Lightweight User-Space Record And Replay

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Abstract

The ability to record and replay program executions with low overhead enables many applications, such as reverse-execution debugging, debugging of hard-to-reproduce test failures, and “black box” forensic analysis of failures in deployed systems. Existing record-and-replay approaches rely on recording an entire virtual machine (which is heavyweight), modifying the OS kernel (which adds deployment and maintenance costs), or pervasive code instrumentation (which imposes significant performance and complexity overhead). We investigated whether it is possible to build a practical record-and-replay system avoiding all these issues. The answer turns out to be yes — if the CPU and operating system meet certain non-obvious constraints. Fortunately modern Intel CPUs, Linux kernels and user-space frameworks meet these constraints, although this has only become true recently. With some novel optimizations, our system RR records and replays real-world workloads with low overhead with an entirely user-space implementation running on stock hardware and operating systems. RR forms the basis of an open-source reverse-execution debugger seeing significant use in practice. We present the design and implementation of RR, describe its performance on a variety of workloads, and identify constraints on hardware and operating system design required to support our approach.

1 Introduction

The ability to record a program execution with low overhead and play it back precisely has many applications [13, 14, 18] and has received significant attention in the research community. It has even been implemented in products such as VMware Workstation [27], Simics [19], UndoDB [1] and TotalView [21]. Unfortunately, deployment of these techniques has been limited, for various reasons. Some approaches [16, 19, 27] require recording and replaying an entire virtual machine, which is heavyweight. Other approaches [6, 13, 25] require running a modified OS kernel, which is a major barrier for users and adds security and stability risk to the system. Some approaches [23, 28, 32] require custom hardware not yet available. Many approaches [1, 7, 21, 31] require pervasive instrumentation of code, which adds complexity and overhead, especially for self-modifying code (commonly used in polymorphic inline caching [24] and other implementation techniques in modern just-in-time compilers). A performant dynamic code instrumentation engine is also expensive to build and maintain.

We set out to build a system that maximizes deployability by avoiding all these issues: to record and replay unmodified user-space applications on stock Linux kernels and x86/x86-64 CPUs, with a fully user-space implementation running without special privileges, and without using pervasive code instrumentation. We assume that RR should run unmodified applications, and they will have bugs (including data races) that we wish to faithfully record and replay, but these applications will not maliciously try to subvert recording or replay. We combine techniques already known, but not previously demonstrated working together in a practical system: primarily, using ptrace to record and replay system call results and signals, avoiding non-deterministic data races that we wish to faithfully record and replay, but these applications will not maliciously try to subvert recording or replay. We combine techniques already known, but not previously demonstrated working together in a practical system: primarily, using ptrace to record and replay system call results and signals, avoiding non-deterministic data races by running only one thread at a time, and using CPU hardware performance counters to measure application progress so asynchronous signal and context-switch events are delivered at the right moment [30]. Section 2 describes our approach in more detail.

With the basic functionality in place, we discovered that the main performance bottleneck for our applications was the context switching required by using ptrace to monitor system calls. We implemented a novel system-call buffering optimization to eliminate those context switches, dramatically reducing recording and replay overhead on important real-world workloads. This optimization relies on modern Linux kernel features: seccomp-bpf to selectively suppress ptrace traps for certain system calls, and perf context-switch events to detect recorded threads blocking in the kernel. Section 3 describes this work, and Section 4 gives some performance results, showing that on important application workloads RR recording and replay slowdown is less than a factor of two.

We rely on hardware and OS features designed for other goals, so it is surprising that RR works. In fact, it skirts
the edge of feasibility, and in particular it cannot be im-
plemented on ARM CPUs. Section 5 summarizes RR’s
hardware and software requirements, which we hope will
influence system designers.

RR is in daily use by many developers as the founda-
tion of an efficient reverse-execution debugger that works
on complex applications such as Samba, Firefox, QEMU,
LibreOffice and Wine. It is free software, available at
https://github.com/mozilla/rr

This paper makes the following research contributions:

- We show that record and replay of Linux user-space
  processes on modern, stock hardware and kernels
  and without pervasive code instrumentation is pos-
  sible and practical.
- We introduce the system-call buffering optimization
  and show that it dramatically reduces overhead.
- We show that recording and replay overhead is low
  in practice, for applications that don’t use much par-
  allelism.
- We identify hardware and operating system design
  constraints required to support our approach.

2 Design

2.1 Summary

Most low-overhead record-and-replay systems depend on
the observation that CPUs are mostly deterministic. We
identify a boundary around state and computation, record
all sources of nondeterminism within the boundary and all
inputs crossing into the boundary, and reexecute the com-
putation within the boundary by replaying the nondeter-
minism and inputs. If all inputs and nondeterminism have
truly been captured, the state and computation within the
boundary during replay will match that during recording.

