# Virtual Memory (start)

## Computer Operating Systems, Spring 2024

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# Administrivia

- PennOS
  - You have the first milestone, which should have been done last week
  - Everyone should have already contacted their group, and should get started working on it.

  - Milestone 1 is due next week
    - Between Tuesday the 9th and Friday the 12th
    - Need to meet with TA again to show significant progress
    - Have a plan (a REAL plan) for how to complete the rest
    - Autograder to be released tomorrow (tentatively)
      - You do not need to pass it for the milestone, but you should be able to showcase work you have done on it.
  - Full Thing due ~April 22nd

# Administrivia

- Check-in was due before today’s lecture
    - Another one will be released this week, due sometime next week

- Exam grades posted
    - Remember the Clobber Policy. Many people benefit from this policy in my courses
    - Regrade are open and will stay open till April 5th at midnight.

# Poll Everywhere

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- Any questions, comments or concerns from last lecture?

# Lecture Outline

- **Problems with old memory model**
- Virtual Memory High Level
- Address Translation

# Poll Everywhere

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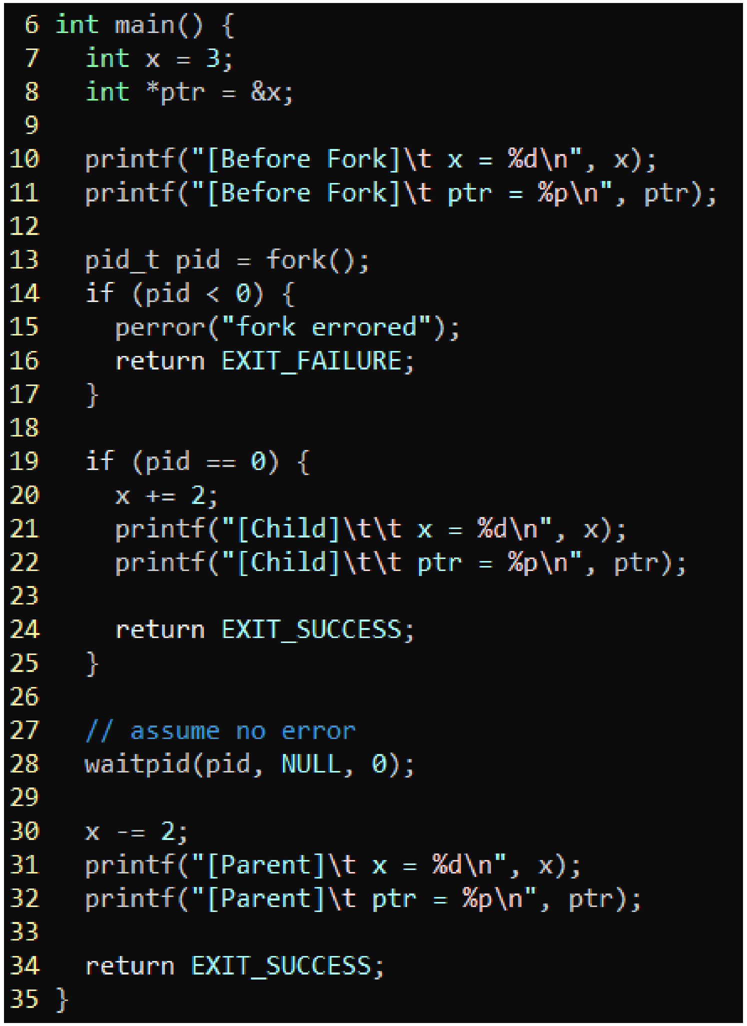
- What does this print for **`x`** at all three points? How does the value of **`ptr`** change?

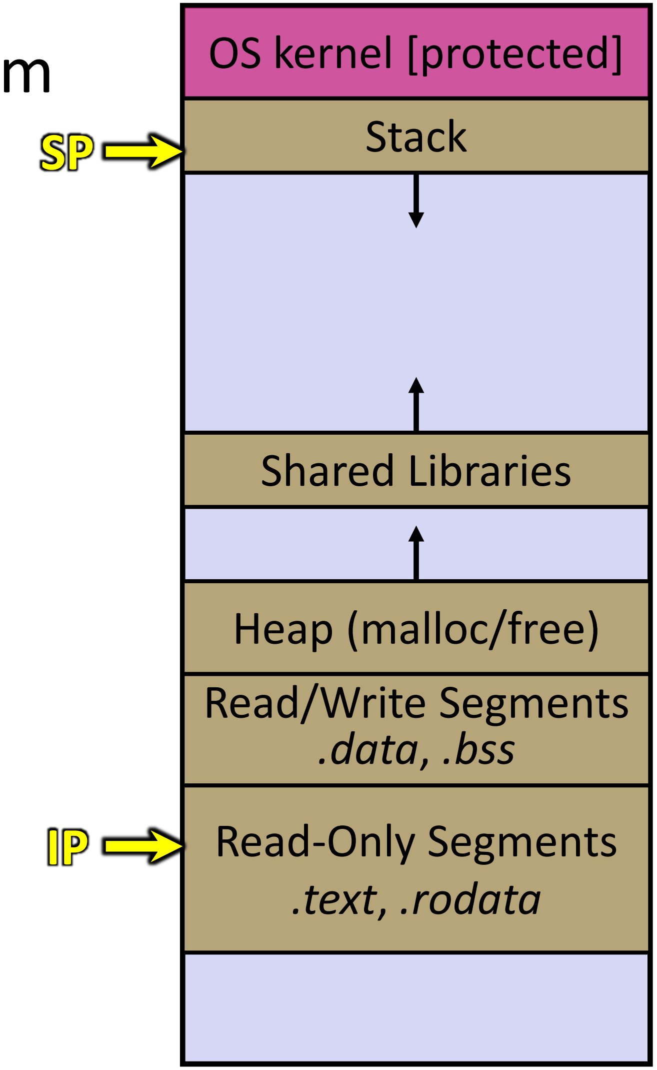


```
int main() {
  int x = 3;
  int *ptr = &x;

  printf("[Before Fork]\t x = %d\n", x);
  printf("[Before Fork]\t ptr = %p\n", ptr);

  pid_t pid = fork();
  if (pid < 0) {
    perror("fork errored");
    return EXIT_FAILURE;
  }

  if (pid == 0) {
    x += 2;
    printf("[Child]\t\t x = %d\n", x);
    printf("[Child]\t\t ptr = %p\n", ptr);

    return EXIT_SUCCESS;
  }

  // assume no error
  waitpid(pid, NULL, 0);

  x -= 2;
  printf("[Parent]\t x = %d\n", x);
  printf("[Parent]\t ptr = %p\n", ptr);

  return EXIT_SUCCESS;
}
```

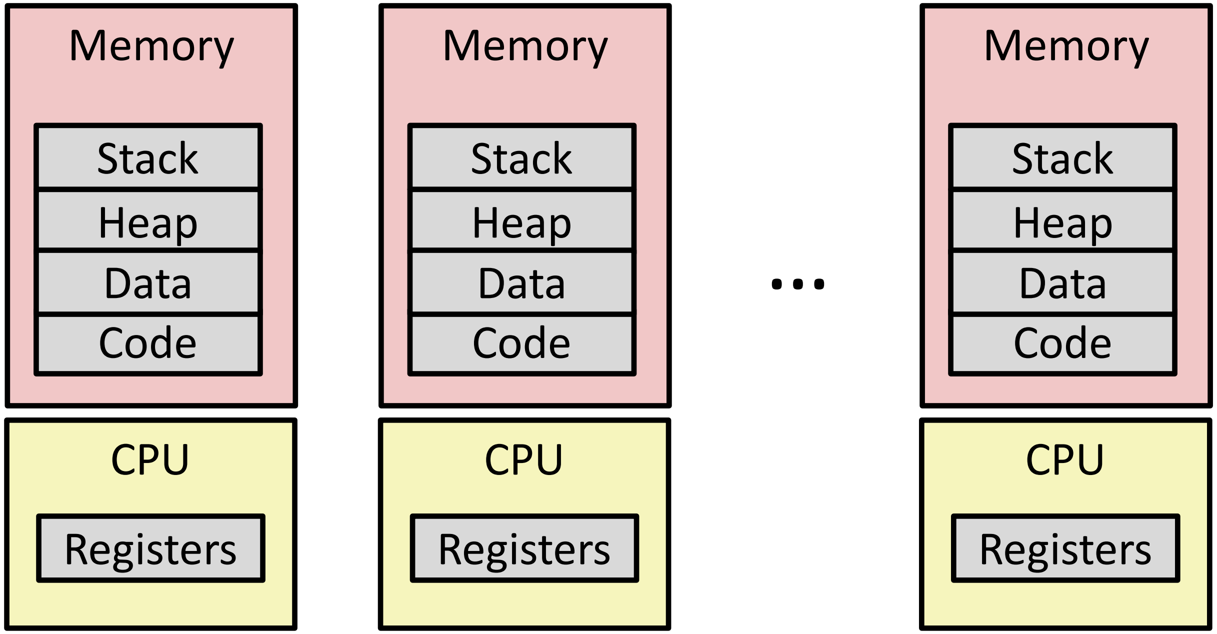
# Review: Processes

- Definition: An instance of a program that is being executed (or is ready for execution)

