CoExist: Preserving Immediate Access to Source Code and Run-time Information of Previous Development States

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Abstract

Programmers make many changes to the program to eventually find a good solution for a given task. Every little change and the respective development state can be of value in future development situations when, for example, promising ideas suddenly turn out inappropriate or the interplay of objects turns out more complex than initially expected before making changes. Programmers would benefit from tool support that provides immediate access to source code and run-time of previous development states of interest. We present IDE extensions, implemented for Squeak/Smalltalk, to preserve, retrieve, and work with this information. With such tool support, programmers can work without worries because they can rely on tools that help them with whatever their explorations will reveal. They no longer have to follow certain best practices only to avoid undesired consequences of changing code.

1. Introduction

Programmers sometimes get irritated when they realize that they have missed something and now have to face tedious work to compensate the result of former coding activities. For example:

- a promising idea unexpectedly turns out inappropriate and the programmer wants to continue exploring a previous idea, but many parts of the source code have already been modified

- the improvement to one part of the program seems to affect the overall program behavior in unexpected ways, but the programmer has difficulties to find out which of the recent changes is causing the undesired behavior

- the source code under current improvement turns out to be more complex than the programmer expected and it is unclear how the code was previously working

- recent changes turn out to represent multiple independent improvements that should be shared in separate increments

In such situations, programmers probably have learned much about their ideas, but now have to face some laborious work, which can easily be frustrating.

To avoid such problems, literature and practitioners recommend a structured and disciplined approach to programming that includes frequent use of testing and versioning tools [1, 2, 4]. For example, the programmer could have made better use of a version control system (VCS) such as Git or Subversion, and could have made more commits during the work. This would have allowed for reverting recent changes easily or recovering knowledge from a previous development state. Similarly, the programmer could have tested the code more regularly and rigorously to discover the bug directly after its introduction. So, scenarios as mentioned above are well-known, and there is a catalog of best practices addressing involved problems.

1.1 Current Limitations

Programmers can just forget to perform the recommended activities. Programmers have to regularly run tests and make meaningful commits parallel to an actual task at hand. It is particularly hard to remember performing those manual activities, when working on difficult problems that require care and focus. Although "backups" or quality assessment are typically of most importance in such difficult situations, programmers can easily forget them while being caught up in creativity.

Additionally, relying on these best practices involves trade-off. Best practices distract from the actual task and

require time. Programmers have to invest time now, to save more in future situations. But following these best practices is similarly problematic. For example, programmers typically do not run an entire test suite after every small change and wait for the feedback, as this might take several seconds to minutes. Also, making a commit after every modification and writing a useful comment of the modification easily turns out overkill. Performing these actions to an extent that guarantees against problems is hardly practical. Furthermore, a continuous distraction is also not good for getting work done. As a result, programmers have to find their own balance between getting their work done and creating a safety net for possible problems that may or may not arise.

Furthermore, applying these best practices might not always be applicable and preferable. Sometimes, programmers "know" that the code is bad and needs improvement, but they cannot see the problem clearly nor do they see a definitive solution. Literature on design methods suggests that externalizing ideas supports the exploration of the problem and possible solutions. For example, creating prototypes help pursue a line of thought and discover unforeseen implications [6, 10]. This is supported by research on inference and cognition. Finding suggest that the creation of external representations inspires new associations [8, 14]. This means programmers are likely to better understand how to improve the code while working on it. Also, contrary to best practice of working only on one thing at a time, literature on creativity suggests that working on dissimilar tasks (lines of thought) can be useful. It seems important to rest on one thought to allow the brain to incubate. In order to avoid wasting time, one can work on something on another line of thought in the meantime. While a structured and disciplined approach to programming is recommended to avoid problems that may or may not arise, various research indicates that other ways of working are preferable for creative problem solving.

1.2 Explore-first programming

We argue that programming environments should provide dedicated tool support in the following respects.

Withdrawing changes. IDEs should provide a safe environment where developers can try out ideas without fear of losing the current stable state of development. Without the need for manual prevention, IDEs should make it easy for programmers to go back to a previous development state and to start over. They should also support programmers in withdrawing only some of all previously made changes.

Recovering knowledge. IDEs should support programmers in studying previous intermediate versions and recovering knowledge from them. They should provide dedicated support for comparing the source code as well as program execution of two (or more) versions. This would avoid the need for a precise understanding of every detail before making any changes.

Correcting recent mistakes. IDEs should support programmers in correcting recent changes. They should provide dedicated support for localizing the cause of a failing test in the history of recent changes. This would allow programmers to focus on the task at hand and to assess quality only when they find it convenient.

Re-assembling changes. IDEs should support programmers in re-assembling their recent and independent changes into incremental improvements. This would allow them to defer the consideration of code sharing and to focus on the task at hand.

Providing such dedicated tool support will allow for a programming approach that we call explore-first programming. Following explore-first programming, programmers will always make changes to the source code immediately as they think of it, without any hesitation or worries about future problems. They can work without worries because they know they can rely on tools that help them with whatever their explorations will reveal.

The central contributions of this paper are as follows:

- We point out the limitations of current practices to deal with the risks of changing programs, and we argue for tool support that preserve immediate access to information of all previous development states.

- We propose structured continuous versioning as foundational support. We present integrated tool support for accessing and working with source code and run-time information of previous versions. (Section 2).

- We describe an implementation of the tools on top of the Squeak/Smalltalk environment (Section 3).

- We provide results of informal user studies and measurements of performance and memory consumption (Section 4). Finally, we detail related approaches and describe differences to traditional tools (Section 5).

2. CoExistence of Program Versions

We propose the coexistence of program versions (CoExist for short) to support *explore-first programming*, as a mechanism that complements undo/redo concepts and version control systems (VCS). We first introduce structured continuous versioning and then present tools that we build on top.

