Arbitrary Instruction Tracing with DTrace

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DTrace quick background

- Dynamic tracing framework.
- Originated in Solaris in 2005.
- Observe kernel behavior in real-time.
- Provider: Module that performs a particular instrumentation in the kernel.
- Probe: Specific point of instrumentation.
- D language.
- https://illumos.org/books/dtrace

The FBT provider

- Trace the entry and return points of a kernel function.
- Cannot trace specific instructions and inline functions.

```
# dtrace -n 'fbt::malloc:entry {printf("%s", execname);}'
dtrace: description 'fbt::malloc:entry ' matched 1 probe
CPU     ID                    FUNCTION:NAME
  3  30654                     malloc:entry dtrace
  0  30654                     malloc:entry pkg
  1  30654                     malloc:entry Xorg
  3  30654                     malloc:entry firefox
  2  30654                     malloc:entry zfskern
  3  30654                     malloc:entry kernel
^C
```

The kinst provider

- Inspired by FBT.
- Trace arbitrary machine instructions in a kernel function.
- Trace inline functions.
- More fine-grained tracing (specific if statements, loops, branches, ...). Requires C-to-Assembly translation skills.
- Available on amd64, arm64 and riscv.
- In the future: build higher-level tooling, detect and put return probes on tail-call optimized functions.
- `sys/cddl/dev/kinst/`

kinst::<function>:

```
# dtrace -n 'kinst::amd64_syscall:'
dtrace: description 'kinst::amd64_syscall:' matched 458
    probes
CPU     ID                    FUNCTION:NAME
  2  80676                amd64_syscall:323
  2  80677                amd64_syscall:326
  2  80678                amd64_syscall:334
  2  80679                amd64_syscall:339
  2  80680                amd64_syscall:345
  2  80681                amd64_syscall:353
  ^C
```

kinst::<function>:<instruction>

```
# kgdb
(kgdb) disas /r vm_fault
Dump of assembler code for function vm_fault:
   0xffffffff80876df0 <+0>:     55      push   %rbp
   0xffffffff80876df1 <+1>:     48 89 e5        mov    %
    rsp,%rbp
   0xffffffff80876df4 <+4>:     41 57   push   %r15

# dtrace -n 'kinst::vm_fault:4 {printf("%#x", regs[R_RSI])
    ;}'
  2  81500                vm_fault:4 0x827c56000
  2  81500                vm_fault:4 0x827878000
  2  81500                vm_fault:4 0x1fab9bef0000
  2  81500                vm_fault:4 0xe16cf749000
  0  81500                vm_fault:4 0x13587c366000
  ^C
```

kinst::<inline_func>:<entry|return>

```
# dtrace -n ’kinst::critical_enter:return’
dtrace: description ’kinst::critical_enter:return’ matched
     130 probes
CPU     ID                    FUNCTION:NAME
  1  71024                spinlock_enter:53
  0  71024                spinlock_enter:53
  1  70992                uma_zalloc_arg:49
  1  70925    malloc_type_zone_allocated:21
  1  70994                uma_zfree_arg:365
  1  70924             malloc_type_freed:21
  0  71024                spinlock_enter:53
  0  70947         _epoch_enter_preempt:122
  0  70949           _epoch_exit_preempt:28
  0  71024                spinlock_enter:53
  0  71024                spinlock_enter:53
  0  70947         _epoch_enter_preempt:122
  0  70949           _epoch_exit_preempt:28
  ^C
```

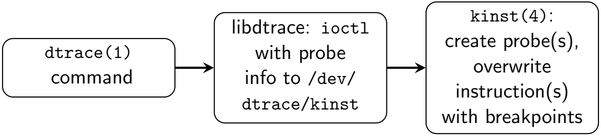
High-level ideas

- How are instructions instrumented?
- Architecture-dependent code.
- Inline function tracing.

Instruction instrumentation

- Probe information is passed from `dtrace(1)` to libdtrace to `kinst(4)` using a character device file in `/dev/dtrace/kinst`.
- kinst disassembles the function and creates probes for each of the target instructions.
- The original instruction is overwritten with a breakpoint instruction.
- When the CPU hits the breakpoint, we jump into `kinst_invop()` through the trap handler.
- kinst decides if the instruction is to be emulated or executed in a trampoline.
- Trace the instruction and continue execution.

