L41 - Lecture 3: The Process Model (1)

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Reminder: last time

1. DTrace
2. The probe effect
3. The kernel source
4. A little on kernel dynamics

I showed you dramatic example of the *probe effect*: 80% overhead for some stack tracing for `malloc()` when running `dd`.

Gosh, that is **really big**, even for the probe effect.

Last time: Probe effect example: dd system time

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

```
fbt::malloc:entry { @traces[stack()] = count(); }
```

```
x no-dtrace
+ dtrace
+--------------------------------------------------------------------------------+
|                                                                            +   |
|     x                                                                      +   |
|     x                                                                      +   |
|     x                                                                      +   |
|     x                                                                      +   |
|x    x x                                                                   +   |
|x    x x                                                              +  + + +|
|  |__A_|                                                                 |_A_||
+--------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  10         0.155         0.187         0.179        0.1757   0.011333824
+  10          0.47         0.503         0.495        0.4925  0.0087717982
Difference at 95.0% confidence
        0.3168 +/- 0.00952196
        180.307% +/- 5.41944%
        (Student's t, pooled s = 0.0101341)
```

So we did a little investigating...

- Number of calls to `malloc` per run: 3

- That's silly overhead for three traces, even with traps for each `malloc`, DIF execution, walking the stack, writing to a buffer, etc.

- Discovered that FreeBSD/arm DTrace `stack()` cost 10M cycles **per frame on the stack**! Doh!
- On all other architectures, tracing stacks is really cheap
- On ARM, you must use EABI unwind tables
  - ... and that look up unwind state for every return address
  - ... which turns out to never have been a fast path before DTrace
  - ... which meant it acquired locks and did linear walks

- Tried module-free kernel on BeagleBone Black
- Now it is basically free (no statistically significant difference)
- TODO: fix module lookup in FreeBSD/ARM for next year

Take two: Probe effect example: `dd` system time

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

```
fbt::malloc:entry { @traces[stack()] = count(); }
```

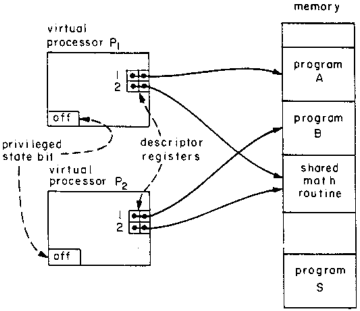
```
x no-dtrace
+ dtrace
* dtrace-better
+------------------------------------------------------------------------------+
|     x  *                                                                 +  |
|     x* *                                                                 +  |
|x   *x*x*                                                                +  |
|x * *x*x*                                                           +  + + +|
|  |_|AA||                                                              |_A_||
+------------------------------------------------------------------------------+
    N           Min           Max        Median           Avg        Stddev
x  10         0.155         0.187         0.179        0.1757   0.011333824
+  10          0.47         0.503         0.495        0.4925  0.0087717982
Difference at 95.0% confidence
0.3168 +/- 0.00952196
180.307% +/- 5.41944%
(Student's t, pooled s = 0.0101341)
*  10         0.165         0.191         0.183        0.1822  0.0088794394
No difference proven at 95.0% confidence
```

I will also need a different example of the probe effect next year.
Turns out, `stack` from every *lock acquire* will work just fine.
Tracing 57,446 mutex acquisitions = $\approx 3.72\times$ overhead – perfect.

This time: the process model

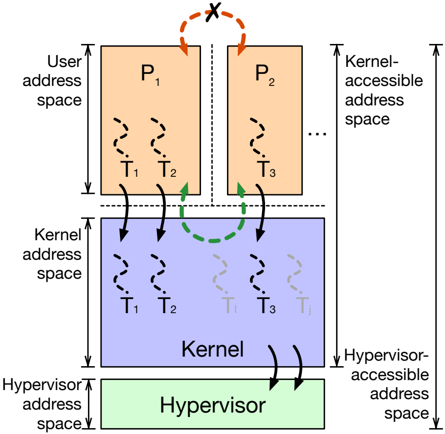
1. The process model and its evolution
2. Brutal pre-introduction to virtual memory
3. Where do programs come from?
4. Traps and system calls
5. Reading for next time

The process model: 1970s foundations



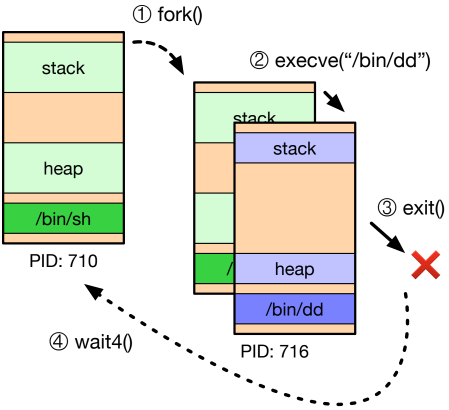
- Saltzer and Schroeder, *The Protection of Information in Computer Systems*, SOSP'73, October 1973. (CACM 1974)
- *Multics* process model
  - 'Program in execution'
  - *Process isolation* bridged by *controlled communication* via supervisor (kernel)
- Hardware foundations
  - Supervisor mode
  - Memory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