- Consists of:
  - Memory (code, heap, stack, etc)
  - Registers used to manage execution (stack pointer, program counter, ...)
  - Other resources

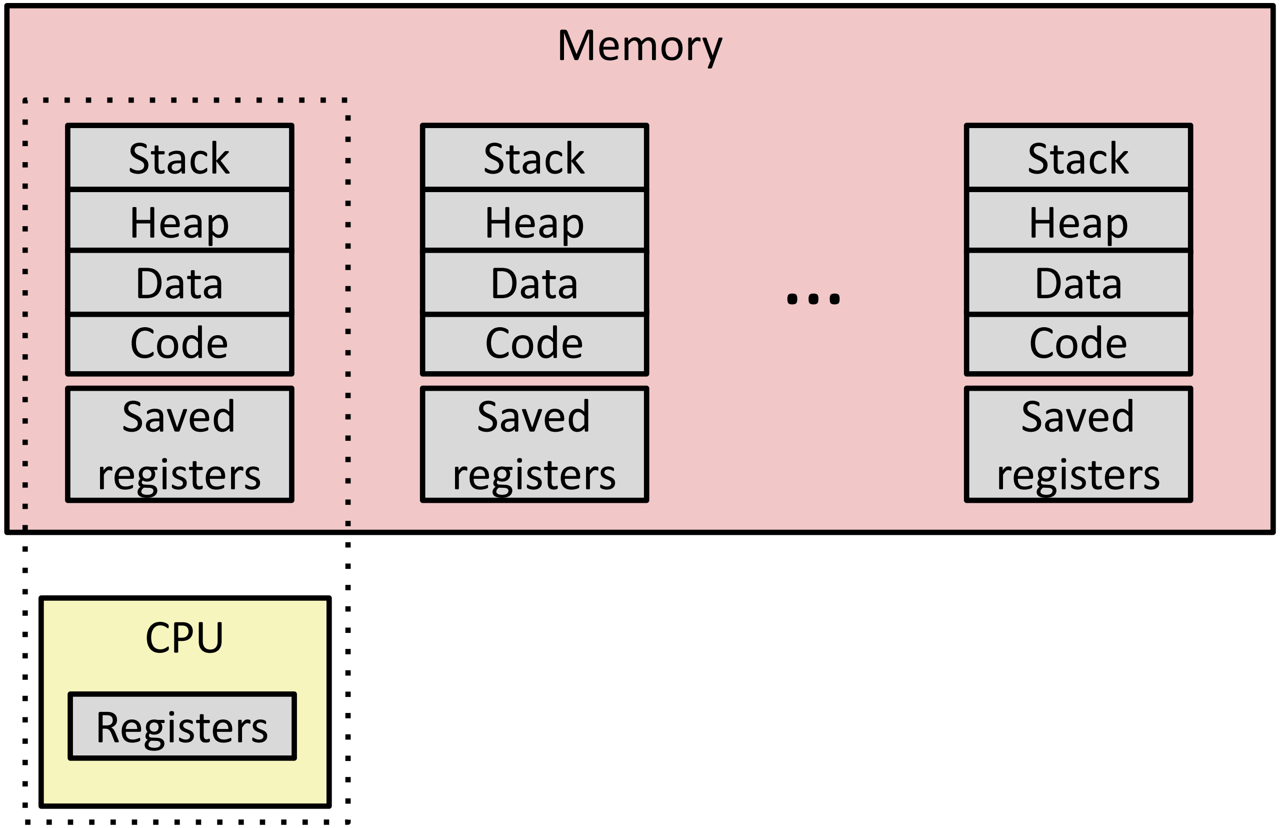


# Multiprocessing: The Illusion



- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

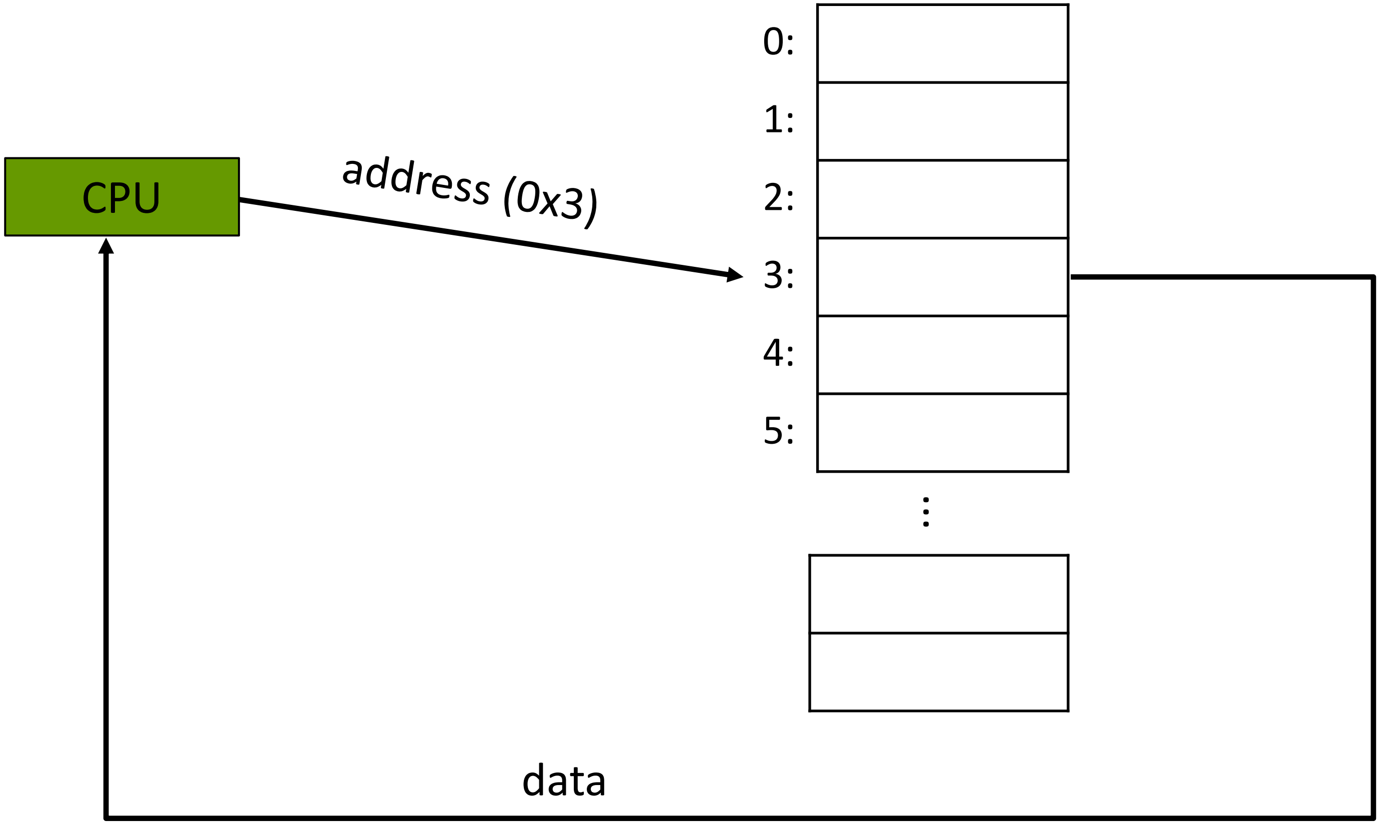
# Multiprocessing: The (Traditional) Reality



- Single processor executes multiple processes concurrently
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system (later in course)
  - Register values for nonexecuting processes saved in memory

