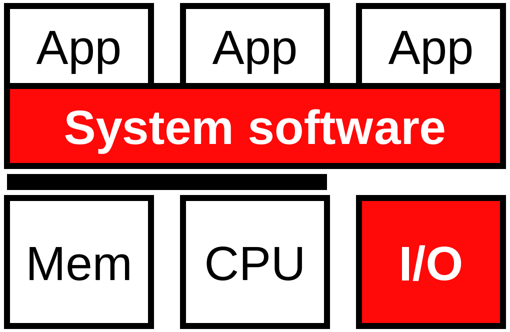
# CSE 560
# Computer Systems Architecture

Virtual Memory

# This Unit: Virtual Memory




- The operating system (OS)
  - A super-application
  - Hardware support for an OS
- Virtual memory
  - Page tables and address translation
  - TLBs and memory hierarchy issues

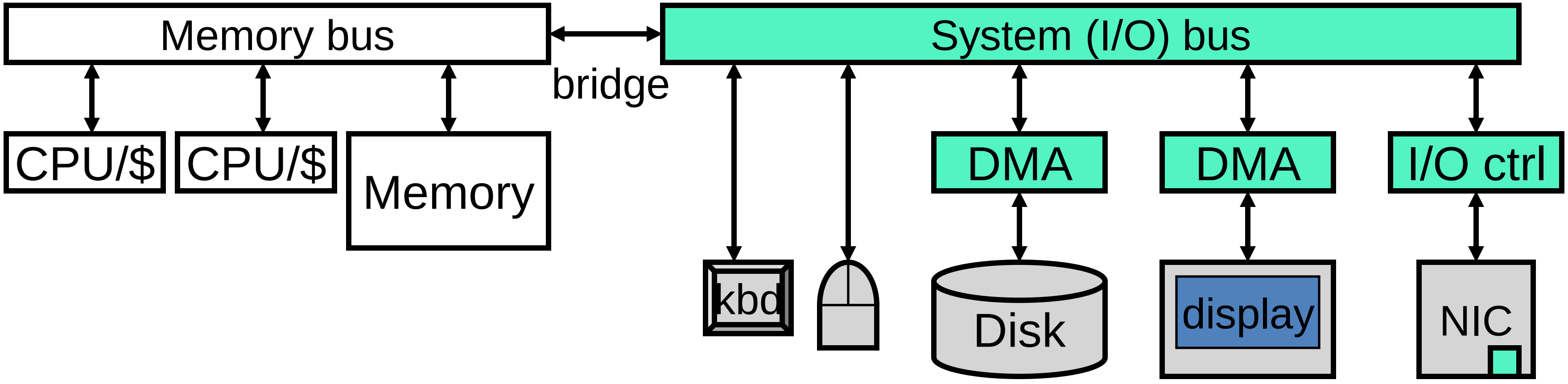
# A Computer System: Hardware

CPUs and memories

- Connected by memory bus

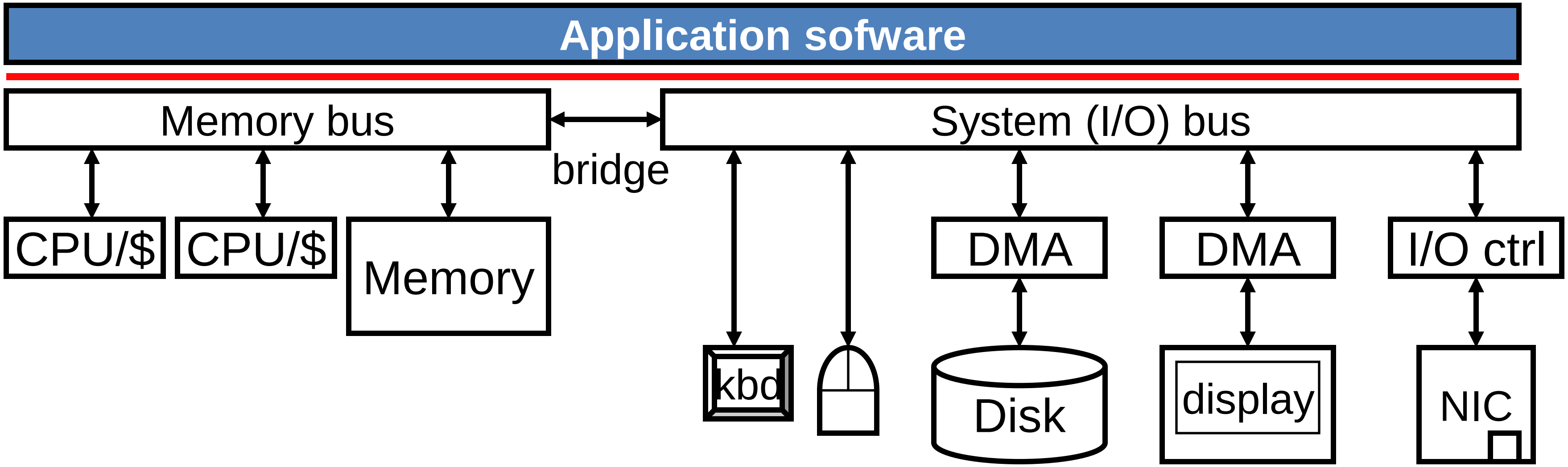
**I/O peripherals**: storage, input, display, network, …
(NIC = Network Interface Controller)

