The Process Model (1)

L41 Lecture 3, Part 2: Processes In Practice

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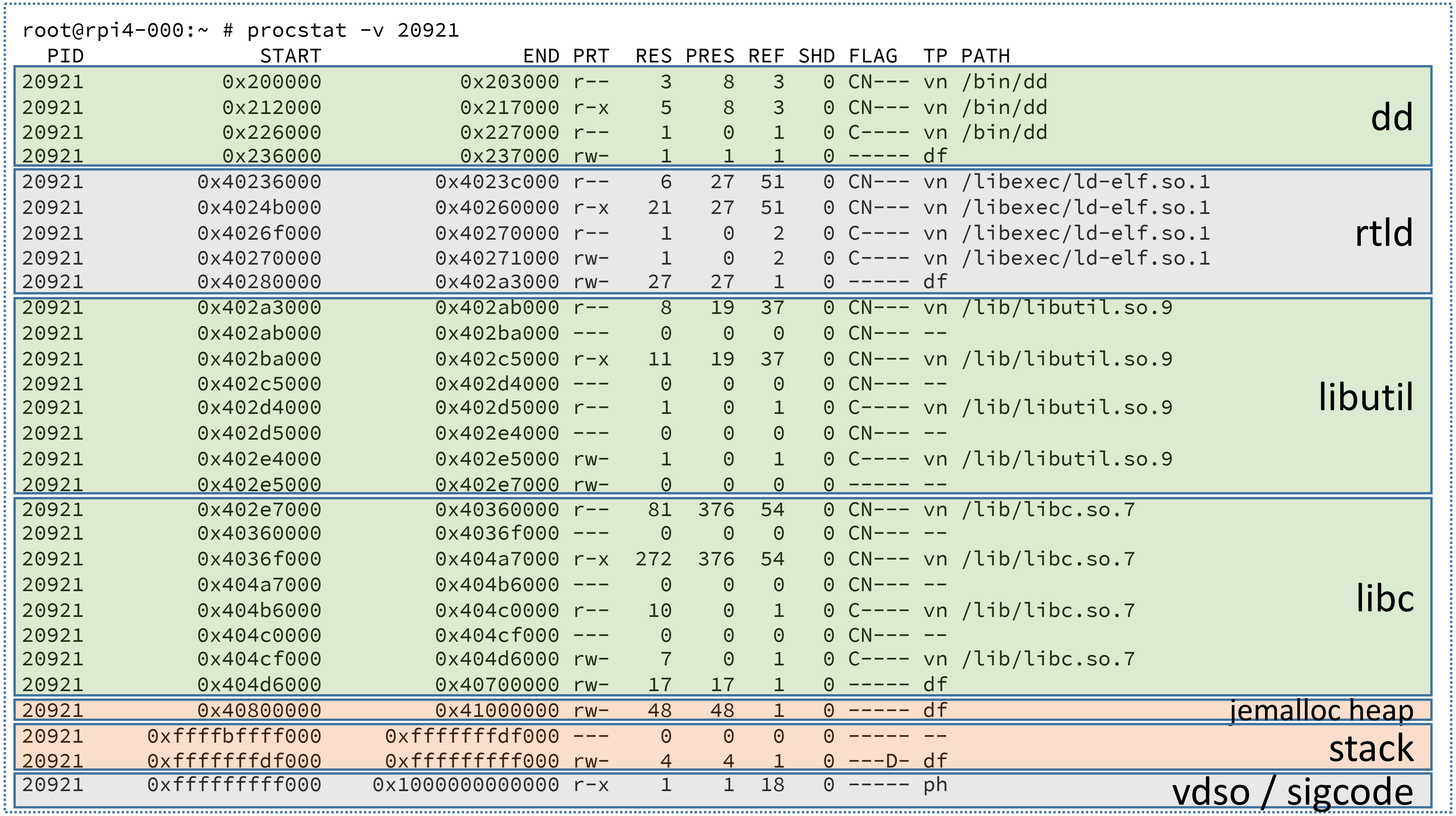
Process address space: dd(1)

