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

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Figure 1: Screenshot of an animated object map displaying a program trace for the construction of a regular expression matcher in the Squeak/Smalltalk programming environment. Blocks represent objects, arrows display references between objects, and color highlights and trails show object activations. The timeline at the bottom provides a temporal overview of the program trace and allows users to control the animation.

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 [38, 27, 51, 42, 63]. 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 [69, 2, 44]. 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 TRACE-4D 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 describe the use of our visualization tool by an example. In section 6, we discuss the potential and limitations of animated object maps through an experience report and a performance evaluation. Finally, we conclude and discuss future work in section 7.

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 [48, 59, 61], *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 [54, 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 [43, 44]. 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, 69, 1, 46, 28, 44].

Topic maps. Unlike treemaps, *topic maps* do not display the programmer-specified organization of a software system but use natural language processing techniques such as source 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 [37, 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 [32], SYNCHROVIS [68], and others [13] also draw connections between modules to visualize dataflow between them; [36] 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 [45, 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 [35, 26].

Communication flow. Call graphs and *control-flow graphs* are two popular ways for displaying entities with their mutual dynamic interactions or communications [16, 35, 37, 53, 65, 7, 52]. Entities can be nodes from an object graph or organizational units such as classes or modules. AVID and PATHOBJECTS [57] 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.

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

In contrast to traditional call graphs, some works have proposed peripheral, hierarchical layouts of nodes such as Extravis' *circular bundle views* [14] or [47]'s 3D hyperbolic layout that provide better scaling for highly connected graphs. Another representation of inter-entity communication is to provide full adjacency matrices of the call graph [50].

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 [31]. [39] 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 [40].

State changes. [40] also proposes a *side-effects graph* [19] (also referred to as *test blueprints* [41]) 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 [63, 64].

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* [33, 66, 70]. 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 [60] and extend [26] this diagram type: for instance, ISVis' *information mural* [30] and Extravis' *massive sequence view* [14] derive miniaturized versions of a sequence diagram [37, sec. 3.4], and Ovation [16] detects execution patterns to reduce sequence diagrams [26].

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 [64].

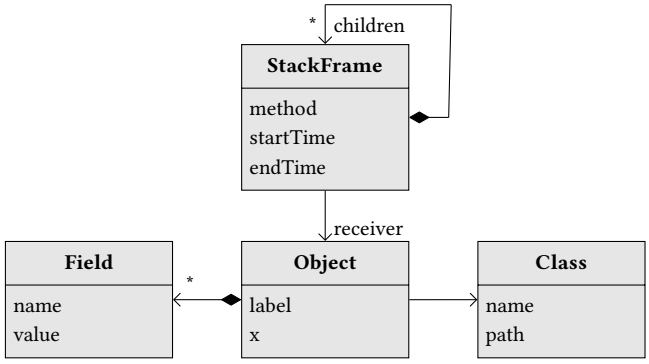

Figure 2: UML class diagram showing the data model of an object-oriented program trace for the visualization.

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 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

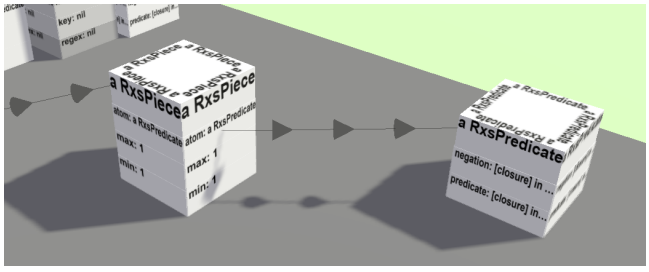

Figure 3: Visual mapping of objects, fields, and references to block entities, plates, and arrows in the object map.