To enable record and replay of arbitrary Linux applica-
tions, without requiring kernel modifications or a virtual
machine, RR records and replays the user-space execu-
tion of a group of processes. To simplify invariants, and
to make replay as faithful as possible, replay preserves
almost every detail of user-space execution. In particu-
lar, user-space memory and register values are preserved
exactly, with a few exceptions noted later in the paper.
This implies CPU-level control flow is identical between
recording and replay, as is memory layout.

While replay preserves user-space state and execution,
only a minimal amount of kernel state is reproduced dur-
ing replay. For example, file descriptors are not opened,
signal handlers are not installed, and filesystem operations
are not performed. Instead the recorded user-space-visible
effects of those operations, and future related operations,
are replayed. We do create one replay thread per recorded
thread (not strictly necessary), and we create one replay
address space (i.e. process) per recorded address space,
along with matching memory mappings.

With this design, our recording boundary is the inter-
face between user-space and the kernel. The inputs and
sources of nondeterminism are mainly the results of sys-
tem calls, and the timing of asynchronous events.

2.2 Avoiding Data Races

If we allow threads to run on multiple cores simultane-
ously and share memory, racing read-write or write-write
accesses to the same memory location by different threads
would be a source of nondeterminism. It seems imprac-
tical to record such nondeterminism with low overhead
on stock hardware, so instead we avoid such races by al-
lowing only one recorded thread to run at a time. RR pre-
emptively schedules these threads, so context switches are
a source of nondeterminism that must be recorded. Data
race bugs can still be observed if a context switch occurs at
the right point in the execution (though bugs due to weak
memory models cannot be observed).

This approach is simple and efficient for applications
without much parallelism. It imposes significant slow-
down for applications with a consistently high degree of
parallelism, but those are still relatively uncommon.

2.3 System Calls

System calls return data to user-space by modifying reg-
isters and memory, and these changes must be recorded.
The ptrace system call allows a process to supervise the
execution of other “tracee” processes and threads, and to
be synchronously notified when a tracee thread enters or
exits a system call. When a tracee thread enters the kernel
for a system call, it is suspended and RR is notified. When
RR chooses to run that thread again, the system call will
complete, notifying RR again, giving it a chance to record
the system call results. RR contains a model of most Linux
system calls describing the user-space memory they can
modify, given the system call input parameters and result.

As noted above, RR normally avoids races by schedul-
ing only one thread at a time. However, if a system
call blocks in the kernel, RR must try to schedule an-
other application thread to run while the blocking sys-

tem call completes. It’s possible (albeit unlikely) that
the running thread could access the system call’s output
buffer and race with the kernel’s writes to that buffer. To
Figure 1: Recording simple system call

...
kernel device drivers, where that non-recorded code can perform writes that race with accesses by tracee threads. Fortunately, this is rare for applications running in common Linux desktop environments, occurring in only four common cases: applications sharing memory with the PulseAudio daemon, applications sharing memory with the X server, applications sharing memory with kernel graphics drivers and GPUs, and vdso syscalls. We avoid the first three problems by automatically disabling use of shared memory with PulseAudio and X (falling back to a socket transport in both cases), and disabling direct access to the GPU from applications.

vdso syscalls are a Linux optimization that implements some common read-only system calls (e.g., gettimeofday) entirely in user space, partly by reading memory shared with the kernel and updated asynchronously by the kernel. We disable vdso syscalls by patching their user-space implementations to perform the equivalent real system call instead.

Applications could still share memory with non-recorded processes in problematic ways, though this is rare in practice and can often be solved just by enlarging the scope of the group of processes recorded by RR.

## 2.6 Nondeterministic Instructions

Almost all CPU instructions are deterministic, but some are not. One common nondeterministic x86 instruction is RDTSC, which reads a time-stamp counter. This particular instruction is easy to handle, since the CPU can be configured to trap on an RDTSC and Linux exposes this via a `prctl` API, so we can trap, emulate and record each RDTSC.

Other relatively recent x86 instructions are harder to handle. RDRAND generates random numbers and hopefully is not deterministic. We have only encountered it being used in one place in GNU libc++. So RR patches that explicitly. XBEGIN and associated instructions support hardware transactional memory. These are nondeterministic from the point of view of user space, since a hardware transaction can succeed or fail depending on CPU cache state. Fortunately so far we have only found these being used by the system pthreads library, and we dynamically apply custom patches to that library to disable use of hardware transactions.

The CPUID instruction is mostly deterministic, but one of its features returns the index of the running core, which affects behavior deep in glibc and can change as the kernel migrates a process between cores. We use the Linux `sched.setaffinity` API to force all tracee threads to run on a particular fixed core, and also force them to run on that core during replay.

