Be Kind, Please Rewind

Adventures in creating a macOS record/replay debugger

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REWIND <<

Why?

```
NSURLSessionDataTask *task = [_session
     dataTaskWithRequest:request
       completionHandler:^(NSData *_Nullable data, NSURLResponse *_Nullable response,
                           NSError *_Nullable err) {
         …
           *stop = YES;
```

```
Thread 2 Crashed::  Dispatch queue:
com.apple.NSXPCConnection.user.com.google.santa.metricservice.63335
0   libobjc.A.dylib       objc_msgSend + 29
1   Foundation            -[NSError copyWithZone:] + 107
2   santametricservice    -[SNTMetricHTTPWriter write:toURL:error:] +
1372
3   santametricservice    -[SNTMetricService exportForMonitoring:] + 475
…
```

Record/Replay: Prior Art

- PANDA (2020)
  - Whole system!
- WinDbg (2017)
- RR (2014)
- Scribe (2010)
- Jockey (2005)
- Flashback (2004)
- ReTrace
- QuickRec
- Revirt (1999)
  - Whole system!

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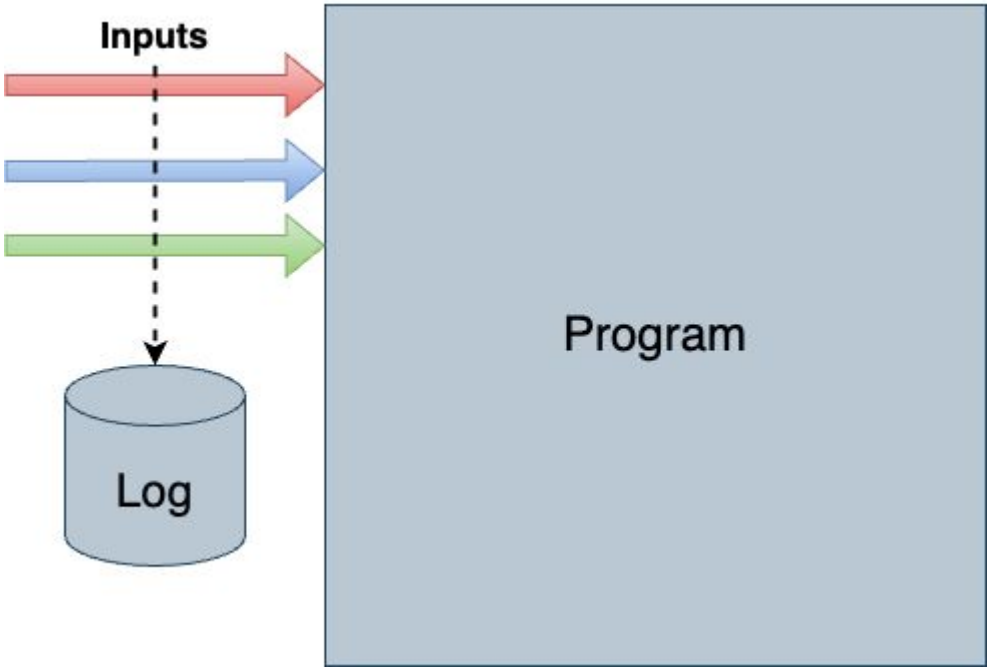
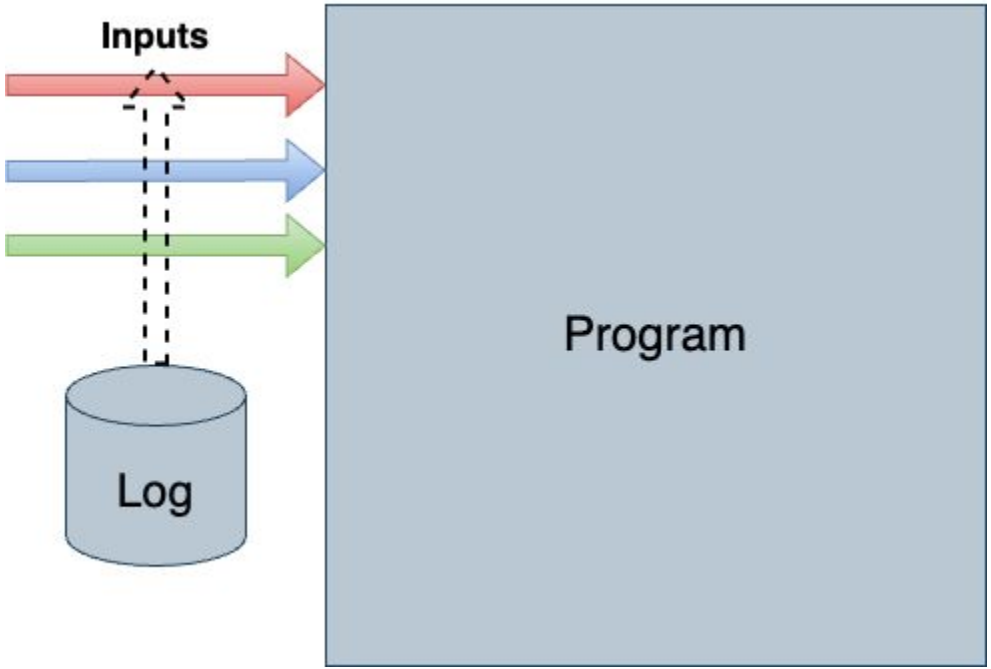
Record / Replay Basics & Goals


