ABSTRACT

Time-traveling in the execution history of a program during debugging enables a developer to precisely track and understand the sequence of statements and program values leading to an error. To provide this functionality to real world developers, we embarked on a two year journey to create a production quality time-traveling debugger in Microsoft’s open-source ChakraCore JavaScript engine and the popular Node.js application framework.

CCS Concepts

•Software and its engineering → Software testing and debugging;

Keywords

Time-Travel Debugging, JavaScript, Node.js

1. INTRODUCTION

Modern integrated development environments (IDEs) provide a range of tools for setting breakpoints, examining program state, and manually logging execution. These features enable developers to quickly track down localized bugs, provided all of the relevant values remain on the call-stack and the root cause of the failure is close to where the error manifests itself. However, they provide only rudimentary support to iteratively track down more difficult errors: developers often resort to repeatedly setting breakpoints and rerunning the program. The dynamic nature of JavaScript and the extensive use of callbacks/promises in Node.js can make this process especially tedious and time-consuming.

Time-traveling debuggers offer an attractive alternative to the iterative process of debugging nontrivial errors using a traditional debugger. Instead of requiring developers to stop debugging, set a new breakpoint, and then reproduce the desired execution to hit that breakpoint, time-traveling debuggers allow a developer to simply press a button to step-back in a program’s execution. We present JARDIS, a time-traveling debugger for JavaScript; it provides a rich set of functionality for recording and navigating the execution history of a program including:

- Options for both using time-travel during local debugging and for recording a trace in production for postmortem debugging or other analysis (Section 2.1).
- Reverse-Step Local and Dynamic operations (Section 2.2) that allow the developer to step-back in time to the previously executed statement in the current function or to step-back in time to the previously executed statement in any frame including exception throws or callee returns.
- Reverse to Callback Origin operation (Section 2.3) that reverses time to the line that registered the currently executing callback e.g. the call to setTimeout(...) where the currently executing function was registered.

In combination with the low-overhead imposed by JARDIS (under 2% runtime increase in Section 4), these features provide a system that is suitable for use as both the default debugger for Node.js applications and for collecting execution histories from in-production deployments. Thus, JARDIS represents a major advance in state of the art debugging tools and provides an enabling technology for related research areas including interrogative debugging, automated fault localization, and performance profiling.

2. FEATURES

JARDIS provides a range of features for debugging programs using JavaScript/Node.js and improves developer productivity in both local and postmortem debugging scenarios.

2.1 Local Debugging and Offline Recording

JARDIS starts by augmenting the conventional graphical debugger, including its variable and call stack displays, breakpoints, and single-stepping, with the ability to reverse step through code execution via its Reverse-Step button as shown in Figure 1.

A video demo of JARDIS is available at [12].
JARDIS also supports postmortem debugging, as shown in the workflow in Figure 2. In this scenario, the developer runs their application under JARDIS’s record mode when deployed to their users, given their consent. When an error occurs, the execution trace is sent to the specified location for debugging later. The collected trace has sufficient information to replay the execution of the program exactly, including any non-determinism, and show the value of any JavaScript program variable that the developer might be interested in. Thus, the debugging experience is the same as if the developer had a debugger attached to the remote Node.js process when the trace was collected.

To record the trace, the developer simply invokes Node with an additional command line flag, `-TTRecord: [uri]`, where the `uri` parameter indicates the location (a file or remote server) to save the data. By default, we continuously record approximately the most recent 2–4 seconds of execution in a ring buffer and save the data if an unhandled exception occurs, a call to `process.exit` is made, or a dump is explicitly requested by the application. All of these parameters can be adjusted as desired.

Later, the developer can load and debug the serialized trace by invoking the replay host with `TTDebugHost [uri]` and attaching a debugger. In Figure 2, Visual Studio Code [23] is configured to do this and execute the code/trace to the point where the exception is thrown. When this point is reached, the debugging experience is virtually identical to the standard local debugging scenario: the developer can inspect any value of interest, view the stack frame, set breakpoints, step forward/back in the code, and even evaluate expressions in the watch window.

### 2.2 Reverse-Step Operations

The first type of reverse-step operation, and most commonly useful, provided by the JARDIS tool is a reverse-step (rs) to the previously executed line in the current call frame. This is simply the reverse version of the forward step provided by existing graphical and command line debuggers. The next type of reverse operation provided by JARDIS is reverse-step dynamic (rsd) which acts as the reverse version of step-into operations in existing debuggers. This operation steps-back in time to the previously executed statement in any frame.

To illustrate the various use cases for these operations and how they differ, consider the code in Figure 3. If the current breakpoint is at line 14, labeled `bp1`, then the `rsd` operation reverse-executes to the return statement of the previously called method (line 2 in `bar`) while the `rs` operation reverse-executes to line 13. When the current position is the result of an exception, line 10 labeled `bp2`, the `rsd` operation reverse-executes to the throwing statement at line 2 in `bar`, while the `rs` operation reverse-executes to line 8. In all other cases, the behavior of `rsd` and `rs` is the same.

