The Process Model (1)

L41 Lecture 3

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Reminder: last time

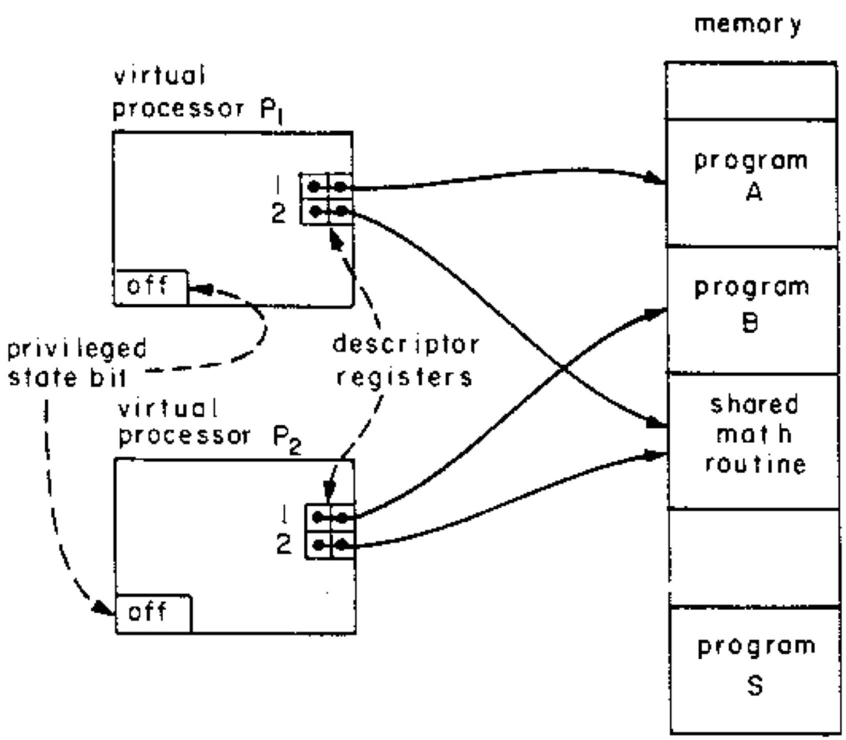
- What is an operating system?
- Operating systems research
- About the module
- Lab reports

- DTrace
- The probe effect
- The kernel: Just a C program?
- A little on kernel dynamics: How work happens

This time: The process model

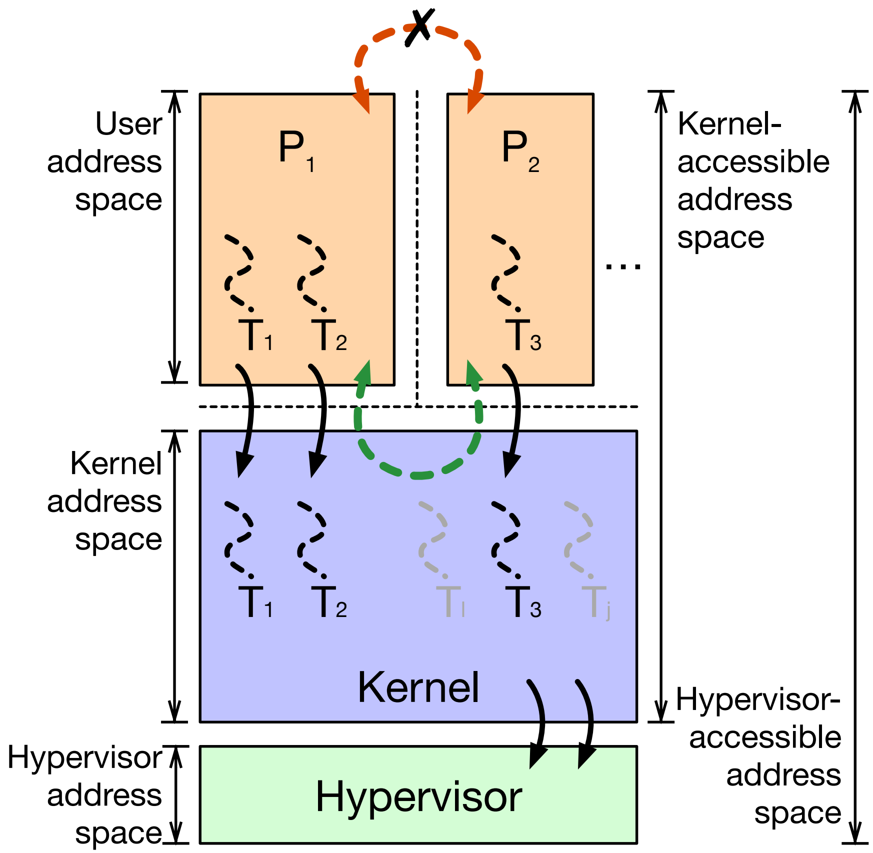
- The process model and its evolution
- Brutal (re, pre)-introduction to virtual memory
- Where do programs come from?
- Traps and system calls
- Reading for next time

