Course website temporary issues + updated slides #875

Giulia Guidi STAFF
4 minutes ago in General

UNPIN STAR WATCHING 3 VIEWS

Hi,

The course website is not updating and deploying correctly. The staff is looking into it but in the meantime please find updated slides for lectures 19-21 in this post.

Best,

Prof. Guidi

19-guidi-syscalls.pdf

20-guidi-syscalls-vm.pdf

21-guidi-vm.pdf

Cornell Bowers C·IS
Computer Science

CS3410: Computer Systems and Organization

LEC21: Virtual Memory

Professor Giulia Guidi
Monday, November 10, 2025

Credits: Bala, Bracy, Garcia, Guidi, Kao, Sampson, Sirer, Weatherspoon

Plan for Today

- Review of system call
- On to virtual memory!

Review of system call

Ex: `fork()`

- `fork()` is used to create a new process by duplicating the calling process
  - The new process is called the **child** process
  - The original process is called the **parent** process

- `fork()` function prototype:

```
pid_t fork(pid_t pid);
```

- `fork()` is called, then both processes continue executing the code **after the `fork()` call**, but they have **different PIDs**

Ex: `exec()`

- `exec()` replaces the current process image with a new process image
  - Commonly used functions: `execl()`, `execp()`, `execv()`, etc.

- `exec()` function prototype:

```
int execl(const char *path, const char *arg, ...);
```

- `exec()` basically ***changes*** what a process does

Ex: `waitpid()`

- `waitpid()` is used to wait for state changes in a child process
  - It can be used to wait for a specific child process to terminate
- `waitpid()` function prototype:

```
pid_t waitpid(pid_t pid, int *status, int options);
```

Return value	**Return value of `waitpid()`**
`> 0`	`PID` of the child whose state has changed
`0`	(only if `WNOHANG` used) — no child has exited yet
`-1`	-1

`waitpid()` vs `wait()`

- `waitpid()` is used to wait for state changes in a child process
  - It can be used to wait for a specific child process to terminate

- `waitpid()` function prototype:

```
pid_t waitpid(pid_t pid, int *status, int options);
```

Call	It means…
`wait(&status)`	It waits for **any** child to terminate
`waitpid(-1, &status, 0)`	Same as `wait()`
`waitpid(pid, &status, 0)`	It waits for **that specific `pid` child**

How Processes Are Terminated?

- The system calls for termination are:
  - **`exit()`**: used by a process to terminate itself
  - **`abort()`**: used by a parent process to terminate a child process
  - **`wait()`** and **`waitpid()`**: used by a parent process to wait for the termination of a child process and retrieve its exit status

False Friend `kill()`

- Despite its name, `kill()` doesn't necessarily *kill* a process; it can send **any** signal, including ones that don't terminate the target
- `kill()` function prototype:

```
int kill(pid_t pid, int sig);
```

Outcome	**Return value of `kill()`**
Success	`0`
Error	`-1`

Conceptual RISC-V Print “Hello”

Conventionally, a7 holds the **system call number**: it tells the OS **which** service the program is asking for

```
# RISC assembly pseudo-code
li    a7, 4            # Load system call code for 'print string'
la    a0, msg          # Load address of message
ecall                  # Call to the OS
...
msg:  .asciiz "Hello!"
```

PC moves from **user** space to **kernel** space (more on this later)

This is a **special instruction** that triggers a **trap** to the operating system (OS)

- The OS looks at `a7` (system call number = 4) and `a0` (address of string)
- It performs the requested service: writing “`Hello!`” to the terminal

Interrupt

An **interrupt** is a signal sent to the processor by hardware or software indicating an event that needs immediate attention

Poll

What is the key difference between a hardware interrupt and a software interrupt?

[PollEv.com /gguidi](https://PollEv.com/gguidi)

Or send **gguidi** to **22333**

Types of Interrupt

- **Hardware Interrupt:** Generated by external hardware devices to get the CPU's attention
    - Keyboard input (key press)
    - Mouse movement or click
    - Disk I/O completion
    - Network packet arrival

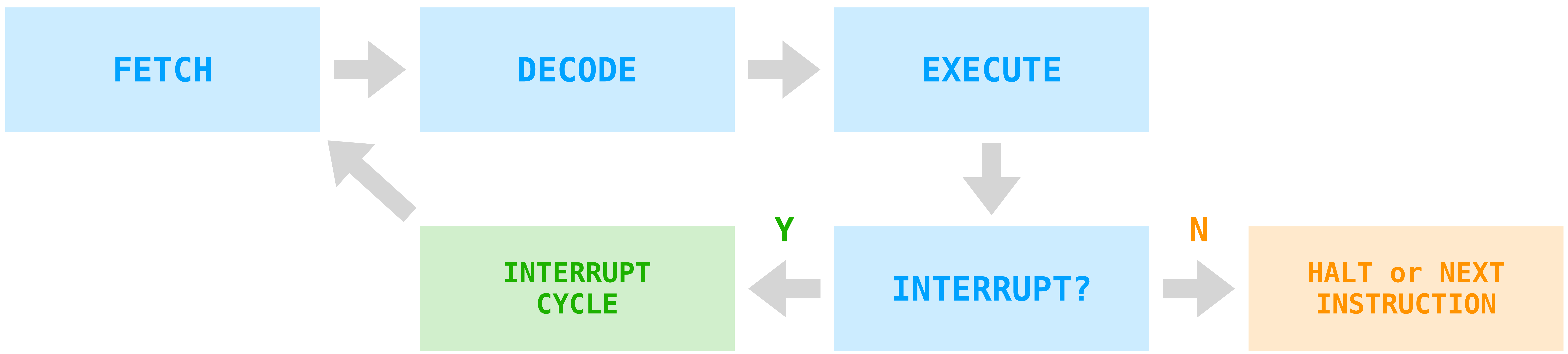
Type	Description
Maskable Interrupt	Can be temporarily "masked" (disabled) by the CPU; used for regular hardware events
Non-Maskable Interrupt	Cannot be disabled; reserved for critical events like hardware failure or power issues

Types of Interrupt

- **Software Interrupt**: Generated by a program or the operating system, typically to request a system service or perform an exception
    - System calls (e.g., syscall instruction)
    - Exceptions like divide-by-zero or invalid memory access
    - Breakpoints during debugging

Type	Description
System Call Interrupt	Triggered by a program to request OS services (e.g., file read/write)
Exception Interrupt	Generated automatically when an error or specific condition occurs (divide by zero, page fault)
Software-Generated Signal	Explicitly triggered in software (e.g., raise(), kill() in Unix)

Instruction Cycle and Interrupt



How Interrupts Work

- **Interrupt Signal**
  - An interrupt signal is sent to the CPU by a hardware device or software
- **Saving State**
  - The CPU saves the current state of the running process (e.g., program counter, registers) so it can resume execution later
- **Interrupt Handling**
  - The CPU transfers control to the interrupt handler associated with the interrupt. The interrupt handler processes the event (e.g., reading data from a device)
- **Restoring State**
  - The CPU restores the saved state and resumes execution of the interrupted process

Ok, introduction to virtual memory

Process = running program

Syscall = how it asks the kernel to do privileged work on its behalf

Big Picture: Processes

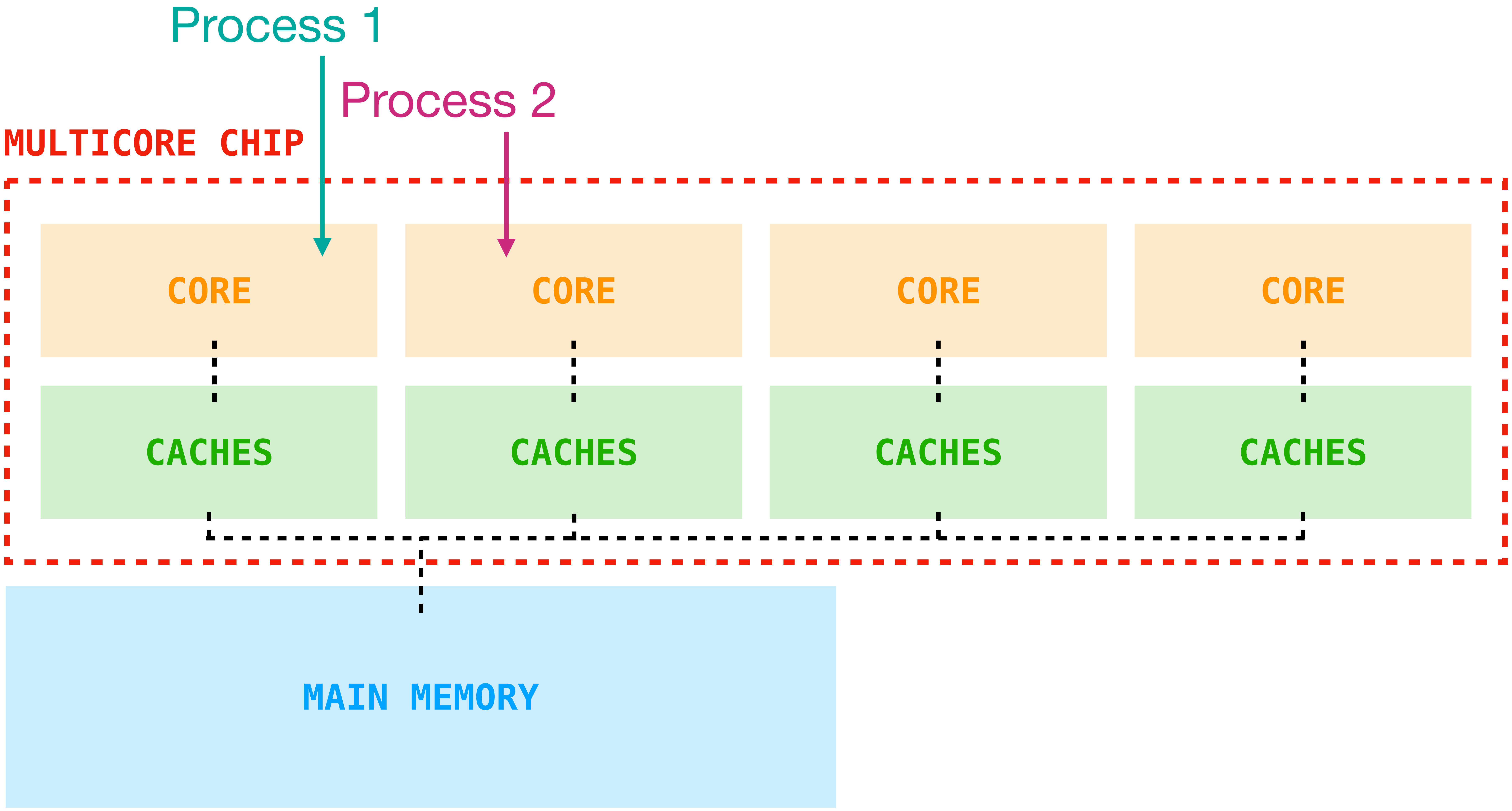
Each process requires memory to hold:

- Its **instructions** (the code to run)
- Its **data** (variables, heap)
- Its **stack** (function calls, local variables)

The **problem**:

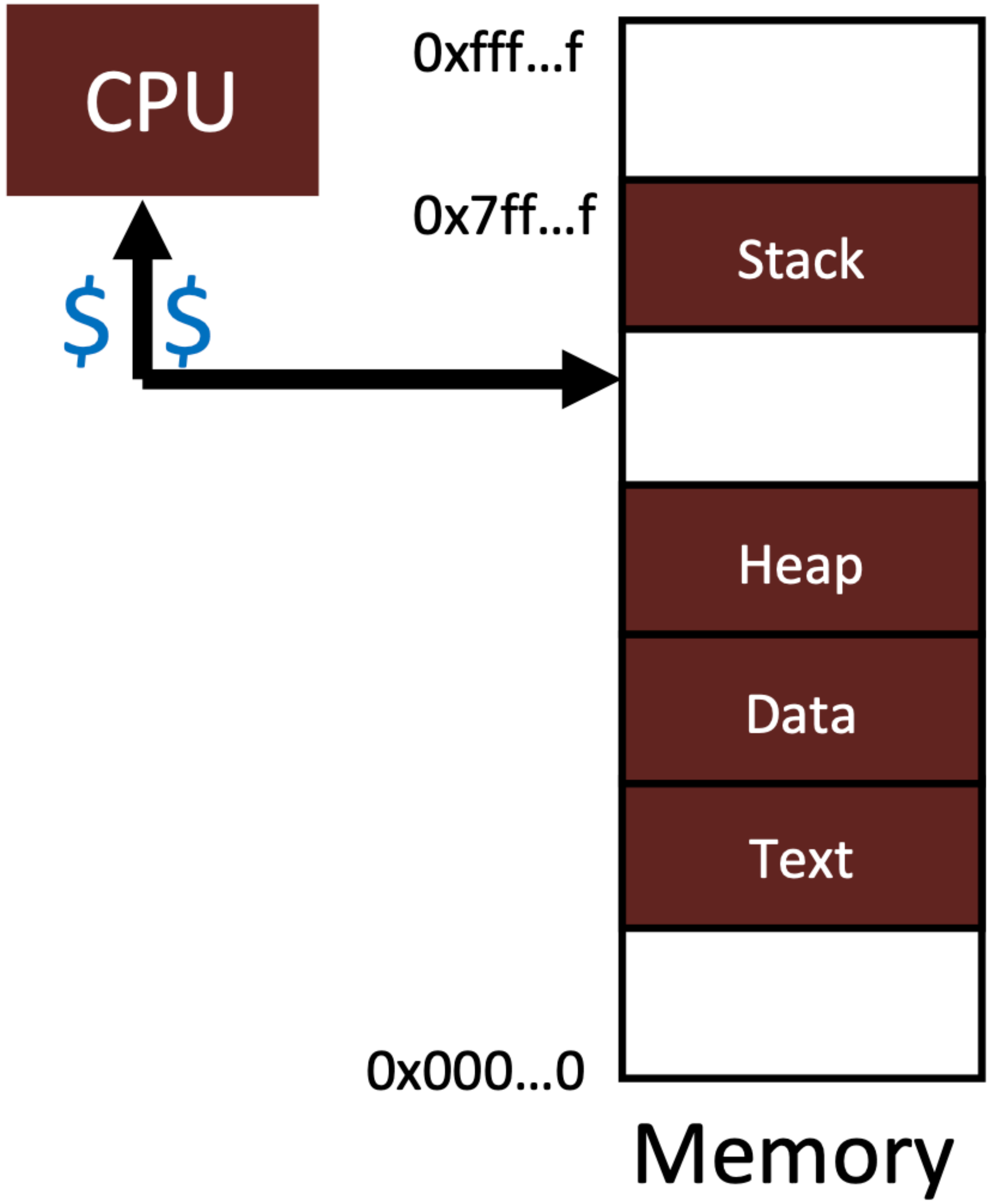
- In reality, multiple processes run **at the same time**
- They all think they're using the same memory addresses (like address `0x400000`)

