**Abstract**

Time-traveling debuggers offer the promise of simplifying debugging by letting developers freely step forwards and backwards through a program's execution. However, web applications present multiple challenges that make time-travel debugging especially difficult. A time-traveling debugger for web applications must accurately reproduce all network interactions, asynchronous events, and visual states observed during the original execution, both while stepping forwards and backwards. This must all be done in the context of a complex and highly multithreaded browser runtime. At the same time, to be practical, a time-traveling debugger must maintain interactive speeds.

This paper presents McFLY, the first time-traveling debugger for web applications. McFLY departs from previous approaches by operating on a high-level representation of the browser’s internal state. This approach lets McFLY provide accurate time-travel debugging—maintaining JavaScript and visual state in sync at all times—at interactive speeds. McFLY’s architecture is browser-agnostic, building on web standards supported by all major browsers. We have implemented McFLY as an extension to the Microsoft Edge web browser, and core parts of McFLY have been integrated into a time-traveling debugger product from Microsoft.

1. **Introduction**

Web applications are notoriously frustrating to debug. JavaScript events can race with one another, leading to Heisenbugs. Network requests can intermittently fail or return unexpected results, leading to unanticipated error states. JavaScript code can also race with the browser itself via the document object model (DOM), since independent browser threads update visual state in parallel with JavaScript execution. These behaviors can make application bugs challenging for developers to diagnose and fix.

To aid debugging, all modern web browsers include integrated debuggers [15, 31, 33]. While these can be useful, they often provide little assistance to developers. If a bug is the result of a specific event order (a Heisenbug), the act of debugging can disrupt the event schedule and prevent the bug from appearing. Even when a bug does recur while debugging, identifying its root cause can be difficult: in event-driven settings like the web, bug symptoms can manifest far from their root causes.

There are two widely used approaches to find these bugs: scattering logging statements around the program (a.k.a. “printf debugging” using `console.log`), or placing breakpoints to pause the program at specific statements. Both are laborious and iterative processes. Poring over logs to identify bugs often reveals the need to rerun the program with new logging statements in place. Using breakpoints, developers step the program forwards until the first sign that something has gone wrong. Unfortunately, if the breakpoint does not precede the root cause of the bug, the developer must reset breakpoints and restart execution from the beginning. As a result, debugging is currently an arduous and painstaking process for web developers.

A widely-proposed debugging approach intended to address these difficulties is reversible or time-travel debugging. A time-traveling debugger would let developers step forwards and backwards through the execution. Rather than needing to repeatedly restart execution from the beginning, placing breakpoints, or adding logging, developers would be able to step forwards until the first symptom of a bug appears, and then step backwards to isolate its root cause. Developers report that they step too far forward during debugging sessions “all of the time”, and that a “back in time [i.e., time-traveling] debugger would be wonderful” [6].
Time-travel debugging has been extensively explored in non-web-based settings [3, 7, 10, 13, 15, 23, 26, 37, 39, 43, 45]. In some of these settings, time-travel debugging is essentially a solved problem. For example, in serial computations with no side effects and no I/O, it is always possible to replay the application from the beginning to the desired point in time. As a standard optimization, time-traveling debuggers take periodic checkpoints of program state (e.g., mutable data and the program counter) and resume execution from the nearest checkpoint. Replay can further be accelerated by eliding pauses resulting from user and network interactions. To address side-effects and I/O, they can log operations during the first execution and replay them during time-travel.

Unfortunately, past approaches are not sufficient to enable time-travel debugging for web applications. Unlike traditional environments, web applications are deeply entangled with their visual state and cannot be debugged in isolation. Most web application bugs are related to interactions with the layout engine [35], and many manifest visually. Because there is no way to checkpoint and roll back a web application’s visual state, a time-traveling debugger would need to re-execute the program from the beginning of time every time the developer steps backwards. Even an optimized re-execution that elides pauses will eventually become too slow to be practical. Given that a web application’s visual state is maintained within a complex multithreaded browser, it is not immediately obvious how a time-travel debugger could efficiently support visual state.

This paper presents McFLY, the first time-traveling debugger for web applications. McFLY overcomes the challenges of the web environment by capturing not only JavaScript program state but also a high-level representation of the layout engine’s internal state, enabling visual state checkpointing and replay. For example, a CSS animation could easily modify thousands of pixels of on-screen content per second. Instead of tracking these pixels, McFLY captures the internal frame counter, which represents the animation in a single integer. McFLY captures high-level state for all core layout engine functionality, including DOM elements, event listeners, and network connections. Because this high-level state is formally described in web standards documents [19], McFLY’s approach is browser-agnostic. During debugging, McFLY manages this high-level state to keep the JavaScript engine and the multithreaded layout engine in sync, making it possible for developers to efficiently step backwards.

We have implemented a prototype version of McFLY as an extension to the Microsoft Edge web browser, and show that its approach enables interactive debugging speeds. Core parts of McFLY have been integrated into a time-traveling debugger product from Microsoft [20].

Contributions
This paper makes the following contributions:

- It details the challenges to time-travel debugging web applications [§2].
- It proposes a browser-agnostic architecture for a time-traveling debugger for web applications [§4].
- It describes McFLY, a prototype time-traveling debugger for web applications [§4] that can achieve interactive debugging speeds [§4].