- With separate or built-in DMA (direct memory access)
- Connected by **system bus** (which is connected to memory bus)



# A Computer System: + App Software

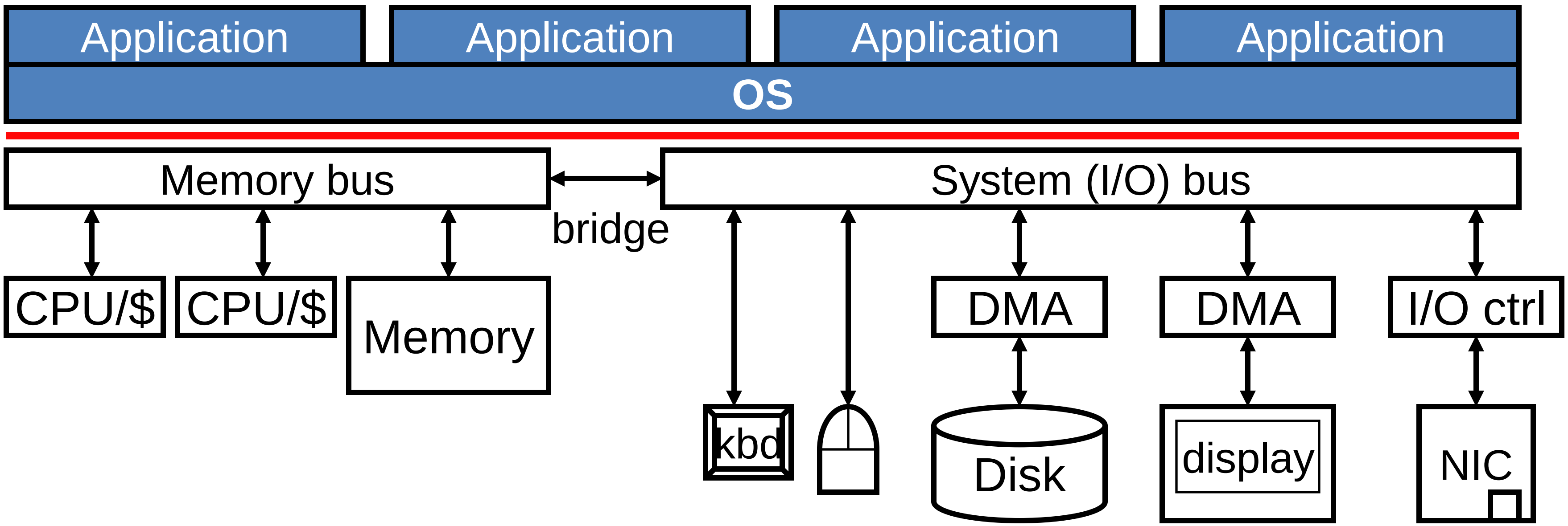
- **Application software**: computer must do something



# A Computer System: + OS

**Operating System (OS):** virtualizes hardware for apps

- **Abstraction**: provides **services** (*e.g.*, threads, files, *etc.*)
  + Simplifies app programming model, raw hardware is nasty
- **Isolation**: gives each app illusion of private CPU, memory, I/O
  + Simplifies app programming model
  + Increases hardware resource utilization



# Operating System (OS) and User Apps

- Sane system development requires a split

- **Operating System (OS)**: a super-privileged process
  - Manages hw resource allocation/revocation for all processes
  - Has direct access to resource allocation features
  - **Aware of:** many nasty hardware details, other processes
  - Talks directly to input/output devices (device driver software)

- **User-level apps**: ignorance is bliss
  - **Unaware of:** most nasty hardware details, other apps, OS
  - Explicitly denied access to resource allocation features

# System Calls

**System Call**: a user-level app "function call" to OS

- Leave description of what you want done in registers
- SYSCALL instruction (also called TRAP or INT)
  - User-level apps not allowed to invoke arbitrary OS code
  - Restricted set of legal OS addresses to jump to (**trap vector**)

