Advanced Operating Systems
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6

Observability, Tracing and Instrumentation

Observability

- **What is the system doing?**
  - Beyond the obvious (i.e. externally visible state changes)
    - Interactive debugging
    - Profiling
    - Tracing
    - Post-mortem analysis
  - Many flavors and requirements
    - Development / testing / production
    - Static / dynamic
    - Intrusive / non-intrusive

Instrumentation

- **Application of measuring instruments**
  - Recording of states and values
  - Safety
    - How the measurement affects the system under observation
  - Overhead
    - How the measurement affects the performance of the system under observation
      - While the instrumentation is active / inactive
  - Scope
    - Global vs. local phenomena

Interactive Debugging

- **Mechanisms**
  - Hardware debugging
    - JTAG serial interface to Test Access Ports
  - Breakpoints
    - Software breakpoints (`BREAK`, `INT3`)
    - Hardware breakpoints
      - E.g. `DR0` to `DR7` debug registers on x86
        - 4 linear addresses, trigger conditions (read, write, execute, I/O, area size), status
  - Single-stepping
    - E.g. trap flag in `FLAGS` + interrupt vector 1 on x86
  - Watchpoints
    - Hardware memory access breakpoints
    - Can be emulated via the paging mechanism
    - `WatchLo`, `WatchHi` on MIPS
      - 1 physical address, trigger conditions (read, write)

Interactive Debugging

- **Debugger**
  - User interface
  - Exception handling code (privileged)
    - Kernel stub
      - Communicating with the debugger UI task
        - `ptrace(2)`, `SIGTRAP`, break-in thread (`DebugActiveProcess()`)
      - Remote debugging
        - Serial, FireWire, USB, virtualization extensions
    - Full-fledged in-kernel debugger (kmdb in Solaris, JDB in Fiasco.OC)
    - 3rd party debugger (SoftICE, Rasta Ring 0)
    - Firmware debugger, hypervisor debugger stub
      - Non-maskable interupts, SysRq
- **Debugging countermeasures**

Interactive Debugging in Linux

```
pid_t pid = fork();
if (pid == 0) {
     ptrace(PTRACE_TRACEME, 0, NULL, NULL);
     // Delivers SIGTRAP to the parent after successful exec
     // Automatically traces all signals
     execve(...);
}

int wstatus;
waitpid(pid, &wstatus, 0);
// Examine wstatus

// Configure which events are traced
ptrace(PTRACE_SETOPTIONS, pid, NULL,
     PTRACE_O_EXITKILL | PTRACE_O_TRACECLONE |
     PTRACE_O_TRACEEXEC | PTRACE_O_TRACEEXIT |
     PTRACE_O_TRACEFORK | ...);

// Examine and control the child
ptrace(PTRACE_GETSIGINFO, pid, NULL, siginfo);
ptrace(PTRACE_GETREGSET, pid, NT_PRSTATUS, iovec);
ptrace(PTRACE_PEEKTEXT, pid, remote_addr, local_addr);
ptrace(PTRACE_POKETEXT, pid, remote_addr, local_addr);
ptrace(PTRACE_SYSCALL, pid);
ptrace(PTRACE_CONT, pid, NULL, NULL);
```

Interactive Debugging in HelenOS

```
errno_t rc;
async_sess_t *session = async_connect_kbox(task_id, &rc);

udebug_begin(session);

// Configure which events are traced
udebug_set_evmask(session,
    UDEBUG_EM_FINISHED | UDEBUG_EM_STOP | UDEBUG_EM_SYSCALL_B |
    UDEBUG_EM_SYSCALL_E | UDEBUG_EM_THREAD_B | UDEBUG_EM_THREAD_E |
    UDEBUG_EM_BREAKPOINT, UDEBUG_EM_TRAP);

thash_t threads[COUNT];
size_t copied;
size_t needed;
udebug_thread_read(session, threads, sizeof(thash_t) * COUNT, &copied,
    &needed);

udebug_event_t ev_type;
sysarg_t val0;
sysarg_t val1;
udebug_go(session, threads[0], &ev_type, &val0, &val1);
// Examine the event type

istate_t context;
udebug_regs_read(session, threads[0], &context);

uint8_t buffer[SIZE];
udebug_mem_read(session, buffer, 0x1000, SIZE);

// ...

udebug_end(session);
async_hangup(session);
```

