

Argus : Debugging Performance Issues in Modern Applications with Interactive Causal Tracing

Abstract

Prior systems used causal tracing, a powerful technique that traces low-level events and builds dependency graphs, to diagnose performance issues. However, they all assume that accurate dependencies can be inferred from low-level tracing by either limiting applications to using only a few supported communication patterns or relying on developers to manually provide dependency schema upfront for all involved components. Unfortunately, based on our own study and experience of building a causal tracing system for a widely used, closed-source operating system macOS, we found that it is extremely difficult, if not impossible, to build accurate dependency graphs. We report patterns such as data dependency and batch processing that introduce inaccuracy. We present Argus, a practical system for effectively debugging performance issues in modern desktop applications despite the inaccuracy of causal tracing. Argus lets a user easily inspect current diagnostics and interactively provide more domain knowledge on demand to counter the inherent inaccuracy of causal tracing. We implemented Argus in macOS and evaluated it on 11 real-world, open spinning-cursor issues in widely used applications. The root causes of these issues were largely previously unknown. Our results show that Argus effectively helped us locate all root causes of the issues and incurred only 7% CPU overhead in its system-wide tracing.

1. Introduction

Today’s web and desktop applications are predominantly parallel or distributed, making performance issues in them extremely difficult to diagnose because the handling of an external request is often spread across many threads, processes, and asynchronous contexts instead of in one sequential execution segment [20]. To manually reconstruct this graph of execution segments for debugging, developers have to sift through a massive amount of log entries and potentially code of related application components [13, 32, 28, 23, 30]. More often than not, developers give up and resort to guessing the root cause, producing “fixes” that sometimes make the matter worse. For instance, a bug in the Chrome browser engine causes a spinning (busy) cursor in macOS when a user switches the input method [8]. It was first reported in 2012, and developers attempted to add timeouts to work around the issue. Unfortunately, the bug has remained open for seven years and the timeouts obscured diagnosis further.

Prior work proposed what we call *Causal tracing*, a powerful technique to construct request graphs (semi-)automatically [31]. It does so by inferring (1) the beginning

and ending boundaries of the execution segments (vertices in the graph) involved in handling a request; and (2) the causality between the segments (edges)—how a segment causes others to do additional handling of the request. Prior causal tracing systems all assumed certain programming idioms to automate inference. For instance, if a segment sends a message, signals a condition variable, or posts a task to a work queue, it wakes up additional execution segments, and prior systems assume that wake-ups reflect causality. Similarly, they assume that the execution segment from the beginning of a callback invocation to the end is entirely for handling the request that causes the callback to be installed [31, 24]. Compared to debuggers such as `spindump` that capture only the current system state, causal tracing is quite effective at aiding developers to understand complex causal behaviors and pinpoint real-world performance issues.

Unfortunately, based on our own study and experience of building a causal tracing system for the commercial operating system macOS, we found that modern applications frequently violate these assumptions. Hence, the request graphs computed by causal tracing are inaccurate in several ways. First, an inferred segment may be larger than the actual event handling segment due to batch processing. Specifically, for performance, an application or its underlying frameworks may bundle together work on behalf of multiple requests with no clear distinguishing boundaries. For instance, `WindowServer` in macOS sends a reply for a previous request and receives a message for the current request using one system call `mach_msg_overwrite_trap`, presumably to reduce user-kernel crossings.

Second, the graphs may be missing numerous causal edges. For instance, consider data dependencies in which the code sets a flag (e.g., “`need_display = 1`” in macOS animation rendering) and later queries the flag to process a request further. This pattern is broader than ad hoc synchronization [27] because data dependency occurs even within a single thread (such as the buffer holding the reply in the preceding `WindowServer` example). Although the number of these flags may be small, they often express critical causality, and not tracing them would lead to many missing edges in the request graph. However, without knowing where the flags reside in memory, a tool would have to trace all memory operations, incurring prohibitive overhead and adding many superfluous edges to the request graph.

Third, in any case, many inferred edges may be superfluous because wake-ups do not necessarily reflect causality. Consider an `unlock()` operation waking up a thread waiting in

`lock()`. This wake-up may be just a happens-stance and the developer intent is only mutual exclusion. However, the actual semantics of the code may also enforce a causal order between the two operations.

We believe that, without detailed understanding of application semantics, request graphs computed by causal tracing are *inherently* inaccurate and both over- and under-approximate reality. Although developer annotations can help improve precision [12, 25], modern applications use more and more third-party libraries whose source code is not available. In the case of tech-savvy users debugging performance issues such as a spinning cursor on her own laptop, the application’s code is often not available. Given the frequent use of custom synchronizations, work queues, and data flags in modern applications, it is hopeless to count on manual annotations to ensure accurate capture of request graphs.

In this work, we present Argus, an interactive system for debugging performance issues in modern desktop applications despite the inaccuracy of causal tracing. Argus does not construct a per-request causal graph which requires extremely accurate causal tracing. Instead, it captures an approximate event graph for a duration of the system execution to aid diagnosis, and tracks both true causality edges as well as weak ones that may or may not reflect causality. It keeps humans in the loop, as a debugger should rightly do, and lets users easily inspect current diagnostics and guide the next steps to counter the inherent inaccuracy of causal tracing. Specifically, during debugging, Argus queries users a judiciously few times to (1) resolve a few inaccurate edges that represent false dependencies, (2) select one out of several vertices as a baseline to the buggy vertex in question; and (3) identify potential data flags. Argus represents a dramatically different approach in the design space of causal tracing because it enables users to provide necessary schematic information on demand, as opposed to full manual schema upfront for all involved applications and daemons [12].

We implemented Argus in macOS, a widely used commercial operating system. macOS is closed-source, as are its common frameworks and many of its applications. This environment therefore provides a true test of Argus. We address multiple nuances of macOS that complicate causal tracing, and built a system-wide, low-overhead, always-on tracer. Argus enables users to optionally increase the granularity of tracing (e.g., logging call stacks and instruction streams) by integrating with existing debuggers such as `lldb`.