# Memory (as we know it now)

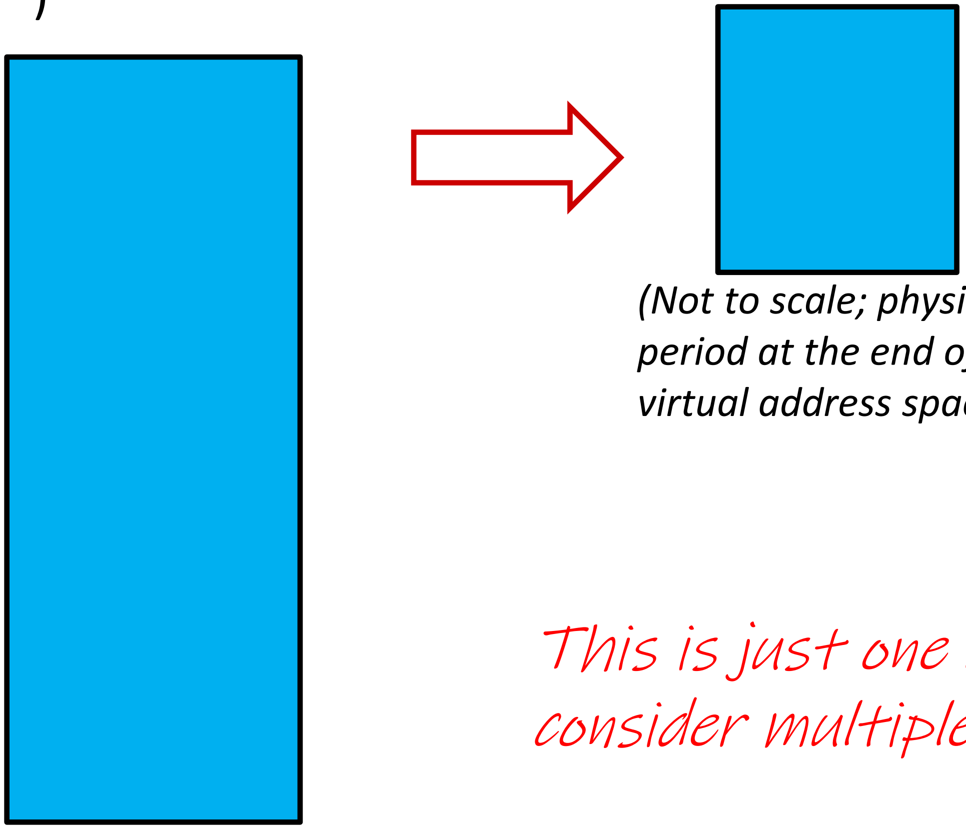
- The CPU directly uses an address to access a location in memory



# Problem 1: How does everything fit?

On a 64-bit machine, there are $2^{64}$ bytes, which is: 18,446,744,073,709,551,616 Bytes ($1.844 \times 10^{19}$)

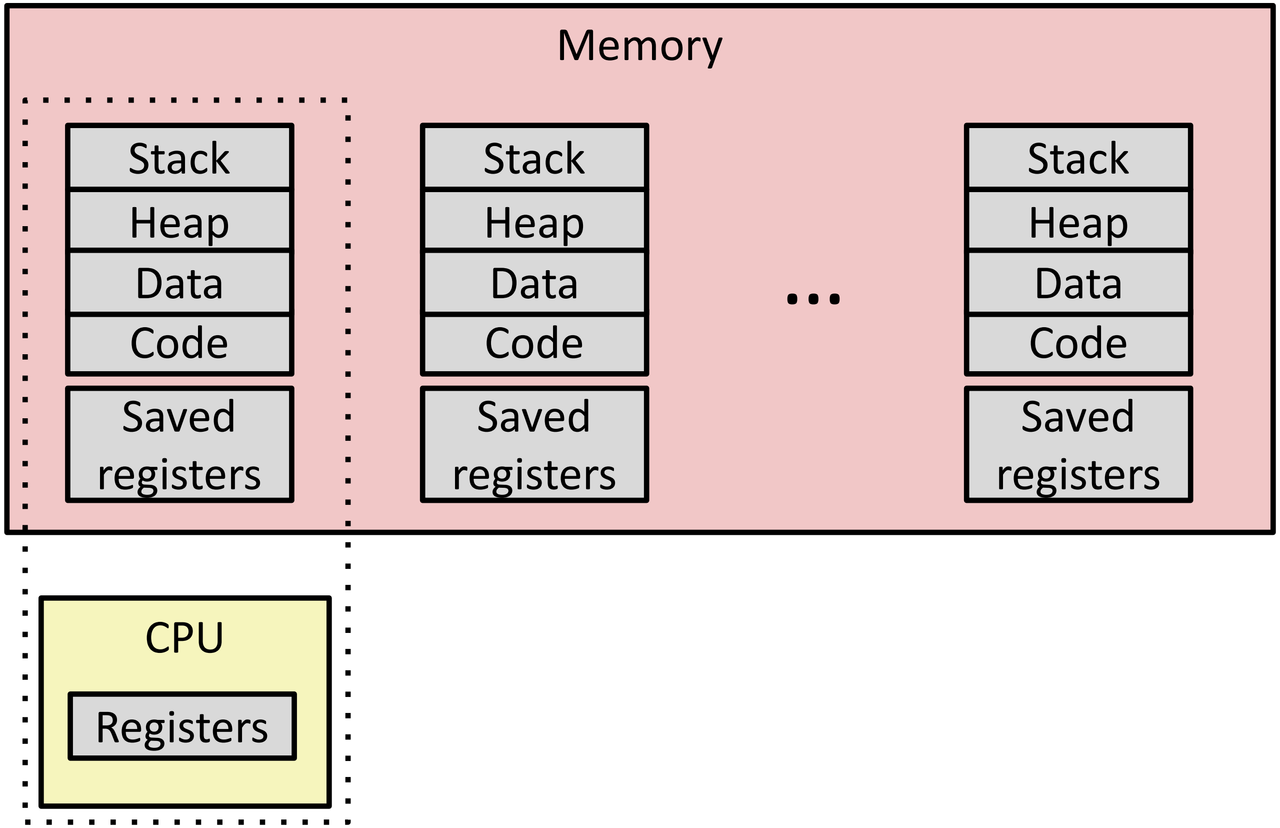
Laptops usually have around 8GB which is 8,589,934,592 Bytes ($8.589 \times 10^{9}$)



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

This is just one address space, consider multiple processes…

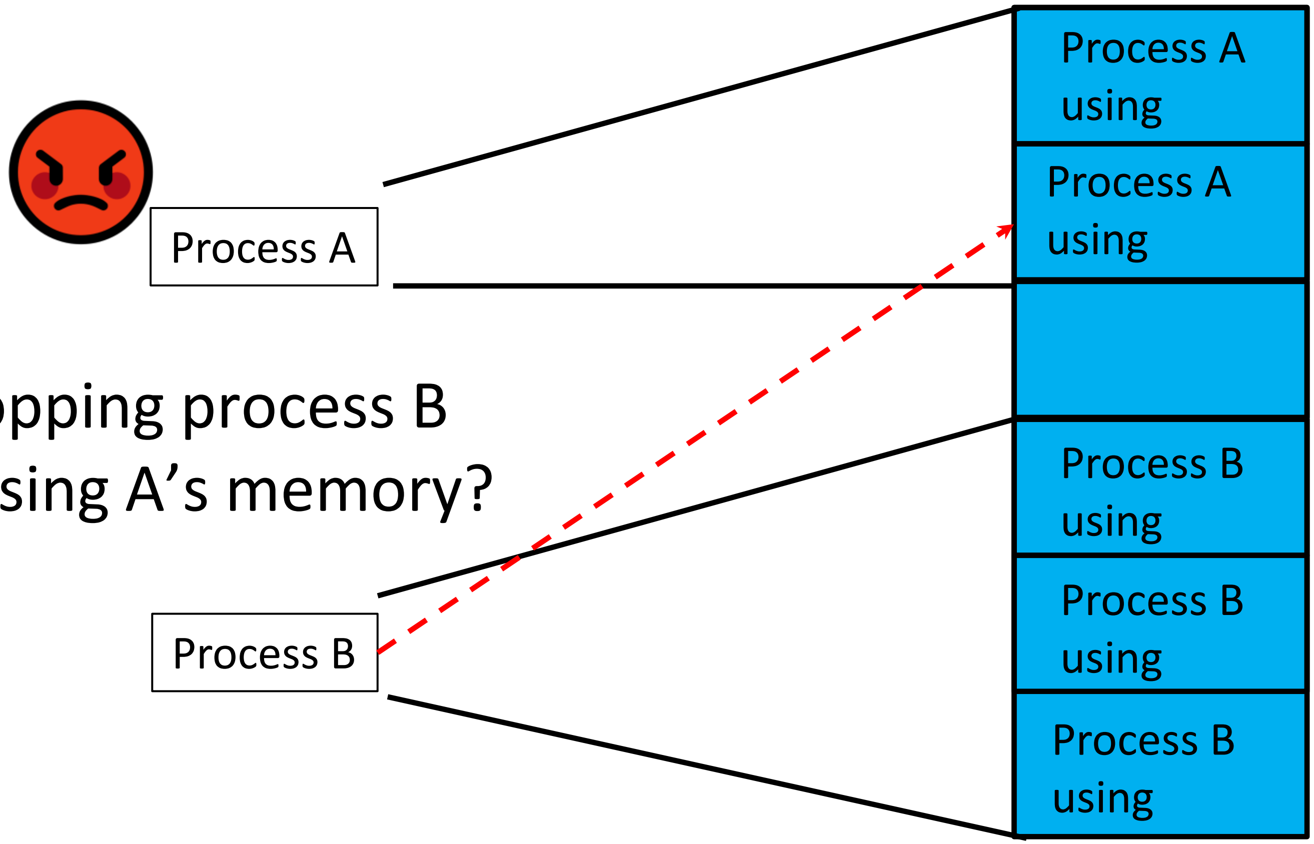
# Problem 2: Sharing Memory



- How do we enforce process isolation?
  - Could one process just calculate an address into another process?

