The Hardware/Software Interface

Processes II, Virtual Memory I

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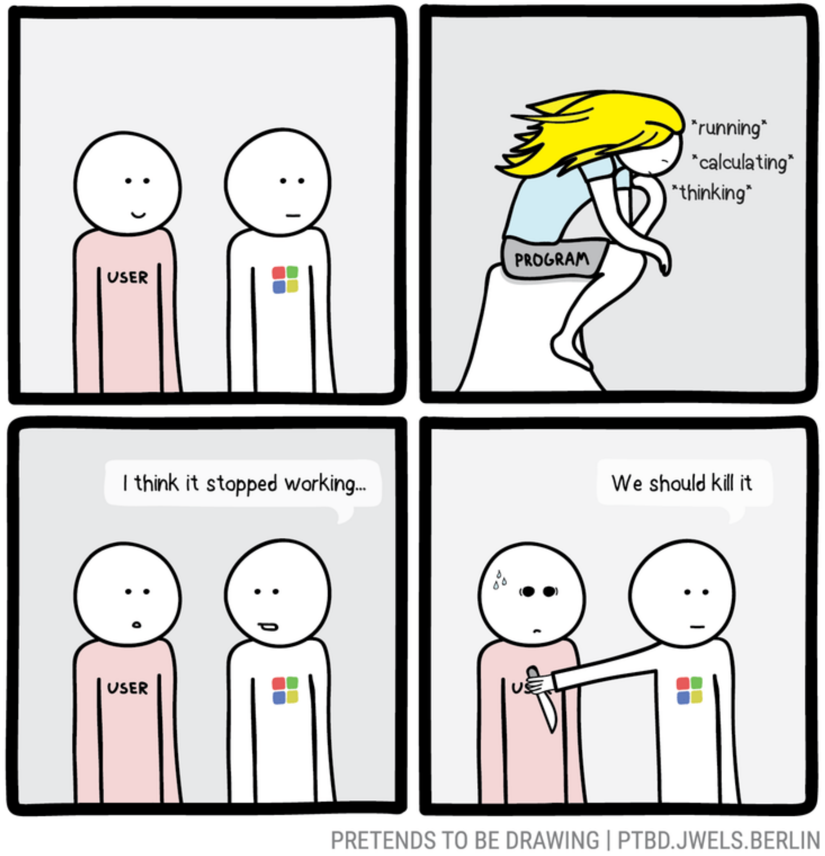

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Relevant Course Information

- HW22 due tonight, HW23 due Monday

- Lab 4 due tonight, submissions close Monday; Lab 5 due 12/4

- Final exam: Wednesday, 12/10 @ 12:30 pm
  - Final review section on 12/4, final review session (hybrid) on 12/5
  - *Cumulative*: Questions will be marked “M” (pre-midterm) or “F” (post-midterm)
    - Scores on the “M” questions will be used for midterm clobber policy
  - TWO double-sided handwritten 8.5×11” cheat sheets
    - Recommended that you reuse or remake your midterm cheat sheet
  - We will distribute copies of the Final Reference Sheet on Monday

Lecture Outline (1/3)

- **`fork` (continued) and `exec*`**
- Ending a Process
- Virtual Memory Introduction

fork Example

```
void fork1() {
  int x = 1;
  pid_t fork_ret = fork();
  if (fork_ret == 0)
    printf("Child has x = %d\n", ++x);
  else
    printf("Parent has x = %d\n", --x);
  printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

- Notes/Reminders:
  - Both processes continue/start execution after `fork`
    - Can't predict execution order between parent and child
  - Both processes start with `x = 1`
    - However, subsequent changes to `x` are independent
  - Shared open files: `stdout` is the same in both parent and child

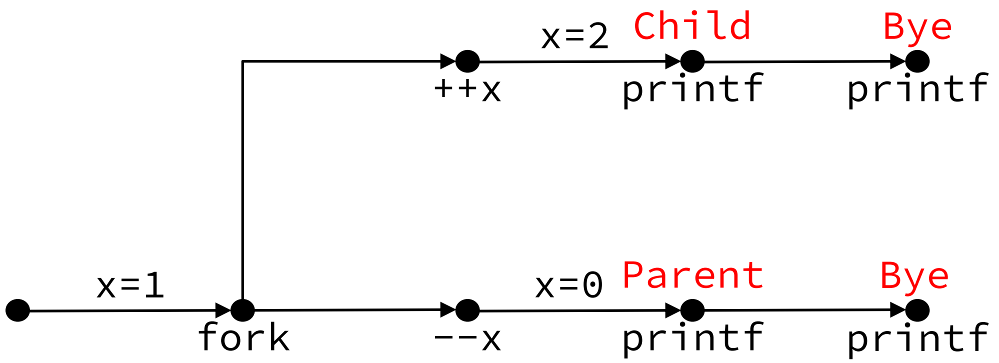
Modeling Concurrency with Process Graphs

- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program
  - Each vertex indicates the execution of a notable statement
  - Edges (a → b) indicate sequential ordering of statements within a process
    - *i.e.*, a must happen before b
  - Vertices and edges can be labeled with important notes
    - *e.g.*, updated variable values on edges, program output on `printf` vertices
  - Each graph begins with a vertex with no in-edges

- Any *topological sort* of the graph corresponds to a feasible total ordering
  - An ordering of nodes that contains every node, and only follows edges (lines between nodes) in the direction of the arrows

fork Example: Process Graph

```
void fork1() {
  int x = 1;
  pid_t fork_ret = fork();
  if (fork_ret == 0)
    printf("Child has x = %d\n", ++x);
  else
    printf("Parent has x = %d\n", --x);
  printf("Bye from process %d with x = %d\n", getpid(), x);
}
```



Polling Questions (1/3)

- Are the following sequences of outputs possible?