1. Processor jumps to OS via trap vector (begin privileged mode)
2. OS performs operation
3. OS does a "return from system call" (end privileged mode)

# Interrupts

**Exceptions**: synchronous, generated by running app

- *E.g.*, illegal instruction, divide by zero, *etc.*

**Interrupts**: asynchronous events generated externally

- *E.g.*, timer, I/O request/reply, *etc.*

**Timer**: programmable on-chip interrupt

- Initialize with some number of micro-seconds
- Timer counts down and interrupts when reaches 0

**"Interrupt" handling**: same mechanism for both

- "Interrupts" are on-chip signals/bits
  - Either internal (*e.g.*, timer, exceptions) or from I/O devices
- Processor continuously monitors interrupt status, when true…
- HW jumps to some preset address in OS code (interrupt vector)
- Like an asynchronous, non-programmatic SYSCALL

# Virtualizing Processors

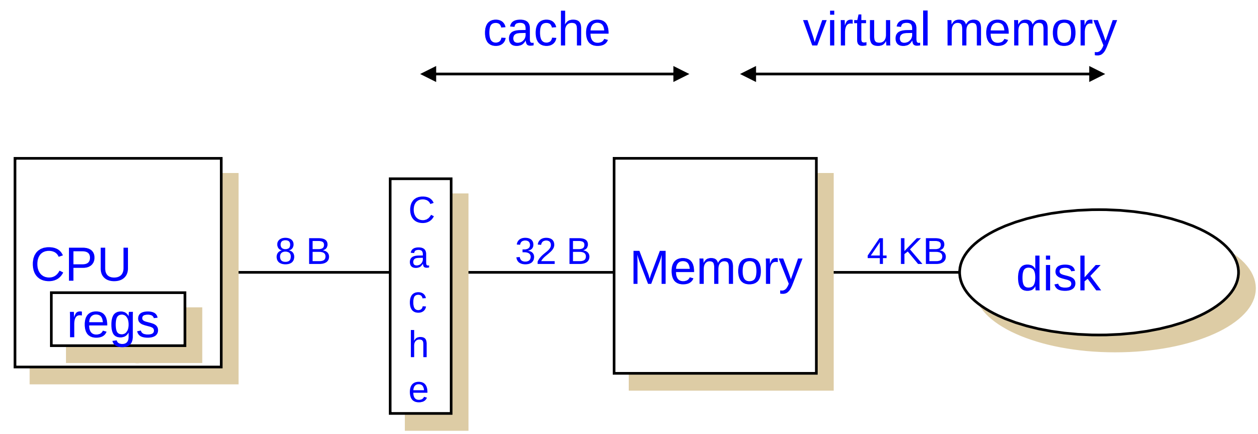
How do multiple apps (and OS) share the processors?
**Goal: applications think there are an infinite # of processors**

Solution: time-share the resource
- Trigger a **context switch** at a regular interval (~1ms)
  - **Pre-emptive**: app doesn't yield CPU, OS forcibly takes it
    + Stops greedy apps from starving others
- **Architected state**: PC, registers
  - Save and restore them on context switches
  - Memory state?
- **Non-architected state**: caches, predictor tables, *etc.*
  - Ignore or flush
- Operating System responsible for handling context switching
  - Hardware support is just a timer interrupt

# Motivations for Virtual Memory

- **Use Physical DRAM as a Cache for the Disk**
  - Address space of a process can exceed physical memory size
  - Sum of address spaces of multiple processes can exceed physical memory
- **Simplify Memory Management**
  - Multiple processes resident in main memory
    - Each process with its own address space
  - Only "active" code and data is actually in memory
    - Allocate more memory to process as needed
- **Provide Protection**
  - One process can't interfere with another
    - because they operate in different address spaces
  - User process cannot access privileged information
    - different sections of address spaces have different permissions

# Levels in Memory Hierarchy




| | Register | Cache | Memory | Disk Memory |
|---|---|---|---|---|
| size: | 32 B | 32 KB-4MB | 1024 MB | 100 GB |
| speed: | 1 ns | 2 ns | 30 ns | 8 ms |
| $/Mbyte: | | $125/MB | $0.20/MB | $0.001/MB |
| line size: | 8 B | 32 B | 4 KB | |

larger, slower, cheaper

# Virtualizing Main Memory

How do multiple apps (and the OS) share main memory?

**Goal: each application thinks it has private memory**

App's insn/data footprint > main memory ?