# Problem 2: Sharing Memory

- How do we enforce process isolation?
  - Could one process just calculate an address into another process?

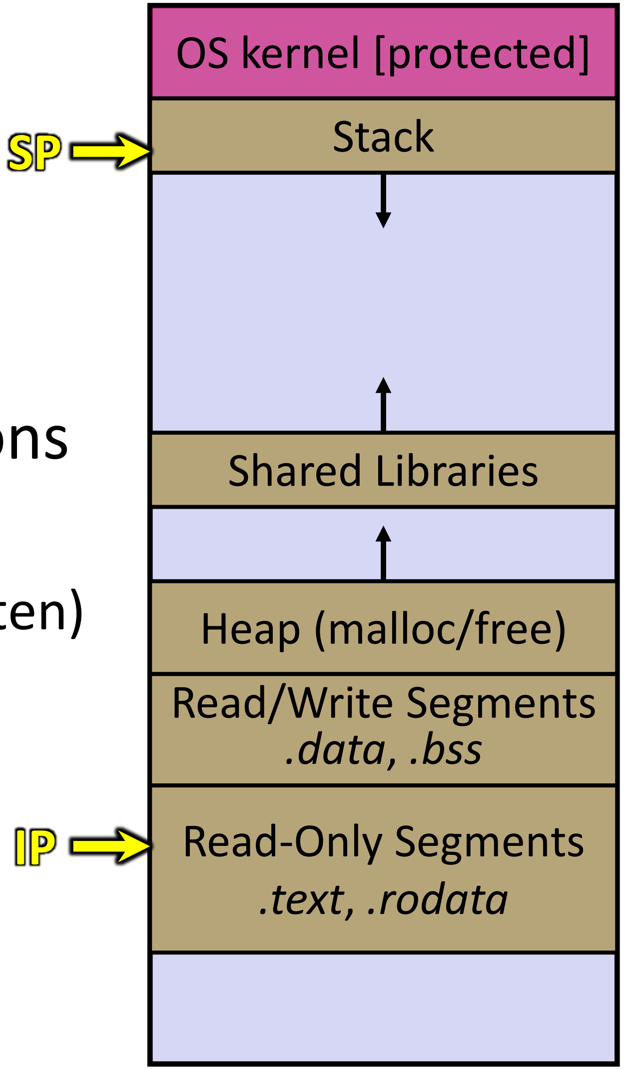


- What is stopping process B from accessing A’s memory?

# Problem 3: How do we segment things

- A process' address space contains many different "segments"

- How do we keep track of which segment is which and the permissions each segment may have?
  - (e.g., that Read-Only data can't be written)

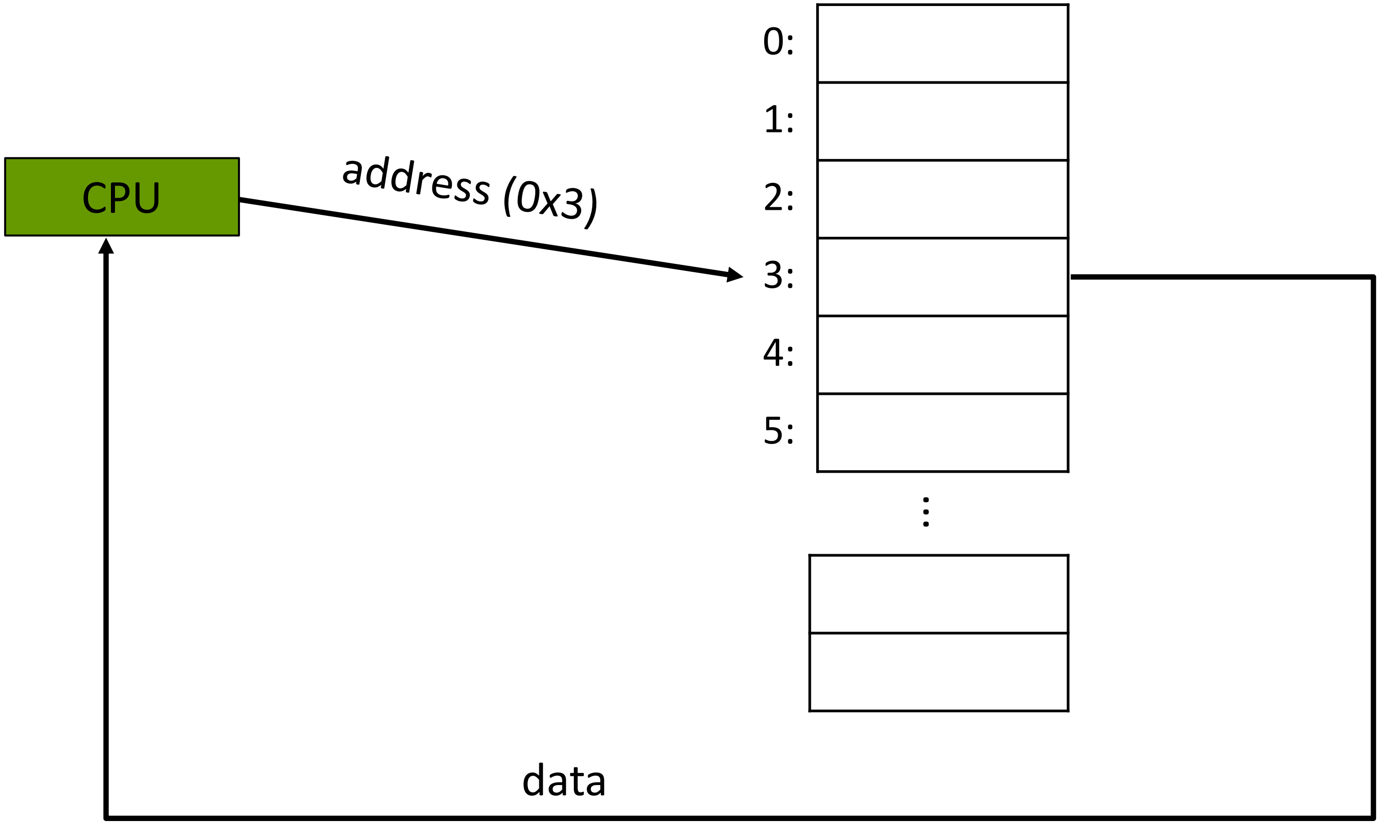


# Lecture Outline

- Problems with old memory model
- **Virtual Memory High Level**
- Address Translation

# This doesn’t work anymore

- The CPU directly uses an address to access a location in memory



# Indirection

- "Any problem in computer science can be solved by adding another level of indirection."
  - David wheeler, inventor of the subroutine (e.g. functions)

- The ability to indirectly reference something using a name, reference or container instead of the value itself. A flexible mapping between a name and a thing allows chagcing the thing without notifying holders of the name.
  - May add some work to use indirection
  - Example: Phone numbers can be transferred to new phones

- Idea: instead of directly referring to physical memory, add a level of indirection

# Idea:

- We don’t need all processes to have their data in physical memory, **just the ones that are currently running**

- For the process’ that are currently running: we don’t need all their data to be in physical memory, **just the parts that are currently being used**

