A Graphical Interactive Debugger for Distributed Systems

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Abstract

Designing and debugging distributed systems is notoriously difficult. The correctness of a distributed system is largely determined by its handling of failure scenarios. The sequence of events leading to a bug can be long and complex, and it is likely to include message reorderings and failures. On single-node systems, interactive debuggers enable stepping through an execution of the program, but they lack the ability to easily simulate failure scenarios and control the order in which messages are delivered.

Oddity is a graphical, interactive debugger for distributed systems. It brings the power of traditional step-through debugging—fine-grained control and observation of a program as it executes—to distributed systems. It also enables exploratory testing, in which an engineer examines and perturbs the behavior of a system in order to better understand it, perhaps without a specific bug in mind. A programmer can directly control message and failure interleaving. Oddity supports time travel, allowing a developer to explore multiple branching executions of a system within a single debugging session. Above all, Oddity encourages distributed systems thinking: rather than assuming the normal case and attaching failure handling as an afterthought, distributed systems should be developed around the possibility of failure and then optimized for performance.

Graduate and undergraduate students used Oddity in two distributed systems classes. Usage tracking and qualitative surveys showed that students found Oddity useful for both debugging and exploratory testing.

1 Introduction

Developing correct distributed systems is difficult. Such systems are inherently nondeterministic. Messages can be dropped or arbitrarily delayed, and nodes can fail and restart. In the “normal” case where messages are delivered in order and nodes remain up and responsive, understanding the behavior of the code, as well as testing and debugging, are all relatively simple. However, bugs are more likely to hide in the unusual failure cases. For example, a version of the widely-used Raft consensus algorithm\textsuperscript{25} was discovered to have a bug in the code to handle changes in the participants to the protocol, depending on the interleaving of reconfiguration requests and a leader failover.

For single-node systems, engineers have step-through debuggers. A debugger helps an engineer reproduce and understand bugs by observing how their system’s state evolves in both normal and buggy executions. However, traditional interactive debuggers are of limited utility in debugging distributed systems: they do not allow programmers to easily control which messages will be delivered and in what order. Since the behavior of a distributed system is determined by the order in which events happen, engineers cannot debug their systems without this control.

Even the simple sanity checks that engineers can do with a traditional debugger in order to ensure that they understand how their system operates (e.g., for a given input, how many times is the inner loop executed?) are out of reach in a distributed system.

To address this, we present Oddity, a graphical, interactive debugger for distributed systems.\textsuperscript{1} It enables engineers to explore and control the execution of their system, including both normal operation and edge cases—message drops, node failures, and delays. Oddity displays the messages and timeouts that are waiting to be delivered and allows the engineer to specify their order. Oddity supports time-travel, allowing the engineer to navigate a branching history of possible executions. This enables users to backtrack and make different choices about the order in which messages and timeouts are delivered, allowing the exploration of many different cases—for instance, all of the possible orderings of a few messages—in a single debugging session. By enabling programmers to easily explore both normal cases and edge cases—indeed, Oddity makes no distinction between these cases—Oddity encourages distributed systems thinking. Rather than assuming the normal case and attaching failure handling as an afterthought, systems should be developed around the possibility of failure and then optimized for performance.

Oddity supports a general execution model: event handlers run in response to received messages or timeouts.

\textsuperscript{1}Oddity is open source and available at http://oddity.uwplse.org
A handler can modify local state, set timeouts, and send messages to other nodes. Handlers can be written in any programming language, needing only to support a simple shim API for interaction with the debugger (sending and receiving messages, setting timeouts, and updating the node’s state).

Oddity differs from previous work in several ways. Unlike previous distributed systems visualization tools, it can be used to visualize and control the network behavior of a real system, developed in any programming language. Other systems only visualize the operation of a model [24] or logs of a particular execution [2]. Similarly, previous debugging systems for distributed systems [1, 7, 12, 14, 19, 2] focused on ex post facto debugging and diagnosis, while Oddity is geared toward interactive exploration of executions. Oddity is extensible and supports multiple representations for viewing or interacting with a distributed system. Oddity supports two visual representations of a system execution. One, shown in Section 3, emphasizes the current state of the nodes and the network, including in-flight messages and timeouts, and also enables navigation through an execution. To demonstrate Oddity’s extensibility, we added a traditional (non-interactive) space-time diagram representation in under 150 lines of code.

This research makes the following high-level contributions:

- Interactive debugging of distributed systems. Oddity is the first system that allows users to interactively control the order of messages and timeouts that are delivered to each node in a distributed system, enabling both debugging and exploratory testing. Oddity is designed to encourage and enable users to reason about the correctness of their systems by exploring edge cases as well as normal cases. Developers can use Oddity to visualize execution traces mined from logs or obtained from a model-checker as a counterexample to a desired invariant.