Multi-Core Processor



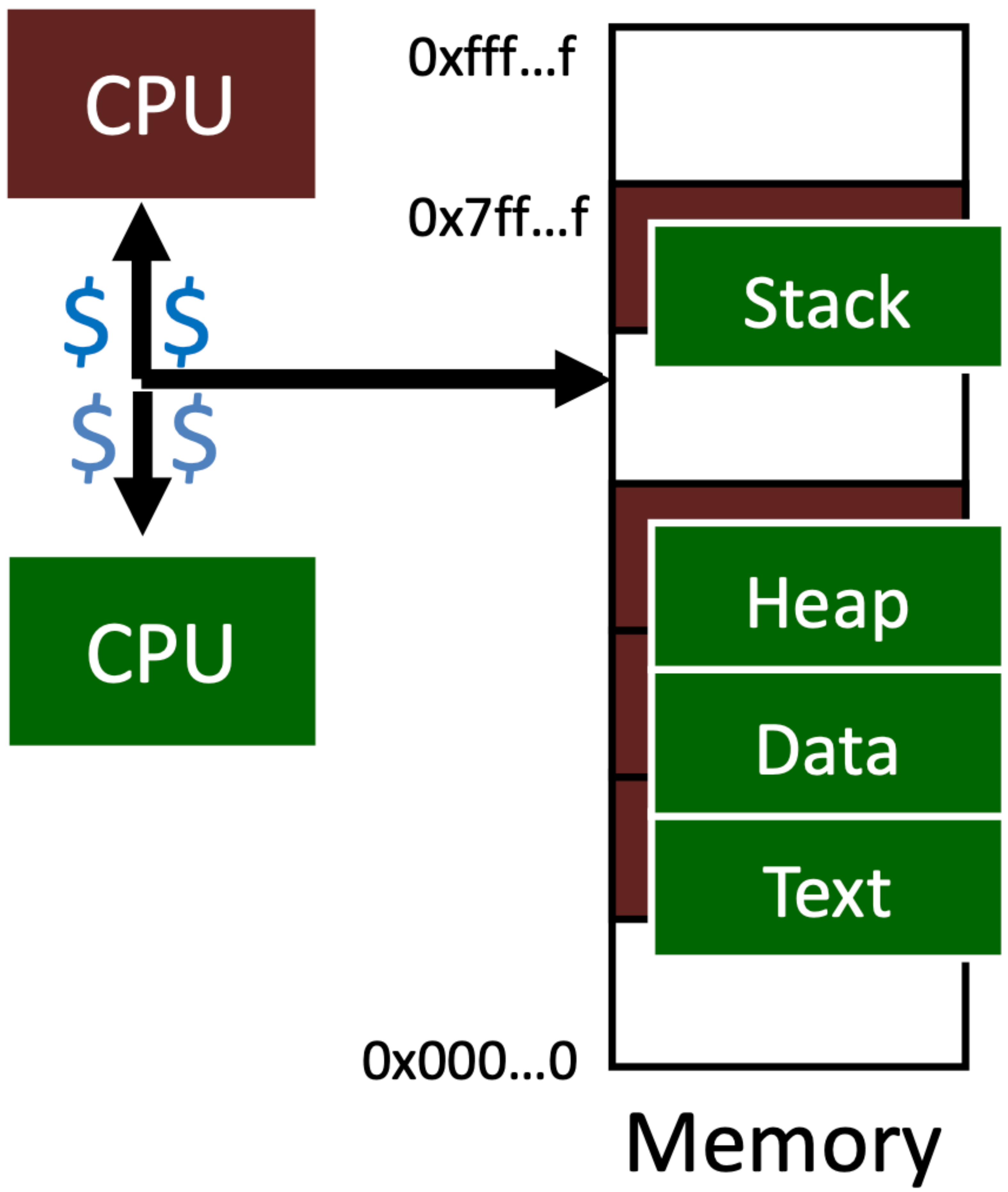
Processor & Memory

- CPU address/data bus...
  - … routed through caches
  - … to main memory
  - It's simple, fast, but…



Processor & Memory

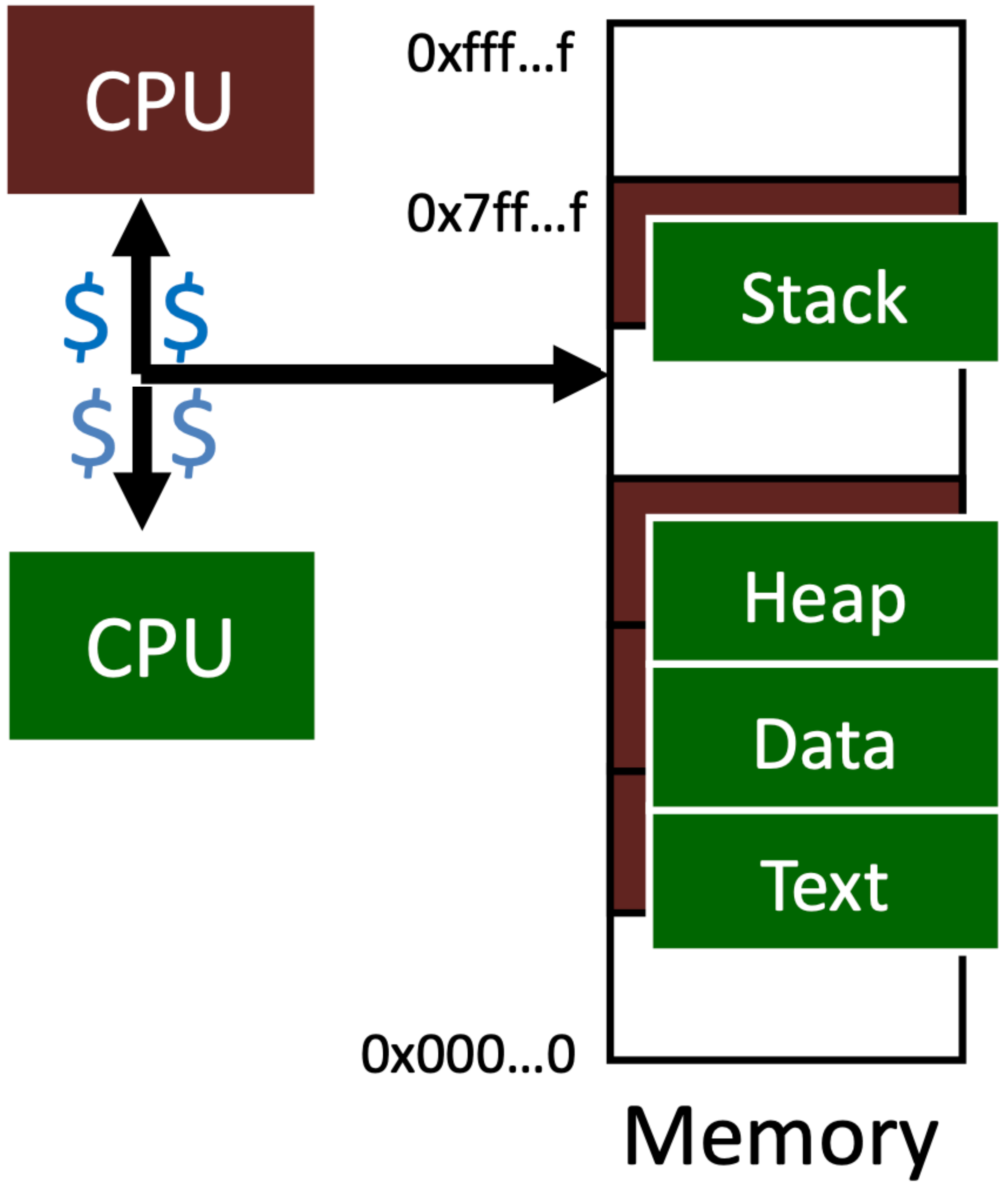
- So what happens when when another program is executed concurrently on another processor?
- The addresses will conflict
  - Even if CPUs take turns using memory bus



Processor & Memory

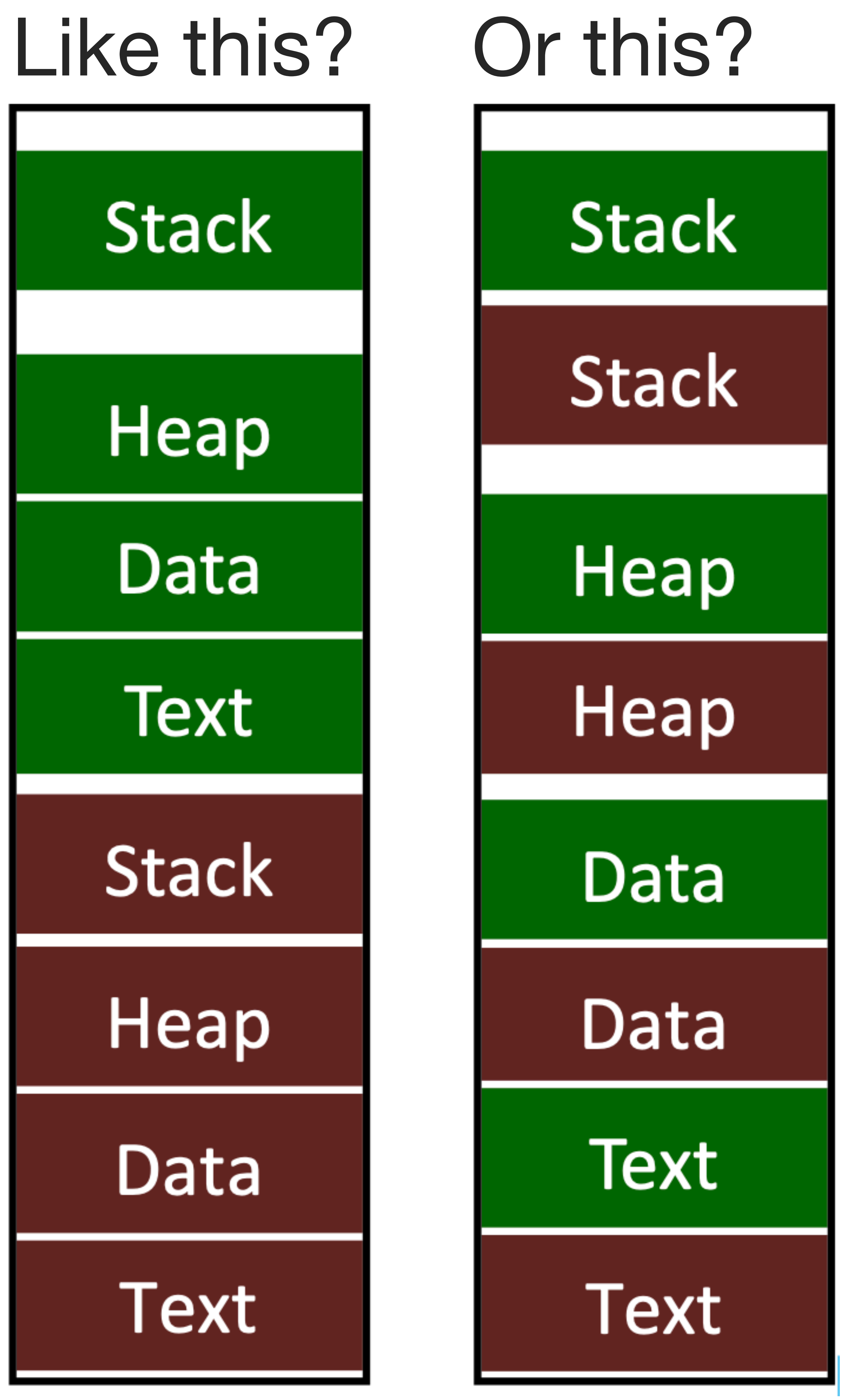
- So what happens when when another program is executed concurrently on another processor?
- The addresses will conflict
  - Even if CPUs take turns using memory bus