2. Challenges to Time-Travel Debugging Web Applications

Time-travel debugging for web applications is challenging for a variety of reasons. To be useful, a time-traveling debugger must provide the developer with visibility into the application’s visual state [§2.1]. In particular, it must keep the JavaScript engine, the layout engine, and the screen in sync at all times (Figure 1). To ensure that time-travel is deterministic, it must correctly capture all I/O and control for nondeterminism (§2.2). To be usable, it must be able to checkpoint and roll back the application’s visual state (§2.3), enabling interactive speeds. Finally, to be practical, it must be straightforward to integrate into modern browsers, which are complex multithreaded applications consisting of millions of lines of code (§2.4).

2.1 Supporting Visual State

Debugging web applications is often a visual experience; when an application does not produce the correct visual output, the developer needs to figure out why. Browsers contain debugging tools, like Microsoft Edge’s DOM Explorer (Figure 2), that let developers examine this state and map it back to the pixels displayed on the screen. Using the DOM Explorer, developers can determine which CSS and HTML properties influence a UI element’s appearance, what JavaScript code is listening for input events, and where a UI element appears on the screen.

To be useful, a time-traveling debugger must support visual state during stepping operations. Failing to do so would make debugging vastly more difficult; developers would not be able to see the GUI or examine its underlying properties in the DOM Explorer.

However, this visual state is not managed by the JavaScript engine; instead, it is managed within the layout engine. Every major web browser has its own layout engine: Blink (for Chrome) [12], WebKit (for Safari) [12], Gecko (for Firefox) [12], and EdgeHTML (for Microsoft Edge) [35]. JavaScript code interacts with the layout engine via a set of standard interfaces commonly referred to as the Document Object Model (DOM) [19].

\[\text{A video from 2015 shows McFLY in action: } \text{https://channel9.msdn.com/blogs/Marron/Time-Travel-Debugging-for-JavaScriptHTML}\]
Figure 2. A web application’s visual state is critical for debugging. Existing browser debugging tools, such as Microsoft Edge’s DOM Explorer shown above, let developers examine this state. A time-traveling debugger that ignores visual state would prevent these tools from working, and would display the application as a blank screen. MCFLY supports debugging tools like the DOM Explorer because it ensures that visual state remains in sync with JavaScript execution.

2.2 Capturing I/O and Controlling for Nondeterminism

A time-travel debugging session can diverge from the original execution if the debugger fails to reproduce the same I/O and nondeterminism observed in the original execution. This divergence can change the control flow of the program and disrupt stepping operations. Thus, it is crucial that a time-traveling debugger accurately capture I/O and control for nondeterminism to ensure a deterministic debugging experience.

To capture I/O, the debugger needs to operate within the layout engine, as I/O operations can be triggered implicitly and explicitly by HTML, CSS, and JavaScript. For example, HTML and CSS can reference external images, which the browser loads asynchronously and independent of JavaScript execution. Via the DOM, JavaScript code can send HTTP requests and process HTTP responses. All of these I/O operations must be captured and synchronized with JavaScript execution during debugging sessions.

The debugger must manage several sources of nondeterminism, including random numbers, JavaScript event orderings, and thread interleavings within the multithreaded layout engine. While random number generation can easily be made deterministic, the remaining two sources of nondeterminism are more complicated to manage.

The order of JavaScript events ultimately determines the high-level control flow of a web application because JavaScript execution is completely event-driven and occurs on a single hardware thread. The layout engine maintains an event queue that contains events that are waiting to execute. JavaScript code subscribes to specific events, such as mouse clicks on a button, using JavaScript event listeners. The layout engine dispatches events to the event queue when they occur, which eventually run the relevant event listeners. During stepping operations, a time-traveling debugger must ensure that events exit the event queue in the same order as the original execution.

Thread interleavings within the multithreaded layout engine determine the order in which certain visual state updates occur. In particular, all major layout engines use a dedicated thread for CSS animations, which manipulates GUI items in parallel with JavaScript execution. A time-traveling debugger must ensure that these visual state updates are synchronized with JavaScript execution at all times. Failing to reproduce these (benign) data races can result in program replay that diverges from the original execution, which prevents time-travel operations from completing successfully.

2.3 Checkpointing Visual State

A time-traveling debugger must be able to checkpoint and roll back a web application’s visual state in order to support stepping operations at interactive speeds. Without these checkpoints, a time-traveling debugger would need to deterministically replay the application from the beginning to support stepping operations, which would be unusably slow on long traces.

The layout engine manages visual state and determines how this state translates into pixels displayed on the screen. A time-traveling debugger must somehow capture this visual state into a checkpoint, and ensure that rolling back to the checkpoint results in the same screen pixels. However, visual state does not exist independent of JavaScript program
state; instead, the two are deeply intertwined. JavaScript objects can retain visual state, such as UI elements that are not visible on the screen. UI elements appear to JavaScript code as ordinary JavaScript objects, but internally, they reflect visual state stored within the layout engine. The layout engine can retain program state, as it stores references to JavaScript functions that have been registered as event listeners. Thus, a time-traveling debugger must accurately checkpoint and restore dependencies between visual and program state.