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 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. In the following, $w\_$ denotes the weight of a force and $\mathrm{org}(o)$ denotes the organizational path of an object o's class (e.g., a file path):

$$F_{\mathrm{class}}(a,b) = \begin{cases} w_{\mathrm{class}}, & \text{if } \mathrm{class}(a) = \mathrm{class}(b); \\ 0, & \text{otherwise.} \end{cases}.$$

$$F_{\mathrm{org}}(a,b) = w_{\mathrm{org}}\big(\mathrm{commonPrefixLength}(\mathrm{org}(a), \mathrm{org}(b))\big)\,.$$

$$F_{\mathrm{ref}}(a,b) = w_{\mathrm{ref}}\big(\text{number of fields in } a \text{ that reference } b\big)\,.$$

$$F_{\mathrm{comm}}(a,b) = w_{\mathrm{comm}}\big(\text{number of messages from } a \text{ to } b\big)\,.$$

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 weight 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 customize the layout. To reduce response times and maintain an experience of immediacy [58, chap. 11, 67], 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.

Table 1: Default configuration of force weights for the object graph layout. References between objects dominate the layout while organizational proximity and communication between objects are weighted lower. Users can override these weights for specific program traces.

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

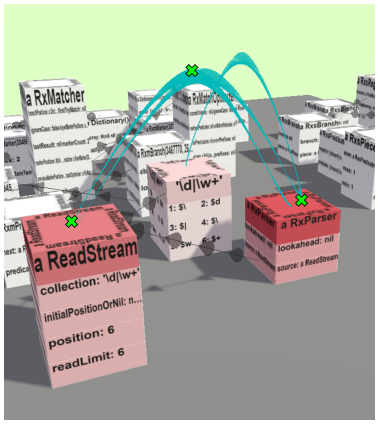

Figure 4: Visual mapping of object behavior to color and trail in the object map. The intensity of the red color indicates the recency of the last message received by each object. The gradient trail connects the most recent object activations (control points of the curve are marked with a ✖ cross).

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. 4). 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.[2]

Next to the color coding, a *trail* connects the $k = 15$ most recent 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 during the animation 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. 5): a *player* with a slider and a play/pause button indicates the current point in time of the program trace and allows to control 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.

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

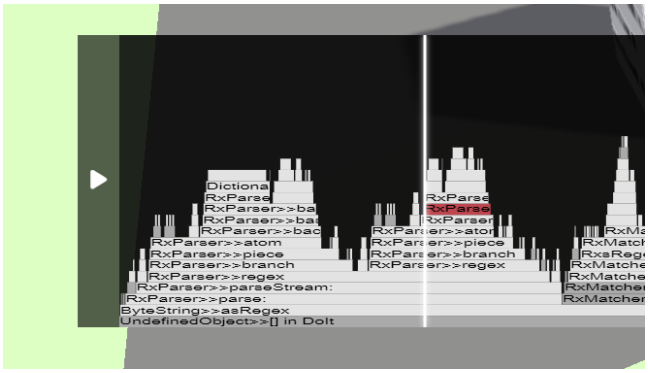

Figure 5: Timeline overlay with widgets for controlling the playback of the program trace and a flame graph with a variable degree of detail for navigating the call tree. The flame graph and the object map are interactively connected, e.g., the user can hover a frame to highlight the corresponding object in the map.

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 forward or rewind the trail in the map to the relevant object activation. Thus, object map and timeline provide two orthogonal means for navigating through the object-oriented program trace with different granularities.

4 IMPLEMENTATION

Here we describe the implementation of animated 2.5D object maps in our prototype TRACE4D that displays program traces from a Squeak/Smalltalk environment in a web application.

Program tracing. Squeak/Smalltalk is an interactive programming environment that is based on the object-oriented paradigm (everything is an object, including classes, methods, and stack frames) and offers programmers rich control for inspecting and manipulating all parts of the system (by instrumenting method objects, recording stack frame objects, etc.) [29, 56, 62]. We use the TRACEDEBUGGER[3] [63], which is an omniscient debugger for Squeak, to record a program trace of interesting behavior such as compiling a method, matching a string against a regular expression, or handling user events in a graphical user interface (GUI).