  - Solutions?
    - **Can we relocate second program?**



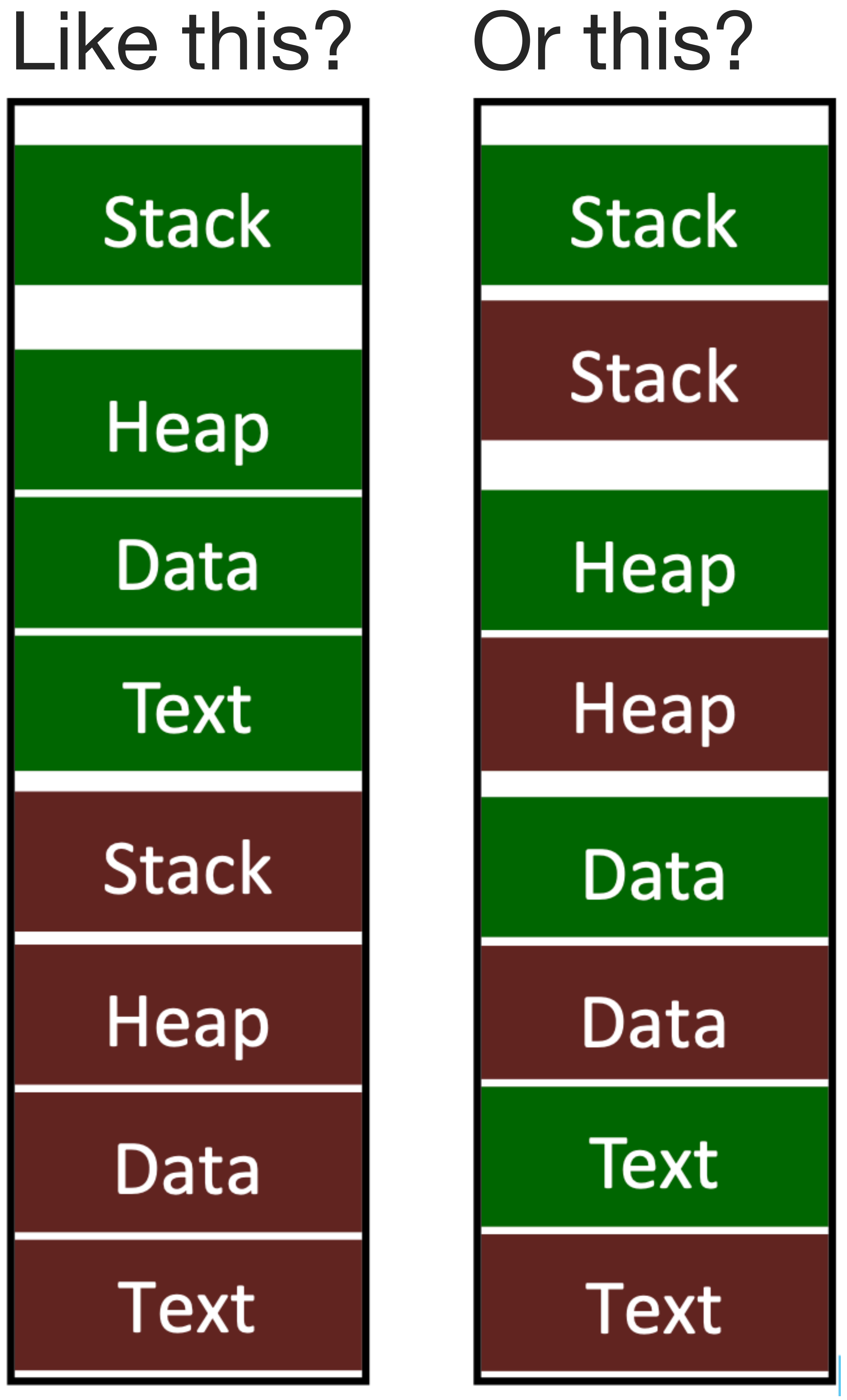
Can We Relocate Second Program?

- Yes but how?



Can We Relocate Second Program?

- Yes but how?
- Do we split 50/50?
  - If they don't fit?
  - If not contiguous?
  - Do I need to recompile?



Poll

True or False: The problem of two processes sharing DRAM only exists on a multicore machine

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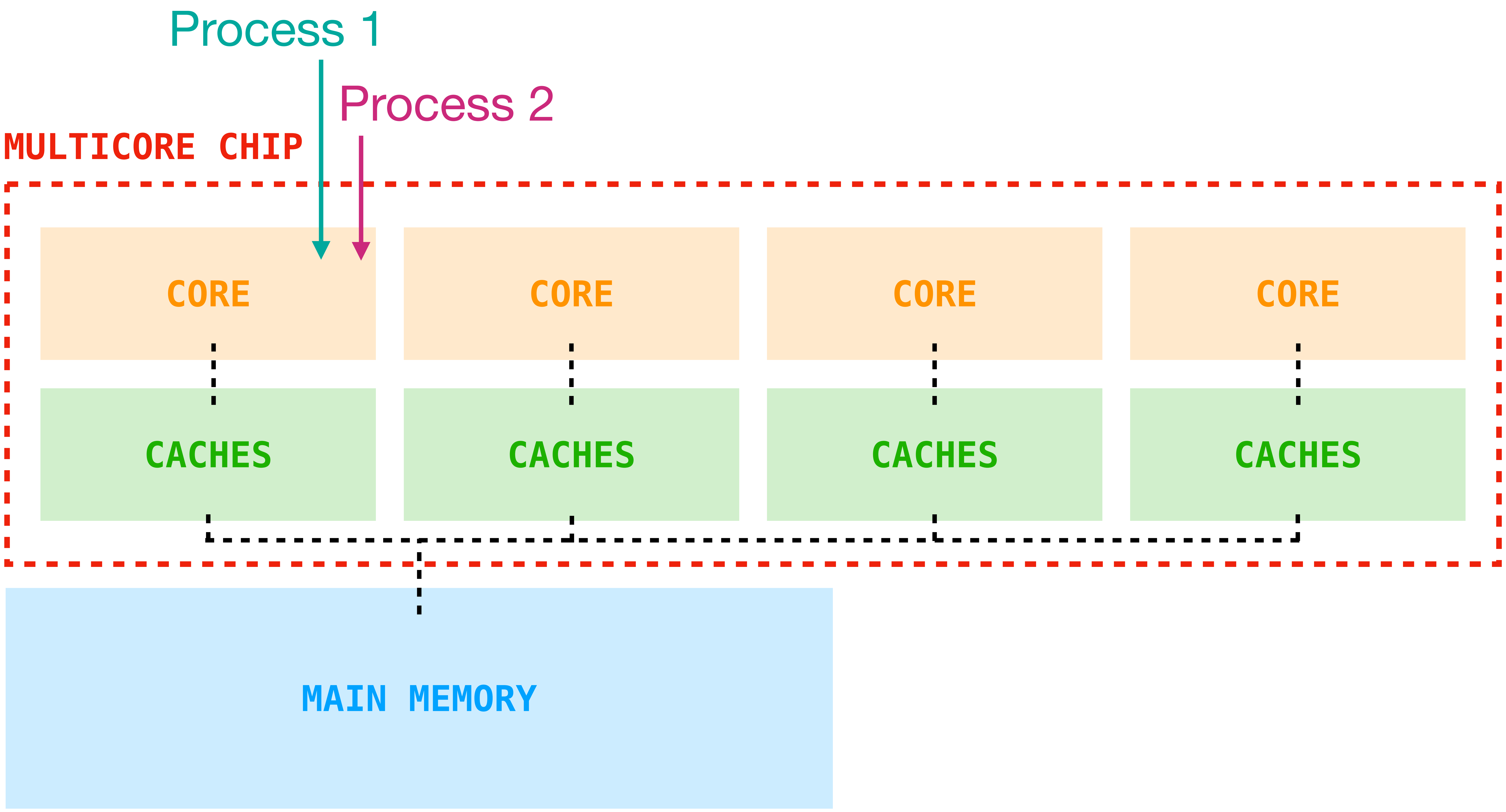
Or send **gguidi** to **22333**

Poll

True or False: The problem of two processes sharing DRAM only exists on a multicore machine

memory **contention** can occur even on a single-core machine due to time-sharing; multicore just increases simultaneous access

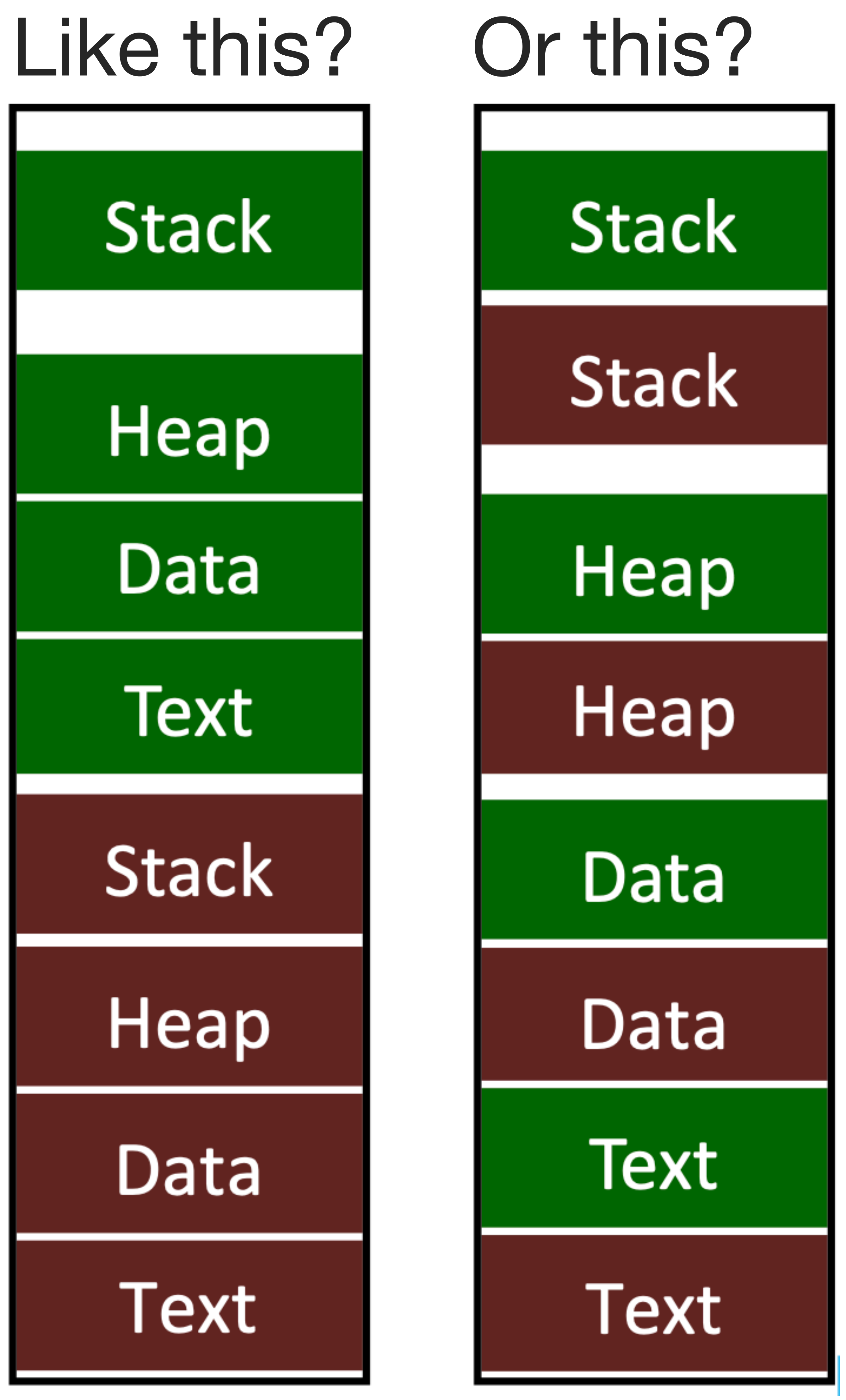
Multi-Core Processor



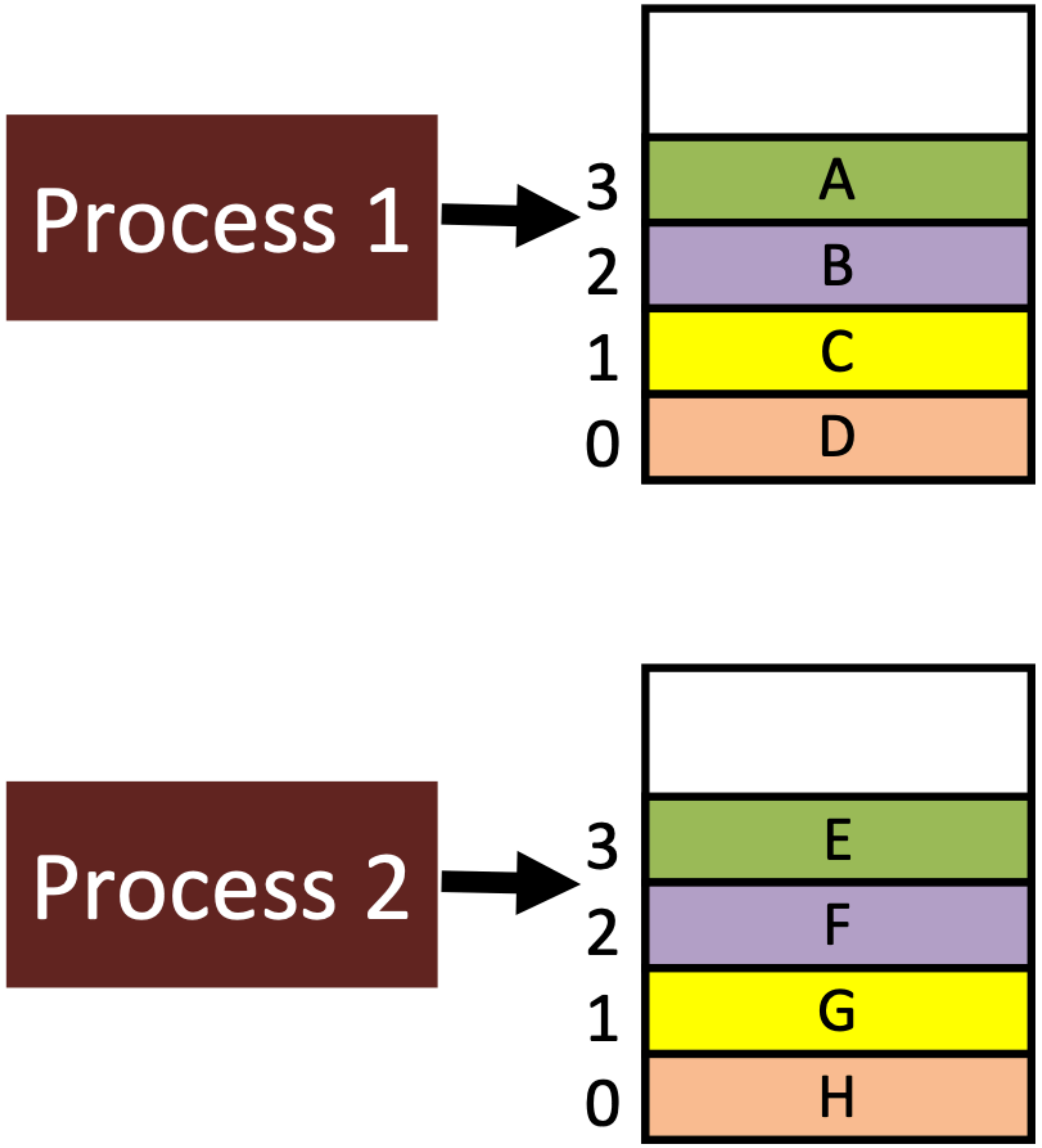
Can We Relocate Second Program?