- **Requires main memory to act like a cache**
  - With disk as next level in memory hierarchy (slow)
  - Write-back, write-allocate, large blocks or "pages"

Solution:

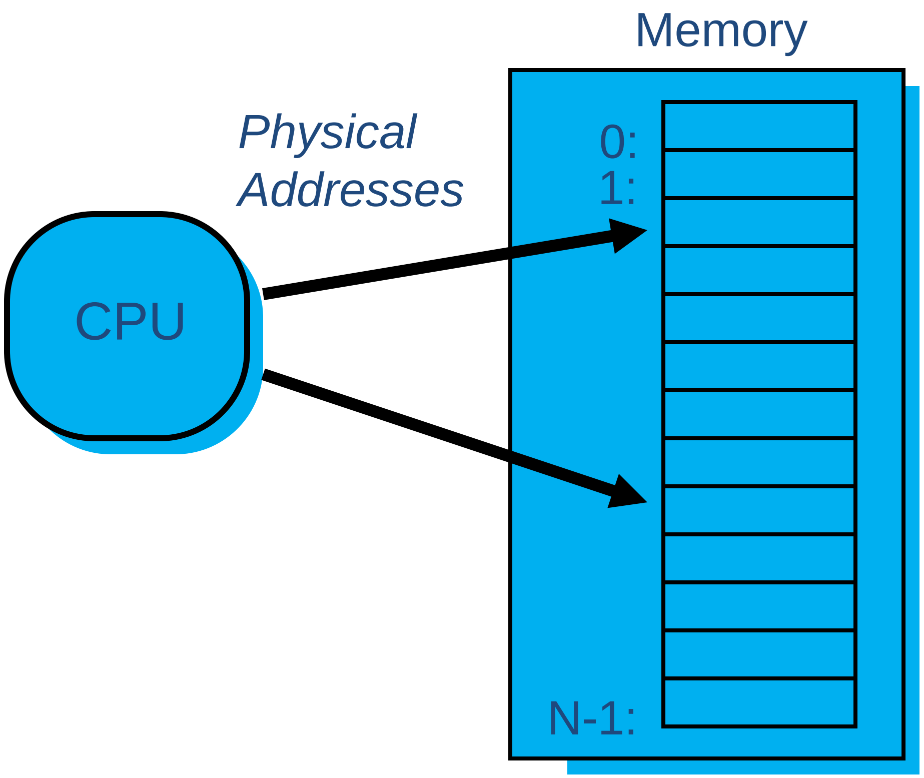
- Part #1: treat memory as a "cache"
- Part #2: add a level of indirection (address translation)

| **Parameter** | **I$/D$** | **L2** | **Main Memory** |
|---|---|---|---|
| $t_{hit}$ | 2ns | 10ns | **30ns** |
| $t_{miss}$ | **10ns** | **30ns** | **10ms (10M ns)** |
| Capacity | 8–64KB | 128KB–2MB | **64MB–64GB** |
| Block size | 16–32B | 32–256B | **4+KB** |
| Assoc./Repl. | 1–4, NMRU | 4–16, NMRU | **Full, "working set"** |

# A System with Physical Memory Only

Examples:

- most Cray machines, early PCs, many embedded systems, etc.