We evaluated Argus on 11 real-world, open spinning-cursor issues in widely used applications such as the Chromium browser engine and macOS System Preferences, Installer, and Notes. The root causes of all 11 issues were previously unknown to us and, to a large extent, the public. Our results show that Argus is effective: it helped us non-developers of the applications find all root causes of the issues, including the Chromium issue that remained open for seven years. Argus needs only less than 3 user queries per issue but they are cru-

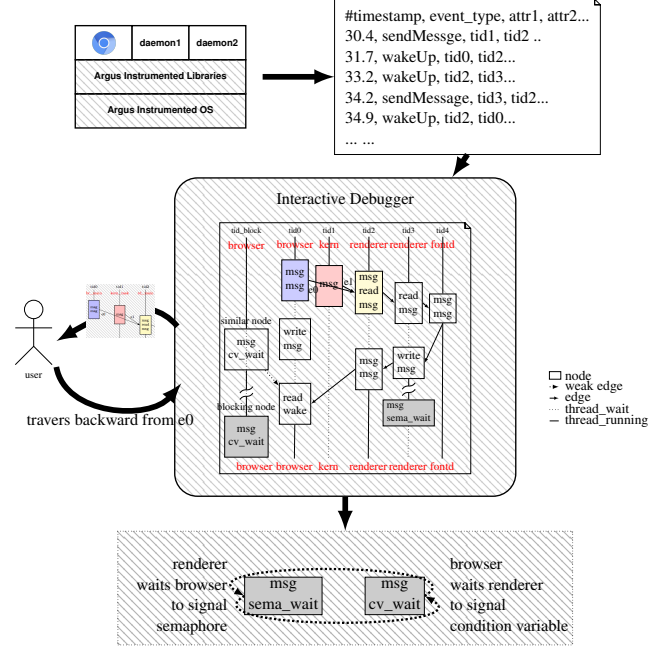


Figure 1: Argus Work Flow

cial in aiding diagnosis. Argus is also fast: its systems-wide tracing incurs only 7% CPU overhead overall.

This paper makes the following contributions: our conceptual realization that causal tracing is inherently inaccurate and that interactive causal tracing is superior than prior work in debugging performance issues in modern applications; our system Argus that performs system-wide tracing in macOS with little overhead and handles several macOS trickeries that complicate causal tracing; and our results diagnosing real-world spinning cursors and finding root causes for performance issues that have remained open for seven years.

This paper is organized as follows. In Section 2, we present an overview of using Argus and a Chromium example. We presents inherently inaccuracy patterns observed in macOS in Section 3. Section 4 describes our event graph from causal tracing, and Section 5 describes our tracing implementation and tools for user interaction. In Section 6 we present other case studies, and Section 7 contains performance evaluation. We summarize related work in Section 8, and end with conclusion in Section 9.

2. Overview

2.1. Argus Work Flow

In this section, we describe the steps a user takes to investigate a performance anomaly with Argus. Figure 1 shows Argus’s work flow with an example of a user investigating a performance problem in Chromium. The system wide tracing tool, which collects data from Argus instrumented library and kernel, generates logs. They are transformed into an *event graph* in Argus’s graph construction component. The event graph is

a generalized control-flow graph which includes inter-thread and inter-process dependencies. Diagnosis and inference are performed within this graph, in a semi-automated fashion: Argus performs searches to trace logical events as they flow through the system, and it judiciously queries the user for guidance. As shown in Figure 1, the Argus debugger asks the user to choose one edge in a subgraph. After this step, Argus runs its diagnosis algorithm and reports the root cause vertices. In the example, the root cause is two vertices which form a circular wait deadlock across multiple threads.

Next, we describe how Argus assists the user to diagnose a performance issue.

2.2. Diagnosis with Graph

Consider a common performance bug on macOS, the *spinning cursor*, which indicates the current application’s main thread has not processed any UI events for over two seconds. To initialize debugging a spinning cursor, Argus first constructs an event graph from the system-wide event log recorded. It then queries the event graph to find the ongoing event in the application’s main thread concurrent to the display of the spinning cursor. Given the event graph and the spinning vertex, Argus runs Algorithm 1 to interactively pinpoint the root cause.

Specifically, upon examining what the main thread is actually doing, there are three potential cases.

- **LongRunning** (lines 3 - 5). The main thread is busy performing lengthy CPU operations. This case is the simplest, and Argus traverses the event graph backwards to find a slice originating from the offending UI event to the long running CPU operations. This slice is particularly useful for further diagnosing the bug. As shown in Function *InteractiveSlicing* in line 26, Argus may encounter vertices with multiple incoming edges or weak edges that may not reflect causality when traversing the graph. It queries the user to resolve them.
- **RepeatedYield** (lines 6 - 11). The main thread is in a yield loop, which is highly indicative it is waiting on a data flag (e.g., “while(!done) thread_switch();”). If Argus cannot find any record of data flags in the spinning vertex, it terminates debugging by prompting the user to identify data flags and re-trace the application. Here we assume that the performance issue reproduces with a reasonable probability because, fortunately, a one-off issue that never reproduces is not as annoying as one that occurs frequently. If Argus finds the data flag the spinning vertex is waiting for, it falls through to the next case.
- **LongWait** (lines 12 - 22). The main thread is in a lengthy blocking wait and the wake-up has been missing. Argus handles this case by finding a baseline scenario where the wake-up indeed arrives, and then figures out which wake-up edge is missing in the spinning scenario along the expected wake-up path. Specifically, Argus first finds a similar vertex to the spinning one based solely on the semantic events such as system calls in each vertex. It then traverses backwards

Algorithm 1 Diagnosis algorithm.

Input: g - EventGraph; $spinning_vertex$ - the vertex in the UI thread when the spinning cursor occurs

Output: $root_cause_vertices$ -collecting root cause vertices for user inspect

```

1: function DIAGNOSE( $g$ ,  $spinning\_vertex$ )
2:   switch  $spinning\_vertex.block\_type$  do
3:     case LongRunning
4:        $slice \leftarrow InteractiveSlice(spinning\_vertex)$ 
5:       return vertex contains UI event
6:     case RepeatedYield
7:       if  $DataFlagEvent \notin \{event\ types\ in\ spinning\_vertex\}$  then
8:         Require users to annotate data flag
9:         abort()
10:      end if
11:      /* Fall through */
12:     case LongWait
13:        $similar\_vertex \leftarrow$  vertex has similar event sequence to  $spinning\_vertex$ 
14:        $baseline\_path \leftarrow InteractiveSlice(similar\_vertex)$ 
15:       for each  $t$  in  $\{threads\ in\ baseline\_path\}$  do
16:          $vertex_t \leftarrow$  vertex in  $t$  before  $spinning\_vertex$  gets spinning
17:         if  $vertex_t \in \{LongRunning, RepeatedYield, LongWait\}$  then
18:            $root\_cause\_vertices.append(vertex_t)$ 
19:            $root\_cause\_vertices.append(Diagnose(g, vertex_t))$ 
20:         end if
21:         /* if  $t$  is normal running, diagnose the next thread */
22:       end for
23:     end switch
24:   return  $root\_cause\_vertices$ 
25: end function

26: function INTERACTIVESLICING( $g$ ,  $vertex$ )
27:   loop
28:      $path\_slice.append(vertex)$ 
29:     if  $vertex$  has 1 incoming edge then
30:        $vertex \leftarrow predecessor\ vertex$ 
31:     else if  $vertex$  has multiple incoming edges then
32:        $vertex \leftarrow$  ask user to pick from predecessors
33:     else if  $vertex$  had weak edges then
34:        $vertex \leftarrow$  ask user to pick from predecessors
35:     else
36:       /* The first vertex of current thread */
37:       return  $path\_slice$ 
38:     end if
39:     if  $vertex$  is invalid then
40:       /* user chooses to stop traversal with invalid input */
41:       return  $path\_slice$ 
42:     end if
43:   end loop
44: end function