2.1 Structured Continuous Versioning

We propose that the programming environment should continuously perform commits in the background and provide an integrated version bar (timeline) into the IDE (Fig. 1). Every change to leads to a new version one can go back to, for example. However, an automatic versioning implies the absence of user-written commit messages, which are essential
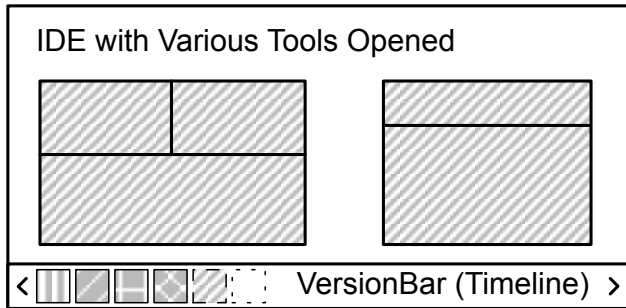
Figure 1. An integrated VersionBar (timeline). Every change creates a new entry.

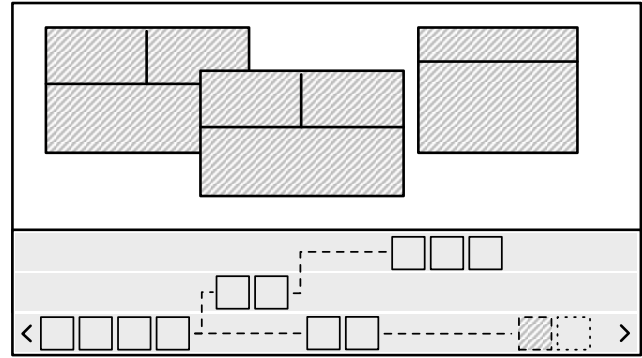**Figure 2.** Timely-ordered versions on different branches.

in current approaches for rapid identification of a particular commit.

To address this problem, we propose to base continuous versioning on the structure of programs. A program typically consists of a large number of hierarchically structured elements such as functions and modules or methods and classes. We propose that the environment tracks the modifications to the structural elements and creates a commit after each modification, which we call a snapshot. This approach allows for recording meta-information and attaching it to the version. The environment knows, for example, that a version has been created because the user changed a method with a particular name, contained in some class. Such meta-information is useful in identifying a version of interest.

An implementation of this concept depends on the characteristics of the respective development environment. In a file-centric environment (such as Eclipse and Emacs), the unit of editing is a file and each file includes multiple program elements. Often, files also represent some form of module. The environment has to track the manipulation of program elements and the moves of the text cursor from on element to another. When the programmer modifies an element and then moves the cursor to another one, the environment has to make a commit. In an image-based environment such as Self and Squeak/Smalltalk, programmers do not edit files. Instead, they are presented with editors limited to a particular method or class declaration. In this case the environment has to make a commit whenever the user finishes editing a program element.

With structured continuous versioning, the environment creates several versions during the process of implementing a feature or improving a program's design. Similar to undo/redo features of traditional editors, tools maintain the version history in the background. Programmers can undo their changes by going back to a previous version, using an offered shortcut for example. Immediately after switching to another version, CoExist updates all integrated tools of the environment to the newly selected version.

The proposed versioning facilities stretch across the entire working environment. Changing a program often re-

quires the manipulation of multiple artifacts (such as files) that may cross the boundary of projects. For example, a major refactoring to a component's interface will require corresponding updates of all available client code. Because of that, CoExist takes snapshots of the entire workspace and manages them in a workspace-wide history. This contrasts with undo/redo capabilities of editors that are typically scoped to single documents, and to capabilities of version control systems (VCS) that are typically scoped to single projects.

CoExist features implicit branching, similar to the undo-branches concept in Vim[1] or in Emacs.[2] When a programmer switches to a previous version to start over, CoExist manages all subsequently created versions on a new branch, which it implicitly creates (Fig. 2). All versions the programmers created always remain accessible. This encourages programmers to try out new ideas from previous versions, as they are now free from considering the potential loss of already implemented ideas.

2.2 Exploring the History

When programmers want to withdraw only a few changes, they can use the provided shortcuts to undo/redo individual changes step by step. In other occasions programmers may require withdrawing a large number of changes, for example, all changes of the last hour. In this scenario, programmers have to identify a version from a large list of created versions, which requires dedicated support.

2.2.1 Providing Change Information

To support scanning a large list of versions, CoExist uses the meta-information about each version. As previously explained, the environment records when programmers create, modify, or remove elements such as methods and classes, and CoExist creates a corresponding version for each such modification. This is sufficient to provide structured overviews as presented in the mockup tables of Figure 3. In this table, each line starting with a number rep-

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[1] `http://www.vim.org/`

[2] `http://www.gnu.org/s/emacs/`

	Kind	Class	Method	Time
► HRMan	10 items			
► HRFin	2 items			

				name
	Kind	Class	Method	Time
▼ HRMan	10 items			
1164	Addition	Person		13:42
1165	Modification	Person		13:42
1166	Addition	Person	name	13:42
1167	Addition	Person	birthdate	13:43
1168	Removal	Person	birthdate	14:08
►	Renaming	Person	name ➡ firstname	
1171	Addition	Employee		14:08
1172	Addition	Employee	arrivalDate	14:08
1173	Addition	Employee	salary	14:08
▼ HRFin	2 items			
1174	Addition	Payment		14:09
1175	Addition	Payment	amount	14:09

Figure 3. Two mockup tables showing lists of versions. The table on top presents two summary lines that, when expanded, change the representation of the table to the one on the bottom. In such tables, the numbers in the first column are the version identifiers. Following are the columns for the kind of change that triggered the creation of the version, the class and method that changed, and the timestamp of the change.

resents a version with an associated change. For example, version 1166 introduces the method `Person>>#name`. Such a table view enables to scan the history by means of the program structure and the used identifiers. This concept is employed in CoExist's *version browser*. Our informal study suggests that the provided information helps users to identify a version of interest within a few seconds (see 4.1). CoExist then associates each line with an action to load the corresponding version into the IDE. This mockup table shares some similarities with Eclipse and Intellij local history views. In the following we present some additional features that can hardly be seen in existing tools.