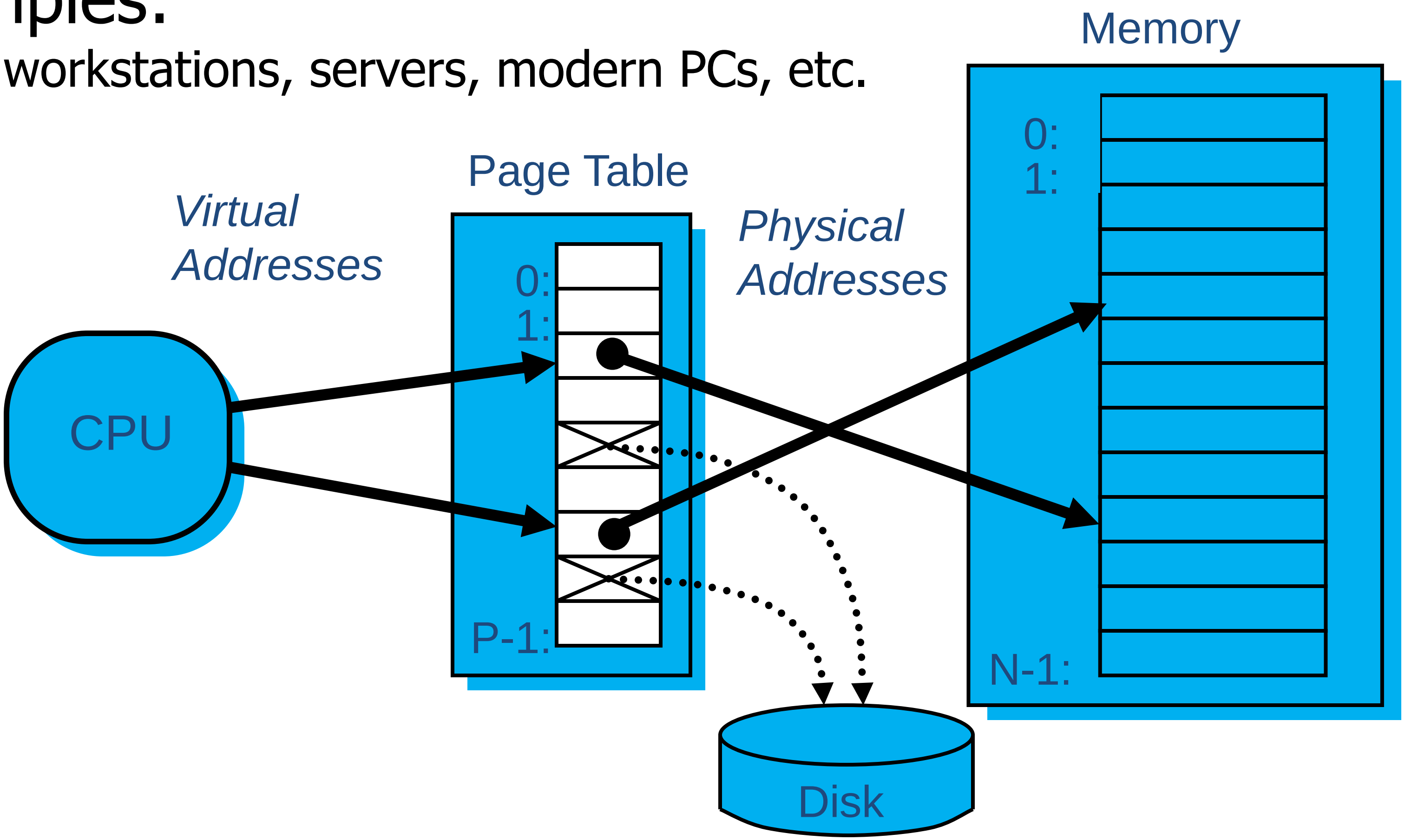



Addresses generated by the CPU correspond directly to bytes in physical memory

# A System with Virtual Memory

Examples:

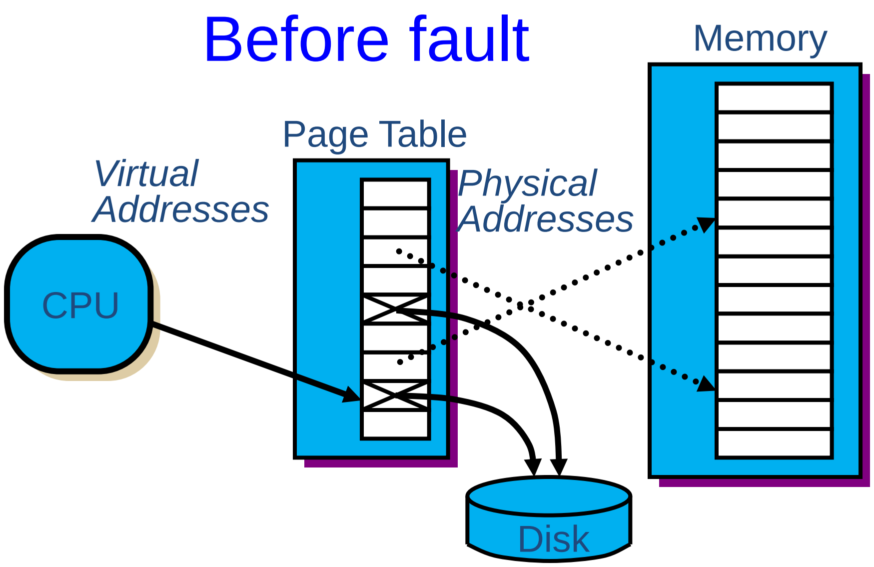
- workstations, servers, modern PCs, etc.

