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# Sensorial software evolution comprehension

Subtitle: Reinventing the World

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I certify that except where due acknowledgement has been given, the work presented in this thesis is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; and the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program.

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Gianlorenzo Occhipinti  
Lugano, Yesterday July 2022



*To my beloved*



Someone said ...

Someone



# Abstract

The comprehension of software evolution is essential for the understandability and maintainability of systems. However, the sheer quantity and complexity of the information generated during systems development make the comprehension process challenging. We present an approach, based on the concept of synesthesia (the production of a sense impression relating to one sense by stimulation of another sense), which represents the evolutionary process through an interactive visual depiction of the evolving software artifacts complemented by an auditive portrayal of the evolution. The approach is exemplified in SYN, a web application, which enables sensorial software evolution comprehension. We applied SYN on real-life systems and presented several insights and reflections.



# Acknowledgements

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# Chapter 1

## Introduction

In 1971 Dijkstra, made an analogy between computer programming an art. It stated that is not important to learn how to compose a software, but instead, it is important to develop its own style and what will be their implications.

### Software Understanding

- Section [Challenges of software understanding] - Section [Challenges of software maintainability] - Section [Software comprehension] - Section [Our approach] We present an approach, based on the concept of synesthesia (the production of a sense impression relating to one sense by stimulation of another sense), which represents the evolutionary process through an interactive visual depiction of the evolving software artifacts complemented by an auditive portrayal of the evolution.



# Chapter 2

## State of the art

### 2.1 Software visualization

Software maintenance and evolution are essential parts of the software development lifecycle. Both require that developers deeply understand their system. Mayrhofer and Vans defined *program comprehension* as a process that "knowledge to acquire new knowledge" [40]. Generally, programmers possess two types of knowledge: general knowledge and software-specific knowledge. Software comprehension aims to increase this specific knowledge of the system, and, it can leverage some software visualization techniques for this purpose. Software visualization supports the understanding of software systems by visually presenting various information about them, e.g., their architecture, source code, or behavior. Stasko et al.[13] conducted a study in 1998 that shows how visualization arguments human memory since it works as external cognitive aid and thus, improves thinking and analysis capabilities.

The earliest software visualization techniques in the literature used 2D diagrams. For example, Haibt, the first to use them in 1959, provided a graphical outline of a program and its behavior with flowcharts [14]. As shown in Figure 2.1, they were 2D diagrams that described the execution of a program. He wrapped each statement in a box, representing the control flow with arrows.

Ten years later, Knuth also confirmed the effectiveness of flowcharts [22]. He evidenced that programs, around that time, were affected by a lack of readability. Therefore, he introduced a tool to generate visualizations from the software documentation automatically.

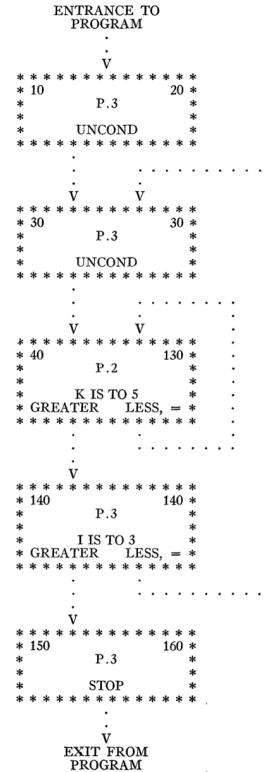


Figure 2.1. Flowchart presented by Haibt in 1959

Nassi and Schneiderman[29], in 1973, introduced the Nassi–Shneiderman diagram (NSD), able to represent the structure of a program. The diagram was divided into multiple sub-block, each with a given semantic based on its shape and position.

The 80s registered two main directions of software visualization. The first was the source code presentation. For example, Hueras and Ledgard [15] then Waters [41] developed techniques to format the source code with a prettyprinter. The second direction was the program behavior, used mainly for educational purposes. One of that period's most prominent visualization systems was Balsa-II [4].

Balsa-II was a visualization system that, through animations, displayed the execution of an algorithm. Programmers were able to customize the view and the control execution of the algorithm, to understand them with a modest amount of effort. The program was domain-independent, and users could use it with any algorithm.

Around the end of the 80s, Müller et al. [28] released Rigi, a tool used to visualize large programs. It exploited the graph model, augmented with abstraction mechanisms, to represent systems components and relationships.

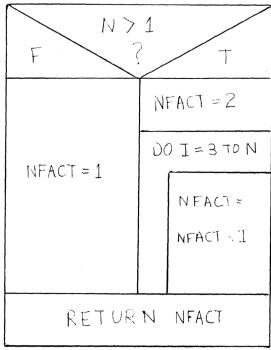


Figure 2.2. NSD of the factorial function.