We could easily avoid most of these issues in well-behaved programs if we could just trap-and-emulate the CPUID instruction, since then we could mask off the feature bits indicating support for RDRAND, hardware transactions, etc. Modern Intel CPUs support this ("CPUID faulting"); we are in the process of adding an API for this to Linux.

## 2.7 Reducing Trace Sizes

For many applications the bulk of their input is memory-mapped files, mainly executable code. Copying all executables and libraries to the recorded trace on every execution would impose significant time and space overhead. RR creates hard links to memory-mapped executable files instead of copying them; as long as a system update or recompile replaces executables with new files, instead of writing to the existing files, the links retain the old file data. This works well in practice.

Even better, modern filesystems such as XFS and Btrfs offer copy-on-write logical copies of files (and even block ranges within files), ideal for our purposes. When a mapped file is on the same file system as the recorded trace, and the file system supports cloning, RR clones mapped files into the trace. These clone operations are essentially free in time and space, until/unless the original file is modified or deleted.

RR compresses all trace data, other than cloned files and blocks, with the zlib "deflate" method.

With these optimizations, in practice trace storage is a non-issue. Section 4.4 presents some results.

## 2.8 Other Details

Apart from those major issues, many other details are required to build a complete record-and-replay system, too many to mention here. Some system calls (e.g. `execve`) are especially complex to handle. Recording and replaying signal delivery are complex, partly because signal delivery has poorly-documented side effects on user-space memory. Advanced Linux kernel features such as `unshare` (kernel namespaces) and `seccomp` require thoughtful handling. Many of these details are interesting, but they do not impact the overall approach.

## 3 System Call Buffering

The approach described in the previous section works, but overhead is disappointingly high (see Figure 5 below). The core problem is that for every tracee system
call, as shown in Figure 1 the tracee performs four context switches: two blocking ptrace notifications, each requiring a context switch from the tracee to RR and back. For common system calls such as gettimeofday or read from cached files, the cost of even a single context switch dwarfs the cost of the system call itself. To significantly reduce overhead, we must avoid context switches to RR when processing these common system calls.

Therefore, we inject into the recorded process a library that intercepts common system calls, performs the system call without triggering a ptrace trap, and records the results to a dedicated buffer shared with RR. RR periodically flushes the buffer to its trace. The concept is simple but there are problems to overcome.

### 3.1 Intercepting System Calls

When the tracee makes a kernel-entering system call, RR is notified via a ptrace trap. It tries to rewrite the system-call instruction to call into the interception library instead. This is tricky because on x86 a system call instruction is two bytes long, but we need to replace it with a five-byte call instruction. (On x86-64, to ensure we can call from anywhere in the address space to the interception library, we also need to also allocate trampolines within 2GB of the patched code.) The vast majority of executed system call instructions are followed by one of only five different instructions; for example, very many system call instructions are followed by a particular cmp instruction testing the syscall result. So we add five hand-written stubs to our interception library that execute those post-system-call instructions before returning to the patched code, and on receipt of a ptrace system-call notification, RR replaces the system call instruction and its following instruction with a call to the corresponding stub.

For simplicity we (try to) redirect all system call instructions to the interception library, but the library only contains wrappers for the most frequently called system calls. For other system calls it falls back to doing a regular ptrace-trapping system call.

### 3.2 Selectively Trapping System Calls

The classic ptrace system-call interception API triggers traps for all system calls, but our interception library needs to avoid traps for selected system calls. Fortunately, modern Linux kernels provide a facility for selectively generating ptrace traps: seccomp-bpf. seccomp-bpf was designed primarily for sandboxing. A process can apply a seccomp-bpf filter function, expressed in bytecode, to another process; then, for every system call performed by the target process, the kernel runs the filter. The filter has access to incoming user-space register values, including the program counter. The filter result directs the kernel to either allow the system call, fail with a given errno, kill the target process, or trigger a ptrace trap. The overhead of filter execution is negligible since filters run directly in the kernel and are even compiled to native code on most architectures.

Figure 2 illustrates recording a simple read system call with system-call buffering. The solid-border box represents code in the interception library and the grey box represents kernel code.

RR injects a special page of memory into every tracee process at a fixed address (immediately after execve). That page contains a system call instruction — the “untraced instruction”. RR applies a seccomp-bpf filter to each recorded process that triggers a ptrace trap for every system call — except when the program counter is at the untraced instruction, in which case the call is allowed. Whenever the interception library needs to make an untraced system call, it uses that instruction.