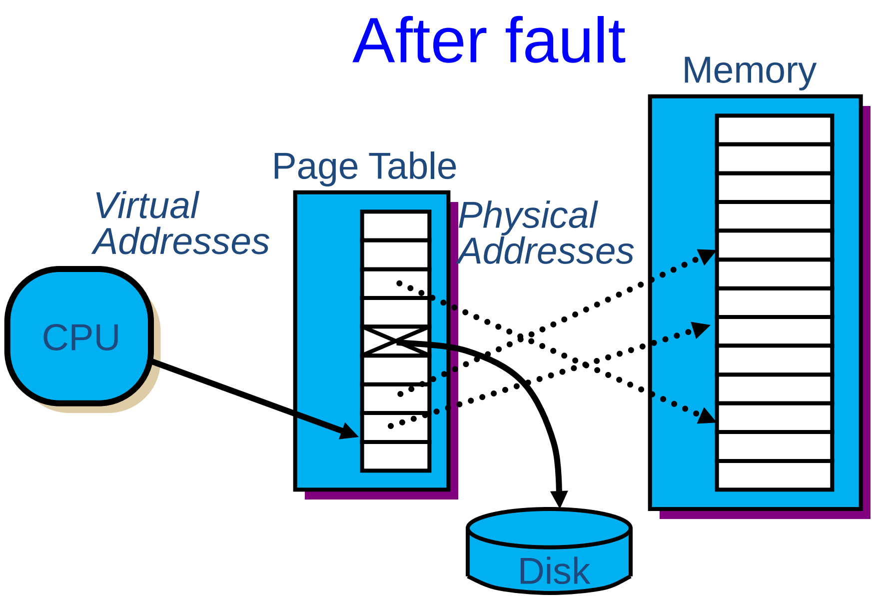



Address Translation: Hardware converts virtual addresses to physical addresses via OS-managed lookup table (page table)

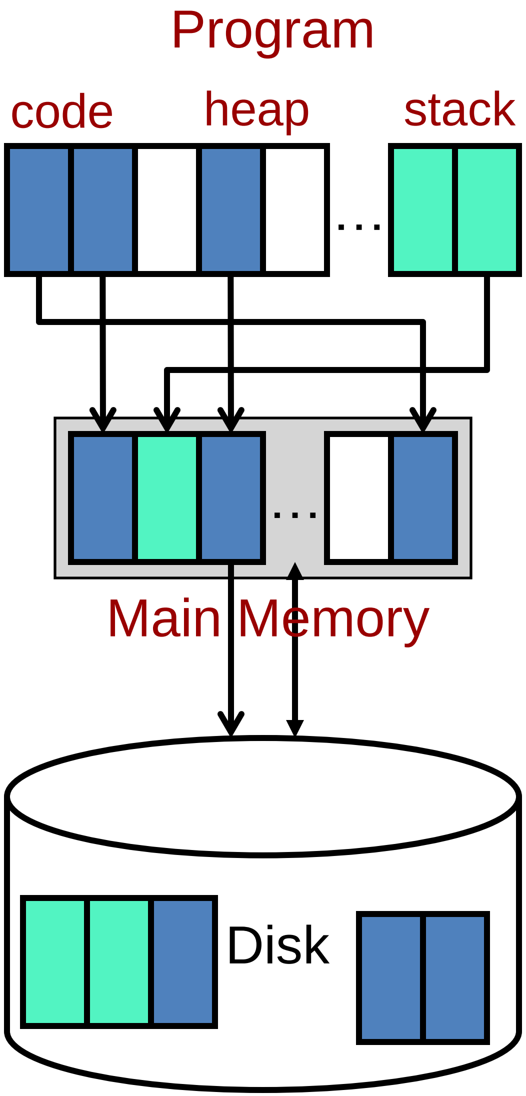
# Page Faults (like "Cache Misses")

- What if an object is on disk rather than in memory?
  - Page table entry indicates virtual address not in memory
  - OS exception handler invoked to move data from disk into memory
    - current process suspends, others can resume
    - OS has full control over placement, etc.



# Virtual Memory (VM)

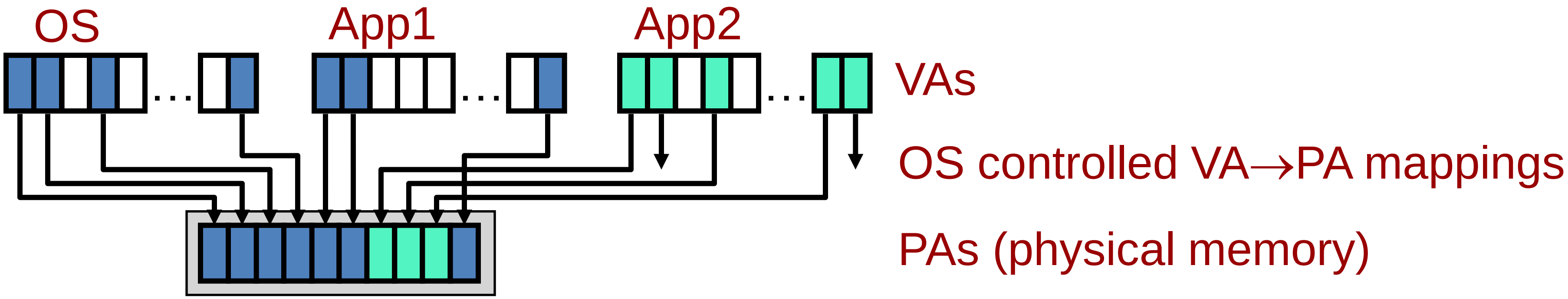



- Programs use **virtual addresses (VA)**
  - $0 \ldots 2^N-1$
  - VA size also referred to as machine size
  - *E.g.*, 32-bit (embedded) or 64-bit (server)
- Memory uses **physical addresses (PA)**
  - $0 \ldots 2^M-1$ (typically M<N, especially if N=64)
  - $2^M$ is most physical memory machine supports
- VA→PA at **page** granularity (VP→PP)
  - By "system" (OS + HW)
  - Mapping need not preserve contiguity
  - VP need not be mapped to any PP
  - Unmapped VPs live on disk (swap)