2.2.2 Highlighting and Grouping

We added standard user interface concepts such as highlighting and grouping to provide additional support in dealing with a large number of fine-grained versions.

Finding an element of interest in a list can be done in various ways. One way is browsing, or scanning, the list, one element after the other. However, if many elements of the list are clearly unrelated to the search, the task can be tedious. For example, our informal user study (see 4.1) revealed that programmers sometimes want to find a version that is close to a change they remember, such as the addition of a partic-

ular method. For such scenarios, CoExist allows to highlight elements or to only show a subset of all. Programmers can query the system with the name of the method they remember (or a part of its name) that is then matched against all the changes. CoExist will highlight the versions that matches, allowing the programmer to focus on their neighborhood instead of scanning the complete list. The mockup tables presented in Figure 3 illustrate this concept: in the table on the bottom, the programmer entered 'name' as a query in the text field on the top right to highlight all changes related to the method `name`.

To increase overview and structure, CoExist's version browser also groups related versions into one summary line. For example, a developer might find it convenient to see the changes at the level of packages instead of a detailed list of all the changes in classes and methods. This is illustrated in Figure 3 where the table on top presents summary groups for consecutive versions that are in the same packages (the packages are `HRMan` and `HRFin` in this case). A programmer can expand a group by clicking on the black triangle on the left.

2.2.3 Composite Versions

A single interaction in an IDE sometimes causes multiple changes to the source code: for example, applying a refactoring or auto-formatting a class will affect multiple methods. While CoExist keeps track of all changes separately, tasks such as finding a version will benefit from summary information about the interaction.

CoExist integrates with other tools of the development environments to get informed about both the beginning and end of automated source code manipulations. CoExist attaches this information to all versions created during the manipulation. Tools leverage this additional meta-information for highlighting and grouping versions as discussed above. Figure 3 illustrates, on the line titled 'Renaming', a composite version for a tool-supported renaming of the method `Person>>#name`. Programmers can expand the composite version to study the involved changes.

2.2.4 Testing

Many software systems are associated with automatic test suites such as unit tests. If they are present, CoExist attaches their results as additional meta-information to support finding a version according to test results. We discuss this in detail in Section 2.4.

2.3 Recovering Knowledge (by Juxtaposing Versions)

Structured continuous versioning allows for tool support to recover knowledge from previous development states. CoExist includes such dedicated support by providing immediate access to previously created versions.

CoExist provides dedicated support for recovering knowledge from previous versions by enabling programmers to work with multiple versions of the program next to each
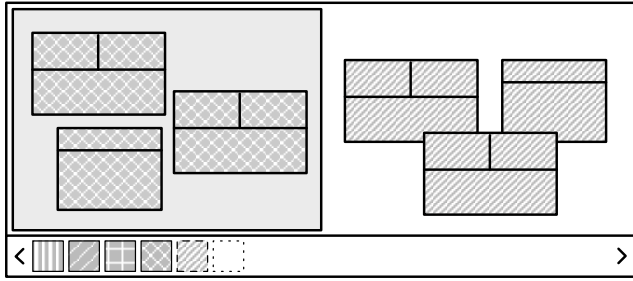
Figure 4. An additional fully-functional working place for a previous version, next to the tools for the current version.

other. Programmers can create an additional *working environment* 4 for any version of interest. Such additional environments are fully functional: they support browsing and modifying source code, running programs, and debugging.

Juxtaposing snapshots allows programmers to recover knowledge from a previous state of development. For example, programmers might be in the middle of a refactoring and realize that their understanding of the system, as it was, is either wrong or insufficient. With the mere push of a button, they can open an additional *working environment* for a previous version of the system. Using this second environment, programmers can study both source code and run-time behavior of the previous version. This supports closing knowledge gaps and getting an in-depth understanding on how the system's parts worked together previously. The possibility to open an additional working environment with little effort allows for recovering knowledge while preserving the current environment and its setup. All tools (or views) can remain open. Programmers have always full access to the current version and can easily continue working.

When users request an additional working environment, CoExist tries to replicate the currently active context. It detects the active tool, and asks the new environment to open the same tool. Thereby, this new instance is requested to present the "same" content as the original instance if possible.[3]

The support for juxtaposing program versions also supports examining differences of alternative solutions for a particular problem, for example, the respective benefits and drawbacks of different possibilities to decouple various aspects from another. The proposed concepts are also useful to perform a smaller task, such as fixing bug, in parallel to another task. Programmers can fix the bug on a stable version by opening an additional environment, so that they can preserve the current setup. Current VCS such as git offer to save the current unfinished work and go back to a previously committed state to study or modify it. This approach unfortunately requires that a commit has been done for the

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[3] We started to investigate this replication approach for debuggers. Replicating a debugger involves adapting its stack to a different source code which is difficult and might even be impossible in some circumstances. Nevertheless, we managed to have the replication work for simple scenarios.

state of interest. Moreover, these VCS do not let programmers rapidly juxtapose multiple versions in the same environment.

2.4 Fine-grained Back-in-Time Impact Analysis

Best practice suggests to run tests regularly during development. Employing this practice helps minimizing the set of recent changes that can cause a newly introduced bug. However, programmers might want to ignore this practice and defer quality considerations in favor of focusing on trying out ideas, for example. This will consequently increase the set of changes that can be the cause of a later observed problem.

CoExist provides dedicated support for reducing this set of problem candidates. It allows for analyzing the impact of every individual change with respect to unit tests whenever it is convenient for the programmer. The infrastructure of CoExist allows for continuously running tests and collecting results for every individual version. It also allows for running a particular, potentially new, test on previously created program versions.