- A conceptual model for distributed systems development. In Oddity, all messages and timeouts for a given node are grouped together in “inboxes,” indicating that any event in any inbox can occur at its node at any time, and that systems cannot assume a “normal” ordering. Oddity models event history as a tree of possible executions, allowing a programmer to explore the consequences of various event orderings by navigating multiple executions of their system.

- A novel graphical interface. Oddity includes a new graphical representation of the partial execution of a distributed system, designed to encourage users to think carefully about the correctness of their systems.

This interface allows users to inspect a single state of the system in detail, while also enabling navigation through an execution of the system.

- A study of student usage of Oddity. Students used Oddity in lab assignments for two distributed systems classes. We studied students’ experiences with Oddity with opt-in usage tracking and an optional survey. In addition to providing evidence that Oddity is useful for distributed systems development, our classroom experiment provides the first insights into student behavior with an interactive debugger for distributed systems.

The rest of the paper is organized as follows. Section 2 presents Oddity from a user’s perspective via a running example: diagnosing a bug in the Raft consensus protocol. Section 3 discusses Oddity’s graphical interface in more detail. Section 4 discusses Oddity’s architecture. Section 5 discusses our prototype implementation of Oddity. Section 6 discusses our deployment of Oddity to two university distributed systems classes; students were able to use Oddity for both debugging and exploratory testing. Section 7 discusses related work, and Section 8 concludes and presents some potential avenues for future work.

## 2 Example usage

We introduce Oddity’s core ideas and interface via a running example: an implementation of Raft [25]. Raft is a consensus protocol, a key component in the construction of strongly-consistent distributed services. A consensus protocol enables a cluster of nodes to agree on a sequence of values to apply to a state machine, despite node failures and arbitrary message delays. To support changes in the nodes participating in the state machine consensus, Raft includes a reconfiguration protocol in which both the new and old sets of nodes must agree on any new configuration. The reconfiguration protocol could be triggered manually by a system administrator or automatically by a cluster management system. In part because it was well-documented and included source code, Raft has become widely deployed in industry.

Ongaro’s dissertation [23] includes a simplified reconfiguration protocol designed for single node changes. Several years after publication, researchers discovered a bug in this simplified protocol: in a cluster with an even number of members, if two competing reconfiguration requests occur with a leader election in between, the cluster can lose data. A simple fix, proposed when Ongaro publicly announced the bug, is to require that new leaders commit an entry to the log in the old configuration before committing a new configuration. Several months
Figure 1: A space-time diagram, generated with Oddity and lightly edited for clarity, illustrating a Raft execution leading to the reconfiguration bug. Each vertical line represents a node in the system, and arrows between them represent messages. The circles represent messages received from clients of the system (elided for presentation).

Passed between the bug being identified and the fix being announced.

For explanatory purposes, we imagine a Raft maintainer has been informed of the existence of the buggy execution; using Oddity, they are trying to determine why it happens and how it can be fixed.

Figure 1 shows an execution leading to the Raft bug. First, a leader (S1) is elected in a 4-node cluster by a majority including itself, S2, and S3. Then, S1 starts to replicate a new configuration that adds a fifth node, S5. In the single-server reconfiguration protocol, each server uses whichever configuration is latest in its log (regardless of whether it is committed). The leader sends this new configuration to S5 (shown on the left of Figure 1) as well as the rest of the cluster (assumed to be delayed or dropped in Figure 1). After this configuration is replicated to S5, S2 starts an election and is elected with votes from S1 and S4. This might occur, for example, if the reconfiguration messages from S1 are delayed to those nodes, e.g., due to a temporary network outage. (Consensus should work even when nodes incorrectly judge that other nodes have failed.) Now that S2 is leader, it starts to replicate a new configuration that removes S1 from the cluster, leaving the three nodes S2, S3, and S4 (since the configuration with S5 was never replicated to S2). It successfully replicates this configuration to S3, at which point it can commit the configuration since it is on a majority of nodes in the new cluster of three nodes. Now S1 starts another election, and becomes leader with votes from S4 and S5. It can now finish replicating its configuration adding S5 to the whole cluster, which overwrites S2’s committed configuration. This is a violation of a crucial Raft safety property: once an entry is committed, it should never be overwritten.