```

from the similar vertex to find the baseline wake-up path. For each thread in the wake-up path, it examines the vertex in the thread right before the spinning vertex waits. If this vertex is also abnormal, Argus appends it to the path of root cause vertices, and applies Function *Diagnose* recursively to diagnose “the culprit of the culprit.” For each such vertex, it queries the user to determine whether to proceed or stop because based on our experience the user needs to inspect only a few vertices to find the root cause.

Our experience suggests that the first case is the most common, but the second and third represent more severe bugs. Long-

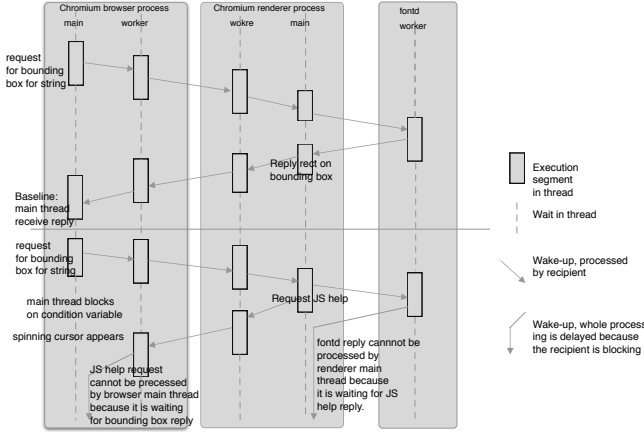


Figure 2: Chromium Example

running CPU operations tend to be more straightforward to diagnose with existing tools such as `spindump` except they do not connect CPU operations back to UI events. Repeated yielding or long waiting cases involve multiple threads and processes, and are extremely hard to understand and fix even for the application’s original developers. Therefore, issues remain unaddressed for years and significantly impact the user experience. Algorithm 1 is semi-automated but can integrate user input to leverage hypotheses or expert knowledge as to why a hang may occur. Our results show that user inputs, albeit few, are crucial in this process (§6).

2.3. Chromium Spinning Cursor Example

One of the authors experienced first-hand the aforementioned performance issue in Chromium, an open-source browser engine that powers Google Chrome and, starting recently, Microsoft Edge [7]. She tried to type in the Chromium search box a Chinese word using SCIM, the default Chinese Input Method Editor that ships with macOS. The browser appeared frozen and the spinning cursor occurs for a few seconds. Afterwards everything went back to normal. This issue is reproducible and always ruins her experience, but is quite challenging to diagnose because two applications Chromium and SCIM and many daemons ran and exchanged messages. It was reported by other users for other non-English input methods, too.

To diagnose this issue with Argus, the author follows the steps in Figure 1. She started system-wide tracing, and then reproduced the spinning cursor with a Chinese search string while the page was loading. After the very first few characters which the browser handles normally, the remaining character triggered a spinning cursor. The entire session took roughly five minutes. She then ran Argus to construct the event graph. The graph was highly complex, with 2,749,628 vertices and 3,606,657 edges, almost fully connected. It spanned across 17 applications; 109 daemons including `fontd`, `mdworker`, `nsurlsessiond` and helper tools by applications; 126 processes; 679 threads, and 829,287 IPC messages. Given the scale of the graph and the diverse communication patterns, it

would be extremely challenging for prior automated causal tracing tools [10, 31, 11, 15] because they handle a fairly limited set of patterns. Tools that require manual schema [12, 25], would be prohibitive because developers would have to provide schema for all involved applications and daemons.

Next she ran interactive debugger in Argus to find the spinning vertex in the main thread of the browser process. Argus returned a `LongWait` event, a `pthread_cond_timewait()` with a timeout of 1.5 seconds. Argus compares the spinning vertex to similar vertex in baseline scenario where the `wait` was signaled quickly. Argus reported three, and confirmed with the user which one she wanted.

Argus then found the baseline wake-up path which connects five threads. The browser main thread was signaled by a browser worker thread, which received IPC from a worker thread of daemon `renderer` where the rendering view and WebKit code run. The worker thread is woken up by the `renderer` main thread, which in turn woken by `fontd`, the font service daemon. Argus further compared the baseline path with the spinning case, as shown in path 1 in Figure 2, and returned the `LongWait` event on semaphore in the `renderer` main thread, the culprit that delayed waking up the browser main thread over four seconds. What caused the wait in the `renderer` main thread though? She thus continued diagnosis and recursively applied Argus to the wait in `renderer`, and it turned out that `renderer` was actually waiting to be woken up by the browser main thread – a circular wait formed.

Inspect of the reported vertices reveals that the browser was waiting for the `renderer` to return the string bounding box for a string, and the `renderer` was waiting for the browser to help render JavaScript. This circular wait was broken by a timeout in the browser main thread (the `wait` on `Cf` timeout was 1,500 ms). While the system was able to make progress, the next key press caused the spinning cursor to display for another 1,500 ms. The timeout essentially converted a deadlock into a livelock.

To verify this diagnosis, we shorten the timeout in the `pthread_cond_timedwait()` call in chromium to 150 milliseconds, which proportionally recuded how often this spinning cursor reproduces.

2.4. Limitations

Argus is designed to support interactive debugging of performance issues. It sometimes requires the user to reproduce a performance issue so Argus can capture more fine-grained event traces such as accesses to data flags. Fortunately, a performance issue that almost never reproduces is probably not as annoying as one that occurs frequently.