2.4 Portability Across Browsers

Modern web browsers are complex pieces of software with millions of lines of code [27]. These browsers are aggressively optimized to edge out the competition on benchmarks. It would be infeasible to significantly change how the browser operates in order to support time-travel debugging. Instead, to be practical, changes must be unintrusive, maintainable, and portable across browsers, which places severe restrictions on how time-travel can be implemented.

3. MCFLY

MCFLY is our prototype time-traveling debugger for web applications that overcomes the challenges presented in Section 2. MCFLY operates on a high-level representation of a browser’s internal state, letting it provide accurate time-travel debugging with support for visual state at interactive speeds. In this section, we present MCFLY’s architecture, which is browser-agnostic.

3.1 Time-Travel Overview

We first provide an overview of how a developer uses MCFLY to debug a web application, which structures the remainder of this section.

Reproducing a bug: The developer loads the web application with MCFLY open, and interacts with the application until they discover buggy behavior. While this happens, MCFLY interacts with the layout engine via a combination of existing DOM interfaces and custom extensions in order to support visual state during time-travel ([3.2]). Specifically, MCFLY creates checkpoints of the application’s program and visual state ([3.3]) at a configurable interval (2 seconds by default), and logs I/O and sources of nondeterminism ([3.4]). By regularly capturing checkpoints, MCFLY makes it possible to quickly time-travel to an arbitrary point in the web application’s execution.

Debugging: When the developer encounters a bug, they can place and trigger a breakpoint to begin a debugging session. At this point, the developer can use MCFLY to step forwards and backwards through the captured program execution to diagnose the bug. To support stepping forwards, MCFLY uses its log to deterministically replay the program execution.

Stepping backwards is more involved ([3.5]), as MCFLY must return the application to a previous state. To go back in time, MCFLY needs to return the application to a target JavaScript statement \( s \) at a specific execution of the statement (at time \( t \)). To track this information, MCFLY extends the JavaScript engine with the branch trace store and timestamp store performance monitors ([3.5]). MCFLY uses these performance monitors to determine \( s \) and \( t \).

Time-travel: To time-travel an application to statement \( s \) at time \( t \), MCFLY loads the last checkpoint taken before \( t \) and replays the log. When execution is at the JavaScript event just prior to \( t \), MCFLY enables the branch trace store and timestamp store, and places a conditional breakpoint on \( s \) that triggers at time \( t \). Conditional breakpoints are a standard feature supported by all major JavaScript debuggers; the JavaScript engine will only trigger the breakpoint if \( s \) executes at time \( t \), which completes the time-travel operation.

Time-travel optimization: MCFLY opportunistically generates checkpoints during replay to reduce the latency of future time travel operations. In particular, if MCFLY is time traveling towards \( t \), and must start from a “faraway” checkpoint (where distance is defined in terms of JavaScript events), MCFLY generates a new checkpoint at the JavaScript event just prior to \( t \). Thus, a sequence of stepping operations within the same JavaScript event will use the new checkpoint; this is similar to an optimization by Boothe [7].

3.2 Supporting Visual State

MCFLY supports visual state during debugging by checkpointing and logging changes to a high-level representation of the layout engine’s visual state. The layout engine already reveals much of its internal state in a high-level form to the JavaScript engine via the DOM. However, some of the layout engine’s internal state is not accessible via standard interfaces, including the state of animations on the web page and lists of active event listeners. MCFLY requires access to this state to be able to checkpoint and deterministically re-execute applications.

MCFLY extends the layout engine with additional debugger-facing interfaces that provide read/write access to a high-level representation of internal layout engine state. These extensions expose the same high-level state described in formal DOM specifications, which all web browsers adhere to [19]. For example, the DOM specification for HTTP request objects (XMLHttpRequest) describes network request objects as a state machine; MCFLY captures these network requests in terms of the internal state machine. As a result, this architecture is portable across all major web browsers. Section 4 details the specific extensions that our prototype version of MCFLY supports, as well as their implementation in a widely-used browser.
3.3 Application Checkpoints

McFLY’s web application checkpoints contain the application’s program state (from the JavaScript engine) and visual state (from the layout engine). As these two types of state are entangled through cross-references, McFLY stores them together inside checkpoints as a single object graph.

**Program State:** At a high level, the program state within the JavaScript engine consists of the heap, the stack, and the program counter. However, the JavaScript engine does not maintain a stack or a program counter between JavaScript events. In addition, JavaScript events are typically short-lived (under a few milliseconds in duration) because JavaScript execution blocks UI interactions [40]; long-running events give the user the impression that the application is frozen. This property is enforced by the web browser; if a JavaScript event runs for too long, the browser crashes the tab or raises an alert.

McFLY defers application checkpoints to occur between JavaScript events. This design constrains where McFLY can checkpoint the application, but does not unduly impact debugging performance since most events complete in under a millisecond.

This design ensures that the only program state that McFLY needs to capture is the JavaScript heap, which all major web browsers can efficiently traverse using existing garbage collection routines. When the traversal encounters an object in the heap that reflects and retains visual state in the layout engine, McFLY serializes its high-level state. To reinstate checkpointed program state, McFLY uses internal interfaces present in all major JavaScript engines to reconstruct serialized objects.