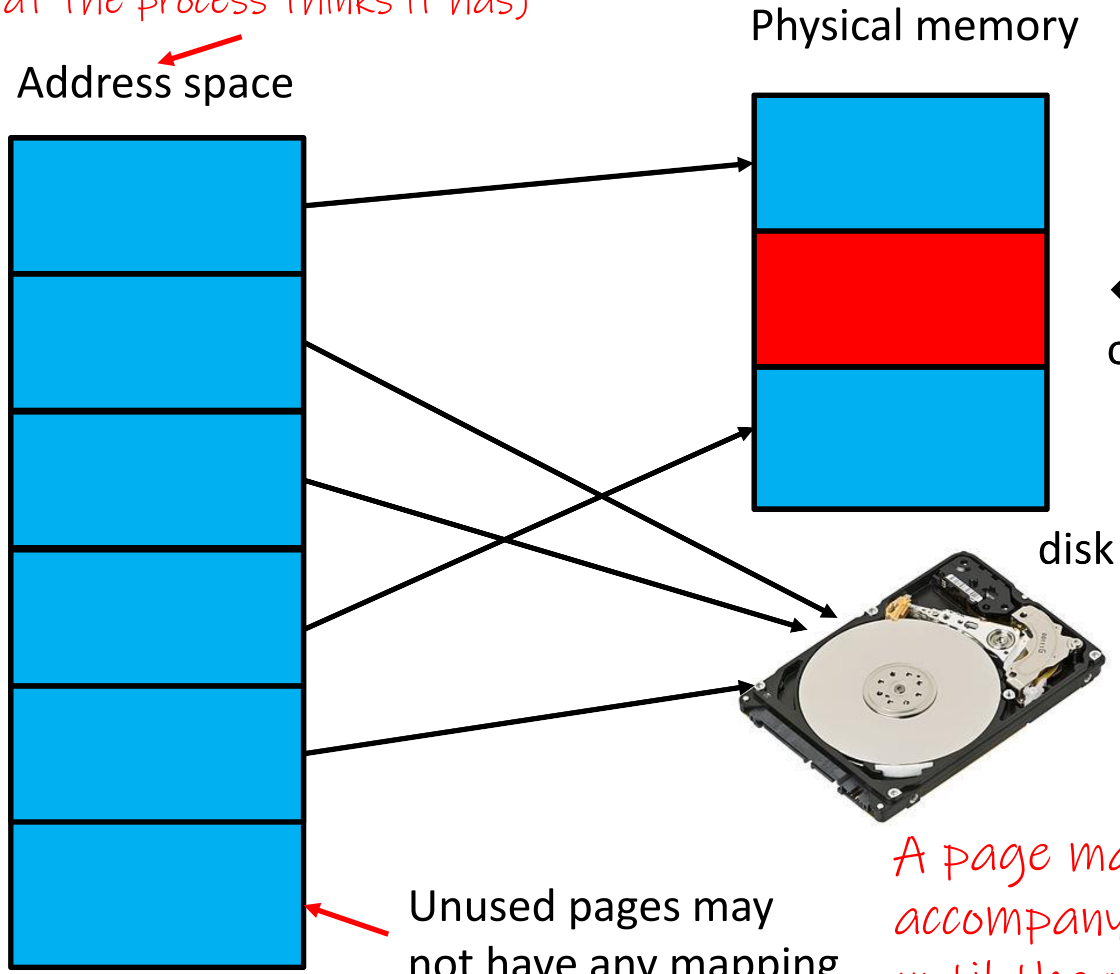
- Data that isn’t currently stored in physical memory, can be stored elsewhere (disk).
  - Disk is "permanent storage" usually used for the file system
  - Disk has a longer access time than physical memory (RAM)

# Pages

Pages are of fixed size ~4KB
4KB -> (4 * 1024 = 4096 bytes.)

- Memory can be split up into units called "pages"

(what the process thinks it has)



Pages currently in use are stored in physical memory (RAM)

← Ram may contain pages from other active processes

Pages in physical memory are called "Page frames"

Pages not currently in use (but were used in the past) are stored on disk

Unused pages may not have any mapping

A page may not have an accompanying page frame until the page is used

# Definitions

Sometimes called "virtual memory" or the "virtual address space"

- Addressable Memory: the total amount of memory that can be theoretically be accessed based on:
  - number of addresses ("address space")
  - bytes per address ("addressability")

IT MAY OR MAY NOT EXIST ONHARDWARE (like if that memory is never used)

- Physical Memory: the total amount of memory that is physically available on the computer

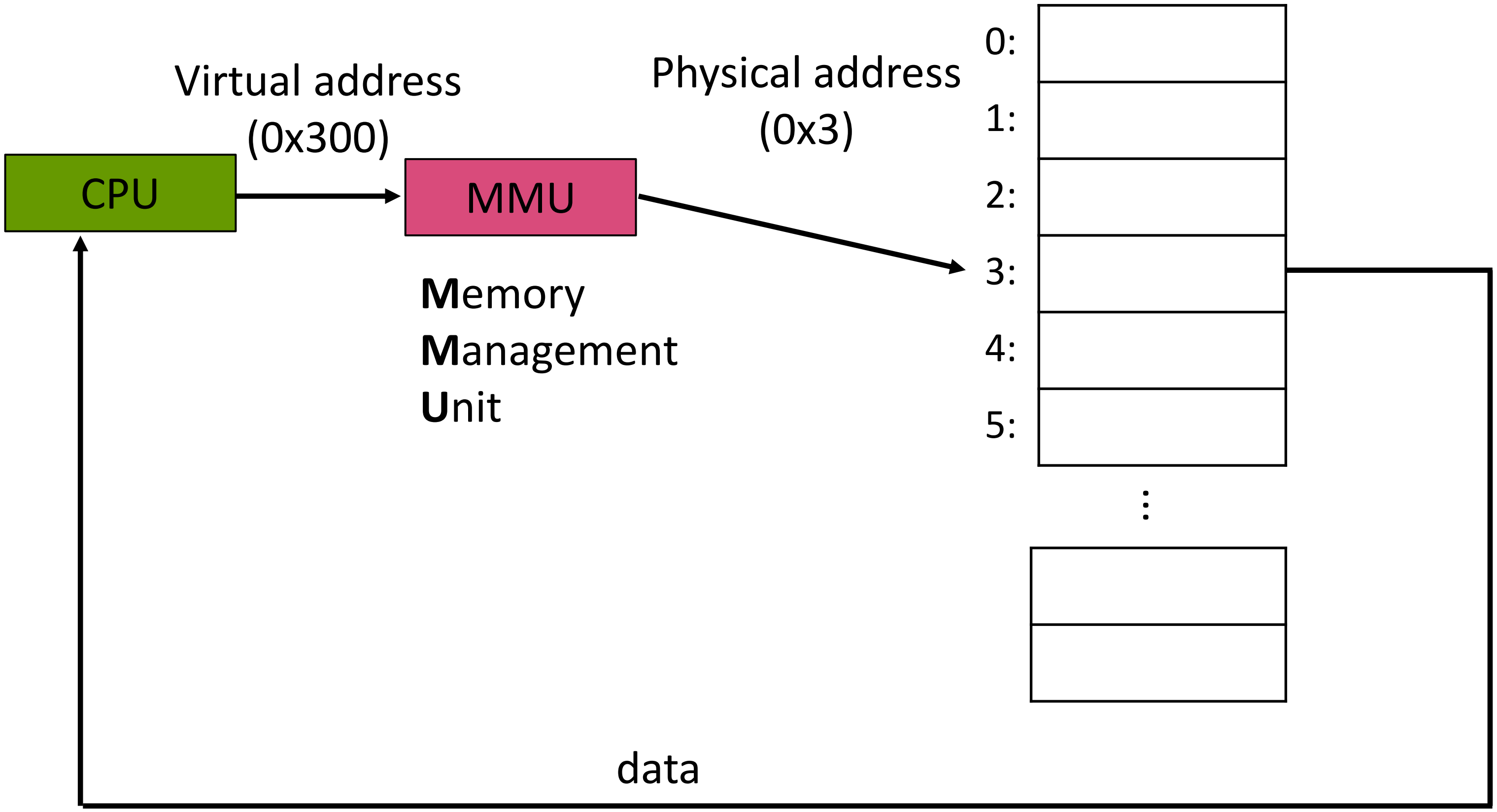
Physical memory holds a subset of the addressable memory being used

- Virtual Memory: An abstraction technique for making memory look larger than it is and hides many details from the programs.

# Virtual Address Translation

THIS SLIDE IS KEY TO THE WHOLE IDEA

- Programs don’t know about physical addresses; virtual addresses are translated into them by the MMU



# Page Tables

More details about translation later

- Virtual addresses can be converted into physical addresses via a page table.

