CSE 120 Principles of Operating Systems

Fall 2021

Lecture 9: Memory Management Overview

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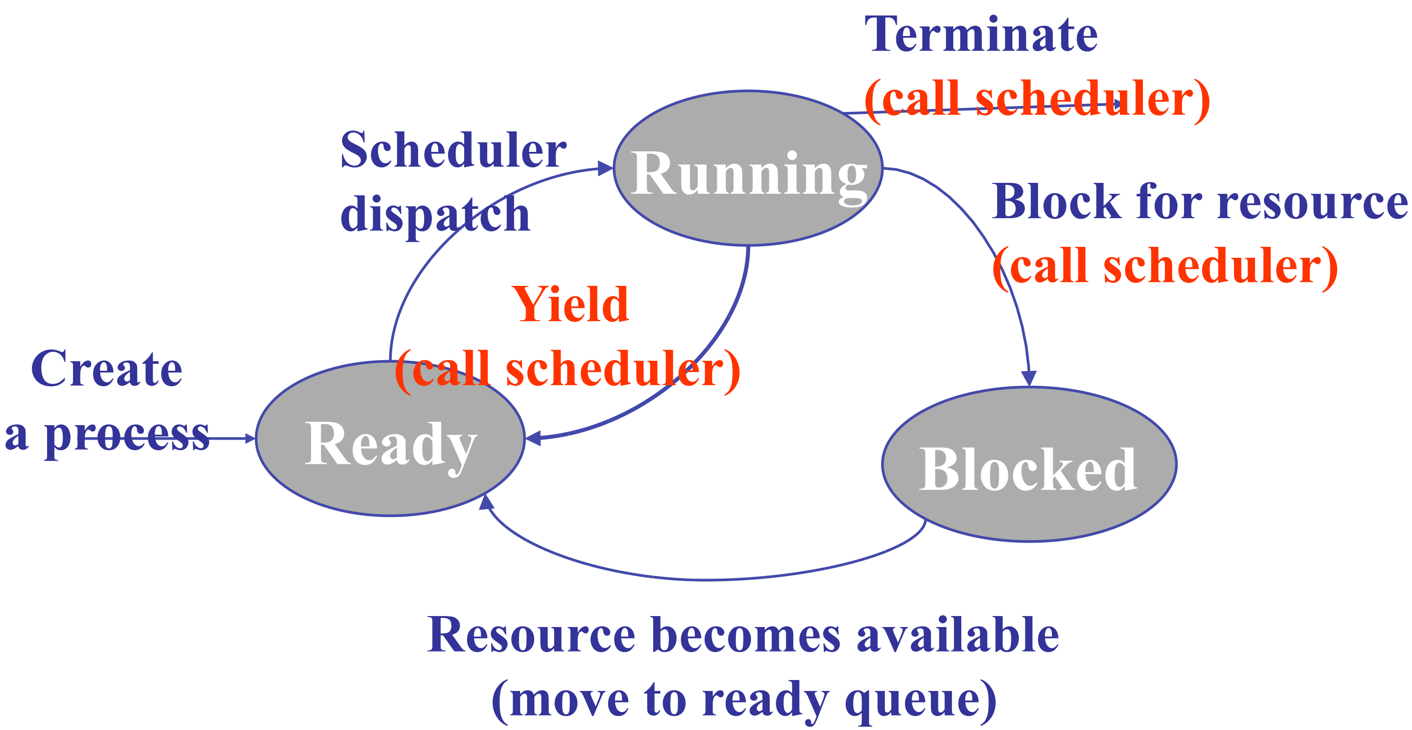
Announcements

- Homework 2 due tonight
- Start working on Project 2!
  - It will be harder than project 1 and need more time