Inputs
Program
Log


Inputs
Program
Log

Goals for our tool

- Only focusing on user-space programs
- Easy to use and deploy – needs to support a stock MBP with/M1,M2
- No DBI / code instrumentation
- Small investment of effort to maintain
- Fast enough to use on real programs

RR’s Requirements for User-Space Replay

Requirement	Does macOS Meet This Out of the Box?
Ability to Record Syscalls	✅
Ability to Record Syscalls Outside Libc	☹️
Ability to determine if a Syscall is blocking	🟡
Ability to Intercept Signals	✅

RR’s Requirements for User-Space Replay (Part 2)

Requirement	Does macOS Meet This Out of the Box?
Ability to pin a process to a single core (cpuset)	
Ability to trap non-deterministic instructions	
Ability to access reliable and deterministic hardware performance counters	


PUSH-OPEN
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NICAM DIGITAL STEREO
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TRACKING
NEXT
MEMORY
AUDIO RECORDING
ON
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AUDIO DUB
INSERT
REWIND
PLAY
FF
PAUSE/STILL
STOP
REC
Hi-Fi REC LEVEL
REMOTE CONTROL UNIT
VTR
CLOCK/COUNTER
AUDIO OUT
REC/PLAY
STILL ADV
SHUTTLE
SEARCH
TRANSMIT

Recording

Recording: It’s not that simple…

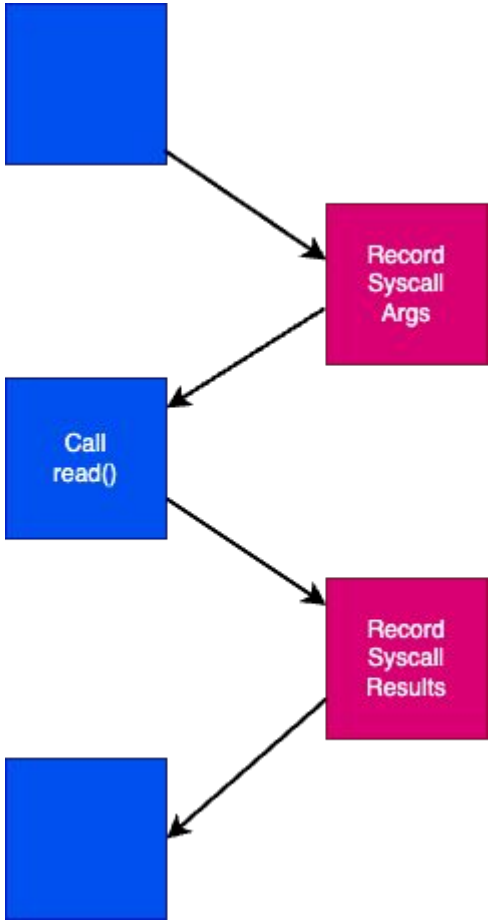
- Mach traps
  - Close enough to syscalls, no big deal
  - … except for a few traps which don’t have normal hook points
- Signals
  - The outside world can “asynchronously” poke the target
- mmap
- Multithreading
  - Well-formed programs shouldn’t have issues (data races), but…
  - Aside: thanks Apple for not giving us cpuset - no easy way to pin to one core
- Commpage
  - Similar to vvar (normally accessed via vDSO) on Linux
- Non-deterministic instructions – mrs x0, cntvct_el0

Recording: Syscalls & Traps

Recording: Syscalls on macOS

- 3 types – BSD, mach traps, machine dependent

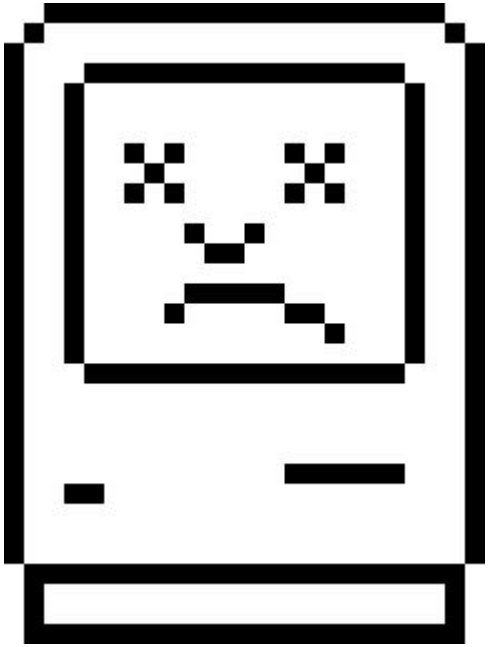
- Need pre- and post-hooks for data gathering



Thanks Apple

- Gutted ptrace implementation – no sysemu

- No seccomp-bpf equivalent



One Option: dtrace

- dtrace hooks, storage, etc.

- Not enough to capture arbitrary syscall data though
  - No conditionals for example - not possible to `switch` in “multiplexed” syscalls

- Strictly async
  - How to pause so userland can get what it needs?
  - Luckily there are “destructive” actions
    - signal(STOP)
    - stop() - mach_task_suspend
  - These only take effect *after* the syscall is processed though…

One Option: dtrace

Seatbelt / Sandbox?