We implemented Argus in the closed-source macOS which presents a harsh test for Argus, but we have not ported Argus to other operating systems yet. It is possible that the ideas and techniques do not generalize to other operating systems. However, modern operating systems share many similarities, and inspire each others’ designs, so we are hopeful that the


```

1 //worker thread in fontd:      1 //main thread in fontd:
2 //enqueue a block             2 //dequeue blocks
3 block = dispatch_mig_sevice;   3 block = dequeue();
4 dispatch_async(block);         4 dispatch_execute(block);

1 //implementation of dipatch_mig_server
2 dispatch_mig_server()
3 for(;;) //batch processing
4     mach_msg(send_reply, rcv_request)
5     call_back(rcv_request)
6     set_reply(send_reply)

```

Figure 3: Dispatch message batching

```

1 //inside a single thread
2 while() {
3     CGXPostReplyMessage(msg) {
4         // send _gOutMsg if it hasn't been sent
5         push_out_message(_gOutMsg)
6         _gOutMsg = msg
7         _gOutMessagePending = 1
8     }
9     CGXRunOneServicePass() {
10        if (_gOutMessagePending)
11            mach_msg_overwrite(MSG_SEND | MSG_RECV, _gOutMsg)
12        else
13            mach_msg(MSG_RECV)
14        ... // process received message
15    }
16 }

```

Figure 4: Batching in event processing

```

1 //Worker thread:              1 //Main thread:
2 //needs to update UI:         2 //traverse all CA objects
3 obj->need_display = 1         3 if(obj->need_display == 1)
                                4     render(obj)

```

Figure 5: CoreAnimation shared flag

ideas in Argus are generally applicable. Similarly, the applications and performance issues used in our evaluation may be non-representative, though we strive to cover a diverse set of common applications ranging from browsers to text editors.

3. Inherent Inaccuracies in Causal Tracing

As explained in §1, causal tracing builds a graph to connect execution segments on behalf of a request that spread across separate threads and processes. Based on our experience building a causal tracing system on commercial, closed-source macOS, we believe such graphs are inherently inaccurate and contain both *over-connections* – edges that do not really map to causality) – and *under-connections* – missing edges between two vertices with one causally influencing the other. In this section, we present several inherently inaccurate patterns we observed and their examples in macOS.

3.1. Over Connections

Over connections usually occur when (1) intra-thread boundaries are missing due to unknown batch processing programming paradigms or (2) superfluous wake-ups that do not always imply causality.

```

1 //NSEvent thread:
2 CGEventCreateNextEvent() {
3     if (sCGEventIsMainThreadSpinning == 0x0)
4         if (sCGEventIsDispatchToMainThread == 0x1)
5             CFRRunLoopTimerCreateWithHandler{
6                 if (sCGEventIsDispatchToMainThread == 0x1)
7                     sCGEventIsMainThreadSpinning = 0x1
8                     CGSCConnectionSetSpinning(0x1);
9             }
10 }

1 //Main thread:
2 {
3     ... //pull events from event queue
4     Convert1CGEvent(0x1);
5     if (sCGEventIsMainThreadSpinning == 0x1){
6         CGSCConnectionSetSpinning(0x0);
7         sCGEventIsMainThreadSpinning = 0x0;
8         sCGEventIsDispatchedToMainThread = 0x0;
9     }
10 }

```

Figure 6: Spinning Cursor Shared Flags

Dispatch message batching While traditional causal tracing assumes the entire execution of a callback function is on behalf of one request, we found some daemons implement their service loop inside the callback function and create false dependencies. In the code snippet below from the `fontd` daemon, function `dispatch_execute` is installed as a callback to a work from dispatch queue. It subsequently calls `dispatch_mig_server()` which runs the typical server loop and handles messages from different apps.

To avoid incorrectly linking many irrelevant processes through such batching processing patterns, Argus adopts the aforementioned heuristics to split an execution segment when it observes that the segment sends out messages to two distinct processes. Any application or daemon can implement its own server loop this way, which makes it fundamentally difficult to automatically infer event handling boundaries.

Batching in event processing Message activities inside a system call are assumed to be related traditionally. However, to presumably save on kernel boundary crossings, WindowServer MacOS system daemon uses a single system call to receive data and send data for an unrelated event from different processed in its event loop. This batch processing artificially makes many events appear dependent.

Mutual exclusion In a typical implementation of mutual exclusion, a thread’s unlock operation wakes up a thread waiting in lock. Such a wake-up may be, but is not always, intended as causality. However, without knowing the developer intent, any wake-up is typically treated as causality.

3.2. Under Connections

We observe that under connections mostly result from missing data dependencies. This pattern is more general than shared-memory flags in ad hoc synchronization [27] because it occurs even within a single thread.

Data dependency in event processing The code for Batching in event processing above also illustrates a causal linkage caused by data dependency in one thread. WindowServer saves the reply message in variable `_gOutMsg` inside function `CGXPostReplyMessage`. When it calls `CGXRunOneServicePass`, it sends out `_gOutMsg` if there is any pending message.

CoreAnimation shared flags As shown in the code snippet below, worker thread can set a field `need_display` inside a `CoreAnimation` object whenever the object needs to be repainted. The main thread iterates over all animation objects and reads this flag, rendering any such object. This shared-memory communication creates a dependency between the main thread and the worker so accesses to these field flags need to be tracked.

Spinning cursor shared flag As shown in Figure 6, whenever the system determines that the main thread has hung for a certain period, and the spinning beach ball should be displayed, a shared-memory flag is set. Access to the flag is controlled via a lock, i.e. the lock is used for mutual exclusion, and does not imply a happens before relationship.

4. Handling Inaccuracies

In this section, we first describe the basics of Argus event graphs (§4.1), and then discuss how Argus mitigates over-connections (§4.2) and under-connections (§4.2) in them.

4.1. Event Graph Basics

To construct event graphs, Argus collects three categories of events in its systems-wide event logs. The first category contains semantic events, such as system calls, call stacks collected when certain operations such as macOS message operations are run, and user actions such as key presses. These events indicate what the developer intents might be, and are stored as contents in each vertex in the event graph. They are primarily for providing information to user during diagnosis and for finding similar vertices (§2).

The second category of events are boundary events that mark the beginning and ending of execution segments or vertices in the graph. Argus handles common callback invocations such as `dispatch_invoke` and `runloop_invoke` and mark their entry and return as boundaries.