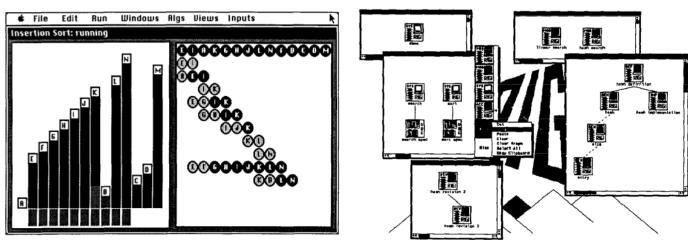


Figure 2.3. Balsa-II

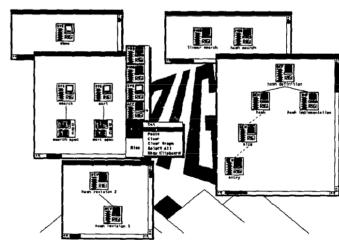


Figure 2.4. Rigi

The 1990s recorded more interest in the field of software visualization. In 1992, Erik et al. introduced a new technique to visualize line-oriented statistics [11]. It was embodied in Seesoft, a software visualization system to analyze and visualize up to 50,000 lines of code simultaneously. On their visualization, each line was mapped to a thin row. Each row was associated with a color that described a statistic of interest.

One year later, De Pauw et al. [9] introduced Jinsight, a tool able to provide animated views of object-oriented systems' behavior.

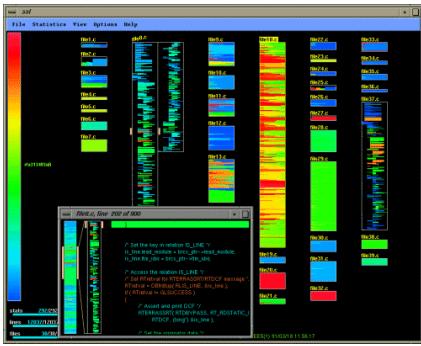


Figure 2.5. Seesoft

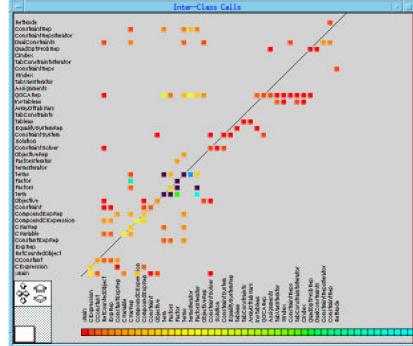


Figure 2.6. Jinsight

That period was favorable also for experimenting with novel research directions for visualization, such as 3D visualization and Virtual Reality.

In 1998, Chuah and Erick [5] proposed three different techniques to visualize project data. They exploited the concept of glyphs, a graphical object that represents data through visual parameters. The first technique was the Timewhell glyph, used to visualize time-oriented information (number of lines of code, number of errors, number of added lines). The second technique was the 3D wheel glyph; it encoded the same attributes of the time wheel, and additionally, it used the height to encode time. Infobug glyph was the last technique, where each glyph was composed of four parts, each representing essential data of the system, such as time, code size, and the number of added, deleted, or modified code lines.

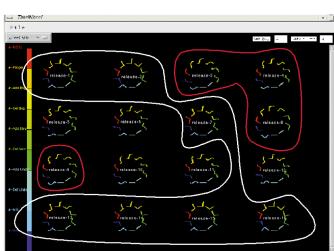


Figure 2.7. Timewhell

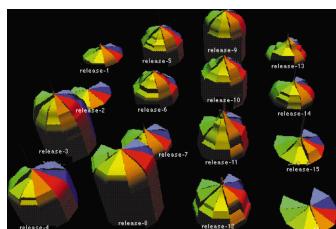


Figure 2.8. 3D wheel

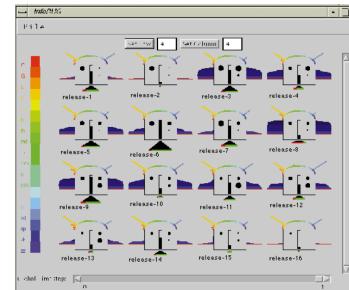


Figure 2.9. Infobug

Also in 1998, Young and Munro [43] explored representations of software for program comprehension in VR.

Finally, in 1999, Jacobson et al. [16] introduced what we now know as de facto the standard language to visualize the design of a system: UML.

Before the beginning of the 21st century, thanks to the spread of version control systems and the open-source movement, visualizing the evolution of a system became a more feasible activity since there was more publicly accessible system information. As a result, many researchers focused their work on software evolution visualization.

Lanza [24] introduced the concept of the Evolution Matrix. It was a way to visualize the evolution of software without dealing with a large amount of complex data. Furthermore, this approach was agnostic to any particular programming language. The Evolution Matrix aimed to display the evolution of classes in object-oriented software systems. Each column represented a version of the software; each row represented a different version of the same class. Cells were filled with boxes whose size depended on evolutionary measurements. The shape of the matrix could also be used to infer various evolutionary patterns.

	Version 1	Version 2	Version 3	Version 4
Class A				
Class B				
Class C				
Class D				
...				

→ TIME →

Figure 2.10. A schematic display of the Evolution Matrix

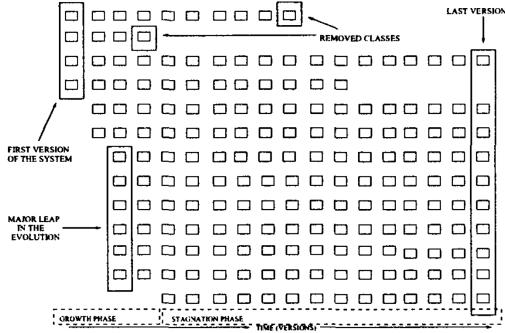


Figure 2.11. Some characteristics of the Evolution Matrix

Taylor and Munro [37], demonstrated that it was possible to use the data contained in a version control repository to visualize the evolution of a system. They developed Revision Tower, a tool that showed change information at the file level. Pinzger et al. [30] visualized the evolution of a software system through Kivat diagrams. RelVis, their tool, was able to depict a multivariate visualization of the evolution of a system.