Without Oddity, the Raft engineer has several options to reproduce and diagnose this failure. They could examine the code and try to imagine an execution that would trigger the bug, but this is both time-consuming and error-prone. They could design an automated test to find the issue, but testing distributed systems is notoriously difficult [20]. Since the issue depends on a failover, the test environment would need to simulate a temporary network partition. The test environment would also need to ensure that messages are delivered in a specific order with respect to other messages and the network outage. The engineer would also need to write an oracle that determines whether the bug has in fact been triggered (i.e., whether data are lost). Finally, the engineer could run their code in a traditional debugger and attempt to trigger the issue. Doing so, however, would still require simulation of failures and control over the order in which messages are delivered.

The rest of this section shows how Oddity makes the Raft engineer’s task easier. This illustrates Oddity’s functionality via one important use case: reproducing and diagnosing a bug in a distributed system. Oddity can also be used for open exploration of a distributed system’s behavior, or for visualizing a counterexample produced from a model checker.

2.1 Initialization

Oddity assumes that the system being debugged is implemented as a set of event handlers: deterministic functions that can read and write the node’s state, send messages, and set timeouts through the Oddity shim API (detailed in

\[2\] A screen-cast version can be found at [http://oddity.umpise.org](http://oddity.umpise.org).
In order to use Oddity, the engineer makes a few changes to the system. The engineer first connects the system’s handlers to Oddity by routing communication through the Oddity shim instead of the standard networking library (this can typically be achieved by a small macro or command line flag). Next, the engineer creates a node to represent the system’s client. This node can set timeouts that cause communication with the rest of the system. In response to a timeout, the Raft client should send the reconfiguration commands from the counterexample in Figure 1. The client can be developed using any language for which an implementation of the Oddity shim is available.

Having linked the system and the client with the shim, the engineer can run the system under Oddity.

### 2.2 Finding a buggy execution

When the engineer first starts Oddity on their system, they will see a screen similar to Figure 2. Each node has an “inbox” next to it, which contains both messages sent by other nodes and also timeouts the node has set itself. At the beginning of time, no messages have been sent, so each node’s inbox contains only the timeouts waiting at that node (including $S_5$, which has not yet been added to the cluster). Timeouts are used to cause events to fire without messages being delivered. For instance, the election timeouts in Figure 2 are fired when a node has not received a message from a leader for sufficient time, and cause the node to start an election.

The engineer will first need to get $S_1$ elected leader. They can click on the $E$ (election) timeout in $S_1$’s inbox to deliver it, causing $S_1$ to send $RV$ (Request Vote) messages to the other nodes in the initial configuration (excluding $S_5$, which has not yet been added). The resulting state of the system, with a $RV$ message in each node’s inbox, is shown in Figure 3. These messages are now waiting to be delivered.

The engineer can then click on each $RV$ message to deliver them, causing them to respond to $S_1$ with their $V$ (Vote) messages. In Figure 4, these messages have been sent and $S_2$’s state is expanded, showing that it voted for $S_1$. Since Raft requires a quorum to elect a leader, once two of these votes are delivered $S_1$ considers itself elected.

Now that $S_1$ is the leader, the engineer can investigate the reconfiguration bug. They can make the client (not shown) send a reconfiguration request to add $S_5$ by delivering a timeout. They can inspect the request by clicking on it, as shown in Figure 5. Once the request is delivered, the leader will try to commit this new configuration to a majority of the new configuration per the single-node reconfiguration protocol.

Once the new configuration has been replicated to $S_5$, the engineer needs to trigger a new leader election in order to continue following the counterexample. They can do so by delivering the $E$ timeout to $S_2$. This timeout is reset every time a heartbeat comes in from the leader, and if it ever arrives the follower decides the leader has failed and makes itself a candidate.
Figure 5: The state of the Raft system in Oddity after client sends its reconfiguration request. The request is open for inspection. As shown, the engineer can choose to duplicate it or drop it rather than delivering it.

The rest of the leader election is elided for brevity. The engineer now clicks on the client’s other timeout, causing it to send a second reconfiguration request dropping $S_1$. It is delivered at $S_2$ and $S_2$ replicates the new configuration to $S_3$; this configuration is now committed, having been replicated to a majority of the new cluster.

The counterexample now calls for $S_1$ to start a new election, which it can do after receiving $S_2$’s RV message and then its E timeout. After getting elected, it replicates the configuration with $S_5$ to the rest of the cluster. Crucially, $S_1$ replicates the updated configuration to $S_2$, overwriting a previously-committed entry and demonstrating that the engineer’s Raft implementation is buggy.