- Yes but how?
- Do we split 50/50?
  - If they don't fit?
  - If not contiguous?
  - Do I need to recompile?

- This is a problem even on a single core machine (runs multiple processes at a time)

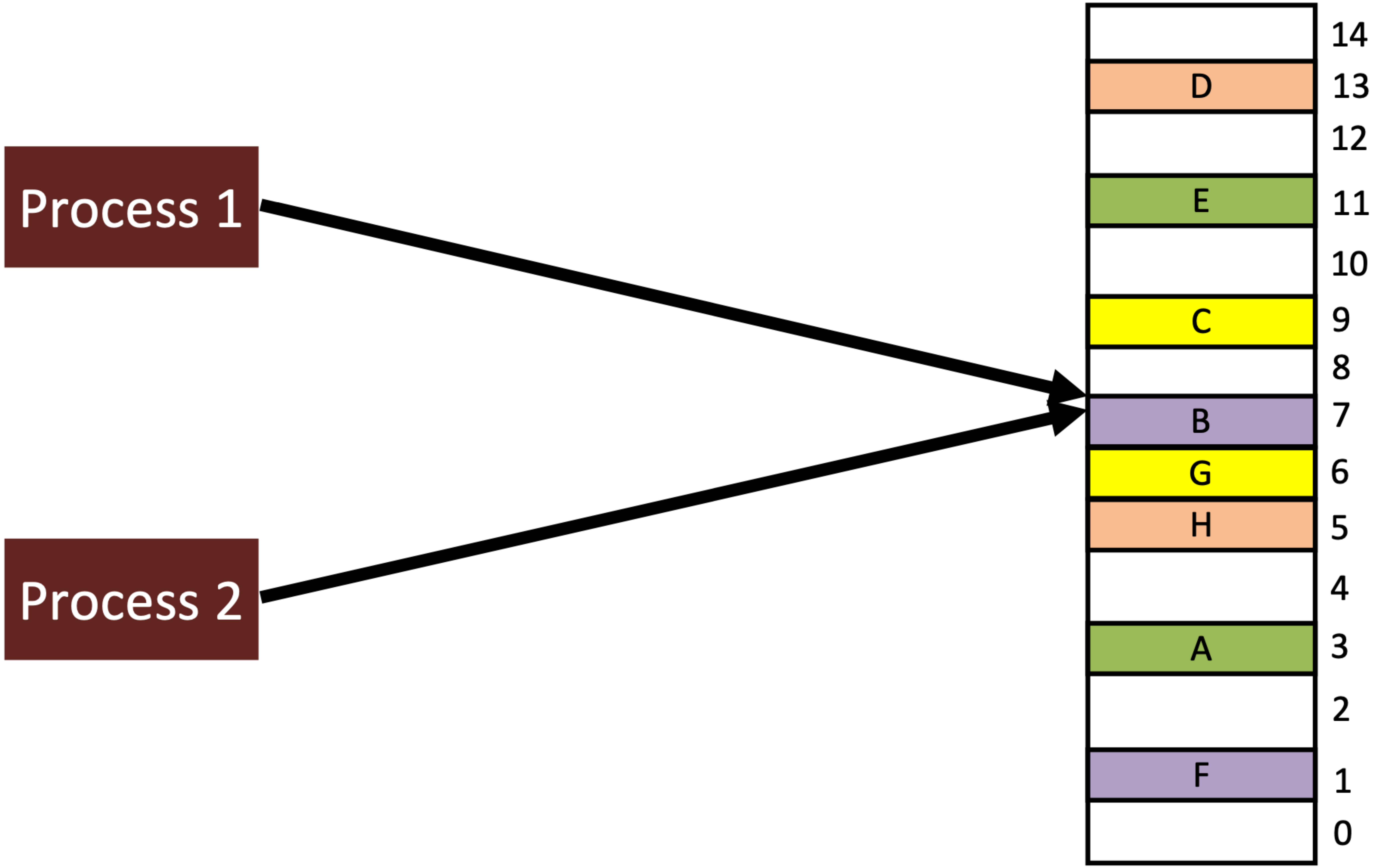


Big Picture: Virtual Memory

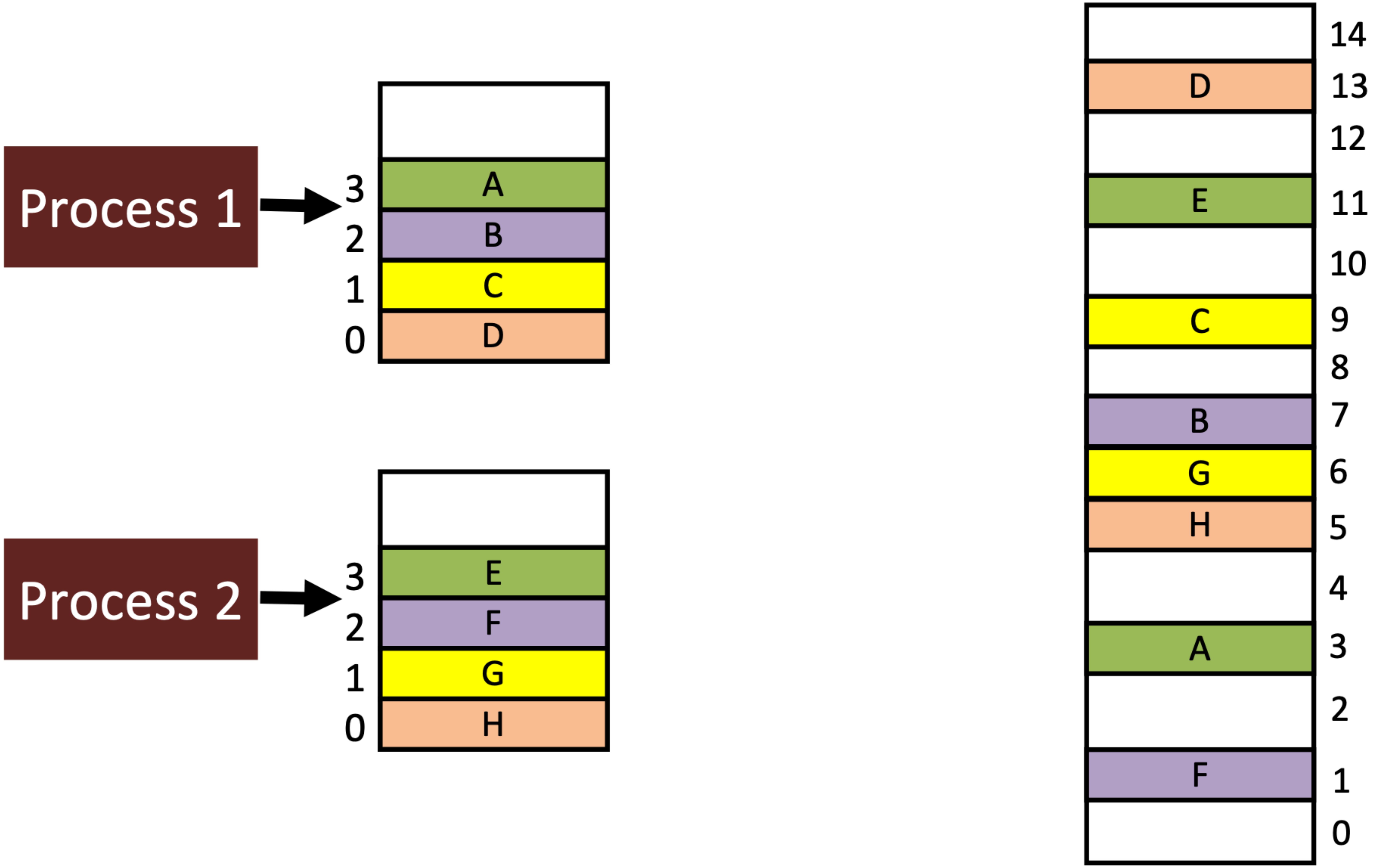


Give each process an **illusion** that it has **exclusive** access to entire main memory

But in Reality



How Do We Create the Illusion?



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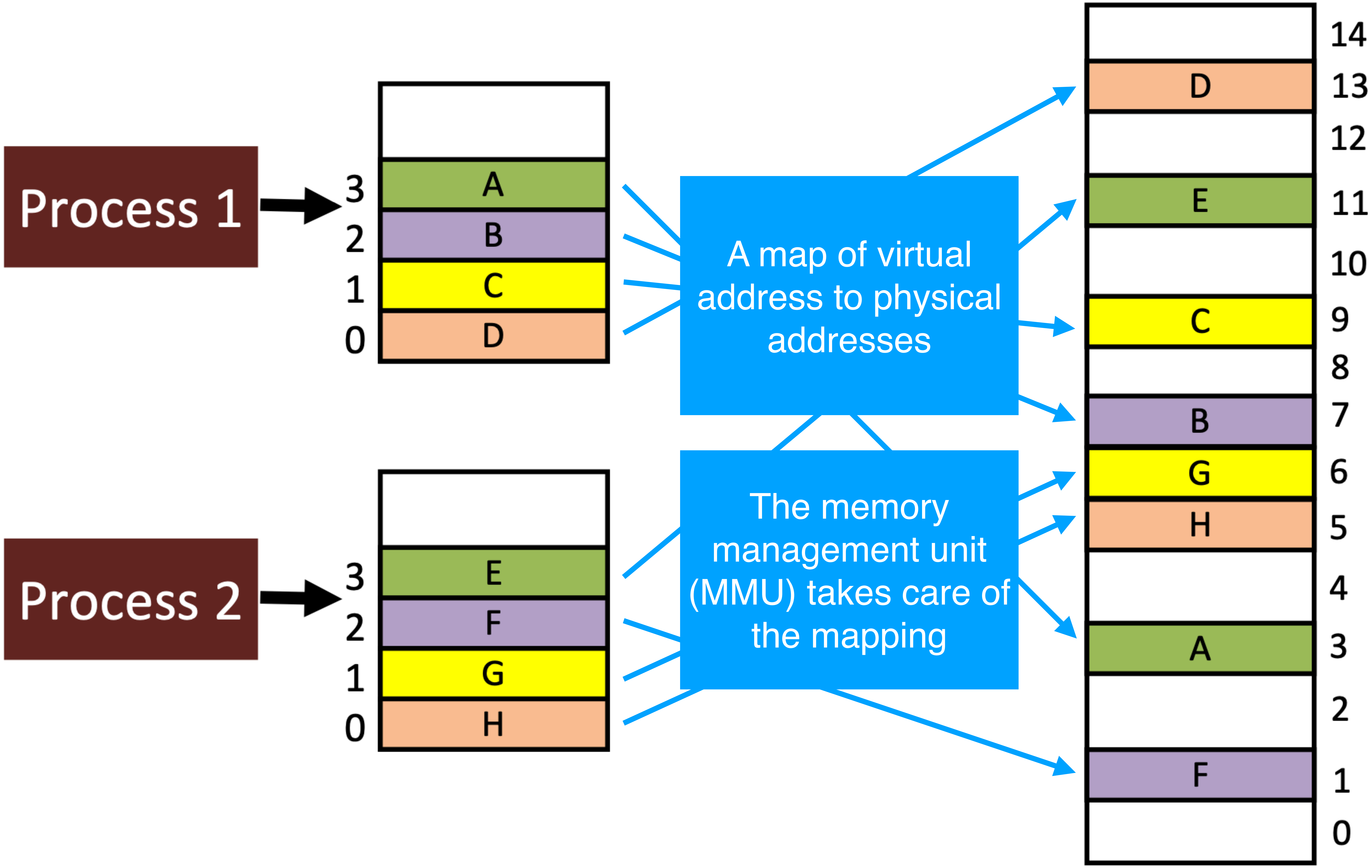

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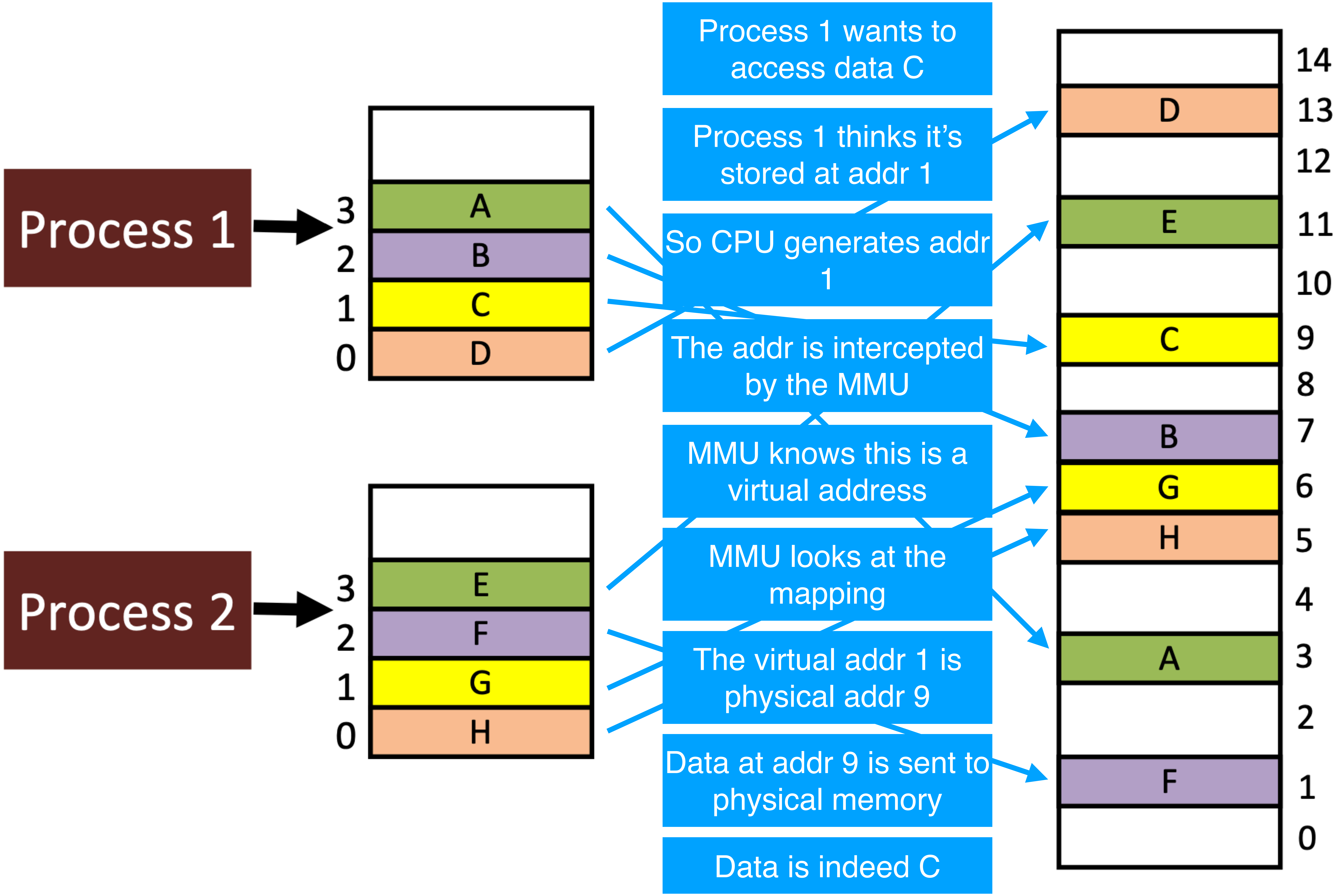