During the same year, Ratzinger et al. presented EvoLens [31], a visualization approach and tool to explore evolutionary data through structural and temporal views.

Langelier et al. [23] investigated the interpretation of a city metaphor [21] to add a new level of knowledge to the visual analysis.

D'Ambros and Lanza [7] introduced the concept of Discrete-Time Figure concept. It was a visualization technique that embedded both historical and structural data in a simple figure. Their approach depicted relationships between the histories of a system and bugs. They also presented the Evolution Radar [8], a novel approach to visualize module-level and file-level logical coupling information.

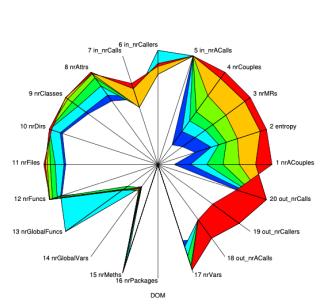


Figure 2.12. RelVis

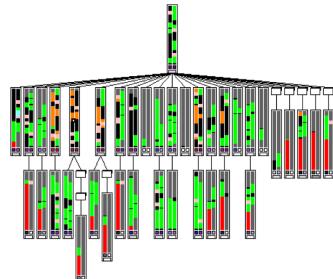


Figure 2.13. Tree of Discrete Time Figures

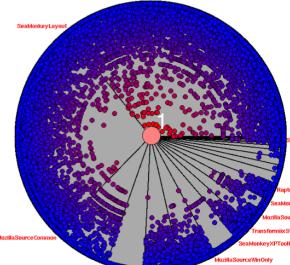


Figure 2.14. Evolution Radar

Steinbrückner and Lewerentz [36] described a three-staged visualization approach to visualize large software systems. Their visualization was supported by a tool called Evo-Streets. Each stage of their approach was responsible for representing a different aspect of the system with the city metaphor.

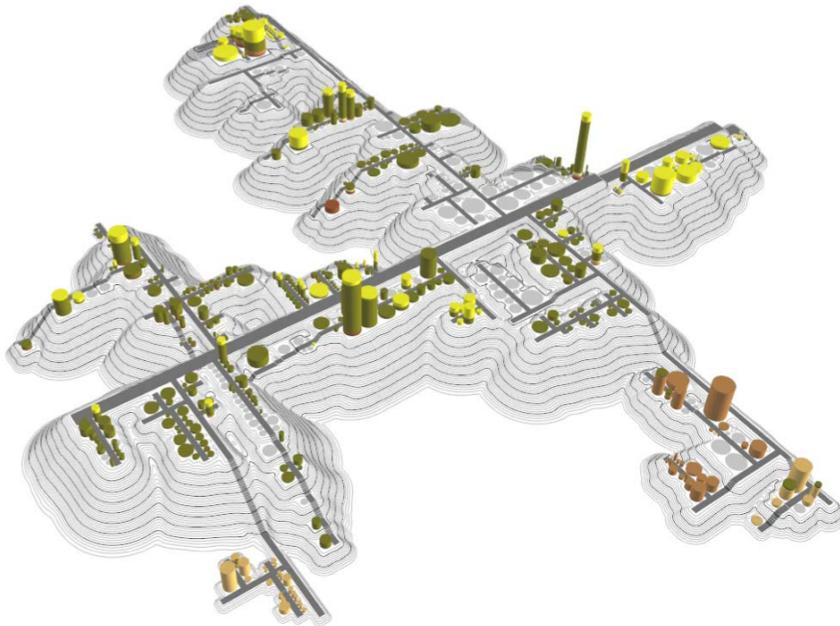


Figure 2.15. Evo-Streets

Wettel revised the city metaphor to represent metrics meaningfully [42]. In his thesis, he represented packages as districts and classes as buildings. The metaphor was used for various purposes, e.g., reverse engineering, program comprehension, software evolution, or software quality analysis. He claimed that the city metaphor brought visual and layout limitations; for example, not all visualization techniques fit well. Under those circumstances, he preferred simplicity over the accuracy, so he obtained a simple visual language that facilitated data comprehension. His approach was implemented as a software visualization tool called CodeCity.

