L41 - Lecture 4: The Process Model (2)

Dr Robert N. M. Watson

3 November 2015

Reminder: last time

1. The process model and its evolution
   - *Isolation* via *virtual addressing* and *rings*
   - *Controlled transition* to kernel via *traps*
   - *Controlled communication* to other processes via the kernel
2. Brutal introduction to virtual memory
3. Programs: *ELF* and *run-time linking*

This time: more about the process model

1. More on traps and system calls
   - Synchrony and asynchrony
   - Security and reliability
   - Entry and return
2. Virtual memory support for the process model
3. ~~Threads and the process model~~
4. Readings for next time

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- Some quirks relative to normal APIs; e.g.,
  - C return values via normal ABI calling convention...
  - ... but also per-thread `errno` to report error conditions
  - ... `EINTR`: for some calls, work got interrupted, try again

System-call synchrony

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  - `_exit()` never returns
  - `fork()` returns ... twice
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- Some syscalls manipulate control flow or process/thread life cycle
  - `_exit()` never returns
  - `fork()` returns ... twice
  - `pthread_create()` creates a new thread
- But most syscalls behave like C functions and are *synchronous*
  - Called with arguments (by value, by reference)
  - Return values (an integer/pointer, or by reference)
  - When the caller regains control, the work is done
  - `getpid()` retrieves the *process ID* via return value
  - `read()` reads data from a file: on return, data is in buffer

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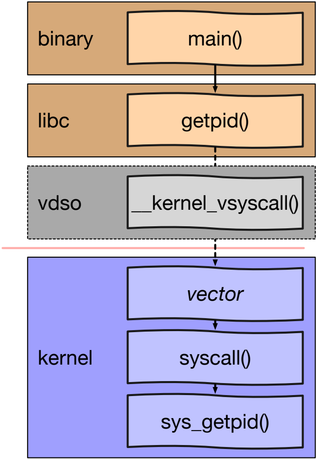
  - `mmap()` maps a file but doesn't load data
  - Caller will trap on attempted access; trigger actual I/O
- Some syscalls are explicitly asynchronous
  - `aio_write()` explicitly requests an asynchronous write
  - Calls to `aio_return()`/`aio_error()` collect results later
  - Caller must wait to re-use buffer ('shared semantics')

System-call invocation from user to kernel



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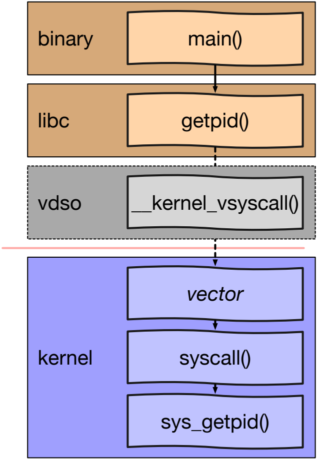

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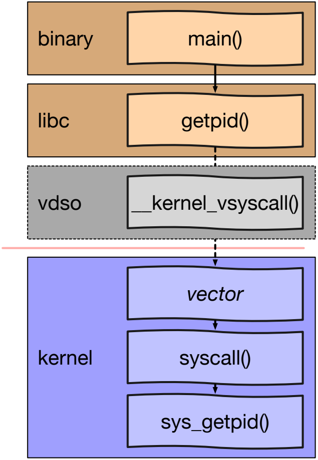

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- Stubs inline system-call instructions, or use dynamic implementations
  - Linux, FreeBSD `vdso`
  - Xen hypercall page
- Low-level vector calls `syscall()`
  - System-call prologue runs (e.g., breakpoints, tracing)
  - Actual kernel service invoked
  - System-call epilogue runs (e.g., more tracing, signal delivery)