Profiling

- **Run-time performance instrumentation**
  - Exact profiling
    - Triggered by specific events
    - Sampling relevant information (timestamp, CPU performance counters, stack trace, etc.)
    - E.g. GNU Profiler
      - `gcc -pg -mrecord-mcount -mnop-mcount`
        - After instrumentation, calls `mcount()` in the given function prologues/epilogues
        - Data collected in `gmon.out`, postprocessed by `gprof`
  - Statistical profiling
    - Sampling relevant information in regular intervals
    - E.g. OProfile (system-wide profiling)

Performance Metrics

- **Resource accounting**
  - Memory (resident / virtual / shared, buffers, caches)
  - Time
    - User time, system time, idle time (precise measurements)
      - %user + %system + %idle = 100 %
      - Utilization: %user + %system
    - Saturation (sampled in regular intervals)
      - How much more work is there than the machine can handle without latency
        - E.g. number of non-idle CPUs + length of the scheduler ready queues
        - Usually exponential moving average: $cur = prev \times decay + n \times (1 - decay)$

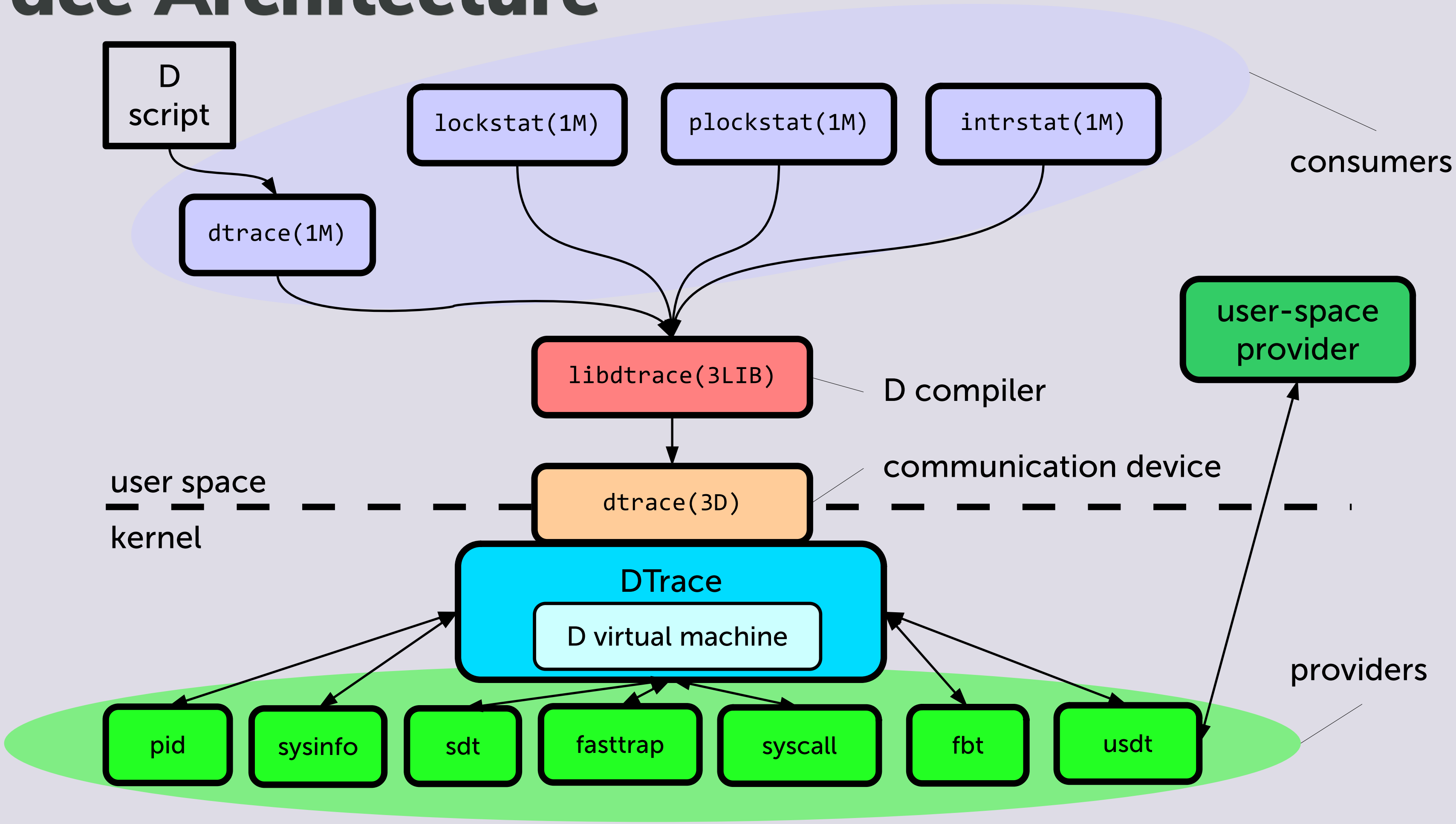
Performance Metrics

- **Microstate accounting**
  - Regular sampled accounting might miss activity that starts and completes between two sampling ticks
  - Logical event counters (per task/thread) might be more useful
    - Page faults (file system, executable, anonymous), interrupts, context switches, locking events, syscalls, thread latency (wait time before being scheduled), page reclamation scan rate (memory pressure indicator)

Tracing

- **Observing events**
  - Similar to debugging, but usually high-level events
  - Similar to logging, but activated on-demand
    - System calls, kernel functions, library/user functions, logical events (context switches, sending/receiving packets, etc.), custom user space events
    - Usually asynchronous (avoiding serialization)
    - `truss(1)`, `strace(2)`, `ltrace(1)`
    - DTrace, SystemTap