**Visual State:** A web application’s visual state consists of active GUI nodes on the webpage, inactive GUI nodes stored in the JavaScript heap, active CSS animations, browser-local persistent storage, the state of the random number generator, event listeners, the number of bytes consumed by each active HTML parser, and the state of network requests. McFLY serializes a high-level representation of these resources into the checkpoint’s object graph using a combination of standard web interfaces and the extensions discussed in Section 3.2.

3.4 I/O and Nondeterminism Log

McFLY logs I/O and sources of nondeterminism that it uses to ensure that stepping operations are deterministic. The log contains different types of entries, which each have a different logging and replay strategy. We describe each type of log entry below; Section 4 details which DOM interfaces use which strategy.

**Simple entries** correspond to synchronous interactions between JavaScript and the layout engine, such as querying for the date, that depend on browser-external state. McFLY logs these values during the original execution, and replays them while debugging.

**Event entries** correspond to JavaScript events. McFLY uses these to ensure that JavaScript events occur in the same order as the developer steps through the program. During the original execution, McFLY logs a high-level form of each event as it occurs. At debug time, McFLY replays events from the log. This replay strategy reproduces event races observed during the original execution.

**Inter-event visual state updates** occur between JavaScript events. While JavaScript is executing, the layout engine defers certain visual state updates. For example, layout engines only transition the internal state machine of HTTP request objects in quiescent periods between events. During the original execution, McFLY scans for and logs state changes for the relevant high-level state before every JavaScript event. During replay, McFLY applies the logged updates before the same event in order to keep the state in sync with JavaScript execution.

**Concurrent visual state updates** occur while JavaScript is executing. The layout engine updates some visual state, such as CSS animations, concurrent with JavaScript execution. Every time JavaScript code synchronously interacts with the layout engine, McFLY scans for and logs any changes to concurrently updated state. During replay, McFLY prevents the layout engine from concurrently updating state and re-applies the state changes itself during the same synchronous interaction, which keeps the state in sync with JavaScript execution.

McFLY uses a counter of synchronous interactions to denote a specific synchronous interaction in the log, and stores the counter value in checkpoints. For example, a log entry with counter value 60 would be applied during the 60th synchronous layout engine interaction, which will be identical across deterministic replays. This strategy preserves any data races between JavaScript code and the layout engine observed during the original execution.

3.5 Debugger Features

McFLY provides a full suite of complements to existing debugger features, and exposes this functionality as an extension to a production JavaScript stepping debugger. We only discuss *step backwards* in this section; the remaining features are implemented similarly.

Step backwards complements *step forwards*, and lets the developer return to the previously-executed program statement. Given that the debugger is paused at the statement $s$ at logical time $t = (c, b)$, where $c$ is the number of times the function has been called since enabling performance monitoring and $b$ is the number of backwards jumps (loop iterations) executed in the current function call, the debugger must determine the statement and logical time of the previously-executed statement, $s'$ and $t'$:

- If $s$ is not the entry point of a basic block, then $s'$ is the previous statement in the block and $t' = t$. 

This replay strategy reproduces event races observed during the original execution.
• If \( s \) is the entry point of a basic block, then \( s' \) is the source statement of the previously taken branch.
  • If \( s' \) is the current statement in the calling function, then \( t' \) is the logical time associated with the caller’s call frame.
  • Otherwise, \( s' \) is from the same function call as \( s \). If \( s' \) is a loop header (e.g., \( \text{while}(\text{someCondition}) \)), then \( s' \) is from a previous loop iteration and \( t' = (c, b - 1) \). Otherwise, \( t' = t \).

Finally, MCFly places a conditional breakpoint on \( s' \) that triggers when the logical time is \( t' \), and replays the program from the previous checkpoint that is closest to the target logical time. If the checkpoint is not close to the target time, MCFly records a new checkpoint just before the target JavaScript event in order to speed up subsequent step-back operations.

3.6 Performance Monitors

To replay execution to a specific statement at a particular point in time, time-traveling debuggers need visibility into the current execution. VM-based time-traveling debuggers typically use performance counters on the processor for this purpose \cite{21,29}, but managed languages, like JavaScript, lack comparable functionality.

MCFly augments the JavaScript engine with two performance monitors. The branch trace store contains the last branch instruction that was taken by each function that is currently on the call stack. The timestamp store contains the timestamp of each function on the call stack. A timestamp is represented as the pair of the function’s call count since enabling performance monitoring and the number of backwards jumps (loop iterations) executed thus far in the function call. For example, given the function

\[
\text{f() \{ while(true) \{ \}}
\]

the timestamp \((3, 2)\) represents the second iteration of the loop during the third call to the function.

3.7 Replay Guarantees

MCFly guarantees that replay is identical to the original execution, including the data returned from supported layout engine interfaces, the sequence of application-observed JavaScript events, and the pixels on the screen. Animations may not move smoothly during replay, as the system fast-forwards animations to each observed state from the original execution whenever JavaScript code calls into the layout engine, but the JavaScript code will observe the same values seen in the original execution. In addition, developers can use existing debugging tools, such as the DOM Explorer shown in Figure 2, to inspect the GUI while debugging.

4. Implementation

We have implemented a prototype of MCFly in Microsoft Edge. This section describes in detail the changes we made to the layout engine to support MCFly’s checkpoints and logs (§4.1), the changes to the JavaScript engine to support performance monitors (§4.2), and the security implications of these changes (§4.3).