### 3.3 Detecting Blocked System Calls

Some common system calls sometimes block (e.g. read on an empty pipe). Because RR runs tracee threads one at a time, if a thread enters a blocking system call without notifying RR, it will hang and could cause the entire recording to deadlock (e.g. if another tracee thread is about to write to the pipe). We need the kernel to notify RR and suspend the tracee thread whenever it blocks in an untraced system call, to ensure we get a chance to schedule a different tracee thread.

We can do this using the Linux perf event system to monitor PERF_COUNT_SW_CONTEXT_SWITCHES. One of these events occurs every time the kernel deschedules a thread from a CPU core. The interception library opens a file descriptor for each thread to monitor these events for that thread, and requests that the kernel send a signal to the

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**Figure 2: Recording with system-call buffering**

```plaintext
Tracee thread T
read(fd, buf, size)
  syscall_hook()
    redirect arg2 to syscall buffer
       N = syscall_result_reg
       write system-call record to syscall buffer
seccomp-bpf filter → ALLOW
sys_read
```
Figure 3: Recording a blocking system call

Thread every time the event occurs. These signals trigger ptrace notifications to RR while preventing the thread from executing further. To avoid spurious signals (e.g. when the thread is descheduled due to normal timeslice expiration), event counting is normally disabled and explicitly enabled during an untraced system call that might block. It is still possible for spurious SWITCHES to occur at any point between enabling and disabling the event; we handle these edge cases with careful inspection of the trace state.

Figure 3 illustrates recording a blocking read system call with system-call buffering. The kernel deschedules the thread, triggering a perf event which sends a signal to the thread, rescheduling it, interrupting the system call, and sending a ptrace notification to the recorder. The recorder does bookkeeping to note that a buffered system call was interrupted in thread T, then checks whether any tracee threads in blocking system calls have progressed to a system-call exit and generated a ptrace notification. In this example T2 has completed a (not system-call-buffered) blocking futex system call, so we resume executing T2.

Resuming a buffered system call that was interrupted by a signal (e.g. T’s read call in Figure 3) is more complicated and requires understanding Linux system call restart semantics, which are too nasty to cover in this paper.

3.4 Handling Replay

Conceptually, during recording we need to copy system call output buffers to a trace buffer, and during replay we need to copy results from the trace buffer to system call output buffers. This is a problem because the interception library is part of the recording and replay and therefore should execute the same code in both cases.

For this reason (and because we want to avoid races of the sort discussed in Section 2.3), the interception library redirects system call outputs so that results are written directly to the trace buffer. After the system call completes, the interception library copies the output data from the trace buffer to the original output buffer(s). During replay the untraced system call instruction is replaced with a no-op, so the system call does not occur; the results are already present in the trace buffer so the post-system-call copy from the trace buffer to the output buffer(s) does what we need.

During recording, each untraced system call sets a result register and the interception library writes it to the trace buffer. During replay we must read the result register from the trace buffer instead. We accomplish this with a conditional move instruction so that control flow is perfectly consistent between recording and replay. The condition is loaded from an is_replay global variable, so the register holding the condition is different over a very short span of instructions (and explicitly cleared afterwards).

Another tricky issue is handling system call memory parameters that are “in-out”. During recording we must copy the input buffer to the trace buffer, pass the system call a pointer to the trace buffer, then copy the trace buffer contents back to the input buffer. If we perform the first copy during replay, we’ll overwrite the trace buffer values holding the system call results we need. During replay we turn that copy into a no-op using a conditional move to set the source address copy to the destination address.

We could allow the replay behavior of the interception library to diverge further from its recording behavior, but it would have to be done very carefully. At least we’d have to ensure the number of retired conditional branches was identical along both paths, and that register values were consistent whenever we exit the interception library or trap to RR within the interception library. It’s simplest to minimize the divergence.

3.5 Optimizing Reads With Block Cloning

When an input file is on the same filesystem as the recorded trace and the filesystem supports copy-on-write cloning of file blocks, for large block-aligned reads the system call buffering code clones the data to a per-thread “cloned-data” trace file, bypassing the normal system-call recording logic. This greatly reduces space and time overhead for file-read-intensive workloads; see the next section.
This optimization works by cloning the input blocks and then reading the input data from the original input file. This opens up a possible race: between the clone and the read, another process could overwrite the input file data, in which case the data read during replay would differ from the data read during recording, causing replay to fail. However, when a file read races with a write under Linux, the reader can receive an arbitrary mix of old and new data, so such behavior would almost certainly be a severe bug, and in practice such bugs do not seem to be common. The race could be avoided by reading from the cloned-data file instead of the original input file, but that performs very poorly because it defeats Linux’s readahead optimizations (since the data in the cloned-data file is never available until just before it’s needed).

4 Results

Our results address the following questions:

- What is the run-time overhead of RR recording and replay, across different kinds of workloads?
- How much of the overhead is due to the single-core limitation?
- What are the impacts of the system-call buffering and block cloning optimizations?
- What is the impact of not having to instrument code?
- How much space do RR traces consume?