DTrace Architecture



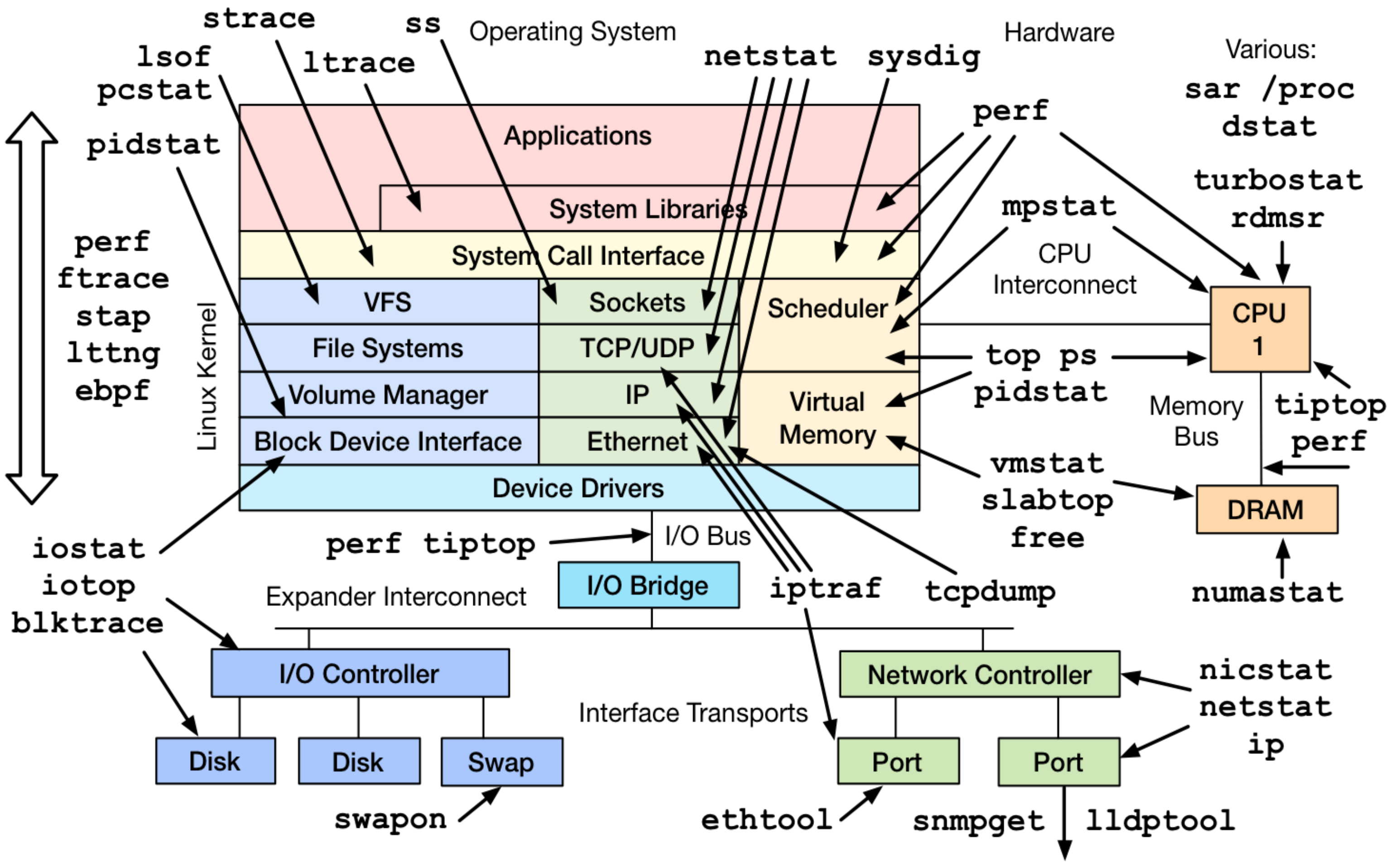
DTrace

- **Features**
  - Probe specification language (D script)
  - Probes
    - Instrumentation points
    - Ideally: zero overhead when inactive, small overhead when active
  - Safety for production system
    - D virtual machine
      - No branching, no loops, no state changes (unless explicitly enabled)
  - No debug builds needed
    - Compact Type Information
  - Correlation of events, aggregate statistics

SystemTap

- **Properties**
  - Probe specification language (SystemTap script)
    - Preprocessed into a kernel module source → kernel module
  - Probes
    - Instrumentation points
    - Ideally: zero overhead when inactive, small overhead when active
  - Safety for production system not guaranteed
    - Uses `ftrace` and `kprobes` as kernel backends
  - Requires debugging kernel build for extended functionality
  - Correlation of events, aggregate statistics

Linux Performance Observability Tools



http://www.brendangregg.com/linuxperf.html 2015

D Language in a Nutshell

```
probe [/predicate/] {
    actions
}
```

- **Probe**
  - *provider*:*module*:*function*:*name*
    - Shell pattern matching, empty component means "any"
    - `BEGIN`, `END`, `ERROR`