CoExist provides infrastructure to perform background computations on every created version. CoExist records test results for further inspection and links these results to the corresponding versions. Such test results can be prepared for a visualization to further help programmers find a version of interest in a list of many versions. For example, a visualization can report the test status across all changes and highlights changes that caused tests to fail or changes that made some tests pass.

Collecting test results and preparing them visually supports deferred quality assessment. Such a visualization can considerably help reducing the set of changes that might be the cause of a recently observed failure. While working on a major task some early changes might make some tests fail, later changes might make some of them pass again, and more recent changes might be the cause for additional problems. The visually prepared information enables to understand the impact of individual changes with respect to test results.

CoExist also allows for running tests (and performing other computations) on previously created versions on-demand. This is useful when programmers want to avoid running the entire test suite for each newly created version, because this might take too long or might consume too many resources. However, running all tests late in the process can reveal problems that an early change has introduced. CoExist supports programmers in localize this change by running the failing tests on all previous versions (or a subset of them). This allows for finding the change that initially caused the test to fail with little effort.

This concept of performing computations on previous versions also presents advantages for other scenarios. For example, when programmers implement a unit test after implementing the corresponding feature, they can still check whether all of the changes have been necessary to make the test pass. Therefore, they can run the test on previous ver-

sions and inspect test results. Another scenario involves the desire to reproduce a recently observed problem that was absent in previous versions of the system but for which no tests exist. CoExist provides additional support for such scenarios where the source code of newly written tests does not exist in previous versions of interest. For such scenarios, the back-in-time analysis involves an additional step: CoExist first applies the changes that represent the newly written tests to the version where the tests need to be executed. Then, CoExist executes the tests, collects the results, and presents them. This feature is somewhat similar to "git-bisect". CoExist advances "git-bisect" by integrating it into the working environment and by preserving access to all intermediate versions between two explicit commits.

2.5   Re-Assembling Changes

Programmers often perform mutual independent modifications during one task. Still, they might want to share these modifications separately. CoExist provides dedicated support for this need and allows for re-assembling changes into incremental improvements, to be shared with a regular VCS.

The support for re-assembling changes is based on the ability to select and re-apply individual changes to any version. CoExist associates with each version the change that caused its creation. Programmers can then apply such a change to a different version, thereby creating a new version. As for all versions, programmers can explore this version in an additional environment, inspect test results, run the application and conduct acceptance tests. This approach is commonly referred to as *cherry picking*.

The support for cherry picking enables programmers to extract incremental improvements that are spread over a set of many changes. Consider for example that a task has involved a refactoring that the programmer must manage and share as a separate improvement. Programmers can first have a look at the list of all versions to identify both the individual changes that constitute the refactoring and the version from which the main task started. Programmers can then apply the refactoring changes to this initial version which will implicitly create a new branch. If programmers consider this branch a meaningful increment, they can share it with other programmers by pushing it to the used VCS. The proposed support for cherry picking can also help programmers to correct problems in isolation of others changes and to clean the source code from remaining glitches, such as debugging instructions. Using the interactive mode of the "git-add" command can help programmers extracting small commits out of many changes. Our approach improves on this command by proposing the selection of changes to commit based on structured elements ordered by time of change instead of selecting lines ordered by their position in a file. Moreover, our approach makes it easy to test a resulting source code prior to committing it.

In summary, CoExist relies on the idea of continuous versioning: any change made to the system triggers the creation of a new version storing the change as well as a complete snapshot of the current system. Because this approach creates many versions, we propose dedicated tools to help finding a version of interest quickly. Programmers can study the source code and behavior of these versions independently or in parallel for example to recover knowledge about a previous state of the system. In addition to that, CoExist reduces the effort needed for starting over from a previous state of development if necessary. Contrary to version control systems our approach copes with scenarios where snapshots have not been explicitly made by the programmer and where changes can affect multiple projects. CoExist also makes it easier to locate the cause of failures by running tests continuously and by allowing programmers to run any test, including new ones, one previous versions. Programmers can apply the changes associated to versions to already existing versions, which implicitly creates new branches and allows programmers to test and share in isolation.
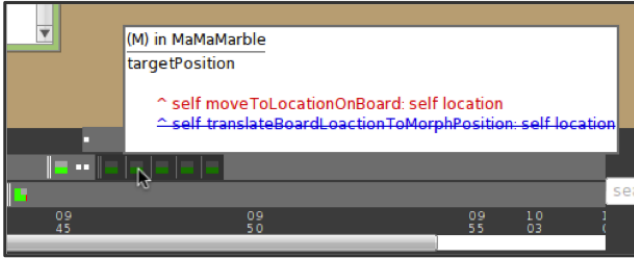
3.   Implementation

We have implemented CoExist in a Squeak/Smalltalk environment. First we briefly introduce the Squeak environment, and then show an overview of the offered tools. We finally give some details on how CoExist provides the developer immediate and full access to any version.

3.1   Extending the Squeak Environment

Squeak is an open-source implementation of Smalltalk. Like other Smalltalks, Squeak provides a development environment where programmers can open, move, and close windows, much like a desktop operating system (multi-window paradigm). Squeak is a "living" system: any system under development (and Squeak itself) is always running and can be modified without being stopped. This results in meta-objects representing the source code (such as classes and methods) being always available and changeable by the programmer. The Squeak environment automatically updates these meta-objects when the programmers modify their source code, for example when a method is changed. After updating the meta-objects Squeak fires an event that contains detailed information about the change, such as the name of the method that was changed and its previous implementation. Our implementation makes use of this event mechanism. When CoExist receives a change event, it creates a version and attaches the change information from the notification to the new version. Recording change information like this might require additional effort in IDEs that miss fine-grained change notifications.

