Virtual Memory I

CSE 351 Spring 2019

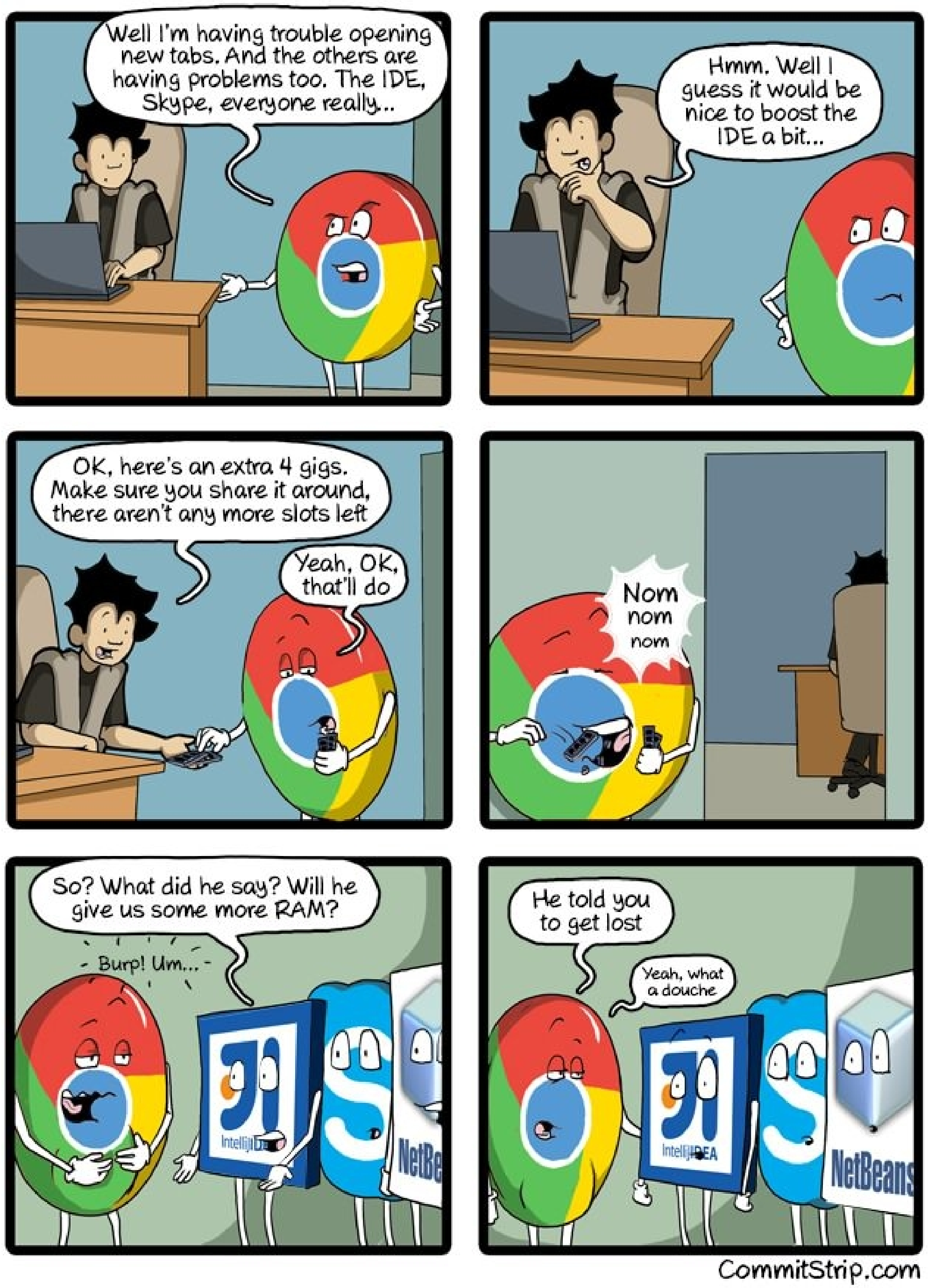
Instructor:

Ruth Anderson

Teaching Assistants:

Gavin Cai
Jack Eggleston
John Feltrup
Britt Henderson
Richard Jiang
Jack Skalitzky
Sophie Tian
Connie Wang
Sam Wolfson
Casey Xing
Chin Yeoh

http://rebrn.com/re/bad-chrome-1162082/



Administrivia

- Homework 4 , due Wed (5/22) (Structs, Caches)
- Lab 4, due Fri (5/24)

Processes

- Processes and context switching
- Creating new processes
  - `fork()`, `exec*()`, and `wait()`
- **Zombies**

Zombies

- 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
- What if parent doesn't reap?
  - If any 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`
  - In long-running processes (e.g. shells, servers) we need *explicit* reaping

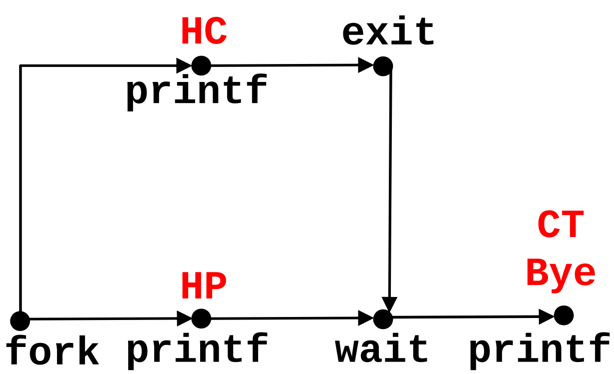
`wait`: Synchronizing with Children

- **`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 **`man 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

wait: Synchronizing with Children

```
void fork_wait() {
   int child_status;

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



Feasible output:

HC	HP
HP	HC
CT	CT
Bye	Bye

Infeasible output:

HP
CT
Bye
HC

Example: Zombie

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

parent persists

forks.c

```
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
```

parent

child

- `ps` shows child process as "defunct"
- Killing parent allows child to be reaped by `init`

Example: Non-terminating Child

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

child persists

forks.c

```
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 kill explicitly, or else will keep running indefinitely

Process Management Summary

- `fork` makes two copies of the same process (parent & child)
  - Returns different values to the two processes
- `exec*` replaces current process from file (new program)
  - Two-process program:
    - First `fork()`
    - **if** (pid == 0) { */* child code */* } **else** { */* parent code */* }
  - Two different programs:
    - First `fork()`
    - **if** (pid == 0) { execv(…) } **else** { */* parent code */* }
- `wait` or `waitpid` used to synchronize parent/child execution and to reap child process

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

Computer system:

- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

Virtual Memory (VM*)

- **Overview and motivation**
- **VM as a tool for caching**
- Address translation
- VM as a tool for memory management
- VM as a tool for memory protection

Warning: Virtual memory is pretty complex, but crucial for understanding how processes work and for debugging performance

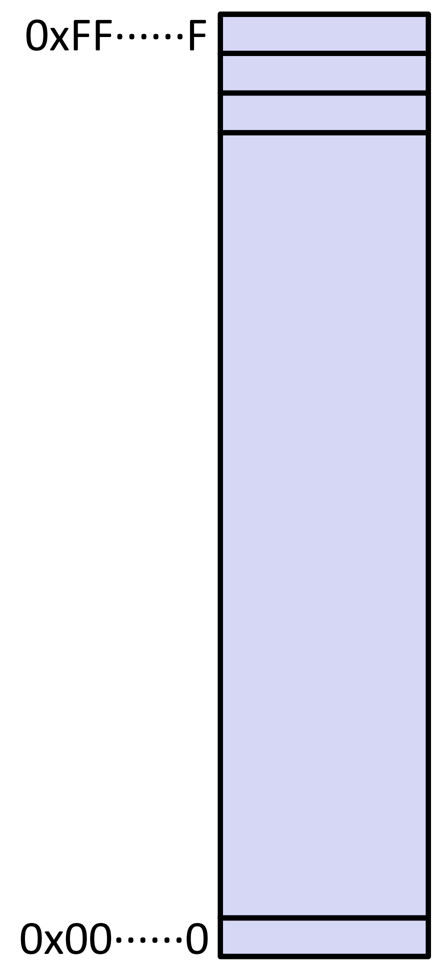
**Not to be confused with "Virtual Machine" which is a whole other thing.*