2.3 Backtracking

Investigating the Raft reconfiguration bug in Oddity involves a number of steps. The engineer might mistakenly click on the wrong message (for instance, delivering the node removal request to $S_2$ before the leader election happens). The engineer might also want to explore alternative executions. The reconfiguration bug can be fixed by requiring that a leader replicate an entry (which could be a no-op) in its term before attempting to reconfigure the system. In order to test this potential bug fix, the engineer could explore an execution in which $S_2$ does this, attempting to replicate a no-op entry in the old configuration. In order to proceed, $S_2$ must replicate the no-op entry to at least three nodes (e.g., $S_2$, $S_3$, and $S_4$) before it can attempt to remove $S_1$ from the replica set. At that point the pending reconfiguration with $S_5$ will not succeed, since $S_1$ will not be able to be elected leader until its log is up to date with the rest of the cluster. The engineer now has some evidence that the Raft reconfiguration bug can be fixed by requiring that a leader replicates an entry in its term before attempting to reconfigure the cluster.

3 Frontend

Oddity’s graphical interface, shown in Figure 6, is designed to enable engineers to easily explore executions of distributed systems, including failure cases. The graphical interface was designed with several requirements in mind:

1. It should be application- and implementation language-agnostic. A user should be able to graphically debug their system without developing a system-specific visualization.

2. It should neither depend on nor suggest to the user any notion of real time. Messages can be arbitrarily
delayed and reordered, and timeouts can be delivered even if no failures occur.

3. It should enable detailed inspection of a single global state of the system (including the contents of all messages and the local state at every node), control over which event should be executed next, and navigation between system states for the purpose of time travel.

In this section, we discuss how Oddity’s frontend addresses each of these requirements.

3.1 Application-agnostic

Distributed systems are designed to provide reliable service in diverse contexts and this is reflected in their structure and operation: Chord [28] and Dynamo [5] maintain a ring structure via pointers at each node, Raft has a single leader who communicates with a number of followers, the DNS system has a loose tree structure, etc. Rather than forcing system developers to develop visualizations for the structure of each system, Oddity’s interface displays the components all distributed systems have in common: a set of nodes communicating via a network. When the user starts Oddity, it displays each system node in a circle. The user can then reposition the nodes as they desire by clicking and dragging.

Oddity does not yet support application-specific extensions to the visualization (for instance, to display a star next to Raft leaders or arrows describing Chord’s ring structure), but we anticipate that these will be easy to add. Thus far, we have focused on making Oddity useful even for developers who are not willing to develop such visualizations.

3.2 No real time

The unreliability of physical clocks due to clock skew is a fundamental problem in distributed systems [15]. Engineers cannot rely on measurements of time being consistent across nodes except within very loose bounds. As a result, most distributed systems are designed around the possibility that messages can be arbitrarily delayed by the network. While messages are often thought of as moving through the network over time to their destination, Oddity does not represent them this way; doing so would imply a semantic meaning to real time. Instead, messages are immediately transferred to the receiver’s inbox and can then be delayed for an arbitrary amount of time (or dropped), under user control. Oddity’s display encourages users to ignore wall-clock time in thinking about distributed systems correctness, and instead think about correctness in the face of all possible event orders.

3.3 State inspection and history navigation

Oddity’s graphical interface is geared towards representing a single state of the system—including in-flight messages and timeouts—in detail, while also enabling users to navigate a branching execution history. Users can click to inspect server state or the contents of messages and timeouts. Enabling detailed inspection is crucial for a debugging interface, since engineers use this information to decide which message or timeout should be delivered next. Oddity supports time travel debugging, allowing engineers to navigate to any previously explored state and explore a branching execution history without starting from scratch.
Table 1: The Oddity API. In order to use Oddity, users must implement a simple, JSON-based message API. Once a system node registers with the server, it responds to each message (including the start message, which is sent at the beginning of a debugging session and after a reset) with its updated state, sent messages, and set and cleared timeouts.

| Message                      | Description             | From/To         |
|------------------------------|-------------------------|-----------------|
| register(name)               | Register a node         | Node to server  |
| start                        | Start the node          | Server to node  |
| timeout(type, body)          | Deliver a timeout       | Server to node  |
| message(from, type, body)   | Deliver a message       | Server to node  |
| response(state, messages, timeouts, cleared) | Response to any event | Server to node  |

4 Architecture

Figure 7 shows the architecture of the Oddity debugger. As shown, Oddity consists of several cooperating components: a browser-based frontend that displays the interface discussed in the previous section; a backend, split between the browser and the server, that tracks the system’s state, implements time travel, and communicates with nodes in the system; and a shim that runs at each system node, communicates with the server, and calls the node’s handlers. Oddity’s graphical interface is independent of its backend; either could be replaced without changing the other.