CoExist provides two complementary interfaces to browse the versions resulting from a programmer's activity (both shown in Figure 5):

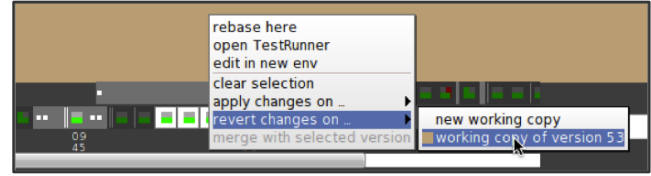**Figure 6.** Hovering above version items shows the change.

Figure 7. Context menu for one item, or a selection of items (with white background). The version browser provides a similar context menu.

The version browser is CoExist's implementation of the mockup table presented in Figure 3. The main differences with the mockup are the presence of 2 columns for unit test results, a screenshot of the Squeak environment as it was when the selected version was created (top-right), and three panes giving more details about the version: the first displays the change associated to the version, the second lists all changes between the selected version and the current one, and the third gives details about the change selected in the second pane. For each version, the user can request a context menu, which provides various commands such as going back/forward to the associated version, juxtaposinging the version with the current one, or applying the associated change to the current code base (or any version the programmer selects).

The version bar shown at the bottom of Figures 5 provides a condensed view of the recent versions. Contrary to the version browser, the version bar is always visible and ready to use by the programmer. However, it presents much less information compared to the browser, which makes it harder to find a version of interest. Each button on the bar represents a version and shows the result of the unit tests. Hovering over such a button displays a tooltip presenting the originating change (as in the second pane of the version browser). Clicking on a button reveals a menu with actions similar to the contextual menu of the version browser.

To provide integrated access to different program versions, we employed Squeak's window metaphor. When the user requests to explore a previous version, CoExist opens a dedicated window inside the environment within which all tools will display code for that particular version. Such inner world windows support browsing and modifying source code, running programs, and debugging.

3.2 Snapshotting and Sharing in Squeak

During the implementation and evaluations of CoExist we understood that, for CoExist to be useful, it has to provide both *immediate* and *full access* to any version of interest. *Immediate access* implies that it should be easy to get the desired information, and that the information is provided fast. According to recommendations such as in [13, Ch. 10], CoExist needs to fullfill user requests that are common in not more than *two seconds*. If programmers have to wait too long to get access to a version they might refrain from applying the proposed approach. *Full access* to any version refers to the idea that programmers should be able to explore, modify, run, and debug any program version.

To provide immediate and full access, we use snapshotting and sharing techniques, similar to many VCS. A snapshot is a data structure that stores the state of a system at a particular point in time. As with many VCS, CoExist snapshots the state of the system under development to avoid applying changes before being able to present a version to the programmer. To limit memory consumption, CoExist takes care of sharing as much of the data structure as possible between snapshots.

CoExist improves responsiveness of the development environment by also snapshotting the meta-objects of the environment. Immediate access to a version's source code is important but insufficient if the development environment takes a long time compiling all this source code and refreshing its internal state. To provide immediate access to any version, CoExist not only snapshots and shares the source code but also all the meta-objects (such as classes and compiled methods) of the Squeak environment. Figure 8 shows that each snapshot contains a dictionary which associates all class meta-objects to their names. Each class meta-object references all its compiled method meta-objects. In Figure 8, version 1172 introduces the `#arrivalDate` method in the class `Employee` (see Figure 3) which results in the duplication of the class `Employee` whereas all other classes (such as the class `Person`) of the system can be shared with version 1171. As Squeak notifies about a change only after updating corresponding meta-objects, the Squeak development tools edit copies of snapshots with no sharing. We call these copies of snapshots with no sharing *working copies*.

To maximize sharing of method meta-objects, CoExist adapts Squeak to defer the binding of class names to class meta-objects. In Squeak, class names in method source code are bound at compile time to their corresponding class meta-object. To maximize sharing among compiled methods, CoExist adapts the Squeak Virtual Machine to bind at run-time class names to their corresponding meta-objects in the current version. We show in the next section that this run-time binding does not prevent CoExist from providing good performances.
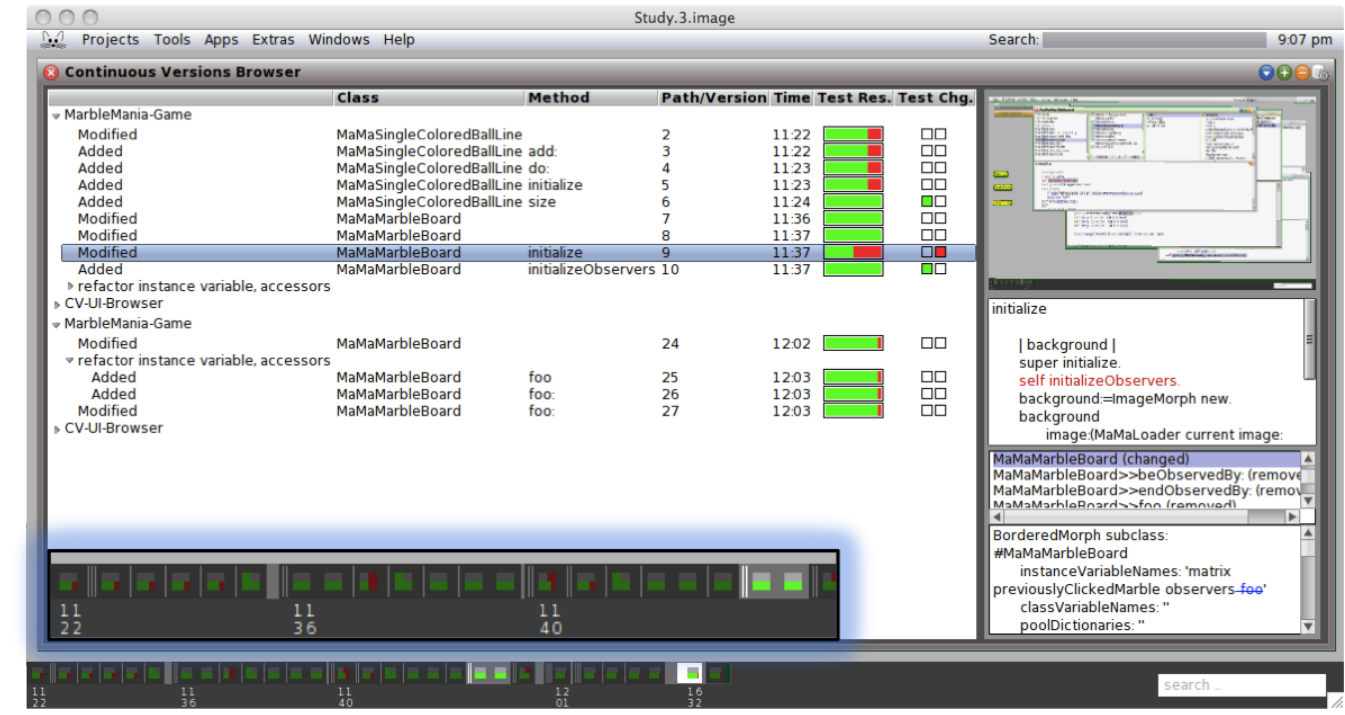
Figure 5. CoExist's version browser and the version toolbar at the bottom (an enlarged part above).

