Bringing Objects to Life: Supporting Program Comprehension through Animated 2.5D Object Maps from Program Traces

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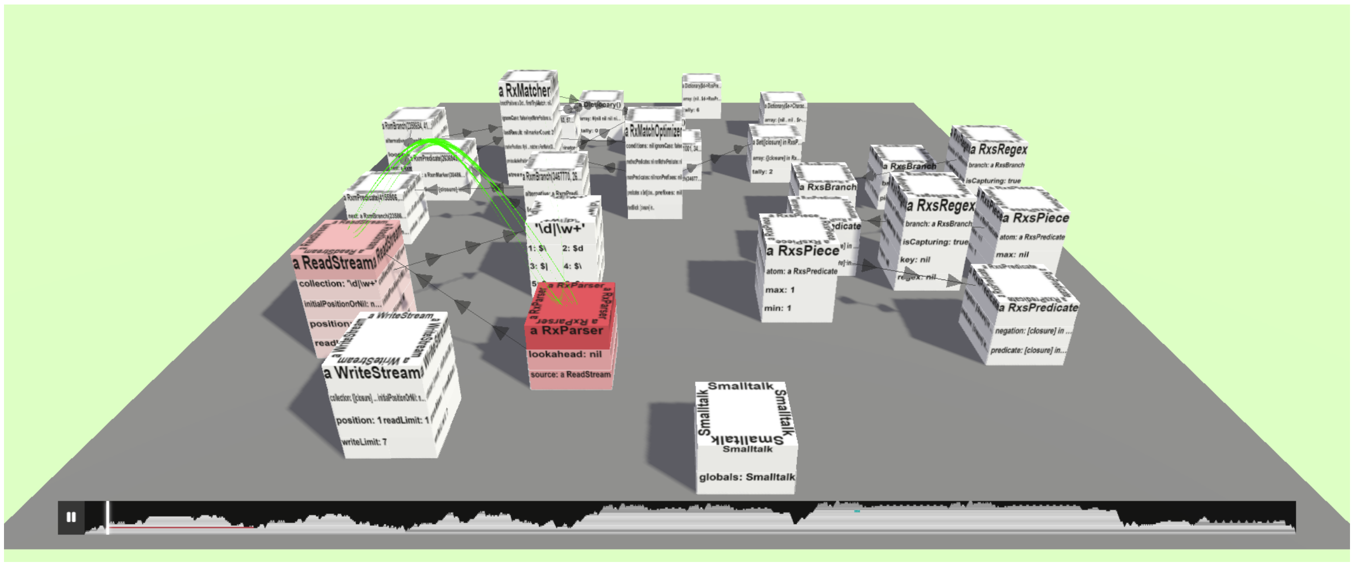


Figure 1: TODO

ABSTRACT

Program comprehension is a key activity in software development. Several visualization approaches such as software maps have been proposed to support programmers in exploring the architecture of software systems, while little attention has been paid to the exploration of program behavior and programmers still rely on traditional code browsing and debugging tools. We propose a novel approach for visualizing program behavior through *animated 2.5D object maps* that depict particular objects and their interactions from a program trace. We describe our implementation of this approach and evaluate it for different program traces through an experience report and performance measurements. Our results indicate that our approach can be beneficial for program comprehension tasks, but that further research is needed to improve scalability and usability.

CCS CONCEPTS

• **Human-centered computing** → **Visualization techniques**; • **Software and its engineering** → Software maintenance tools.

KEYWORDS

software visualization, software maps, object-oriented programming, program comprehension, omniscient debugging

1 INTRODUCTION

Exploring and understanding software systems play a central role in software development. Programmers frequently get thrown into unknown systems that they want to fix, change, or extend. For this, they need to build up a mental model that connects the system's visible behavior to its high-level architecture and low-level implementation artifacts.

Traditionally, programmers explore software systems by reading their source code. An alternative approach is to explore the system's behavior by example: programmers can start by invoking the system with a particular input or by running a test case and then use a debugger to step through the program's execution, identify relevant units and actors, and explore their interactions. As traditional debuggers are constrained to the temporal execution order of the program, *omniscient debuggers* (also referred to as *time-travel debuggers* or *back-in-time debuggers*) exist that record a *program trace* and allow programmers to explore the program's behavior in a non-linear fashion [35, 26, 47, 39, 56]. However, omniscient debuggers are not well suited for exploring large program traces involving several subsystems and dozens of interacting objects: while their fine-grained display of source code and variables is useful for debugging-related activities, it impedes the exploration of the system's high-level architecture and behavior.