We serialize the resulting program trace consisting of a call tree, an object graph, and a class hierarchy and export it to a JSON file. To retrieve the fields for each object, we use Squeak's built-in inspector tool [62, chap. 6, sec. 3] which collects all instance variables or array elements from each object but also provides higher-level views on the state of known domain objects; for instance, a dictionary will not be presented with its internal overallocation array structure but with a more comprehensible collection of key-value pairs. Regarding the objects referenced as values from fields, we only include those objects in the serialization that receive at least one message in the program trace but only store a flat string representation of any other objects to avoid traversing the entire object graph of the system whose largest part is not relevant to the particular program trace.

Visualization. We implement the visualization frontend of TRACE-4D as a JavaScript web application. The web app retrieves a serialized program trace and offers a programmatical interface for customizing the visual configuration (section 3.2). To build the 2.5D object map, we generate and display a 3D scene from the program trace using the JavaScript 3D library THREE.JS[4] and layout the object blocks using the `d3-force` module of the visualization framework D3.JS[5]. To build the timeline, we create a flame graph using the `d3-flame-graph` plugin for D3.JS[6] and combine it with a custom HTML widget for the player controls[7]. To animate the visualization, we traverse the call tree with a configurable speed (defaulting to 50 bytecode instructions per second) and update the color highlights and trail for activated objects at each animation tick.

5 USE CASE: EXPLORING INTERNALS OF A REGULAR EXPRESSION ENGINE

In this section, we illustrate how a programmer can use the TRACE-4D visualization to explore the way a regular expression engine constructs a matcher from a pattern. The `Regex` package in Squeak provides a Smalltalk-specific flavor of regular expressions. To construct a matcher, the package first parses the pattern string into an abstract syntax tree (AST) and then compiles the AST into a non-deterministic finite automaton (NFA). In this example, our programmer visualizes the construction of the simple regular expression `\d|\w+` to gain a closer understanding of the involved subsystems and their interactions.

To create the visualization, the programmer records and exports a trace of the program `'\d|\w+' asRegex` in Squeak and loads it into the TRACE4D web app[8]. As the visualization loads, she can see about 25 objects moving around in the object map and arranging themselves into a semi-structured graph within a few seconds (fig. 1). By navigating through the scene, she discovers several meaningful objects and clusters of objects:

- the pattern string `'\d|\w+'`;
- an `RxParser` object accessing the string through a `ReadStream`;
- eight objects referencing each other whose class names start with the prefix `Rxs`, identifying them as nodes of the AST;
- a `RxMatcher` object surrounded by six objects whose class names start with `Rxm`, identifying them as states of the matcher's NFA;
- several other loosely structured objects, including an `RxMatchOptimizer` object, four `Dictionarys`, and a `Set`.

[3] https://github.com/hpi-swa-lab/squeak-tracedebugger

[4] https://threejs.org/

[5] https://d3js.org/

[6] https://github.com/spiermar/d3-flame-graph

[7] As `d3-flame-graph` at the time of writing does not support a notion of starting points but only lengths for frames, we inject auxiliary transparent frames into the flame graph to adjust the horizontal layout of actual frames (see https://github.com/spiermar/d3-flame-graph/issues/227).

[8] The interactive visualization of the described program trace is available at https://linqlover.github.io/trace4d/app.html?trace=traces/regexParse.json and in the Wayback Machine of the Internet Archive.

Table 2: Ratings of our experience with animated object maps for program comprehension (appendix A). We gained the most insights from smaller program traces that thoroughly model behavior through communication between objects and avoid many similar objects.