- **Predicate**
  - Optional integer or pointer expression serving as a guard
- **Actions**
  - List of statements delimited by semicolon, implicit default action (usually probe name printout)
  - C types and operators (conditional expression instead of branching), structures, scalar arrays, strings, associative arrays (scalar types as keys), associative arrays for statistical aggregation (`count()`, `sum()`, `avg()`, `min()`, `max()`, `quantize()`, etc.)
  - Global variables, thread-local variables (`self->`), clause-local variables (`this->`)

D Language in a Nutshell

```
probe [/predicate/] {
    actions
}
```

- **Actions**
  - Access to kernel variables, state-dependent values (arguments, return value, `errno`, caller, current thread / process / working directory / CPU / user / group / timestamp, executable name, etc.)
  - `print()`, `stack()`, `ustack()`, `alloca()`, `bcopy()`, `copyin()`, `copyinstr()`, `strlen()`, `strjoin()`, `basename()`, `dirname()`, `cleanpath()`, `rand()`, `mutex_owned()`, `mutex_owner()`, `exit()`
  - Unsafe actions when explicitly enabled
    - `stop()`, `raise()`, `panic()`, `copyout()`, `copyoutstr()`, `system()`, `breakpoint()`, `chill()`
  - Speculative tracing
    - `speculation()`, `speculate()`, `commit()`