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



```
root@rpi4-000:~ # procstat -v 20921
  PID              START                END PRT  RES PRES REF SHD FLAG  TP PATH
20921           0x200000           0x203000 r--    3    8   3   0 CN--- vn /bin/dd
20921           0x212000           0x217000 r-x    5    8   3   0 CN--- vn /bin/dd
20921           0x226000           0x227000 r--    1    0   1   0 C---- vn /bin/dd
20921           0x236000           0x237000 rw-    1    1   1   0 ----- df
20921         0x40236000         0x4023c000 r--    6   27  51   0 CN--- vn /libexec/ld-elf.so.1
20921         0x4024b000         0x40260000 r-x   21   27  51   0 CN--- vn /libexec/ld-elf.so.1
20921         0x4026f000         0x40270000 r--    1    0   2   0 C---- vn /libexec/ld-elf.so.1
20921         0x40270000         0x40271000 rw-    1    0   2   0 C---- vn /libexec/ld-elf.so.1
20921         0x40280000         0x402a3000 rw-   27   27   1   0 ----- df
20921         0x402a3000         0x402ab000 r--    8   19  37   0 CN--- vn /lib/libutil.so.9
20921         0x402ab000         0x402ba000 ---    0    0   0   0 CN--- --
20921         0x402ba000         0x402c5000 r-x   11   19  37   0 CN--- vn /lib/libutil.so.9
20921         0x402c5000         0x402d4000 ---    0    0   0   0 CN--- --
20921         0x402d4000         0x402d5000 r--    1    0   1   0 C---- vn /lib/libutil.so.9
20921         0x402d5000         0x402e4000 ---    0    0   0   0 CN--- --
20921         0x402e4000         0x402e5000 rw-    1    0   1   0 C---- vn /lib/libutil.so.9
20921         0x402e5000         0x402e7000 rw-    0    0   0   0 ----- --
20921         0x402e7000         0x40360000 r--   81  376  54   0 CN--- vn /lib/libc.so.7
20921         0x40360000         0x4036f000 ---    0    0   0   0 CN--- --
20921         0x4036f000         0x404a7000 r-x  272  376  54   0 CN--- vn /lib/libc.so.7
20921         0x404a7000         0x404b6000 ---    0    0   0   0 CN--- --
20921         0x404b6000         0x404c0000 r--   10    0   1   0 C---- vn /lib/libc.so.7
20921         0x404c0000         0x404cf000 ---    0    0   0   0 CN--- --
20921         0x404cf000         0x404d6000 rw-    7    0   1   0 C---- vn /lib/libc.so.7
20921         0x404d6000         0x40700000 rw-   17   17   1   0 ----- df
20921         0x40800000         0x41000000 rw-   48   48   1   0 ----- df
20921     0xffffbffff000     0xfffffffdf000 ---    0    0   0   0 ----- --
20921     0xfffffffdf000     0xfffffffff000 rw-    4    4   1   0 ---D- df
20921     0xfffffffff000    0x1000000000000 r-x    1    1  18   0 ----- ph
```

r: read

w: write

x: execute

C: Copy-on-write

D: Downward growth

N: Needs copy

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@rpi4-000:~ # objdump -p /bin/dd
/bin/dd:         file format elf64-littleaarch64
```