Memory as we know it so far… is *virtual!*

- Programs refer to virtual memory addresses
  - `movq (%rdi),%rax`
  - Conceptually memory is just a very large array of bytes
  - System provides private address space to each process
- Allocation: Compiler and run-time system
  - Where different program objects should be stored
  - All allocation within single virtual address space
- But…

  2^{64} bytes

  - We *probably* don't have 2^w bytes of physical memory
  - We *certainly* don't have 2^w bytes of physical memory ***<u>for every process</u>***
  - Processes should not interfere with one another
    - Except in certain cases where they want to share code or data



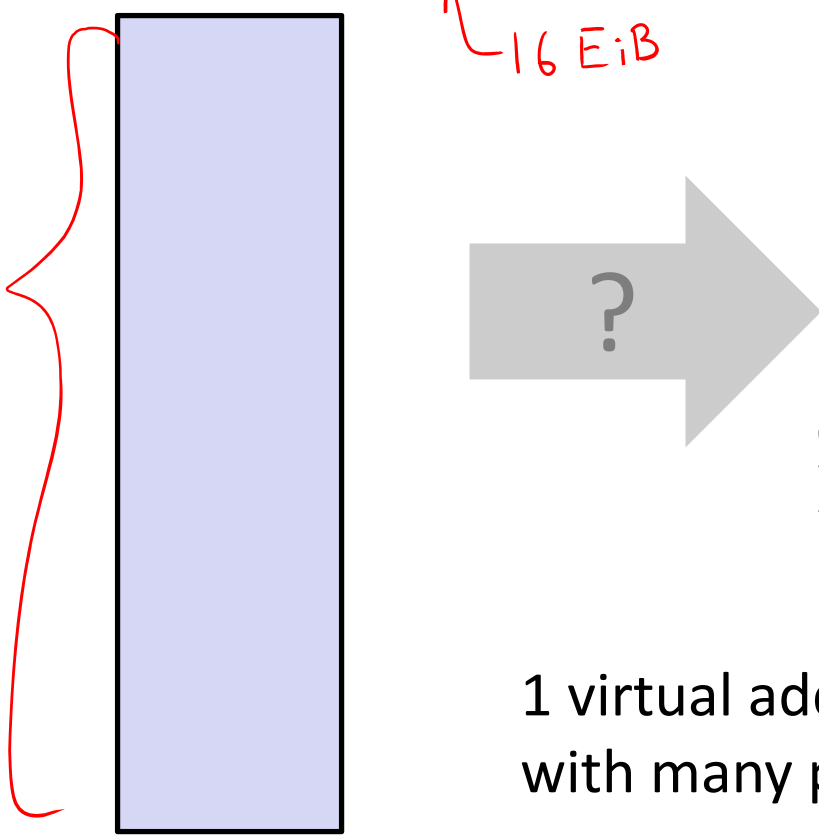
Problem 1: How Does Everything Fit?

64-bit virtual addresses can address several exabytes (18,446,744,073,709,551,616 bytes)

16 EiB

Physical main memory offers a few gigabytes (*e.g.* 8,589,934,592 bytes)

8 GiB



(Not to scale; physical memory would be smaller than the period at the end of this sentence compared to the virtual address space.)

smaller than this!

1 virtual address space per process, with many processes…

Problem 2: Memory Management

We have multiple processes:

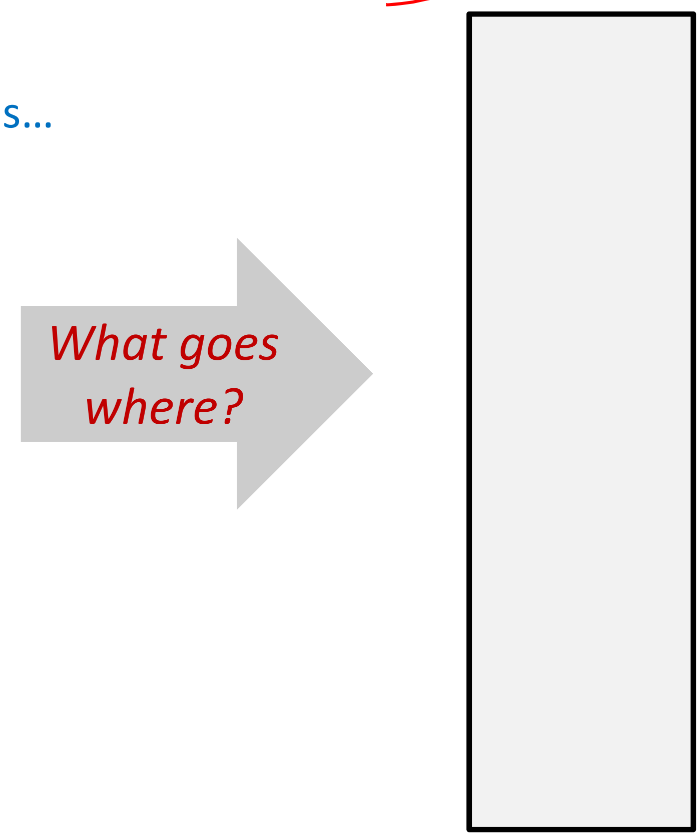
- Process 1
- Process 2
- Process 3
- …
- Process n

