# L41 - Lecture 4: The Process Model (2)

Dr Robert N. M. Watson

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# Reminder: last time

1. The process model and its evolution
   - *Isolation*
   - *Controlled communication* to kernel and other processes
   - Kernel must initiate communication, but can continue after return
2. Brutal pre-introduction to virtual memory
3. Where do programs come from?
4. Traps and system calls
5. Reading for next time

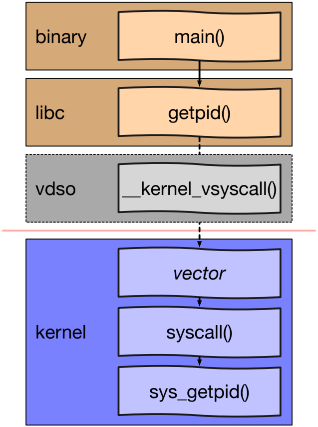
# This time: more about the process model

1. More on traps and system calls
2. Virtual memory support for the process model
3. Threads and the process model
4. Readings for next time

# System calls

- *System calls* allow user processes to request kernel services
  - `read()` reads data from a file descriptor to user memory
  - `fork()` creates a new process
- Exposed to userspace as system-library functions (e.g., `libc`)
- Under the hood, a *hardware trap* transfers control to the kernel
- Once the work is done, the kernel returns control to userspace
- Mostly synchronous, like normal C functions, but not always:
  - `_exit()` never returns
  - `sigreturn()` returns ... but not to a caller
  - `fork()` returns ... twice
- Even if a call is synchronous, its work is often asynchronous
  - `send()` writes data to a socket .. to get somewhere eventually
  - `aio_write()` explicitly performs an asynchronous write; later calls to `aio_return()`/`aio_error()` collect results

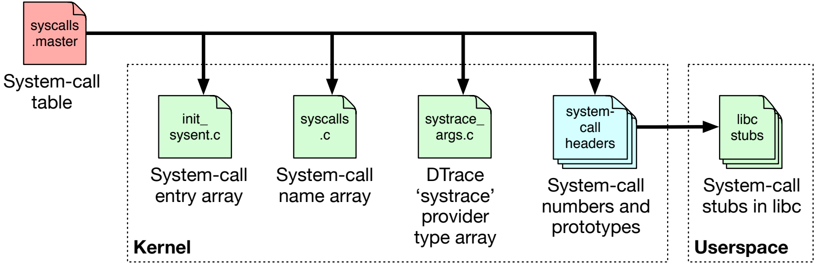
# System-call invocation from user to kernel




- libc system-call function stubs provide linkable symbols
- Stubs can execute system-call instructions directly, or use dynamic implementations
  - Linux 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); }
35   AUE_FCHFLAGS  STD      { int fchflags(int fd, u_long flags); }
36   AUE_SYNC      STD      { int sync(void); }
37   AUE_KILL      STD      { int kill(int pid, int signum); }
38   AUE_STAT      COMPAT   { int stat(char *path, struct ostat *ub); }
39   AUE_GETPPID   STD      { pid_t getppid(void); }
...
```




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

# Security and reliability

- System calls perform work on behalf a user thread
  - Work authorised by the thread's credential
  - Resources (e.g., CPU time, memory) billed to the thread
  - Debugging/profiling information exposed to the thread's owner
- Kernel interface is key *Trusted Computing Base* (TCB) surface
  - *Isolation* goals: *integrity*, *confidentiality*, *availability*
  - Scope global effects except as specified for service
  - Enforce access-control policies on all operations
  - Provide mechanisms for accountability (e.g., event auditing)
- But the kernel cannot trust user thread
  - Handle failures gracefully: terminate process, not kernel
  - Avoid priority inversions, unbounded resource allocation, etc
  - Confidentiality is expensive; e.g., zero pages, structure padding
  - Be aware of *covert channels*, *side channels*
- User code is the adversary – may try to break isolation
  - System-call arguments and return values are data, not code
  - Access user addresses safely (e.g., `copyin()`, `copyout()`)

# System-call entry – the guts: `syscallenter`

| | |
|---|---|
| `cred_update_thread` | Update thread cred from process |
| `sv_fetch_syscall_args` | ABI-specific `copyin()` of arguments |
| `ktrsyscall` | `ktrace` syscall entry |
| `ptracestop` | `ptrace` syscall entry breakpoint |
| `IN_CAPABILITY_MODE` | Capsicum capability-mode check |
| `syscall_thread_enter` | Thread drain barrier (module unload) |
| `systrace_probe_func` | DTrace system-call entry probe |
| `AUDIT_SYSCALL_ENTER` | Security event auditing |
| `sa->callp->sy_call` | **System-call implementation! Woo!** |
| `AUDIT_SYSCALL_EXIT` | Security event auditing |
| `systrace_probe_func` | DTrace system-call return probe |
| `syscall_thread_exit` | Thread drain barrier (module unload) |
| `sv_set_syscall_retval` | ABI-specific return value |

# getauid: return process audit ID