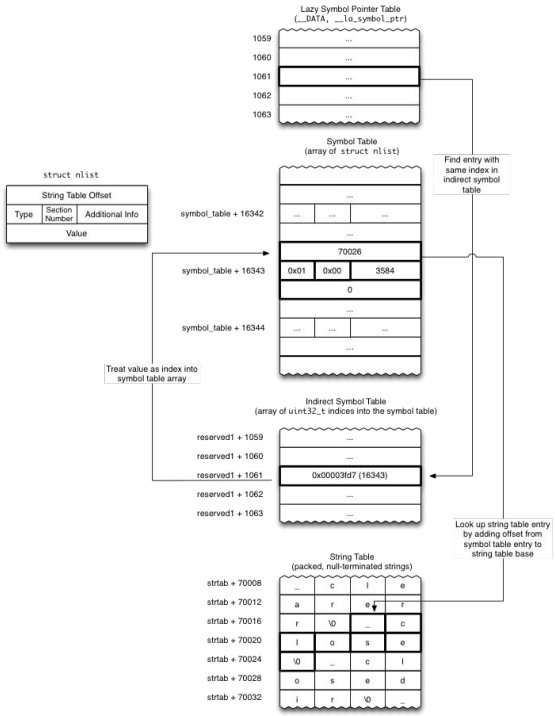
- Seatbelt is wired up into every syscall maybe?

- Trace mode for recording
  - Not a good API, minimal log entries

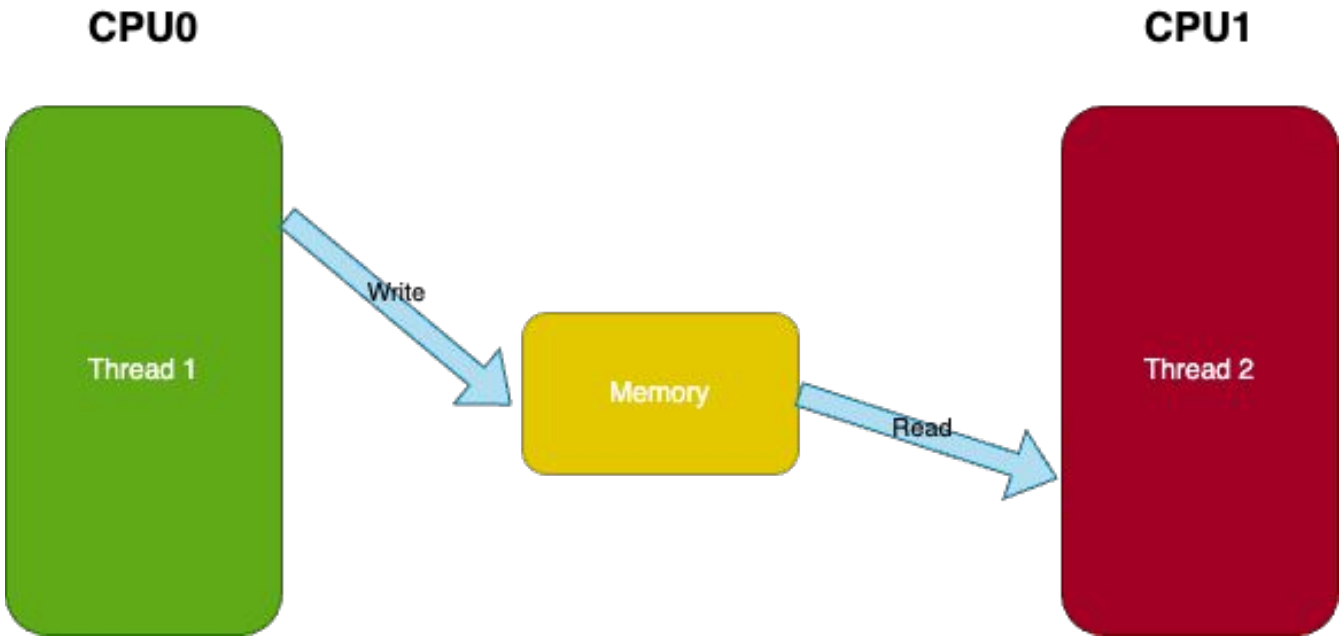
- No way to not kill on replay

Interposing / Dynamic Interposing / Symbol Rebinding

- macOS is a BSD!
  - ABI compatibility is at the libc level not the kernel
  - Can we just hook libsystem_kernel?
- We can interpose on the symbol
  - Could use [fishhook]
- Doesn’t catch direct syscalls…



Recording: Dealing with Data Races

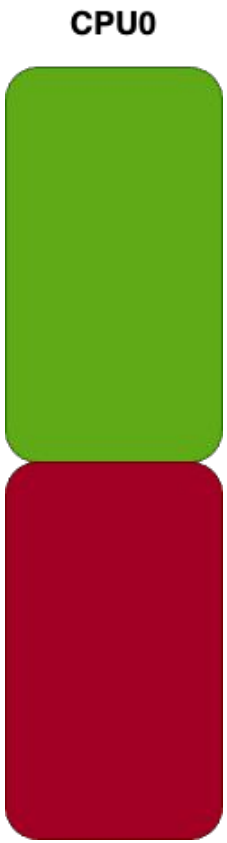

CPU0
CPU1
Thread 1
Write
Memory
Read
Thread 2

How Does RR Handle This?