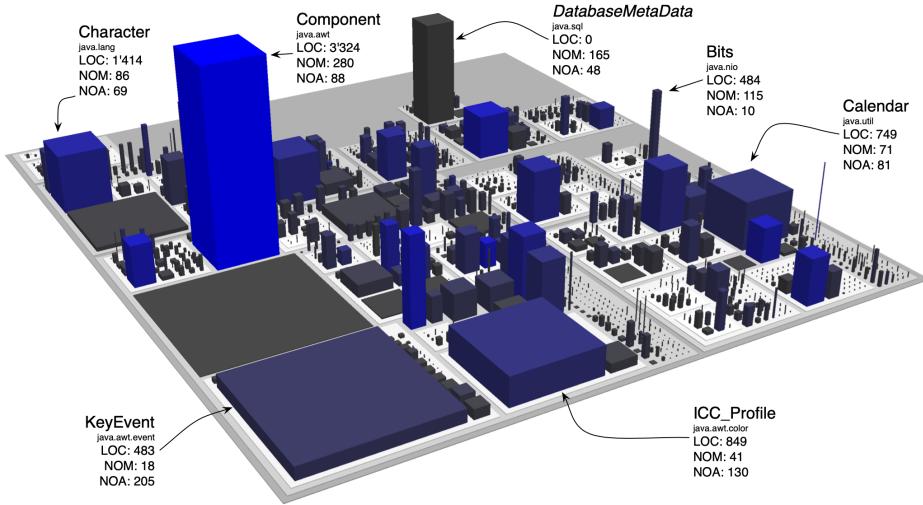


Figure 2.16. CodeCity

Ens et al. [12] applied visual analytics methods to software repositories. His approach helped users comprehend co-evolution information by visualizing how source and test files were developed together.

Kapec et al. [19] proposed a graph analysis approach with augmented reality. They made a prototype of a tool that provided a graph-based visualization of software, and then they studied some interaction methods to control it with augmented reality.

Schneider et al. [33] presented a tool, CuboidMatrix, that employed a space-time cube metaphor to visualize a software system. A space-time cube is a well-known 3D representation of an evolving dynamic graph.

Merino et al. [27] aimed to augment software visualization with gamification. They introduced CityVR, a tool that displays a software system through the city metaphor with a 3D environment. Working with virtual reality, they scaled the city visualization to the physically available space in the room. Therefore, developers needed to walk to navigate the system.

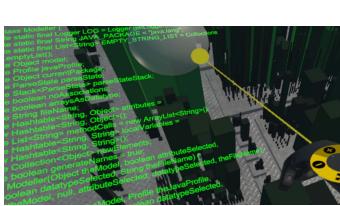


Figure 2.17. CityVR

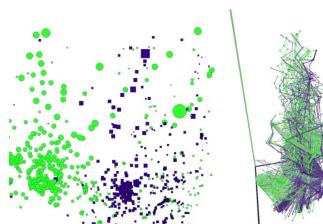


Figure 2.18. ChronoTwigger

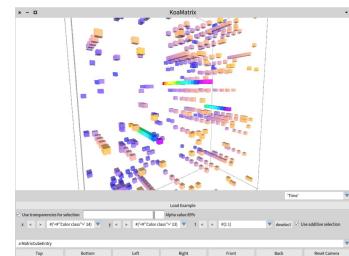


Figure 2.19. CuboidMatrix

Khaloo et al. [20] revised the idea of gamification with a 3D park-like environment. They

mapped each class in the codebase with a facility. The wall structure depended on constituent parts of the class e.g., methods and signatures.

Finally, we mention Alexandru et al., who proposed a method to visualize software structure and evolution, with reduced accuracy and a fine-grained highlighting of changes in individual components [2].

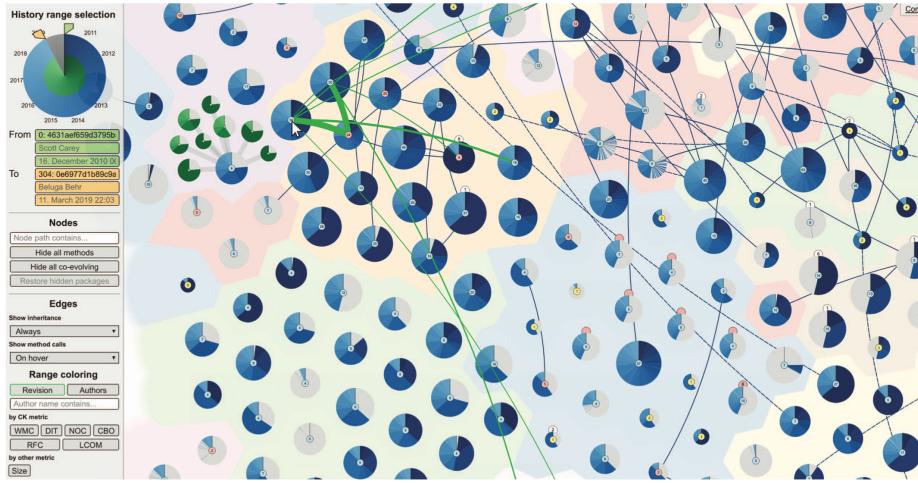


Figure 2.20. Evo-Clock

## 2.2 Analysis of software evolution

Software repositories contain historical data about the evolution of a software system. Thanks to the spread of the git protocol, and consequently of GitHub, Mining Software Repositories (MSR) has become a popular research field.

D'Ambros et al. in [1] presented several analysis and visualization techniques to understand software evolution. They developed an approach based on a Release History Database (RHDB). In essence, it is a database that stores historical information about source code and bugs. The strength of RHDB was the association between historical versions of files and bugs. Having this information stored on a database, they were able to run some evolution analysis to obtain information such as how many developers worked on a file to fix a bug or how was the effort to fix it.

Finally, they concluded by evidencing two main challenges in MSR:

- Technical challenge: repositories contain a sheer amount of data, and this poses scalability problems.
- Conceptual challenge: how to do something meaningful with the collected data. Most of the approaches present in literature to visualize software evolution have unanswered questions about the effectiveness of the comprehension.