Program	Configuration effort	Clarity of objects	Object layout	Animation	Program comprehension
`Regex` *engine*					
• Construction	+	+	+	+	+
• Matching	+	+	+	○	+
`Morphic` *UI framework*					
• Event handling	−	−	○	○	○
• Layouting	○	○	+	○	−
`Inspector` tool initialization	−	−	−	−	−
HTML parsing	○	+	+	+	+

After she has gained a rough overview of the object graph, she starts the animation of the program trace through the player in the timeline. By observing the trail of object activations and the position of the cursor in the timeline (default running time: 77 seconds), she notices the following rough segments of the program execution:

(1) Invoked by the pattern string, the parser dominates the first third of the program, accesses the pattern through the `ReadStream`, and talks to the AST nodes, presumably to initialize them.
(2) Next, the matcher gets active and accesses the AST nodes and the NFA states simultaneously, presumably to compile the AST into the NFA.
(3) For the remaining half of the program time, the match optimizer is active, accessing the AST again and talking to the set.

Thus, our programmer was able to gain an initial overview of the different parts of the `Regex` package and their collaboration to realize the construction of the matcher. Besides, she also noticed that almost 50% of the time were spent in the match optimizer. Without a closer idea of the role of this object, she suspects this step to be a bottleneck of the construction and wonders whether the optimization might be optional and could be skipped for certain uses of the regular expression. To dive deeper into the implementation of the `Regex` package, she expands the flame graph of the timeline, identifies a few entry point methods of the objects that she found most interesting (e.g., `RxParser»parseStream:` or `RxMatchOptimizer»initialize:ignoreCase:`), and opens them in the Squeak environment to browse their source code.

6 DISCUSSION

In this section, we discussion the potential and limitations of our visualization approach by reporting on our experience and evaluating the performance of the TRACE4D prototype for six different use cases.

6.1 Experience Report

To estimate the use of animated object maps for program comprehension, we explored six different program traces from the domains of string processing, GUIs, and programming tools in the TRACE-4D prototype and gave a reasoned rating of our experience with each example on a three-point Likert scale for five different criteria regarding the usability, clarity, and insightfulness of the visualization (table 2). We provide a full protocol of the experience report in appendix A.

Suitable traces. We made better experiences when using the visualization for smaller program traces such as different string processing examples. On the contrary, we were more challenged trying to understand the behavior of larger program traces such as operations in a GUI system or in a programming tool. In general, we found animated object maps most practical for systems that thoroughly adhere to the principles of object-oriented design by defining many fine-grained, highly coherent objects and describing behavior through extensive communication between these objects. On the other hand, program traces involving many homogenous objects or unrelated subsystems contain more repetitive or irrelevant elements and are typically less suited for exploration through animated object maps. Thus, it is the task of programmers to condense interesting behavior to a minimum program by reducing inputs and eliminating dependencies, as they already use to do when preparing a minimal reproducible example to locate the defect in a program.

Program comprehension. For suitable program traces, we were able to gain several kinds of insights and benefits from the visualization: we managed to discover characteristic regions of the object graph (e.g., the input, the AST, and the NFA for the regular expression use case, section 5) as well as significant segments of the program behavior (e.g., the parsing, compiling, and optimization stages in the regular expression use case). Based on this overview, we could develop or refine our mental model of the explored system's functioning and connect it to particular classes and objects in their implementation. Further, the interactive visualization helped us explore and analyze communication patterns, reflect upon the system design, and share and discuss these mental models with other developers.

Object graph layout. The structure of the object graph layout is determinant for the comprehension of the program state. Our force-directed graph approach provides a simple yet effective way to describe a layout based on different static and behavioral relations between objects and allows different kinds of relations to dominate the layout depending on the characteristics of the program trace. Especially for smaller program traces, the resulting layout allowed us to distinguish between essential regions of the object graph. Still, the overall structure of the force-directed layout could be considered too weak for an optimal visual intuition.

As an alternative to the force-directed layout, we consider clustering objects into discrete groups that could be displayed in a clearer structure through color coding or a hierarchical layout of objects. Clusters could either be collected from the existing force-directed layout or based on other distance metrics for objects such as their class organization, their communication patterns, or embedding representations derived from their source code or documentation.