- There is one page table per processes, managed by the MMU

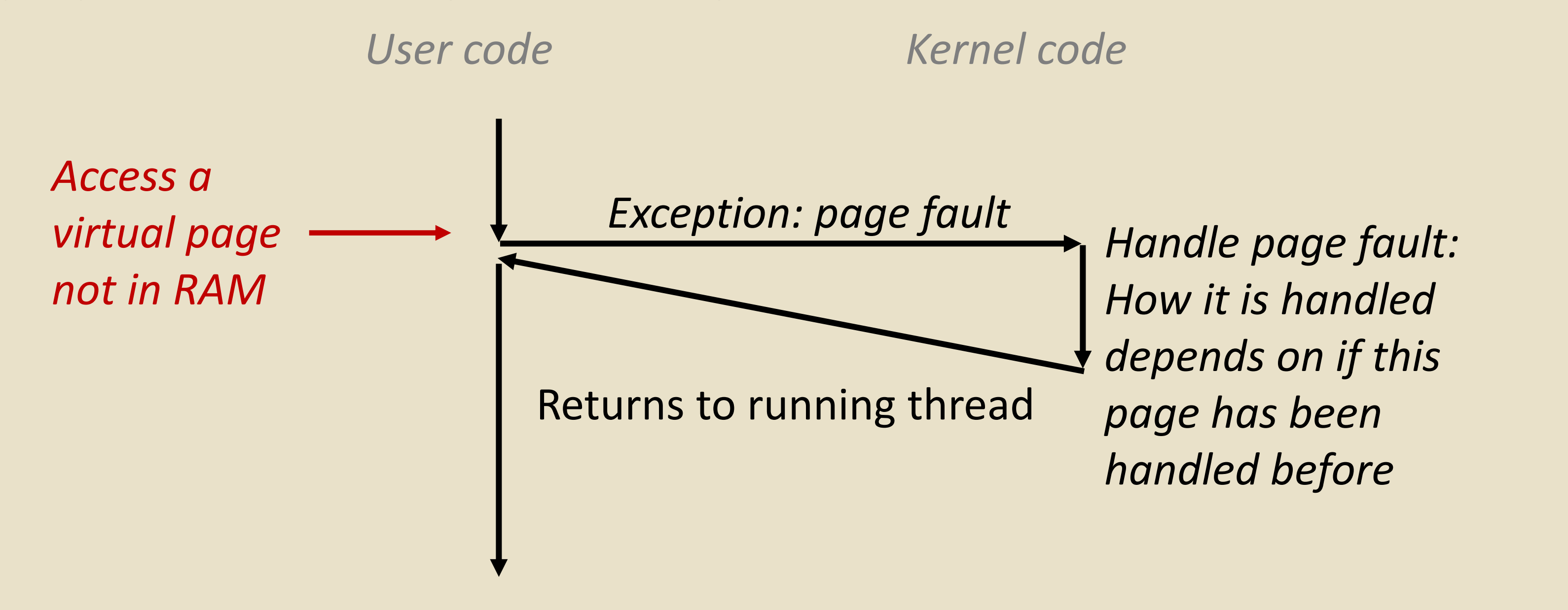
| **Virtual page #** | **Valid** | **Physical Page Number** |
|---|---|---|
| 0 | 0 | null //page hasn't been used yet |
| 1 | 1 | 0 |
| 2 | 1 | 1 |
| 3 | 0 | disk |

Valid determines if the page is in physical memory

If a page is on disk, MMU will fetch it

# Page Fault Exception

- An *Exception* is a transfer of control to the OS *kernel* in response to some ***synchronous event*** *(directly caused by what was just executed)*
- In this case, writing to a memory location that is not in physical memory currently



# Problem: Paging Replacement

More details about page replacement later

- We don’t have space to store all active pages in physical memory.

- If physical memory is full and we need to load in a page, then we choose a page in physical memory to store on disk in the **swap file**

- If we need to load in a page from disk, how do we decide which page in physical memory to “evict”

- Goal: Minimize the number of times we have to go to disk. It takes a while to go to disk.

# Poll Everywhere

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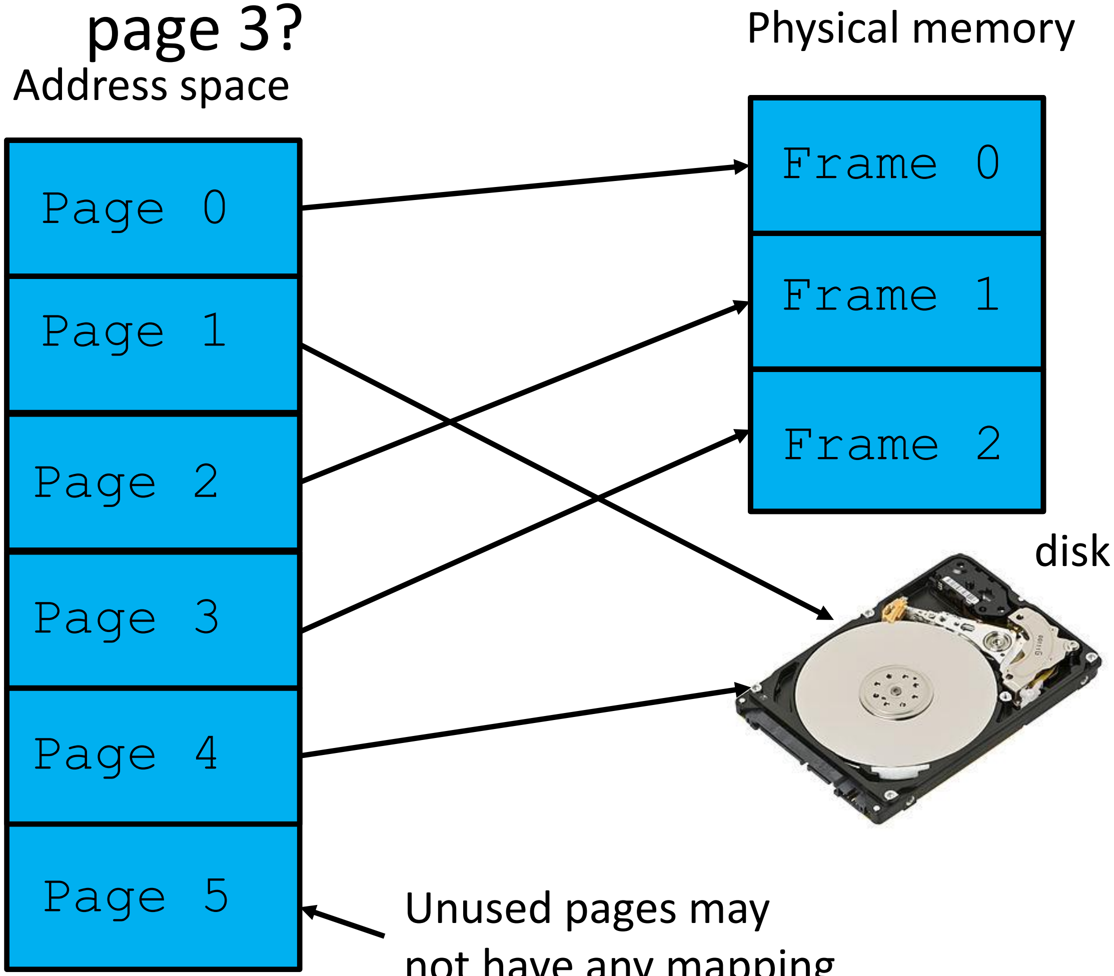
- What happens if this process tries to access an address in page 3?



Pages currently in use are stored in physical memory (RAM)

Pages not currently in use (but were used in the past) are stored on disk

Unused pages may not have any mapping

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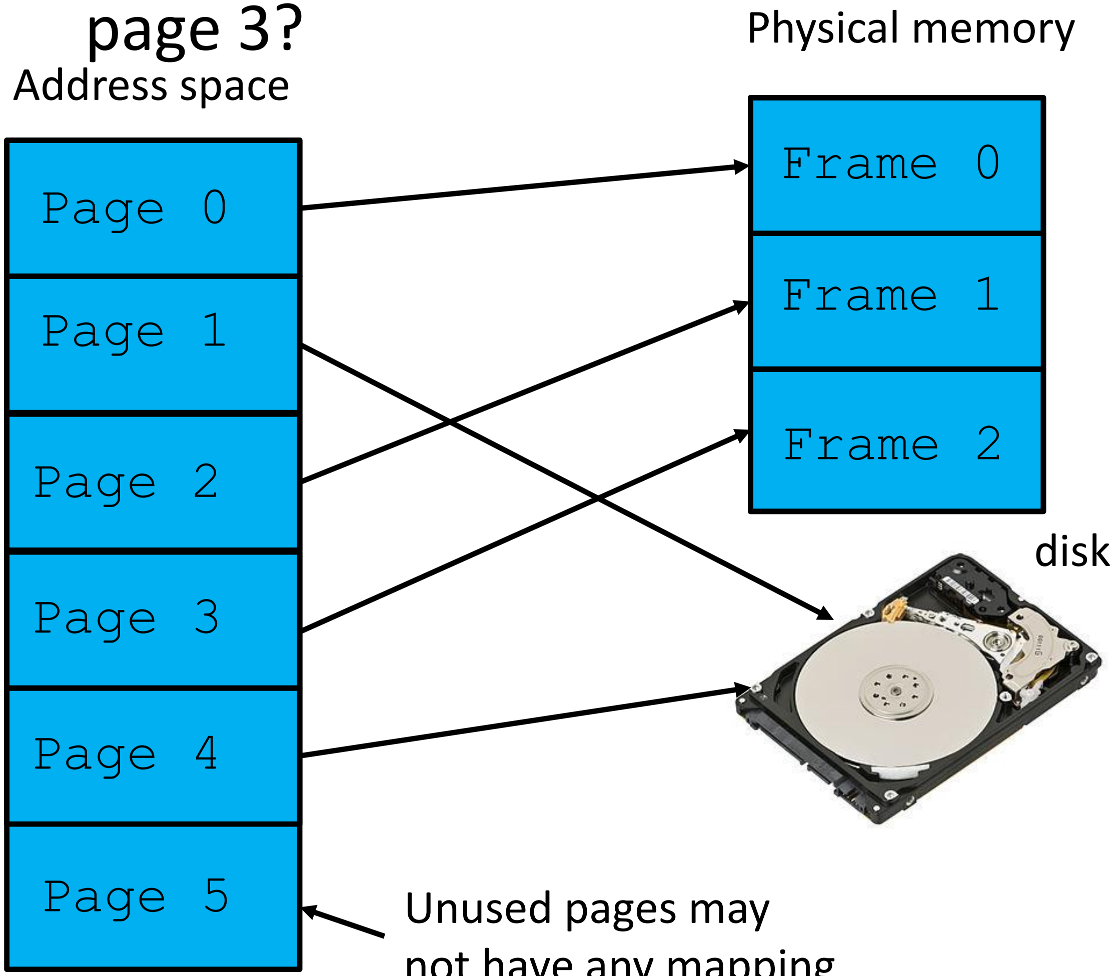