4.1 Debugger backend

The debugger backend tracks the state of the system, including the local state at each node and in-flight messages and timeouts. It also tracks the event history. Each event is either a message delivery or a timeout delivery; a special “start” event represents the beginning of time. When the user clicks on a message or a timeout, the backend records this event and then sends the message or timeout to the Oddity shim instance running on the appropriate node. When it receives the response, it updates the display to reflect the new messages and timeouts and the modified local state.

When the user clicks on a state in the history display, the debugger backend resets the system to that point by replaying all of the events that led to that state (including the special “start” event). The user can then explore alternative executions starting from that state. This technique will not work if the system has non-deterministic handlers or accesses persistent state outside the debugger’s control. Oddity could be extended to support such systems by recording a snapshot of each node’s state after every event. We leave such an extension for future work.

4.2 Oddity shim

The Oddity shim is a library written in the user’s implementation language that implements communication with the Oddity server and is responsible for tracking the local state of the system. It must implement the API shown in Table 1 for communication with the Oddity server, and must call the user’s event handlers for start, timeout, and message calls from the server. It must provide user code with some mechanism for updating the local state of the node, as well as sending messages and setting timeouts.

The Oddity shim currently assumes that the user’s code is written as a set of event handlers. Oddity cannot currently be used to debug systems developed against a different programming model, such as multi-threaded servers using blocking RPC calls. This limitation is not fundamental, and Oddity’s architecture and visualizations can be extended to support such systems. We discuss this potential future extension in more detail in Section 7.

4.3 Trace display

Model checkers have been applied to distributed systems to great effect [32, 11]. The counterexamples they produce, however, can be long and complex. Rather than starting Oddity on a system and debugging from the beginning of time, a user can start Oddity with a trace of that system’s execution, produced by a model-checker as a counterexample to a desired property. A common use pattern is for the engineer to use time-travel to explore the sequence of events that led to the invariant violation. The user can also use Oddity to investigate other executions branching off of the trace. The same approach facility can also be used to investigate traces mined from system logs by tools such as DEMi [27] to investigate bugs encountered during testing or production use. Oddity enhances techniques such as model-checking and log analysis by providing the engineer with tools to explore the context of the bug as well as alternative executions that might or might not trigger the same problem.

5 Implementation

Our research prototype of the Oddity debugger is implemented in approximately 1400 lines of Clojurescript (for
the browser-based frontend) and 500 lines of Clojure (for the backend). Its interface uses SVG, and we have not found rendering performance to be an issue even with large systems and long execution traces. The current user interface is more limited—it is intended to be used with roughly 10 or fewer nodes for regular debugging and exploration tasks. The frontend uses a Websocket to communicate with the backend, which communicates with the shim over TCP.

We have implemented the Oddity shim for Python (121 lines of code) and Java (293 lines of code), and we have developed several systems against each implementation. It is easy to develop a new shim in any language with libraries for JSON serialization and network communication. The course labs discussed in the following section use the Java implementation of the shim. Table 2 shows all of the systems that have been debugged using Oddity, which version of the shim they used, and approximate lines of code for each system. The largest system we have debugged using Oddity is a sharded linearizable key-value store using Multi-Paxos replication to provide exactly-once, highly available operations on each key. The shard allocations are dynamic, and the system also supports simple multi-key transactions.

6 Evaluation

We have deployed Oddity to two classes: a 40-student graduate-level distributed systems class, which served as a pilot, and a 180-student undergraduate-level distributed systems class. In both cases, Oddity was given to students as part of the lab framework they used to do their homework assignments. The labs come with extensive test suites, and include a model-checker. Students can run Oddity in two modes: they can start their system and explore from the beginning of time, or run Oddity on a counterexample trace produced by the model-checker when an invariant is violated.

We had two goals in studying students’ experience with Oddity. One was to determine whether Oddity’s features are useful. The other was to examine student behavior when given access to an interactive debugger for distributed systems, in line with previous work that examines student usage of traditional step-through debuggers and developer usage of trace visualization tools. We hope that our experiences can inform future work in the same area.

We studied student experiences with Oddity in several ways. We instrumented the Oddity interface in order to track users’ clicks on various interface elements in order to see how they interacted with the system (this feature was only enabled if students opted into it). We sent out an optional survey to students after they completed the first major lab assignment, a primary-backup-based key-value store (as of this writing, other labs are ongoing). The survey is shown in Figure 2. We also informally discussed Oddity with students, recording anecdotes about their usage of the system on the primary-backup lab as well as the next lab, a Paxos-based key-value store.