X

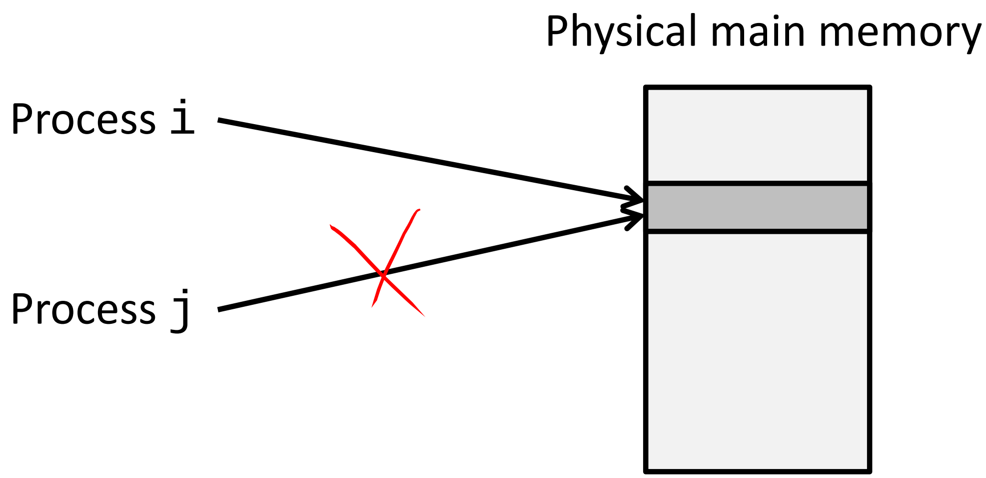
Each process has…

stack
heap
`.text`
`.data`
…

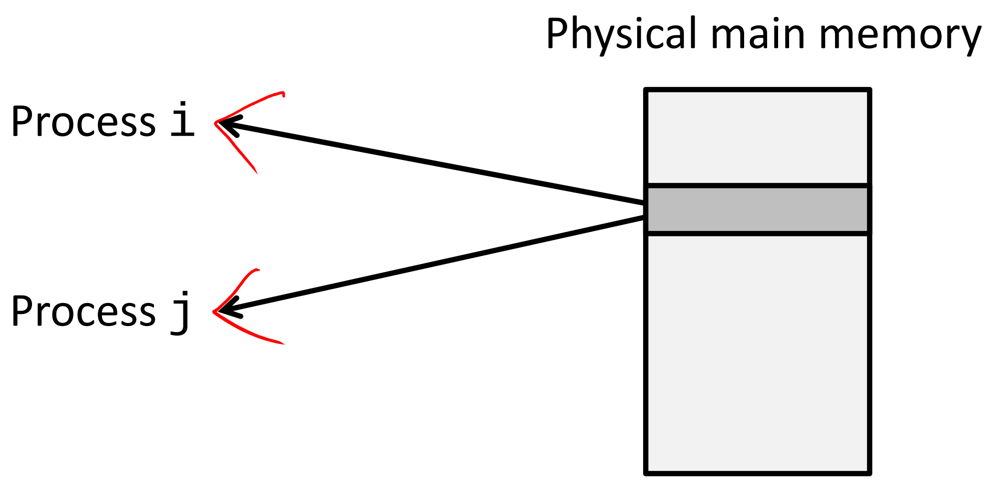
Physical main memory



Problem 3: How To Protect

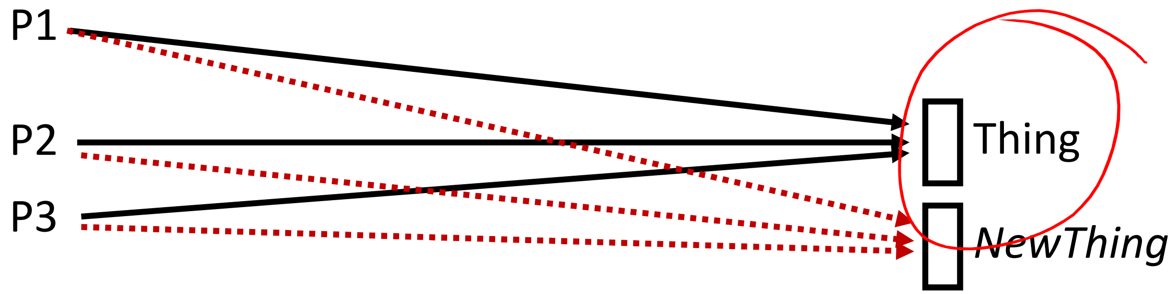


Problem 4: How To Share?

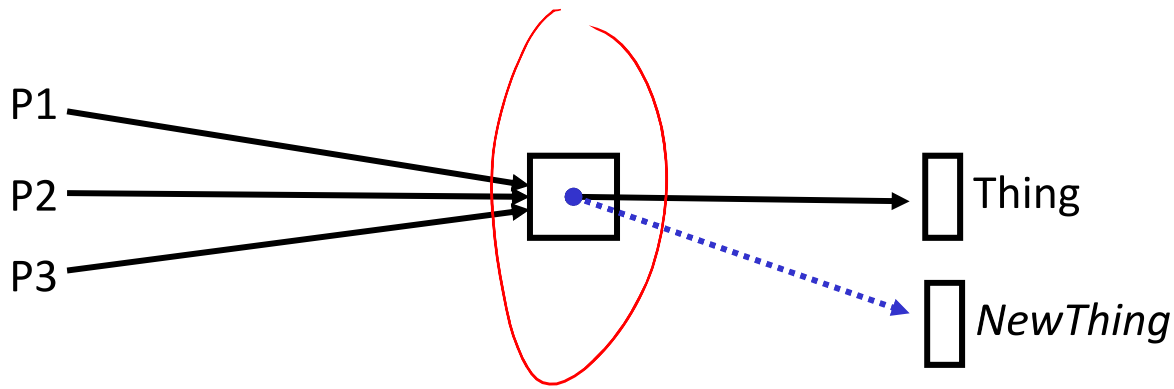


How can we solve these problems?

- "Any problem in computer science can be solved by adding another level of **indirection**." *– David Wheeler, inventor of the subroutine*
- Without Indirection



- With Indirection

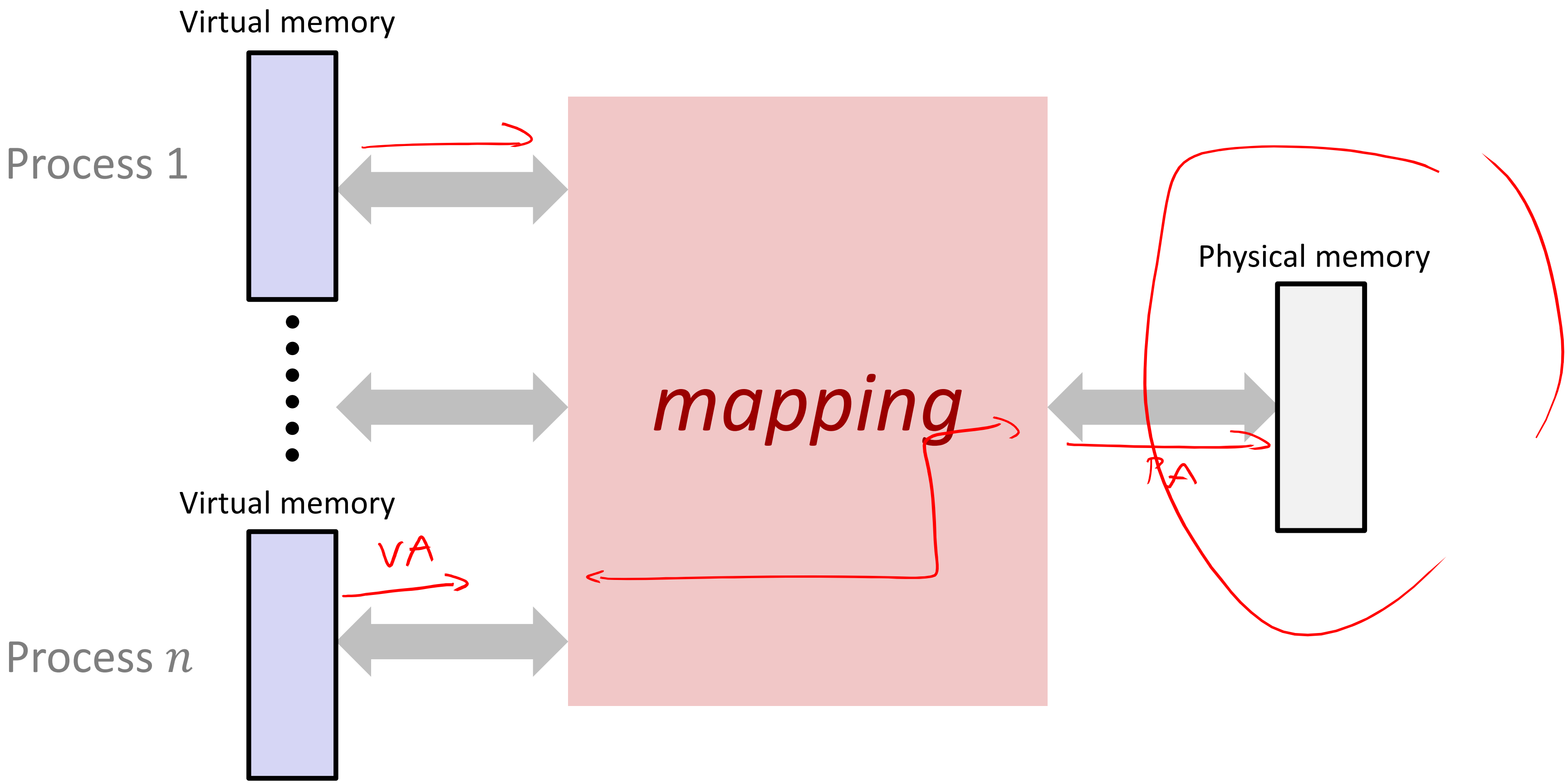


What if I want to move Thing?

Indirection

- *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 have to look up 2 things instead of 1)
  - But don't have to track all uses of name/address (single source!)
- Examples:
  - **Phone system:** cell phone number portability
  - **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!