Limitations. A general challenge of information visualization lies in reducing the complexity of the underlying data to a comprehensible but meaningful level [55]. For animated object maps, this

challenge manifests as users being overwhelmed by the amount of objects and messages in the visualization of larger program traces. To address this challenge, our approach already provides a configuration interface that allows users to reduce the complexity of the visualization by filtering objects or improving the structure of the object graph. Still, the configuration requires manual effort and is thus a barrier for users to overcome. To lower this barrier, we aim to improve the convenience of the configuration interface in our prototype by allowing users to refine the configuration directly in the running visualization; however, we see more potential in further research on automatic configuration techniques that can generate a suitable configuration for individual program traces.

Another source of complexity in animated object maps is the cluttered communication between different objects, e.g., lengthy handshakes between objects or messages that are not relevant for the high-level program behavior. To address this challenge, we want to apply trace summarization techniques to eliminate implementation details from the underlying program trace [25, 49].

6.2 Evaluation of Performance

Another challenge regards the technical performance of the visualization which affected our experience for larger program traces. We evaluate the performance of our prototype with regard to the tracing and serialization of program traces, the start-up time of the visualization, the rendering frame rates during the initial force simulation as well as when playing the animation of the program trace, and the memory consumption (table 3).

To reduce network latency, we run the TRACE4D prototype locally using Node.js' built-in HTTP server `http-server`[9] and view the visualization in a Google Chrome browser on the same machine. To measure the frame rate, we instrument the `stats.js` library[10] to record the number of frames per second (FPS) and report the average frame rate after rendering the scene for 30 seconds. We retrieve the memory consumption from the Chrome Task Manager for the tab of the TRACE4D prototype and for the GPU process; to estimate the effective GPU consumption of the visualization, we subtract the GPU consumption before starting the visualization from the later GPU consumption. To avoid distortions from the garbage collector, we invoke the visualization of each trace from an empty browser tab, exclude the first two seconds from the frame rate measurements, log the minimum memory consumption from a 30-second interval for each measurement, and report the best frame rate average and memory consumption of three runs for each trace.

While computational efficiency was not a design goal for our current implementation of the TRACE4D prototype, it already delivers practical performance for most of our considered program traces; still, there is a need for optimizing the frame rate, graphic memory consumption, and saving/loading times of program traces. Note that the limited frame rate during the force simulation is a deliberate trade-off to reduce the time until the layout stabilizes and the animation can be played.

To speed up the saving/loading times, we see great optimization potential in applying object filters in the backend (IDE) prior the serializing the program trace. To improve the responsiveness of the visualization, we consider replacing the current force-simulation libary `d3-force` by a more efficient alternative and extracting it from the UI thread into a parallel web worker. Finally, we believe that the 3D rendering performance could be improved significantly through several optimizations such as applying a level-of-detail strategy, optimizing the memory management of the application, or reducing the visual complexity of the scene.

[9] `http-server` v14.1.1, node v16.8.0.
[10] https://mrdoob.github.io/stats.js/

7 CONCLUSION AND FUTURE WORK

In this paper, we proposed a noval approach to visualize the behavior of object-oriented programs through animated 2.5D object maps that depict particular objects and their interactions from a program trace. We described the visual design of our approach and implemented it in a prototypical web application that displays program traces from a Squeak/Smalltalk environment. We described how programmers can use our tool to explore the behavior of object-oriented programs and found that especially for smaller and coherent program traces, they can gain several insights regarding the structure of the object graph and the segments of the program behavior while larger and more redundant program traces still pose practical challenges regarding the configuration of the object map, the clarity of the object graph, irrelevant details in the communication between objects, and the performance of the visualization.