```
int
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,
            sizeof(td->td_ucred->cr_audit.ai_auid)));
}
```

- Current thread, system-call argument structure
  - Security checks: lightweight virtualisation, privilege
  - Copy value to user address space – can't write to it directly!
  - No synchronisation as all fields thread-local
- Does it matter how fresh the credential pointer is?

# System-call return – the guts: `syscallret`

| | |
|---|---|
| `userret` | Complicated things like signals |
| → `KTRUSERRET` | `ktrace` syscall return |
| → `g_waitidle` | Wait for disk probe to settle |
| → `addupc_task` | System-time profiling charge |
| → `sched_userret` | Scheduler adjusts priority |
| | ... various debugging assertions ... |
| `p_throttled` | `racct` resource throttling |
| `ktrsysret` | Kernel tracing: syscall return |
| `ptracestop` | `ptrace` syscall return breakpoint |
| `thread_suspend_check` | Single-threading check |
| `P_PPWAIT` | `vfork` wait |

- 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

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
0.000u 0.396s 0:00.39 100.0%    25+170k 0+0io 0pf+0w

  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
          3205967
```

NB: ≈ 3ms 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/ {
        length = timestamp - self->start; @trap_time = sum(length);
}

END {
        printa(@syscalls); printa(@syscall_time);
        printa(@traps); printa(@trap_time);
}
```

```
              65
         2953756
            5185
       380762894
```

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

# Traps in practice: dd (1)

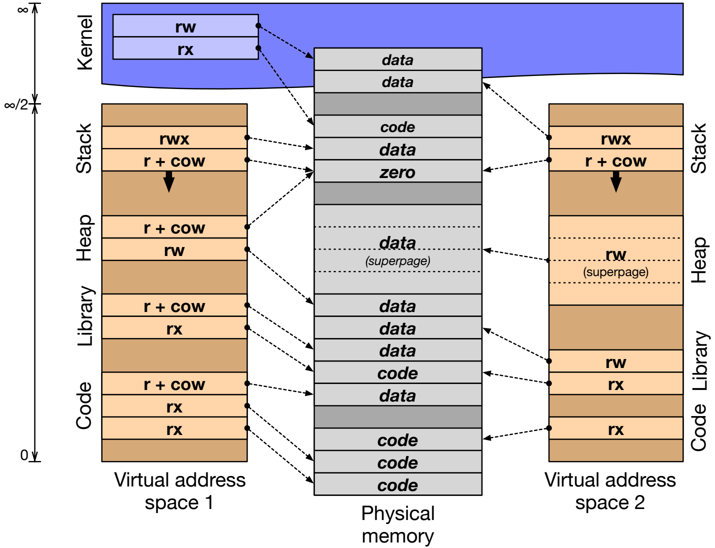
```
profile-997 /execname == "dd"/ { @traces[stack()] = count(); }

...
              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
```

- A sizeable fraction of time is spent in `pagezero`: on-demand zeroing of previously untouched pages; but why ≈5120 faults?
- This is ironic, as the kernel is presumably filling pages with zeroes only to immediately `copyout()` zeros to it from `/dev/zero`

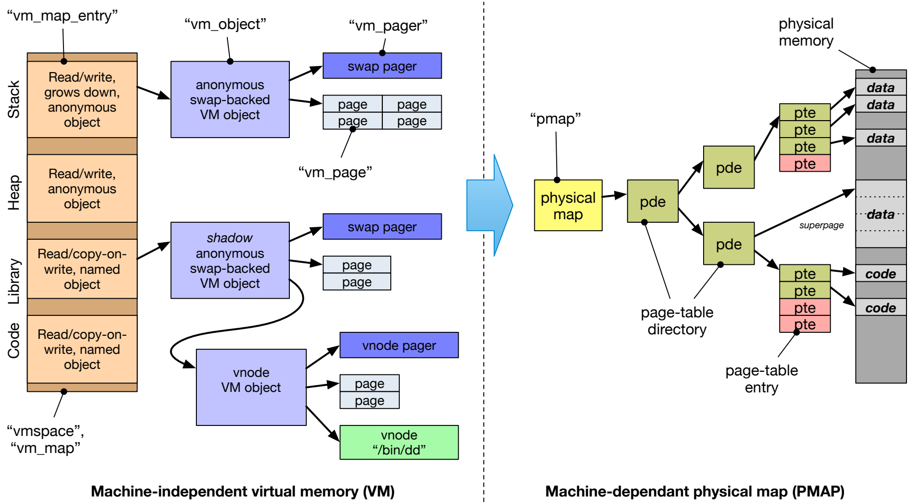
# So: back to virtual memory (VM)

- The process model's isolation guarantees incur real expenses
- But the virtual-memory subsystem works quite hard to avoid them
  - Memory sharing – and Copy-on-Write, 'page flipping'
  - 'Page flipping': both process/kernel and between processes
  - Background page zeroing
  - Superpages to improve TLB efficiency
- VM optimisation avoids work, but also manage memory footprint
  - Memory as a *cache* of secondary storage (files, swap)
  - Demand paging vs. I/O clustering
  - LRU / Preemptive swapping/paging to maintain free page pool
  - Working-set modelling
  - 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→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



# Mach VM in other operating systems

- In Mach, VM mappings, objects, pages, etc, were first-class objects exposed to userspace via system calls
- In two directly derived systems, quite different stories:

  **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:
  - In efficiently implement UNIX APIs such as `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 first lab: DTrace and I/O
- Dig into processes, system calls, etc

- Gregg and Mauro, Chapter 1 (*Introduction to DTrace*) and Chapter 2 (*D Language*)
- Handout *L41: DTrace Quick Start*

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