4. Evaluation of CoExist

In this section, we present the evaluation of CoExist concerning its usability and performance. Over the course of development we conducted three informal user studies, which helped us discover usability problems and opportunities. We
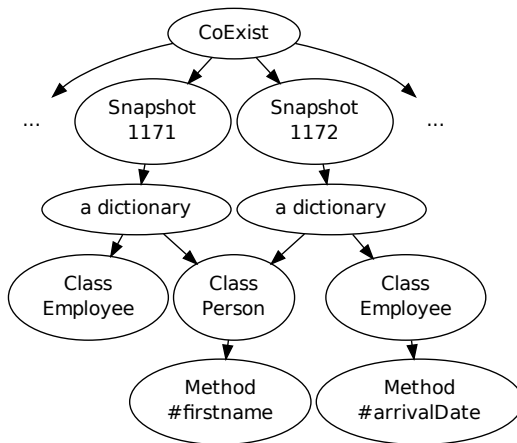

Figure 8. CoExist shares the meta-objects of the development environment between snapshots. The (extract of) snapshots 1171 and 1172 presented here are the same as those of the mockup tables of Figure 3.

improved our prototypes taking the results of those studies into consideration.

4.1 Informal User Studies

During our work on CoExist, we regularly asked members of our research group to use our system. We did informal user studies in three phases of our research project: (1) for an early prototype that only supported going back and forward one step at a time, (2) for a midterm prototype that improved speed and provided access to any existing version, and (3) for the final prototype as described in this article.

4.1.1 Early Prototype

Status: The early prototype provided only a simple undo/redo mechanism. Users could go back and forward by triggering commands. Visualizations were not yet available.

Purpose: We wanted to evaluate whether subjects find a project-wide undo/redo feature interesting and meaningful.

Procedure: We demonstrated our prototype to three graduate students. We asked them to perform arbitrary changes and to use the tools to undo/redo these changes.

Results: One student was skeptical about the benefit of the prototype whereas two others were enthusiastic and saw potential. All of them were dissatisfied with the responsiveness of the tool.

4.1.2 Midterm Prototype

Status: Whereas the early prototype only offered simple undo/redo commands, the midterm prototype provided a ver-

sion bar to identify and go back to any version of interest. The midterm prototype also provided juxtaposing access to multiple versions. Finally, this prototype significantly improved responsiveness by snapshotting meta-objects in addition to source code.

Purpose: We wanted to evaluate if and how subjects make use of the tools. More specifically, we wanted to evaluate our assumption that programmers have a need for withdrawing changes when they perform tasks. We also wanted to better understand whether the provided version bar is appropriate for identifying a previous version.

Procedure: One graduate student, one PhD student, and one post-doc were asked to spend one to two hours improving the design of a 2D puzzle game named MarbleMania, implemented by undergraduate students in the context of a previous lecture. The game worked properly and was covered by 39 unit tests (all of them passing) but implementation showed room for many improvements. At the beginning of the experiment we introduced the game play and gave a conceptual overview of the implementation. Then we asked our subjects to study the source code and to freely refactor the pieces that they felt needed improvement. We encouraged the subjects to implement their ideas as they came to mind without evaluating them mentally. One evaluator sat next to each subject to take notes and to answer questions about the proposed prototypes. We also used screen recording for later analysis.

Results: All three subjects went back to a previous state and continued working from there (two subjects went back two times and one subject one time), which supports our assumption that programmers experience the need for withdrawing changes. In addition to that, we discovered that the version bar is inadequate for finding a version of interest, because it lacks an overview of version information. This motivated the creation of the version browser.

This study also highlighted the need for juxtaposing. Two subjects opened a previous version in a separate environment to study aspects of this version. One of them wanted to study a test execution in a previous version. To do this, he opened an additional environment, found the test, opened a debugger, and stepped to the place of interest. This led us to develop the replication feature that allows for re-creating the currently active view for a different version with just one click.

Furthermore, the subjects felt positive about the tools. Even some weeks after the studies, subjects sometimes dropped in and reported a situation where the proposed tools would have helped for their own project.

4.1.3 Current Prototype

Status: Compared to the midterm prototype, the current prototype includes the version browser (Figure 5), and provides features such as search, highlighting, and grouping.

Purpose: The purpose of this study was to evaluate whether the version browser appropriately allows for identifying a previous version of interest (because the version bar turned out to be insufficient in the preceding study).