Address Spaces

bits

$n = \lceil \log_2 N \rceil$ ceiling function (round up)

- Virtual address space: Set of $\mathrm{N} = 2^n$ virtual addr
  - {0, 1, 2, 3, …, N-1}

bytes

$m = \lceil \log_2 M \rceil$

- Physical address space: Set of $\mathrm{M} = 2^m$ physical addr
  - {0, 1, 2, 3, …, M-1}

- Every byte in main memory has:
  - one physical address (PA)
  - zero, one, *or more* virtual addresses (VAs)

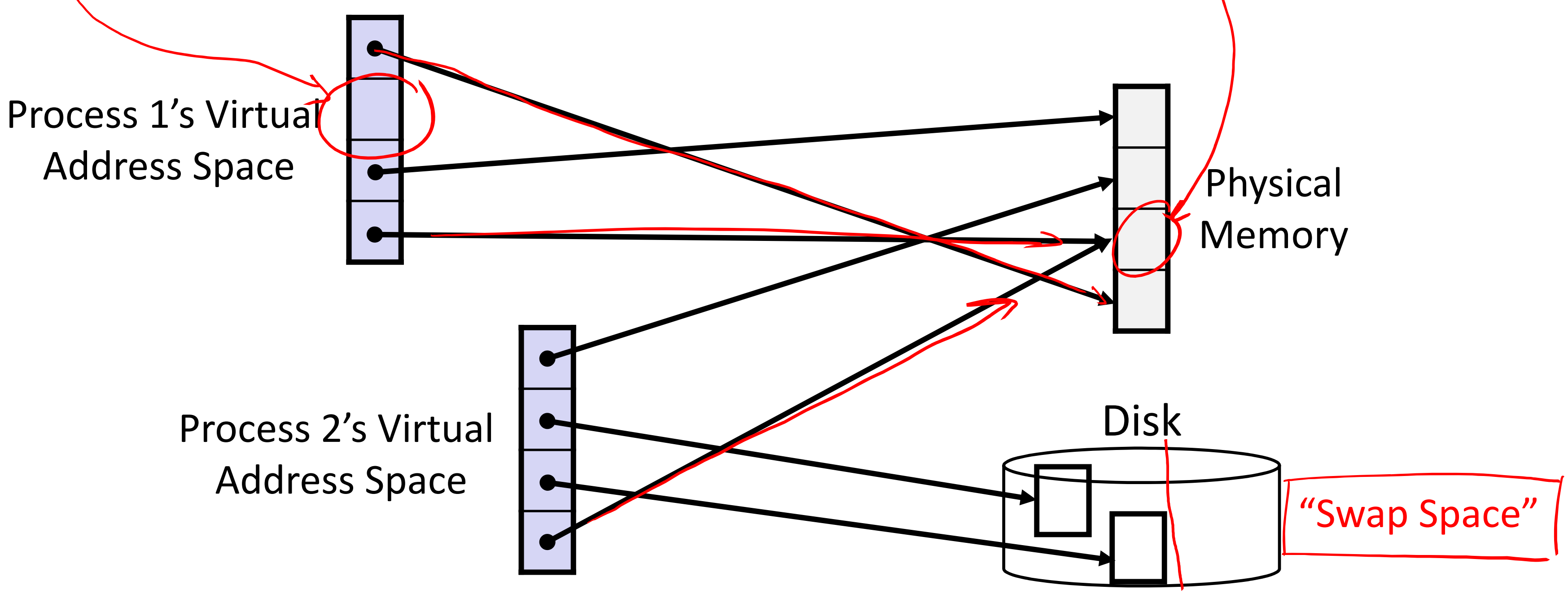
unused

used by one process

used by many processes

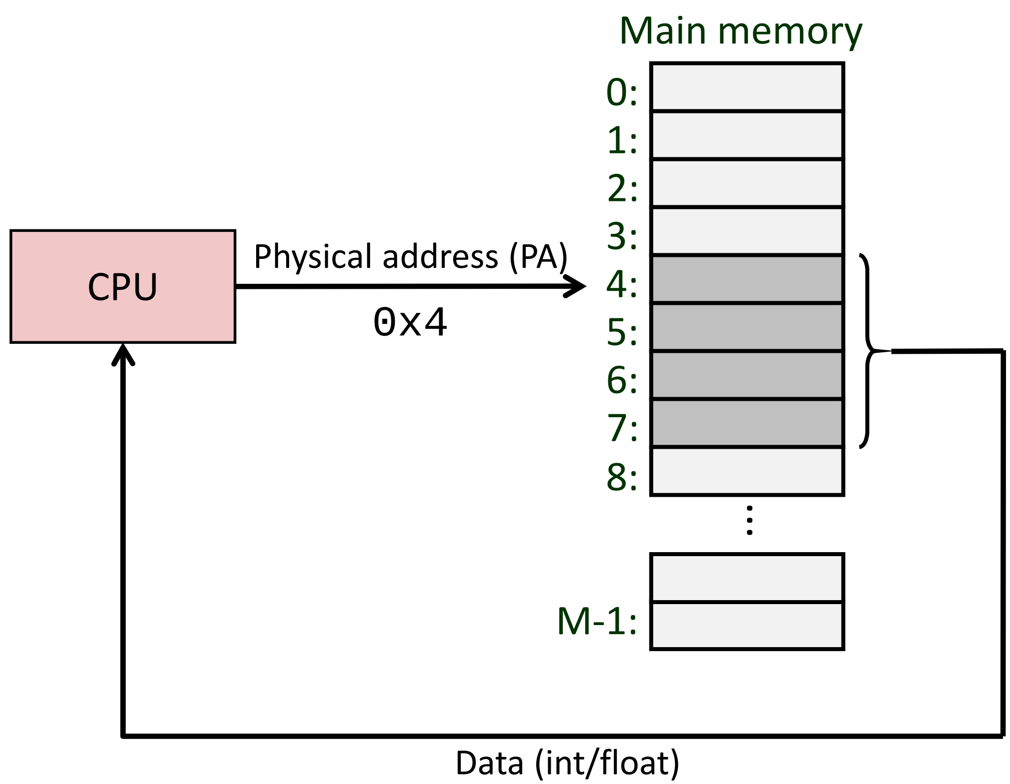
Mapping

- A virtual address (VA) can be mapped to either physical memory or disk
  - Unused VAs may not have a mapping
  - VAs from *different* processes may map to same location in memory/disk