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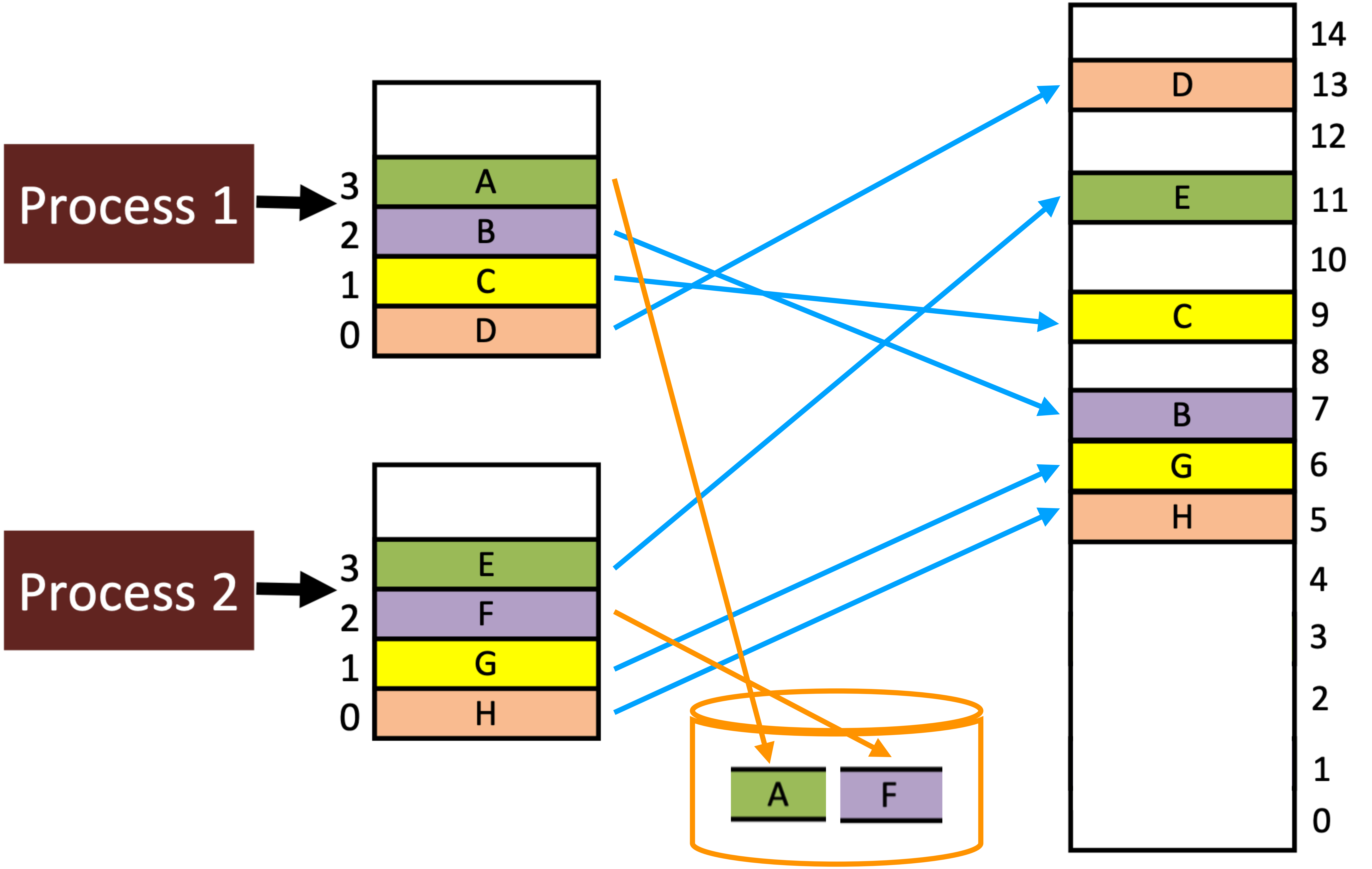

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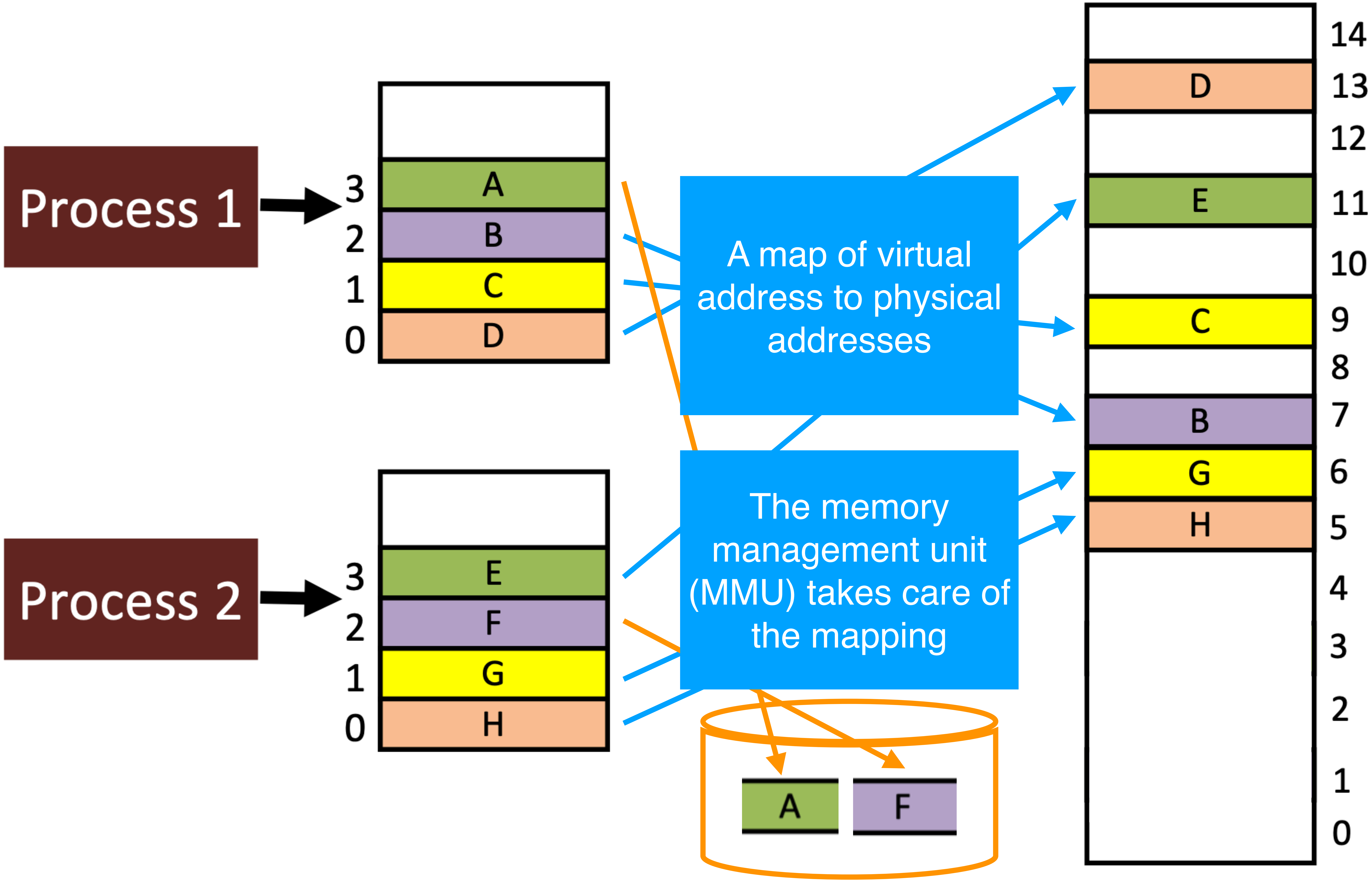
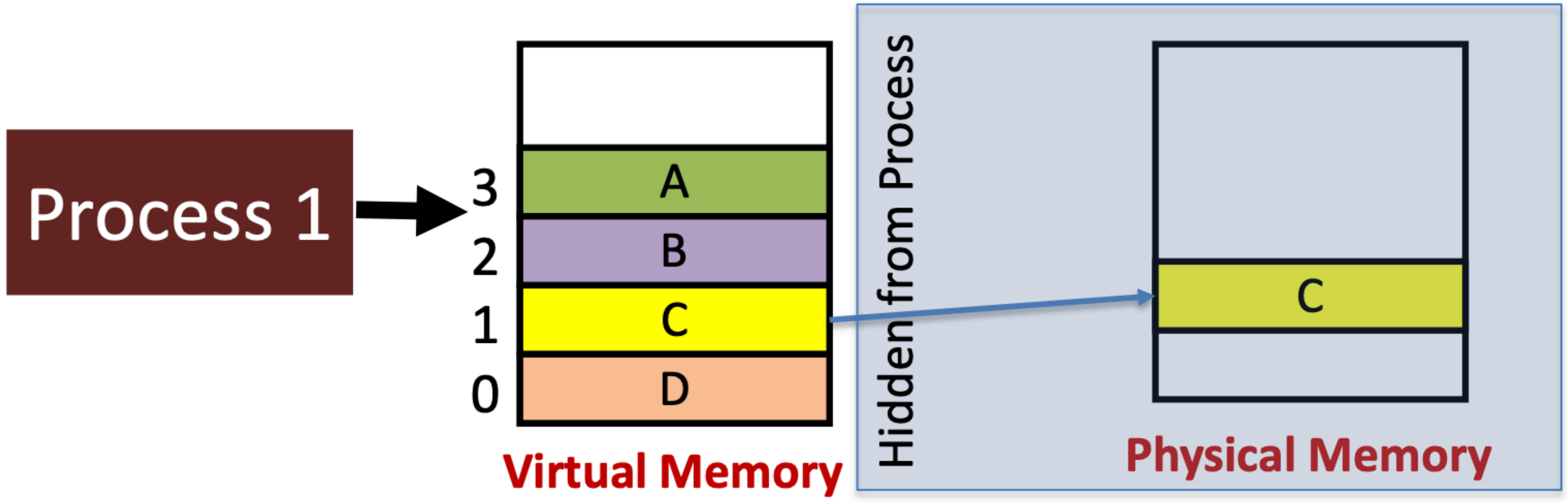


Big Picture: (Virtual) Memory

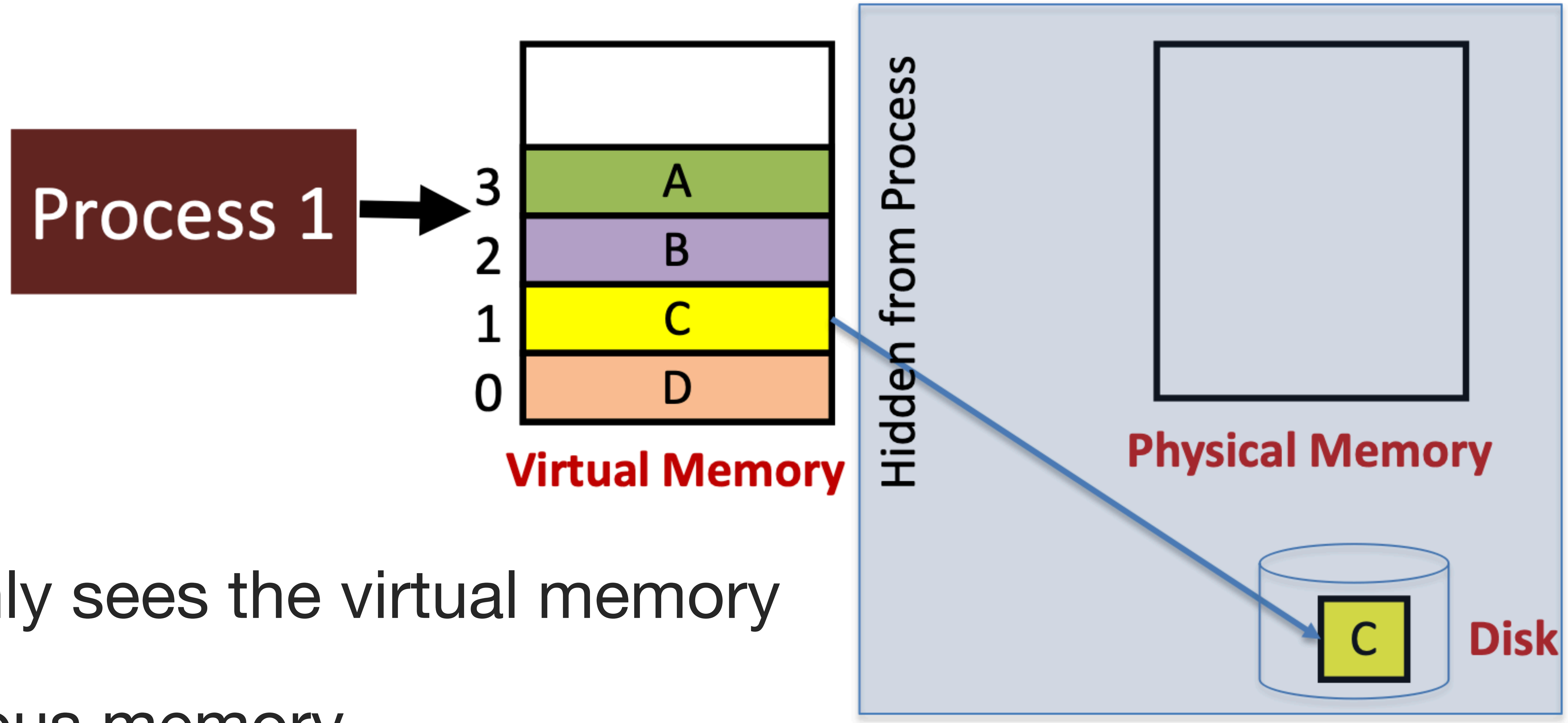
- From a process's perspective –



- Process only sees the virtual memory
    - If run out of memory, MMU maps data on disk in a transparent manner