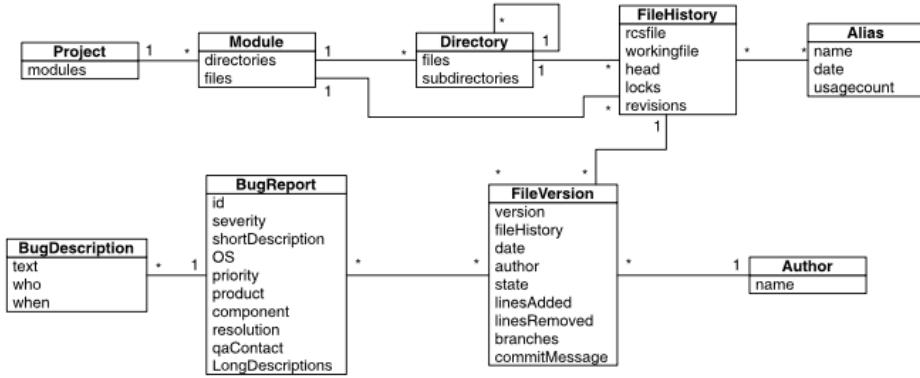


Figure 2.21. RHDB

In 2022, the number of GitHub repositories lays around 200 million. Even if it seems a promising source of data, Kalliamvakou et al. raised some issues with its mining. [18] For example, they evidenced that a repository does not always match with a project. A reason for this can be found in the fact that most repositories had had very few commits before becoming inactive. When they made their research, over 70 percent of the GitHub projects were personal, and some of them weren't used for software development. Finally, the last perils that they raise, were related to GitHub features that are not properly used by software developers. They considered only projects with a good balance between the number of commits, the number of pull requests and the number of contributors to find actively developed repositories.

Spadini, Aniche and Bacchelli [35]. They developed a Python framework called PyDriller, enabling users to mine software repositories. Their tool can be used to extract information about the evolution of a software system from any git repository.

We also mention the work done by Salis and Spinellis [32]. They introduced RepoFS, a tool that allows navigating a git repository as a file system. Their approach sees commits, branches, and tags as a separate directory tree. Figure 2.22 shows an example of a repository data structure.

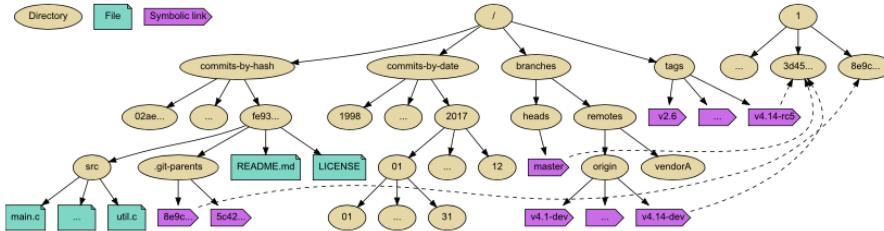


Figure 2.22. RepoFS

Clem and Thomson [6], members of the semantic code team at GitHub, built a static analyzer of repositories to implement symbolic code navigation. That feature was released on

GitHub some years ago and lets developers click on a name identifier to navigate to the definition of that entity. They were looking for a solution that would not bring them scalability problems. Moreover, they built the symbolic navigation feature around some ideas like:

- Zero configuration needed by the owner of a repository
- Incrementality of the process. There was no need to process the entire repository for every commit made by a developer. Instead, they analyzed only the files that had changed.
- Language agnosticism of the static analysis.

Working on that feature, they recognized the difficulty of scaling a static analysis like that regarding human behavior. Nevertheless, their idea was to have an agnostic static analyzer, they cannot reach this goal and they were forced to implement it for just nine programming languages.

## 2.3 Data sonification

External auditory representations of programs (known as "program auralisation") is a research field that is getting even more interest in the recent years.

Sonnenwald et al. made one of the first attempts. [34] They tried to enhance the comprehension of complex applications by playing music and special sound effects. This approach was supported by a tool called InfoSound It was mainly adopted to understand the program's behavior.

Many other researchers followed this first technique. To cite some of them, DiGiano and Baecker [10] made LogoMedia, a tool to associate non-speech audio with program events while the code is being developed. Jameson [17]] developed Sonnet, audio-enhanced monitoring and debugging tool. Alty and Vickers [39] had a similar idea. Using a structured musical framework, they could map the execution behavior of a program to locate and diagnose software errors.

Despite the usefulness of these tools, they adopted an essential kind of mapping, and thus they had a limited musical representation. Vickerts [38] evidenced the necessity of a multi-threaded environment to enhance the comprehension given by the musical representation. He proposed adopting an orchestral model of families of timbres, to enable programmers to distinguish between different activities of different threads.

The size and the complexity of systems can represent a problem for the effectiveness of a visual representation of a software system. Having a large number of visual information, observers might find it difficult to focus only on the relevant aspects. Boccuzzo and Gall [3] supported software visualization with sonification. They used audio melodies to improve navigation and comprehension of their tool, called CocoViz. Their ambient audio software exploration approach, exploited audio to intuitively describe the position of an entity in the space. Thanks to the adoption of surround sound techniques, the observers perceived the origin of an audio source so, it could adjust his navigation in the visualization. Each kind of entity played a different sound, based on mapping criteria.