4.1 Layout Engine State

Below, we walk through how our prototype implementation of MCFly captures the high-level layout engine state described in Figure 3. Although the table lists many different resources, we only need to make a small number of modifications to the layout engine because standard browser interfaces already make a large amount of high-level state available to the debugger.

Random numbers: JavaScript applications use \( \text{Math.random}() \) to generate random numbers, but cannot read or write the internal state of the PRNG. We modify the layout engine to let MCFly query and reset the PRNG’s state. MCFly stores the PRNG state in program checkpoints, and reinstates it prior to replaying from a checkpoint.

Current time: The layout engine contains a \text{Date} interface that lets programs observe the current time as a \text{Date} object, which it queries from the OS. We modify the layout engine to let MCFly log and replay date requests. To serialize \text{Date} objects into checkpoints, we use the existing \text{getDay()} function on the object to retrieve its timestamp.

Timer status: JavaScript applications create one-shot timers via \text{setTimeout()}, and recurring timers via \text{setInterval()}. Each timer is assigned a unique ID that the layout engine arbitrarily determines. The layout engine does not provide an interface for enumerating the set of active timers or for controlling their IDs. We extend the layout engine to expose the set of active timers and to let MCFly log and replay timer ID assignments. We use the former modification to store active timers in checkpoints, and the latter to deterministically replay timer IDs. MCFly deterministically replays the timer schedule as discussed under sequence of events.

Events: JavaScript code can register functions as handlers for events. For example, a program can register handlers for mouse click events. Applications can register event listeners in three ways: through properties on HTML tags (e.g.,<div onclick="a()"/>), properties on the DOM elements (e.g., .div.onclick=a;), or through the \text{addEventListener()} DOM interface (e.g., .div.addEventListener(‘click’,a)). JavaScript code can enumerate event listeners registered using the first two approaches, since the listeners are reflected as properties on the associated DOM objects. However, the layout engine does not let JavaScript code enumerate handlers which were registered via \text{addEventListener()}. Furthermore, the layout engine dispatches events to event handlers in the order in which the handlers were registered, regardless of the registration technique employed. The layout engine does not expose this order, which must be recreated at replay time.

All DOM objects that generate events implement the \text{EventTarget} interface. We modify the layout engine to let
McFLY enumerate all event handler information that is associated with an EventTarget. McFLY uses this extension to store handler orders into checkpoints, and restore handler orders from checkpoints using the preexisting handler registration interfaces.

**Sequence of events:** Each JavaScript execution context is single-threaded and completely event-driven, but the layout engine contains and controls the JavaScript event queue. The layout engine does not expose the queue to JavaScript code, but events must be replayed in the same order as the original execution in order to reproduce event races. We extend the layout engine to let McFLY intercept events added to the event queue, which it uses to log and reproduce the original event order during a debugging session.

**GUI:** JavaScript code interacts with the GUI through the DOM tree. Each HTML tag on a web page has a corresponding element object in the tree. Each element object provides JavaScript code with read and write access to tag-specific state, such as the URL for an `<img>` tag or the text in a form field. We use existing JavaScript interfaces to serialize and deserialize the entirety of the DOM tree into checkpoints. McFLY extend the layout engine to expose the current byte offset in each document’s parse stream. McFLY extend the layout engine to let McFLY log and replay network fetches.

**External resources:** A web page often includes external objects, e.g., HTML tags which specify a `src` attribute and whose content must be fetched from remote servers. The layout engine loads this content in parallel with JavaScript execution on an I/O thread. When the content finishes loading, the layout engine silently updates the applicable HTML element with attributes, such as the `height` and `width` of an image. We modify the layout engine to let McFLY log and replay network fetches.

**HTML parsing progress:** A web page contains one or more HTML documents, with secondary HTML documents appearing in frames. The browser incrementally loads and parses HTML documents in parallel with JavaScript execution, which causes new nodes to appear in the DOM. We extend the layout engine to expose the current byte offset in each document’s parse stream. McFLY logs offset changes during the original execution. During replay, McFLY feeds the network stack the new bytes at the appropriate time (via the extension discussed in external resources) and waits for the parser to consume them.

**CSS animations:** The DOM does not expose the CSS animation state of an HTML tag—that state resides within the layout engine. If McFLY cannot read CSS animation state, then it cannot record an animation’s progress with respect to concurrently executing JavaScript code; this would prevent McFLY from faithfully recreating the behavior. To enable high-fidelity replays of animations, we modify the layout engine to let McFLY read and write the frame counts corresponding to active CSS animations. Using this interface, McFLY can “seek” to a specific point in the animation, and keep it synchronized with JavaScript execution.