Pages currently in use are stored in physical memory (RAM)

The MMU access the corresponding frame (frame 2)

Pages not currently in use (but were used in the past) are stored on disk

Unused pages may not have any mapping

# Poll Everywhere

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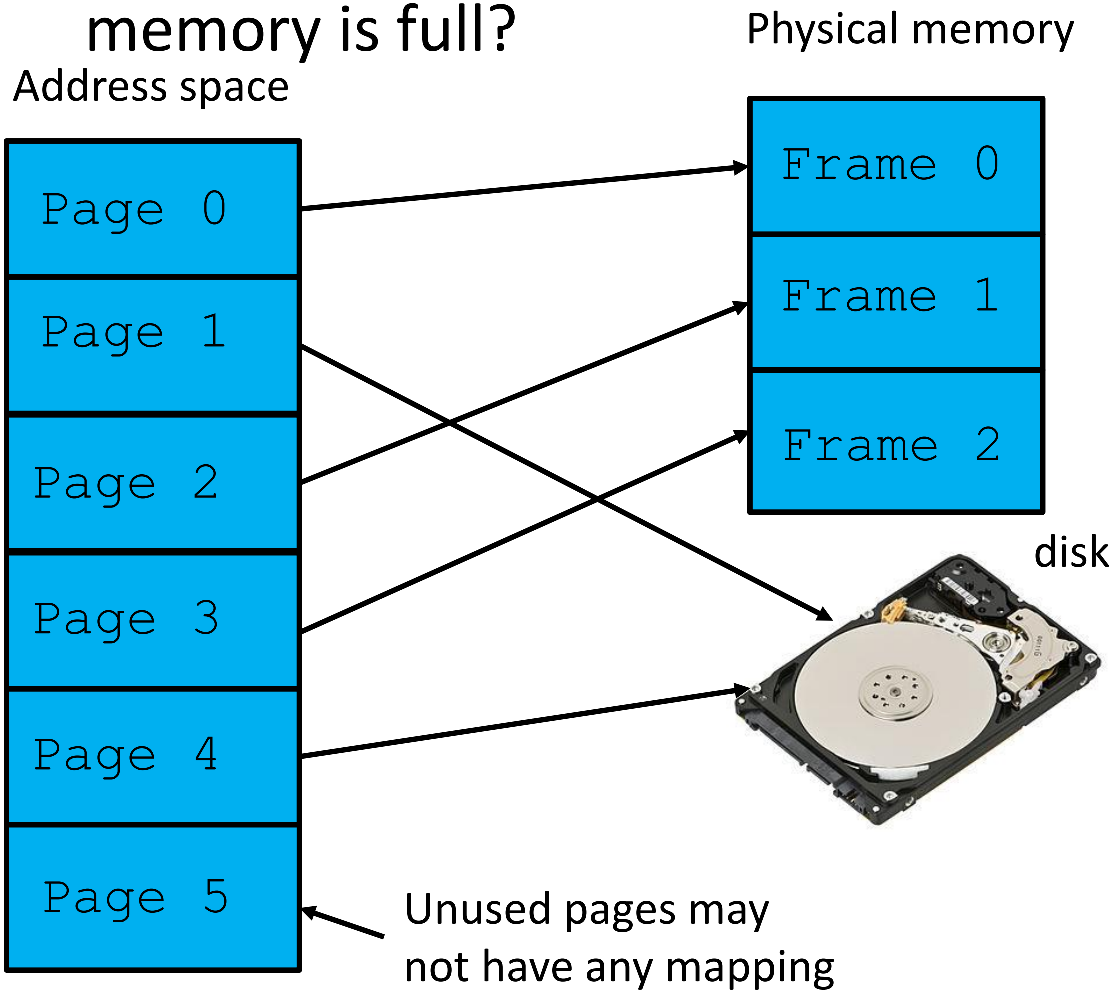
- What happens if we need to load in page 1 and physical memory is full?



Address space

Page 0

Page 1

Page 2

Page 3

Page 4

Page 5

Physical memory

Frame 0

Frame 1

Frame 2

disk

Pages currently in use are stored in physical memory (RAM)

Pages not currently in use (but were used in the past) are stored on disk

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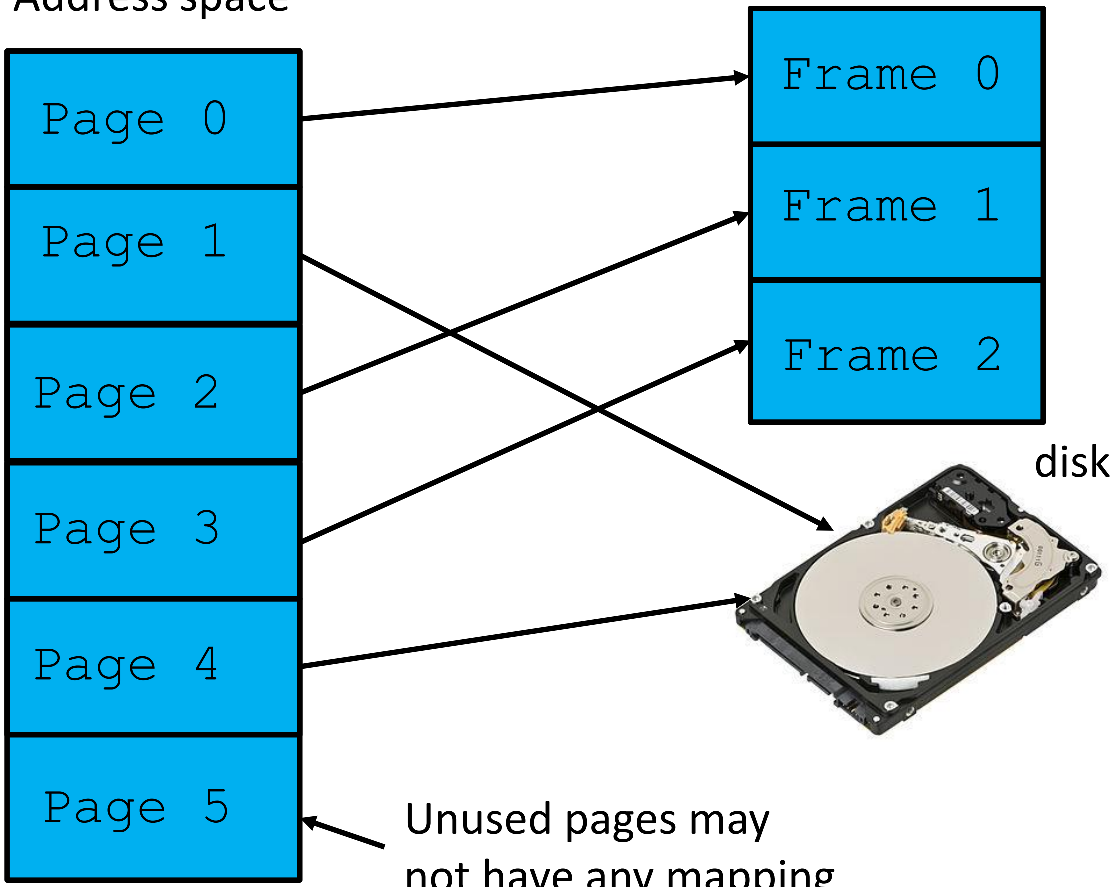

Pages currently in use are stored in physical memory (RAM)

We get a page fault, the OS evicts a page from a frame, loads in new page into that frame

Pages not currently in use (but were used in the past) are stored on disk

Unused pages may not have any mapping

# Lecture Outline

- Problems with old memory model
- Virtual Memory High Level
- **Address Translation**

# Aside: Bits

- We represent data on the computer in binary representation (base 2)
- A bit is a single “digit” in a binary representation.
- A bit is either a 0 or a 1