Instruction instrumentation

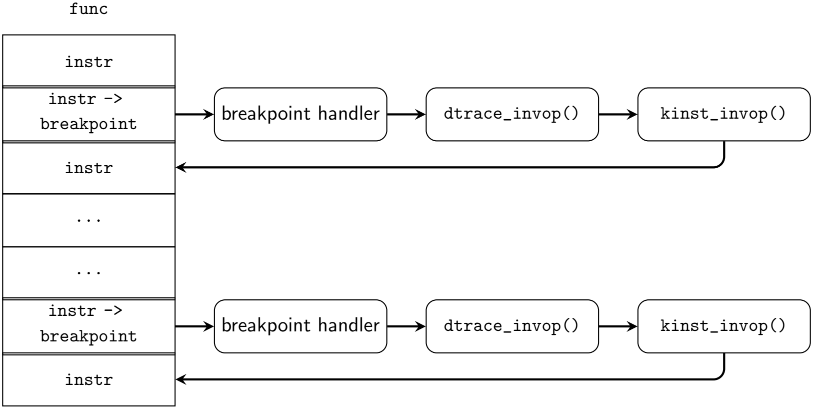


`dtrace(1)` command

libdtrace: `ioctl` with probe info to `/dev/dtrace/kinst`

`kinst(4)`: create probe(s), overwrite instruction(s) with breakpoints

Instruction instrumentation



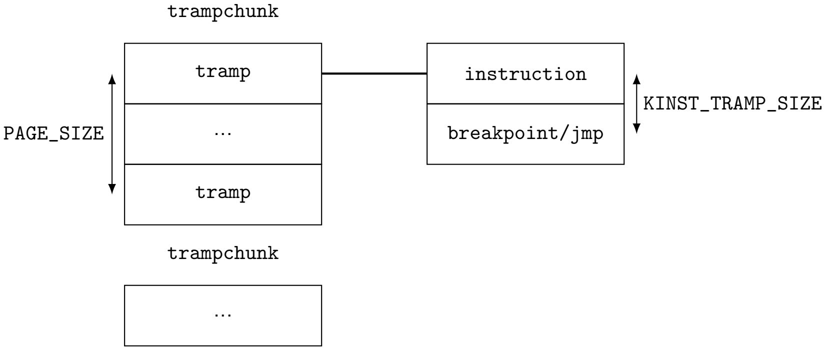
Trampoline: Overview

- Emulating every single instruction for each architecture is tedious and error prone.
- Target instruction is copied there and execution is transferred to the trampoline manually.
- How do we return back?

Trampoline: Under the hood

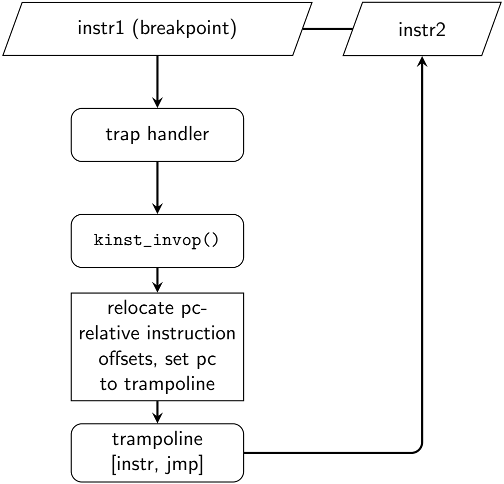
- Executable block of memory.
- Memory "chunks" of size `PAGE_SIZE` stored in a `TAILQ`
- `vm_map_find(9)` with `VM_PROT_EXECUTE`, `vm_map_remove(9)`, `kmem_back(9)`, `kmem_unback(9)`, `malloc(9)`.
- Allocated above `KERNBASE` (amd64), or `VM_MIN_KERNEL_ADDRESS` (rest).
- Logically divided into individual trampolines using `BITSET(9)`.
- `kinst_trampoline_alloc()` finds and returns the next free trampoline.