We have defined several research questions, each based on a different use-case for Oddity: exploration of a system from the beginning of time in order to understand its operation and to find possible bugs; diagnosing and understanding a particular known bug; and replaying a trace from a model-checking counterexample. The research questions are as follows:

RQ1: Do developers explore their systems starting from the beginning of time? When doing so, do developers use Oddity to test their systems’ edge case behavior?

RQ2: Do developers find the debugger useful in diagnosing and repairing bugs? When doing so, do developers explore multiple branches?

RQ3: Is the ability to explore alternative executions starting from a model-checking trace useful for understanding why the bug occurred?

We discuss each of these questions in detail below. The two modes in which a student can start the Oddity debugger are (1) to start it on their system and explore from the system’s start state and (2) to start it on a trace generated by the model-checker when it finds a counterexample to a desired invariant. We use these as rough proxies for (A) exploratory testing, in which developers explore systems in order to understand them and find bugs and (B) diagnosing a specific bug, respectively; this is imperfect, since students may start their system from the beginning of time but with a specific bug in mind.

RQ1. Do developers explore their systems starting from the beginning of time? When doing so, do developers use Oddity to test their systems’ edge case behavior? We found that 74.5% of Oddity runs started from the beginning of time, as opposed to from a model-checking trace. In these runs, users explored an average of 37.3 states per run, with a median of 23 states per run. From this we can conclude that students did use the debugger for exploratory testing. We received some survey data to suggest that students were able to explore edge cases using this mode. One student said that “It was useful for one bug where I found out there was unexpected behavior from the [view server] when both the primary and backup timed out at the same time.” This indicates that students used Oddity to explore edge case behavior. We also received an anecdote from a student about a bug in which their Paxos implementation sent redundant messages under certain conditions (specifically: when a proposer re-
Table 2: Systems that have been debugged using Oddity, the version of the shim they used, and lines of code for the system implementation.

| System                              | Shim Language | SLOC |
|-------------------------------------|---------------|------|
| Lamport mutual exclusion            | Python        | 73   |
| Raft (with reconfiguration)         | Python        | 240  |
| At-most-once RPC                    | Java          | 280  |
| Primary-backup replication          | Java          | 380  |
| Paxos replication                   | Java          | 550  |
| Sharded transactional key-value store | Java        | 1390 |

ceived more than a majority of replies to its “prepare” messages, it ended up sending extra “accept” messages). The student did not suspect the existence of this bug before noticing it in Oddity, and believed they would not have found the bug at all without Oddity (the provided test suite did not test for the presence of these extra messages). Without an interactive debugger that can control message and timeout ordering, exploratory testing of distributed systems is tedious, and the usage tracking and survey results indicate that students find this feature very useful.

A number of students said that they did not explore their systems starting from the beginning because they only debugged their system when a test case from the provided test suite failed. Our results may be biased as a result of our setting: with an extensive test suite, some students may not have felt a need to understand their system behavior independently of its behavior on the tests. It is possible that without such an extensive test suite, students would have found it more useful to start their systems in the debugger. On the other hand, our evaluation is of students and not professional developers. The students were learning about the protocols at the same time as they were implementing and debugging them, so it is possible that exploratory testing was a more compelling option for students than it would be for more experienced developers.

**RQ2.** Do developers find the debugger useful in diagnosing and repairing bugs? When doing so, do developers explore multiple branches? We found that 25.5% of Oddity runs started from a model-checking trace. In response to survey question 2, students reported that Oddity “helped [them] diagnose [their] handling of state transfer and state transfer acknowledgements” and that they were able to use it to diagnose a bug in which they “had some delayed messages arriving and causing problems.” A student reported successfully using Oddity to diagnose a bug in which the system had stopped making any progress after their latest change, which implemented deduplication of redundant client requests. They stepped through a simple test case and found that servers were never actually responding to clients; they were then able to fix the issue.

**RQ3.** Is the ability to explore alternative executions starting from a model-checking trace useful for understanding why the bug occurred? When students started their systems from a model-checking trace, 23.6% of those executions explored multiple branches. In those cases, those state graphs branched an average of 1.5 times. From this we can conclude that at least some students explored alternative executions when viewing a model-checking counterexample. In response to survey question 3, some students did report that exploring alternative executions was useful. One student said that

1. Did the debugger help you to discover any bugs in your system? Describe one.

2. Did the debugger help you to diagnose any bugs you were already aware of? Describe one.

3. When using the debugger to view a search-test counterexample, did you also explore other executions? Did this help you to understand the counterexamples? Describe an instance of this being useful.