- Only runs one thread to run at a time (non-parallel)

- Limits threads to the same core using processor affinity

- Schedules threads and records the choice in the log (**can mixup order on replay to find bugs**)

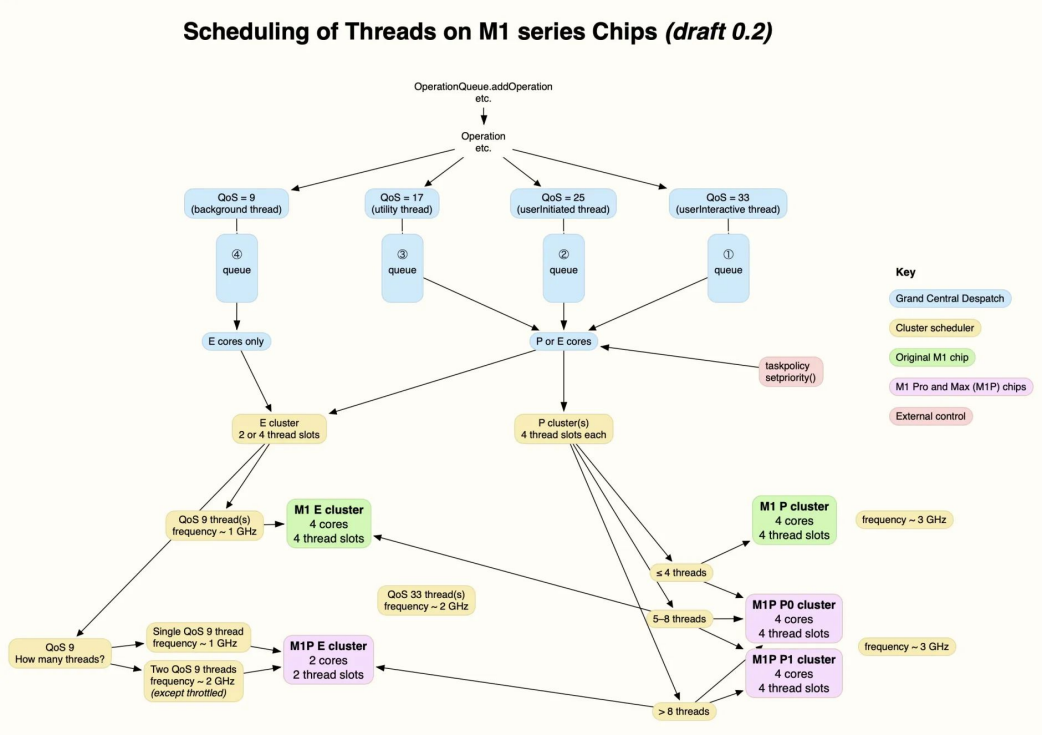


Thread scheduling on macOS not guaranteed

- No `cpu_set(3)`
- Can we use `THREAD_AFFINITY_POLICY`?

```
/*
 *      thread_bind:
 *
 *      Force the current thread to execute on the specified processor.
 *      Takes effect after the next thread_block().
 *
 *      Returns the previous binding.  PROCESSOR_NULL means
 *      not bound.
 *
 *      XXX - DO NOT export this to users - XXX
 */
processor_t
thread_bind(
        processor_t             processor)
{
        thread_t                self = current_thread();
        processor_t             prev;
```

P-cores and E-cores



From: https://eclecticlight.co/2022/01/13/scheduling-of-processes-on-m1-series-chips-first-draft/

Can we shutdown cores?

- In the old OS X internals books there was an example showing how to shutdown cores using `processor_exit`
- Can we just limit ourselves to a core?

```
[ user@watervile ~ ]
$  sudo ./print_processors
Password:
Number of processors: 12
CPU: slot 0(master)
CPU: slot 1
//snipped.
CPU: slot 11
[ user@waterville ~ ]
$  sudo ./processor_xable
processor_exit: (os/kern) service not supported
```

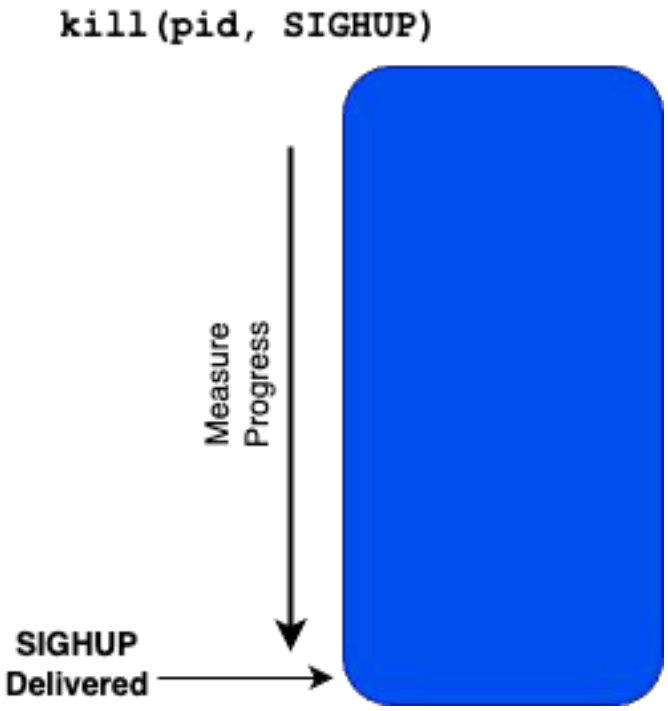
Recording: Asynchronous Events

Signals & Scheduling

- Need to be able to intercept signals and record register state of where the signal was delivered or program interrupted for scheduling.