Trampoline: Under the hood



- amd64: Per-thread and per-CPU trampolines.
- arm64 and riscv: Per-probe trampolines.

Trampoline: amd64 control flow (to be deprecated)


instr1 (breakpoint)

instr2

trap handler

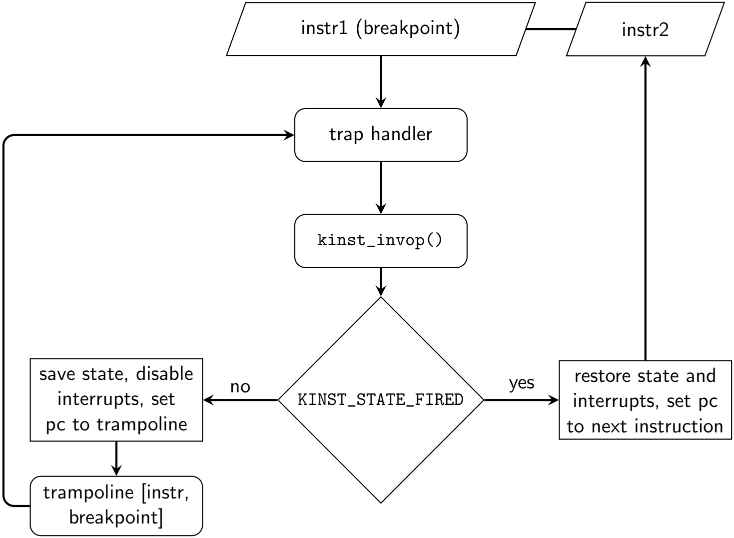
`kinst_invop()`

relocate pc-relative instruction offsets, set pc to trampoline

trampoline [instr, jmp]

The per-thread/per-CPU trampolines are rewritten upon every instrumentation. Will be replaced by the arm64/riscv mechanism and use per-probe trampolines to avoid race bugs.

Trampoline: arm64/riscv control flow



Synchronization is done through a `DPCPU(9)` `kinst_cpu_state` structure.

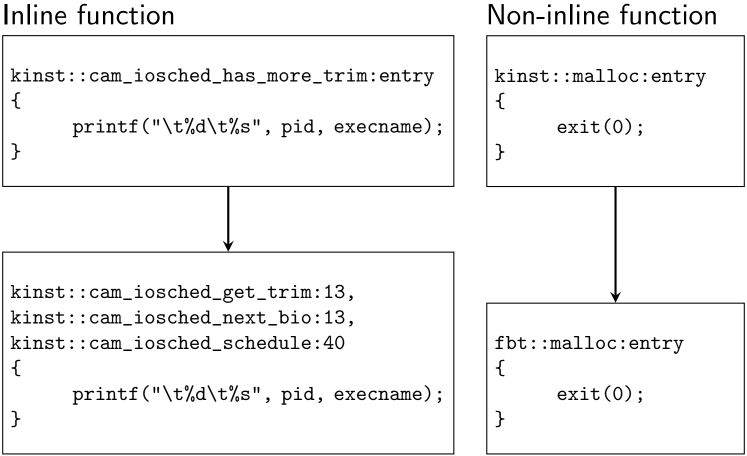
Architecture-specific caveats

- amd64
  - The ISA is... complicated. Lots of "special" instructions to handle during disassembly parsing.
  - RIP-relative instructions have to have their displacements re-encoded to be relative to the trampoline in order to be executed in a trampoline.
  - `call` instructions have to be emulated in assembly (see `bp_call` label in `sys/cddl/dev/dtrace/amd64/dtrace_asm.S`).
- arm64, riscv
  - Unlike amd64, encoding trampoline-relative offsets for PC-relative instructions is not possible in a single instruction. All PC-relative instructions have to be emulated in `kinst_emulate()`.
- Some functions and instructions are unsafe to trace (listed in man page).