[lec8] Non-Preemptive Scheduling

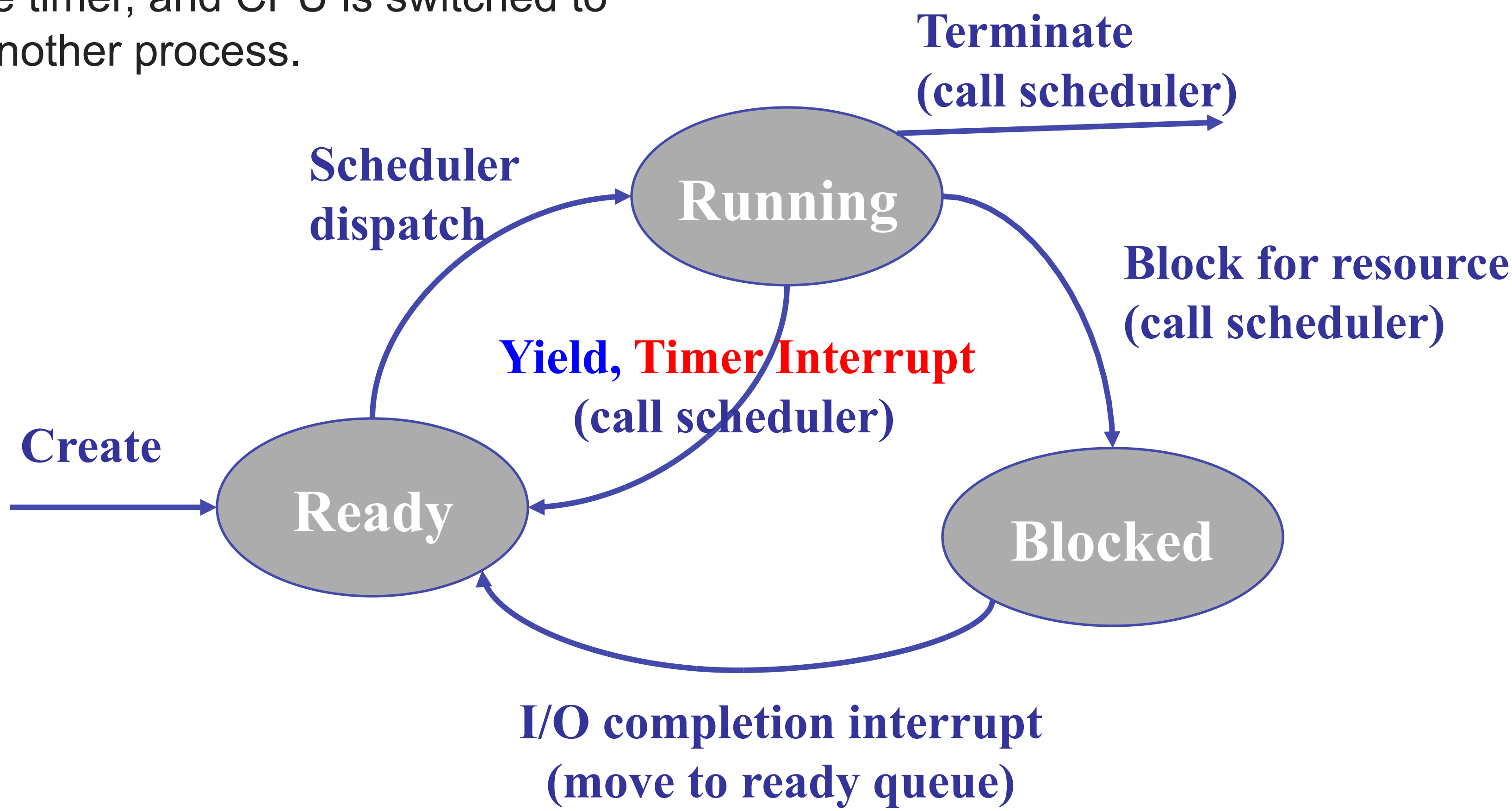
- OS only has a chance to schedule threads on a core when the current running thread leaves its running state
  - Yield, terminate, blocked by I/O, etc.



- How can we force a thread off its running state?

[lec8] Preemptive Scheduling

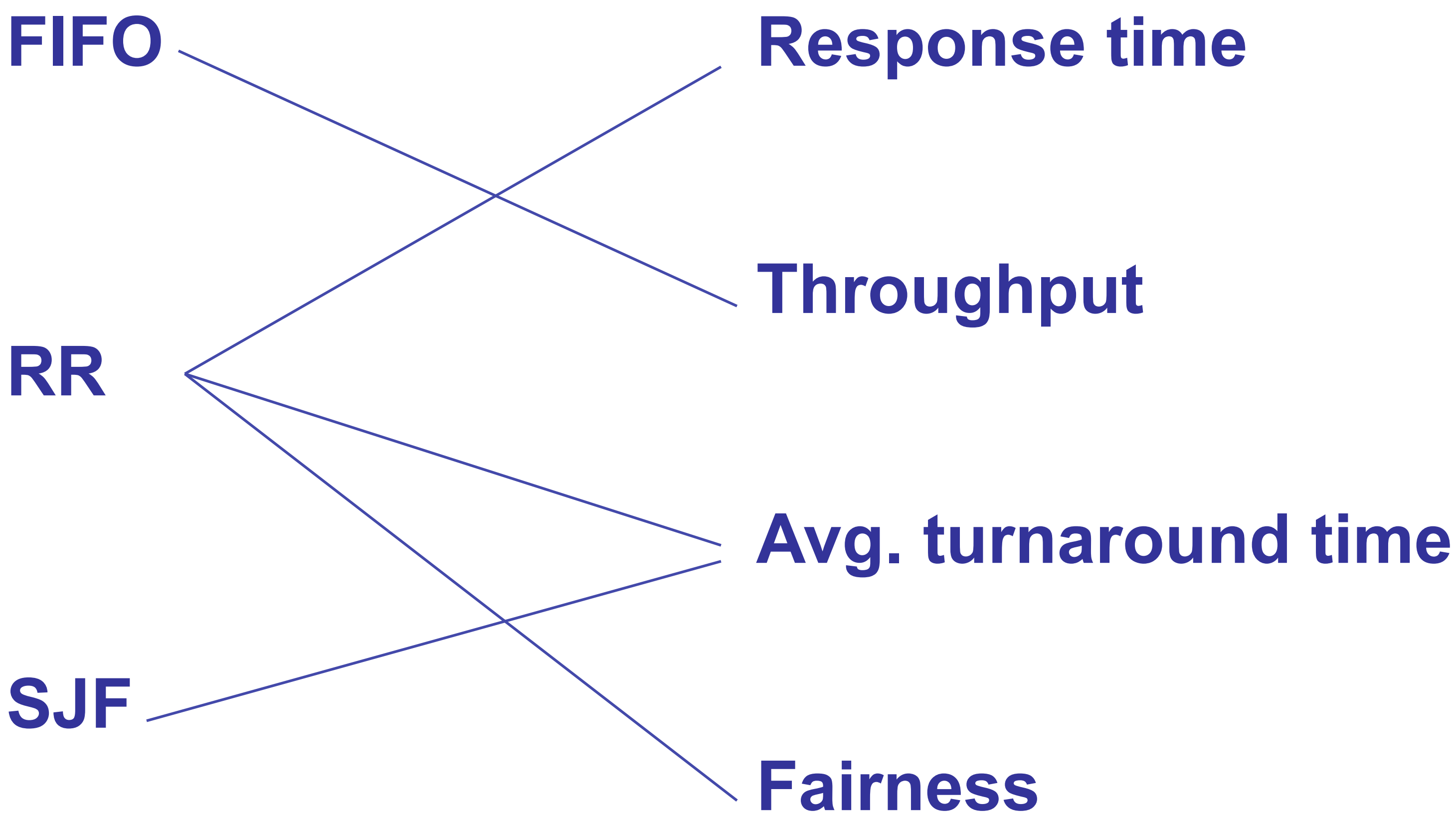
A running process is interrupted by the timer, and CPU is switched to run another process.