```
void nestedfork() {
  printf("L0\n");
  if (fork() == 0) {
    printf("L1\n");
    if (fork() == 0) {
      printf("L2\n");
    }
  }
  printf("Bye\n");
}
```

Seq 1:	Seq 2:
L0	L0
L1	Bye
Bye	L1
Bye	L2
Bye	Bye
L2	Bye

	Seq 1	Seq 2
A.	No	No
B.	No	Yes
C.	Yes	No
D.	Yes	Yes
E.	We're lost...	

Fork-Exec

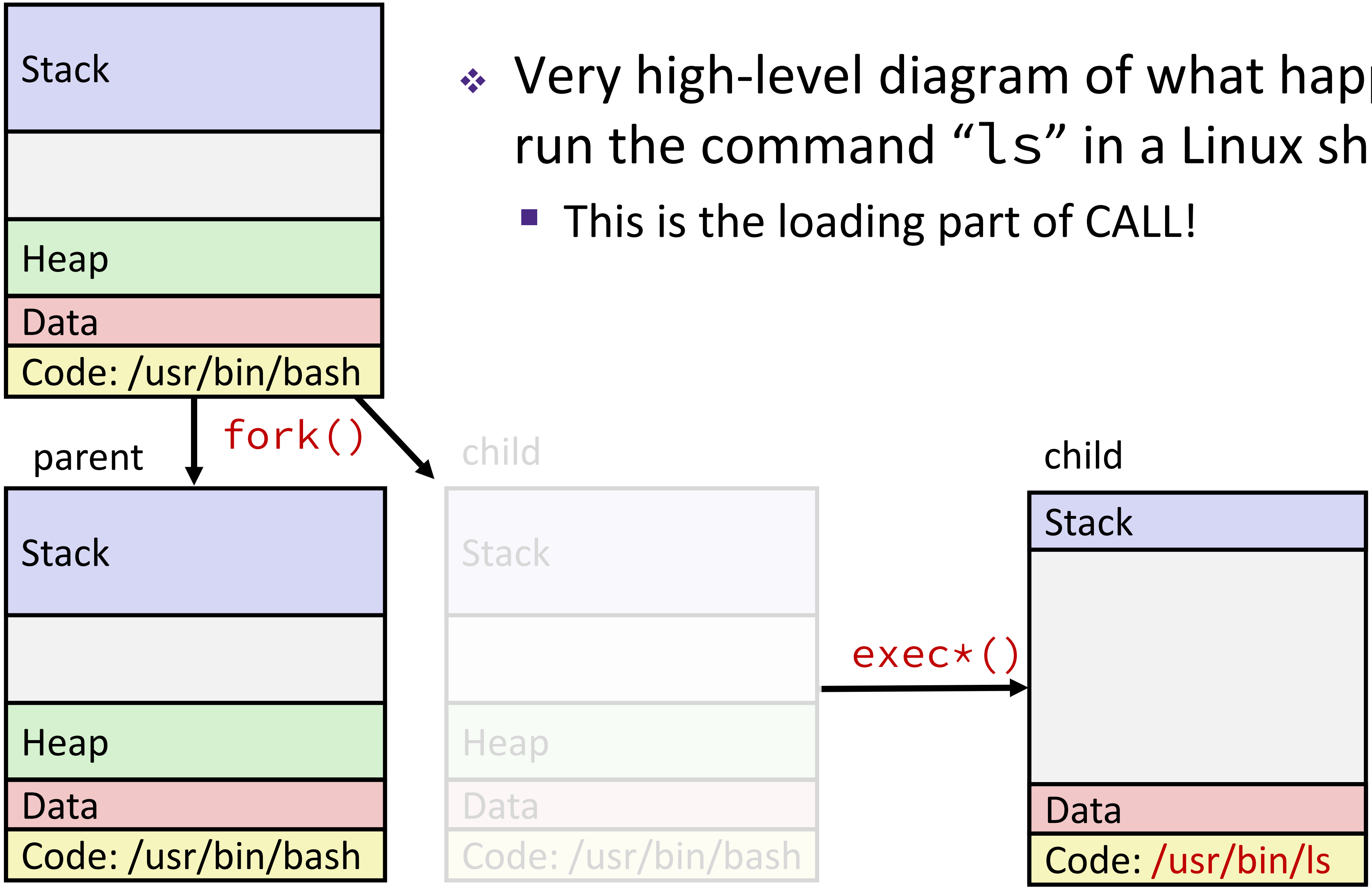
Note: The return values of `fork` and `exec*` should be checked for errors

- fork-exec model:
  - `fork()` creates a copy of the current process
  - `exec*()` replaces the current process' code and address space with the code for a different program
    - Whole family of `exec` calls – see `exec(3)` and `execve(2)`

```
// Example arguments: path="/usr/bin/ls",
//     argv[0]="/usr/bin/ls", argv[1]="-ahl", argv[2]=NULL
void fork_exec(char* path, char* argv[]) {
  pid_t fork_ret = fork();
  if (fork_ret != 0) {
    printf("Parent: created a child %d\n", fork_ret);
  } else {
    printf("Child: about to exec a new program\n");
    execv(path, argv);
  }
  printf("This line printed by parent only!\n");
}
```

Exec-ing a New Program

- Very high-level diagram of what happens when you run the command "`ls`" in a Linux shell
  - This is the loading part of CALL!



Lecture Outline (2/3)

- `fork` (continued) and `exec*`
- **Ending a Process**
- Virtual Memory Introduction

Ending a Process (Review)

- **`void exit(int status)`**
  - Explicitly exits a process
    - Status code: 0 is used for a normal exit, nonzero for abnormal exit
- The `return` statement from `main()` also ends a process in C
  - The return value is the status code
- An *abort* from an exception handler

Zombies! 🧟‍♀️ 🧟‍♂️ (Review)

- A terminated process still consumes system resources
  - Various tables maintained by OS
  - Called a "zombie" (a living corpse, half alive and half dead)
- *Reaping* is performed by parent on terminated child
  - Parent is given exit status information and kernel then deletes zombie child process
  - In long-running processes (*e.g.*, shells, servers) we need *explicit* reaping
- If parent terminates without reaping a child, then the orphaned child will be reaped by `init` process (PID 1)
  - **Note:** on recent Linux systems, `init` has been renamed `systemd`

`wait`: Synchronizing with Children

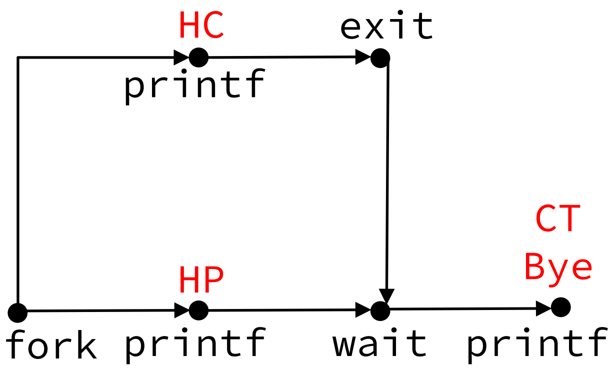
- **`int wait(int* child_status)`**
  - Suspends current process (*i.e.*, the parent) until one of its children terminates
  - Return value is the PID of the child process that terminated
    - *On successful return, the child process is reaped*
  - If `child_status != NULL`, then the `*child_status` value indicates why the child process terminated
    - Special macros for interpreting this status – see **`wait(2)`**

- **Note:** If parent process has multiple children, `wait` will return when *any* of the children terminates
  - `waitpid` can be used to wait on a specific child process

Example: wait