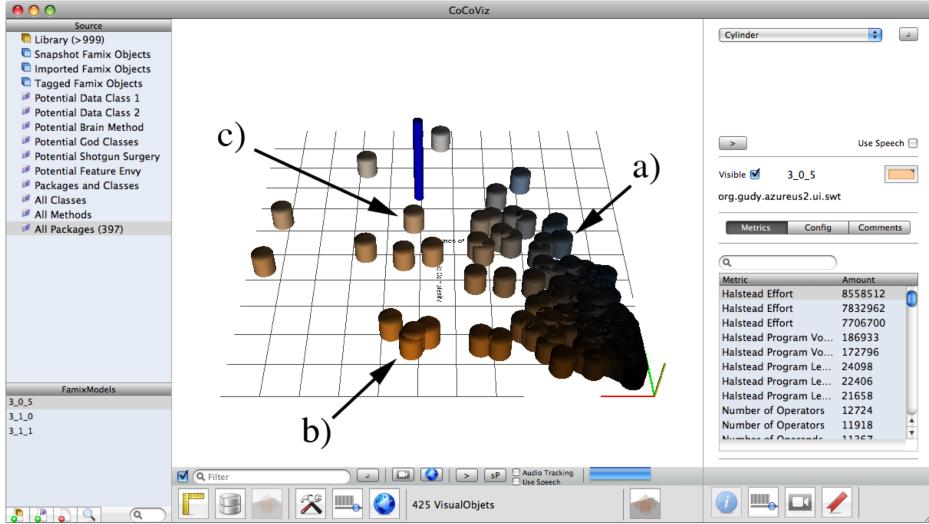


Figure 2.23. CocoViz

McIntosh et al. [26] explored the use of a parameter-based sonification, to produce a musical interpretation of the evolution of a software system. Their technique mapped musical rests to an inactive period of development and consonance and dissonance to interesting phenomena (like co-changing of components).

Finally, Mancino and Scanniello [25] presented an approach to transforming source code metrics into a musical score that can be both visualized and played.

## 2.4 Conclusion

do the same but in a different way Most of the visualization techniques used colors and shapes to enhance the strength of the comprehension. We aim to do the same but in a different way



# Chapter 3

## Approach

In this chapter we will present an approach that produce a visual and auditive depiction of the evolution of a system. Our approach consists of two parts: In the first part we modelled the evolution of the software artifacts, and we engineered a tool that implement it. In the second part, we used the concept of synesthesia (the production of a sense impression relating to one sense by stimulation of another sense) to enhance the effectiveness of the visualization.

### 3.1 Evolutionary model

Analyzing the evolution of a systems requires to consider numerous aspects. In our approach we focus on systems that resides on git repositories. We made this choice because git is the most common repository management system and it also track all the changes made to the system. As a consequence we can use it to reconstruct the history of a system.

In our approach, we model the evolution of repository files, therefore we model its history. To do that, we considered all the information that can be extracted from a git repository: files and commits.

The git protocol is responsible for tracking the changes made to the system. To do that, every time we made a commit, it stores only a list of files that have been modified. Every commit is represented by a tree of hashes, each one representing a file.

Git has the possibility to inspect every commit of a repository by using the command `git checkout`. In this way, we can navigate through the history of a repository, to track all the files, their changes and their metrics.

A commit operation contains also other meta-information such as the author, the date and the message.

We built our model on the top of the Lanza's evolution matrix [24] with some adoption to work well with the git protocol. We represented the history of a repository as a matrix with the following properties:

- Each column of the matrix represent a commit, a version of the software.
- Each row of the matrix represent a file, named FileHistory.

	C1	C2	C3	C4	C5	C6	C7
A	A						
B	A	M		RenJ			
B1				Proj	M		
C		A	M	H			
D		A	M	DI	X		
E			A	M			
B				A	M	H	

Figure 3.1. Evolution matrix of a repository

- Each cell of the matrix represent the different versions of a file. Empty cells represent a file that has not been modified.
- A file can have multiple names (tolerant to renaming and moving operations).
- Files are sorted by addition time, on the top we will have all the files that were added in the first commit of the repository.

For now on, we will use the following notation:

- A **FileHistory** represents a row of the matrix.
- A **ProjectVersion** represents a column of the matrix.
- A **FileVersion** represents a cell of the matrix.

Therefore, a FileHisory represents the history of an entity of our system. The name of the file is not a concern for us, until a file is not deleted it will always represent the same entity.

Git is smart enough to recognize five types of changes:

- **Add:** a file is added in the repository.
- **Delete:** a file is deleted in the repository.
- **Modify:** a file is modified in the repository.
- **Rename:** a file is renamed in the repository.
- **Move:** a file is moved in the repository.

