e.*, to split it into smaller reusable components that eventually can be maintained or sold separately. A single-view architectural visualization may again help to communicate componentization issues and costs among management, developers, and re-engineers, using analyses such as pattern matching, class membership, and SCC.

For example, consider the analysis of class membership violations. As described in Section 2.2, a class membership analysis determines fragmented member functions, *i.e.*, member functions declared in the same C++ class (usually header file) but defined in different source files. Suppose a file represents a component. From a reusability perspective, a "good" coding style might prefer that all member functions of one class be implemented in the same source file. A re-engineer might write a simple analysis to check this condition and print the results as text to the screen.

Though this screen dump provides useful information, this information might be of limited use if the original developers are not present to guide changes. An architectural visualization, on the other hand, might supply some of the developers' expertise through additional metrics visualized at the same time. For instance, consider Figure 4, where the class membership relationship is indicated by assigning the same color to each member function of a class. In Figure 4, the directory "/wpp3D/" contains four source files and one header file. The header file contains one class (pillar) that contains eight member functions, indicated by their red coloration. We see that one member function is defined in a different source file, *i.e.*, a fragmentation is present. However, due to the additional LOC information, even a non-expert could conclude that the exceptional member function has been refactored due to its size.

Our single-view architectural visualization helps us to understand the specific analysis problem at hand. Moreover, it shows the entire context of all additional entities and relationships involved. For example, one can determine whether the exceptional method described above occurs in

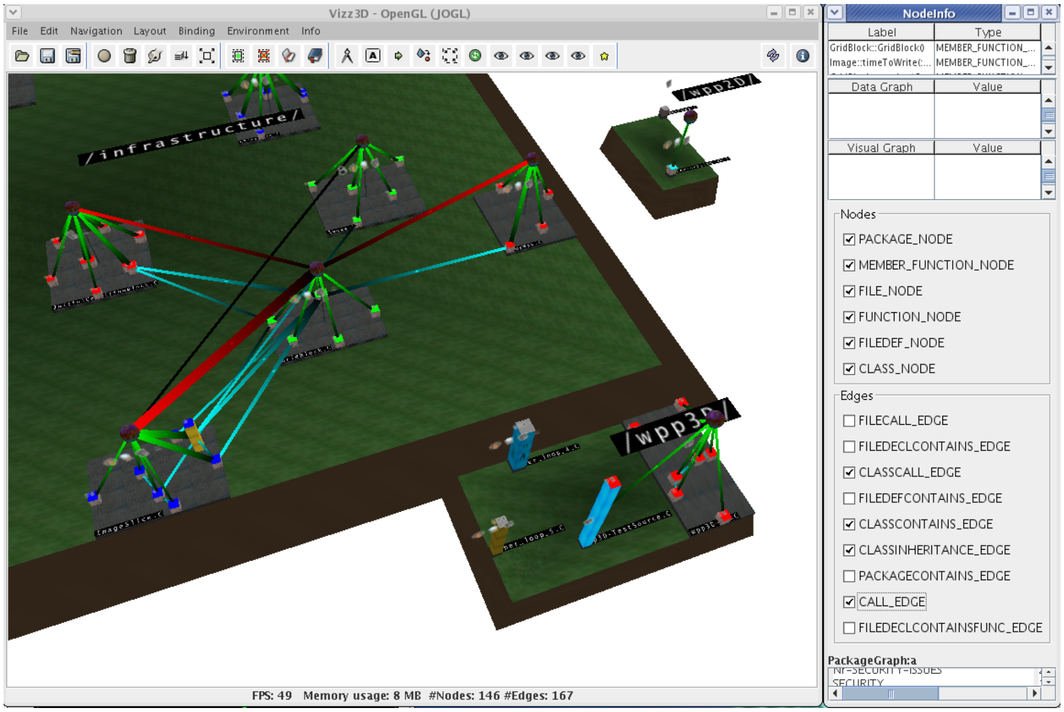


Figure 4. Class Membership Visualization.

the same directory as the other methods in its class or not. Furthermore, call edges may be activated turning the Class Contains graph into a merge of the Class Contains and Function Call graphs. The additional information may help to investigate the purpose of certain functions in the context of the whole program.

Another example is the detection of strongly connected components. Again, if only printed to the screen as a list, the context might be lost. For instance, Figure 5 shows an architectural visualization of a file call graph. The files themselves are color coded; a green color indicates a cycle. Seeing the analysis result in the context of the directory structure, one could assume that all files in the cycle belong to the lower right directory. There are however two exceptions. It is now up to the developer or re-engineer to determine whether the exceptional files should be moved.

6. Comparison to Related Work

There is a large literature on existing architectural visualization tools. We can classify these approaches according to the number of aspects they visualize using how many views.