4. Were there any bugs you think you would have found earlier if you had used the debugger? If not, how could the debugger have been more useful to you?

5. Do you have any other feedback about the debugger?

Figure 9: The optional survey sent to students after completing a homework assignment. We referred to tests that called the model checker as “search tests.”
7 Discussion

Oddity provides an extensible platform for investigating many aspects of distributed systems beyond the examples illustrated in earlier sections. Below we describe how Oddity could facilitate new tools and methodologies for debugging, implementing, and designing distributed systems. We have left these features for future work.

7.1 Interactive space-time diagrams

In addition to the primary “nodes and inboxes” visualization, Oddity supports visualizing a system’s execution as a space-time diagram (e.g., Figure 1). Space-time diagrams are useful for viewing a summary of an entire execution trace at once. Because of Oddity’s extensible design, adding a traditional (non-interactive) version of space-time diagrams required less than 150 lines of code: Oddity simply pipes a formatted version of the system trace through GraphViz [8], and displays the resulting SVG image in the browser.

In Oddity, space-time diagrams could be enriched with more detailed information about the currently executing system, e.g., by adding JavaScript hooks so that when a user hovers over a node in the space-time SVG, the state of that individual node at that point in history is displayed. Such an enriched space-time diagram would provide a bridge between the “nodes and inboxes” and branching trace history visualizations. Adding these additional features introduces new design and user interaction challenges:

- How should in-flight messages and timeouts be represented?
- How should users interactively control system execution or time travel from such a diagram?
- In what scenarios is one visualization simpler or more effective than another?

Oddity is well-suited for exploring these challenges: the Oddity API abstracts away many of the tedious details for modeling the network, controlling implementations of nodes, and interacting with different programming languages.

7.2 System-specific interface components

The Oddity frontend is built around a generic SVG-based canvas which makes integrating other visualization tools straightforward (e.g., for space-time diagrams as discussed above). In particular, Oddity could easily support systems which control aspects of their own visual representation by providing a mechanism to add additional shapes to the frontend SVG. This could be as simple as nodes (optionally) providing a special field in their local state with literal SVG objects to add to the visualization relative to the node’s own position. These extensions would enable generic system-specific visualization. For instance, the developer of a state-machine replication system might want to display the log of commands seen at each node as an array of boxes colored by term, while the developer of a ring maintenance system such as Chord might want to display the successor and predecessor of each node as arrows to other nodes. This would involve adding an API for systems to write elements to Oddity’s SVG-based interface, and perhaps developing a library of commonly-useful components (such as the arrows mentioned above). In general, Oddity’s architecture makes integrating new visualizations easy. Oddity’s browser-based frontend also simplifies building on recent advances in data visualization libraries such as D3 [3].

7.3 System model

Initially, we have focused on using Oddity to debug and explore distributed systems where node implementations behave as deterministic, single-threaded event handling loops. This class of systems corresponds to the example protocols used in lectures and exercises for the courses where Oddity has been used to date (Section 6). It also corresponds to the model used by recent projects formally verifying implementations of distributed systems [31, 9, 18]. However, many distributed systems rely on some combination of nondeterministic choice, blocking RPC-based communication, and local multi-threading at nodes.

For basic control and visualization, Oddity already supports nondeterministic distributed systems. However, Oddity’s replay-based approach to time travel will not correctly restore local node states with nondeterministic handlers. To correctly provide time-travel in the face of nondeterminism, Oddity could require that each node send a snapshot of its current state after each event, or we could extend the Oddity shim to fork a child process after each event to effectively save a “paused” instance of a node’s process. Equipped with such an extension to the backend (and without any changes to the frontend), Oddity could support time travel for nondeterministic systems by restoring arbitrary previous states from snapshots.

Many implementations of distributed systems allow for the concurrent execution of event handlers for higher performance; for example, updates to different keys in a key-value store can be safely handled in parallel on different processors of a multi-core server, e.g., using locks to arbitrate access to shared data structures. Thus, the system behavior may depend on the thread scheduling decisions made on the local node. If the bug being diagnosed is invariant to the local thread schedule, it may suffice to
simply enforce a single canonical thread execution order, such as with deterministic multi-threading [6]. If the bug manifests due to the interaction of the local schedule and distributed event delivery, then we would need to extend the visualization model to allow the programmer to control both.

Supporting RPC-based systems adds another layer of complexity to the interface between the debugger and the system. Oddity’s system model assumes that nodes atomically send messages in response to receiving a message or timeout and then immediately return to the top of the event loop, ready to handle the next (arbitrary) input event. With RPC systems, the event loop is inverted. Although the code performs the same computation in the same order as in an event system, a message arrival is “handled” only when a thread retrieves it, e.g., in response to a previous send.