4.1 Workloads

We present a variety of workloads to illuminate RR’s strengths and weaknesses. Benchmarks were chosen to fit in system memory (to minimize the impact of I/O on test results), and to run for about 30 seconds each (except for cp where a 30s run time would require it to not fit in memory).

- cp duplicates a git checkout of glibc (revision 2d02fd07) using cp -a (15200 files constituting 732MB of data, according to du -h). cp is single-threaded, making intensive use of synchronous reads and a variety of other filesystem-related system calls.
- make builds DynamoRio [8] (version 6.1.0) with make -j8 (-j8 omitted when restricting to a single core). This tests potentially-parallel execution of many short-lived processes.
- octane runs the Google Octane benchmark under the Mozilla Spidermonkey Javascript engine (Mercurial revision 9bd900888753). This illustrates performance on CPU-intensive code in a complex language runtime.

htmltest runs the Mozilla Firefox HTML forms tests (Mercurial revision 9bd900888753). The harness is excluded from recording (using mach mochitest -f plain --debugger rr dom/html/test/forms). This is an example from real-world usage. About 30% of user-space CPU time is in the harness.

sambatest runs a Samba (git revision 9ee4678b) UDP echo test via make test TESTS=samba4.echo.udp. This is an example from real-world usage.

All tests run on a Dell XPS15 laptop with a quad-core Intel Skylake CPU (8 SMT threads), 16GB RAM and a 512GB SSD using Btrfs in Fedora Core 23 Linux.

4.2 Overhead

Table 1 shows the wall-clock run time of various configurations, normalized to the run time of the baseline configuration. For octane, because the benchmark is designed to run for a fixed length of time and report a score, we report the ratio of the baseline score to the configuration-under-test score instead — except for replay tests, where the reported score will necessarily be the same as the score during recording. For octane replay tests, we report the ratio of the baseline score to the recorded score, multiplied by the ratio of replay run time to recording run time. Each test was run six times, discarding the first result and reporting the geometric mean of the other five results. Thus the results represent warm-cache performance.

“Single core” reports the overhead of just restricting all threads to a single core using Linux taskset.

“Record no-syscallbuf” and “Replay no-syscallbuf” report overhead with the system-call buffering optimization disabled (which also disables block cloning). “Record no-cloning” reports overhead with just block cloning disabled.

“DynamoRio-null” reports the overhead of running the tests under the DynamoRio [8] (version 6.1.0, the latest stable version at time of writing) “null tool”, to estimate a lower bound for the overhead of using dynamic code instrumentation as an implementation technique. (DynamoRio is reported to be among the fastest dynamic code instrumentation engines.)

4.3 Observations

Overhead on make is significantly higher than for the other workloads. Just forcing make onto a single core imposes major slowdown. Also, make creates many short-lived processes; it forks and execs 2430 processes. (The next most prolific workload is sambatest with 89.) Our
system-call buffering optimization only starts working in a process once RR’s preload library has been loaded, but typically at least 80 system calls are performed before that completes, so the effectiveness of system-call buffering is limited with short-lived processes.

Figure 4 shows the overall recording and replay overhead for workloads other than make. Error bars in figures show 95% confidence intervals; these results are highly stable across runs.

Excluding make, RR’s recording slowdown is less than a factor of two. Excluding make, RR’s replay overhead is lower than its recording overhead. Replay can even be faster than normal execution, in cp because system calls do less work. For interactive applications, not represented here, replay can take much less time than the original execution because idle periods are eliminated.

octane is the only workload here other than make making significant use of multiple cores, and this accounts for the majority of RR’s overhead on octane.

Figure 5 shows the impact of system-call buffering and blocking cloning on recording. The system-call buffering optimization produces a large reduction in recording (and replay) overhead. Cloning file data blocks is a major improvement for cp recording but has essentially no effect on the other workloads.

Figure 6 compares RR recording overhead with the overhead of DynamoRio’s “null tool”, which runs all code through the DynamoRio instrumentation engine but does not modify the code beyond whatever is necessary to maintain supervised execution; this represents a minimal-overhead code instrumentation configuration. DynamoRio crashed on octane because it runs a lot of Javascript with dynamically generated and modified machine code. Implementing record-and-replay on top of dynamic instrumentation would incur significant additional overhead, so we would expect the resulting system to have significantly higher overhead than RR.