- *Single-aspect, single-view*. Illustrate only one aspect of a software architecture, *e.g.*, CrocoCosmos [18], sv3D [21].
- *Multi-aspect, single-view*. Our work is an example of this class. Another example is SHriMP [31], allowing the interactive, single-view navigation between architecture and source code. SHriMP is a great tool for architectural browsing and understanding of source code. However, SHriMP was not developed with stakeholder communication in mind; it does not support a natural metaphor or the ability to add multiple analysis and metric results within the view.
- *Multi-aspect, multi-view*. Illustrate multiple views of the architecture level, *e.g.*, CodeCrawler [17], BLOOM [30][3].

Other approaches, such as ArgoUML [1], exist. However, these applications visualize not just architectural level information, but rather a combination of architecture and middle level. Further recommendations and cognitive studies on (architectural) multi-views can be found in [10, 16, 32].

We believe that multiple views are important for detecting and answering many problems, especially when depicting low-level analysis results in middle-level visualizations. In such cases, it is impossible to view all the possible aspects of software in one image. However, when illustrating the architecture of a software system to various stakeholders, we believe that showing the different architectural aspects

[3]Note that some architecture level tools might also be used for other purposes, *e.g.*, CodeCrawler supports also class blueprints and therefore could as well qualify as a multi-level, multi-view visualization tool.

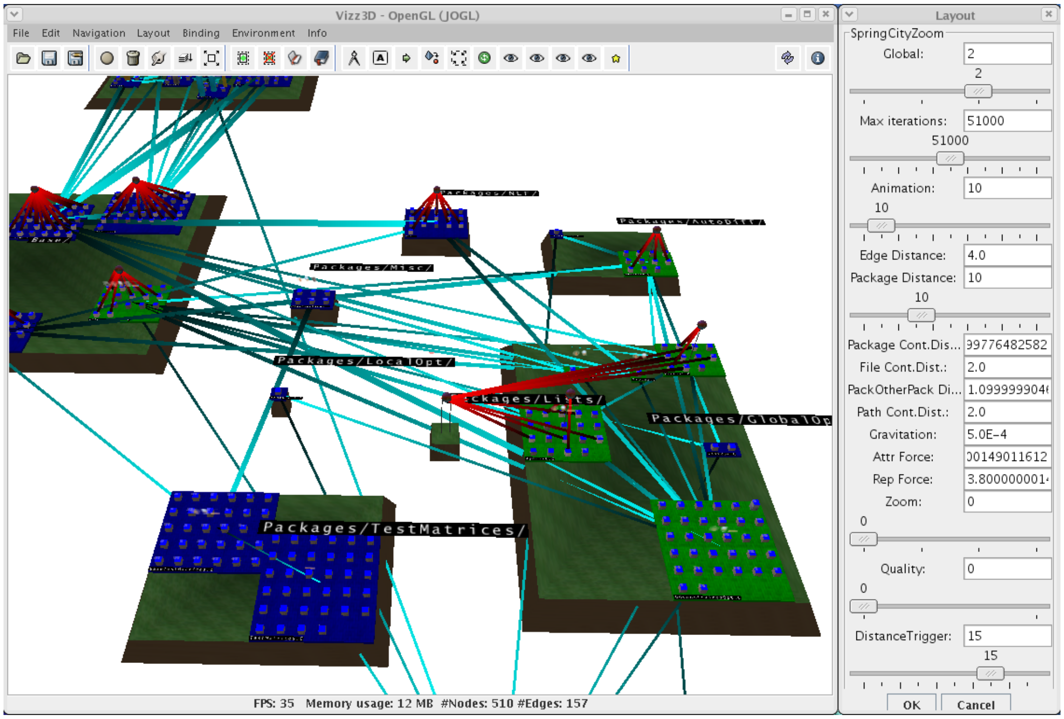


Figure 5. Strongly Connected Components Visualization.

in the same view with the same metaphor and layout is desirable. In this paper, we have suggested how it is possible to merge and filter the essential information for different stakeholders. This helps stakeholders get precise answers to their questions and, moreover, enables them to communicate the answers among themselves and others.

7. Conclusion and Future Work

Our tool is a proof-of-concept design for a multi-aspect, architecture-level, single-view visualizer. This paper reviews our philosophy and implementation, with particular emphasis on how different stakeholders can use such visualizations as an aid in collaborative understanding, development, maintenance, and re-engineering of a large-scale software system. The key features of our approach are the use of an intuitive city metaphor for representing the structure of the system architecture, a single view for visualizing multiple aspects and analysis results, and powerful filtering and focusing techniques built into the tool implementation.

We have integrated and extended a variety of analysis and visualization tools, allowing us in future work to evaluate the trade-offs of using a unified single-view for architecture-level program visualization and communication. In preparation for such future experiments, we have classified and implemented program analyses, identified and implemented complexity reduction techniques for large scale visualizations, and implemented a layout algorithm and metaphor in our visualization tool, Vizz3D.

8. Acknowledgments

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