Big Picture: (Virtual) Memory

- From a process's perspective –



- Process only sees the virtual memory
  - Contiguous memory
  - There's no need to recompile — Only mappings need to be updated

Virtual Memory

- Each process has its own virtual address space:
    - Program/CPU can access any address from 0 … 2^N N = number of bits in the virtual address
    - A process is a program being executed
    - Programmer can code as if they own all of memory

If the CPU uses 32-bit virtual addresses, then:

$$N = 32$$

The virtual addresses go from:

$$0 \text{ to } 2^{32} - 1$$

~4 GB of addressable space per process

Virtual Memory

- Each process has its own virtual address space:
  - Program/CPU can access any address from 0 … 2^N N = number of bits in the virtual address
  - A process is a program being executed
  - Programmer can code as if they own all of memory
- On-the-fly at runtime, for each memory access:
  - So all accesses are *indirect* through a virtual address
  - Then, **map** translate fake virtual address to a real physical address
  - Redirect load/store to the physical address

The Advantages of Virtual Memory

- **Easy relocation**
  - Can put code/data anywhere in physical memory
  - The virtual addresses are the same; the MMU translates them

E.g.:

- Program A is mapped to virtual addresses 0-1 MB
- Program B is also mapped to virtual addresses 0-1 MB

A and B's "pieces" of memory are physically at different DRAM places, but both see a contiguous 0-1 MB address space

The Advantages of Virtual Memory

- **Higher memory utilization**
    - The virtual memory to only load “pieces” of program that are used into RAM
    - Physical memory can be **overcommitted**

E.g.:

- Program A allocates 1 GB of memory but only actually accesses 100 MB
- Only those 100 MB are loaded into DRAM; the rest stays on disk

This enables multiple programs to run **concurrently**, even if total memory exceeds DRAM

The Advantages of Virtual Memory

- **Easy sharing**
  - Processes can share the **same physical memory** via virtual memory mapping

E.g.:

- Shared libraries (like `libc.so`) are mapped into many processes' virtual address spaces
- Each process sees the library at its own virtual address, but there's only one copy in DRAM

Outline

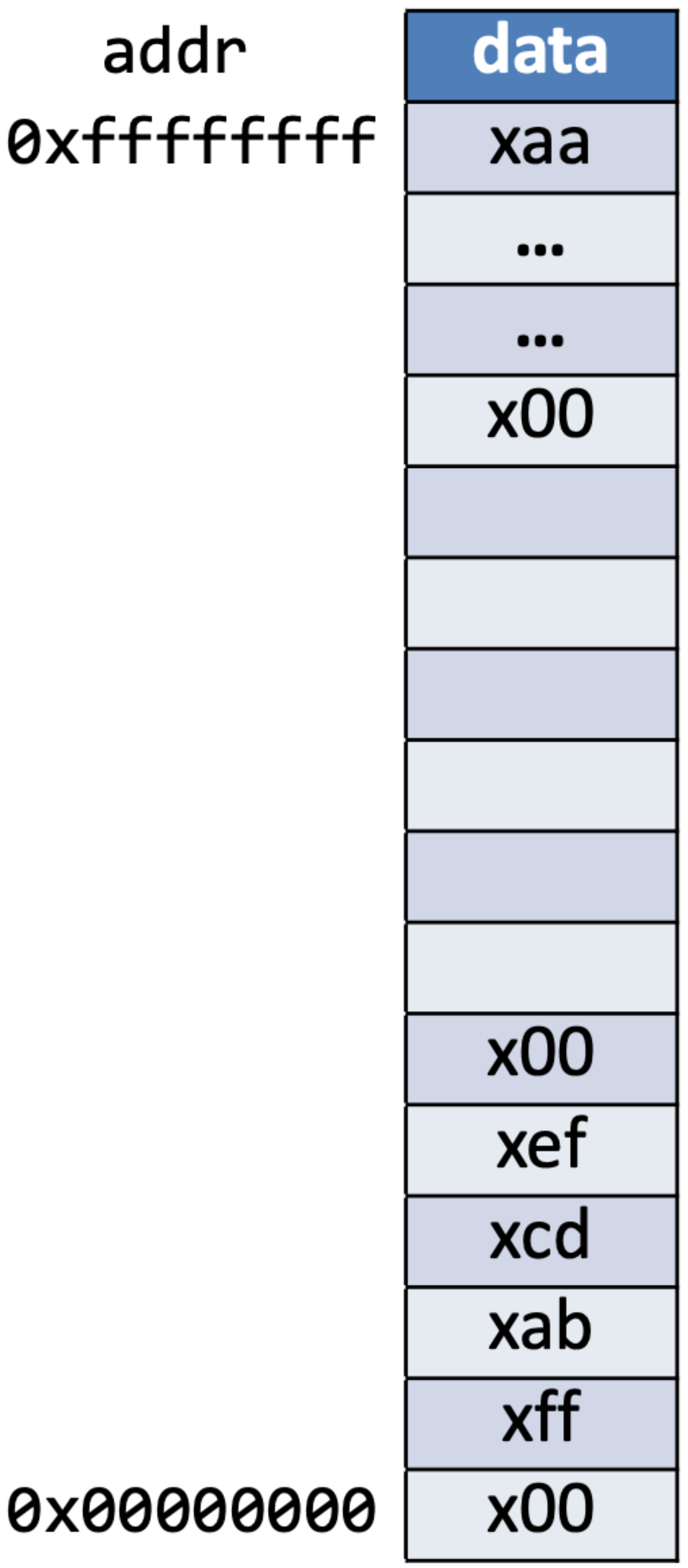
- How do we run multiple processes together?
- How does virtual memory work?
  - i.e., how do we create the “map” that maps a **virtual address** generated by the CPU to a **physical address** used by main memory?

Outline

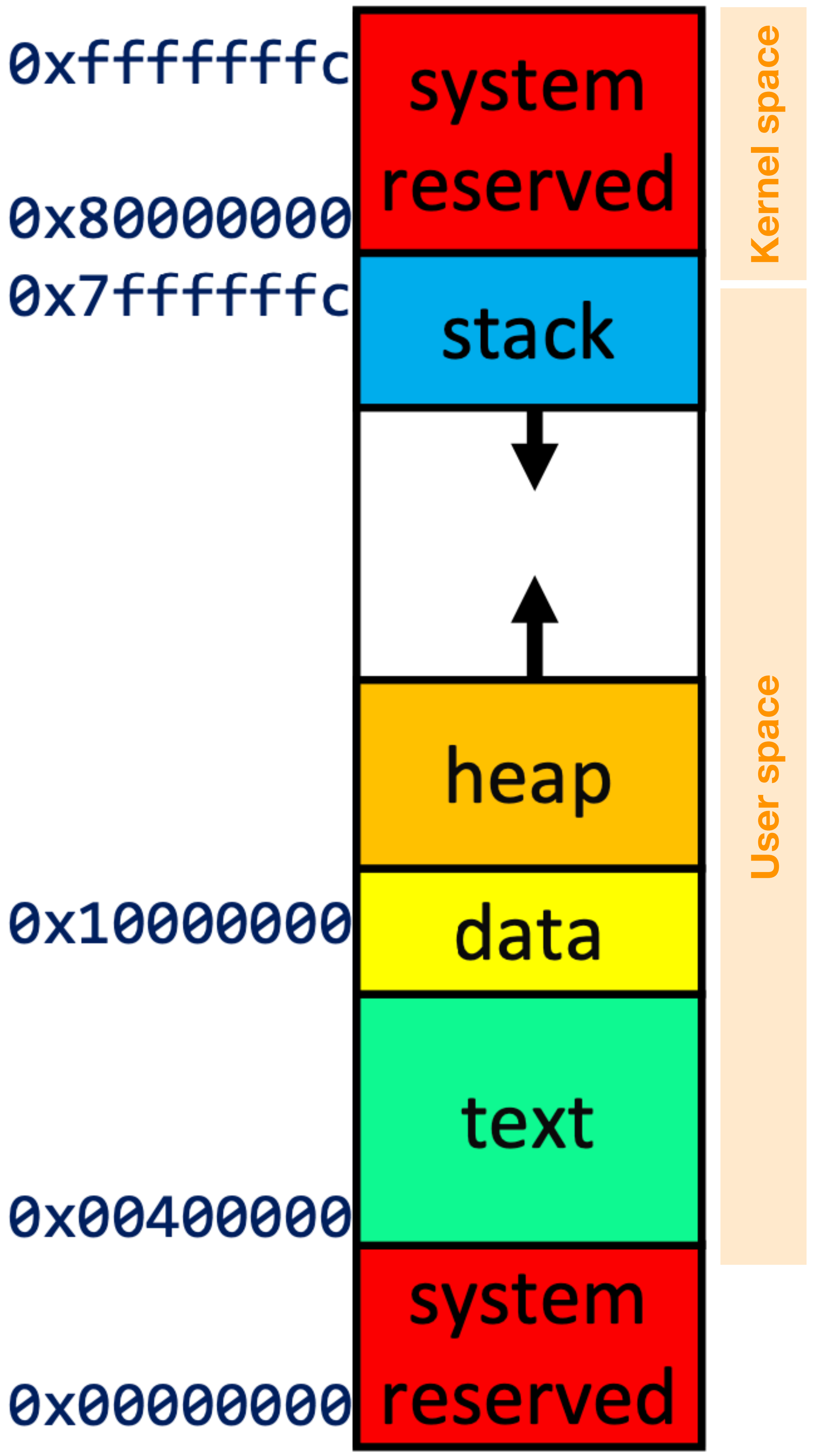
- How do we run multiple processes together?
- How does virtual memory work?
  - i.e., how do we create the “map” that maps a **virtual address** generated by the CPU to a **physical address** used by main memory?
    - Address Translation
    - Overhead
    - Paging

Picture Memory As …

Byte Array:



Segments:

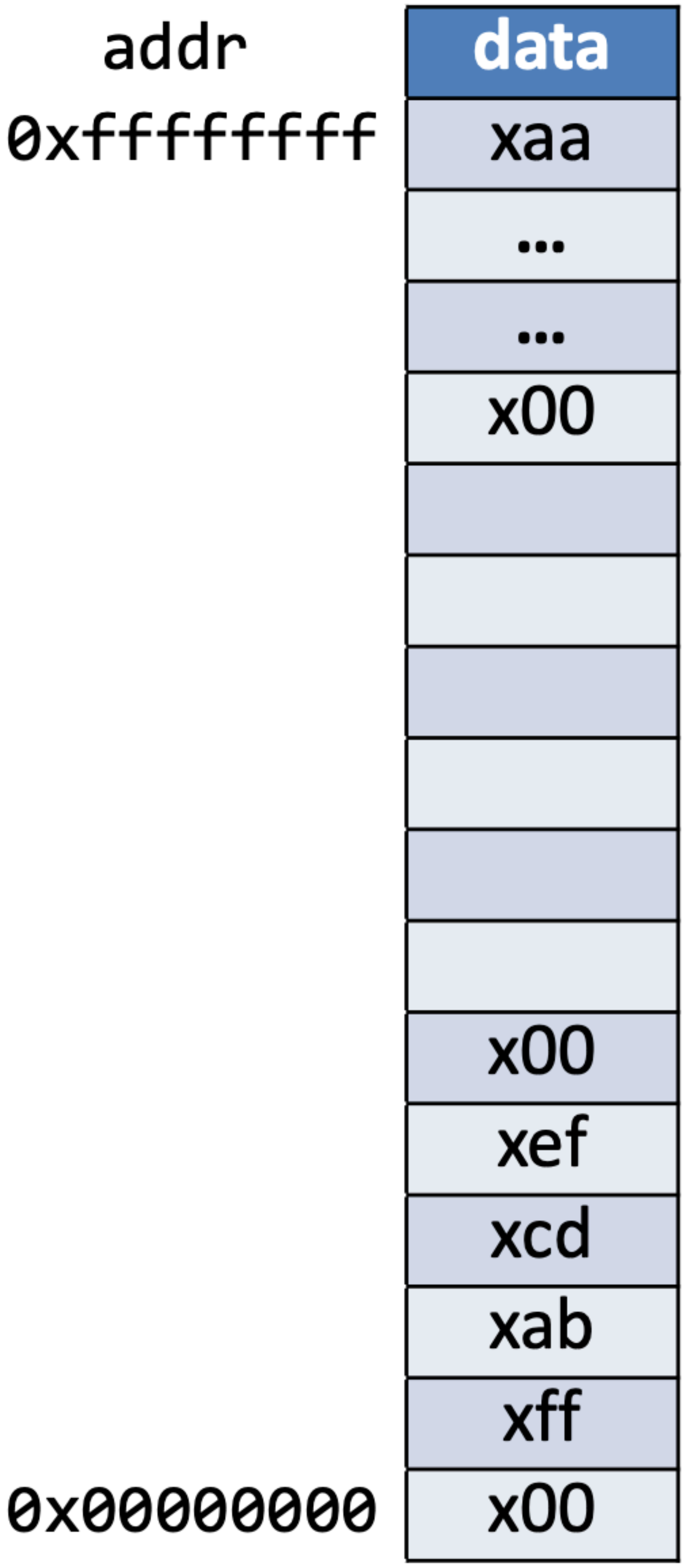


The virtual-to-physical address mapping

- The **CPU generates a virtual address** when running a program
- The OS wants to give each process the illusion of a contiguous, linear memory space
- To do this, the CPU uses a **page table**, which is a “map” maintained by the OS that links virtual pages to physical frames