# Virtual Memory (VM)

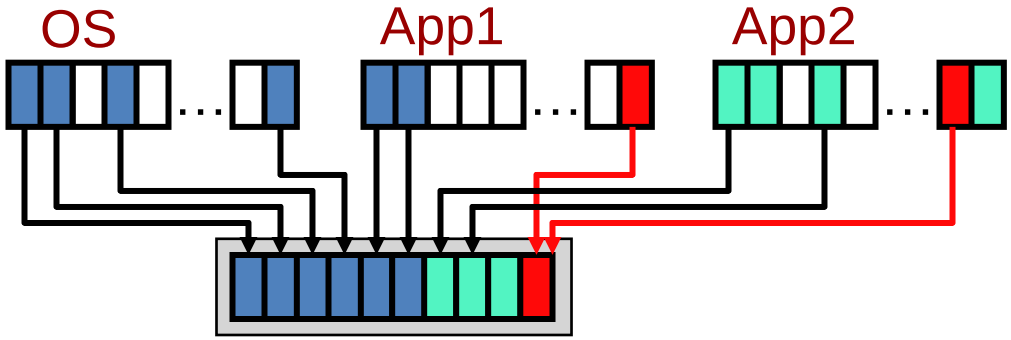
**Virtual Memory (VM)**:

- Level of indirection
- Application generated addresses are **virtual addresses (VAs)**
  - Each process ***thinks*** it has its own $2^N$ bytes of address space
- Memory accessed using **physical addresses (PAs)**
- VAs translated to PAs at some coarse granularity
- OS controls VA to PA mapping for itself and all other processes
- Logically: translation performed before every insn fetch, load, store
- Physically: hardware acceleration removes translation overhead



# Uses of Virtual Memory

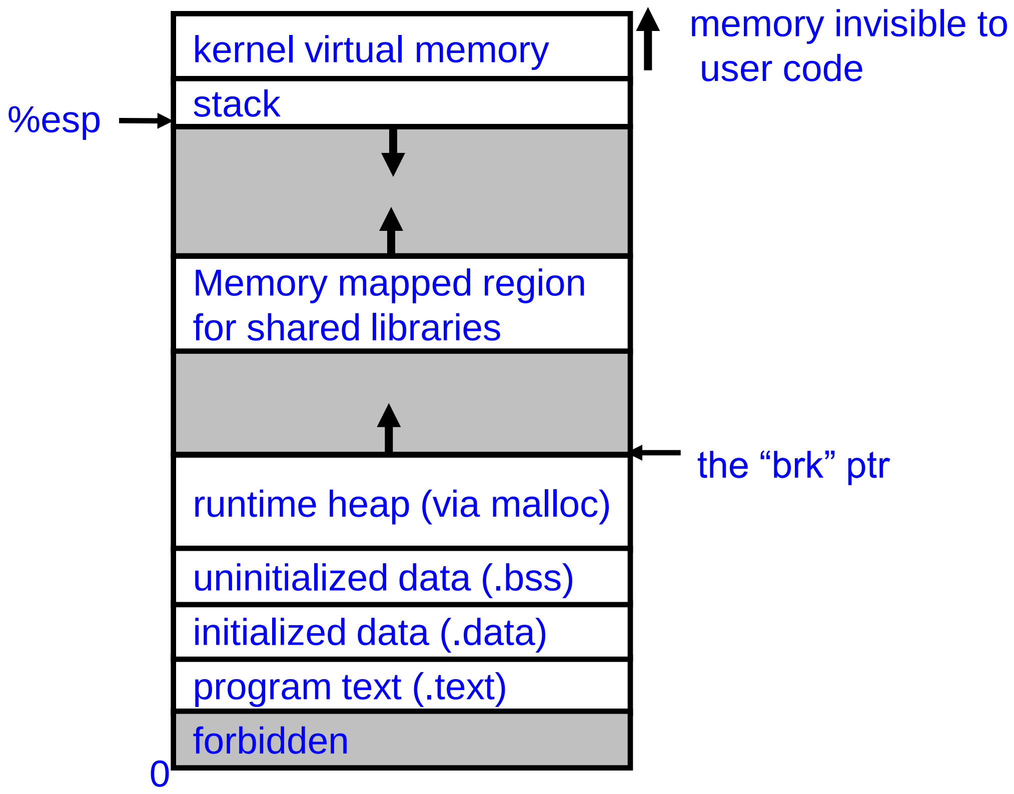
- **Isolation** and **Multi-programming (Memory Management)**
  - Each app thinks it has $2^N$ B of memory that starts @ 0
  - Apps can't read/write each other's memory
    - Can't even address the other program's memory!
- **Protection**
  - Each page has read/write/execute permission set by OS
  - Enforced by hardware
- **Inter-process communication**
  - Map same physical pages into multiple virtual address spaces
  - Or share files via the UNIX `mmap()` call