**Connection status:** JavaScript applications communicate with remote servers via XMLHttpRequest objects. Each object encapsulates the state of a single HTTP request. At logging time, the debugger can observe the state of each request, including the content of the HTTP response, using existing methods on XMLHttpRequest objects. The debugger needs a mechanism to recreate logged XMLHttpRequest objects without creating actual network connections. We extend the lay-

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| Resource          | Interface          | High-level State        | Logged Data          | Type of Log Entries |
|-------------------|--------------------|-------------------------|----------------------|---------------------|
| Random Numbers    | Math.random()      | PRNG state              | None                 |                     |
| Time              | Date               | Internal timestamps     | Current time         | Simple entries      |
| Timers            | setTimeout, setInterval | Active timers           | Timer IDs           | Simple entries      |
| Events            | EventTarget        | Active event listeners   | None                 | Sequence of events  |
| GUI               | DOM                | Live DOM nodes          | Form changes,        | Inter-event updates |
|                   | CSS Animations     | Animation status        | external resource loads, HTML parsing progress | Concurrent updates |
| Network Requests  | XMLHttpRequest     | State machine           | State machine changes | Inter-event updates |
| Storage           | localStorage, Cookies | Contents of storage     | None                 |                     |

**Figure 3. The core browser interfaces that McFLY supports.** The table above summarizes the different resources that the browser’s layout engine provides to JavaScript code, the high-level representation of their internal state, the data that McFLY records into its log, and the types of log entries used. In the “interface” column, Indirect means that a program’s interactions with the resource are implicit, i.e., the interactions do not use an explicit JavaScript interface.
out engine to let the debugger create `XMLHttpRequest` objects from scratch, and set their internal state to arbitrary values.

**Storage:** Web applications manage persistent local data using cookies and the `localStorage` interface [18,19]. Both mechanisms export a key/value API. The layout engine creates a separate storage area for each origin, and prevents different origins from accessing each other’s data. A page’s origin is the 3-tuple of the protocol, hostname, and port in the page’s URL. Since all of the active origins on a web page execute within the same JavaScript engine, McFLY can pose as any origin and manipulate its storage using the same interfaces that are exposed to regular applications.

**Additional browser features:** McFLY supports a core set of browser interfaces, which is sufficient to time-travel many existing web applications. Browsers regularly add new features, such as WebGL and Web Audio, that McFLY does not support. McFLY can be extended to support these features with additional browser modifications to expose their hidden state.

### 4.2 Performance Monitors

For simplicity, we implement the *branch trace store* and *timestamp store* by augmenting the browser’s JavaScript interpreter. When a performance monitor is enabled, we disable the browser’s JIT compiler, forcing JavaScript execution to use the interpreter. As we mention in Section 3.1, McFLY only requires performance monitoring when a replayed execution nears a target line of interest, so this design has minimal performance impact.

### 4.3 Security Implications

The layout engine modifications described in §4.1 are only exposed to debugging tools. They are not accessible to web applications via public JavaScript APIs. These modifications do not affect the security model for web content—at logging time and during replay, browsers still use the same-origin policy to isolate content.

### 5. Evaluation

We evaluate McFLY by running it on a corpus of web applications. Our evaluation addresses the following questions:

- **Faithfulness:** Does McFLY faithfully and deterministically re-execute web applications?
- **Performance:** Does McFLY support time-travel debugging at interactive speeds?
- **Overhead:** Does McFLY impose acceptable overhead during normal web application execution?

We performed the evaluation on a desktop with a quad-core Intel Xeon E5-1620 clocked at 3.6 GHz with 16GB of RAM and a 7200 RPM SATA hard drive.

### 5.1 Applications

There are no established benchmark suites for time-traveling debuggers for web applications, so we collected one. To perform a controlled evaluation, we chose applications that we had the source code to and that we could run locally in a non-production setting. Conducting performance experiments on web applications running in production poses severe methodological challenges. Every experiment is likely to capture a different version of the web application, due to updates or A/B testing, and with different content. For example, Facebook regularly conducts experiments on its users that changes the code and presentation of the website, and Facebook’s feed contains different advertisements, posts, and third-party code across visits. While we did not use production applications in this evaluation, we have verified that McFLY works on production websites.

We focus our qualitative and quantitative evaluation on benchmarks that exercise different components of McFLY:

- **Delta-Blue, Earley-Boyer, RayTrace, and Splay** are from the *Octane* benchmark suite [17], and are memory-intensive workloads that stress McFLY’s checkpoints. We modify the benchmarks to extend their runtime to ∼10 seconds to isolate McFLY overhead from parsing/JIT warmup overhead. Unlike the other benchmarks, these programs have no I/O and are deterministic; we exclude these benchmarks from parts of the performance evaluation that use McFLY’s nondeterminism and I/O log.
- **RayTrace (GUI)** [9] is the RayTrace program from the Octane benchmark suite with its original HTML GUI, which introduces I/O to the program.
- **ColorGame** [22] is an implementation of a test that demonstrates the Stroop effect [42]. It uses AngularJS and jQuery, which are both complicated and commonly used libraries, and result in ColorGame having ∼3× as much code as the next largest benchmark. AngularJS exercises a wide variety of DOM features, and encodes crucial application data into the DOM directly. Thus, it is crucial that McFLY correctly support this application’s visual state during debugging sessions.
- **CRUD** is a standard content management interface that uses jQuery to manage its user interface. CRUD uses HTML forms to let users create, update, and delete content, which McFLY must correctly support for debugging to be deterministic.
- **PacMan** [44] is an implementation of the classic Pac-Man game using the HTML5 canvas. It uses timers to update the contents of the canvas every 80ms, and stresses McFLY’s ability to quickly serialize large DOM objects into checkpoints and log frequent events.