The third category of events are for forming edges in the graph. For instance, an operation that installs a callback is connected to the execution of the callback. A message send is connected to a message receive. The arming of a timer is connected to the execution of the timer callback. A unique design in Argus is to trace general wake-up and wait operations inside the kernel to ensure coverage across many diverse user-level, possibly custom wake-up and wait operations because their implementations almost always use kernel wake-up and wait. This approach necessarily includes spurious edges in the graph, including those due to mutual exclusion; Argus handles

them by querying the user when it encounters a node with multiple incoming causal edges during diagnosis (see §2). We also observed that a waiting kernel thread is frequently woken up to perform tasks such as interrupt handling and scheduler maintenance; Argus recognizes them and culls them out from the graph automatically.

Compared to tools such as `spindump` that capture only the current system state, event graphs capture the causal path of events, enabling users to trace across threads and process to events happened in the past (hence cannot be captured by `spindump`) that explain present anomalies.

4.2. Mitigating Over-Connections

From a high-level, Argus deals with over-connections by heuristically splitting an execution segment that appears mixing handling of multiple requests. It adds weak causal edges between the split segments in case the splitting was incorrect. When a weak edge is encountered during diagnosis, it queries users to decide whether to follow the weak edge or stop (§2).

Specifically, Argus splits based three criteria. First, Argus recognizes a small set of well-known batch processing patterns such as `dispatch_mig_server()` in §3 and splits the batch into individual items. Second, when a wait operation such as `recv()` blocks, Argus splits the segment at the entry of the blocking wait. The rationale is that blocking wait is typically done at the last during one step of event processing. Third, if a segment communicates to too many peering processes, Argus splits the segment when the set of peers differs. Specifically, for each message, Argus maintains a set of two peers including (1) the direct sender or receiver of the message and (2) the beneficiary of the message (macOS allows a process to send or receive messages on behalf of a third process). Argus splits when two consecutive message operations have non-overlapping peer sets.

4.3. Mitigating Under-Connections

Under-connections are primarily due to data dependencies. Currently Argus queries the user to identify the memory locations of the data flags. It is conceivable to leverage memory protection techniques to infer them automatically, as demonstrated in previous record-replay work [22, 17], it is out of the scope of this paper and we leave it for future work. Currently, to discover a data flag, the user re-runs the application with Argus to collect instruction traces of the concurrent events in both the normal and spinning cases and detects where the control flow diverges. She then reruns the application with Argus to collect register values for the basic blocks before the divergence and uncovers the address of the data flag. Once the user identifies a data flag, Argus traces it using either binary instrument, such as the `need_display` flag in `CoreAnimation` (§3), or with watchpoints. Argus add a causal edge between a write to a data flag to the corresponding read to the flag.

5. Implementation

In this section, we discuss how Argus collects tracing events from both kernel and libraries, and user interactions which Argus leverages to ease diagnosis.

5.1. Event Tracing

Current macOS systems support a system-wide tracing infrastructure built by Apple [1]. By default, the infrastructure temporarily stores events in memory and flushes them to screen or disk when an internal buffer is filled. We extended this infrastructure to support larger-scale tests and avoid filling up the disk with a file-backed ring buffer. Each log file is 2GB by default, which users can override. This size corresponds corresponds to approximately 19 million events (about 5 minutes with normal operations).

The default tracing points in macOS provide too limited information to enact causal tracing. As a result, we instrumented both the kernel ref[2] (at the source level) and key libraries (at the binary level), to gather more tracing data. We instrumented the kernel with 1,193 lines of code, and binary-instrumented the following libraries: `libsystem_kernel.dylib`, `libdispatch.dylib`, `libpthread.dylib`, `CoreFoundation`, `CoreGraphics`, `HIToolbox`, `AppKit` and `QuartzCore` in 57 different places.

5.2. Instrumentation

Most libraries as well as many of the applications used day-to-day are closed-source in macOS. To add tracing points to such code, techniques such as library preloading to override individual functions are not applicable on macOS, as libraries use two-level executable namespace [3]. Hence, we implemented a binary instrumentation mechanism that allows developers to add tracing at any location in a binary image.

Like Detour [21], we use static analysis to decide which instrumentation to perform, and then enact this instrumentation at runtime. Firstly, the user finds a location of interest in the image related to a specific event by searching a sequence of instructions. Then the user replaces a call instruction to invoke a trampoline target function, in which we overwrite the victimized instructions and produce tracing data with API from Apple. All of the trampoline functions are grouped into a new image, as well as an initialization function which carries out the drop-in replacement. Then command tools from Argus help to configure the image with the following steps: (1) re-export all symbols from the original image so that the original code can be called like an shared library; (2) rename the original image, and use original name for the new one to ensure the modifications are properly loaded; (3) invoke the initialization function externally through `dispatch_once` during the loading.

5.3. Tracing Data Flags

As described in (§3), under-connection due to the missing data dependency requires users' interaction. Users specify that reads and writes to a given global variable should be considered data dependencies. Global-variable tracing is possible through Argus's binary rewriting, but we also provide a simple command line tool which uses watchpoint registers to record `data_flag_write` and `data_flag_read` events. The tool takes as input the process ID, path to the relevant binary image, and the symbol name of the global variable. Here is a simple example of how a user would ask Argus to trace `_gOutMsgPending`:

```
1 ./breakpoint_watch Pid/of/WindowServer Path/to/CoreGraphics \
2 _gOutMsgPending
```

At load time, Argus hooks the watchpoint break handler in `CoreFoundation` to make sure that it is loaded correctly into the address space of our target application. The handler invokes Apple's event tracing API to record the value of the data flag and the operation type (read or write).

5.4. Tracing Instructions and Calls

Users may need to gather more information, such as individual instructions and call stacks, to come up with and verify a binary patch. Argus integrates with `lldb` to capture this information and add it to the corresponding vertices in the event graph.

We gather call stacks only at relevant locations, to reduce the data collection overhead. Our `lldb` scripts go through the instructions of apps and frameworks step by step to capture the parameters tainted by user inputs. Only at each beginning of a function call does the script record a full call stack. We also step over and record the return value of APIs from low-level libraries (i.e. those with the filename extension `.dylib`).

The combination of instruction-level tracing and occasional call-stacks offers more than enough detail to diagnose even the most arcane issues, and in our experience has been very helpful in multiple steps of an Argus diagnosis.

5.5. Find Baseline Scenario

Argus leverages a baseline scenario to discover missing wake-up edges in **Long Wait** cases.