# Memory Management

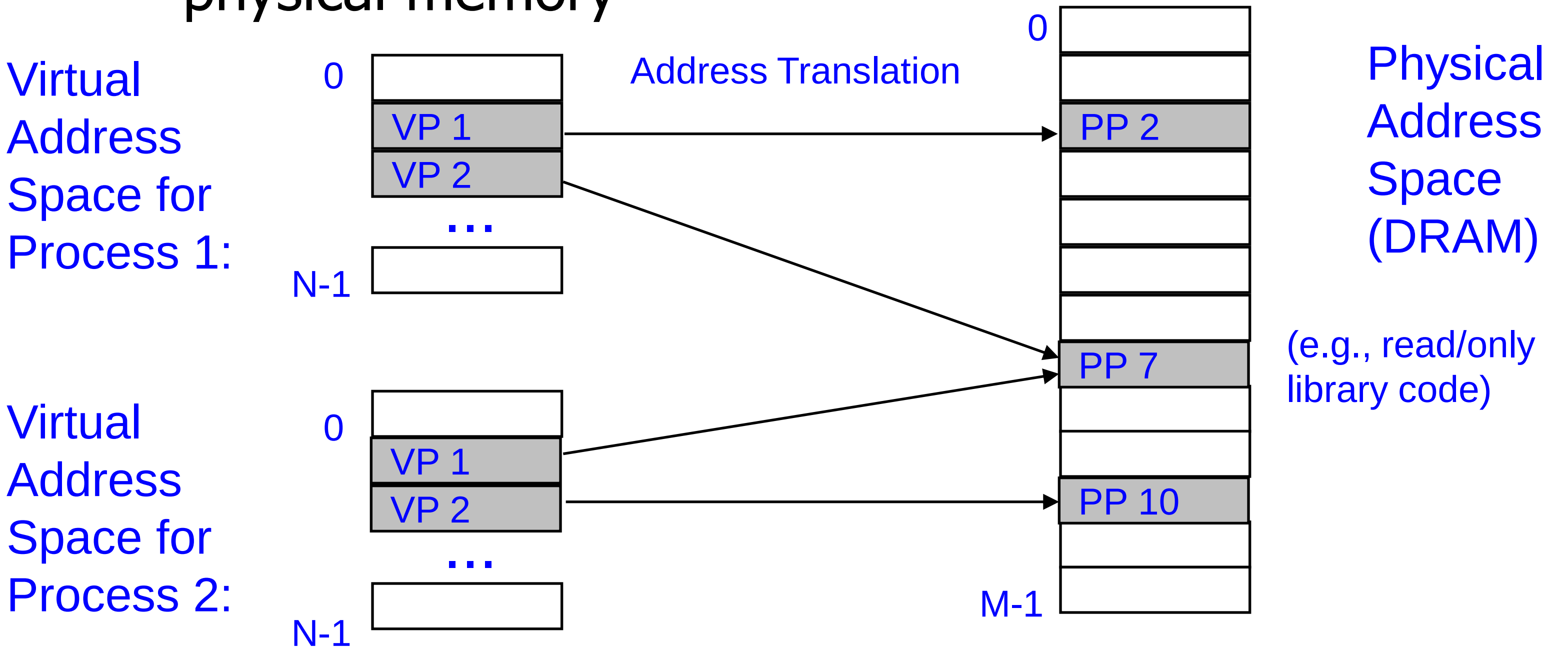
- Multiple processes can reside in physical memory.
- How do we resolve address conflicts?
  - what if two processes access something at the same address?

Linux/x86 process memory image



# Solution: Separate Virt. Addr. Spaces

- Virtual and physical address spaces divided into equal-sized blocks
  - blocks are called "pages" (both virtual and physical)
- Each process has its own virtual address space
  - operating system controls how virtual pages as assigned to physical memory



# Protection

- Page table entry contains access rights information
  - hardware enforces this protection (trap into OS if violation occurs)