In future work, we want to scale our approach to larger program traces by experimenting with different (hierarchical) layout approaches [34, 4], heuristics for automatic configuration, and techniques for trace summarization [25, 49] as well as by investing in technical optimizations of our prototype. To further improve the compactness and oversight of larger object graphs, we also consider defining state filters for hiding irrelevant fields of objects or defining conditions for aggregating similar objects into collapsed blocks.

Similarly, we hypothetize that the clarity of object graphs could benefit significantly from the use of domain-specific knowledge about the explored system [12]. For instance, particular domains such as the `Regex` engine or the `Morphic` UI framework could provide meaningful labels for objects (e.g., "\d" instead of "a RxsPredicate"), recommended filter presets, or structural hints (e.g., suggesting the use of the variables `submorphs` and `owner` to display the composite structure of a Morphic widget tree in the object map).

To explore the full potential of animated object maps for programmers, we want to integrate it into their usual development process by embedding the visualization into an IDE such as the Squeak/Smalltalk environment. This would allow programmers to immediately switch between the program trace visualization and existing code browsing and debugging tool to take different views on the system under exploration; for example, they could open an animated object map from an omniscient debugger, select an object in the map to inspect it in an inspector tool, click on a stack frame in the flame graph to browse it in an editor, or even monitor a running program in the visualization. In addition, this integration could improve the performance of our prototype as data (e.g., the fields of filtered objects) could be streamed on demand into the

Table 3: Performance evaluation of the TRACE4D prototype for different program traces with respect to frame rate, memory consumption, and saving/loading times. We measure the frame rate both during the initial force simulation and when playing the animation afterward. We find the performance to be practical for most of the considered program traces but see the need for optimization for larger program traces with respect to trace serialization, force simulation, and 3D rendering.

Program	Backend (Squeak)[a,b]			Frontend (THREE.js)[a,c]				
	Tracer[d] [s]	Serializer[d] [s]	Serialization [kB]	Start-up [s]	Frame rate (force simulation) [FPS]	Frame rate (animation) [FPS]	RAM [MB]	GPU [MB]
`Regex` *engine*								
• Construction	76	3317	138	1247	21.7	58.6	224	479
• Matching	104	10 127	316	2250	15.1	34.0	386	491
`Morphic` *UI framework*								
• Event handling	159	31 725	365	1571	22.3	52.1	267	530
• Layouting	74	14 164	369	2998	10.2	23.4	279	645
`Inspector` tool initialization	147	18 044	616	4676	5.6	15.3	397	1805
HTML parsing	176	17 494	453	7089	18.1	34.6	458	2022

[a] System: Windows 10 64-bit 22H1, Intel Core i7-8550U 1.80GHz, 16GB RAM, Intel UHD Graphics 620 8GB.
[b] Backend: TRACEDEBUGGER 2022-12-29, Squeak 6.1Alpha #22599, OpenSmalltalk VM 202206021410.
[c] Frontend: THREE.js r156, single-threaded, Chrome 117.0.5938.62 (inner window size: 1920 × 963).
[d] Excluding garbage collection.

visualization instead of serializing the complete trace in a single operation[11].

Finally, we see another interesting research direction in including the historic state of objects into our visualization [63, 64]. In the object map, we could add or remove object blocks based on their lifecycle in the program trace or highlight state changes in their fields. This would allow programmers to explore the evolution of the object graph by playing the animation or to navigate along state changes by selecting relevant fields of objects.

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[11] In terms of our TRACE4D prototype, one implementation strategy for this would be to embed the web app in Squeak using the MAGICMOUSE package (https://github.com/cmfcmf/MagicMouse) and exchange events and data through a WebSockets connection between the frontend and the backend.

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A PROTOCOL OF EXPERIENCE REPORT

Here we provide the raw data of our experience report in subsection 6.1.

A.1 Criteria

(1) *Configuration effort*: How many operations are required to reach a usable configuration in terms of filters and forces?
(2) *Clarity of objects*: Is the quantity of displayed objects manageable or overwhelming?
(3) *Object layout*: Is it possible and easy to identify regions of the object graph? How meaningful are the identified patterns?
(4) *Animation*: Is it possible and easy to recognize, follow, and perceive the flow of activity?
(5) *Program comprehension*: Is it possible and easy to identify sections of the program execution? How meaningful are the identified patterns?