The **Process Model**: 1970s foundations



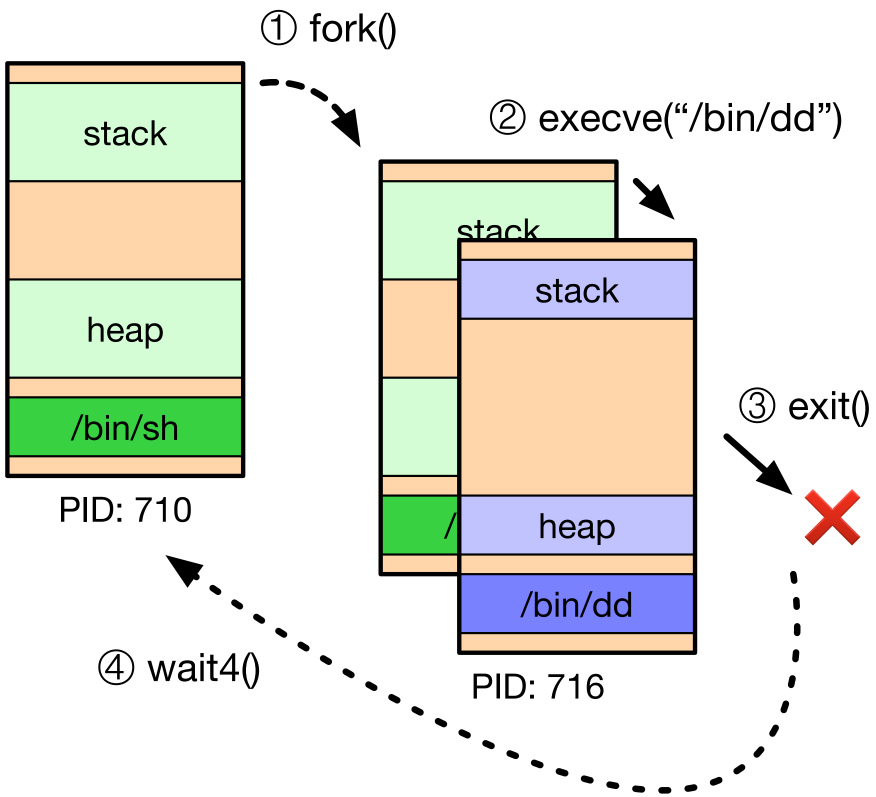
- Saltzer and Schroeder, **The Protection of Information in Computer Systems**, SOSP'73, October 1973. (CACM 1974)
- **Multics process model**
  - 'Program in execution'
  - **Process isolation** bridged by **controlled communication** via **supervisor** (kernel)
- Hardware foundations
  - Supervisor mode
  - Memory segmentation
  - Trap mechanism
- Hardware protection rings (Schroeder and Saltzer, 1972)

The **process model**: today



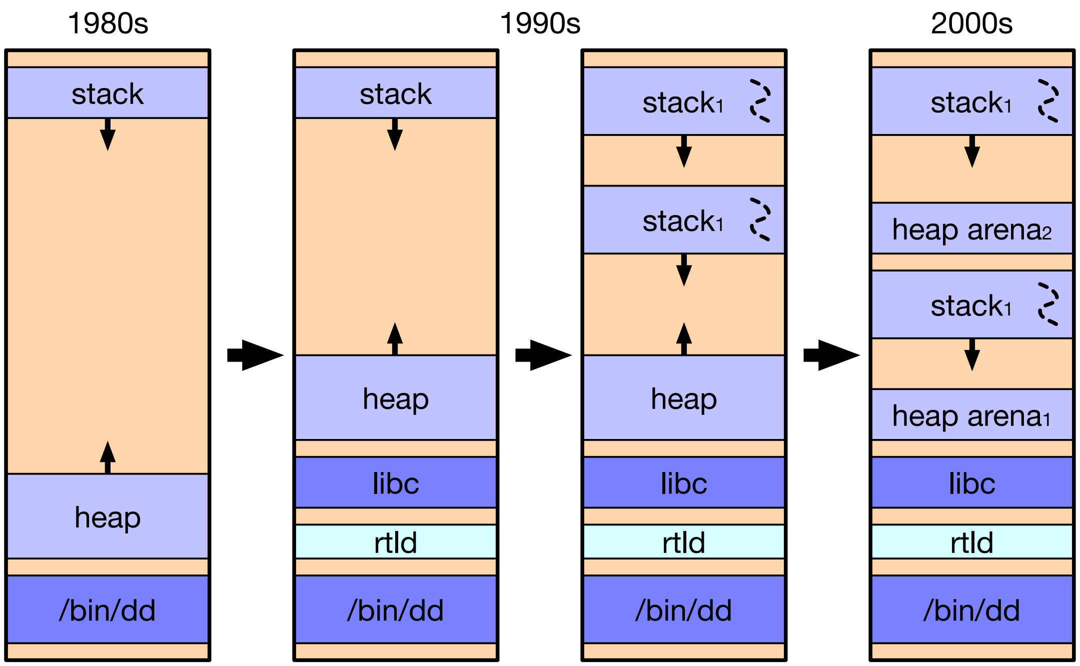
- 'Program in execution'
  - **Process** ≈ address space
  - **Threads** execute code
- Unit of **resource accounting**
  - Open files, memory, …
- Kernel interaction via **traps**: system calls, page faults, …
- Hardware foundations
  - Rings control MMU, I/O, etc.
  - Virtual addressing (MMU) to construct **virtual address spaces**
  - Trap mechanism
- Details vary little across {BSD, OS X, Linux, Windows, …}
- Recently: OS-Application trust model inverted due to untrustworthy operating systems – e.g., Trustzone, SGX, …

The UNIX process life cycle



- **fork()**
  - Child inherits address space and other properties
  - Program prepares process for new binary (e.g., stdio)
  - Copy-on-Write (COW)
- **execve()**
  - Kernel replaces address space, loads new binary, starts execution
- **exit()**
  - Process can terminate self (or be terminated)
- **wait4()** (et al)
  - Parent can await exit status
- NB: **posix_spawn()**?