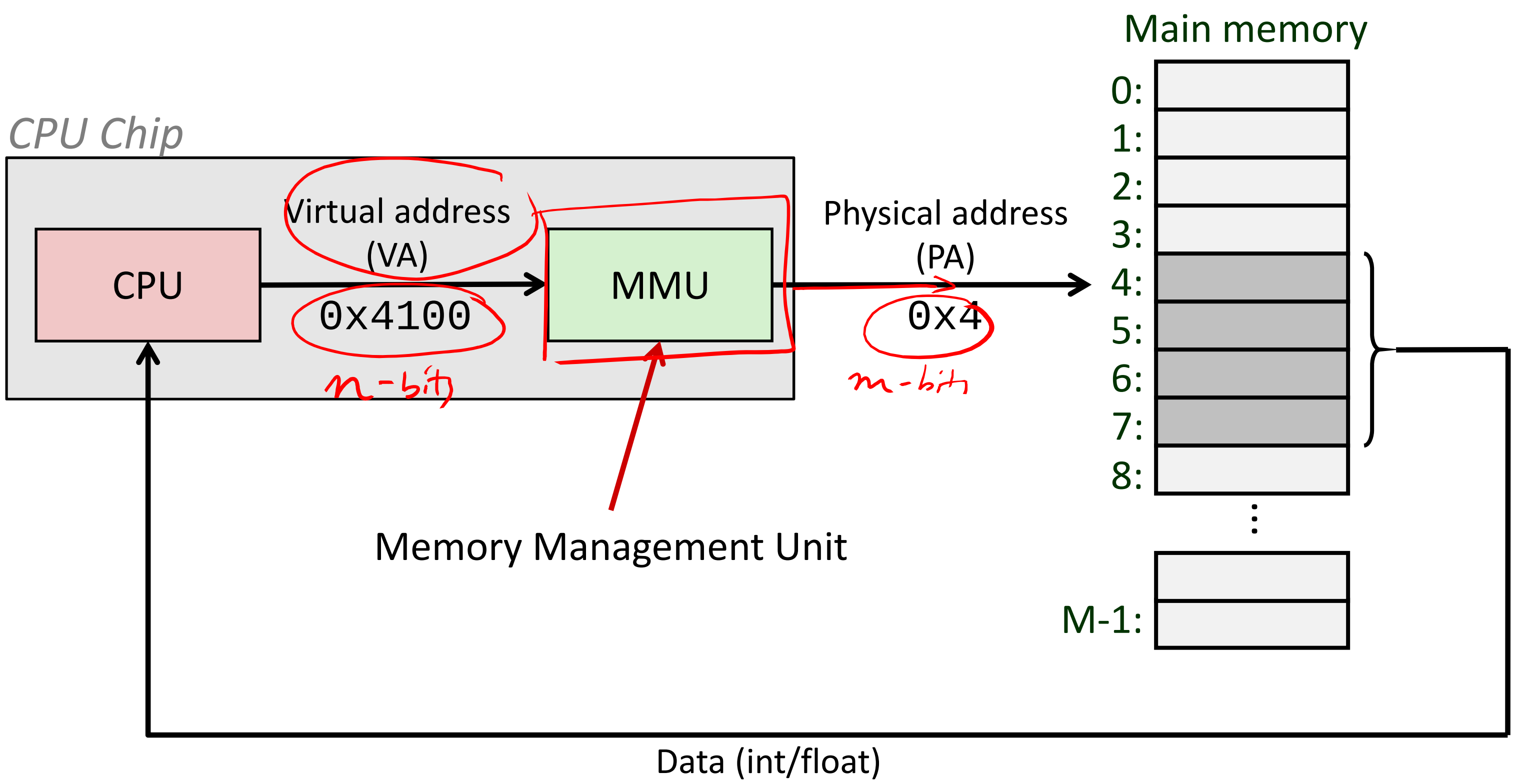
Aside:

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

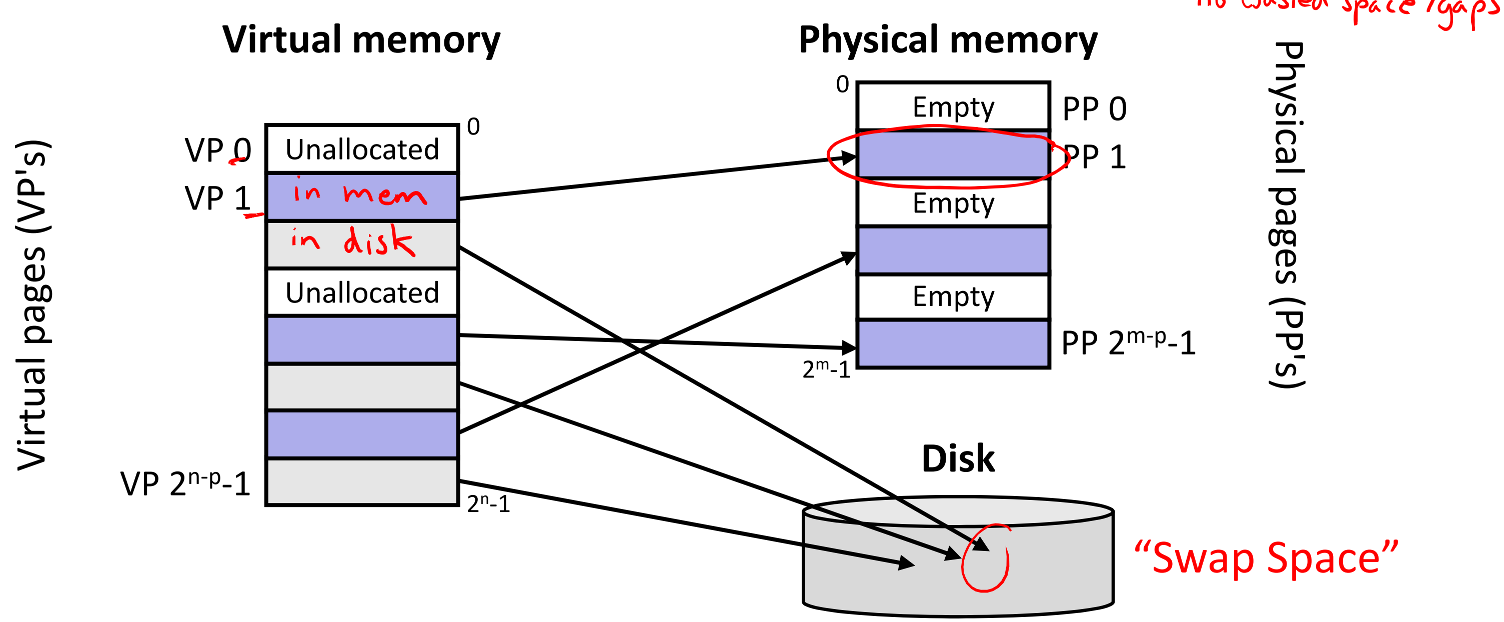
Why Virtual Memory (VM)?

- 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 (protection)
  - One process can't interfere with another's memory
    - They operate in *different address spaces*
  - User process cannot access privileged information
    - Different sections of address spaces have different permissions

VM and the Memory Hierarchy

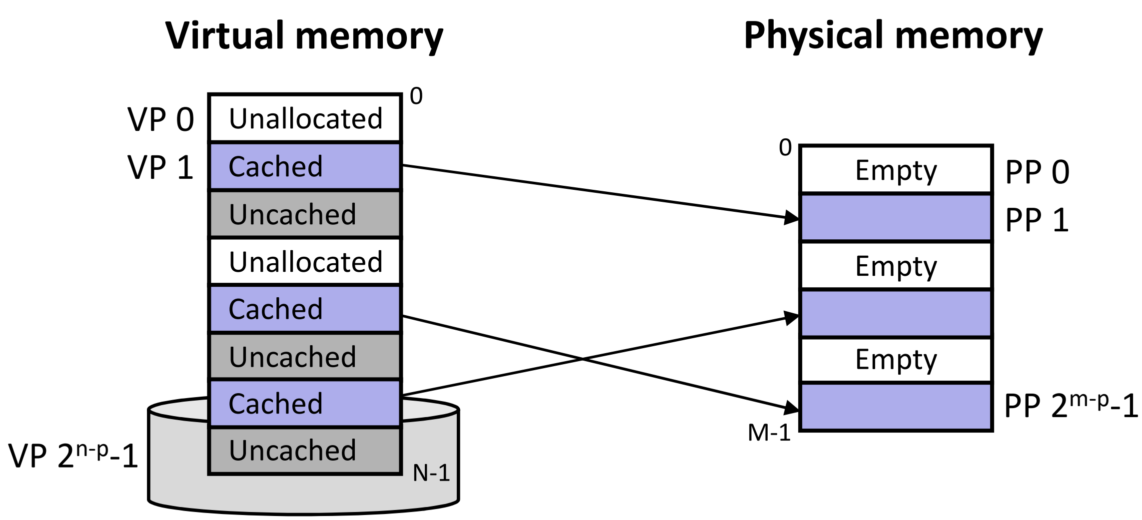
- Think of virtual memory as array of $N = 2^n$ contiguous bytes
- *Pages* of virtual memory are usually stored in physical memory, but sometimes spill to disk $p = \lceil \log_2 P \rceil$
  - Pages are another unit of aligned memory (size is $P = 2^p$ bytes)
  - Each virtual page can be stored in *any* physical page (no fragmentation!)

no wasted space/gaps



or: Virtual Memory as DRAM Cache for Disk

- Think of virtual memory as an array of $\mathrm{N} = 2^n$ contiguous bytes stored *on a disk*
- Then physical main memory is used as a *cache* for the virtual memory array
  - These "cache blocks" are called *pages* (size is $\mathrm{P} = 2^p$ bytes)