```
void fork_wait() {
  int child_status;

  if (fork() == 0) {
    printf("HC: hello from child\n");
    exit(0);
  } else {
    printf("HP: hello from parent\n");
    wait(&child_status);
    printf("CT: child has terminated\n");
  }
  printf("Bye\n");
}
```



Feasible output:	Infeasible output:
HC	HP
HP	CT
CT	Bye
Bye	~~HC~~

Example: Zombie

- Parent in infinite loop, terminated child

```
void fork7() {
  if (fork() == 0) {
    /* Child */
    printf("Terminating Child, PID = %d\n",
           getpid());
    exit(0);
  } else {
    /* Parent */
    printf("Running Parent, PID = %d\n",
           getpid());
    while (1);  /* Infinite loop */
  }
}
```

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

  - ps shows child process as "defunct"
  - Terminating parent allows child to be reaped by `init` (both are now gone)

Example: Non-Terminating Child

- Child in infinite loop, terminated parent

```
void fork8() {
  if (fork() == 0) {
    /* Child */
    printf("Running Child, PID = %d\n",
           getpid());
    while (1);  /* Infinite loop */
  } else {
    /* Parent */
    printf("Terminating Parent, PID = %d\n",
           getpid());
    exit(0);
  }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

  - Child process still active even though parent has terminated
  - Must terminate child explicitly, or else will keep running indefinitely

Polling Questions (2/3)

- For the following scenarios, what will the outcome be for a child process that executes `exit(0)`:

Scenario	Outcome for child		
Parent is still executing:	Alive	Reaped	Zombie
Parent has called `wait()`:	Alive	Reaped	Zombie
Parent has terminated:	Alive	Reaped	Zombie

Processes Demos (If Time)

- How many processes are running on my computer right now?

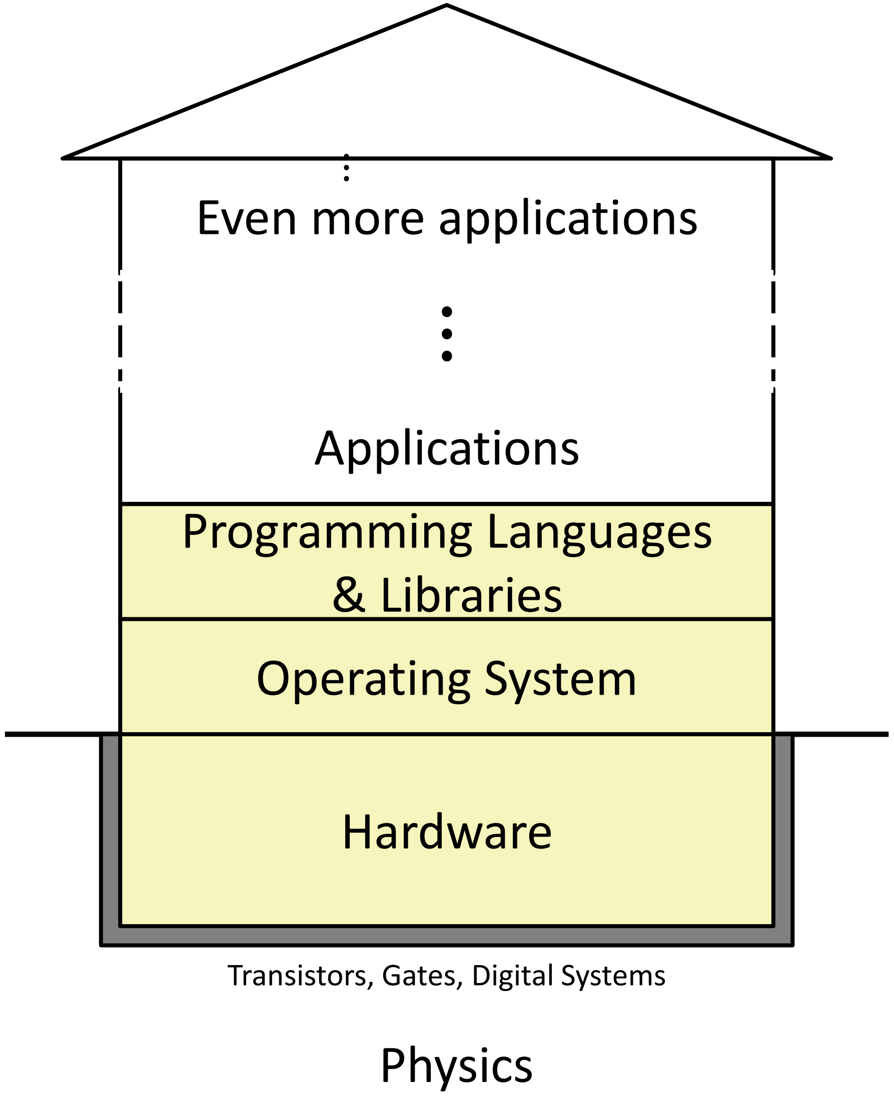
- In Linux, the `ps` utility gives a snapshot of currently-running processes and `pstree` formats these as a tree
  - Can run "`man ps`" and "`man pstree`" for more info
  - Let's see a simple `pstree`
  - Let's check `attu` for some 351 zombie processes

Lecture Outline (3/3)

- `fork` (continued) and `exec*`
- Ending a Process
- **Virtual Memory Introduction**