Evolution of the process model



- **1980s**: Code, heap, and stack
- **1990s**: Dynamic linking, threading
- **2000s**: Scalable memory allocators implement multiple **arenas** (e.g., as in jemalloc)
- Co-evolution with virtual memory (VM) research
  - Acetta, et al: *Mach* microkernel (1986)
  - Nararro, et al: *Superpages* (2002)

Process address space: dd(1)

- Inspect dd process address space with `procstat -v`

```
root@beaglebone:/data # procstat -v 734
  PID       START         END PRT   RES PRES REF SHD FLAG TP PATH
  734      0x8000      0xd000 r-x     5    5   1   0 CN-- vn /bin/dd
  734     0x14000     0x16000 rw-     2    2   1   0 ---- df
  734 0x20014000 0x20031000 r-x    29   32  31  14 CN-- vn /libexec/ld-elf.so.1
  734 0x20038000 0x20039000 rw-     1    0   1   0 C--- vn /libexec/ld-elf.so.1
  734 0x20039000 0x20052000 rw-    16   16   1   0 ---- df
  734 0x20100000 0x2025f000 r-x   351  360  31  14 CN-- vn /lib/libc.so.7
  734 0x2025f000 0x20266000 ---     0    0   1   0 ---- df
  734 0x20266000 0x2026e000 rw-     8    0   1   0 C--- vn /lib/libc.so.7
  734 0x2026e000 0x20285000 rw-     7  533   2   0 ---- df
  734 0x20400000 0x20c00000 rw-   526  533   2   0 --S- df
  734 0xbffe0000 0xc0000000 rwx     3    3   1   0 ---D df
```