*Figure 4* describes the code size of each of these benchmarks, including HTML documents and JavaScript libraries.
5.2 Faithfulness

We evaluated the faithfulness of McFLY’s time-travel debugging by using McFLY to debug the benchmark applications. While using breakpoints and McFLY’s stepping operations, we observed each application’s visual and program states, and checked that it matched the original execution.

We manually verified that, across all of our benchmarks, McFLY faithfully and deterministically reproduces the program and visual states observed during the original execution. Using McFLY, we were able to deterministically step forwards and backwards through web application executions while visual state updates, including those induced by CSS animations and network dependencies, remained synchronized with the JavaScript execution.

5.3 Performance

In order to be useful, McFLY must step through an execution of a web at interactive speeds. While stepping forwards is straightforward and involves deterministic replay, stepping backwards in time involves more costly operations. Specifically, stepping backwards involves resuming execution from the nearest checkpoint and playing forwards to the JavaScript statement of interest. In addition, the first time the developer steps backwards, the debugger creates a checkpoint just prior to the JavaScript event that executes the statement of interest.

McFLY’s step backwards overhead has two components:

- **Startup Cost**: The first time the developer steps backwards, McFLY replays the execution from the nearest checkpoint and creates a new checkpoint just prior to the JavaScript event of interest.

- **Resuming Execution from Checkpoint**: Once the startup cost is paid, the cost of subsequent step backwards operations within the same JavaScript event is dominated by the time to resume from the newly created checkpoint.

We drive each benchmark through a fixed series of events using a PowerShell script that provides application inputs. Each script lasts approximately 10 seconds. We run all benchmark programs and checkpoint their state every second for the checkpoint cost evaluation in order to collect more data points, and every two seconds for the startup cost evaluation to reflect a more representative value for everyday usage. We calculate the average time to resume from a checkpoint (from disk), and the time to take the first backwards step from 10 random breakpoints. From our results, we observe the following:

- **McFLY’s stepping operations run at interactive speeds in the common case**. After paying a one-time startup fee, the time to execute a backwards step in McFLY is dominated by the time it takes to resume from the nearest checkpoint (0.36s on average, as shown in Figure 4).

- **McFLY imposes an acceptable backwards step startup cost**. This startup cost is, on average, 3.8 seconds on our benchmark applications or roughly twice the checkpoint rate (Figure 5).

5.4 Overhead

To be usable, McFLY must not impose significant time and space overheads during normal web application execution. The following metrics contribute to McFLY’s runtime and space overheads:

- **Log Growth**: The growth rate of the nondeterminism and I/O log. Since a fast-growing log will exhaust disk and memory resources, this metric bounds the practical duration of program executions that McFLY can support.

- **Checkpoint Size**: The size of application checkpoints, which McFLY takes at a regular and configurable interval during the original execution. If checkpoints are large, then it will be impractical to take frequent checkpoints, which increases the initial cost return to a specific point in an execution. The compressed size indicates the checkpoint’s size on disk when compressed with gzip.

- **Checkpoint Creation Time**: The amount of time it takes to create a checkpoint. If it takes a long time to create a checkpoint, then McFLY will induce noticeable slowdowns during the initial execution of the program.

To measure these, we again drive each benchmark through a fixed series of events using a PowerShell script for approximately 10 seconds. For checkpoint operations, we run each benchmark in a configuration that takes a checkpoint every second. For log growth, we run each benchmark without taking any checkpoints, maximizing log size. For overall overhead during a normal execution, we measure the runtime of each benchmark in a configuration that takes a checkpoint every two seconds, the default configuration, and compare with the benchmark’s runtime without McFLY. As Figure 4 shows, checkpoint creation takes less than an eighth of a second on our benchmark applications. McFLY takes an average of 100 milliseconds to create a checkpoint and 120 milliseconds to serialize the checkpoint to disk. McFLY’s checkpoint operations are fast enough to support frequent checkpoints with acceptable overhead.

McFLY checkpoints compress to less than a megabyte on our benchmark applications (Figure 4). McFLY checkpoints contain the web application’s complete state as a lightweight high-level representation that is amenable to compression. Compressed McFLY checkpoints are two orders of magnitude smaller than the browser’s memory footprint at the process-level.

McFLY’s nondeterminism and I/O log grows at less than 2KB/s (Figure 6). The benchmark with the most nondeterminism, PacMan, has the largest log growth rate of 1.5KB/s. At that rate, McFLY could record PacMan’s execution for over 11 years on a 500GB hard drive.

With checkpoints every two seconds, McFLY’s overall overhead is 4% on average on our benchmark applica-
6. Related Work

Although McFLY is the first time-traveling debugger for web applications, time-traveling debuggers exist in several other non-graphical settings ([6.1]. Plain record-and-replay systems exist for GUI applications, but these are unable to support time-travel debugging at interactive speeds because they cannot checkpoint and roll back program and visual state ([6.2]. Figure 7 summarizes prior work that supports replaying web application executions.

### 6.1 Time-Travel Debugging

McFLY is the first time-traveling debugger for web applications. Previous time-traveling debuggers for other settings fall into three main categories: application-level debuggers, VM-level debuggers, and omniscient debuggers.