On the other hand, several visualization approaches have been proposed to support programmers in exploring the architecture of software systems. In particular, *software maps* that display the static structure of systems using several metaphors such as cities or forests were found to be useful for program comprehension tasks [62, 2, 41]. Yet, most approaches neglect the dynamic behavior of systems and take a coarse-grained view of their structure, which makes them unsuitable for developing a mental model of the system's behavior that situates particular interacting objects and connects them to the overall functioning of the system.

To bridge this gap between coarse-grained static software maps and fine-grained omniscient debugging views, we propose a novel approach for visualizing the behavior of object-oriented software systems through animated 2.5D maps depicting particular objects and their interactions from a program trace. In particular, we make the following contributions:

1. We present a novel visualization approach for object-oriented program behavior through animated 2.5D object maps.
2. We describe the implementation of our prototype TRACE4D that applies this approach using program traces from a Squeak/Smalltalk environment and the THREE.js 3D library.
3. We discuss the potential and limitations of our approach by reporting on our experience with it and by evaluating the performance of our implementation for different program traces.

We make all artifacts of this work available at a public repository[1].

The remainder of this paper is structured as follows: in section 2, we discuss related work on software maps, object-oriented programs, and program traces. In section 3, we present our visualization approach for program traces. In section 4, we describe our implementation of this approach. In section 5, we discuss our approach through an experience report and a performance evaluation. Finally, we conclude and discuss future work in section 6.

2 RELATED WORK

Several approaches for visualizing the architecture and behavior of software systems have been proposed in the past. In the broad field of program visualization [45, 53, 55], *algorithm animation* is an early approach that mainly focuses on visualizing procedural algorithms and data structures in educational contexts [8]. During the last decades, more approaches have been proposed that allow to create general-purpose visualizations for the architecture and behavior of arbitrary software systems [50, 11, 12, 17].

2.1 Software Architecture Visualization

The term *software maps* describes a family of approaches that use metaphors from cartography to visualize the architecture of software systems.

Treemaps. *Treemaps* display the static structure of software systems by visualizing their hierarchical organization of packages and classes, folders and files, autc. as a nested set of shapes [40, 41]. They offer different visual variables such as the size, color, and position of the shapes to encode additional information about the system's size or evolution. Shapes are usually rectangles but can also be polygons as in Voronoi tesselation treemaps [6]. A popular modern type of treemaps is *2.5D treemaps* that add a third dimension to the visualization by transforming each shape into a right prisma (usually cuboid) of a variable height. Many approaches use the *software city* metaphor to style the cuboids of a 2.5D treemap as buildings of a city [18, 62, 1, 43, 27, 41].

Topic maps. Unless treemaps, *topic maps* do not display the programmer-specified organization of a software system but use natural language processing techniques such as soruce code topic models, latent dirichlet allocation, and multidimensional scaling to arrange units of the software in a 2D or 3D graph [4]. Different metaphors have been proposed to embody these graphs in a map, including boardgames [3] and landscapes such as forests [2] and galaxies [5].

Animated software maps. Next to using static visual variables, some approaches enrich software maps with animations to display dynamic information over time [34, sec. 3.4]. Dynamic information can refer to the behavior or evolution of software: for instance, EvoSpaces [18] highlights classes in a software city when they are activated, while DynaCity [15], ExplorViz [30], SynchroVis [61], and others [13] also draw connections between modules to visualize dataflow between them; [33] gradually constructs a software city and updates the geometries and colors of buildings to represent development activity, and Gource [10] enhances the construction animation of a file tree with moving avatars representing code authors. Some approaches allow programmers to monitor a system in real-time [20] while others replay a previously recorded trace of software activity [18].

2.2 Entity-Centric Behavior Visualization

To provide visual insights into the behavior of software, a natural choice is to attribute behavior to different entities of the software. Entities can be organizational units such as modules or classes but also individual object instances of object-oriented programs.