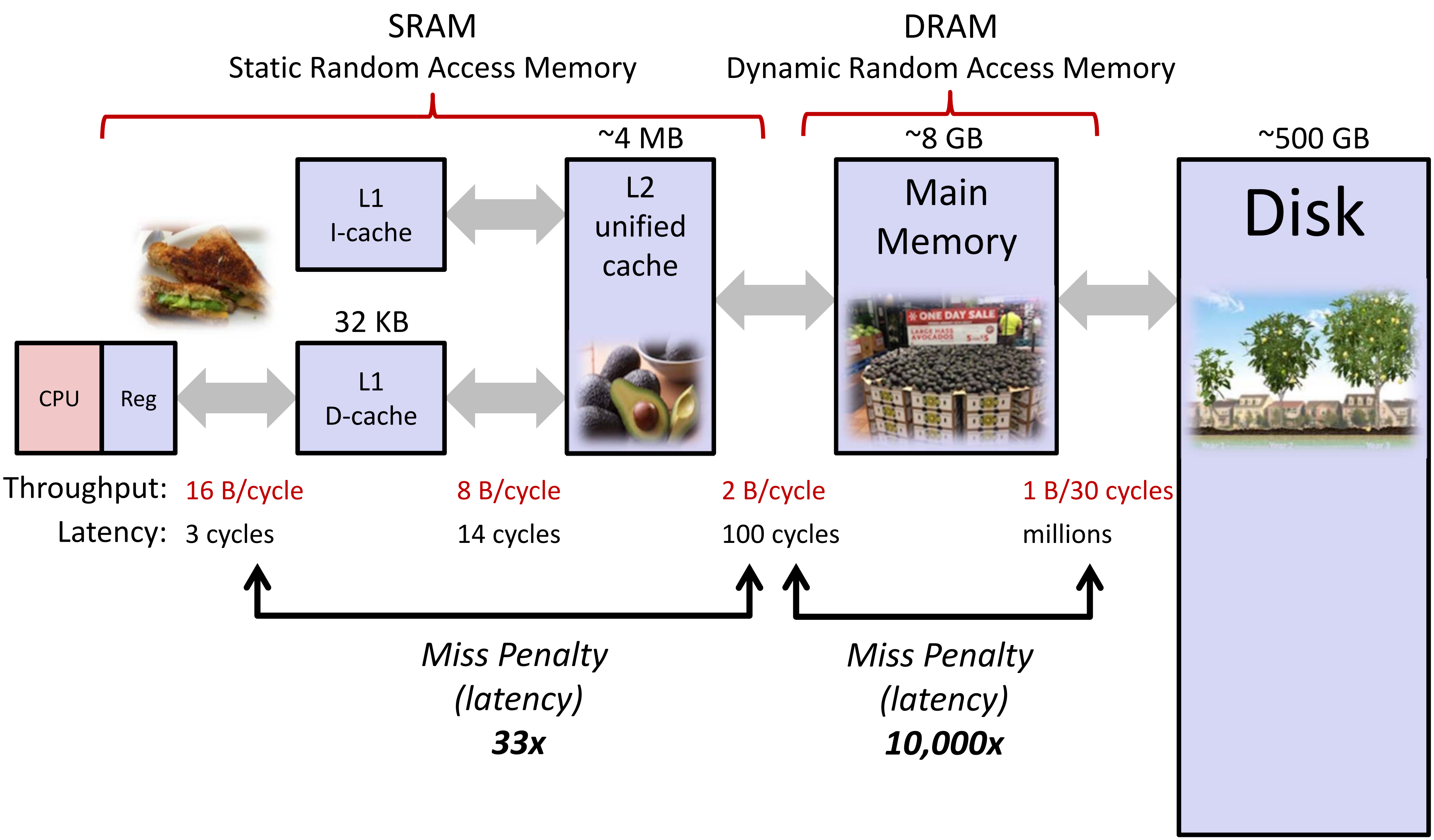


Virtual pages (VPs) "stored on disk"

Physical pages (PPs) cached in DRAM

Memory Hierarchy: Core 2 Duo

Not drawn to scale



Virtual Memory Design Consequences

- Large page size: typically 4-8 KiB or 2-4 MiB
  - *Can* be up to 1 GiB (for "Big Data" apps on big computers)
  - Compared with 64-byte cache blocks
- Fully associative (physical memory is single set)
  - Any virtual page can be placed in any physical page
  - Requires a "large" mapping function – different from CPU caches
- Highly sophisticated, expensive replacement algorithms in OS
  - Too complicated and open-ended to be implemented in hardware
- *Write-back* rather than *write-through* (track dirty pages)
  - *Really* don't want to write to disk every time we modify something in memory
  - Some things may never end up on disk (*e.g.* stack for short-lived process)

Why does VM work on RAM/disk?

- Avoids disk accesses because of *locality*
  - Same reason that L1 / L2 / L3 caches work

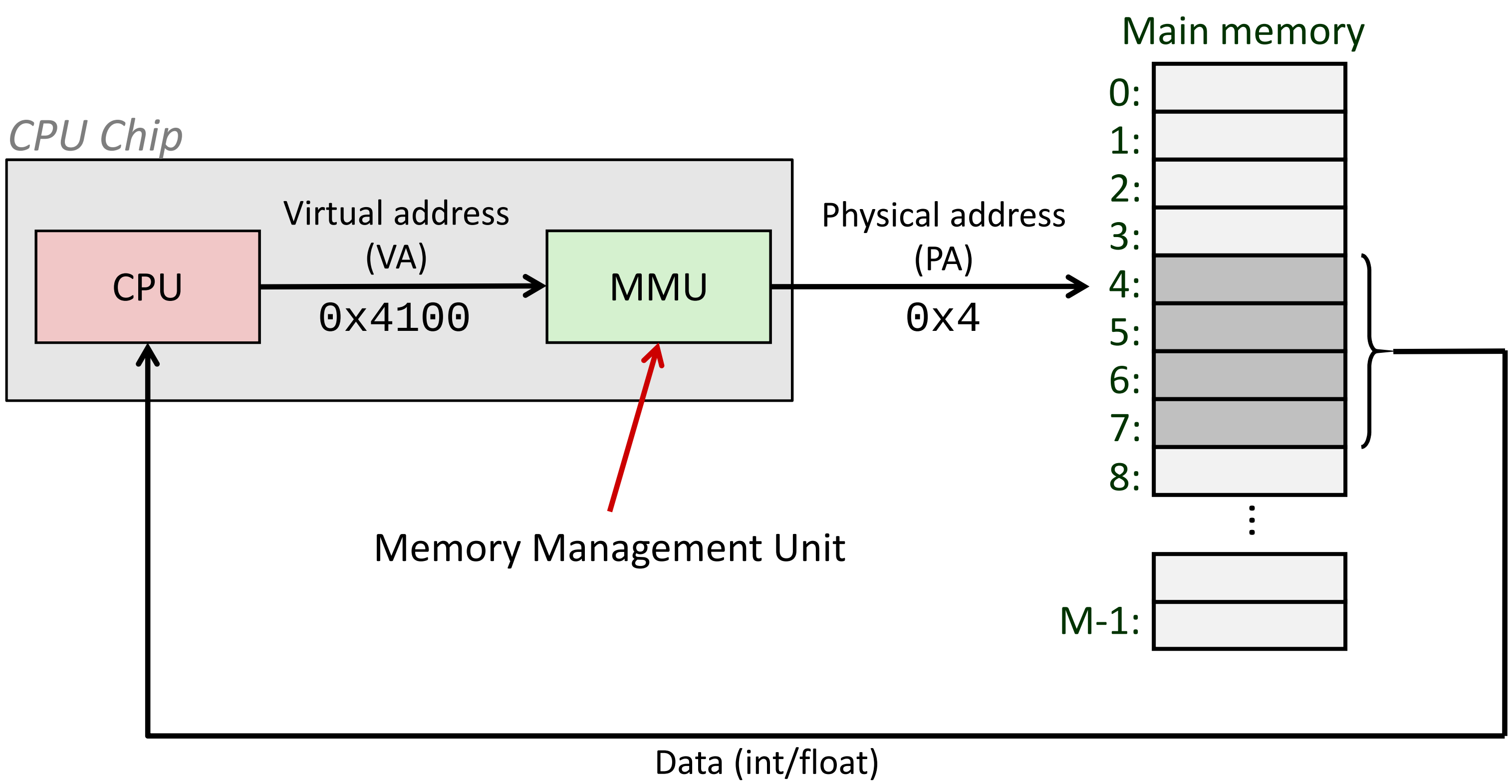
- The set of virtual pages that a program is "actively" accessing at any point in time is called its *working set*
  - If (*working set of one process* ≤ *physical memory*):
    - Good performance for one process (after compulsory misses)
  - If (*working sets of all processes* > *physical memory*):
    - ***Thrashing:*** Performance meltdown where pages are swapped between memory and disk continuously (CPU always waiting or paging)
    - This is why your computer can feel faster when you add RAM