[lec8] Goals and Assumptions

- Goals (Performance metrics)
  - Minimize turnaround time
    - avg time to complete a job
    - $T_{turnaround} = T_{completion} - T_{arrival}$
  - Maximize throughput
    - operations (jobs) per second
    - Minimize overhead of context switches: large quanta
    - Efficient utilization (CPU, memory, disk etc)
  - Short response time
    - $T_{response} = T_{firstrun} - T_{arrival}$
    - type on a keyboard
    - Small quanta
  - Fairness
    - fair, no starvation, no deadlock

[lec8] Scheduling policies



[lec8] Multiple Queue Scheduling

- Motivation: processes may be of different nature and can be easily classified
  - e.g. foreground jobs vs. background jobs

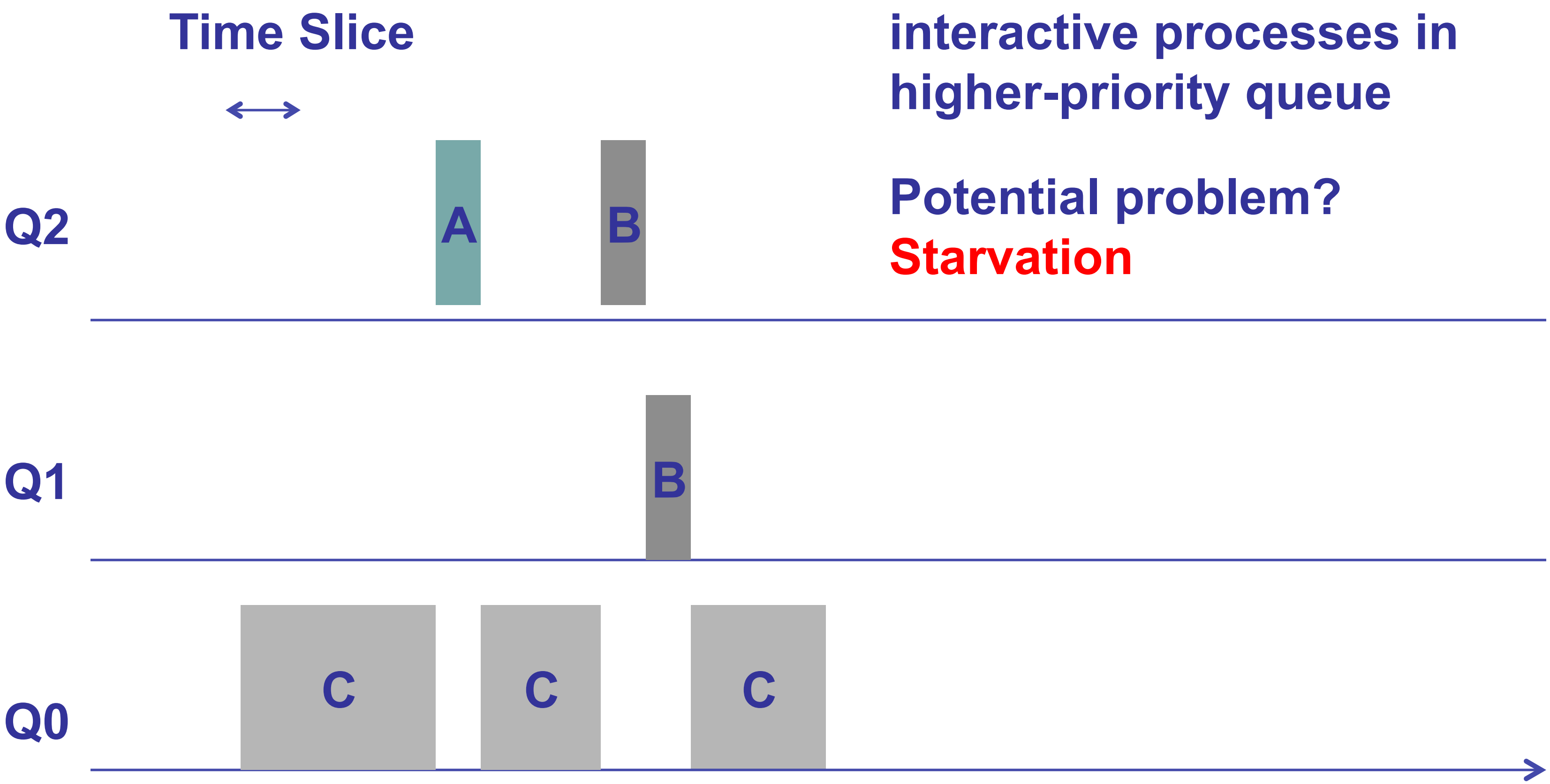
- The method:
  - Processes permanently assigned to one queue, based on processes priority / type
    - Preference to jobs with higher priorities
  - Each queue can have its own scheduling algorithm
    - e.g. RR for foreground queue, FCFS for background queue
  - Need a scheduling among the queues
    - e.g. fixed priority preemptive scheduling (high-pri queue trumps other)
    - e.g. time-slice between queues