The process model: today



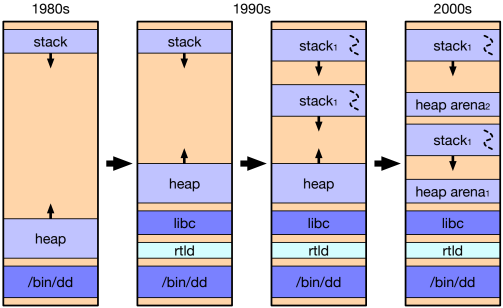
- 'Program in execution'
  - Process ≈ address space
  - 'Threads' execute code
  - Kernel interaction via *traps*: system calls, page faults, ...
  - Unit of resource accounting: open files, credentials, memory, scheduling, ...
- Hardware foundations
  - Rings control MMU, I/O, etc.
  - MMU virtual addressing
  - Trap mechanism
- Details vary only a little over {UNIX, Linux, Windows, ...}

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

Process model evolution



- 1980s: Code, heap, and stack
- 1990s: Dynamic linking, multithreading
- 2000s: Scalable memory allocators implement multiple *arenas* (e.g., `jemalloc`)
- Coevolution with virtual memory research (Acetta, et al: *Mach* microkernel (1986); Navarro, et al *Superpages* (2002))

Process address space: dd

- 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.
  734 0x20038000 0x20039000 rw-    1    0   1   0 C--- vn /libexec/ld-elf.
  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
```

Program binary,
Run-time linker,
Shared library,
BSS, Heap, Stack

`r`: read
`w`: write
`x`: execute

`C`: Copy-on-write
`D`: Downward growth
`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 headers using `objdump -p`:

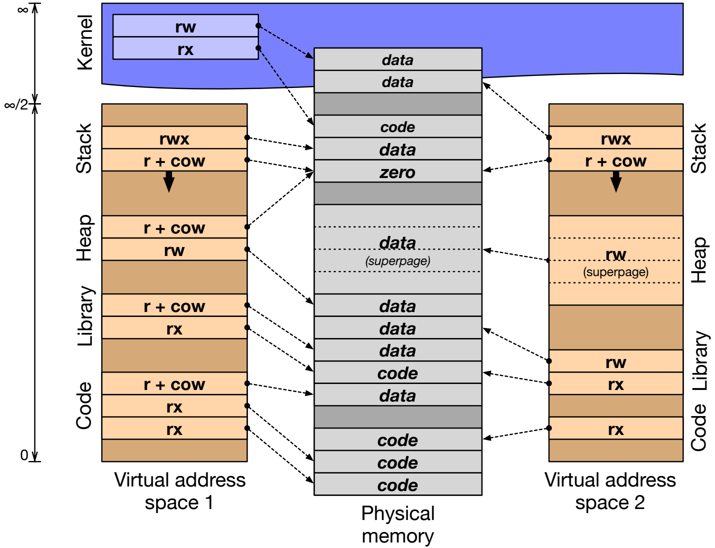
```
root@beaglebone:~ # objdump -p /bin/dd
/bin/dd:     file format elf32-littlearm

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)

- Memory Management Unit (MMU)
  - Control available only to the supervisor
  - Mediates/transforms memory access (instruction fetch, load, store)
  - Trap fired on failure (e.g., permissions) to be handled by software
- Page tables
  - Memory is laid out in *pages* (4K)
  - OS-managed *Page tables* map *virtual pages* into *physical frames*
  - Access permissions, page attributes (e.g., caching)
  - Variable-size pages (now) supported
- The Translation Look-aside Buffer (TLB)
  - Hardware cache of entries – avoid walking tables
  - Content Addressable Memory (CAM); 48? 1024? entries
  - TLB entry *tagging*: entries *global* or for a specific process
  - Software- vs. hardware-managed
- Virtual address spaces
  - Isolation vs. sharing
  - BSS, *Copy-on-Write*, *Superpages*
- Hypervisors and I/O MMUs

Virtual memory (quick but painful primer) (cont)



Role of the run-time linker (`rtld`)

- Static linking: program and libraries linked into a single binary
- Dynamic linking: binary contains only the application, no libraries
  - Shared libraries conserve memory by avoiding code duplication
  - The run-time linker (`rtld`) loads and links libraries
  - Program binaries contain a list of their *library dependencies*
  - Also used for plug-ins via `dlopen()`, `dlsym()`
- *Loading*, *relocating*, and *run-time linking*

```
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 an ELF segment
  - `execve` maps `rtld` **and** the application into memory
  - The kernel starts userspace execution in `rtld`
  - `rtld` loads and links dynamic libraries, runs constructors
  - `rtld` calls `main()`
- Slightly complicating: *lazy binding*

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, reliably, securely
  - RISC: $pc saved, $epc installed, control coprocessor (MMU, ...) made available, kernel memory access enabled, reserved exception registers in ABI. Software must save other state (e.g., registers)
  - CISC: All that and: context saved to in-memory trap frame
- NB: User context switch = trap to kernel, restore a different context

For next time

- We will continue with system calls and traps
- Then more on virtual memory
- Threading models: the great debate

- McKusick, et al: Chapter 6 (*Memory Management*)
- Optional: Anderson, et al, on *Scheduler Activations*