Virtual Memory (VM)

- Overview and motivation
- VM as a tool for caching
- **Address translation**
- VM as a tool for memory management
- VM as a tool for memory protection

Address Translation

How do we perform the virtual → physical address translation?



Address Translation: Page Tables

VPN width $n-p \Leftrightarrow$ we have 2^{n-p} pages in VA space

page size P bytes $\Leftrightarrow p = \lceil \log_2 P \rceil$ bits

- CPU-generated address can be split into:

$n-p$ bits | p bits

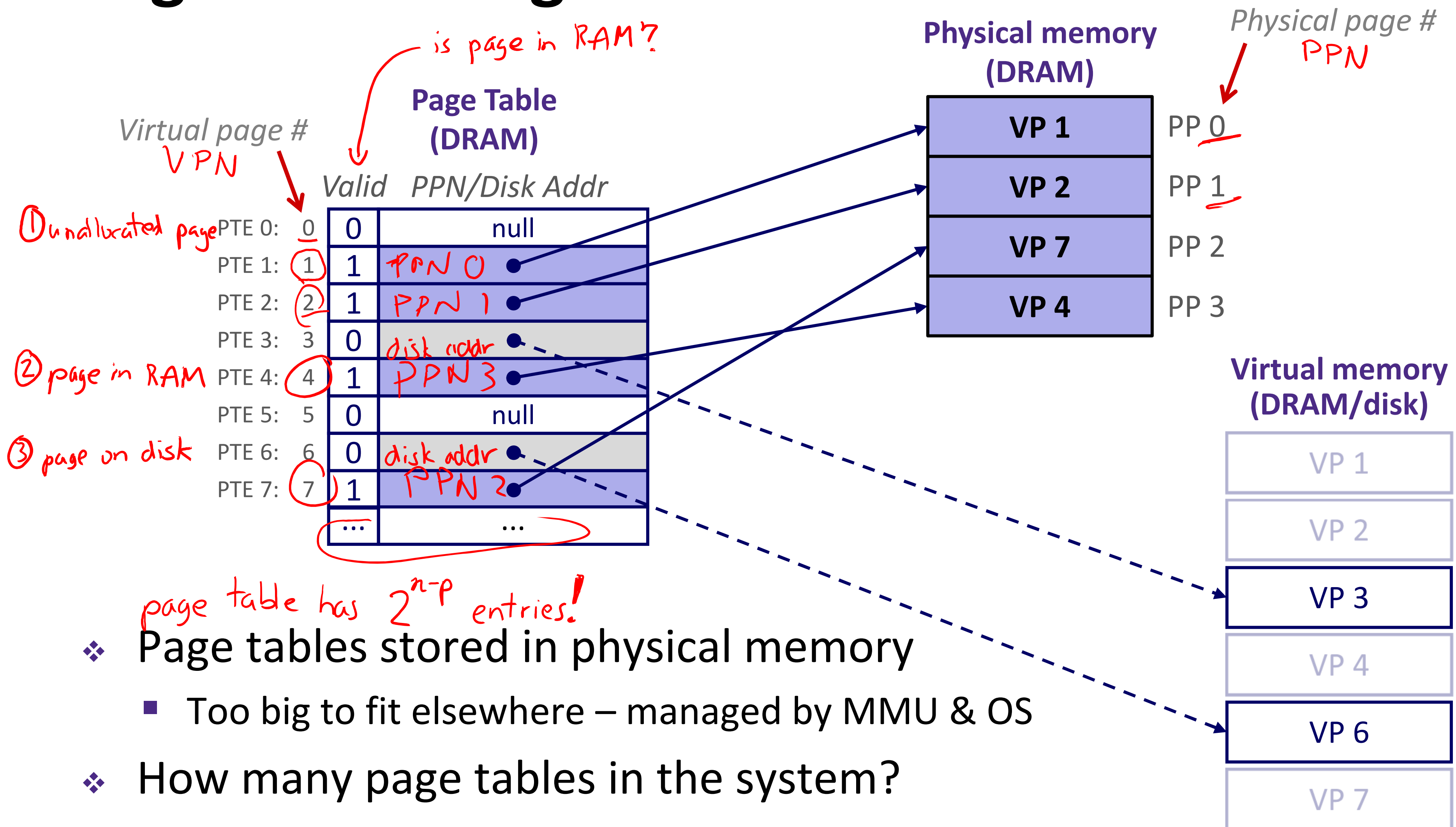
n-bit address: | Virtual Page Number | Page Offset |

analogous to: | block number | block offset | for caches

  - Request is Virtual Address (VA), want Physical Address (PA)
  - Note that Physical Offset = Virtual Offset (page-aligned)

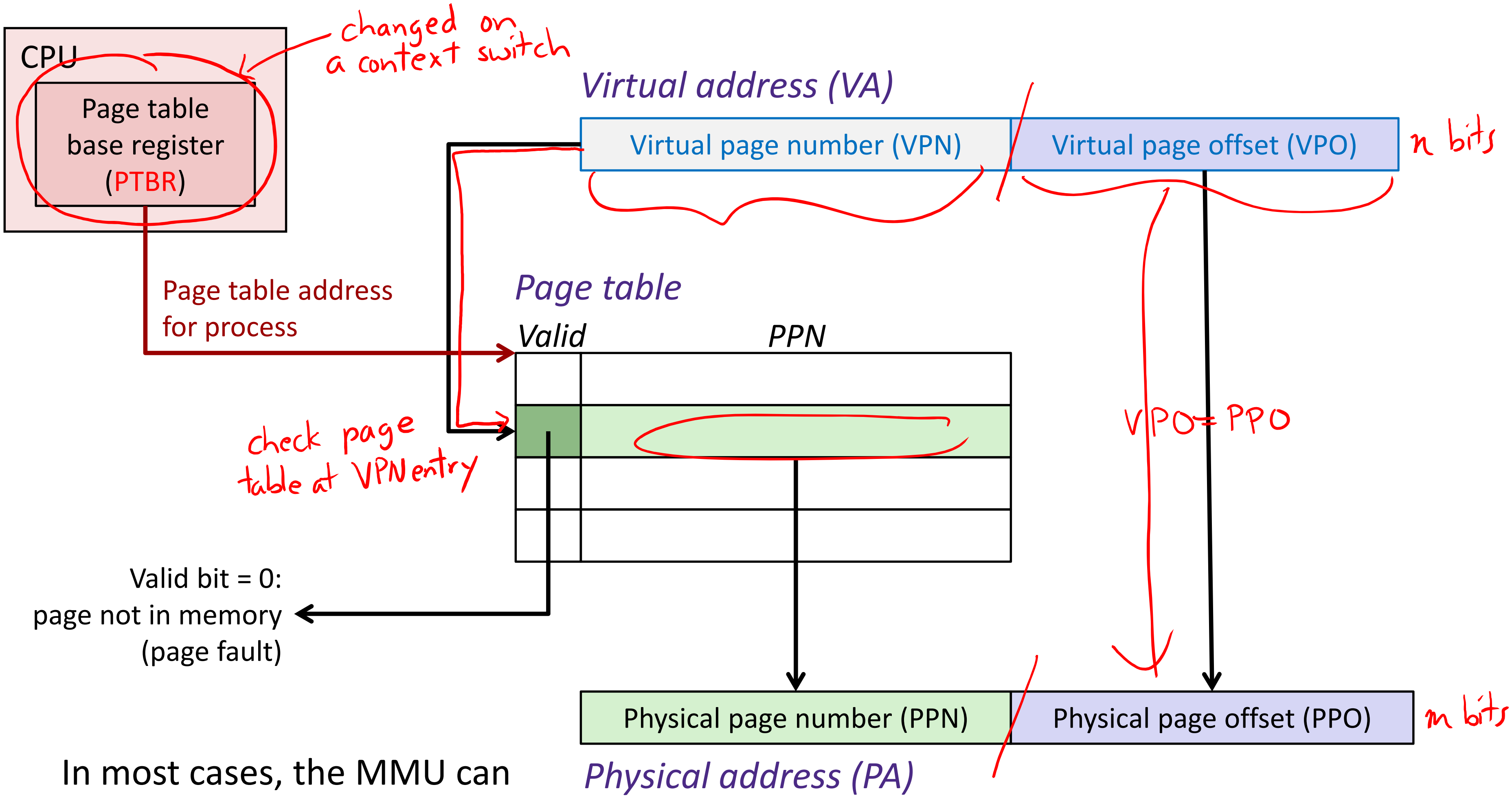
- Use lookup table that we call the *page table* (PT)
  - Replace Virtual Page Number (VPN) for Physical Page Number (PPN) to generate Physical Address
  - Index PT using VPN: page table entry (PTE) stores the PPN plus management bits (*e.g.* Valid, Dirty, access rights)
  - Has an entry for *every* virtual page – why?