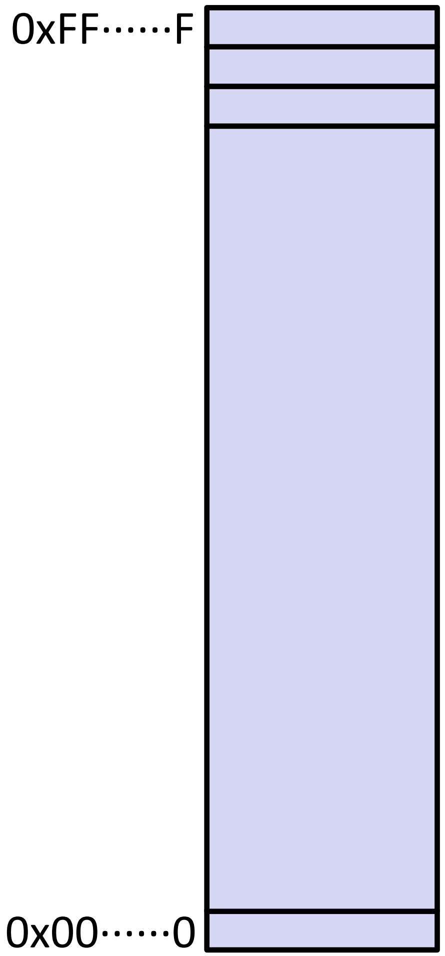
House of Computing Check-in

- Topic Group 3: **Scale & Coherence**
  - Caches, Memory Allocation, Processes, **Virtual Memory**
- How do we maintain logical consistency in the face of more data and more processes?
  - How do we support control flow both within many processes and things external to the computer?
  - *How do we support data access, including dynamic requests, across multiple processes?*



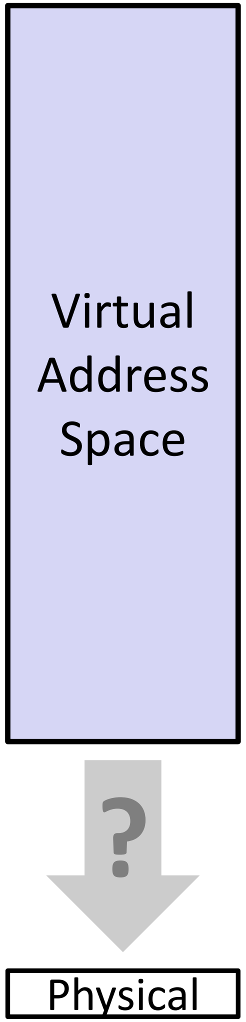
Our View of Memory So Far… is Virtual!

- Programs refer to virtual memory addresses
  - *Private, virtual* address space (array of bytes) for each process
  - *e.g.*, `movq (%rdi),%rax  # virtual addresses!`
- Allocation managed by compiler and run-time system
  - *i.e.*, figure out where different program objects should be stored
- However, there seem to be some potential issues with this setup…



Problem 1: How Does Everything Fit?

- *Virtual address space* is set of $\mathrm{N} = 2^n$ virtual addresses
  - *e.g.*, 64-bit virtual addresses can address several exabytes (> 18×10^{18} bytes)
- *Physical address space* is set of $\mathrm{M} = 2^m$ physical addresses
  - *e.g.*, 8 GiB main memory offers 8.6×10^{9} bytes
  - Note: Not to scale – physical memory would be much smaller than this period: .
- 1 virtual address space per process, with many processes…



Problem 2: Memory Management

- Multiple processes:
  - Process 1
  - Process 2
  - Process 3

    . . .
  - Process n

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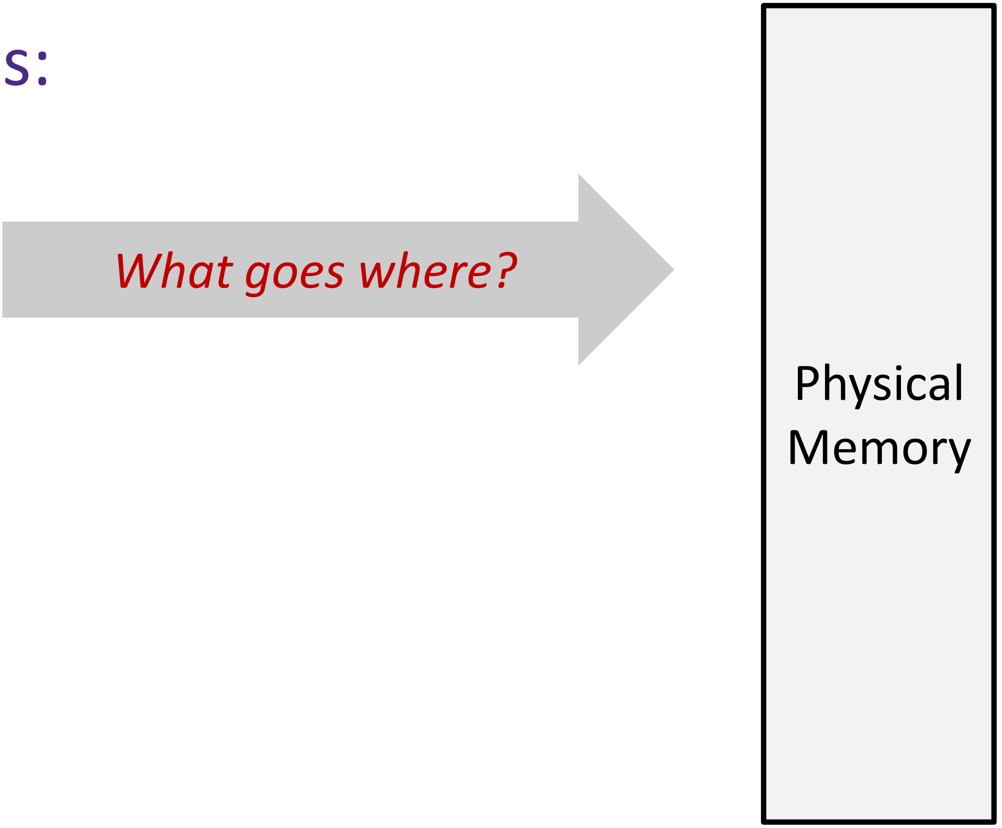
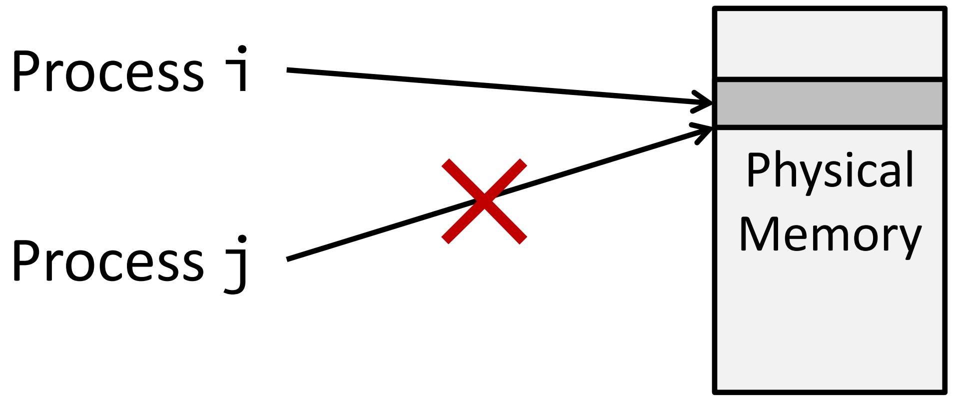
- Each process has:
  - Stack
  - Heap
  - `.text`
  - `.data`

    . . .