Object graphs. Several tools allow programmers to explore relevant portions of a program's object graph [42, 23]. Some graphs resemble the look of UML object diagrams and provide details about objects's internal state while others choose more compact representations. To reduce the visual complexity of graph displays, some tools provide programmers with means for filtering objects based on their organization or relation to program slices [32, 25].

Communication flow. *Call graphs* and *control-flow graphs* are two popular ways for displaying entities with their mutual dynamic interactions or communications [16, 32, 34, 49, 58, 7, 48]. Entities can be nodes from an object graph or organizational units such as classes or modules. Avid and PathObjects [51] provide animated object graphs where users can explore the control flow interactively. [7] merges the stack frames from a control-flow graph and the nodes from an object graph into a single *memeograph* that can be explored through animation.

In contrast to traditional call graphs, some works have proposed peripheral, hierarchical layouts of nodes such as Extravis' *circular bundle views* [14] or [44]'s 3D hyperbolic layout that provide better scaling for highly connected graphs. Another representation of

[1]https://github.com/LinqLover/trace4d

inter-entity communication is to provide full adjacency matrices of the call graph [46].

Dataflow. Another perspective that can be taken on the object graph is how state is transferred through the system. The WHYLINE approach allows programmers to ask questions about why certain behaviors did or did not happen or where certain values came from and presents the answers in a sliced control-flow graph [29]. [36] proposes an *inter-unit flow view* that displays the amount of data or objects exchanged between different classes or modules in a directed weighted graph; this graph can also be embedded into a traditional call graph [37].

State changes. [37] also proposes a *side-effects graph* [19] (also referred to as *test blueprints* [38]) that displays connections between objects changing each other's state. Similarly, *object traces* describe a way to slice a call graph for exploring the state evolution of single objects [56, 57].

2.3 Time-Centric Behavior Visualization

Next to the communication between entities, another perspective that visualizations commonly take on software behavior is the temporal order of program execution.

Call trees. A call tree is a hierarchy of stack frames or message sends that can be gained from a program trace. Besides naive graph representations of this data structure, several approaches display call trees using hierarchical layouts such as treemaps, sunbursts, or *icicle plots* [31, 59, 63]. Similarly to icicle plots, *flame graphs* show the historical call stack over time, but they also assign colors to stack frames for displaying additional performance data from profiling tools [24].

Sequential displays. UML sequence diagrams are a traditional approach for displaying communication between objects over time. Several tools adopt [54] and extend [25] this diagram type: for instance, ISVIS' *information mural* [28] and EXTRAVIS' *massive sequence view* [14] derive miniaturized versions of a sequence diagram [34, sec. 3.4], and OVATION [16] detects execution patterns to reduce sequence diagrams [25].

3 VISUALIZATION APPROACH

In this section, we describe the prerequisites and the design of our proposed visualization approach.

3.1 Data Model

The data source of our visualization is the program trace of an object-oriented program. In this programming paradigm, all behavior is described as *messages* sent from one object to another. Each object is characterized by its *identity* which distinguishes it from all other objects in the system, its *state* which is represented by its fields such as array elements and instance variables, and its *behavior* which is implemented by methods that are invoked to receive messages [57].

We assume a minimal data model of the program trace (fig. 2): the *call tree* is represented as a composite structure of *stack frames* each of which specifies a time interval, an invoked method, and a receiver object. Each *object* is assigned a label, a list of named