- In decimal -> 243
- In binary -> 0b11110011

# Hexadecimal

- Base 16 representation of numbers

- Allows us to represent binary with fewer characters
  - 0b11110011 == 0xF3
    ^ **b**inary ^ he**x**

| Decimal | Binary | Hex |
|---|---|---|
| 0 | 0000 | 0x0 |
| 1 | 0001 | 0x1 |
| 2 | 0010 | 0x2 |
| 3 | 0011 | 0x3 |
| 4 | 0100 | 0x4 |
| 5 | 0101 | 0x5 |
| 6 | 0110 | 0x6 |
| 7 | 0111 | 0x7 |
| 8 | 1000 | 0x8 |
| 9 | 1001 | 0x9 |
| 10 | 1010 | 0xA |
| 11 | 1011 | 0xB |
| 12 | 1100 | 0xC |
| 13 | 1101 | 0xD |
| 14 | 1110 | 0xE |
| 15 | 1111 | 0xF |

# Poll Everywhere

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- A page is typically 4 KiB -> $2^{12}$ -> 4096 bytes

- If physical memory is 32 KiB, how many page frames are there?
  A. 5 B. 4 C. 32 D. 8 E. We're lost…

- If addressable memory for a single process consists of 64 KiB bytes, how many pages are there for one process?
  A. 64 B. 16 C. 20 D. 6 E. We're lost…

- If there is one page table per process, how many entries should there be in a single page table?
  A. 6 B. 8 C. 16 D. 5 E. We're lost…

# Poll Everywhere

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- A page is typically 4 KiB -> $2^{12}$ -> 4096 bytes

- If physical memory is 32 KiB, how many page frames are there?

  **A.** 5 **B.** 4 **C.** 32 **D.** 8 **E.** We're lost…

32 KiB / 4 KiB = 8 frames

- If addressable memory for a single process consists of 64 KiB bytes, how many pages are there for one process?

  **A.** 64 **B.** 16 **C.** 20 **D.** 6 **E.** We're lost…

64 KiB / 4 KiB = 16 pages

- If there is one page table per process, how many entries should there be in a single page table?

  **A.** 6 **B.** 8 **C.** 16 **D.** 5 **E.** We're lost…

One entry per page

# Addresses

- Virtual Address:
  - Used to refer to a location in a virtual address space.
  - Generated by the CPU and used by our programs

- Physical Address
  - Refers to a location on physical memory
  - Virtual addresses are converted to physical addresses

# Page Offset

- This idea of Virtual Memory abstracts things on the level of Pages (4096 bytes == $2^{12}$ bytes)
- On almost every machine, memory is ***byte-addressable*** meaning that each byte in memory has its own address
- How many different addresses correspond to the same page? 4096 addresses to a single page
- How many bits are needed in an address to specify where in the page the address is referring to?

12 bits

# Poll Everywhere

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- If there are 16 pages, how many bits would you need to represent the number of pages?
- If there are 8 pages frames, how many bits would we need to represent the number of page frames?

| | Page bits | Frame bits |
|---|---|---|
| **A.** | **4** | **2** |
| **B.** | **4** | **3** |
| **C.** | **3** | **3** |
| **D.** | **5** | **3** |

**E. We're lost…**

# Poll Everywhere

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- If there are 16 pages, how many bits would you need to represent the number of pages?

num_bits = $\log_2(16)$ = 4
or
16 = $2^4$, so 4

- If there are 8 pages frames, how many bits would we need to represent the number of page frames?

num_bits = $\log_2(8)$ = 3
or
8 = $2^3$, so 3

| | Page bits | Frame bits |
|---|---|---|
| A. | 4 | 2 |
| [✓ B.] | 4 | 3 |
| C. | 3 | 3 |
| D. | 5 | 3 |
| E. | We're lost… | |

# Steps For Translation

- Derive the virtual page number from a virtual address
- Look up the virtual page number in the page table
  - Handle the case where the virtual page doesn't correspond to a physical page frame
- Construct the physical address

# Address Translation: Virtual Page Number

- A virtual address is composed of two parts relevant for translating:

| | |
|---|---|
| **Virtual Page Number** | **Page Offset** |

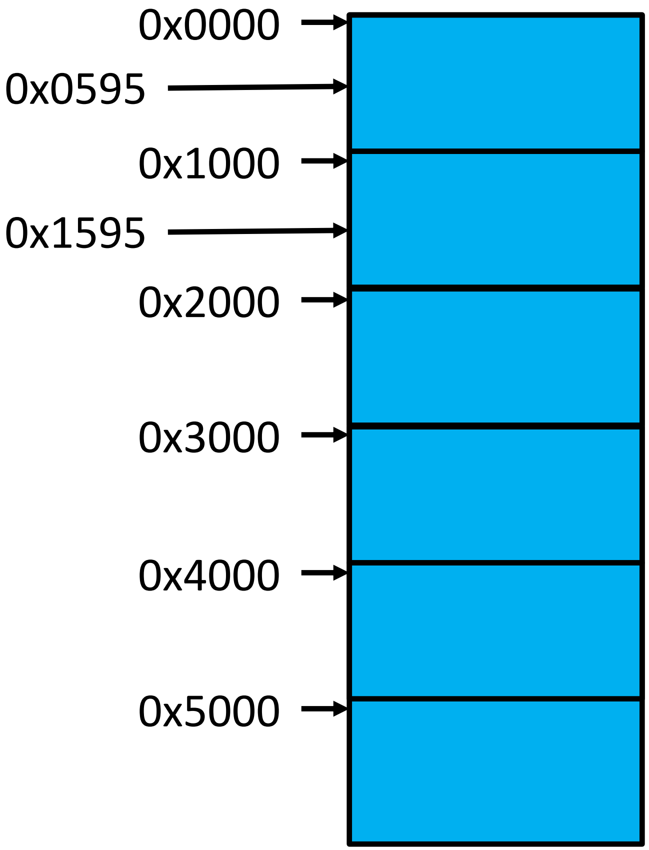
  - Virtual Page Number length = bits to represent number of pages
  - Page offset length = bits to represent number of bytes in a page

- The virtual page number determines which page we want to access

- The page offset determines which location within a page we want to access.
  - Remember that a page is many bytes (~4KiB -> 4096 bytes)

# Virtual Address High Level View

- High level view:
  - Each page starts at a multiple of 4096 (0X1000)
  - If we take an address and add 4096 (0x1000) we get the same offset but into the next page



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- Example address: 0x1234
  - What is the page number?
  - What is the offset?
  - Reminder: there are 16 virtual pages, and a page is 4096 bytes

# Address Translation: Virtual Page Number

- A virtual address is composed of two parts relevant for translating:

| | |
|---|---|
| **Virtual Page Number** | **Page Offset** |

  - Virtual Page Number length = bits to represent number of pages
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- Example address: 0x1234 `0001 0010 0011 0100`
  - What is the page number? `0001 -> 0x1`
  - What is the offset? `0010 0011 0100 -> 0x234`
  - Reminder: there are 16 virtual pages, and a page is 4096 bytes

# Address Translation: Lookup & Combining

- Once we have the page number, we can look up in our page table to find the corresponding physical page number.
  - For now, we will assume there is an associate page frame

| Virtual page # | Valid | Physical Page Number |
|---|---|---|
| 0x0 | 0 | null |
| 0x1 | 1 | 0x5 |
| … | … | … |

- With the physical page number, combine it with the page offset to get the physical address

| Physical Page Number | Page Offset |
|---|---|

  - Since we only need 3 bits to represent the physical page number, we only 15 bits for the address (as opposed to 16).
  - In our example, with 0x1234, our physical address is 0x5234

Translation Done!

# Page Faults

- What if we accessed a page whose page frame was not in physical memory?

| **Virtual page #** | **Valid** | **Physical Page Number** |
|---|---|---|
| 0x0 | 0 | null |
| 0x1 | 1 | 0x0 |
| 0x2 | 1 | 0x5 |
| 0x3 | 0 | Disk |
| … | … | … |

- In this example, Virtual page 0x0 and 0x3

# Page Faults

| Virtual page # | Valid | Physical Page Number |
|---|---|---|
| 0x0 | 0 | null |
| 0x1 | 1 | 0x0 |
| 0x2 | 1 | 0x5 |
| 0x3 | 0 | Disk |
| … | … | … |

- In this example, Virtual page 0x3, whose frame is on disk (page 0x3 handled before, but was evicted at some point)
  - MMU fetches the page from disk
  - Evicts an old page from physical memory if necessary
    - Uses LRU or some page replacement algorithm
    - Writes the contents of the evicted page back to disk
  - Store the previously fetched page to physical memory

# Page Faults

| **Virtual page #** | **Valid** | **Physical Page Number** |
|---|---|---|
| 0x0 | 0 | null |
| 0x1 | 1 | 0x0 |
| 0x2 | 1 | 0x5 |
| 0x3 | 0 | Disk |
| … | … | … |

- In this example, Virtual page 0x0, which has never been accessed before
  - Evict an old page if necessary
  - Claim an empty frame and use it as the frame for our virtual page