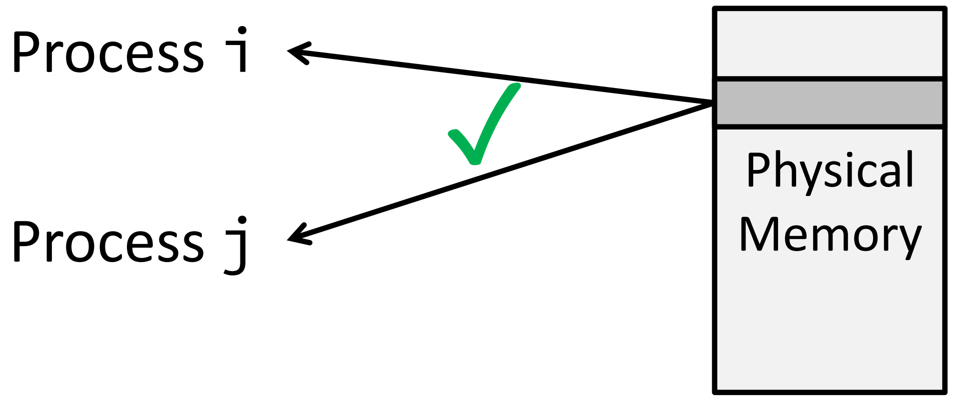


Problem 3: Protection and Sharing

- Protection:



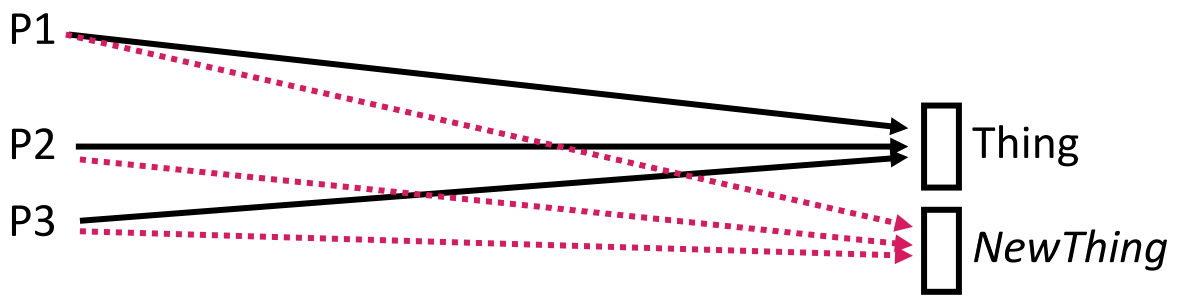
- Sharing:



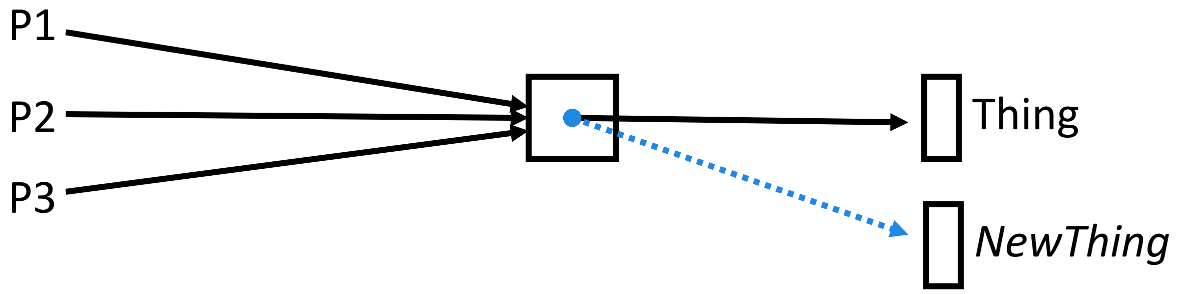
The Solution

- "Any problem in computer science can be solved by adding another level of **indirection**." – *David Wheeler, inventor of the subroutine*

- Without Indirection:



- With Indirection:



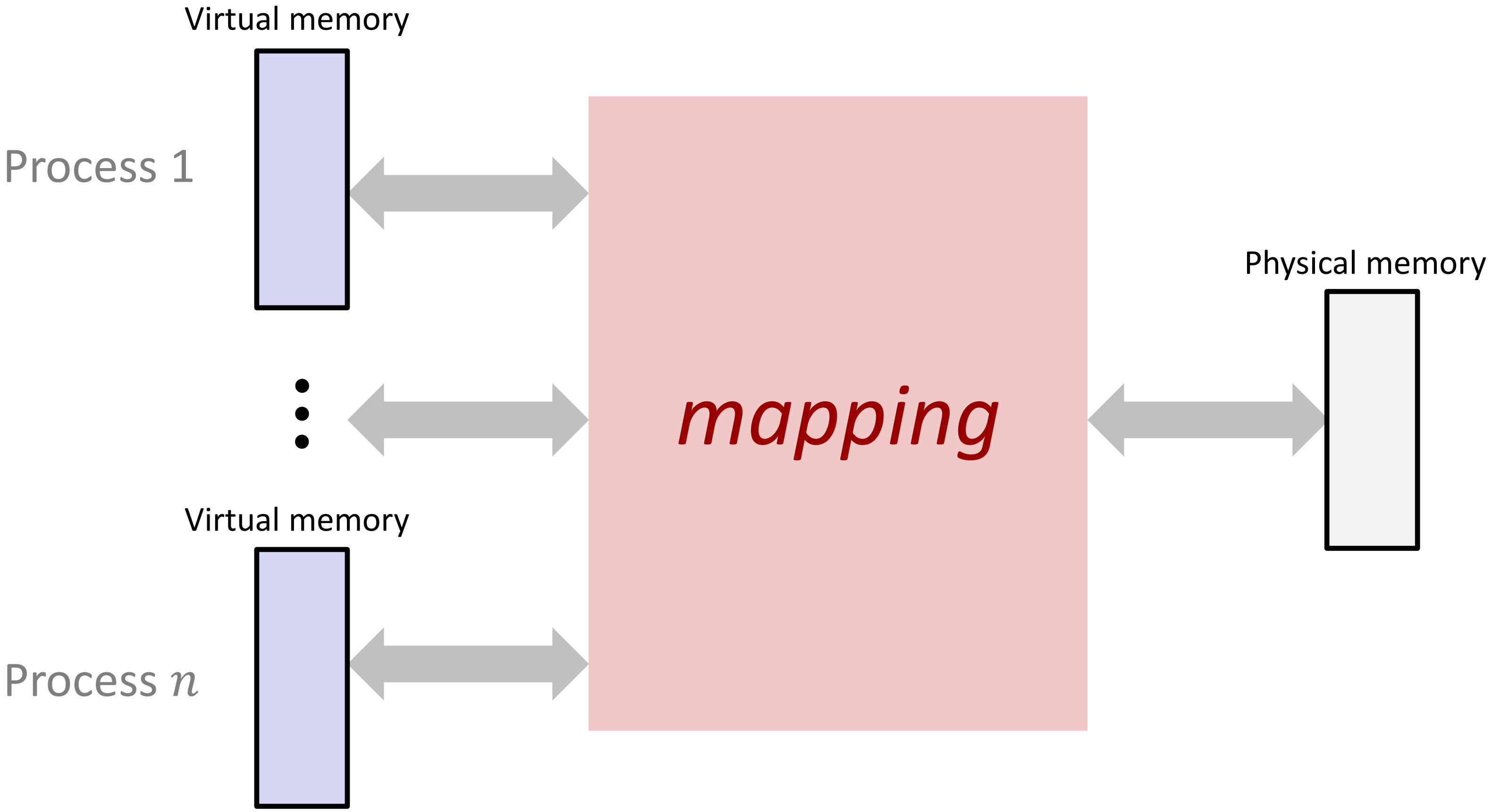
What if I want to move Thing?