And we will use them in our model to identify the action associated to aFileVersion. Figure 3.1 present a schematic evolution matrix of a repository with seven versions. As we can see, in the first ProjectVersion, there were added two files, A and B. In the second revision B was modified, and in the third revision C and D were added. The fourth revision recorded a rename

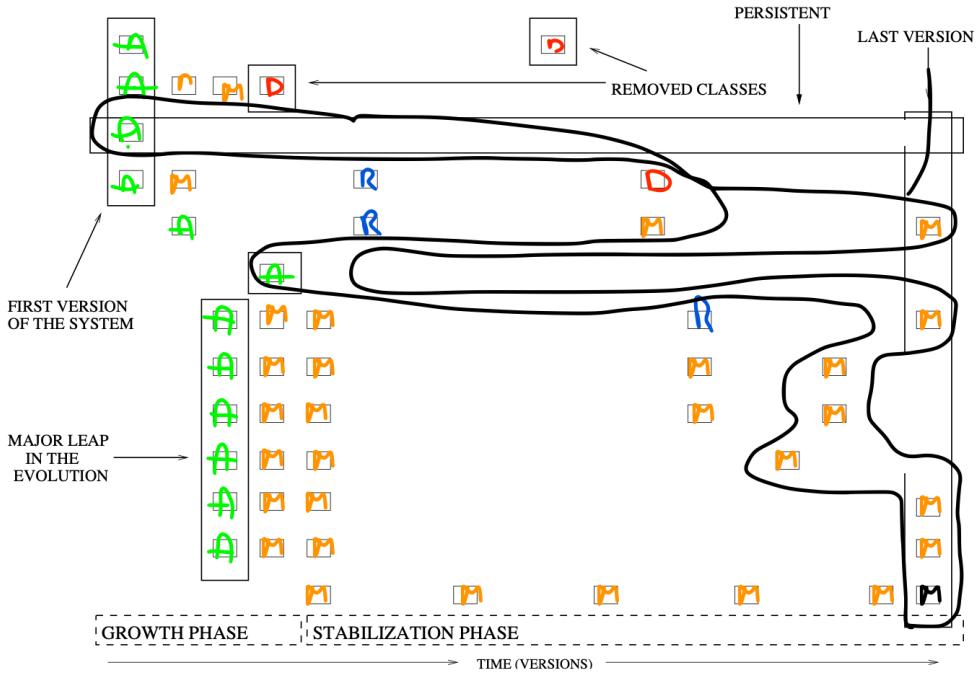


Figure 3.2. Evolution matrix of a repository

of B to B1. It's important to notice that B and B1 represent the same entity, therefore they are represented by the same FileHistory.

Based on our aim, we can read this matrix as follows:

- **by rows**, if we are interested on the history of a particular entity of our system. For example, the FileHistory represented by the first third row in figure 3.1, represents the history of the file D. The file D was added in the third ProjectVersion (so the third commit), modified in the fourth and fifth ProjectVersion, and then deleted in the sixth ProjectVersion. The figure 3.1 is also a good example to understand why we cannot rely on the name of the file to identify the entity. We can notice that the file B represented by the second FileHistory, was added on the first version and then renamed on the fourth from B to B1. Then, in the fifth version, a new file called B was added. Nonetheless the name of the files are the same, they must represent two different entity. We would have had the same result, even if the file B was been added in the version four.
- **by columns**, if we are interested on which entities were updated on each ProjectVersion. For example, on the first ProjectVersion we have added the first and the second entity. On the fourth ProjectVersion we have renamed the second entity, we have modified both the third and the fourth, and finally we have added the fifth entity.

Figure 3.2 shows an example of how to recover evolution information from the matrix. As we have seen, each version doesn't represent a snapshot of the system. Instead it represents only the difference in term of changes made to the previous version. Given that, to recover a

snapshot of a specific version, we need to consider the last changes made before that specific version. Under those circumstances, for each FileHistory, we need to go back in time until we find the leftmost change. Of course, if the leftmost change was a delete, we have to ignore the released FileHistory. In contrast, if we have to display the evolution of a snapshot, we need to consider only the changes made after that snapshot. So, each time we need to display a ProjectVersion, we have to take all its FileVersions and merge them with the current state of the snapshot.

### 3.2 Visualization model

Software systems are hard to understand due to the complexity and the sheer size of the data to be analyzed. Our approach aims to make the analysis of a system easier and more for the engineers, through the exploitation of the human senses. This is the reason why we have chosen to leverage on the phenomenon of the Synesthesia. The phenomenon of the synesthesia occurs when a stimulation of a sense or a cognitive pathway leads to the involuntarily stimulation of another sense or a cognitive pathway. We experience synesthesia when two or more things are perceived as the same. For example, synesthetic people might associate the red color with the letter D or the green color with the letter A. There are many forms of synesthesia, each one representing a different type of perception, such as visual forms, auditory, tactile, etc.

In our approach we use the following visual aspects to trigger involuntarily associations:

- **Color:** we use the color of the entity to describe the last action made on that entity.
- **Shape:** we use the shape of the entity to describe the type of the entity. For example, a java file could be represented by a cube whereas a binary file could be represented by a sphere.
- **Height:** we use the height of the entity to describe the value of a representative metric, used to compare entities.

Entities are displayed with an outward spiral layout to emphasize their order on the evolution matrix.

There are several ways to traverse the history of a repository. The visualization needs to start from the first moment and then go forward until the end. The question is, how we should go forward in time? We came up with two strategies:

- We can display n version at time, so we are traversing the history as it was written. A limitation of this approach is that we lose the concept of time. We cannot have any idea about how much time was passed between two commit, thus we cannot distinguish active development phases from unactive development phases.
- We can group version by their timestamp. So, all the commit made in the same time period, will be displayed at the same time. This strategy works very well if we need to comprehend how the system evolved and at which speed in time.