```
Program Header:
    PHDR off    0x0000000000000040 vaddr 0x0000000000200040 paddr 0x0000000000200040 align 2
         filesz 0x0000000000000268 memsz 0x0000000000000268 flags r--
  INTERP off    0x00000000000002a8 vaddr 0x00000000002002a8 paddr 0x00000000002002a8 align 2**0
         filesz 0x0000000000000015 memsz 0x0000000000000015 flags r--
    LOAD off    0x0000000000000000 vaddr 0x0000000000200000 paddr 0x0000000000200000 align 2**16
         filesz 0x0000000000002f3c memsz 0x0000000000002f3c flags r--
    LOAD off    0x0000000000002f3c vaddr 0x0000000000212f3c paddr 0x0000000000212f3c align 2**16
         filesz 0x00000000000034a4 memsz 0x00000000000034a4 flags r-x
    LOAD off    0x00000000000063e0 vaddr 0x00000000002263e0 paddr 0x00000000002263e0 align 2**16
         filesz 0x00000000000001a8 memsz 0x00000000000001a8 flags rw-
    LOAD off    0x0000000000006588 vaddr 0x0000000000236588 paddr 0x0000000000236588 align 2**16
         filesz 0x00000000000001e8 memsz 0x00000000000004d0 flags rw-
 DYNAMIC off    0x00000000000063f0 vaddr 0x00000000002263f0 paddr 0x00000000002263f0 align 2**3
         filesz 0x0000000000000180 memsz 0x0000000000000180 flags rw-
   RELRO off    0x00000000000063e0 vaddr 0x00000000002263e0 paddr 0x00000000002263e0 align 2**0
         filesz 0x00000000000001a8 memsz 0x00000000000001a8 flags r--
...
```

ELF interpreter (run-time linker)

Actual loaded content

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

Virtual memory (quick but painful primer)

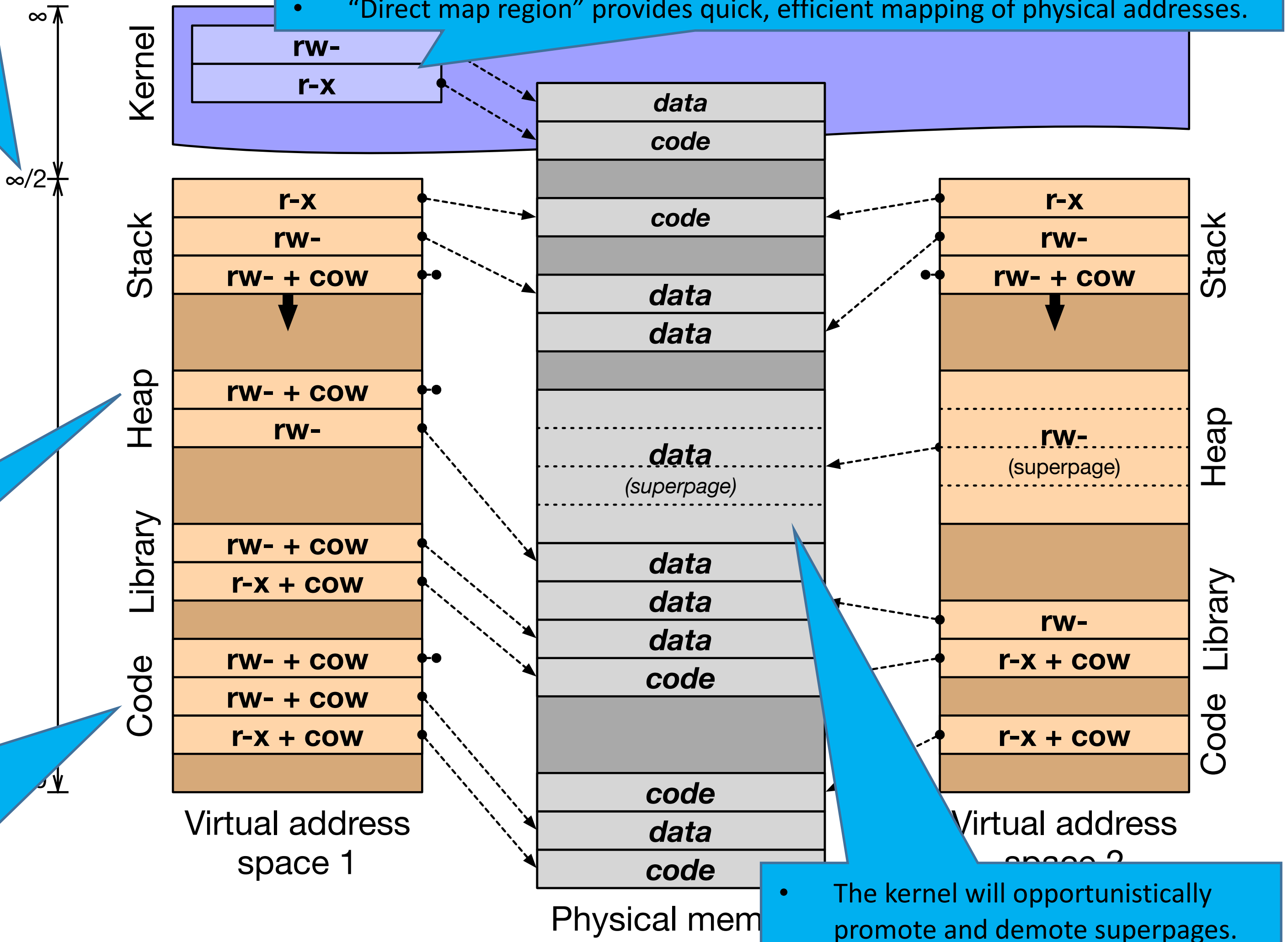
- A fixed partition between user and kernel address space makes checks quick and easy to implement.
- On some architectures (e.g., ARMv8-A), this point is configurable
- The kernel also needs substantial address space. It’s a squeeze in 32 bits, and fine with 64.

- Pages will be zero filled on demand – e.g., for BSS or heap memory

Memory mappings from program binaries include:

- Read-write (COW) demand-zeroed pages (BSS)
- Read-write (COW) mappings of data
- Read-execute mappings of program text (COW)

- Kernel address space is also managed using the MMU.
- Unified global kernel address space (with certain exceptions).
- Kernel mappings may “borrow” pages from userspace.
- “Direct map region” provides quick, efficient mapping of physical addresses.



- The kernel will opportunistically promote and demote superpages.
- This requires physical, and not just virtual, alignment and contiguity.

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
- The run-time linker also plays a role in debugging
  - Its internal state is inspected and understood by the debugger

Starting a binary (and dependencies)