r: read C: Copy-on-write

w: write D: Downward growth

x: execute S: Superpage

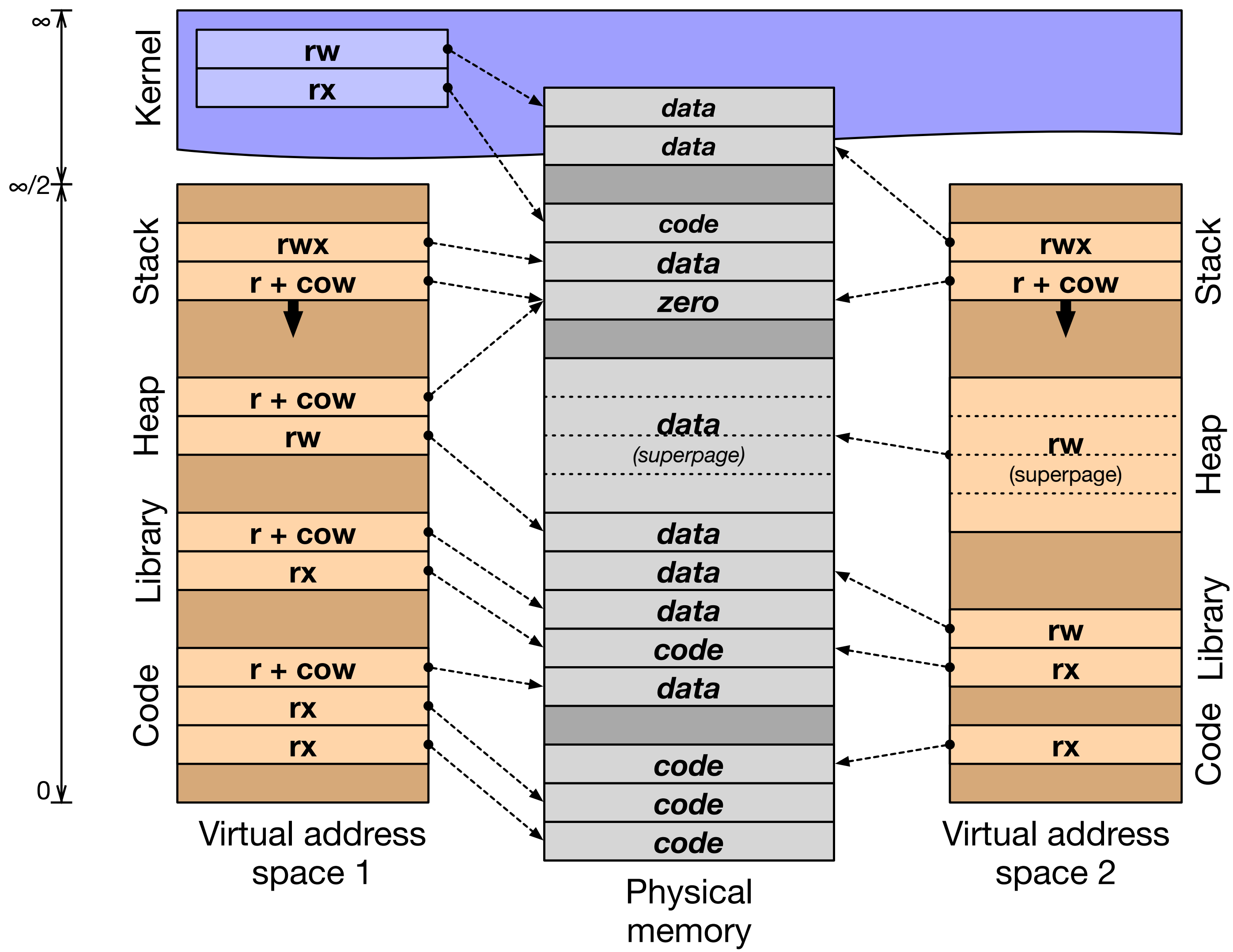
ELF binaries

- UNIX: Executable and Linkable Format (ELF)
- Mac OS X/iOS: Mach-O; Windows: PE/COFF; same ideas
- Inspect dd ELF program header using `objdump -p`:

```
root@beaglebone:~ # objdump -p /bin/dd
/bin/dd: file format elf32-littlearm
```

```
Program Header:
0x70000001 off    0x0000469c vaddr 0x0000c69c paddr 0x0000c69c align 2**2
         filesz 0x00000158 memsz 0x00000158 flags r--
    PHDR off    0x00000034 vaddr 0x00008034 paddr 0x00008034 align 2**2
         filesz 0x000000e0 memsz 0x000000e0 flags r-x
  INTERP off    0x00000114 vaddr 0x00008114 paddr 0x00008114 align 2**0
         filesz 0x00000015 memsz 0x00000015 flags r--
    LOAD off    0x00000000 vaddr 0x00008000 paddr 0x00008000 align 2**15
         filesz 0x000047f8 memsz 0x000047f8 flags r-x
    LOAD off    0x000047f8 vaddr 0x000147f8 paddr 0x000147f8 align 2**15
         filesz 0x000001b8 memsz 0x00001020 flags rw-
 DYNAMIC off    0x00004804 vaddr 0x00014804 paddr 0x00014804 align 2**2
         filesz 0x000000f0 memsz 0x000000f0 flags rw-
    NOTE off    0x0000012c vaddr 0x0000812c paddr 0x0000812c align 2**2
         filesz 0x0000004c memsz 0x0000004c flags r--
```

Virtual memory (quick but painful primer)



Virtual memory (quick but painful primer)

- **Memory Management Unit (MMU)**
  - Transforms **virtual addresses** into **physical addresses**
  - Memory is laid out in **virtual pages** (4K, 2M, 1G, …)
  - Control available only to the supervisor (historically)
  - Software handles failures (e.g., store to read-only page) via **traps**
- **Page tables**
  - SW-managed **page tables** provide **virtual-physical mappings**
  - Access permissions, page attributes (e.g., caching), dirty bit
  - Various configurations + traps implement BSS, COW, sharing, ...
- **Translation Look-aside Buffer (TLB)**
  - Hardware cache of entries – avoid walking pagetables
  - Content Addressable Memory (CAM); 48? 1024? entries
  - TLB **tags**: entries **global** or for a specific **address-space ID (ASID)**
  - Software- vs. hardware-managed TLBs
- Hypervisors and **IOMMUs**:
  - I/O performs **direct memory access (DMA)** via virtual addres space

Role of the run-time linker (rtld)

- **Static linking**: program, libraries linked into one binary
  - Process address space laid out (and fixed) at compile time
- **Dynamic linking**: program, libraries in separate binaries
  - Shared libraries avoid code duplication, conserving memory
  - Shared libraries allow different update cycles, ABI ownership
  - Program binaries contain a list of their **library dependencies**
  - The run-time linker (`rtld`) loads and links libraries
  - Also used for plug-ins via `dlopen()`, `dlsym()`
- Three separate but related activities:
  - **Load**: Load ELF segments at suitable virtual addresses
  - **Relocate**: Rewrite **position-dependent code** to load address
  - **Resolve symbols**: Rewrite inline/PLT addresses to other code

Role of the run-time linker (rtld)

```
root@beaglebone:~ # ldd /bin/dd
/bin/dd:
        libc.so.7 => /lib/libc.so.7 (0x20100000)
```

- When the `execve` system call starts the new program:
  - ELF binaries name their **interpreter** in ELF metadata
  - Kernel maps `rtld` and the application binary into memory
  - Userspace starts execution in `rtld`
  - `rtld` loads and links dynamic libraries, runs constructors
  - `rtld` calls `main()`
- Optimisations:
  - **Lazy binding**: don't resolve all function symbols at load time
  - **Prelinking**: relocate, link in advance of execution
  - Difference is invisible – but surprising to many programmers

Arguments and ELF auxiliary arguments

- C-program arguments are `argc`, `argv[]`, and `envv[]`:

```
root@beaglebone:/data # procstat -c 716
  PID COMM                ARGS
  716 dd                  dd if=/dev/zero of=/dev/null bs=1m
```

- The run-time linker also accepts arguments from the kernel:

```
root@beaglebone:/data # procstat -x 716
  PID COMM                AUXV                VALUE
  716 dd                  AT_PHDR             0x8034
  716 dd                  AT_PHENT            32
  716 dd                  AT_PHNUM            7
  716 dd                  AT_PAGESZ           4096
  716 dd                  AT_FLAGS            0
  716 dd                  AT_ENTRY            0x8cc8
  716 dd                  AT_BASE             0x20014000
  716 dd                  AT_EXECPATH         0xbfffffc4
  716 dd                  AT_OSRELDATE        1100062
  716 dd                  AT_NCPUS            1
  716 dd                  AT_PAGESIZES        0xbfffff9c
  716 dd                  AT_PAGESIZESLEN     8
...
```