Procedure: We asked two graduate students (different than the ones before) to perform a refactoring we specified on the MarbleMania game and then to find the version they started with after half an hour of work. To make finding the version harder, immediately before the experiment, we generated a couple of changes so that the target version is not the first item in the list and so that time-based information do not help the subjects.

Results: The first subject remembered the source code elements he changed first when he started the refactoring. Because the version browser shows the names of each modified element, the subject was able to find the target version within a few seconds. The second subject produced significantly more changes during the evaluation, which made the task of finding the target version more difficult. As a result, the subject took around 20 seconds to identify the target version. During that period of time, the subject first identified a range of candidate versions and then inspected the details of the associated changes.

4.1.4 Discussion

These informal user studies helped us understand the benefits and problems of both our approach and implementation. We understood the need for responsiveness to make the tools attractive. We also discovered the need for the version browser. Indeed, the information presented by the version bar was insufficient to identify a previous version of interest.

4.2 Performance

User interface guidelines suggest to stay within two to four seconds for frequent user operations [13, Ch. 10]. Furthermore, the results of our informal user studies suggest that performance characteristics are an important factor for the adoption of the proposed tool support. In the following, we report on several performance evaluations.

Setup: As the system under evaluation, we use the Seaside[4] web application framework, because it extends many parts of the Squeak environment, which challenges the current implementation strategy for sharing meta-objects.[5] We artificially created 243 versions by loading 5 consecutive releases (from 3.0.0 to 3.0.4). The entire system including Seaside contains 3,312 classes and 68,950 methods. We used the 4.2 release of Squeak/Smalltalk. All measurements were performed on an Apple MacBook Pro 2.93 GHz Intel Core 2 Duo with 4 GB of RAM.

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[4] `http://www.seaside.st`

[5] For every change in a class meta-object, each subclass' meta-object needs to be copied to create the new version. The higher in the hierarchy a class is, the more subclasses need to be copied.

Performance of checking out: Checking out is the action of installing a snapshot into the IDE by copying all meta-objects (as explained in Section 3.2). Checking out requires 1.6 seconds on average, which is below the threshold of 2 seconds.

Performance of loading: Loading is the action of updating a working copy to a different version. Updating a working copy can be implemented either by checking out (1.6 seconds) or by applying a set of changes to the current working copy. We use the latter option as an optimization when the target version has few changes with respect to the current one. Using this option, CoExist requires 188 ms to withdraw 30 changes, approximately corresponding to 30-60 minutes of work (according to our experience from the studies). *These results suggest that our implementation of CoExist meets the desired response time.*

Memory consumption: CoExist consumes memory to maintain snapshots of source code and meta-objects. The 243 created Seaside versions roughly amount to a day of work (at a rate of 30 versions per hour). CoExist requires 68 MB of memory to maintain snapshots of these 243 versions of Seaside, indicating that the size of each version is less than 300 KB on average. *These results suggest that CoExist uses a reasonable amount of memory.*

Development slow-down: In a Squeak environment, applications are executed in the same process as the IDE and thus, IDE performance impacts applications. We measured the overhead that the presence of CoExist in the IDE introduces by timing 10 executions of the 617 Seaside unit-tests: on average, the execution takes 270 ms with CoExist installed and 217 ms without. Using CoExist thus makes executing programs around 1.24 times slower, mostly due to the binding of the class names that must be done at run-time with CoExist. *These results suggests that static class binding (compile/load-time) does not yield a significant performance improvement compared to class binding at run-time. These results also suggests that having CoExist always running does not significantly slowdown the execution of programs.*

This first evaluation of CoExist is promising. The results show that subjects appreciated the tools and even missed them after the experiment. Furthermore, CoExist is fast enough for frequent user operations and only consume a reasonable amount of memory. We plan to conduct empirical usability studies to identify to what degree our approach helps programmers perform better (get a better design and implement faster).

5. Related Work

We discuss the proposed concepts with respect to related approaches and highlight differences.

5.1 Versioning

The undo/redo feature of text editors is very convenient for changing recently entered text. However, undo/redo works on the level of characters, which makes going back to a less recent version of a file rather tedious. Mac OS X 10.7 provides the feature to regularly save files without explicit request. It provides visual feedback to support finding a previous version visual.[6] This auto-save feature also allows for juxtaposing the current version with previous ones. Nevertheless, such undo/redo concepts handle files independently of each other, while programming typically involves the manipulation of multiple files. Thus, making undone changes requires the developer to manually apply the undo feature an unknown and different amount of time for each changed.

Version control systems (VCS), which are sometimes referred to or part of configuration management systems (CM), can manage multiple files of a project and allow for reverting all files to a snapshot where they were at a given point in time. Developers can employ a VCS to support withdrawing changes. Either developers snapshot manually from time to time, or they let tools automatically snapshot at regular intervals, for example, after each save operation. However, both approaches exhibit limitations. Using the former approach, developers are required to foresee the future, which remains hard. Developers have to continuously assess the likelihood that a future situation requires to discard changes and to go back to the current state. Unfortunately, this is hard to assess and there will be situations where a developer forgot to snapshot at the most appropriate time. Furthermore, this approach makes it hard to focus on the design task, because a control loop keeps reminding the developer to consider snapshotting now. To overcome these problems, another approach is to snapshot at regular intervals.[7] However, if performed in an unstructured, way it easily results in a huge amount data that is hard to browse, because it lacks one of both meaningful meta-information or meaningful commit messages. In contrast, our approach creates versions that contain information such as the kind of change that happened that guide programmers in finding the snapshot they are looking for, even in the presence of many of them.