A.2 Ratings

A.2.1 `Regex` *engine.*

Construction. Program trace: `regexParse.json`.

Criterion	Positive	Negative	Rating
Configuration effort	• no additional configuration required	-	+
Clarity of objects (26)	-	-	+
Object layout	• identified groups: input, AST, NFA	-	+
Animation	• manageable, overly consistent speed • no noise	• long delay in hidden dictionaries of `RxMatchOptimizer`	+
Program comprehension	• identified sections: parsing, compiling, optimizing	-	+

Matching. Program trace: `regexMatch.json`.

Criterion	Positive	Negative	Rating
Configuration effort	• no additional configuration required	• wait a few seconds for force simulation to stabilize	+
Clarity of objects (31)	-	• too many similar input characters	+
Object layout	• identified groups: input, NFA	-	+
Animation	• overly consistent speed • no noise	• too lengthy animation / too slow speed	+
Program comprehension	• identified single matches	-	+

A.2.2 `Morphic` *UI framework.*

Event handling. Program trace: `mouseDown.json`.

Criterion	Positive	Negative	Rating

Configuration effort	-	• required force weights:
		`globalFactor = 0.1`
		• required object filters:
		`excludedClassNames.push('MorphExtension', 'Dictionary')`
		• wait many seconds for force simulation to stabilize
			–

Clarity of objects (53)	-	• too many morphs, too many events with redundant state • many irrelevant fields in morphs • labels too small when zooming out, poor font quality • did not find central button morph	–
Object layout	• identified groups: kinds of morphs, events	• overwhelmingly large cluster of morphs	○
Animation	• followable	• too lengthy animation • some delays in hidden objects	○
Program comprehension	• identified sections: event dispatching	• not identified receiver morph for event	○

Layouting. Program trace: `fullBoundsTextView.json`.

Criterion	Positive	Negative	Rating
Configuration effort	-	• required force weights: `globalFactor = 0.1`	○
Clarity of objects (29)	-	• many irrelevant fields in morphs • labels too small when zooming out	○
Object layout	• identified groups: central morphs, peripheral state	-	+
Animation	• followable	• too lengthy animation	○
Program comprehension	• identified sections: very rough tree traversal	• not understood tree structure or its implications on layout	–

A.2.3 *Inspection tool construction.* Program trace: `inspectorResetFields.json`.

Criterion	Positive	Negative	Rating

Configuration effort	-	• required force weights:
		`repulsion = .4`
		`communication = 0`
		`globalFactor = .4`
		• required object filters:
		`excludedObjectNames.push('an Object')`
		• wait many seconds for force simulation to stabilize
			–

Clarity of objects (46)	-	• too many homogeneous inspector fields	–
Object layout	• identified groups: inspector fields, streams, texts	• cannot distinguish versions of inspector fields	–
Animation	-	• too lengthy animation • insufficient frame rate • some delays in hidden objects	–
Program comprehension	• identified sections: very rough traversal of inspector fields	• not identified different versions / traversals of inspector fields • not identified object under inspection	–

A.2.4 *HTML parsing.* Program trace: `asTextFromHtml.json`.

Criterion	Positive	Negative	Rating

Configuration effort	-	• required object filters:
		`excludedClassNames.push('ByteString', 'Character')`
		• cannot filter on single relevant string
		• required player configuration:
		`player.stepsPerSecond = 200`
			○

Clarity of objects (21)	-	-	+
Object layout	• identified groups: parser with stack, text parts, streams	-	+
Animation	• followable	• slightly too lengthy animation	+
Program comprehension	• identified sections: parsing of HTML tags, pushing / popping of stack, construction of text parts	-	+