[lec8] Multilevel Feedback Queue (MLFQ)

- Problem: how to change priority?

- Jobs start at highest priority queue
- Feedback
  - If a job uses up an entire time slice while running, its priority is reduced (i.e., it moves down one queue).
  - If a job gives up the CPU before the time slice is up, it stays at the same priority level.
  - After a long time period, move all the jobs in the system to the topmost queue (aging)

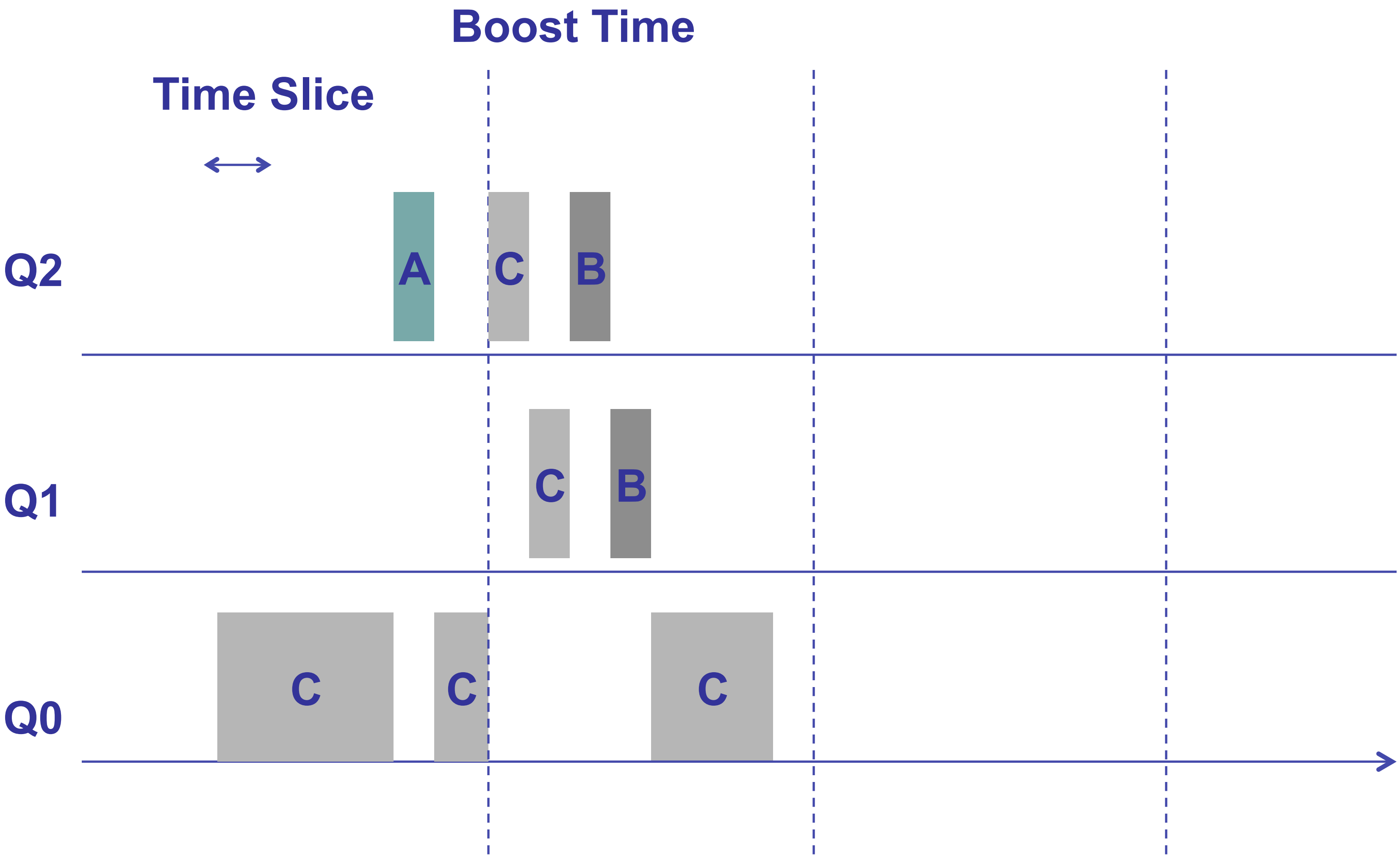
[lec8] MLFQ Example – a long job + short jobs in between