Orwell [15] is an early VCS / CM that provides both source and object sharing for Smalltalk systems. Compared to other VCS that employ files as the unit of versioning, Orwell manages versions of classes as well as editions of methods and clasess among other. Orwell requires class ownership, but provides a owner with a complete development history. The programmer can also work on multiple versions (or releases) of one class. Nevertheless, according to our understanding, Orwell's versioning scheme is scoped to classes. This means, the user cannot easily withdraw changes that span multiple classes and application parts. The Envy sys-

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[6] `http://www.apple.com/macosx/whats-new/auto-save.html`

[7] `http://stackoverflow.com/questions/688546/continuous-version-control`

tem [11], which is based on Orwell, provides baselining as an additional concept. This allows for creating named snapshots of all artifacts involved in a project. In contrast, CoExist continuously creates snapshots of the entire system, so the possibilties for exploring without hesitation are not restricted to scopes such as classes.

Changeboxes [3] is an approach to capture the history of a system and permit the existence of simultaneous versions in a single virtual machine and development environment. Because a Changebox encapsulates a particular change in the history of a system it is possible to use Changeboxes to go back to a particular state of this system. Nevertheless, Changeboxes have not been designed to allow going back and, as a result, doing so is tedious: going back requires finding a Changebox in a tree with no meta-information, creating a branch out of it, giving it a name and a color, closing all code browsers, and opening new ones. Our approach makes going back simpler by automating most of the process and presenting all versions of a system with visual meta-information. Moreover, the Changebox prototype implementation shows an important slowdown when used on a project with close to 2,000 methods: in this setup, the system becomes around 4.9 times slower on average. Contrary to the Changebox prototype, CoExist versions the entire workspace (around 69,000 methods). Still, our approach exhibits only insignificant run-time overhead (a slowdown of only 1.2 on average).

5.2 Exploring the History

Many tools and visualizations have been proposed to study the evolution of software systems. One that is close to our work is VPraxis, a language which models the history of source code through commands like "create class Person", and "add field 'name'".[8] Finding a version of interest can then be done via queries such as "which commit last changed this method?". VPraxis can be attached to a development environment to monitor code changes while programmers are doing them. Except for the unit test results and the refactoring-level grouping, VPraxis could propose tables such as the one in Figure 5. Nevertheless, VPraxis lacks support dedicated to needs such as withdrawing changes to start over, juxtaposing program versions, or back-in-time impact analysis. Moreover, VPraxis is not integrated in a development environment in such a way that multiple versions can be browsed and edited independently.

5.3 Juxtaposing Versions

Orion is an interactive prototyping tool that allows to compare the impact of multiple changes on a software system [9]. Orion uses models as an abstraction to source code and model transformations as an abstraction to changes. Orion has been implemented to permit the manipulation of very large models including more than 600,000 entities, such

as classes and methods. As a result of using abstractions instead of source code, Orion can not be used to execute a previous version of a software system or even study its source code. Moreover, even if Orion's implementation shares some similarities with ours, its goal is inherently different: Orion has been designed for re-engineering changes (such as the removal of dependencies) whereas CoExist target all kinds of source code changes. As a result, CoExist is fully integrated in the development environment and versions are created automatically whereas, with Orion, changes have to be explicitly expressed as a model transformation.

Hartmann and others propose Juxtapose [7], a tool that facilitates the creation and comparison of alternatives through a dedicated code editor. Juxtapose also allows the execution of multiple alternatives in parallel. Nevertheless, Juxtapose is not associated to the history of a software system and thus cannot propose going back or re-assembling changes into incremental improvements.

5.4 Fine-grained Back-in-Time Impact Analysis

There are various approaches that make use tests to support fault localization. For example, the continuous testing approach proposes to run tests automatically after each change [12]. Because this approach can only execute tests on the system currently in the development environment, the execution of a test suite is aborted after each change. Nevertheless, it immediately presents the results to the programmer so that he can fix problems as they appear. CoExist improves on that by recording the test results and link them to the corresponding changes, which allows for analyzing test results only when it is convenient. In addition, CoExist also supports running (long/acceptance) tests on previous versions.

The Git VCS provides the "git-bisect" command, which uses binary search on a sequence of commits to find the first commit that introduced a bug. CoExist advances this concept by integrating it into the working environment and, more important, by preserving access to all intermediate versions between two explicit commits. Furthermore, CoExist can also run unit tests in the background during development, and it provides support for running newly defined tests on all previous versions.

A continuous integration server monitors commits to a VCS and automatically builds and executes tests on each one [5]. By providing history of test results for every commit, these servers allow for back-in-time impact analysis. Unfortunately, these tools can only provide fine-grained analysis if the commits are themselves fine-grained which requires time and discipline: When the commits contain many changes, the programmers have to study all these changes to locate faults.

5.5 Re-Assembling Changes

Best practices include doing small commits (sometimes qualified atomic or logical) that only affects one aspect of

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[8] http://harmony.googlecode.com

the system to facilitate activities such as going back, fault localization, and reviewing [1]. Using the interactive mode of the "git-add" command can help programmers extracting small commits out of many changes. This command allows programmers to define the boundaries of a commit by selecting a subset of the modified lines in each modified file. Our approach improves on this command by proposing change-level selection instead of line-level selection, by ordering the changes by timestamp, and by support to run tests for the defined increments.

6. Conclusion

We have pointed out limits of certain recommended practices to deal with the risks of changing programs. We have called for *explore-first programming* and argued for the need to preserve immediate access to source code and run-time information of all development states.

We have proposed structured continuous versioning as foundational support. Our approach provides a dense and structured history, and allows for identifying a version of interest fast without requiring programmers to write commit messages. We have presented various tools, built on this foundation, to address the needs of *explore-first programming*. The presented tools make it easy to withdraw a set of selected changes and to recover knowledge by exploring and debugging a previous version next to the current one. Programmers can also defer quality assessment, because Co-Exist allows for running tests regularly for each commit as well as backward in time. We have implemented a prototype in Squeak/Smalltalk, guided by informal user studies. Our studies suggest that users identify a previous version of interest within a few seconds and that they appreciate the tools. We can conclude that *explore-first programming* is a valuable and feasible alternative to current approaches to deal with the risks of changing programs.

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