Inline function tracing

- Syntax: `kinst::<inline_func>:<entry|return>`
- All the hard work is done in libdtrace, instead of `kinst(4)`.
- Uses the DWARF and ELF standards.
    - If the function is an inline, libdtrace calculates the function boundaries and offsets and creates regular kinst probes for each one of the inline copies found.
    - If the function is *not* an inline, the probe is converted to an FBT one, to avoid code duplication.
- Done for each loaded kernel module. Painfully slow...
- Can handle nested inline functions.
- `cddl/contrib/opensolaris/lib/libdtrace/common/dt_sugar.c`
- https://margiolis.net/w/dwarf_inline/
- https://margiolis.net/w/kinst_inline/

Inline function tracing



Inline function

```
kinst::cam_iosched_has_more_trim:entry
{
        printf("\t%d\t%s", pid, execname);
}
```

```
kinst::cam_iosched_get_trim:13,
kinst::cam_iosched_next_bio:13,
kinst::cam_iosched_schedule:40
{
        printf("\t%d\t%s", pid, execname);
}
```

Non-inline function

```
kinst::malloc:entry
{
        exit(0);
}
```

```
fbt::malloc:entry
{
        exit(0);
}
```

Inline function tracing

```
# dtrace -n 'kinst::vm_page_mvqueue:entry,kinst::
    vm_page_mvqueue:return'
```

Inline function tracing: DWARF

- Debugging information is represented as a tree of entries, one tree per compilation unit. Entries correspond to functions, variables, arguments, etc.
- Entries are called DIE (I know...); Debugging Information Entry.
- Each DIE has various attributes (name, location, file, ...).
- Functions that get inlined have an "inlined" attribute set.

Inline function tracing: DWARF

Inline function declaration entry:

```
<1><1dfa144>: Abbrev Number: 94 (DW_TAG_subprogram)
   <1dfa145>   DW_AT_name         : (indirect string)
   vfs_freevnodes_dec
   <1dfa149>   DW_AT_decl_file    : 1
   <1dfa14a>   DW_AT_decl_line    : 1447
   <1dfa14c>   DW_AT_prototyped   : 1
   <1dfa14c>   DW_AT_inline       : 1
```

What we care about:

- `0x1dfa144`: DIE address
- `DW_TAG_subprogram`: Function
- `DW_AT_inline`: Inlined
- `DW_AT_name`: Function name

Inline function tracing: DWARF

Inline copy entry:

```
<3><1dfe45e>: Abbrev Number: 24 (
   DW_TAG_inlined_subroutine)
   <1dfe45f>   DW_AT_abstract_origin: <0x1dfa144>
   <1dfe463>   DW_AT_low_pc      : 0xffffffff80cf701d
   <1dfe46b>   DW_AT_high_pc     : 0x38
   <1dfe46f>   DW_AT_call_file   : 1
   <1dfe470>   DW_AT_call_line   : 3458
   <1dfe472>   DW_AT_call_column : 5
```

What we care about:

- `DW_TAG_inlined_subroutine`: Inline copy
- `DW_AT_abstract origin`: Points to `0x1dfa144`.
- `DW_AT_lowpc`: Location in memory.
- `DW_AT_highpc`: Size.

Inline function tracing: Calculating call boundaries

Two ways to define locations:

- `DW_AT_lowpc` and `DW_AT_highpc`.
- `DW_AT_ranges`.

Inline function tracing: Calculating call boundaries

```
<3><1dfe45e>: Abbrev Number: 24 (
   DW_TAG_inlined_subroutine)
   <1dfe45f>   DW_AT_abstract_origin: <0x1dfa144>
   <1dfe463>   DW_AT_low_pc      : 0xffffffff80cf701d
   <1dfe46b>   DW_AT_high_pc     : 0x38
   <1dfe46f>   DW_AT_call_file   : 1
   <1dfe470>   DW_AT_call_line   : 3458
   <1dfe472>   DW_AT_call_column : 5
```

Listing 1: DIE with low and high PC boundaries

- `lower_bound = low_pc`
- `upper_bound = low_pc + high_pc`

Inline function tracing: Calculating call boundaries

- `DW_AT_ranges` refers to the `.debug_ranges` section of debug files.
- Usually means that the inline copy has been split into multiple different locations in memory (early `returns`).
- We end up with more than one `return` probe.

```
<3><1dfd2e2>: Abbrev Number: 58 (
  DW_TAG_inlined_subroutine)
   <1dfd2e3>   DW_AT_abstract_origin: <0x1dfa144>
   <1dfd2e7>   DW_AT_ranges        : 0x1f1290
   <1dfd2eb>   DW_AT_call_file     : 1
   <1dfd2ec>   DW_AT_call_line     : 3405
   <1dfd2ee>   DW_AT_call_column   : 3
```