SystemTap Language in a Nutshell

```
probe probe {
    actions
}
```

- **Original motto**
  - *“Painful to use, but more painful not to”*
- **Probe**
  - *provider*[(*arguments*)].*event_type*[(*arguments*)][.*name*] [?]
  - Wildcard pattern matching
  - begin, end, error
  - syscall.*name*[.return], kernel.function(“*pattern*”)[.return], module(“*pattern*”).function(“*pattern*”)[.return], kernel.statement(“*pattern*”), kprobe.function(“*pattern*”)[.return], kprobe.module(“*pattern*”).function(“*pattern*”)[.return], kernel.trace(“*pattern*”), process(“*path*”).label(“*pattern*”), timer.jiffies(*n*), timer.ms(*n*)

SystemTap Language in a Nutshell

```
probe probe {
    actions
}
```

- **Actions**
  - List of statements delimited by whitespace, implicit default action (usually probe name printout)
  - C control structures, foreach iteration, C types and operators, member operator, structures, strings, associative arrays (scalar types as keys), aggregates (`@count()`, `@sum()`, `@min()`, `@max()`, `@avg()`, `@hist_linear()`)
  - Conditional compilation, simple preprocessor macros
  - Embedded C
  - Context variables (with pretty-printers)
    - $1, $2, …, @1, @2, …
  - `pid()`, `tid()`, `execname()`, `caller()`, `log()`, `printf()`, `sprintf()`, `print_backtrace()`, `print_ubacktrace()`
  - Speculative tracing
    - `speculation()`, `speculate()`, `commit()`, `discard()`

DTrace Example

```
#! /usr/sbin/dtrace -s

syscall:::entry {
    @count[probefunc] = count();
    self->ts = timestamp;
    self->tag = 1;
}

syscall:::return /self->tag == 1/ {
    self->tag = 0;
    self->ts_diff = timestamp - self->ts;
    @total[probefunc] = sum(self->ts_diff);
    @average[probefunc] = avg(self->ts_diff);
}

END {
    printa("%s count=%@u sum=%@u average=%@u\n", @count, @total, @average);
}
```

SystemTap Example

```
#! /usr/bin/stap

global tag
global ts
global syscalls

probe syscall.* {
      tag[tid()] = 1
      ts[tid()] = local_clock_ns()
}

probe syscall.*.return  {
      if (!tag[tid()])
            next

      tag[tid()] = 0
      ts_diff = local_clock_ns() - ts[tid()]
      syscalls[name] <<< ts_diff
}

probe end {
      foreach (syscall in syscalls)
            printf("%s count=%u sum=%u average=%u\n", syscall,
                        @count(syscalls[syscall]),
                        @sum(syscalls[syscall]),
                        @avg(syscalls[syscall]))
}
```

DTrace Example

```
#! /usr/sbin/dtrace -s

#pragma D option quiet

hotspot$target:::method-entry {
    self->indent++;
    self->trace = 1;
    printf("%*s -> %s.%s\n", self->indent, "", stringof(copyin(arg1, arg2)), stringof(copyin(arg3, arg4)));
}

hotspot$target:::method-return /self->trace == 1/ {
    printf("%*s <- %s.%s\n", self->indent, "", stringof(copyin(arg1, arg2)), stringof(copyin(arg3, arg4)));
    self->indent--;
    self->trace = (self->indent == 0) ? 0 : self->trace;
}

pid$target:libc::entry /self->trace == 1/ {
    self->indent++;
    printf("%*s => %s\n", self->indent, "", probefunc);
}

pid$target:libc::return /self->trace == 1/ {
    printf("%*s <= %s\n", self->indent, "", probefunc);
    self->indent--;
}

syscall:::entry /self->trace == 1/ {
    self->indent++;
    printf("%*s :> %s\n", self->indent, "", probefunc);
}

syscall:::return /self->trace == 1/ {
    printf("%*s <: %s\n", self->indent, "", probefunc);
    self->indent--;
}
```