Leave I/O bound and interactive processes in higher-priority queue

Potential problem?
Starvation

[lec8] MLFQ Example – a long job+short jobs, with boost



[lec8] Scheduling Overhead

- Operating systems aim to minimize overhead
  - Context switching is not doing any useful work and is pure overhead
  - Overhead includes context switch + making a scheduling decision
- Modern time-sharing OSes (Unix, Windows, …) time-slice processes in ready list
  - A process runs for its quantum, OS context switches to another, next process runs, etc.
  - A CPU-bound process will use its entire quantum (e.g., 10ms)
  - An IO-bound process will use part (e.g., 1ms), then issue IO
  - The IO-bound process goes on a wait queue, the OS switches to the next process to run, the IO-bound process goes back on the ready list when the IO completes

[lec8] CPU Utilization

- CPU utilization is the fraction of time the system is doing useful work (e.g., not context switching)
- If the system has
  - Quantum of 10ms + context-switch and decision making overhead of 0.1ms
  - 3 CPU-bound processes + round-robin scheduling
- In steady-state, time is spent as follows:
  - 10ms + 0.1ms + 10ms + 0.1ms + 10ms + 0.1ms
  - CPU utilization = time doing useful work / total time
  - CPU utilization = (3*10ms) / (3*10ms + 3*0.1ms) = 30/30.3
- If one process is IO-bound, it will not use full quantum
  - 10ms + 0.1ms + 10ms + 0.1ms + 1ms + 0.1ms
  - CPU util = (2*10 + 1) / (2*10 + 1 + 3*0.1) = 21/21.3

[lec8] Scheduling Summary

- Scheduler (dispatcher) is the module that gets invoked when a context switch needs to happen
- Scheduling algorithm determines which process runs, where processes are placed on queues
- Many potential goals of scheduling algorithms
  - Utilization, throughput, wait time, response time, etc.
- Various algorithms to meet these goals
  - FCFS/FIFO, SJF, Priority, RR
- Can combine algorithms
  - Multiple-level feedback queues

Memory Management

Next few lectures are going to cover memory management

- Goals of memory management
  - To provide a convenient abstraction for programming
  - To allocate scarce memory resources among competing processes to maximize performance with minimal overhead
- Mechanisms
  - Physical and virtual addressing
  - Techniques: partitioning, paging, segmentation
  - Page table management, TLBs, VM tricks
- Policies
  - Page replacement algorithms

Virtual Memory

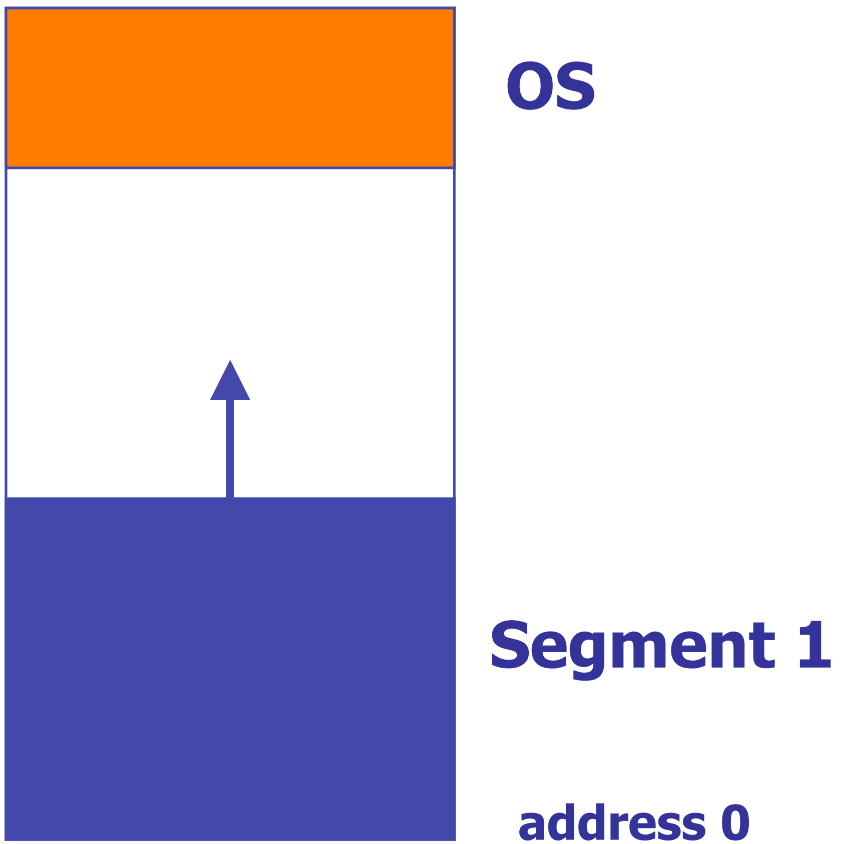
- The abstraction that the OS provides for managing memory is virtual memory (VM)
  - Virtual memory enables a program to execute with less than its complete data in physical memory
    - A program can run on a machine with less memory than it "needs"
    - Can also run on a machine with "too much" physical memory
  - Many programs do not need all of their code and data at once (or ever) – no need to allocate memory for it
  - OS will adjust amount of memory allocated to a process based upon its behavior
  - VM requires hardware support and OS management algorithms to pull it off
- Let's go back to the beginning…

In the beginning...