Traps and system calls

- Asymmetric domain transition, **trap**, shifts control to kernel
  - **Asynchronous traps**: e.g., timer, peripheral interrupts, Inter-Processor Interrupts (IPIs)
  - **Synchronous traps**: e.g., system calls, divide-by-zero, page faults
- $pc to **interrupt vector**: dedicated OS code to handle trap
- Key challenge: kernel must gain control safely, securely

RISC	User $pc saved, handler $pc installed, control coprocessor (MMU, …) Kernel address space becomes available for fetch/load/store Reserved registers in ABI ($k0, $k1) or banking ($pc, $sp, ...) Software must save other state (i.e., other registers)
CISC	HW saves context to in-memory trap frame (variably sized?)

- User context switch:
  - (1) trap to kernel, (2) save register context; (3) optionally change address space, (4) restore another register context; (5) trap return

Break

The Process Model (2)

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The process model (2)

- More on **traps** and **system calls**
  - **Synchrony** and **asynchrony**
  - **Security** and **reliability**
  - Kernel work in system calls and traps
- **Virtual memory** support for the process model

System calls

- User processes request kernel services via **system calls**:
  - **Traps** that model **function-call semantics**; e.g.,
  - `open()` opens a file and returns a file descriptor
  - `fork()` creates a new process
- System calls appear to be library functions (e.g., `libc`)
  1. Function triggers trap to transfer control to the kernel
  2. System-call arguments copied into kernel
  3. Kernel implements service
  4. System-call return values copied out of kernel
  5. Kernel returns from trap to next user instruction
- 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

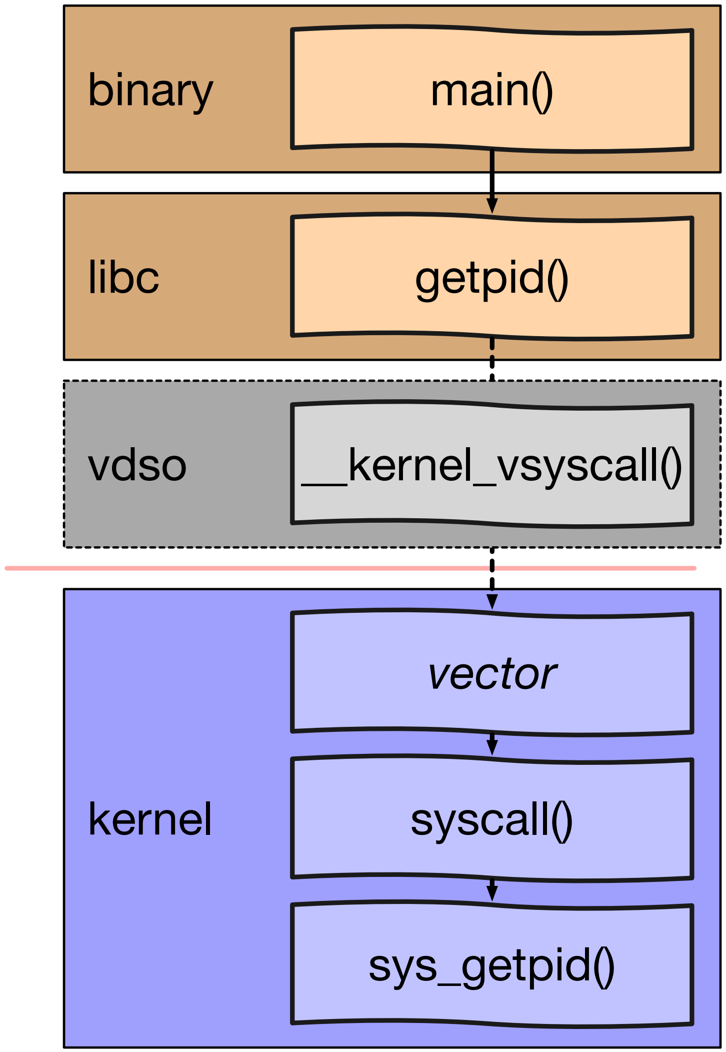
System-call synchrony

- Most syscalls behave like **synchronous** C functions
  - Calls with arguments (**by value** or **by reference**)
  - Return values (an integer/pointer or by reference)
  - Caller regains control when the work is complete; e.g.,
    - `getpid()` retrieves the **process ID** via a return value
    - `read()` reads data from a file: on return, data in buffer
- Except .. some syscalls manipulate **control flow** or **process thread/life cycle**; e.g.:
  - `_exit()` never returns
  - `fork()` returns … twice
  - `pthread_create()` creates a new thread
  - `setucontext()` rewrites thread register state

System-call asynchrony

- Synchronous calls can perform **asynchronous work**
  - Some work may not be complete on return; e.g.,
  - `write()` writes data to a file .. to disk .. eventually
  - Caller can re-use buffer immediately (**copy semantics**)
  - `mmap()` maps a file but doesn't load data
  - Caller traps on access, triggering I/O (**demand paging)**
  - Copy semantics mean that user program can be unaware of asynchrony (… sort of)
- Some syscalls have **asynchronous call semantics**
  - `aio_write()` requests an asynchronous write
  - `aio_return()/aio_error()` collect results later
  - Caller must wait to re-use buffer (**shared semantics**)