DTrace Code Instrumentation

	uninstrumented	instrumented
squeue_enter_chain+0x1af:	xorl %eax,%eax	xor %eax,%eax
squeue_enter_chain+0x1b1:	nop	nop
squeue_enter_chain+0x1b2:	nop	nop
squeue_enter_chain+0x1b3:	nop	lock nop
squeue_enter_chain+0x1b4:	nop	
squeue_enter_chain+0x1b5:	nop	nop
squeue_enter_chain+0x1b6:	movb %bl,%bh	movb %bl,%bh
ufs_mount:	pushq %rbp	int $0x3
ufs_mount+1:	movq %rsp,%rbp	movq %rsp,%rbp
ufs_mount+4:	subq $0x88,%rsp	subq $0x88,%rsp
ufs_mount+0xb:	pushq %rbx	pushq %rbx
……		
ufs_mount+0x3f3:	popq %rbx	popq %rbx
ufs_mount+0x3f4:	movq %rbp,%rsp	movq %rbp,%rsp
ufs_mount+0x3f7:	popq %rbp	popq %rbp
ufs_mount+0x3f8:	ret	int $0x3

replaced by the call instruction

ftrace Code Instrumentation

- **Using `gcc -pg` to call `__fentry__()` in every prologue**
  - Patched out at kernel load time

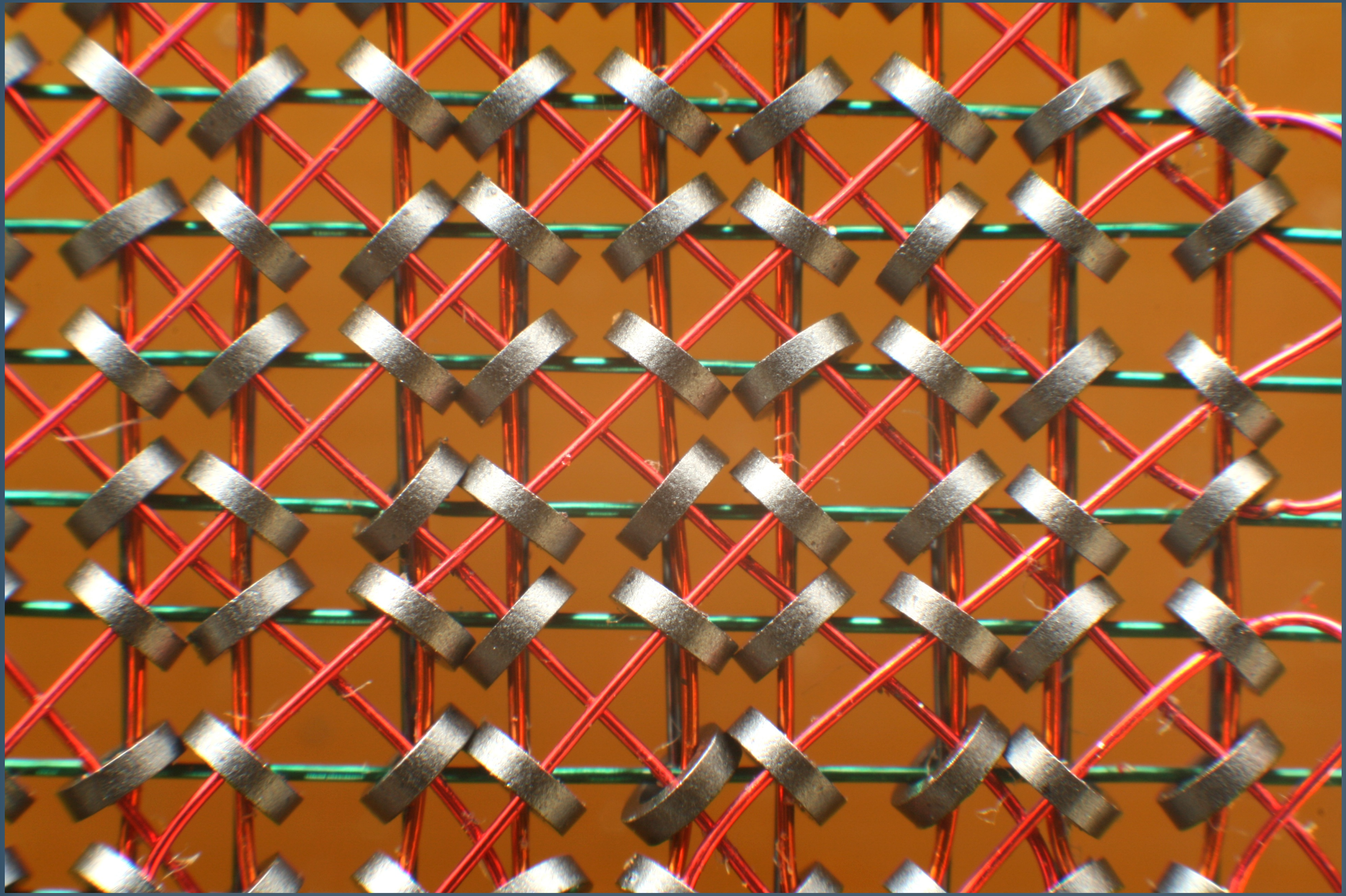
	uninstrumented	instrumented	
`exit_mmap:`	`nop`	`int $0x3`	2: replaced by the call opcode
`exit_mmap+1:`	`nop`	`nop`	
`exit_mmap+2:`	`nop`	`nop`	1: replaced by the address
`exit_mmap+3:`	`nop`	`nop`	
`exit_mmap+4:`	`nop`	`nop`	