Picture Memory As …

Byte Array:



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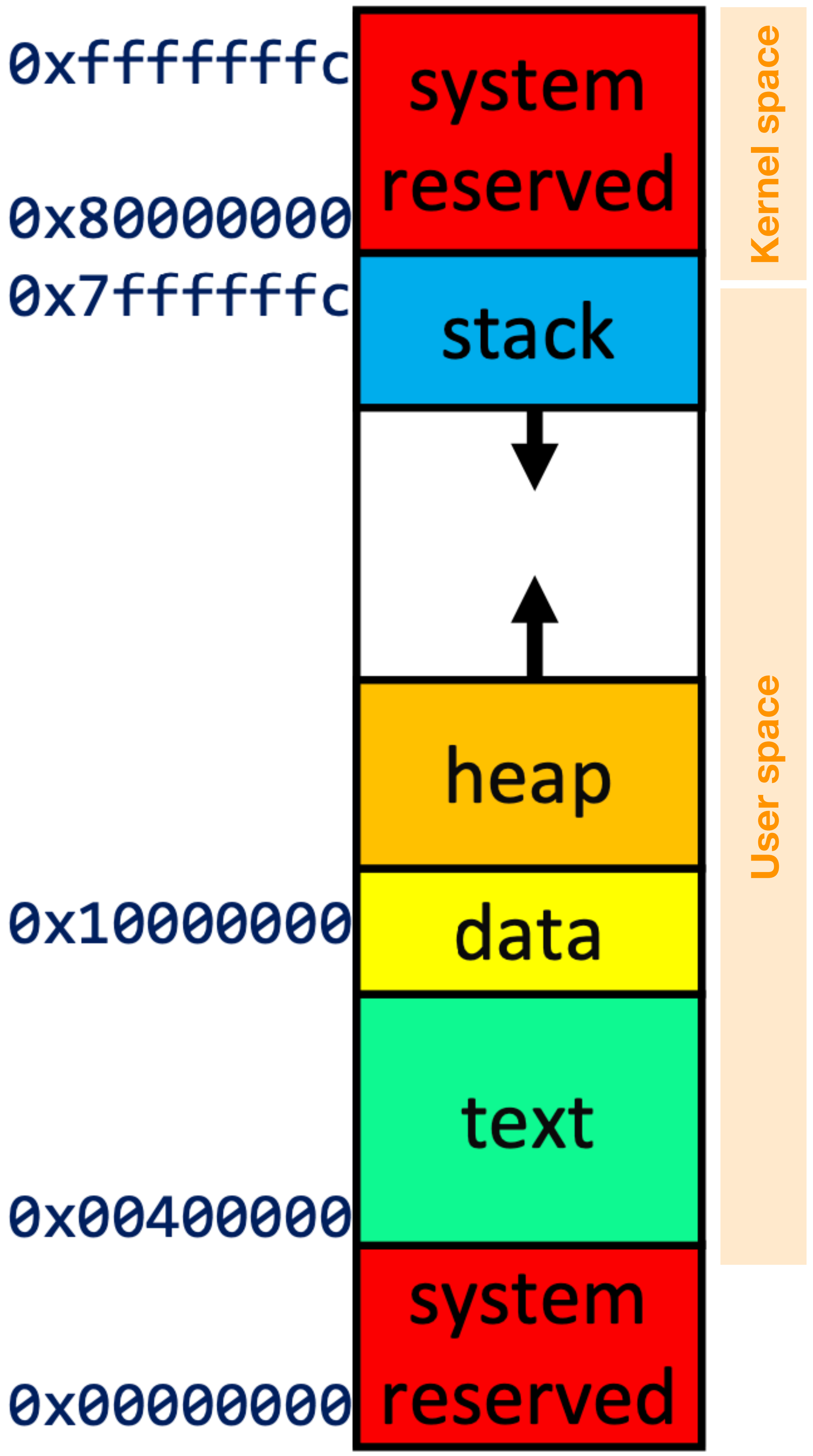
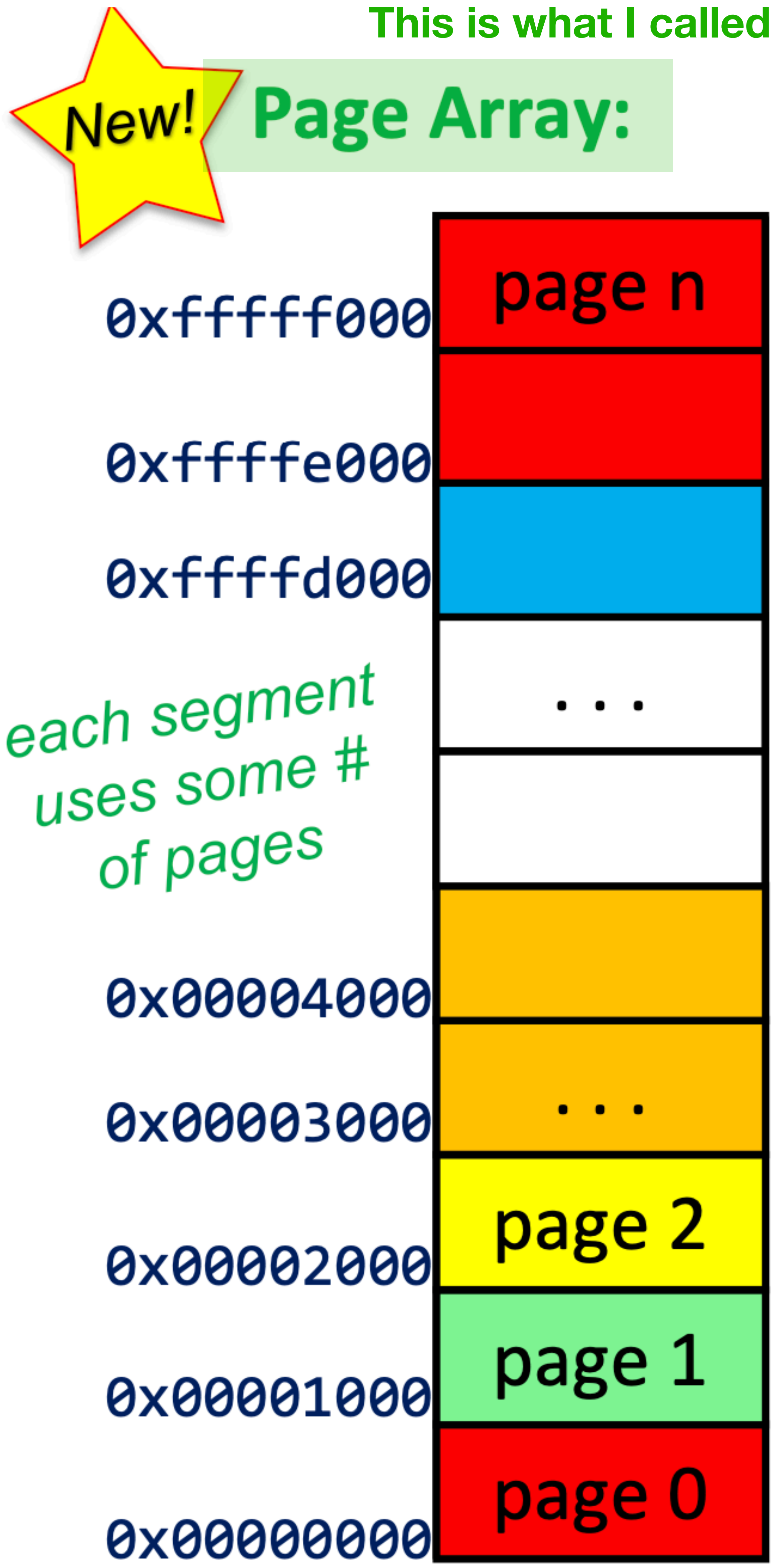


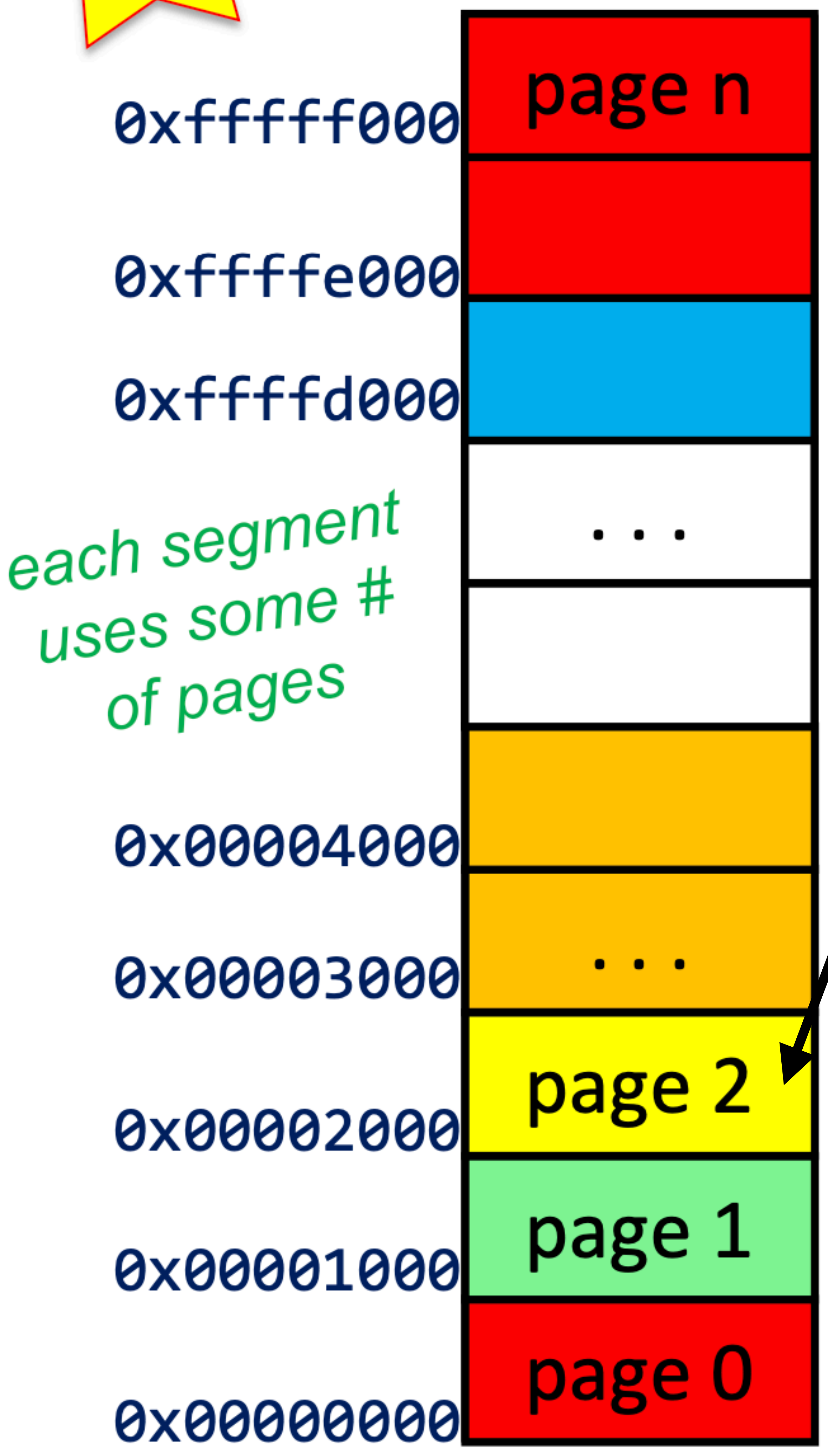
This is what I called "pieces" earlier!

Page Array:



Pages

New! **Page Array:**



- Let's suppose each page is 4KB
- Then anything in **page 2** has (hex) address: 0x00002**xxx**
- The lower 12 bits specify which byte you are in the page

  0x00002**200 = 0010 0000 0000 = byte 512**

- The upper bits = page **number** (PPN)
- The lower bits = page **offset**

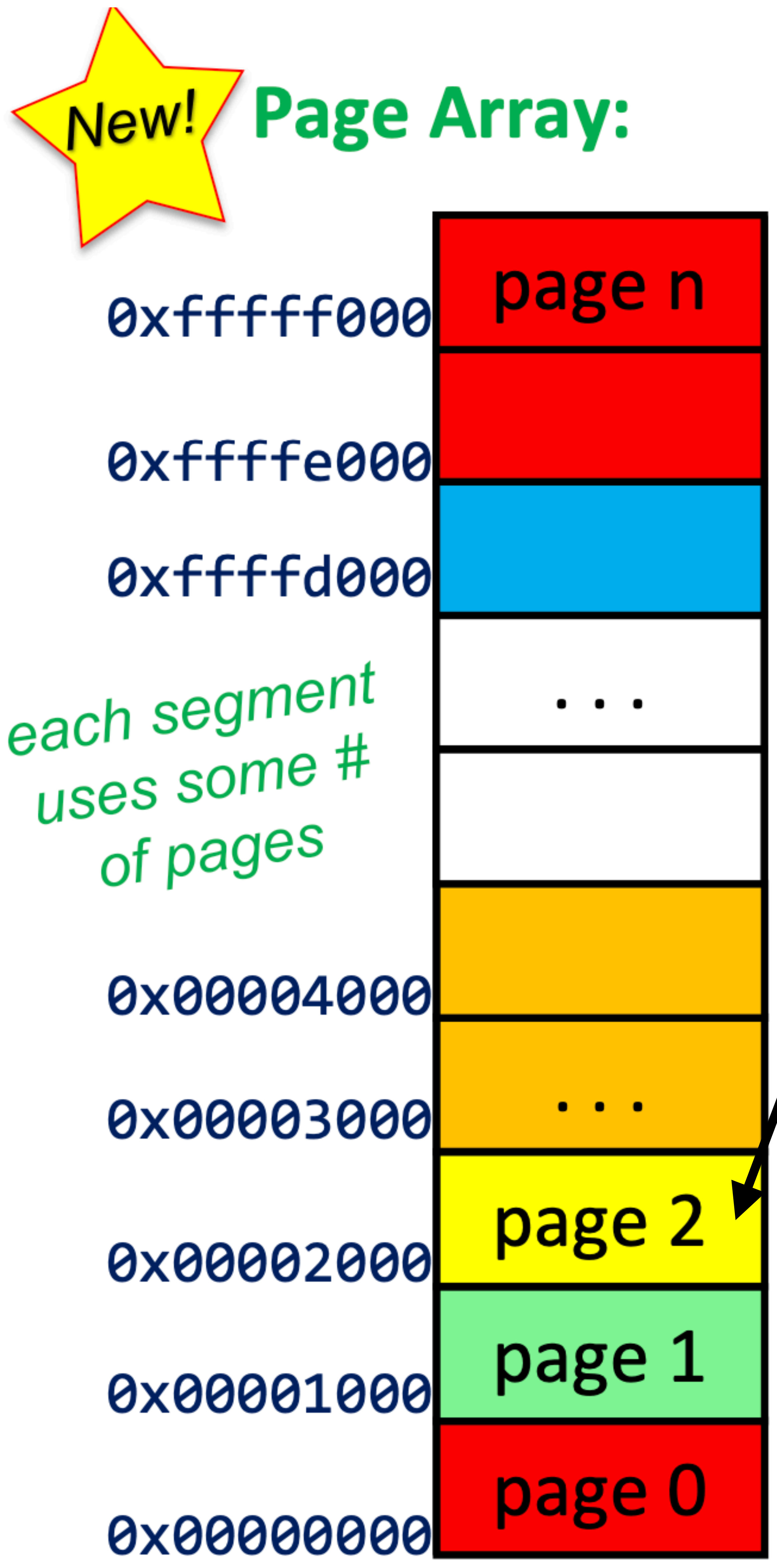
The virtual address breakdown

A virtual address is divided into:

- **Page number** → identifies which virtual page is being accessed
- **Offset** within the page → identifies the exact byte inside that page

```
        32-bit = [20 bit][12-bit]
virtual address = [page number][offset]
```

Sounds Familiar?



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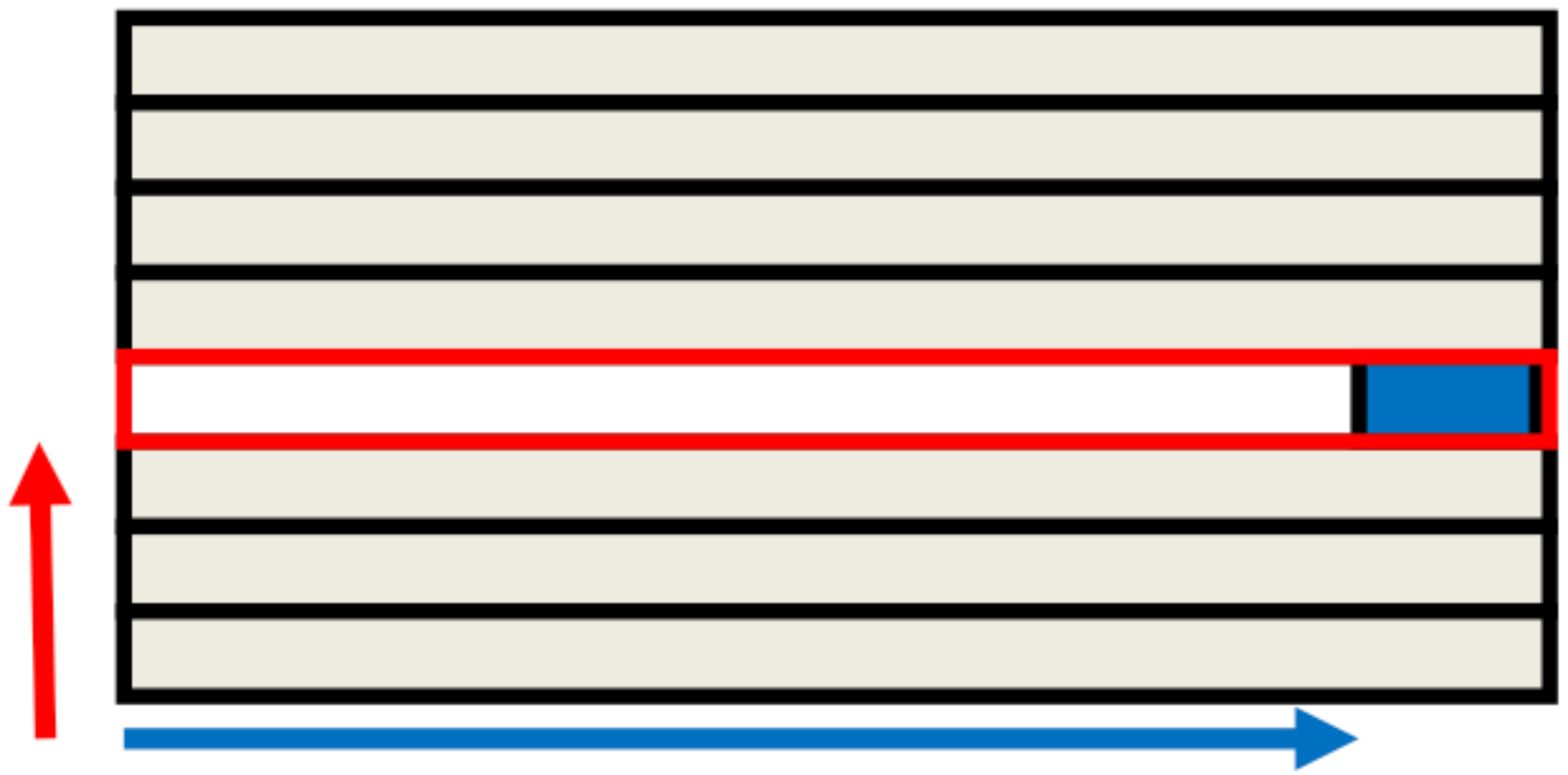
Data Granularity

- **ISA:** instruction specific: LB, LH, LW (ISA)
- **Registers:** 32 bits or 64 bits (ISA)

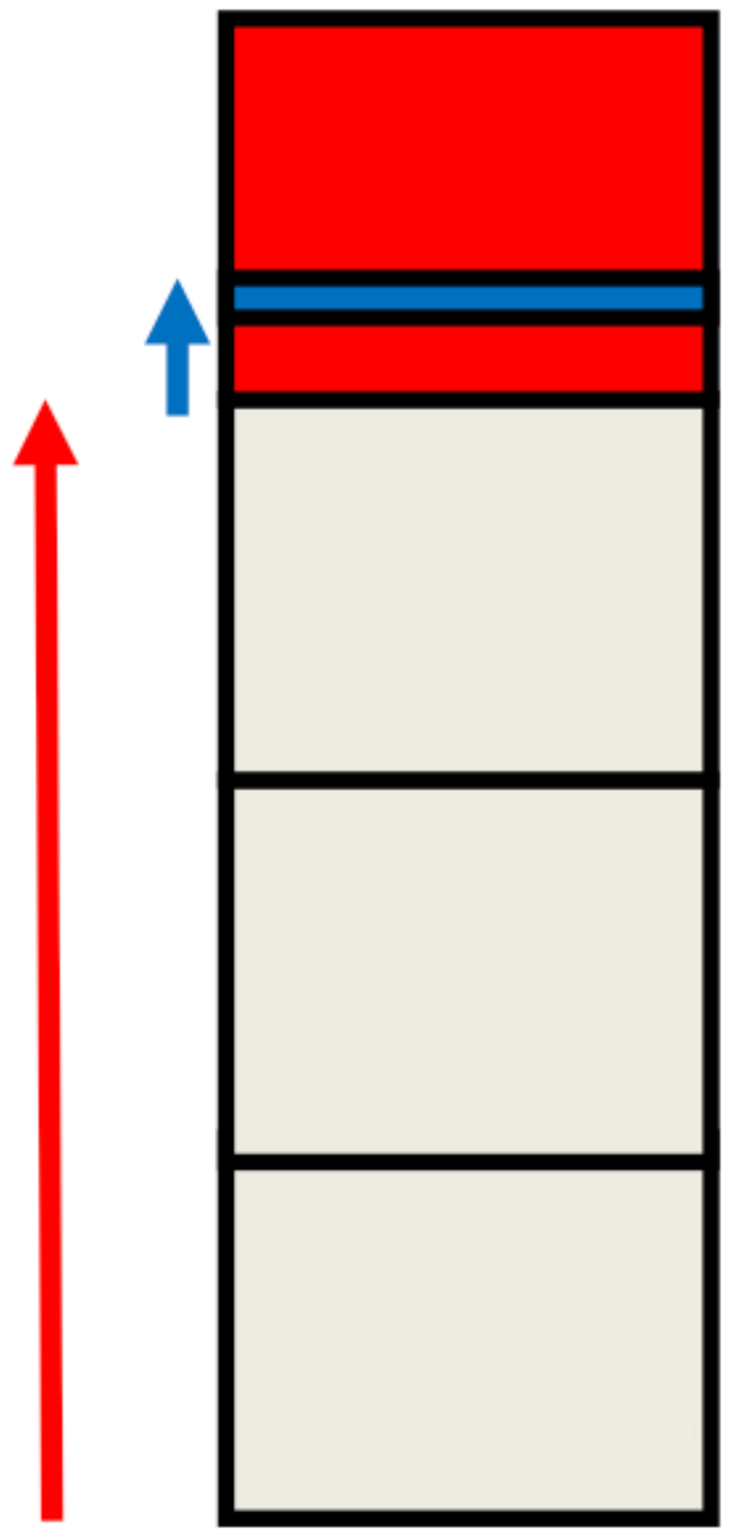
- **Caches:** Cache line/block (µarch)
  - The address bits divided into:
    - tag: sanity check for address match
    - index: which entry in the cache
    - offset: which byte in the line



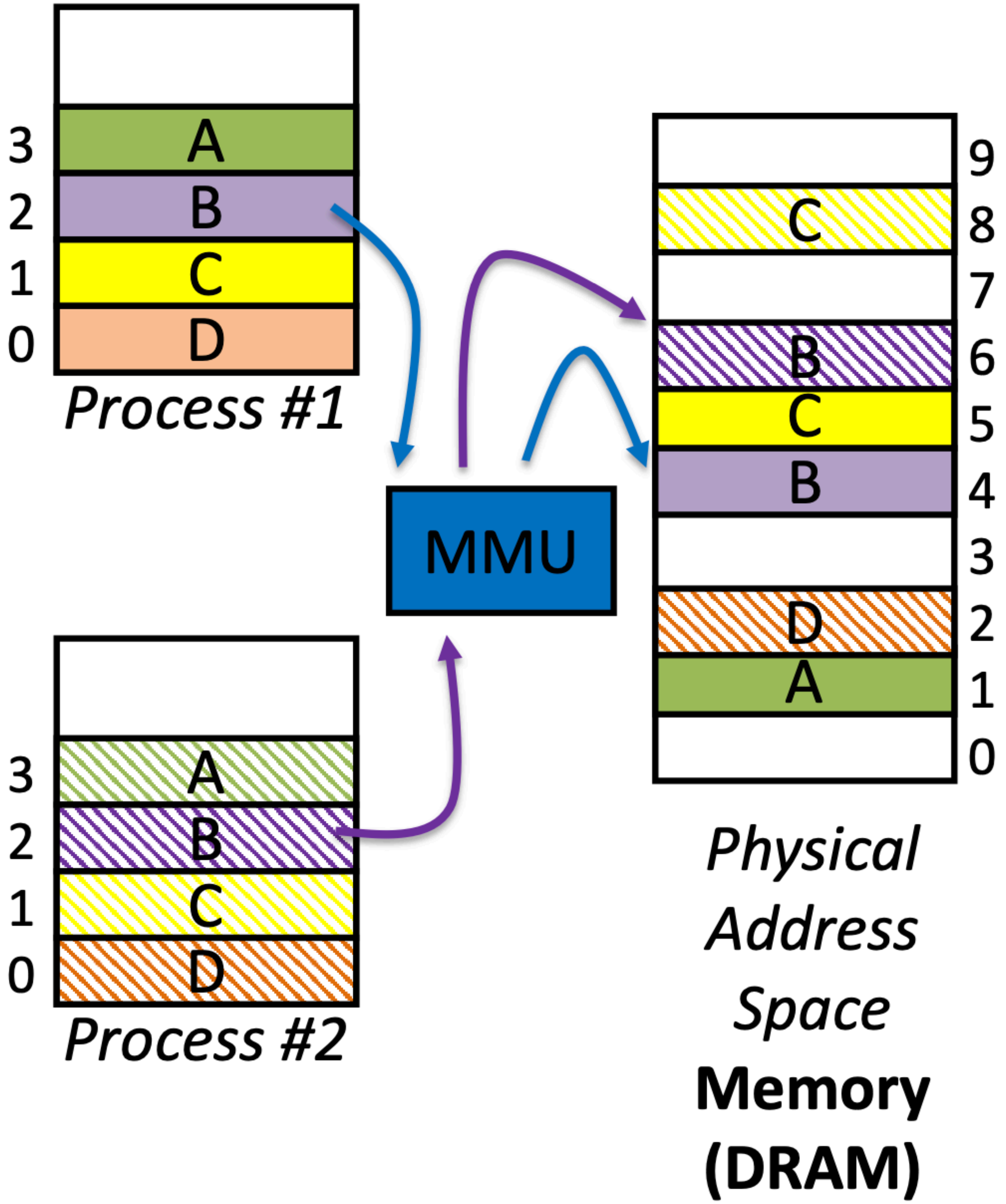
Data Granularity

- **ISA:** instruction specific: LB, LH, LW (ISA)
- **Registers:** 32 bits or 64 bits (ISA)

- **Memory:** Page
  - The address bits divided into:
    - page number: which page in memory
    - offset: which byte in the page



Address Translator (MMU)



- Processes use virtual memory
- DRAM uses physical memory
- **Memory Management Unit (MMU)**
  - It's <u>hardware</u>!
  - It translates virtual addresses to physical addresses on the fly