- Rewind to the very old days
  - Programs use physical addresses directly
  - OS loads job, runs it, unloads it

1. Simple uniprogramming:
Single segment per process

Physical memory



Simple uniprogramming:
Single segment per process

- Highest memory holds OS
- Process is allocated memory starting at 0, up to the OS area
- The single segment contains code, data, stack, heap
- When loading a process, just bring it in at 0
  - Directly using physical addresses

- Examples:
  - early batch monitor which ran only one job at a time
    - if the job wrecks the OS, reboot OS
  - 1st generation PCs operated in a similar fashion

- Pros / Cons?

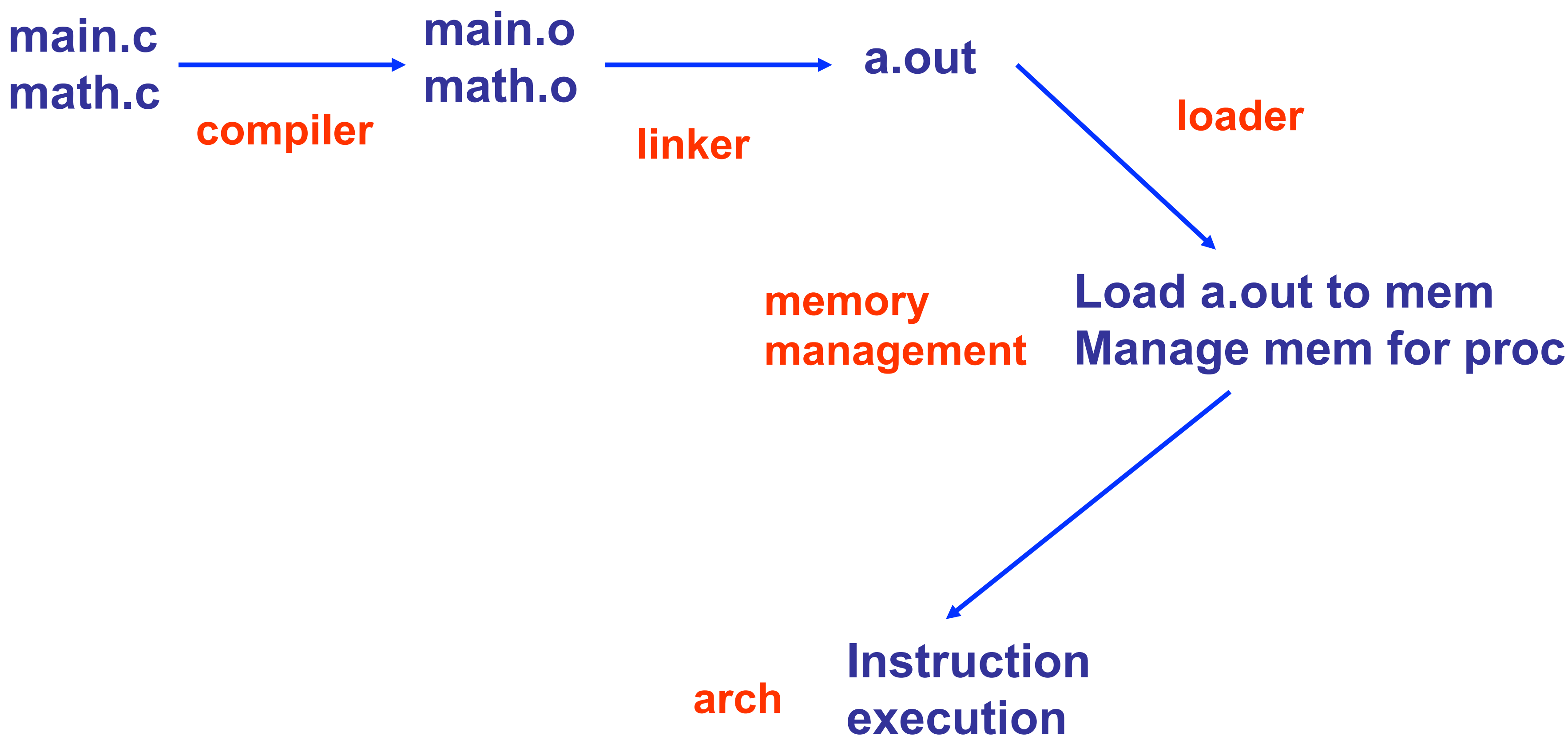
Multiprogramming

- Want to let several processes coexist in main memory

Issues in sharing main memory

- Transparency:
  - Processes should not know memory is shared
  - Run regardless of the number/locations of processes
- Safety:
  - Processes cannot corrupt each other
- Efficiency:
  - Both CPU and memory utilization shouldn't be degraded badly by sharing