The system-call table: `syscalls.master`

```
...
33  AUE_ACCESS    STD     { int access(char *path, int amode); }
34  AUE_CHFLAGS   STD     { int chflags(const char *path, u_long flags); }
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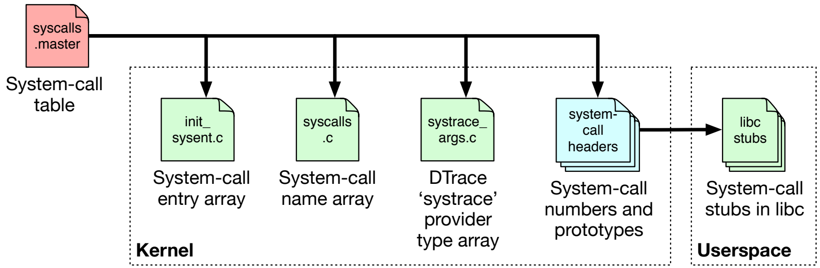

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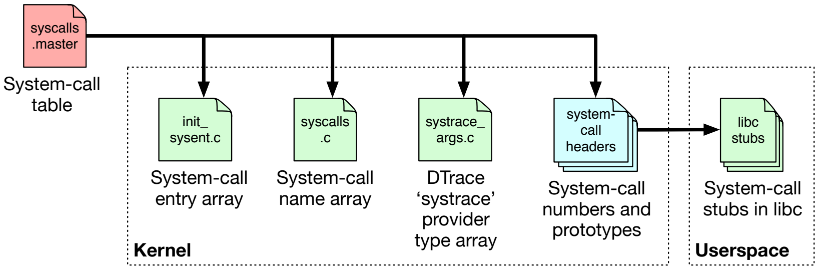

NB: If this looks like RPC stub generation .. that’s because it is.

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- Kernel must be robust to user-thread misbehaviour
  - Handle failures gracefully: terminate process, not kernel
  - Avoid priority inversions, unbounded resource allocation, etc.

Security and reliability (cont)

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  - Prevent kernel-user data leaks (e.g., in structure padding)
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  - Kernel `NULL`-pointer vulnerabilities
  - Intel Supervisor Mode Access Prevention (SMAP)

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- That's a lot of tracing hooks – why so many?

getauid: return process audit ID

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sys_getauid(struct thread *td, struct getauid_args *uap)
{
        int error;

        if (jailed(td->td_ucred))
                return (ENOSYS);
        error = priv_check(td, PRIV_AUDIT_GETAUDIT);
        if (error)
                return (error);
        return (copyout(&td->td_ucred->cr_audit.ai_auid, uap->auid,
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- Does it matter how fresh the credential pointer is?

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- That is a lot of stuff that largely **never happens**
- The trick is making all this nothing fast – e.g., via a small number of per-thread flags and globals that remain in the cache

System calls in practice: dd

```
# time dd if=/dev/zero of=/dev/null bs=10m count=1 status=none
0.000u 0.396s 0:00.39 100.0% 25+170k 0+0io 0pf+0w
```

System calls in practice: dd

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syscall:::entry /execname == "dd"/ {
        self->start = timestamp;
        self->insyscall = 1;
}

syscall:::return /execname == "dd" && self->insyscall != 0/ {
        length = timestamp - self->start;
        @syscall_time[probefunc] = sum(length);
        @totaltime = sum(length);
        self->insyscall = 0;
}

END {
        printa(@syscall_time);
        printa(@totaltime);
}
```

System calls in practice: dd (2)

```
# time dd if=/dev/zero of=/dev/null bs=10m count=1 status=none
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```

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```
  sysarch                                                    7645
  issetugid                                                  8900
  lseek                                                      9571
  sigaction                                                 11122
  clock_gettime                                             12142
  ioctl                                                     14116
  write                                                     29445
  readlink                                                  49062
  access                                                    50743
  sigprocmask                                               83953
  fstat                                                    113850
  munmap                                                   154841
  close                                                    176638
  lstat                                                    453835
  openat                                                   562472
  read                                                     697051
  mmap                                                     770581
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  mmap                                                     770581
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```

NB: ≈ 3.2ms total – but `time(1)` reports 396ms system time?

Traps in practice: dd (1)

```
syscall:::entry /execname == "dd"/ {
        @syscalls = count();
        self->insyscall = 1;
        self->start = timestamp;
}

syscall:::return /execname == "dd" && self->insyscall != 0/ {
        length = timestamp - self->start; @syscall_time = sum(length);
        self->insyscall = 0;
}

fbt::trap:entry /execname == "dd" && self->insyscall == 0/ {
        @traps = count(); self->start = timestamp;
}

fbt::trap:return /execname == "dd" && self->insyscall == 0/ {
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END {
        printa(@syscalls); printa(@syscall_time);
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```
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             5185
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```
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             5185
        380762894
```

NB: 65 system calls at ≈3ms; 5185 traps at ≈381ms! But which traps?

Traps in practice: `dd` (1)

```
profile-997 /execname == "dd"/ { @traces[stack()] = count(); }
```

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```
profile-997 /execname == "dd"/ { @traces[stack()] = count(); }

...
              kernel`PHYS_TO_VM_PAGE+0x1
              kernel`trap+0x4ea
              kernel`0xffffffff80e018e2
                5

              kernel`vm_map_lookup_done+0x1
              kernel`trap+0x4ea
              kernel`0xffffffff80e018e2
                5

              kernel`pagezero+0x10
              kernel`trap+0x4ea
              kernel`0xffffffff80e018e2
              346
```

Traps in practice: dd (1)