Indirection

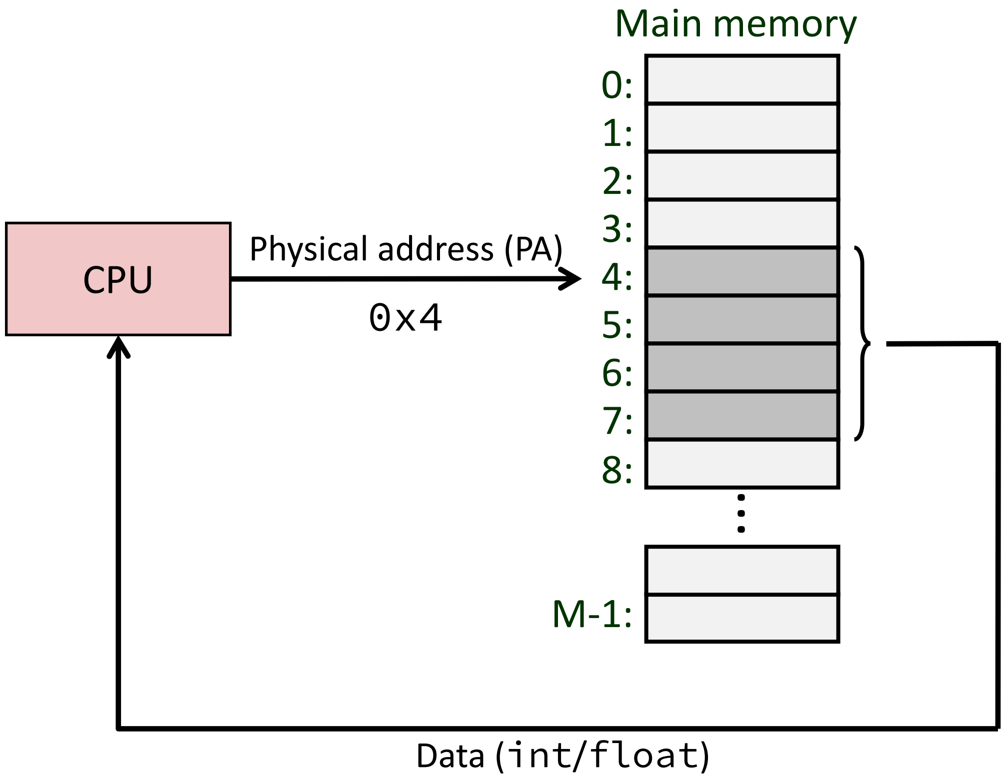
- The ability to reference something using a name, reference, or container instead of the value itself. A **flexible mapping** between a name and a thing allows **changing the thing without notifying holders of the name**.
  - Adds some work (now we must look up 2 things instead of 1)
  - But don't have to track all uses of name/address (single source!)
- Examples:
  - **Domain Name Service (DNS):** Translation from name to IP address
  - **Call centers:** Route calls to available operators, etc.
  - **Dynamic Host Configuration Protocol (DHCP):** Local network address assignment

Indirection in Virtual Memory

- Each process gets its own private virtual address space
  - Solves the previous problems!