We concretized our strategies with the concept of **moment**. A moment is a group of version that will be displayed at the same time.

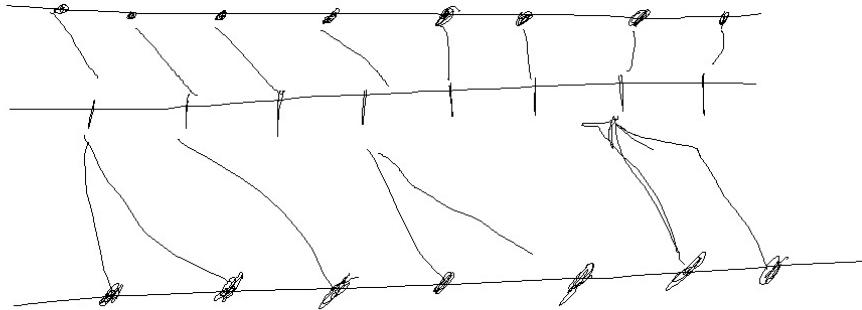


Figure 3.3. Example of two different strategies to identify moments. On the first strategy, we mapped one commit with one moment, so the total number of moments will be equals to the total number of commit. Alternatively, on the second strategy, we created a moment every day. As a result, we have some moments with many commits, and some without anyone. With this strategy, the number of moments will be the same as the number of days that have passed between the first and the last commit.

Figure 3.3 highlights the difference between the two strategies mentioned above.

## Color

The color of the entity should recall the last action made on that entity. To achieve this purpose, we used the color association described in figure 3.4. Nonetheless each person has its own perception, we can not assume that this color will work in the same way for all the people. To remedy this issue, users can customize the color palette as they wish.

Moreover, we decided to put another information on the color of the entity: the **aging**. We define the aging of an entity as the number of moments since the last modification of that entity happened. To do that, we mapped the age of an entity with the darkness of its color. As a result, older entities will be displayed with a darker color. In this way, users can immediately recognize the last action and the amount of time passed since the entity was modified.

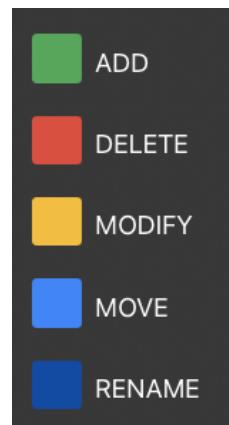


Figure 3.4. Color association

### Shape

The shape of the entity defines the type of the entity itself. It should be something fully customizable by the user, so it can chose on which entity he can focus on.

### Height

The height of an entity should represent the value of a metric.

## 3.3 Auditive model

# Chapter 4

## Implementation

This chapter details sensorial SYN, a tool that implements the software evolution comprehension approach defined in chapter X.

### 4.1 Platform overview

SYN is a platform tools that allows developers to have a visual and auditive depiction of an evolving system. This section aims to describe the tools and modules that are part of SYN.

#### 4.1.1 SYN CLI

SYN CLI is a command line interface that allows developers to interact with SYN. It gives to developers full control over the system. For example, with the command `syn project create` it is possible add a project and then, analyze it with the command `syn analyze`.

\* LIST OF AVAIL COMMANDS - APPENDIX? \*

#### 4.1.2 SYN Analyzer

SYN works with evolutionary metrics that represents the history of a system. To this aim, we developed SYN Analyzer, a Java tool on top of jGit. Having a language-agnostic implementation, it can analyze every git repository written in any programming language.

Four steps compose the analysis process:

1. The repository is cloned.
2. The source code of the HEAD revision is obtained.
3. All the files are analyzed and the metrics are obtained.
4. If the revision has a parent, the step 2 is repeated with the parent revision.

As a result, starting from the HEAD revision it will go back in time until the first revision. All the collected metric will be stored in a object, called analysis result, that can be serialized in a JavaScript Object Notation (JSON) object. We chose JSON because is a lightweight, easy to use and human readable format. It is capable to analyze large repositories, as it uses a join algorithm to merge these analysis results if they are computed in parallel.

#### 4.1.3 SYN Server

SYN Server is responsible for providing the elaborated information, given by the analysis results, in an intermediate language between the front-end (SYN Debugger) and the back-end. We chose to spin up a GraphQL web server, that uses JSON as exchange language between the front-end and the back-end. In this way, the front-end can ask exactly for the information it needs, and the back-end can send it back once they are computed.

The computation made by the back-end, is responsible to create the view that will be shown in the front-end. To do that, the server processes a *view specification*, *that must be given by the front-end, and then provides to the front-end JSON objects representing only the object that must be depicted. Although the information provided by the server are limited to the view itself, it also provides debugging information if requested.*

#### 4.1.4 SYN Debugger

*SYN Debugger is a web application that allows developers to interact with SYN. It is written with React.js, a popular JavaScript framework. The aim of this application is to have a visual depiction of the view generated by the server, plus some additional information. For example, it allows you to click on an entity and see the information that is related to it. The visualization is based on Babylon.js, a popular 3D library. SYN Debugger provides different kinds of customizations to the view, such as the shape and the colors of the entities. All these customizations are sent to the back-end server, through a view specification file.*

*The main purpose of this application is to debug the view and explore all the possible visualization combinations of a system.*

#### 4.1.5 SYN Sonic

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