- Need to know where you are in the programs execution so you can inject your signals in the right place during replay

- Replay: when using something interrupt driven must account for late firing interrupts



Using PMUs from macOS

- RR works on Asahi Linux and uses the PMU can we?
  - Uses the count of retired conditional branches as progress indicator (0x8c)
  - Can reset for an interrupt when replaying

- macOS does not have an interface for setting PMUs from EL0

```
[ user@waterville  ~/src/pmu_counters  ]
$  sudo ./counter_test
loaded db: a15 (Apple A15)
number of fixed counters: 2
number of configurable counters: 8
counters value:
        cycles: 41865278
  instructions: 91998218
      branches: 21071096
 branch-misses: 53779
[ user@waterville  ~/src/pmu_counters  ]
$  sudo ./counter_test
loaded db: a15 (Apple A15)
number of fixed counters: 2
number of configurable counters: 8
counters value:
        cycles: 41946121
  instructions: 92093331
      branches: 0
 branch-misses: 0
```

panic(cpu 5 caller 0xfffffe0017c66cd8): kperf: timer fired at 2793246644070, but sampling is disabled @kptimer.c:328
Debugger message: panic

Supporting Nondeterministic Execution in Fault-Tolerant Systems*

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Abstract

We present a technique to track nondeterminism resulting from asynchronous events and multithreading in log-based rollback-recovery protocols. This tech-

with the end users [11]. Efficient tracking of nondeterminism is thus crucial to supporting interactive applications [14].

Different flavors of logging have been suggested with different performance and resilience character-

```
Decrement Register
Branch to handler if register = 0
```

Options without PMU or DBI

- We can count the number of syscalls and then single step forward then inject the signal (set a breakpoint and invoke the signal handler)

- Do what scribe(10) does and simply deliver the signal at the next syscall and replay interrupted syscall (special case for signals like SIGSEGV that originate in user space.)

- If we need to go further than say 10,000 instructions we can use an high res clock (e.g. pacman) to trap back to us

```
    // set up the registers for our counter
    asm!(
        "mov x3, {running}",
        "mov x4, x0",    // store backed up copy o
        "ldr x0, [x0]", // load the value of coun
        "1:",
        "isb",
        "ldr x2, [x3]",  // load the value of run
        "sub x0, x0, 1", // decrement the counter
        "cbz x2, 456f",  // break the loop if we'
        "cbnz x0, 1b",   //  if we've not underflo
        "123:",
        "mov {interrupted}, 1", // set interrupte
        "456:",
        "str xzr, [x3]", // set running to false
        "str x0, [x4]",  // store the value of co
        in("x0") count_addr,
        interrupted = out(reg) interrupted,
        running = in(reg) running_addr,
    );
```


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STOP
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REMOTE CONTROL UNIT
VTR
CLOCK/COUNTER
AUDIO OUT
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STILL ADV
SEARCH
TRANSART

Darling

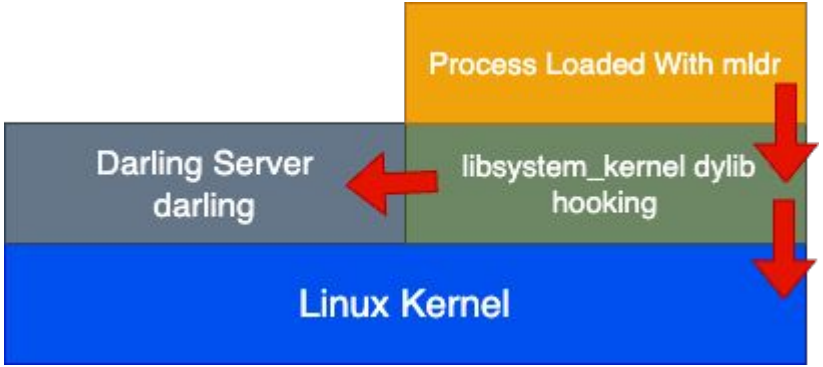
Darling

- “A Translation Layer that lets you run macOS software on Linux”

- Uses a custom loader, interposing of libsystem_kernel, a lot of duct tape code and userland a server to translate macOS syscalls to Linux syscalls

- Can run software like xcode on Linux

High Level: How Darling Works

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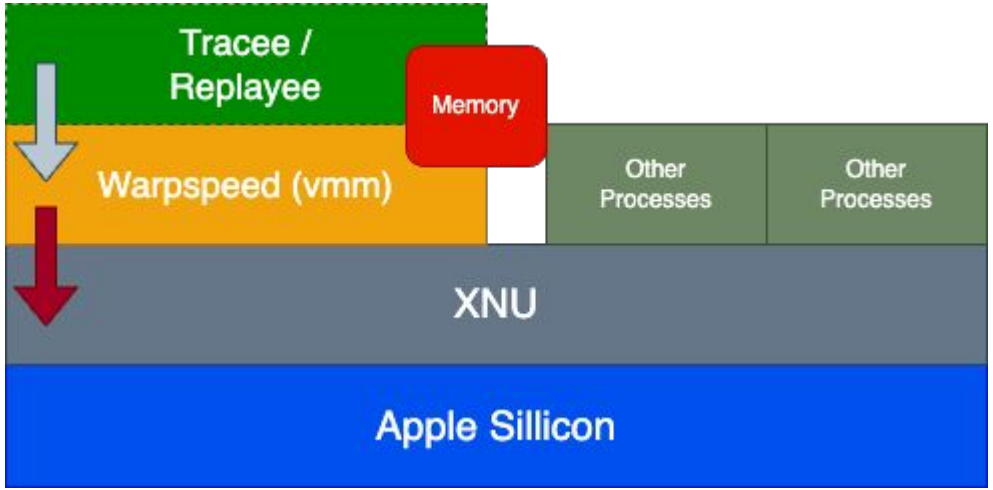
Warpspeed