7.4 Deeper model-checker integration

Oddity is designed to use event traces as a common representation for communication between the frontend and backend and between the backend and node shims. This design choice made integration with a model checker straightforward: the backend can simply walk a counterexample produced from the model checker as a trace and use each step to replay events on the nodes as in time travel debugging. As discussed in Section 6 this straightforward technique for integrating model checkers has already proved valuable for Oddity users. To further integrate model-checker functionality, Oddity could highlight particular components of a system state that violate the desired invariant.

More ambitiously, a model-checker could also be used to provide Oddity with “breakpoints.” Many systems do some initial bootstrapping and setup that may be tedious to simulate manually in Oddity (for instance, electing an initial leader). Instead, a developer could specify that they want to debug the system starting in some state meeting a global property (such as after a successful election). Oddity could ask the model-checker to find such a state, and then allow the user to explore the system’s execution starting from the state returned by the model-checker.

8 Related Work

Oddity builds on previous work in several areas, including distributed systems correctness, distributed systems log exploration, and distributed systems visualization. We discuss each of these areas in detail below. In addition, Oddity depends on a long line of work on single-node program debugging; many aspects of Oddity’s design were inspired by graphical step-through debuggers such as DDD [33].

Distributed Systems Correctness  Systems such as TLA+ [17], Alloy [10], and Ivy [26] have been used for bug-finding and verification of high-level, abstract models of distributed systems (Ivy has recently been extended to support extraction to runnable code [30]). All three share Oddity’s goal of enabling users to understand the behavior of their systems and encouraging correct distributed systems thinking. TLA+ and Alloy use bounded model-checking; Oddity could be used in conjunction with these systems to display model-checking counterexamples. Ivy enables automatic verification of distributed systems specified in a carefully-crafted subset of first-order logic; it includes a graphical representation of counterexamples. Oddity complements these systems by enabling users to interactively debug both models and working implementations of distributed systems during development and after deployment.

Distributed systems log analysis  There has been a large amount of work on collecting and analyzing logs of distributed systems [1, 2, 12, 13, 14, 34, 19, 2] and, relatedly, datacenter networks [21, 29]. Many of these systems, such as ShiViz [2], provide a graphical interface, allowing users to interactively explore the logs produced by their system. ShiViz’s visualization is based on spacetime diagrams; it allows users to explore large and complex executions by querying the log and collapsing and expanding events. Like Oddity, these tools are designed for debugging and understanding distributed systems implementations. Unlike Oddity, these tools are for ex post facto debugging of system logs, rather than interactive debugging of a system’s behavior; log analysis systems do not enable exploratory testing. These two use cases complement each other: having obtained and examined a system log using ShiViz, an engineer can replay the log locally using Oddity in order to understand it and diagnose any problems that were encountered. Using Oddity, a user can explore alternative message orderings to determine whether they also produce bugs; existing log analysis systems do not support this.

Distributed systems animations  Runway [24] is a system for visualizing models of distributed systems. It consists of a domain-specific high-level modeling language based on TLA-like actions. An interpreter for this language is written in Javascript and an API for extracting values from the interpreter for visualization. Several models and animations have been developed using Runway, including a visualization of the Raft consensus protocol.

Oddity’s visualization was inspired by those created for Runway. Oddity is much more general, however. Users
of Runway must create protocol-specific visualizations, e.g., there is a visualization for Raft that would not apply even to related protocols such as Multi-Paxos or primary-backup. The students to whom we gave Oddity would have had to write their own Runway visualizations, since they were instructed to implement against a specification but were not forced to use any particular algorithm. Additionally, Oddity can be used to debug systems written in any language, while Runway requires users to model their systems in its domain-specific language.

9 Conclusion

Oddity is the first interactive graphical debugger for distributed systems. It allows users to control the delivery of events to the distributed system and observe the resulting execution. Oddity provides time travel to enable debugging multiple executions in order to explore normal- and edge-case behavior. Oddity introduces a new visualization and interaction mode that encourages distributed systems thinking: rather than assuming the normal case and attaching failure handling as an afterthought, users are shown the vast range of possible behaviors and provided with the tools needed to effectively explore. Dozens of student users learning about distributed systems across graduate and undergraduate courses have reported the value of such exploration when debugging and learning what makes systems (not) work. Finally, Oddity provides an extensible platform that can support research investigating new questions about how best to visualize and explore a greater range of systems.

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