The baseline scenario is identified from the vertices which share the same high level semantics as the spinning vertex, but exposes different execution results. Argus recognizes high level semantics of vertices with semantic events, including system calls, call stacks, user actions. Their sequential order and runtime unrelated attributes are treated as hallmarks. For example, Argus compares vertices with system call numbers and symbol names in call stacks. To improve the accuracy, Argus also checks the events forming edges, including messages, dispatch queue operations, runloop operations, `data_flag_read` and `data_flag_write`, as they might reflect the low-level behaviors of developers' intent. More over,

a user can also instruct Argus to inspect proceeding vertices for accuracy purpose. By default, Argus discriminate the execution results with the time cost and wait results. If multiple similar vertex are identified, Argus usually asks users for a confirmation, or choose the most recent one heuristically.

6. Case Studies

In this section, we demonstrate how Argus helps to diagnose 11 spinning-cursor cases in popular applications. Table 1 describes these spinning-cursor cases, which are detailed in sections that follow. We compared Argus with traditional causal tracing methods on edges and vertices mitigated. The portions of over-connection filtered out and incognito under-connections disclosed are studied. Even with our technique, the filtered graph remains too inaccurate for automatic causal tracing. Fortunately, user interactions compensate the inaccuracy in causal path slicing, while not overwhelming in the diagnosis process.

Our results in Table 2 show the portion of connections filtered with heuristics is limited. User interaction is still required for diagnosis, but in most cases, up to 3 user queries suffice to find root cause path accurately. Although a complex application like 8-MSWord and 1-Chromium requires 22 and 13 queries respectively, many of them results from repeated patterns. They can be easily identified by users, as discussed below. Our interactively path slicing exclude much noise, and are shorter and easier to inspect.

Overall, in the case of simple text editing applications, Argus can identify the UI event that causes a spinning cursor by merely relying on a few heuristics. However, these heuristics may make the wrong decision in complicated cases, and misidentify the relationships between intra/inter-thread events. It is unlikely that there exists a single graph search method that works in all cases, e.g. when given the choice between multiple incoming edges, the most recent match is sometimes correct, but sometimes not. This is why our system relies on expert knowledge of users to reconstruct a developer’s intent and accurately diagnose performance issues.

How Argus Detects Spinning Cursors When the spinning cursor shows up, a hang reporting tool, `spindump` usually kicks in automatically to sample callstacks for debugging. To figure out the spinning vertex in the main thread, we turn to the event graph, and slice path backward from the launch of `spindump`. The path shows that `spindump` is launched after receiving a message from `WindowServer`, which received a message from the `NSEvent` thread of the freezing app. The call stack attached to the messages further reveals the `NSEvent` thread fetches `CoreGraphics` events from `WindowServer`, converts and creates `NSApp` events for the main thread. If the main thread fails to process an `NSApp` event before the timer fires, `NSEvent` thread sends a message to `WindowServer` via the API “`CGSConnectionSetSpinning`” from the timer handler, and `WindowServer` notifies the

Bug ID	Application	Bug description
1-Chromium	Chromium	Typing non-english in search box causes webpage freeze.
2-SystemPref	System Preferences	Disabling an online external monitor and rearranging windows causes System Preferences freeze.
3-SequelPro	Sequel Pro	Lost connection freezes the APP.
4-Installer	Installer	Moving cursor out of an authentication window causes freeze.
5-TexStudio	TeXStudio	Modification on bib file with vim causes its main window hang.
6-Notes	Notes	Launching Notes where stores a long note before causes freeze.
7-TextEdit	TextEdit	Copying text over 30M causes freeze.
8-MSWord	Microsoft Words	Copying a document over 400 pages causes hang.
9-SIText	Sublime Text	Copying in a file over 49000 lines causes freeze.
10-TextMate	TextMate	Pasting text over 4000 lines causes freeze.
11-CotEditor	CotEditor	Pasting in file with 4000 lines context causes freeze.

Table 1: Bug Descriptions.We assign each bug in Column Bug ID to ease discussion

`CoreGraphics` to draw a spinning cursor over the application window. To avoid sending more events to an already-spinning main thread, the `NSApp` thread uses two data flags to track the main thread status, `is_mainthread_spinning` and `dispatch_to_mainthread`. These flags are also modified by the main thread to update its status. Argus leverages this API to identify the spinning vertex in the main thread.

6.1. Long Wait and Repeated Yield

In this section, we discuss the cases where the spinning vertex is blocking on wait event or yielding loop, corresponding to Long Wait and Repeated Yield.

2-SystemPref System Preferences provides a central location in macOS to customize system settings, including configuring additional monitors. A tool called `DisableMonitor` [9] provides full functionality including the ability to enable/disable monitors online. We blocked on the spinning cursor while disabling an external monitor and rearranging windows in `Display` panel.

The log collected with Argus contains 1) a baseline scenario where the displays are rearranged with the enabled external monitor, and 2) a spinning scenario in which we disable the external monitor with `DisableMonitor` and rearrange the displays. The spinning vertex in the main thread is dominated by system calls, `mach_msg` and `thread_switch`, which falls into the category of Repeated Yield. We discovered two missing data flags with `lldb`, “`_gCGWillReconfigureSeen`” and “`_gCGDidReconfigureSeen`”, which signify the configuration status and break the thread-yield loop. Argus learns from the baseline scenario that the main thread is responsible to set both of them after receiving specific datagrams from `WindowServer`. Conversely, the setting of

Bug ID	% of connections filtered out	% of connections added by heuristics	# of user provided data flag	# of user interactions	size of baseline/spinning path with		auto slicing
					interactive slicing	automatic slicing	interactive slicing
1-Chromium	0.02	0.02	0	13	32	303	9.47
2-SystemPref	0.56	2.48	2	1	2	30	15.00
3-SequelPro	0.49	0.35	0	2	5	264	52.80
4-Installer	4.39	2.83	0	2	6	36	6.00
5-TeXStudio	2.43	0.58	0	3	6	44	7.33
6-Notes	2.97	11.53	0	2	10	42	4.20
7-TextEdit	7.97	0.72	0	3	21	21	1.00
8-MSWord	6.72	1.04	0	22	67	136	2.03
9-SIText	4.07	0.92	0	1	3	3	1.00
10-TextMate	2.15	2.18	0	0	3	3	1.00
11-CotEditor	4.81	5.32	0	1	4	6	1.50

Table 2: Graph Comparison

The first and second column presents the portion of connection adjusted by Argus compared to traditional causal tracing. Column 3 is the number of data flag added for diagnosis in addition to the default flag Argus tracks. The forth and fifth column illustrates the vertices in the paths, which are sliced backward with and without user interaction. The last column shows that without user interaction, the path sliced by Argus, even with our filtering heuristics, still includes too much vertices for inspection.