![Figure 2: Remote recording with a telemetry service, followed by postmortem debugging at full fidelity.](image)

![Figure 3: Reverse-Step (rs) vs. Reverse-Step Dynamic (rsd).](image)
re-execute the needed actions in the ChakraCore engine e.g. loading JavaScript code from files, calling JavaScript functions, or creating/modifying JavaScript objects.

2. Internal ChakraCore code paths that involve non-deterministic data, such as getting the current Date/Time, the invocation of external native code, or where enforcing deterministic execution was impractical. Property enumeration is an example where forcing a deterministic order is impractical.

3. Node host actions that bypass the JsRT API and directly modify BYTE* buffers for efficiency, as well as cases where the host has diagnostic information that ChakraCore cannot access, such as event loop status or callback dispatch dependencies (Section 3.3).

When invoked, the replay host TTDebugHost loads the specified log file, finds the first snapshot in the log, inflates the program state from this snapshot, and then begins replaying events from the log until hitting a breakpoint. Some of the events in the log correspond to external actions (event categories 1 and 3) and are directly replayed by the host. For example, we may have recorded that the Node runtime accessed a property of an object, created an ArrayBuffer, and then directly initialized the contents of the buffer with data from the network. To replay the original execution correctly, the replay host must explicitly simulate all of these actions. Other events in the log, event category 2, are replayed implicitly by the ChakraCore engine during its execution. During the original run, for example, the JavaScript Date.now function records its result into the log; at replay time, the ChakraCore engine simply reads this value from the log and returns it.

To allocate and record each event with a very low overhead, we use a bump-pointer allocator with fixed-size 40 byte entries and the occasional entries that need more space can allocate a second buffer. As JavaScript extensively dynamically loads and evaluates code, JARDIS’s logger maintains a second log to record the URI origin of code, whether the code was loaded from a file, via eval, or new Function, and the code’s source and associated internal sourceld information.

3.2 Snapshots

JARDIS takes snapshots of the program state at regular intervals. These snapshots allow a developer to jump between points in time in the recording, avoiding replay from the start of the log, and allow a developer to start a recording at any point during a program’s execution. The snapshot extraction is based on Barr and Marron’s work [2] with modifications needed to support unique features of the JavaScript object model, such as support for dynamically modifiable type layouts and the range of specialized representations for JavaScript builtin types.

Node.js is built around an event loop that dispatches JavaScript actions from internal worklists. This loop is an ideal point for forming snapshots. In it, the JavaScript execution stack is empty, reducing the size of the program state we need to capture and eliminating the need to snapshot call-frames and associated invocation data. Further, we can check if additional work is pending and delay taking a snapshot or, if the event loop is idling, preferentially take a snapshot early.

Figure 5 shows the textual snapshot representation. The snapshot starts with standard information. The URI for the root code file and the value of the PNRG seed at snapshot time. The Roots are a list of vId values which are simply unique integer identifiers for each JavaScript root in the heap. Next is the Code list which contains codeId values that map to code load information in the log and indicates the code loaded into the program at this point.

The next set of components in the snapshot describe the layouts of the rest of the data in the snapshot. The Types component provides information on the associated prototype (protold), the enum value (jsKind) indicates if this is a special builtin type and which one, flags for frozen etc. info, and a list of SlotInfo entries. Each SlotInfo contains information on a single entry in a slot array that describes where each propertyId maps to in the object’s slot array and an attribute value containing enumerable etc. information.

Finally, we have the actual data from the program. The Vals list contains information for all the primitive values including strings, numbers, the special null/undefined values, etc. These values have the enum value jsKind and void* data that is interpreted as needed for each of the primitive jsKind tags. The objects refer to a typeld that gives us a Type entry that is used to interpret the Slots array and the ObjData pointer. The Slots array is an array of void* pointers which are interpreted via tag bits that indicate if the values are tagged integers (and can be cast directly) or pointer-based values that we treat as vld values (and can lookup in the snapshot to find the corresponding data).

3.3 Callback Dependence Tracking

To implement the reverse to callback origin (rcbo) operation, we require three pieces of information: 1) when callbacks are registered, 2) when they are dispatched, and 3) if they are canceled at some point. In the Node.js architecture, the runtime host manages this information in its internal event loops where the ChakraCore cannot directly inspect it. Thus, we modified the APIs that register callbacks to wrap and tag the registered callback function with the current index in the event log idx. When this wrapped function is dispatched from an event loop, we record the register index idx, in the event log entry for the function invocation. When a developer uses the rcbo operation, we simply scan the event log to find the enclosing function invocation event log entry, get the idx, value, and then time travel back to that point in the execution.
Table 1: Performance overheads when running JARDIS in record mode. Process Size is the baseline memory used by the Node.js process without JARDIS. The Time and Space overheads are the increase in runtime and memory seen when running the benchmark with JARDIS set to recording mode; the † symbol marks when the recording and baseline execution times were indistinguishable. Log Size is the size of the compressed (2–4 second) log when written to disk after the run completes.