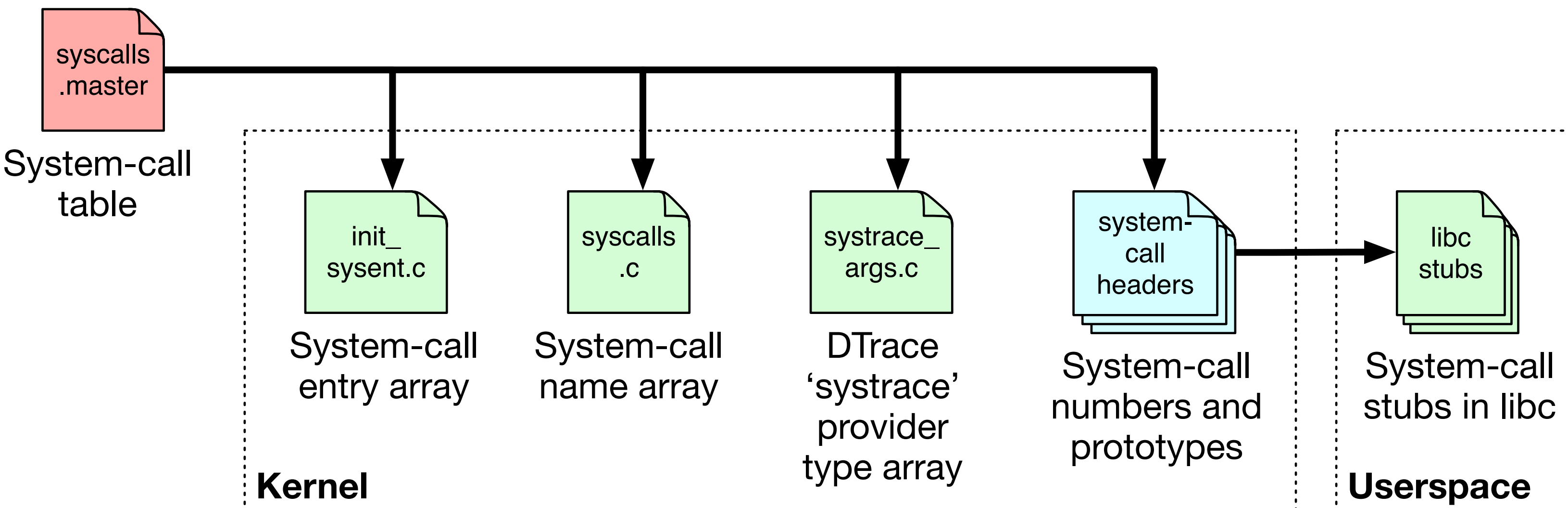
System-call invocation



- `libc` system-call stubs provide linkable symbols
- Inline system-call instructions or dynamic implementations
  - Linux `vdso`
  - Xen **hypercall page**
- **Machine-dependent trap vector**
- **Machine-independent** function `syscall()`
  - Prologue (e.g., breakpoints, tracing)
  - Actual service invoked
  - Epilogue (e.g., tracing, signal delivery)

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); }
...
```



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

Security and reliability (1)

- User-kernel interface is a key **Trusted Computing Base (TCB)** surface
  - *Minimum software required for the system to be secure*
- Foundational security goal: **isolation**
  - Used to implement **integrity**, **confidentiality**, **availability**
  - Limit scope of system-call effects on global state
  - Enforce access control on all operations (e.g., MAC, DAC)
  - Accountability mechanisms (e.g., event auditing)

Security and reliability (2)

- System calls perform work on behalf of user code
  - **Kernel thread** operations implement system call/trap
- **Unforgeable credential** tied to each process/thread
  - Authorises use of kernel services and objects
  - Resources (e.g., CPU, memory) billed to the thread
  - Explicit checks in system-call implementation
  - Credentials may be cached to authorise asynchronous work (e.g., TCP sockets, NFS block I/O)
- 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 (3)

- **Confidentiality** is both difficult and expensive
  - Explicitly zero memory before re-use between processes
  - Prevent kernel-user data leaks (e.g., in struct padding)
  - Correct implementation of process model via rings, VM
  - **Covert channels**, **side channels**
- User code is the adversary – may try to break access control or isolation
  - Kernel must carefully enforce all access-control rules
  - System-call arguments, return values are data, not code
  - Extreme care with user-originated pointers, operations

Security and reliability (4)

- What if a user process passes a kernel pointer to system call?
  - System-call arguments must be processed with rights of user code
  - E.g., prohibit `read()` from storing via kernel pointer, which might (e.g.,) overwrite in-kernel credentials
  - Explicit `copyin()`, `copyout()` routines check pointer validity, copy data safely
- Kernel dereferences user pointer by accident
  - Kernel bugs could cause kernel to access user memory "by mistake", inappropriately trusting user code or data
  - Kernel `NULL`-pointer vulnerabilities
  - Intel Supervisor Mode Access Prevent (SMAP), Supervisor Mode Execute Prevention (SMEP)
  - ARM Privileged eXecute Never (PXN)

System-call entry – `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

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

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

System-call return – `syscallret`

`userret`	Complicated things, like signals
➟ `KTRUSERRET`	`ktrace` syscall return
➟ `g_waitidle`	Wait for disk probing to complete
➟ `addupc_task`	System-time profiling charge
➟ `sched_userret`	Scheduler adjusts priorities
	… 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 of this nothing fast – e.g., via per-thread flags and globals that remain in the data cache

System calls in practice: dd (1)

```
# 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: ≈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/ {
        length = timestamp - self->start; @trap_time = sum(length);
}

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

NB: trap() FBT probes are machine-dependent and these examples are from x86_64.
On ARMv7, use **fbt::abort_handler:{entry,return}**.