“_gCGDidReconfigureSeen” is missing in the spinning case, where the main thread yields repeatedly to send messages to WindowServer for such datagram.

In conclusion, we discovered that the bug is inherent in the design of the CoreGraphics library, and would have to be fixed by Apple. We verified this diagnosis by creating a dynamic binary patch with lldb to fix the deadlock. The patched library makes DisableMonitor work correctly, while preserving correct behavior for other applications.

3-SequelPro Sequel Pro [4] is a fast, easy-to-use Mac database management application for working with MySQL databases. It allows user to connect to database with a standard way, socket or ssh.

We experienced the non-responsiveness of Sequel Pro while its network connection got lost and it tried re-connections. The tracing data collected by Argus contains 1) a quick network connection during login, and 2) Sequel Pro lost connection for a while. Although Argus identified the spinning vertex and corresponding (baseline) similar vertex with ease, it cannot get the correct causal path in the baseline scenario without user interaction. The backward slicing on vertex has multiple incoming edges, including one from a kernel thread, which means that operations are likely to be batched together and inseparable by heuristics. Our interactively search is extremely helpful in this step, greatly reducing the noise in the path. Close examination of the spinning vertex based on the causal path tells us that the main thread is waiting for the kernel thread, which in turn waits for the ssh thread. Existing debugging tools like lldb and spindump cannot determine the root cause, because both of them diagnose with only call stacks, missing the dependency across processes.

4-Installer Installer [5] is an application included in macOS that extracts and installs files out of .pkg packages. When Installer pops up a window for privileged permission during the installation of jdk-7u80-macosx-x64, moving the cursor out of the popup window triggers a spinning cursor.

As we put in the password before the round of triggering

the spinning cursor, Argus successfully records the baseline scenario. Examining the spinning vertex and its similar vertex, Argus figures out the daemon authd blocks on semaphore while the main thread is waiting for authd. Further checking on authd, Argus reveals it is the SecurityAgent that processes user input and wakes up authd in baseline scenario. In conclusion, moving the mouse out of the authentication window causes the missing edge from SecurityAgent to authd, which in turn blocks Installer.

We also discovered a communication pattern in Installer underpinning the crucial of interactive debugging. It involves four vertices in four threads, vertex $Vertex_{main}$ in the main thread, and $Vertex_1$ to $Vertex_3$ in three worker threads. First, the main thread wakes up three worker threads. Then one worker thread is scheduled to run. At its end, another worker thread, which waits on mutex lock, is woken in $Vertex_2$, which in turn wakes up the next worker thread in $Vertex_3$. While Argus is slicing backward, $Vertex_3$ has two incoming edges: one is from $Vertex_{main}$, and the other one is from $Vertex_2$. Since users can peek the edges before making decision, they are likely to figure out that the three worker threads contend with mutex lock, and all of them are successors of $Vertex_{main}$.

6.2. Long Running

In this section, we discuss the cases where the spinning vertex is busy on the CPU. Most text editing apps fall into this bug category. We studied bugs on TeXstudio, TextEdit, Microsoft Word, Sublime Text, Text Mate and CotEditor, listed in Table 1 to reveal their root causes.

5-TeXStudio TeXstudio [6] is an integrated writing environment for creating LaTeX documents. We noticed a user reported spinning cursor when he modified his bibliography (bib) file. Although the issue was closed by the developer, due to insufficient information to reproduce the bug, we reproduced it with a large bib file opened in a tab. Each time we touched the file through another editor, vim for example, the application window showed a spinning cursor.

Argus recognizes the spinning vertex belongs to the category of Long Running. Slicing causal path from the vertex, Argus reaches daemon “fseventd” and figures out that the long-running function is invoked by a callback function from this daemon to sync data. The advantage of Argus over other debugging tools is it helps to narrow down the root cause with the inter-thread execution path.

7-TextEdit TextEdit is a simple word processing and text editing tool shipped by Apple, which often hangs on the editing of large files. When Argus is used to diagnose this issue, the automated heuristics are frequently powerful enough to find the true root cause. The graph reveals a communicating pattern in the vertices where a kernel thread was woken up from blocking IO by another kernel thread; and it processed the timer armed by TextEdit and woke up one of its threads. The first incoming edge is from the second kernel thread, and the second incoming edge is from TextEdit(from vertex where the timer armed to where it is processed). Users can make decision on the vertex base on the event sequence, which implies the story: TextEdit first arms the timer for IO work, then kernel threads work for it, and finally it processes the timer and wakes up TextEdit when finished.

The success of our automated analyses is not surprising because the pattern of vetices fits our expected bug structure, where we choose the most recent incoming edge. Although the automatic heuristics works for this particular application, it is not general enough to succeed for all patterns.

8-MSWord Microsoft Word is a large and complex piece of software. Argus can analyze the event graph, but it identifies multiple possible root causes: the length of path interactively sliced from the spinning vertex is 67, while the automatic slicing generates a path of 136 vertices.

We compared the path and find that the earliest difference exists in the predecessor of the third vertex in backward paths. In the vertex, user can learn from the call stack that Microsoft Word launches a service `NSServiceControllerCopyServiceDictionary` after being woken by another Microsoft Word thread; this thread then sends a message to `launchd` to register the new service and waits for a reply message. With the most recent edge heuristics in automatic slicing, Argus chose `launchd` as its predecessor, but the user can more accurately identify that the execution segment is on behalf of the first thread. We rely on user interaction in this case to find the true root cause, since Argus has identified multiple possibilities.