<table>
<thead>
<tr>
<th>Program</th>
<th>Code</th>
<th>Process Size</th>
<th>Time Overhead</th>
<th>Memory Overhead</th>
<th>Log Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>gbemu</td>
<td>11 kloc</td>
<td>45 MB</td>
<td>2%</td>
<td>56%</td>
<td>7.3 MB</td>
</tr>
<tr>
<td>nvier</td>
<td>0.5 kloc</td>
<td>17 MB</td>
<td>1%</td>
<td>71%</td>
<td>6.3 MB</td>
</tr>
<tr>
<td>raytrace</td>
<td>1 kloc</td>
<td>60 MB</td>
<td>1%</td>
<td>27%</td>
<td>4.5 MB</td>
</tr>
<tr>
<td>dash</td>
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<td>12 MB</td>
<td>†</td>
<td>83%</td>
<td>5.2 MB</td>
</tr>
<tr>
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<td>96 kloc</td>
<td>73 MB</td>
<td>2%</td>
<td>74%</td>
<td>8.9 MB</td>
</tr>
<tr>
<td>twitter</td>
<td>41 kloc</td>
<td>42 MB</td>
<td>†</td>
<td>55%</td>
<td>7.8 MB</td>
</tr>
</tbody>
</table>

4. EVALUATION

We focus our evaluation on the performance overhead when running a Node.js application in record mode. Our benchmarks consist of the compute/memory intensive Octane [19] workloads gbemu, nvier, and raytrace modified to run in Node.js as well as more traditional Node.js workloads of a code status dashboard (dash) [9], a task tracking application (tasks) [21], and a twitter bot (twit).

We configured Node.js to take snapshots approximately every 2 seconds and keep the most recent 2 snapshots to retain approximately the last 2–4 seconds of execution. We setup all the benchmarks to run for 4–8 seconds to reduce measurement noise and ensure we fill the TTD log. We ran our experiments 10 times (with highest/lowest values discarded) on an Intel Sandy Bridge class Xeon processor at 3.6 GHz with 16 GB of RAM and a SSD drive.

Table 1 shows that, for both the compute intensive and the application based benchmarks, the recording overheads are exceptionally small. For all benchmarks, the runtime overheads are under 2%. For two of the application benchmarks, the runtimes for the baseline version of Node and JARDIS with recording were indistinguishable. For the application benchmarks, the Node worklist was frequently empty during execution allowing JARDIS to take snapshots during the idle period. Even in the compute bound benchmarks, where there are no idle periods, the snapshot cost is a very small part of the overall runtime. Despite creating 1000’s of events in some benchmarks, the cost to record each action — a bump allocation and writing a few fields — is trivial compared to the work to dispatch and execute the action.

The memory overheads in Table 1 are larger, ranging from 27% to 83%, due to the fact that the log and uncompressed snapshots are kept in memory. Despite keeping up to 2 snapshots of the entire JavaScript program state in the log at a time, the memory overhead is less than 100% for all our benchmarks, indicating that the live object based snapshots are substantially smaller than what a naive process memory page snapshot would produce. The Log Size column shows that these snapshots and the log compress remarkably well, ranging from 4.5 MB to 8.9 MB.

Previous work has employed call-stack stitching [6] (or long stack traces [4]) to ease debugging asynchronous calls. This approach copies the call-stack when a callback is registered and appends it to the call-stack when the call-back is invoked. Unfortunately, copying a call-stack is expensive and can keep references alive. Further, the copies are also shallow so heap allocated values may be modified after the copy is made leaving the debugger information in an inconsistent state.

A number of research areas depend on, or would benefit from the availability of, a low cost method for obtaining the execution history for a program [1, 13, 15, 17]. The cost of producing the history, at the needed level of detail, is a limiting factor in the applicability of all these techniques. Thus, the ability to efficiently record snippets of a program’s execution, and replay offline later while tracking exactly the required information, is an enabler for further work in these areas.

6. CONCLUSION

As shown, the open source JARDIS tool provides a rich set of functionality for recording, then inspecting and navigating the execution history of a program in a debugger. Additionally, JARDIS’s extremely low recording overhead represents a major opportunity for research and tools that rely on collecting execution histories from in-production deployments. JARDIS represents a major advance in state of the art debugging tools and is an enabling technology for research areas including interrogative debugging, automated fault localization, and postmortem diagnostics.

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8. REFERENCES