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**Table 1: Run-time overhead**

<table>
<thead>
<tr>
<th>Workload</th>
<th>Baseline duration</th>
<th>Record</th>
<th>Replay</th>
<th>Single core</th>
<th>Record</th>
<th>Replay</th>
<th>Record</th>
<th>DynamoRio-null</th>
</tr>
</thead>
<tbody>
<tr>
<td>cp</td>
<td>1.04s</td>
<td>1.49×</td>
<td>0.72×</td>
<td>0.98×</td>
<td>24.53×</td>
<td>15.39×</td>
<td>3.68×</td>
<td>1.24×</td>
</tr>
<tr>
<td>make</td>
<td>20.99s</td>
<td>7.85×</td>
<td>11.93×</td>
<td>3.36×</td>
<td>11.32×</td>
<td>14.36×</td>
<td>7.84×</td>
<td>10.97×</td>
</tr>
<tr>
<td>octane</td>
<td>32.73s</td>
<td>1.79×</td>
<td>1.56×</td>
<td>1.36×</td>
<td>2.65×</td>
<td>2.43×</td>
<td>1.80×</td>
<td>crash</td>
</tr>
<tr>
<td>htmltest</td>
<td>23.74s</td>
<td>1.49×</td>
<td>1.01×</td>
<td>1.07×</td>
<td>4.66×</td>
<td>3.43×</td>
<td>1.50×</td>
<td>14.03×</td>
</tr>
<tr>
<td>sambatest</td>
<td>31.75s</td>
<td>1.57×</td>
<td>1.23×</td>
<td>0.95×</td>
<td>2.23×</td>
<td>1.74×</td>
<td>1.57×</td>
<td>1.43×</td>
</tr>
</tbody>
</table>

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1We reported DynamoRio’s crash on our “octane” workload to the developers at https://github.com/DynamoRIO/dynamorio/issues/1930.
4.4 Storage Space Usage

RR traces contain three kinds of data:

- Cloned (or hard-linked) files used for memory-map operations

- Cloned file blocks

- All other trace data, especially event metadata and the results of general system calls

Memory-mapped files are almost entirely just the executables and libraries loaded by tracees. As long as the original files don’t change and are not removed, which is usually true in practice, their clones take up no additional space and require no data writes. For simplicity, RR makes no attempt to eliminate duplicate file clones, so most traces contain many duplicates and reporting meaningful space usage for these files is both difficult and unimportant in practice.

Table 2 shows the space usage of each workload, in megabytes per second, for the general trace data and the cloned file blocks. We compute the geometric mean of the data usage for each trace and divide by the run-time of the baseline configuration of the workload. The space consumed by each trace shows very little variation between runs.

Like cloned files, cloned file blocks do not consume space as long as the underlying data they’re cloned from persists.

The different workloads have highly varying space consumption rates, but several megabytes per second is easy for modern systems to handle. Compression ratios vary depending on the kind of data being handled by the workload. In any case, in real-world usage trace storage has not been a concern.

4.5 Memory Usage

Table 3 shows the memory usage of each workload. Every 10ms we sum the proportional-set-size (“PSS”) values of all workload processes (including RR if running); we determine the peak values for each run and take their geometric mean. In Linux, each page of memory mapped into a process’s address space contributes $1/n$ pages to that process’s PSS, where $n$ is the number of processes mapping the page; thus it is meaningful to sum PSS values over processes which share memory. The same data are shown in Figure 7. In the figure, the fraction of PSS used
by the RR process is shown in orange. Memory usage data was gathered in separate runs from the timing data shown above, to ensure the overhead of gathering memory statistics did not impact those results.

Given these experiments ran on an otherwise unloaded machine with 16GB RAM and all data fits in cache, none of these workloads experienced any memory pressure. cp uses almost no memory. In make, just running on a single core reduces peak PSS significantly because not as many processes run simultaneously. In octane memory usage is volatile (highly sensitive to small changes in GC behavior) but recording significantly increases application memory usage; recording also increases application memory usage a small amount in sambatest but slightly decreases it in htmltest. (We would expect to see a small increase in application memory usage due to system-call buffers and scratch buffers mapped into application processes.) These effects are difficult to explain due to the complexity of the applications, but could be due to changes in timing and/or effects on application or operating system memory management heuristics.

Replay memory usage is similar to recording except in htmltest, where it’s dramatically lower because we’re not replaying the test harness.

The important point is that RR’s memory overhead is relatively modest and is not an issue in practice.

5 Hardware and Software Design Constraints

5.1 Performance Counters

As discussed in Section 2.4.1, RR uses hardware performance counters to measure application progress. We need a counter that increments very frequently so that the pair (counter, general purpose registers) uniquely identifies a program execution point in practice, and it must be “deterministic” as described earlier. Performance counters are typically used for statistical analysis, which does not need this determinism property, so unsurprisingly it does not hold for most performance counter implementations [37]. We are indeed fortunate that there is one satisfactory counter in Intel’s modern Core models. The ideal performance counter for our purposes would count the exact number of instructions retired as observed in user-space (e.g., counting an instruction interrupted by a page fault just once); then the counter value alone would always uniquely identify an execution point.