Traps 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
```

```
       65
  2953756
     5185
380762894
```

65 system calls

2.95ms in system calls

5,185 traps

380.76ms in traps

- 65 system calls at ≈3ms; 5,185 traps at ≈381ms!
- But which traps?

traps in practice: dd (3)

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

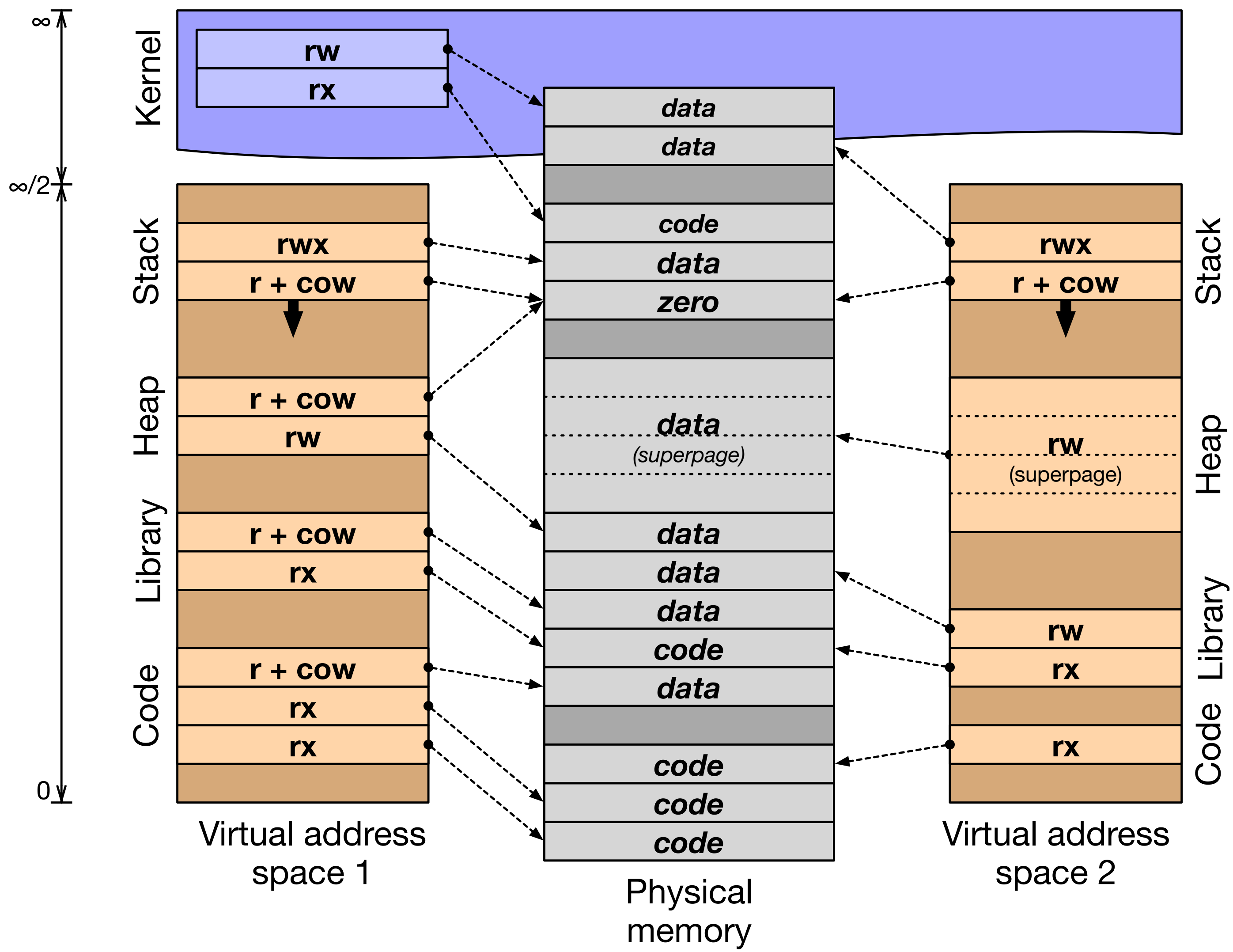
```
...
              kernel`PHYS_TO_VM_PAGE+0x1
              kernel`trap+0x4ea
              kernel`0xffffffff80e018e2
                5

              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
- Ironically (?), the kernel is demand filling pages with zeroes only to `copyout()` zeroes to it from `/dev/zero`