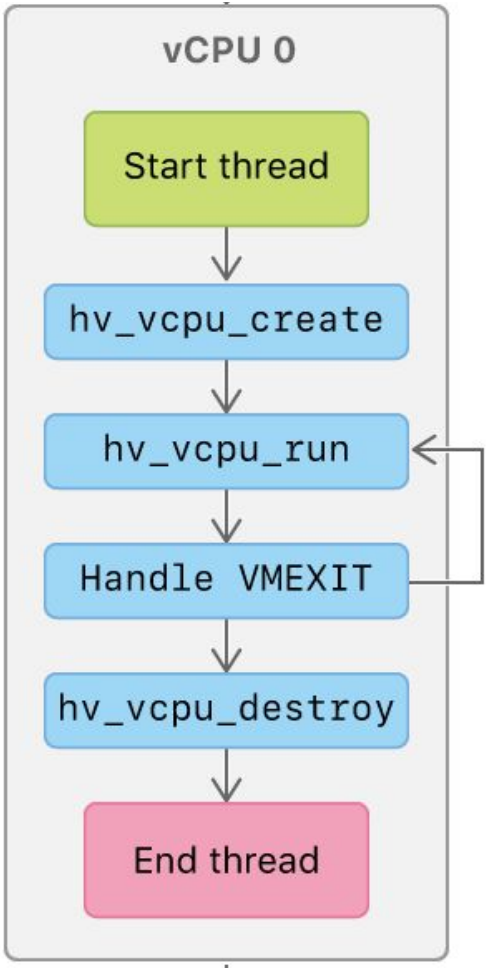
Warpspeed

- Isolate target inside a VM with 1 core
- Proxy syscalls
- Both signal slide + SoftPMU to approximate program progression
- Manual thread scheduling



Hypervisor.framework

- Super light-weight framework
  - Little as possible in the kernel
- Usage:
  - Create a VM
  - Map memory (from hypervisor address space)
  - Create vCPU
  - Set regs
  - Run
  - Trap out to <u>userland</u> on VM exit
  - GOTO 5
  - *That's it*



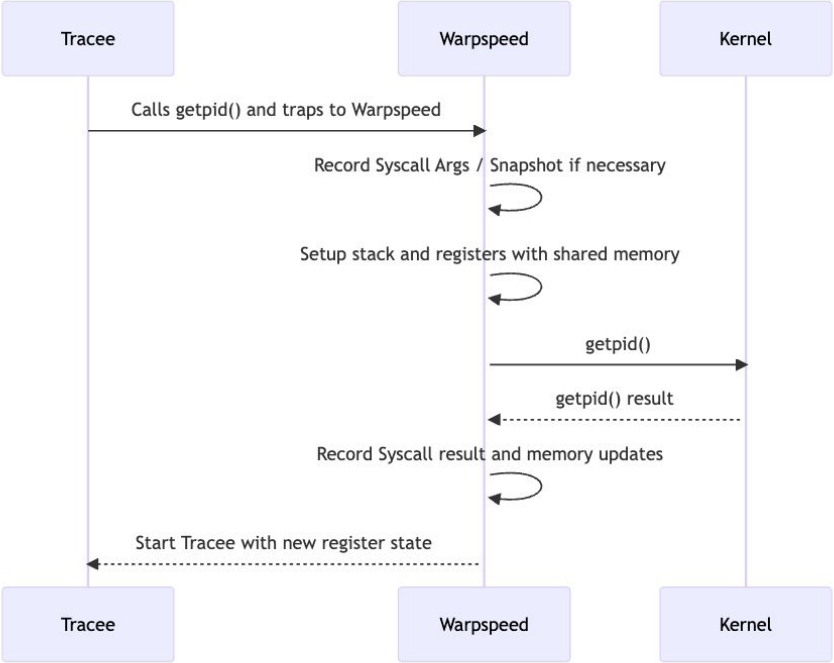
Warpspeed: VM/Hypervisor

- Use modified darling's loader (mldr) to map in target program and dyld
- Load in shared cache
- "Share" an address space with the guest
  - 1:1 map the regions of the loaded target into VM at the same virtual address
- Trap out and forward syscalls

- All based on Hyperpom (Rust!)

- Lets us control the execution of the program perfectly
  - Only have one virtual core
  - Manually schedule threads