Page Table Diagram



- Page tables stored in physical memory
  - Too big to fit elsewhere – managed by MMU & OS
- How many page tables in the system?
  - *One per process*

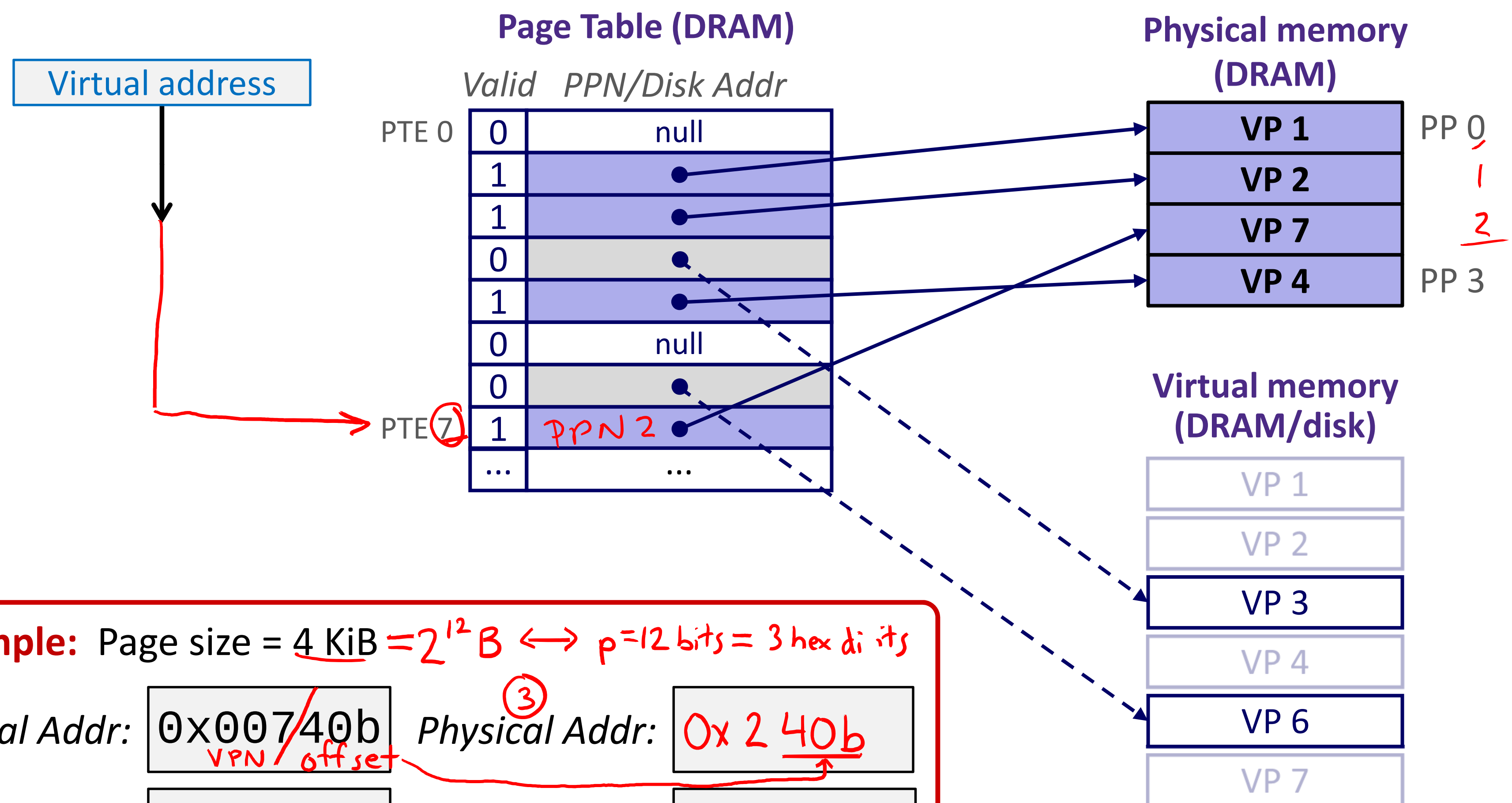
Page Table Address Translation



In most cases, the MMU can perform this translation without software assistance

Page Hit

- ***Page hit:*** VM reference is in physical memory



Example: Page size = 4 KiB $= 2^{12}$ B $\leftrightarrow$ $p = 12$ bits = 3 hex digits

Virtual Addr:	0x007/40b (VPN / offset)	3 *Physical Addr:*	0x 2 40b
1 *VPN:*	7	2 *PPN:*	2

Summary

- Virtual memory provides:
  - Ability to use limited memory (RAM) across multiple processes
  - Illusion of contiguous virtual address space for each process
  - Protection and sharing amongst processes
- Indirection via address mapping by page tables
  - Part of memory management unit and stored in memory
  - Use virtual page number as index into lookup table that holds physical page number, disk address, or NULL (unallocated page)
  - On page fault, throw exception and move page from swap space (disk) to main memory

BONUS SLIDES

Detailed examples:

- `wait()` example
- `waitpid()` example

wait() Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10() {
   pid_t pid[N];
   int i;
   int child_status;
   for (i = 0; i < N; i++)
      if ((pid[i] = fork()) == 0)
         exit(100+i); /* Child */
   for (i = 0; i < N; i++) {
      pid_t wpid = wait(&child_status);
      if (WIFEXITED(child_status))
         printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
      else
         printf("Child %d terminated abnormally\n", wpid);
   }
}
```

waitpid(): Waiting for a Specific Process

pid_t waitpid(**pid_t** pid, **int** &status, **int** options)

- suspends current process until specific process terminates
- various options (that we won't talk about)

```
void fork11() {
   pid_t pid[N];
   int i;
   int child_status;
   for (i = 0; i < N; i++)
      if ((pid[i] = fork()) == 0)
         exit(100+i); /* Child */
   for (i = 0; i < N; i++) {
      pid_t wpid = waitpid(pid[i], &child_status, 0);
      if (WIFEXITED(child_status))
         printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
      else
         printf("Child %d terminated abnormally\n", wpid);
   }
}
```