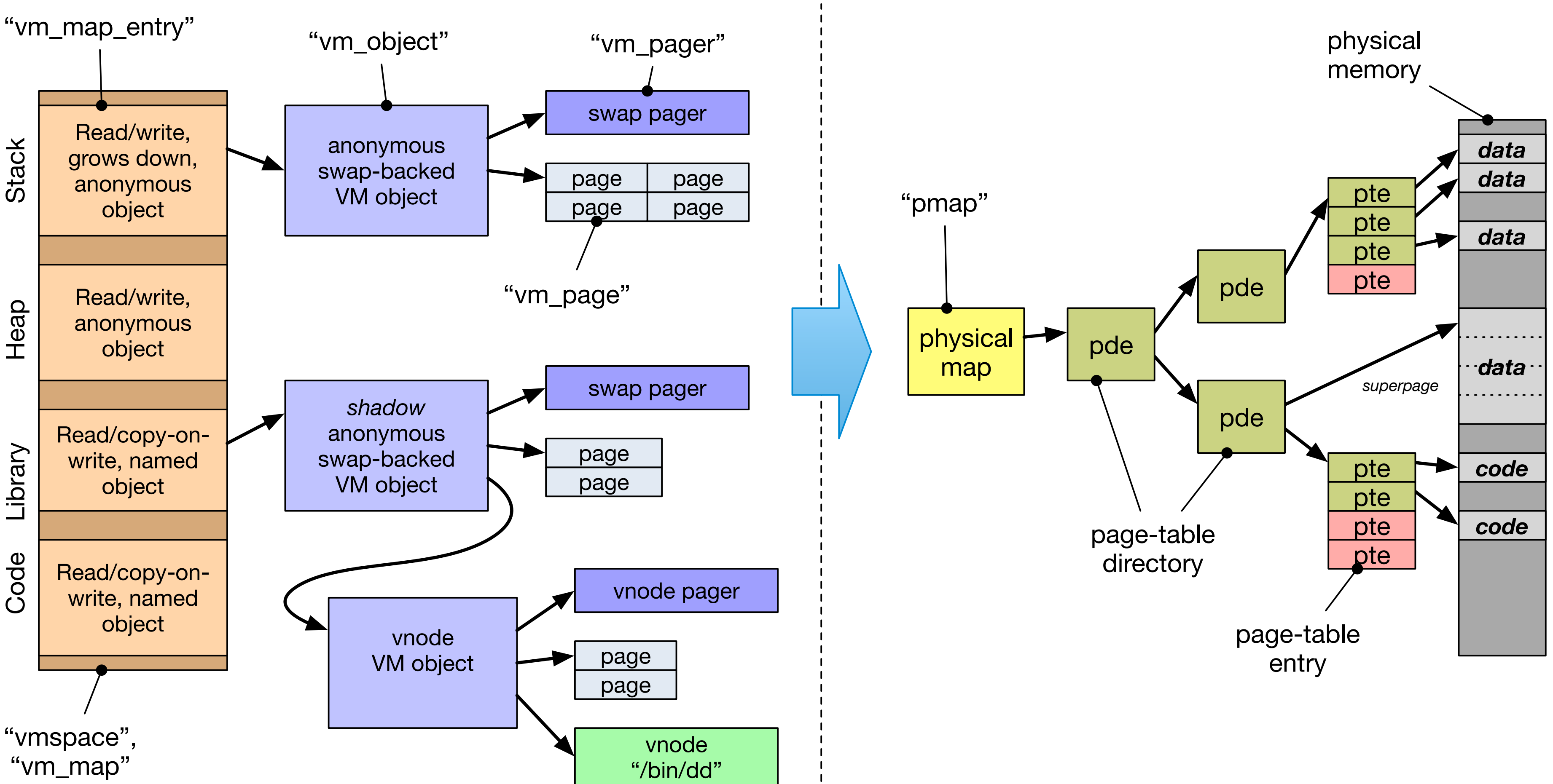
Virtual memory (quick, painful)



So: back to Virtual Memory (VM)

- The process model's isolation guarantees incur real expense
- The VM subsystem works quite hard to avoid expense
  - **Shared memory**, **copy-on-write**, **page flipping**
  - **Background page zeroing**
  - **Superpages** to improve TLB efficiency
- VM avoids work, but also manages memory footprint
  - Memory as a **cache** of secondary storage (files, swap)
  - **Demand paging** vs. **I/O clustering**
  - LRU / preemptive swapping to maintain free-page pool
  - Recently: **memory compression** and **deduplication**
- These ideas were known before Mach, but…
  - Acetta, et al. impose principled design, 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**

Kernel programmer view of VM



Machine-independent virtual memory (VM)

Machine-dependant physical map (PMAP)

Mach VM in other operating systems

- **Mach**: VM mappings, objects, pages, etc., are first-class kernel services exposed via system calls
- In two directly derived systems, quite different stories:

Mac OS X	Although not a microkernel, Mach's VM/IPC Application Programming Interfaces (APIs) are available to user programs, and widely used for IPC, debugging, …
FreeBSD	Mach VM is used as a foundation for UNIX APIs, but is available for use only as a Kernel Programming Interface (KPI)

- In FreeBSD, Mach is used:
  - To efficiently implement UNIX's `fork()` and `execve()`
  - For memory-management APIs – e.g., `mmap()` and `mprotect()`
  - By VM-optimised IPC – e.g., `pipe()` and `sendfile()`
  - 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

- Review ideas from the first lab report
- Lab 2: DTrace and IPC
  - Explore Inter-Process Communication (IPC) performance
  - Leads into Lab 3: microarchitectural counters to explain IPC performance
- McKusick, et al: Chapter 6 (*Memory Management*)
- Optional: Anderson, et al, on *Scheduler Activations*
  - (Exercise: where can we find scheduler-activation-based concurrent programming models today?)
- Ellard and Seltzer 2003