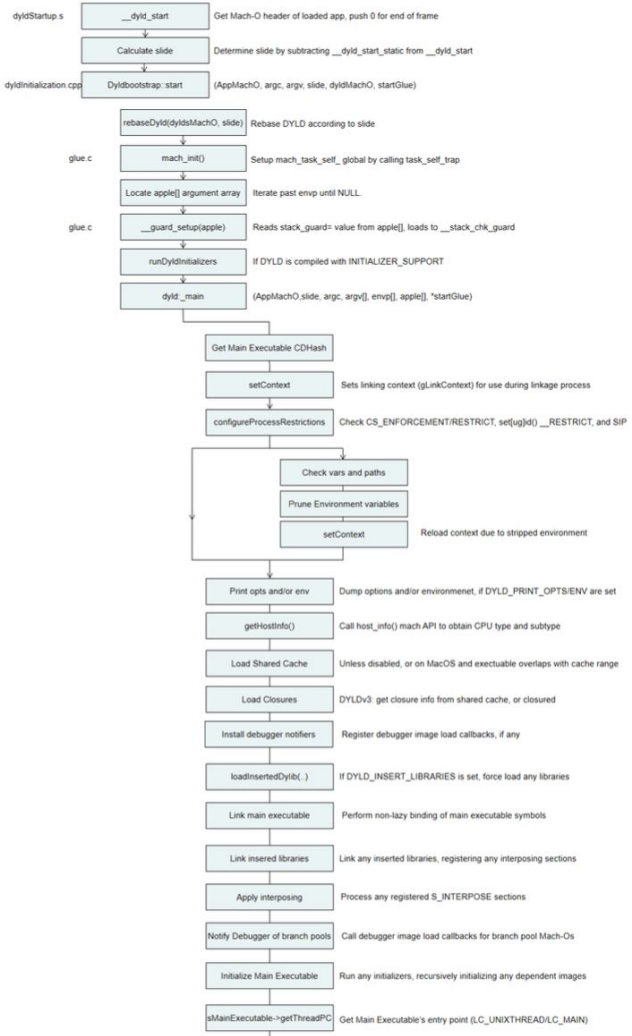
Warpspeed: VM/Hypervisor



```
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: 267: Forwarding syscall 99(0x[0, 134088000, 0xf, 0, 0, 0, 0, 0x0, 0, 101, 4000
, 5f5e00, 1ae7, 134006530, 2db3ffb40, 2db3ff4a0])
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: Changed pages: []
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Returning 0xf @ 4000030
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: ELR_EL1: 0x18031c8a0
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Incoming syscall 6([0x[0, 134088000, 134080000, 0, 4000c402, 2, 2, 0x0, 101, 10
3, 0, 27, 134000000, 1, 134000000, 4000c402])
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: 268: Forwarding syscall 0x0xD(, 134000000, 134000000, 0, 4000c402, 2, 2, 0x0,
101, 103, 0, 27, 134000000, 1, 134000000, 4000c402])
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: Changed pages: []
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Returning 0 @ 4000030
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: ELR_EL1: 0x18031c8a0
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Incoming syscall 5([0x[101b01f00, 1000104, 0, 101b01be1, 0, 50, 0, 0x0, 101b010
e1, 0, 12002027, 1, 1, 134000540, 2db3ffb40, 2db3ff4a0])
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: open(/System/appleInternal/Library/FeatureFlags/GlobalDiscloseOverrides.plist
)
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: 269: Forwarding syscall 5(0x[101b01000, 1000104, 0, 101b01b40, 0, 50, 0, 0x0,
101b01b40, 0, 12002027, 1, 1, 134000540, 2db3ffb40, 2db3ff4a0])
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: Changed pages: []
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Returning 3 @ 600003c0
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: ELR_EL1: 0x18031c8a0
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Incoming syscall 5([0x[101b01f00, 1000104, 0, 101b01bcf, 0, 50, 0, 0x0, 101b010
cf, dd6037244cf2e8b6, 12002027, 1, 1, 134000540, 2db3ffb40, 2db3ff4a0])
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: open(/System/Library/FeatureFlags/ProfileDiscloseOverrides.plist)
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: 270: Forwarding syscall 5(0x[101b01000, 1000104, 0, 101b01bcf, 0, 50, 0, 0x0,
101b01bcf, dd6037244cf2e8b6, 12002027, 1, 1, 134000540, 2db3ffb40, 2db3ff4a0])
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: Changed pages: []
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Returning 3 @ 600003c0
[2023-06-09T03:19:56Z  TRACE  mrr::warpspeed: ELR_EL1: 0x18031c8a0
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: Incoming syscall 5([0x[101b01f00, 1000104, 0, 101b01bcf, 0, 50, 0, 0x0, 101b010
cf, dd6037244cf2e8b6, 12002027, 1, 1, 134000540, 2db3ffb40, 2db3ff4a0])
[2023-06-09T03:19:56Z  INFO  mrr::warpspeed: open(/System/Library/FeatureFlags/SettingsDiscloseOverrides.plist)
```