Being able to run RR in virtual machines is helpful for deployability. KVM, VMware and Xen support virtualization of performance counters, and RR is known to work in KVM and VMware (Xen not tested). Interestingly the VMware VM exit clustering optimization [4], as implemented, breaks the determinism of the retired-conditional-branch counter and must be manually disabled. Given a pair of close-together CPUID instructions separated by a conditional branch, the clustering optimization translates the code to an instruction sequence that runs entirely in the host, reducing the number of VM exits from two (one per CPUID) to one, but performance counter effects are not emulated so the conditional branch is not counted. In some runs of the instruction sequence the clustering optimization does not take effect (perhaps because of a page fault?), so the count of retired conditional branches varies.

5.2 Nondeterministic Instructions

Most CPU instructions are deterministic. As discussed in Section 2.6, the nondeterministic x86(-64) instructions can currently be handled or (in practice) ignored, but this could change, so we need some improvements in this area.

Extending Linux (and hardware, where necessary) to support trapping on executions of CPUID, as we can for RDTSC, would let us mask off capability bits so that well-behaved software does not use the newer non-deterministic instructions. Trapping and emulating CPUID is also necessary to support trace portability across machines with different CPU models and would let us avoid pinning recording and replay to a specific core.

We would like to support record-and-replay of programs using hardware transactional memory (XBEGIN/XEND). This could be done efficiently if the hardware and OS could be configured to raise a signal on any failed transaction.

Trapping on all other nondeterministic instructions (e.g. RDRAND) would be useful.

Porting RR to ARM failed because all ARM atomic memory operations use the “load-linked/store-conditional” approach, which is inherently nondeterministic. The conditional store can fail because of non-user-space-observable activity, e.g. hardware interrupts, so counts of retired instructions or conditional branches for code performing atomic memory operations are nondeterministic. These operations are inlined into very many code locations, so it appears patching them is not feasible except via pervasive code instrumentation. On x86(-64), atomic operations (e.g. compare-and-swap) are deterministic in terms of user-space state, so there is no such problem.
5.3 Use Of Shared Memory

As noted in Section 2.5, RR does not support applications using shared memory written to by non-recorded processes or kernel code — unless there’s some defined protocol for preventing read-after-write races that RR can observe, for example as is the case for Video4Linux. Fortunately, popular desktop Linux frameworks (X11, PulseAudio) can be automatically configured per-client to minimize usage of shared memory to a few easily-handled edge cases.

5.4 Operating System Features

RR performance depends on leveraging relatively modern Linux features. The seccomp-bpf API, or something like it, is essential to selectively trapping system calls. The Linux PERF_COUNT_SW_CONTEXTSWITCHES performance event is essential for handling blocking system calls. The Linux copy-on-write file and block cloning APIs reduce overhead for I/O intensive applications.

5.5 Operating System Design

Any efficient record-and-replay system depends on clearly identifying a boundary within which code is replayed deterministically, and recording and replaying the timing and contents of all inputs into that boundary. In RR, that boundary is mostly the interface between the kernel and user-space. This works well with Linux: most of the Linux user/kernel interface is stable across OS versions, relatively simple, and well-documented, and it’s easy to count hardware performance events occurring within the boundary (i.e. all user-space events for a specific process). This is less true in other operating systems. For example, in Windows, the user/kernel interface is not publicly documented, and is apparently more complex and less stable than in Linux. Implementing and maintaining the RR approach for an operating system like Windows would be considerably more challenging than for Linux, at least for anyone other than the OS vendor.

6 Related Work

6.1 Whole-System Replay

ReVirt [16] was an early project that recorded and replayed the execution of an entire virtual machine. VMware [27] used the same approach to support record-and-replay debugging in VMware Workstation, for a time, but discontinued the feature. The full-system simulator Simics has long supported reverse-execution debugging via deterministic reexecution [19]. There have been multiple independent efforts to add some amount of record-and-replay support to QEMU [14, 15, 35]. Whole-system record-and-replay can be useful, but for many users it is inconvenient to have to hoist the application into a virtual machine. Many applications of record-and-replay also require cheap checkpointing, and checkpointing an entire system is generally more expensive than checkpointing one or a few processes.

6.2 Replaying User-Space With Kernel Support

Scribe [25], dOS [6] and Arnold [13] replay a process or group of processes by extending the OS kernel with record-and-replay functionality. Requiring kernel changes makes maintenance and deployment more difficult — unless record-and-replay is integrated into the base OS. But adding invasive new features to the kernel has risks, so if record-and-replay can be well implemented outside the kernel, moving it into the kernel may not be desirable.