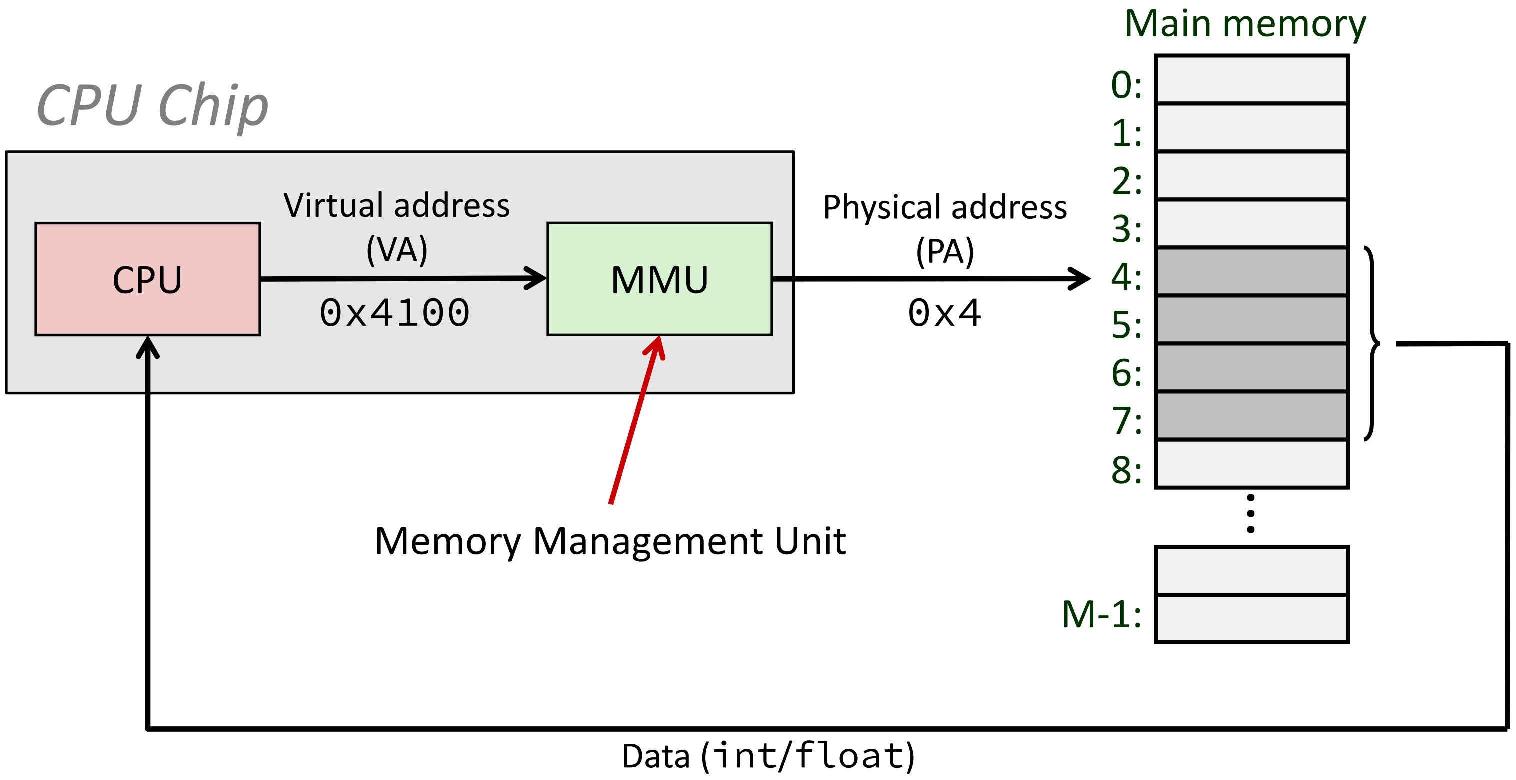


A System Using Physical Addressing



- Used in "simple" systems with (usually) just one process:
  - Embedded microcontrollers in devices like cars, elevators, and digital picture frames

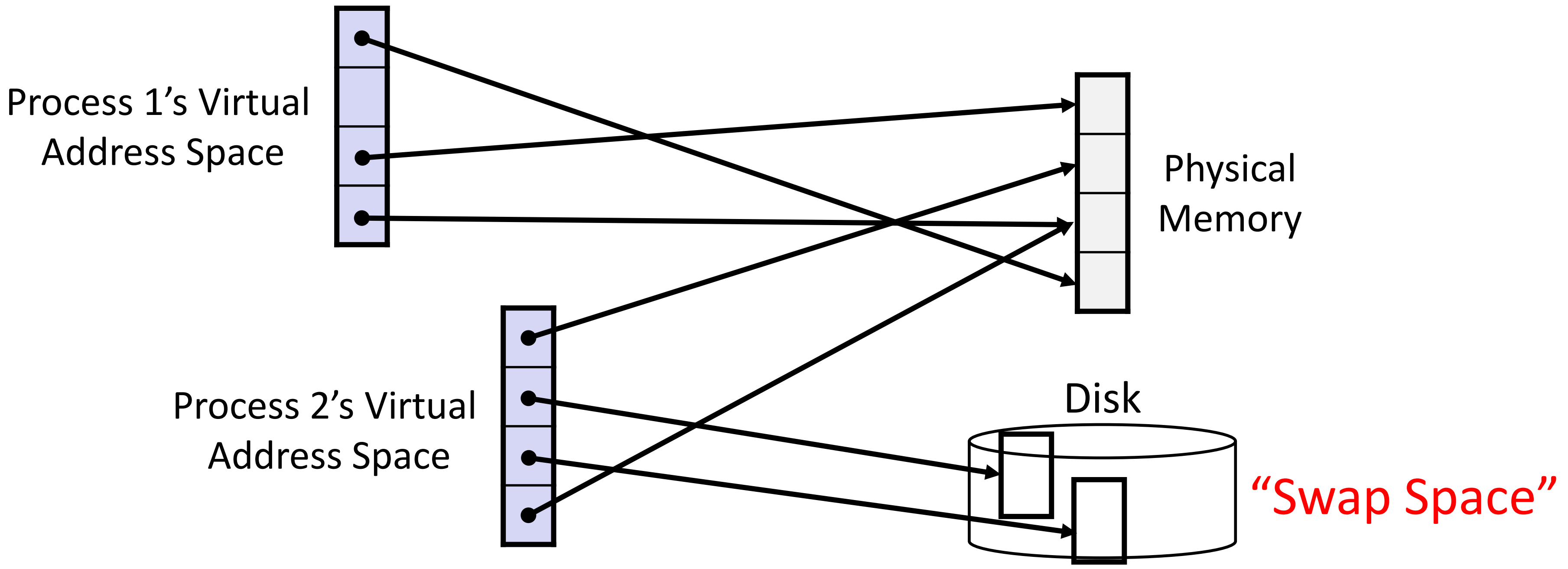
A System Using Virtual Addressing



- Physical addresses are *completely invisible to programs*
  - Used in all modern desktops, laptops, servers, smartphones…
  - One of the great ideas in computer science

Address Mapping

- A *virtual address (VA)* can map to (1) physical memory, (2) the *swap space* on disk, or (3) nothing (*i.e.*, unused VA)
  - Virtual addresses from *different* processes may map to same location
  - Every byte in main memory has 1 *physical address (PA)* and 0+ VAs



Polling Questions (3/3)

- On a 64-bit machine currently running 8 processes, how much virtual memory is currently available?