dyld

Figure 7-2: The flow of dyld



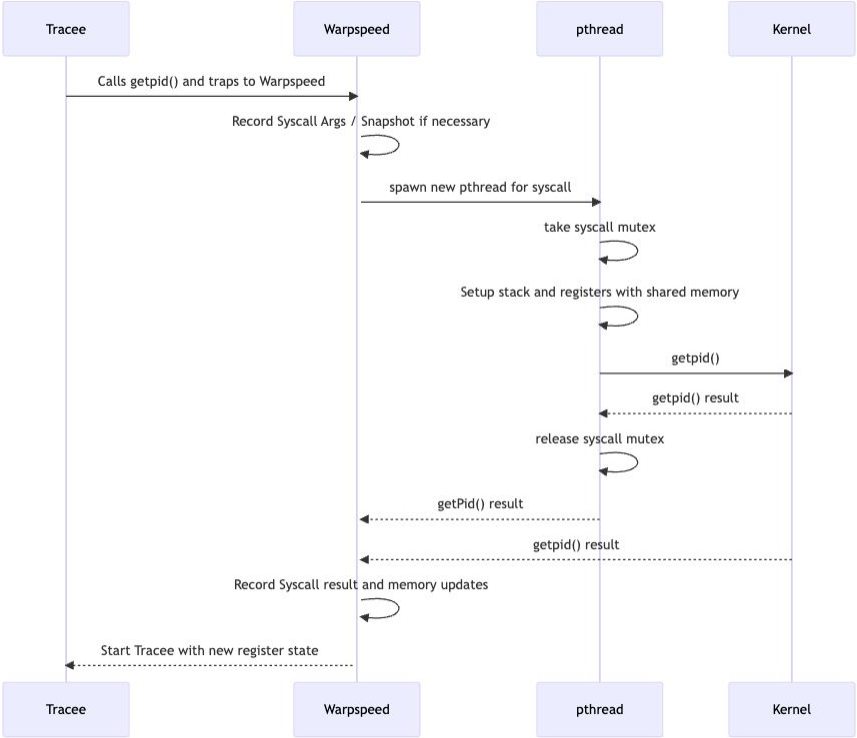
Warpspeed: Unimplemented Features

- LLDB/GDB interface
- Optimizing/compressing log format
- The hypervisor itself is responsible for performing the syscalls
  - What happens on a blocking call?
  - Could deadlock on mutex wait
- Handling blocking syscalls
  - Manually enumerate and perform some non-blocking alternative
  - or…

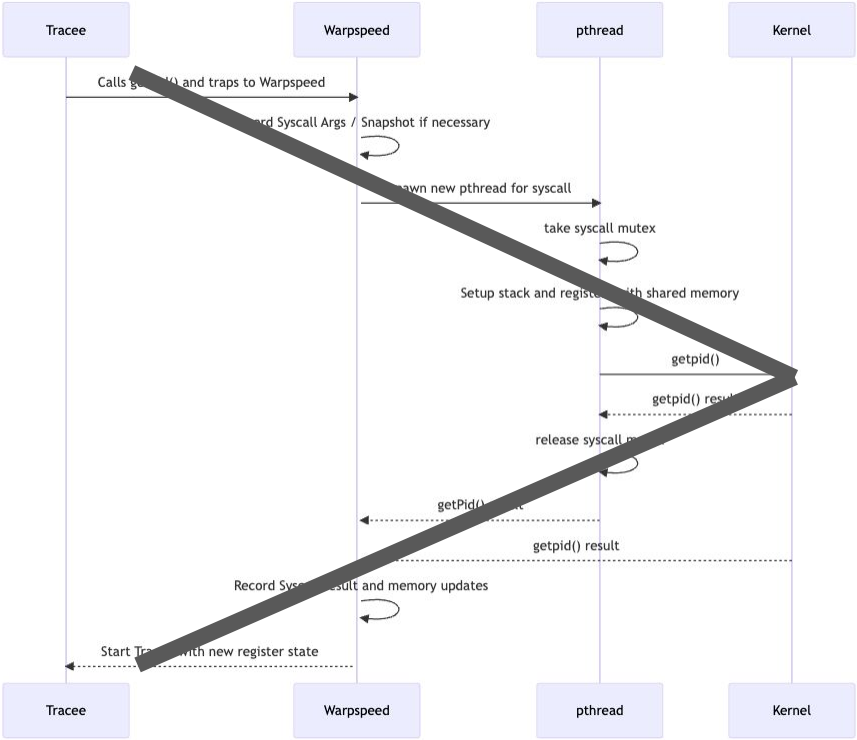
```
nickgregory@Nick-Virtual-Machine ~ $ echo $$
1486
nickgregory@Nick-Virtual-Machine ~ $ ls
```

```
nickgregory@Nick-Virtual-Machine ~ $ sudo ./dtrace_kdebug_blocking 1486

Threads: [0010]
[/usr/demos/kdebug_blocking.rs:50] "{:?}" = "{:?}"
[/usr/demos/kdebug_blocking.rs:51] event = KdBuf {
    timestamp: 1458004516,
    arg1: 1,
        0,
        0,
        0,
        0,
        0x0,
    },
    debugid: 20971500,
    cpuid: 0,
    __unused: 0,

[/usr/demos/kdebug_blocking.rs:50] "{:?}" = "{:?}"
[/usr/demos/kdebug_blocking.rs:51] event = KdBuf {
    timestamp: 1457154600,
    arg1: 1,
        0,
        0,
        0,
        0,
        0x0,
    },
    debugid: 20971500,
    cpuid: 2,
    __unused: 0,
```

Warpspeed: VM/Hypervisor



Warpspeed: VM/Hypervisor



Warpspeed: Outstanding Issues

- MMIO
- Entitlements

That’s Only Half the Battle

Replay

- If you can figure out recording, replay is much simpler
  - Set breakpoints where something happened in recording
  - Mimic side-effects
  - Continue
- SoftPMU needed here in case we end up with an async event in a hot loop

Replay: GUI

- UI is core to macOS
- How can we “pass through” events on replay to the OS (to see the app running) while not introducing nondeterminism?
  - *In theory* it will “just work”
  - No (easy) way to show the UI on replay though

Recap

- Tool is WIP
- But principles work!
- Stay posted for more


INPUT SELECT
HICAM DIGITAL STEREO
SUPER 4-HEAD
VHS
REWIND
PLAY
FF
PAUSE/STILL
STOP
REC
TRACKING
MEMORY
AUDIO DUB
INSERT
REMOTE CONTROL UNIT
AUDIO OUT
TRANSART

Questions?