```
root@rpi4-000:~ # ldd /bin/dd
/bin/dd:
        libutil.so.9 => /lib/libutil.so.9 (0x402a3000)
        libc.so.7 => /lib/libc.so.7 (0x402e7000)
```

- 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
  - `rtld` runs library and application binary 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@rpi4-000:~ # procstat -c 20921
  PID COMM             ARGS
20921 dd               dd if=/dev/zero of=/dev/null bs=1k
```

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

```
root@rpi4-000:~ # procstat -x 20921
  PID COMM             AUXV              VALUE
20921 dd               AT_PHDR           0x200040
20921 dd               AT_PHENT          56
20921 dd               AT_PHNUM          11
20921 dd               AT_PAGESZ         4096
20921 dd               AT_FLAGS          0
20921 dd               AT_ENTRY          0x213148
20921 dd               AT_BASE           0x40236000
20921 dd               AT_EHDRFLAGS      0
20921 dd               AT_EXECPATH       0xffffffffefd8
20921 dd               AT_OSRELDATE      1300138
20921 dd               AT_CANARY         0xffffffffef98
20921 dd               AT_CANARYLEN      64
20921 dd               AT_NCPUS          4
20921 dd               AT_PAGESIZES      0xffffffffef80
20921 dd               AT_PAGESIZESLEN   24
20921 dd               AT_TIMEKEEP       0xfffffffff1c0
20921 dd               AT_STACKPROT      NONEXECUTABLE
20921 dd               AT_HWCAP          0x83
20921 dd               AT_HWCAP2         0
20921 dd               AT_BSDFLAGS       0x1
20921 dd               AT_ARGC           4
20921 dd               AT_ARGV           0xffffffffea68
20921 dd               AT_ENVC           24
20921 dd               AT_ENVV           0xffffffffea90
20921 dd               AT_PS_STRINGS     0xffffffffefe0
```

Address of binary's ELF program header

Entry address for binary

Base address of binary (or rtld if used)

Command-line arguments and environment above stack

Wrapping up

- In this lecture, we have talked about:
  - The basics and history of the process model
  - A few gory implementation details

- Our next lecture, also on the process model, will explore:
  - Traps and system calls
  - Ideas about isolation, security, and reliability
  - More gory details of the VM system

- Readings for the next lecture:
  - Paper - Navarro, et al. 2002. (**L41 only**)