Other Editing Apps Select, copy, paste, delete, insert and save are common operations for text editing. However, these operations on a large context usually trigger spinning cursors. Due to their implementation, CotEditor and TextMate successfully avoid hangs on copy and selection operations. Argus can help the developer to figure out the more efficient way to implement event handlers. In Table 3, we list the reports from each application’s spinning vertex, including the event handler

BUG-ID	costly API	UI
6-Notes	1) NSDetectScrollDevices ThenInvokeOnMainQueue	system defined event
9-SIText	1) px_copy_to_clipboard 2) __CFToUTF8Len	key c
10-TextMate	1) -[OakTextView paste:] 2) CFAttributedStringSet 3) TASCIIEncoder::Encode	key v
11-CotEditor	1) CFStorageGetValueAtIndex 2) -[NSBigMutableString characterAtIndex:]	key Return

Table 3: Root cause of spinning cursor in editing Apps

	1st	2nd	3rd	4th	5th
without Argus	5.98	6.23	6.18	6.05	6.28
with Argus	6.29	6.01	6.09	6.28	6.01
average overhead	0.13%				

Table 4: Score From iBench

and most costly functions, and the user input event (derived from path slicing) that triggers the hang.

7. Performance Evaluation

In this section we present the performance impact of the live deployment of Argus. We deployed Argus on a MacBookPro9,2, which has Intel Core i5-3210M CPU with 2 cores and 4 thread, 10GB DDR3 memory and a 1T SSD.

Argus has a very small space overhead with the configuration of its tracing tool. It uses the ring buffer with configured 2G by default to collect tracing events. The memory used to store events is fixed to 512M by Apple, which is pretty low with regards to the memory usage of modern applications. In the remaining of this section, we measure Argus’s overhead overall with iBench scores, IO throughput degradation with bonnie++, iозone and CPU overhead with chromium benchmarks.

iBench We first show the five runs of iBench with and without Argus to evaluate the overall performance. The machine is clean booted for each run, and the higher score means it performs better. As shown in Table 4, their performance are

	kb/s	With Argus	Without Argus	overhead
bonnie++	read char	21922	22149	0.01
	read block	226931	244089	0.07
	rewrite	246807	267491	0.08
	write char	22924	22936	0.00
	write block	4073361	4396387	0.07
seq	file create	17391	17381	0.00
	file delete	18089	19401	0.07
random	create	17472	17887	0.02
	delete	8849	9567	0.08
iозone	initial write	1199453	1318572	0.09
	rewrite	3663066	4059912	0.10
	average	-	-	0.05

Table 5: IO throughput with bonnie++ and iозone

Chromium Benchmark (in seconds)	with Argus			without Argus			Overhead		
	real	user	sys	real	user	sys	real	user	sys
system_health.memory_desktop	11592	18424	1821	11317	18401	1415	0.02	0.00	0.29
rasterize_and_record_micro.top_25	1579	2142	135	1654	2166	116	-0.05	-0.01	0.16
blink_perf	16210	17227	959	15877	16724	766	0.02	0.03	0.25
web rtc	726	2023	225	725	2130	168	0.00	-0.05	0.34
memory_desktop	1231	2238	267	1188	2200	190	0.04	0.02	0.41
loading_desktop.network_service	24580	52751	6294	23696	52327	4197	0.04	0.01	0.50
dromaeo	206	227	15	192	212	12	0.07	0.07	0.29
dummy_benchmark.histogram	49	48	8	33	36	4	0.50	0.32	0.96
v8.browsing_desktop	2462	4489	491	2325	4440	303	0.06	0.01	0.62
octan_desktop	112	142	8	98	124	5	0.14	0.15	0.44
speedometer	618	802	31	600	782	24	0.03	0.03	0.32
page_cycler_v2.typical_2	8020	14435	1453	7847	14215	1019	0.02	0.02	0.43
smoothness.oop_rasterization.top_25_smooth	864	1450	156	833	1412	126	0.04	0.03	0.24
AVERAGE	-	-	-	-	-	-	0.07	0.05	0.4

Table 6: Chromium benchmark

almost of no difference, only 0.13% degradation on average.

IO Throughput Next, we evaluate the IO throughput with *bonnie++* and *iozone*. As shown in the Table 5, the throughputs of sequential read and write by characters with and without Argus are almost same. Read and write by block impose less than 10% overhead in both microbenchmarks, *bonnie++* and *iozone*. With selected events in our system, the tracing tool integrated in Argus only adds 5% IO overhead on average.

CPU We evaluate Argus’s CPU overhead with chromium benchmarks by recording their time usage on real, user and sys. Although the overhead on sys is relatively higher than other two, due to the tracing events usually crossing the kernel boundary, they are not triggered too frequently in our daily software usage, including browsers. The time cost is mostly under 5%, except the *dummy_benchmark.histogram*. As shown in Table 6, the time overhead for real, user and sys are 7%, 5% and 40% respectively.

8. Related Work

While there is currently no system that can help users debug performance issues in closed-source applications on proprietary macOS, several active research topics are closely related.

Event tracing. Panappticon [31] monitors a mobile system and uses the trace to characterize the user transactions of mobile apps. Although it aims to track system-wide events and correlate them without developer input, it supports only two models of communication: work queue and thread pooling. AppInsight [24] instruments application to identify the critical execution path in a user transaction. It supports the event callback pattern, and does not trace across process or app boundaries. Magpie [12] monitors server applications in Windows with the goal to model the normal behaviors of a server application in response to a workload. This model further helps detecting anomalies statistically. Magpie requires a manual-written event schema for all involved applications to capture precise request graphs, whereas Argus has a simple, application-agnostic schema for system-wide tracing and en-

ables users to provide more application-specific knowledge on demand.

Aguilela [10] uses timing analysis to correlate messages to recover their input-output relations while treating the application as a black box. XTrace, Pinpoint and etc [18, 13, 14] trace the path of a request through a system using a unique identifier attached to each request and stitch traces together with the identifier. Argus comes up violation patterns and does not assume the presence of a unified identifier in closed-source, third-party applications, frameworks, and libraries.

Performance anomaly detection. Several systems detect performance anomalies automatically. [19, 30] leverage the user logs and call stacks to identify the performance anomaly. [15, 26, 28, 16] apply the machine learning method to identify the unusual event sequence as an anomaly. [29] generates the wait and waken graph from sampled call stacks to study a case of performance anomaly.

These systems are orthogonal to Argus as Argus’s goal is to diagnose an already-detected performance anomaly. These systems can help Argus by detecting more accurately when a performance issue arises.

9. Conclusion

Our key insight in this paper is that causal tracing is inherently inaccurate. We have reported patterns we observed that pose big precision challenges to causal tracing, and built Argus, a practical system for effectively debugging performance issues in macOS applications despite the inaccuracy of causal tracing. To do so, it lets a user provide domain knowledge interactively on demand. Our results show that Argus effectively helped us locate all root causes of the issues, including a bug in Chromium, 01 and incurred 7% CPU overhead overall in its system-wide tracing.

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