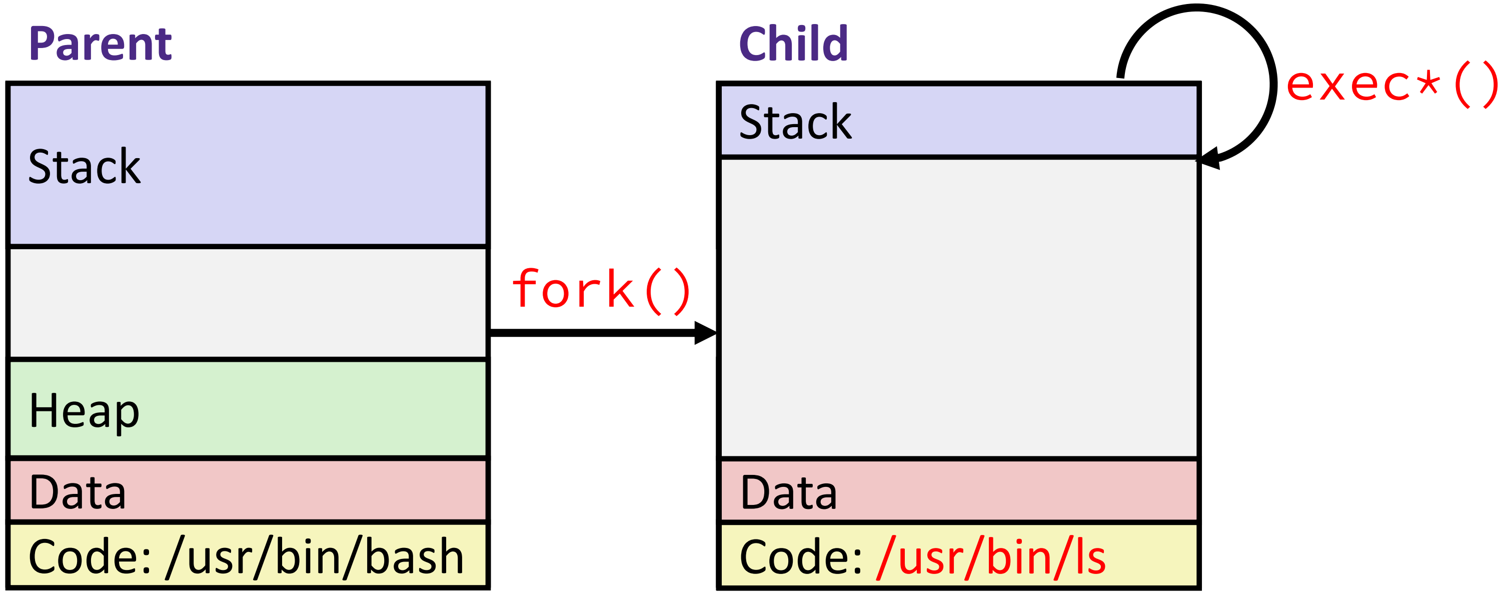
- True or False: A 32-bit machine with 8 GiB of RAM installed would never use all of it (in theory).

Why Virtual Memory (VM)?

- Efficient use of limited main memory (RAM)
  - Use RAM as a cache for the parts of a virtual address space
    - Some non-cached parts stored on disk, some (unallocated) non-cached parts stored nowhere
  - Keep only active areas of virtual address space in memory
    - Transfer data back and forth as needed
- Simplifies memory management for programmers
  - Each process "gets" the same full, private linear address space
- Isolates address spaces (*i.e.*, provides protection)
  - A process can't interfere with another's memory – *different address spaces*
  - User process cannot access privileged information – implements memory permissions (*i.e.*, different memory layout segments)

Summary (1/4)

- The ***fork-exec model***
  - Every process is assigned a unique ***process ID*** (pid)
  - Every process has a parent process except for `init/system` (pid 1)
  - `fork()` returns 0 to child, child's PID to parent
  - `exec()` replaces the current process' code and address space with the code for a different program



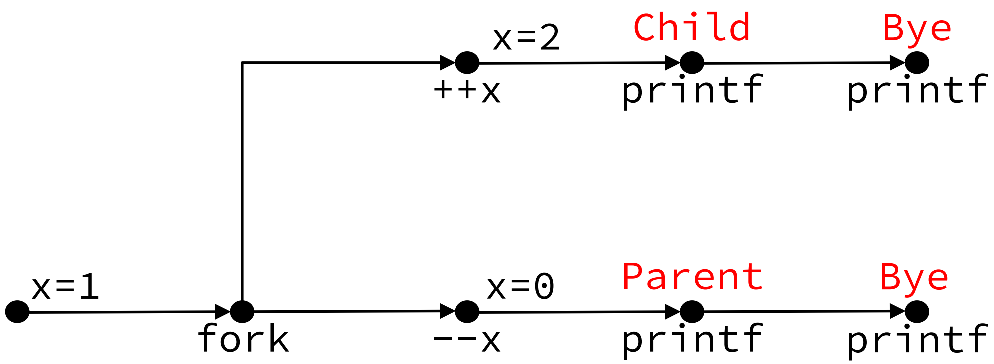
Summary (2/4)

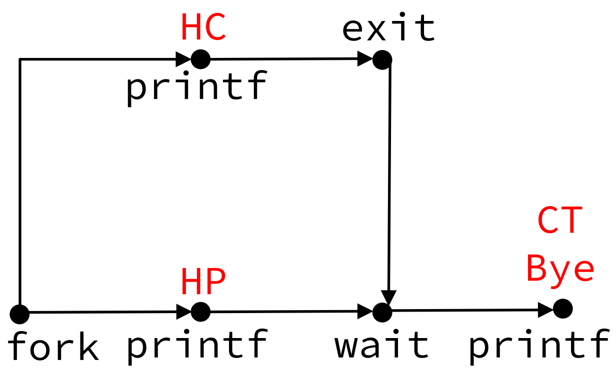
- Terminating a process
  - Return from `main()` or explicit call to `exit(status)`
  - Passes a ***status code*** (`main`'s return value or `exit`'s argument) to parent process
    - 0 for normal exit, nonzero for abnormal exit

- Processes and resources
  - A terminated (***zombie***) process still consumes system resources until ***reaped***
  - Child is reaped when parent process terminates or explicitly calls `wait`/`waitpid`
  - Orphaned children reaped by `init`/`systemd`

Summary (3/4)

- Concurrency and ***process diagrams***
  - Concurrently executing processes are scheduled non-deterministically by the operating system
  - A process graph is a useful tool for capturing the partial ordering of statements in a concurrent program
    - Vertices are program statements, directed edges capture sequencing *within a process*
    - Flexible visualization tool:





Summary (4/4)

- ***Virtual memory*** is software's perspective (*e.g.*, memory layout), ***physical memory*** is hardware's perspective (*e.g.*, memory hierarchy)

- Virtual memory manages the memory for multiple concurrently running processes
  - Each process has its own virtual address space that gets mapped into parts of the physical address space
  - When run out of physical address space, put least recently used data in disk