Listing 2: DIE with `DW_AT_ranges` boundaries

Inline function tracing: Calculating call boundaries

Look for range at `0x1f1290`:

```
# dwarfdump -N dbgfile
...
Ranges group 38809:
ranges: 3 at .debug_ranges offset 2036368 (0x001f1290) (48
     bytes)
[ 0] range entry    0x000025c8 0x000025f9
[ 1] range entry    0x0000261a 0x00002621
...
```

- Values relative to the root (compilation unit) DIE's `DW_AT_lowpc`.

Inline function tracing: Calculating call boundaries

```
<0><1dee9fb>: Abbrev Number: 1 (DW_TAG_compile_unit)
   ...
   <1deea02>   DW_AT_name         : (indirect string) /usr
   /src/sys/kern/vfs_subr.c
   ...
   <1deea0e>   DW_AT_low_pc       : 0xffffffff80cf4020
   <1deea16>   DW_AT_high_pc      : 0xde3d
```

Listing 3: Compilation unit DIE

Inline function tracing: Calculating call boundaries

First range location:

$$Loc1_{lower} = Root_{lower} + Rng1_{lower}$$
$$Loc1_{upper} = Root_{lower} + Rng1_{upper}$$

Second range location:

$$Loc2_{lower} = Root_{lower} + Rng2_{lower}$$
$$Loc2_{upper} = Root_{lower} + Rng2_{upper}$$

- $Loc1_{lower}$ is the `entry` point of the inline function.
- $Loc1_{upper}$ and $Loc2_{upper}$ are the `return` points.

Inline function tracing: Finding the caller function

For each inline copy:

- We know its boundaries.
- Need to scan ELF information to figure out which function the copy is inlined in.

The name of the caller function corresponds to the name of the symbol satisfying the following condition:

$$Sym_{lower} \leq Inl_{lower} \leq Inl_{upper} \leq Sym_{upper}$$

Inline function tracing: `entry` and `return` offsets

The entry and return offsets are then calculated as:

$$Entry = Inl_{lower} - Caller_{lower}$$

$$Return = Inl_{upper} - Caller_{lower}$$

- Not exactly that simple, but out of scope. Please see https://margiolis.net/w/kinst_inline/#heuristic-entry-return
- 1e136a9cbd3a added a `-d` option to dtrace(1) to able to dump the resulting D script.

Inline function tracing

And **FINALLY**...

Inline function tracing

```
# dtrace -n 'kinst::vm_page_mvqueue:entry,kinst::
    vm_page_mvqueue:return'
CPU     ID                    FUNCTION:NAME
  3  95381             vm_page_activate:13
  3  95389            vm_page_activate:146
  2  95381             vm_page_activate:13
  2  95389            vm_page_activate:146
  1  95387              vm_page_advise:332
  1  95400              vm_page_advise:421
  1  95387              vm_page_advise:332
  1  95400              vm_page_advise:421
  1  95387              vm_page_advise:332
^C
```

Inline function tracing

- D38825
- D39259
- D40874

Acknowledgments

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Mitchell Horne <mhorne@FreeBSD.org>

References

- Illumos Operating System “Dynamic Tracing Guide”. https://illumos.org/books/dtrace
- FreeBSD src “kinst” https://cgit.freebsd.org/src/tree/sys/cddl/dev/kinst
- Tamches, Ariel & Miller, Barton P. “Fine-Grained Dynamic Instrumentation of Commodity Operating System Kernels”. https://www.usenix.org/legacy/publications/library/proceedings/osdi
- The DWARF Standard. https://dwarfstd.org/
- Christos Margiolis “Using DWARF to find call sites of inline functions“. https://margiolis.net/w/dwarf_inline/
- Christos Margiolis “Inline function tracing with the kinst DTrace provider”. https://margiolis.net/w/kinst_inline/
- GitHub, inlinecall(1). https://github.com/christosmarg/inlinecall