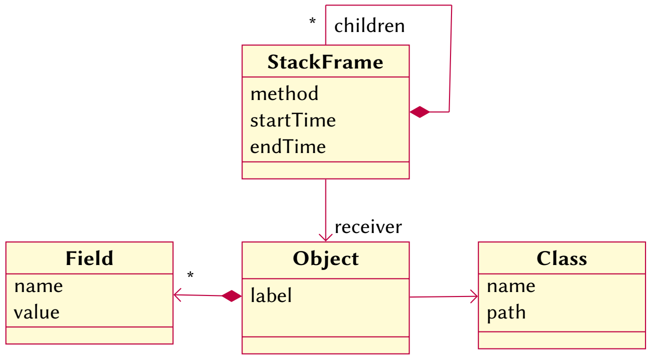


Figure 2: TODO

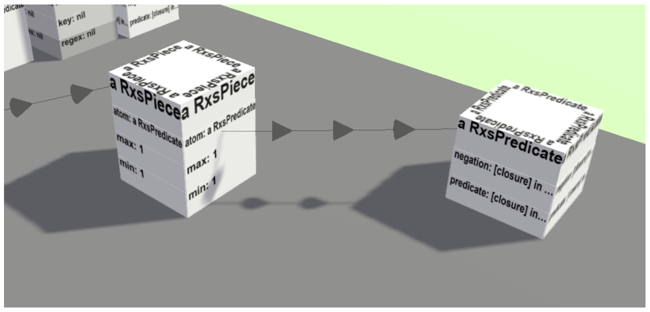


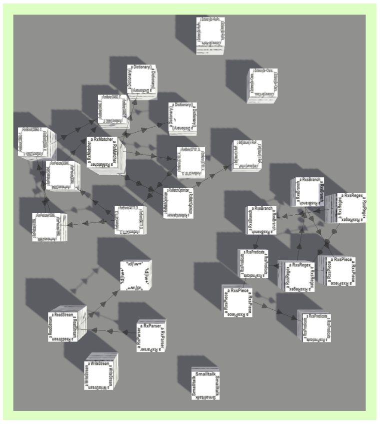
Figure 3: TODO

fields, and a class. Each *class* is described through a name and an organizational path in the file or package structure of the software system. We neglect runtime changes to the state, label, or class membership of objects as well as metaprogramming specifics such as the implementation of classes or methods as objects.

3.2 Visual Mapping

We describe the design of our visualization and the mapping of parts from the program trace to elements and visual variables of our visualization (fig. 1). At the highest level, an animated 2.5 object map is an interactive information landscape that displays objects and their interactions from the program trace. Users can replay the program trace and watch the activation and interaction of objects. They can unrestrictedly navigate through the visual scene using their keyboard and pointing devices and view the map from all sides.

Objects. Each object is represented as a square cuboid *block* entity that displays the label and fields of the object (fig. 3). To maximize legibility from any perspective, the label is repeated on all four sides and in four orientations on the top of the block. Fields are displayed as *plates* that are arranged in a row-wise uniform-sized grid layout and repeated on each side of the block for better legibility. References between objects are rendered as *directed arrows* from the closest plate of the referencing field to the closest label of the referenced object's entity. To indicate the direction of arrows, we place between one and ten evenly distributed *chevrons* on the



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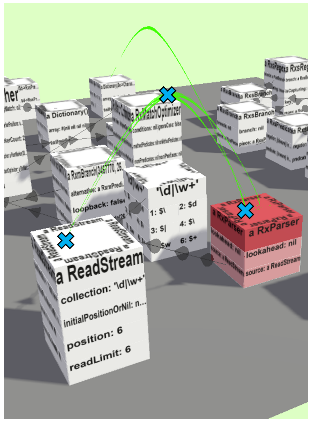

Figure 5: TODO

Table 1: TODO

w_{class}	w_{org}	w_{ref}	w_{comm}	w_{repulse}	w_{center}
0.001	$F \mapsto 0.005\left(\log_{10}(F)+1\right)$	0.1	0.00001	0.2	0.00142

arrow line; each chevron is displayed as a cone whose direction can be recognized from any perspective.

Object graph. To arrange object blocks in the 2.5D object map, we define a force-directed graph layout [21]. Between each pair of object blocks (a, b), we apply several *weighted attractive forces* based on the class membership, the organizational proximity of classes, and the references and communication between objects (fig. 4):

$$\begin{aligned} F_{\text{class}}(a,b) &= w_{\text{class}}\left(\begin{cases}1, & \text{if class}(a) = \text{class}(b);\\ 0, & \text{otherwise.}\end{cases}\right), \\ F_{\text{org}}(a,b) &= w_{\text{org}}\left(\text{LCP}^{2}\left(\text{org}^{3}(a), \text{org}(b)\right)\right), \\ F_{\text{ref}}(a,b) &= w_{\text{ref}}\left(\left|\left\{(k,v) \in \text{fields}(a) \,\middle|\, v = b\right\}\right|\right), \\ F_{\text{comm}}(a,b) &= w_{\text{comm}}\left(\left|\left\{\text{frame } f \,\middle|\right.\right.\right. \\ &\qquad \left.\left.\left. f.\text{receiver} = a \wedge f.\text{parent.receiver} = b\right\}\right|\right). \end{aligned} \tag{1}$$

In addition to the attractive forces, we define globally weighted *repulsion* and *centripetation* forces on all blocks to control the entropy of the graph, and we define *radial constraints* to avoid collisions between blocks.