6.3 Pure User-Space Replay

Approaches based on user-space interception of system calls have existed since at least MEC [10], and later Jockey [33] and liblog [20]. Those systems did not handle asynchronous event timing. Also, techniques relying on library injection, such as liblog and Jockey, do not handle complex scenarios such as ASAN [34] or Wine [3] with their own preloading requirements. PinPlay [31], iDNA [7], UndoDB [1] and TotalView ReplayEngine [21] use code instrumentation to record and replay asynchronous event timing. Unlike UndoDB and RR, PinPlay and iDNA instrument all loads, thus supporting parallel recording in the presence of data races and avoiding having to compute the effects of system calls, but this gives them higher overhead than the other systems.

As far as we know RR is the only pure user-space record-and-replay system to date that eschews code instrumentation in favour of hardware performance counters for asynchronous event timing, and it has the lowest overhead of the pure user-space systems.

6.4 Higher-Level Replay

Record-and-replay features have been integrated into language-level virtual machines. DejaVu [11] added record-and-replay capabilities to the Jalapeño Java VM. Microsoft IntelliTrace [2] instruments CLR bytecode to
record high-level events and the parameters and results of function calls; it does not produce a full replay. Systems such as Chronon [12] for Java instrument bytecode to collect enough data to provide the appearance of replaying execution for debugging purposes, without actually doing a replay. Dolos [9] provides record-and-replay for JS applications in Webkit by recording and replaying the nondeterministic inputs to the browser. R2 [22] provides record-and-replay by instrumenting library interfaces with assistance from the application developer. Such systems are all significantly narrower in scope than the ability to replay general user-space execution.

6.5 Parallel Replay

Recording application threads running concurrently on multiple cores, with the possibility of data races, with low overhead, is extremely challenging. PinPlay [31] and iDNA [7] instrument shared-memory loads and report high overhead. SMP-ReVirt [17] tracks page ownership using hardware page protection and reports high overhead on benchmarks with a lot of sharing. Double-Play [36] runs two instances of the application and thus has high overhead when the application alone could saturate available cores. ODR [5] has low recording overhead but replay can be extremely expensive and is not guaranteed to reproduce the same program states.

The best hope for general low-overhead parallel recording seems to be hardware support. Projects such as FDR [38], BugNet [29], Rerun [23], DeLorean [28] and QuickRec [32] have explored low-overhead parallel recording hardware.

7 Future Work

RR perturbs execution, especially by forcing all threads onto a single core, and therefore can fail to reproduce bugs that manifest outside RR. We have addressed this problem by introducing a “chaos mode” that intelligently adds randomness to scheduling decisions, enabling us to reproduce many more bugs, but that work is beyond the scope of this paper. There are many more opportunities to enhance the recorder to find more bugs.

Putting record-and-replay support in the kernel has performance benefits, e.g. reducing the cost of recording context switches. We may be able to find reusable primitives that can be added to kernels to improve the performance of user-space record-and-replay while being less invasive than a full kernel implementation.

Recording multiple processes running in parallel on multiple cores seems feasible if they do not share memory — or, if they share memory, techniques inspired by SMP-ReVirt [17] or dthreads [26] may perform adequately for some workloads.

The applications of record-and-replay are perhaps more interesting and important than the base technology. For example, one can perform high-overhead dynamic analysis during replay [13, 14, 31], potentially parallelized over multiple segments of the execution. With RR’s no-instrumentation approach, one could collect performance data such as sampled stacks and performance counter values during recording, and correlate that data with rich analysis generated during replay (e.g. cache simulation). Always-on record-and-replay would make finding and fixing bugs in the field much easier.

Supporting recording and replay of parallel shared-memory applications with potential races, while keeping overhead low, will be very difficult without hardware support. Demonstrating compelling applications for record-and-replay will build the case for including such support in commodity hardware.

8 Conclusions

The current state of Linux on commodity x86 CPUs enables single-core user-space record-and-replay with low overhead, without pervasive code instrumentation — but only just. This is fortuitous; we use software and hardware features for purposes they were not designed to serve. It is also a recent development; five years ago seccomp-bpf and the Linux file cloning APIs did not exist, and commodity architectures with a deterministic hardware performance counter usable from user-space had only just appeared (Intel Westmere)\(^2\). By identifying the utility of these features for record-and-replay, we hope that they will be supported by an increasingly broad range of future systems. By providing an open-source, easy-to-deploy, production-ready record-and-replay framework we hope to enable more compelling applications of this technology.

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\(^2\)Performance counters have been usable for kernel-implemented replay [16, 30] for longer, because kernel code can observe and compensate for events such as interrupts and page faults.
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