Code Instrumentation

- **Static instrumentation of executables**
  - Non-intrusive
    - Avoiding shifting instruction locations (complicated unless the code is position-independent)
    - Replacing a byte of an instruction by a trap instruction
      - At run-time, replacing the trap with a call
      - The call emulates the original instruction(s) that are replaced and jumps back to the next instruction
  - Intrusive
    - Techniques similar to binary translation
    - Internal representation of code basic blocks
      - Instrumentation is equal to inserting a new back block and updating jump/call locations
      - Tricky with self-modifying code, dynamic dispatch, etc.
  - Valgrind, DynInst, Pin, Vulcan, BIRD, PEBIL

Post-Mortem Analysis

- **Analyzing a root cause of a crash**
  - Core dump
    - Snapshot of a single process
    - On-disk format similar to an executable format
      - Added state/register context and other metadata
      - Can be opened in an interactive debugger
  - Crash dump
    - Snapshot of an entire system
      - Sometimes without user pages and other sensitive data
      - Created by a failing system, rescue system (`kexec`), firmware or out-of-band management
      - Non-maskable interrupt
      - Used by special analysis tools



Source: Konstantin Lanzet, https://commons.wikimedia.org/wiki/File:KL_Kernspeicher_Makro_1.jpg

Core/Crash Dump Analysis

- **Identifying the *immediate* cause**
  - Examining the crash IP location, register context, stack trace, log buffer, instrumentation values (if available)
- **Identifying the *root* cause**
  - Art, science and craft
    - Values of registers (esp. scratch) and arguments can be lost or misleading
    - Control flow only partially obvious from stack traces (at best, if frame pointers are used)
    - The more the code is optimized (leaf calls, tail calls, inlining) the worse it is to understand (usually)
  - Heuristic tools to analyze typical crashes
    - `::findlocks` in mdb for Solaris
    - Crash tool for Linux
  - Gradually reconstructing the events prior to the crash
    - Formulating hypotheses while distrusting the information encountered
    - Analyzing data structures, threads, locks, etc.
    - Looking for interesting literals (`0xdeadbeef`, `0xbaddcafe`, `0xfeedface`)

References

[1] Frank Hofmann: *The Solaris Operating System on x86 Platforms, Crashdump Analysis, Operating System Internals*, https://www.cs.dartmouth.edu/~sergey/cs258/solaris-on-x86.pdf

[2] Chris Drake, *Kimberley Brown: PANIC! UNIX System Crash Dump Analysis Handbook*

[3] Igor Ljubuncic: *Linux Kernel Crash Book*

[4] Richard McDougall, Jim Mauro, Brendan Gregg: *Solaris Performance and Tools: DTrace and MDB Techniques for Solaris 10 and OpenSolaris*

Thank you!

Questions?