We provide an empirical base configuration for all force weights but enable users to override them for specific program traces. By default, we prioritize reference forces the highest and organizational forces the lowest with a distance of six orders of magnitudes and scale organizational forces logarithmically (table 1). This configuration fosters a state-centric layout of the object graph while leaving a margin for the characteristic of particular program traces (e.g., their ratio between intrinsic and extrinsic state [22, p. 218ff]) towards a more dataflow-driven layout. Additionally, users can drag and drop blocks to override the layout. To reduce response times and maintain an experience of immediacy [52, chap. 11, 60], we render the graph continuously before the force simulation has converged.

Object selection. Usually, even after restricting the object graph to the receivers from the call tree (section 3.1), only a small part of it is relevant for comprehending the high-level behavior of a program while many other objects fulfill lower-level implementation details. In our visualization, we use a filtering system for excluding objects based on their label, class, or organization. Similarly to the layout configuration (object graph), we provide an empirical default configuration that excludes certain base objects such as collections, booleans, and numbers, but allow users to customize these filters.

Object behavior. The color of each object block displays its recent activity: *inactive* blocks are colored in a neutral light gray while *active* blocks whose objects have received a message recently are highlighted in a bright red (fig. 5). After the control flow passes on to other objects, blocks linearly fade back to the base color within one second, thus applying a single-hue continuous sequential color scheme by Brewer et al.[3]

Next to the color coding, a *trail* connects the most recent $k = 15$ object activations to support the delayed observation of short activations and the recognition of exact activation order. The trail curve is based on a centripetal Catmull-Rom spline [9] whose control points are placed on the top of each relevant block and are alternated with intermediate points between blocks. Block control points are normally randomized to make multiple activations of the same object distinguishable. Intermediate control points are vertically elevated to give the curve a wave-like shape that makes activated objects identifiable. The direction of the trail is displayed by continuously moving it to the next object and applying a linear translucency gradient to fade out the tail of the curve.

Timeline. The object map integrates a *timeline* overlay at the bottom of the viewport that provides a time-centric navigational aid. The timeline consists of two widgets stacked on top of each other (fig. 6): a *player* with a slider and a play/pause button indicates the current point in time of the program trace and allows to control

[2]LCP(u, v): Largest common prefix of two sequences u and v.
[2]org(o): Organizational path to an object o's class (e.g., a file path).

[3]Cynthia Brewer and Mark Harrower. 2013 – 2021. ColorBrewer: Color Advice for Cartography. Pennsylvania State University. URL: https://colorbrewer2.org/

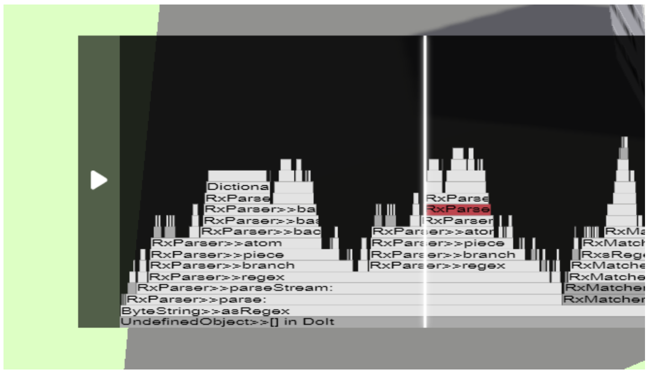

Figure 6: TODO

the time and animation state. Behind the player, a collapsed *flame graph* displays the course of the call stack depth. Users can resize the timeline to explore the full call tree hierarchy and examine single frames in the flame graph.

Both the flame graph and the object map are interactively connected, i.e., users can hover an object in the map to discover all of its activations in the timeline, or vice versa, they can click on a frame to move the trail in the map to the relevant activation of the object. Thus, object map and timeline provide two orthogonal means for navigating through the object-oriented program trace with different granularities.

4 IMPLEMENTATION

5 DISCUSSION

6 CONCLUSION

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