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              kernel`0xffffffff80e018e2
                5

              kernel`pagezero+0x10
              kernel`trap+0x4ea
              kernel`0xffffffff80e018e2
              346
```

- A sizeable fraction of time is spent in `pagezero`: on-demand zeroing of previously untouched pages
- Ironically, the kernel is filling pages with zeroes only to immediately `copyout()` zeros to it from `/dev/zero`

So: back to virtual memory (VM)

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  - Background page zeroing
  - Superpages to improve TLB efficiency

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- VM optimisation avoids work, but also manages memory footprint
  - Memory as a *cache* of secondary storage (files, swap)
  - Demand paging vs. I/O clustering
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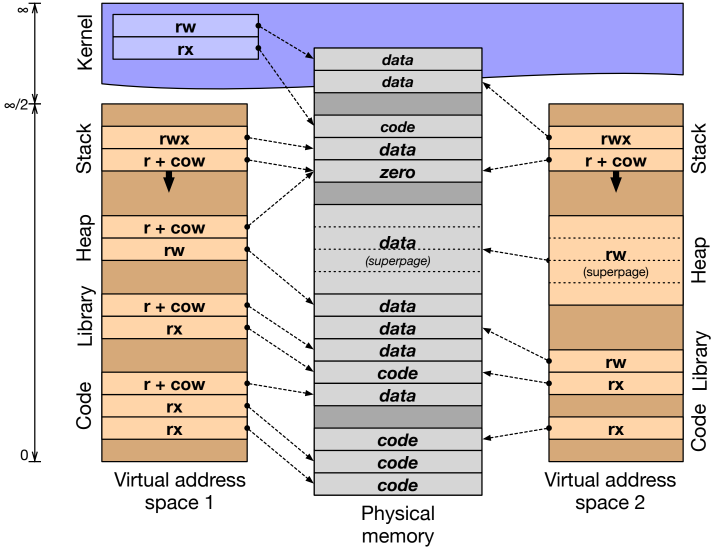
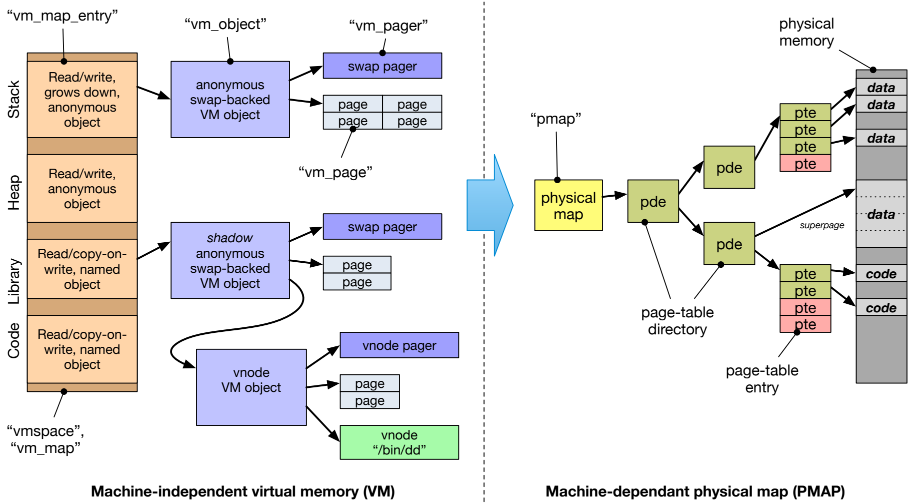
  - Memory compression and deduplication
- These ideas were known before Mach, but ...
  - Acetta, et al turn them into an art form
  - Provide a *model* beyond V$\rightarrow$P mappings in page tables
  - And ideas such as the *message-passing–shared-memory duality*

Last time: virtual memory (quick but painful primer)



A (kernel) programmer model for virtual memory



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  - **Mac OS X** Although XNU is not a microkernel, Mach's VM/IPC APIs are visible to applications, and used frequently
  - **FreeBSD** Mach VM is used as a foundation and are only available as a Kernel Programming Interface (KPI)
- In FreeBSD, Mach VM KPIs are used:
  - To efficiently implement UNIX's `fork()` and `execve()`
  - For memory-management APIs such as `mmap()` and `mprotect()`
  - By the filesystem to implement a merged VM-buffer cache
  - By device drivers that manage memory in interesting ways (e.g., GPU drivers mapping pages into user processes)
  - By a set of VM worker threads, such as the *page daemon*, *swapper*, *syncer*, and page-zeroing thread

For next time

- The second lab: DTrace and I/O
- Begin to explore Inter-Process Communication (IPC) performance

- Ellard and Seltzer 2003

If you are having trouble getting hold of the course texts: Please ask the department librarian or your college librarian to order copies.