#### Application-level
Tardis [3], Jardis [4], UndoDB [43], Boothe [7], and RR [34] record and replay program interactions with a well-defined interface to an external environment, but do not recreate state in the external environment during debugging. In other words, these debuggers do not recreate a GUI application’s visual state. Tardis and Jardis debug .NET CLR and Node.js programs respectively, and replays interactions with native (C/C++) methods. UndoDB, RR, and Boothe debug the user space of processes, and replay interactions with the kernel and hardware. Boothe and RR use a similar optimization as McFLY to recreate checkpoints during replay to amortize time-travel cost. RR can step forwards and backwards through a Firefox execution, but it is designed to debug the browser itself rather than web applications and imposes single-threaded browser execution at all times.

#### VM-level
VM-level hypervisors like XenTT [10], ReVirt [14, 15], ReTrace [45], and TTVM [23] can time-travel entire virtual machines, but at the expense of large program traces and slow time-travel. Reverse-step debugging, like that provided by McFLY, requires time-travel at interactive speeds to be practical.

#### Omniscient
Omniscient debuggers provide time-traveling features by recording program state changes after every instruction, which produces large program traces and imposes high overhead during execution. Examples of omniscient debuggers include Chronon [13], TOD [38], ODB [26], and Tralfamadore [25].

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**Figure 4.** McFLY takes a fraction of a second to create or restore a checkpoint. Checkpoints are also significantly smaller than the size of the browser process they capture.

| Program   | Overhead | Startup |
|-----------|----------|---------|
| Color-Game| 4%       | 4.5 s   |
| CRUD      | 0%       | 3.2 s   |
| PacMan    | 6%       | 4.7 s   |
| RayTrace  | 5%       | 2.9 s   |
| Average   | 4%       | 3.8 s   |

**Figure 5.** Reverse-debugging overhead: Overall, McFLY imposes low overhead on our benchmark applications (up to 6% w/ checkpoints every 2 seconds) and requires a short one-time startup cost to initialize efficient reverse-step debugging.

| Program      | Log Growth |
|--------------|------------|
| Color-Game   | 0.6 KB/s   |
| CRUD         | 0.2 KB/s   |
| PacMan       | 1.5 KB/s   |
| RayTrace (GUI)| 0.9 KB/s |
| Average      | 0.8 KB/s   |

**Figure 6.** Log overhead: McFLY’s uncompressed nondeterminism and I/O log grows slowly.
6.2 Deterministic Replay

Pure deterministic replay systems can record and replay an application’s execution, but do not support periodic checkpoints or reverse debugging. As a result, these systems are unable to support backwards stepping operations at interactive speeds. We center our discussion on three different runtime environments.

**Browser:** Mugshot [28] and Timelapse [8] deterministically replay web application executions by recording and replaying the event schedule and I/O operations; we compare these systems to MCFLY in Figure 7. To accomplish this goal, Mugshot uses program rewriting and JavaScript reflection while Timelapse modifies the WebKit layout engine. While MCFLY also modifies the layout engine, Timelapse’s “hypervisor-like record/replay strategy relies on the layered architecture of WebKit” and is not portable to other browsers; in contrast, MCFLY’s architecture builds on web standards that are supported across all major browsers. Neither system is able to provide step-backward debugger commands at interactive speeds because they are unable to capture application checkpoints. Furthermore, Mugshot and Timelapse do not support layout engine operations that mutate visual state in parallel with JavaScript execution, such as CSS animations, which can cause divergent application replays.

Jalangi [41] supports selectively recording and replaying a subset of a program’s code in support of dynamic analyses. On the user-selected subset of code, Jalangi logs and replays interactions with the browser’s native functions with considerable overhead (26X during recording and 30x during replay), and does not support visual state during replay.

**Android:** The Android runtime environment is similar to the browser environment in that applications are event-driven and use a single thread to update the GUI. Valera [20] and ReRan [16] interpose on the interface between Android applications and the Android platform to capture nondeterministic event schedules and I/O operations.

**JVM:** JVM applications communicate with the environment and internal JVM components via native methods. Existing record-and-replay systems for the JVM treat state below the native methods, such as visual state, as external to replay. DejaVu assumes all native methods are deterministic, preventing applications from using nondeterministic APIs [11]. ORDER records and replays select nondeterministic APIs, preventing developers from inspecting or observing JVM-external state, like the GUI, during replay [46].

7. Conclusion

This paper presents MCFLY, the first time-traveling debugger for web applications. MCFLY provides accurate time-travel debugging that maintains JavaScript and visual state in sync at all times. We show that MCFLY lets developers freely step forwards and backwards through a web application’s execution at interactive speed. Core parts of MCFLY have been incorporated into a time-traveling debugger product from Microsoft [30].

Acknowledgements

We would like to thank Nikhil Khandelwal and Rob Paveza for their initial drive to start this project in Chakra. Akrosh Gandhi, Sandeep Agarwal, Arunesh Chandra, and Fiona Fung provided extensive help working in the Chakra codebase and managing the project. Edgardo Zoppi contributed during an internship at Microsoft Research. Priyank Desai, James Lissiak, and Rob Lourens helped add prototype time-travel support to the F12 and Visual Studio Code debuggers. Finally, we wish to thank Ed Maurer, Gaurav Seth, Dan Moseley, and Andy Sterland, who supported the development of the JavaScript component of McFly that is used to time-travel Node.js applications.
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