The Big Picture

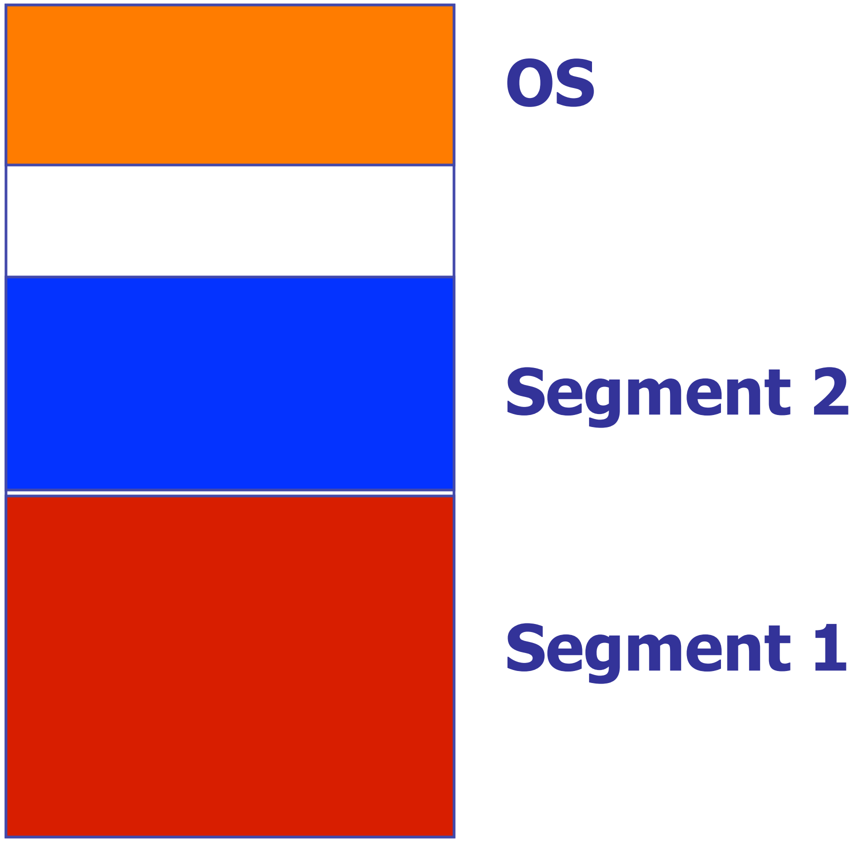


2. Simple multiprogramming

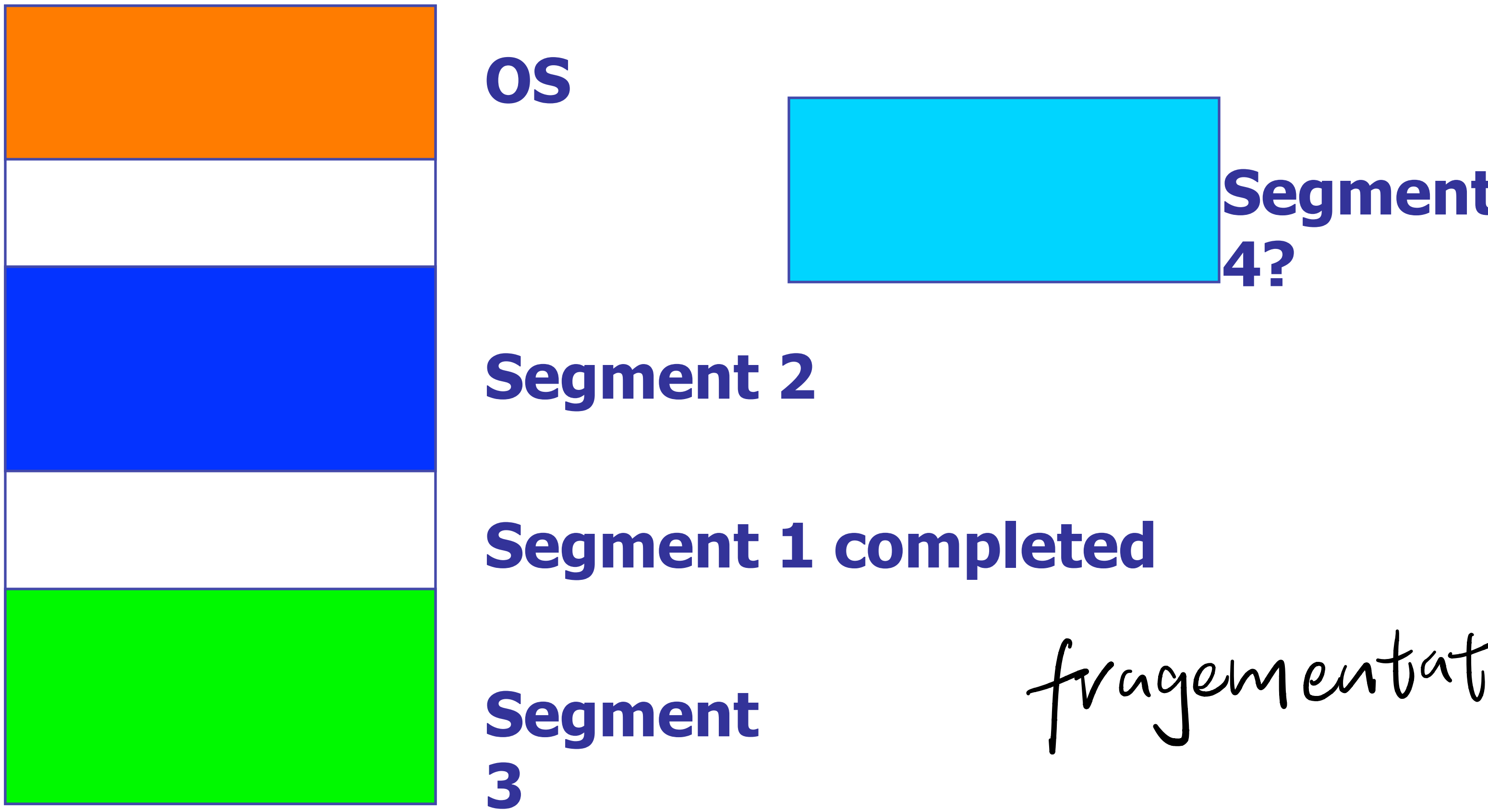
With static software memory relocation, no protection, 1 segment per process:

- Highest memory holds OS
- Processes allocated memory starting at 0, up to the OS area
- When a process is loaded, relocate it so that it can run in its allocated memory area

Simple multiprogramming:
Single segment per process, static relocation



Simple multiprogramming:
Single segment per process, static relocation



fragementation

Simple multiprogramming:
Single segment per process, static relocation

- four drawbacks
  1. No protection
  2. Low utilization -- Cannot relocate dynamically
     » Addresses in binary is fixed (after loading)
     » Cannot do anything about holes
  3. No sharing -- Single segment per process
     » Cannot share part of process address space (e.g. text)
  4. Entire address space needs to fit in mem
     » Need to swap whole, very expensive!

What else can we do?

- Already tried
  - Compile time / linking time
  - Loading time

- Let us try execution time!

3. Dynamic memory relocation

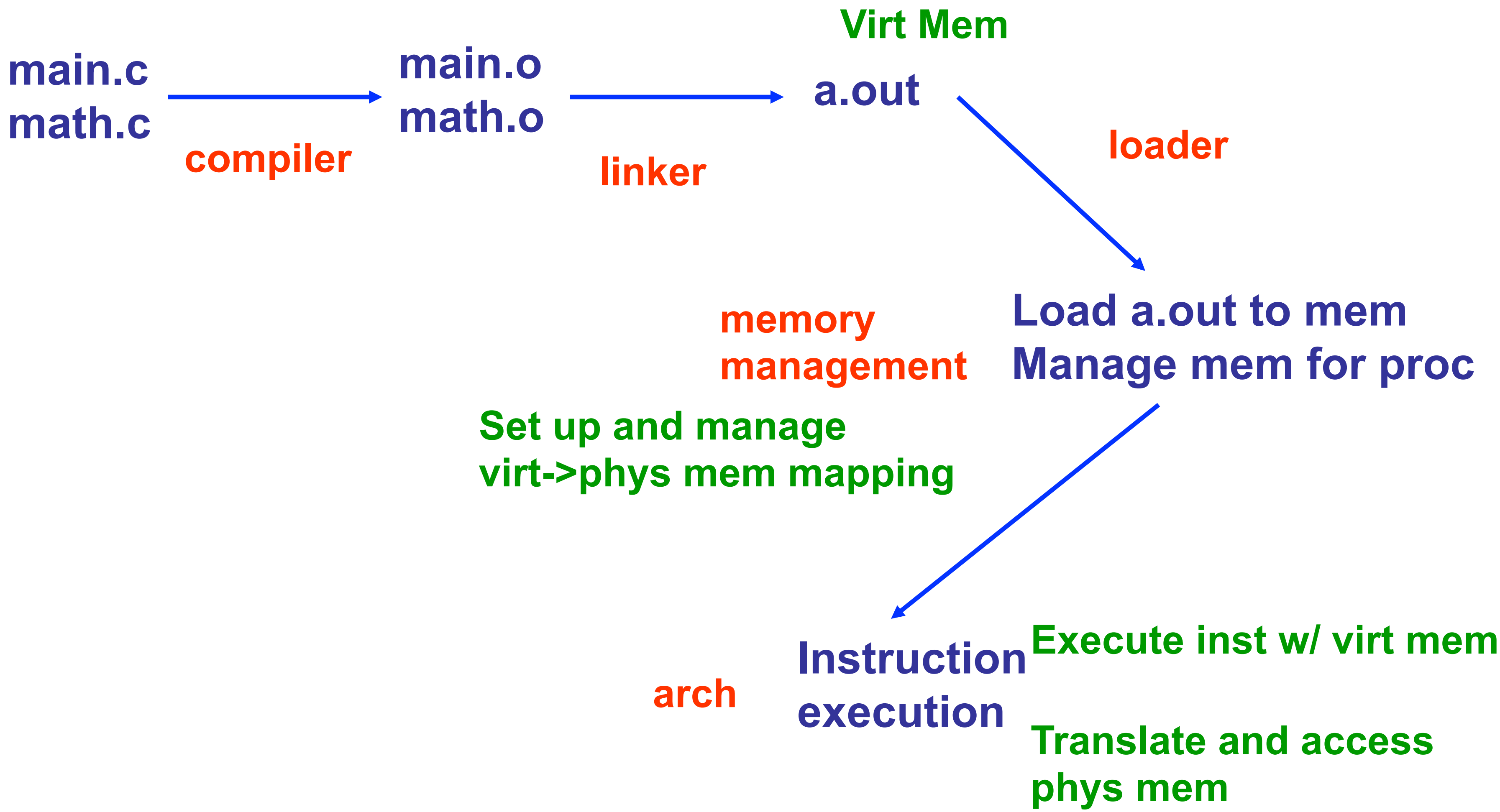
- Instead of changing the address of a program before it's loaded, change the address dynamically *during every reference*

Can this be done in software?

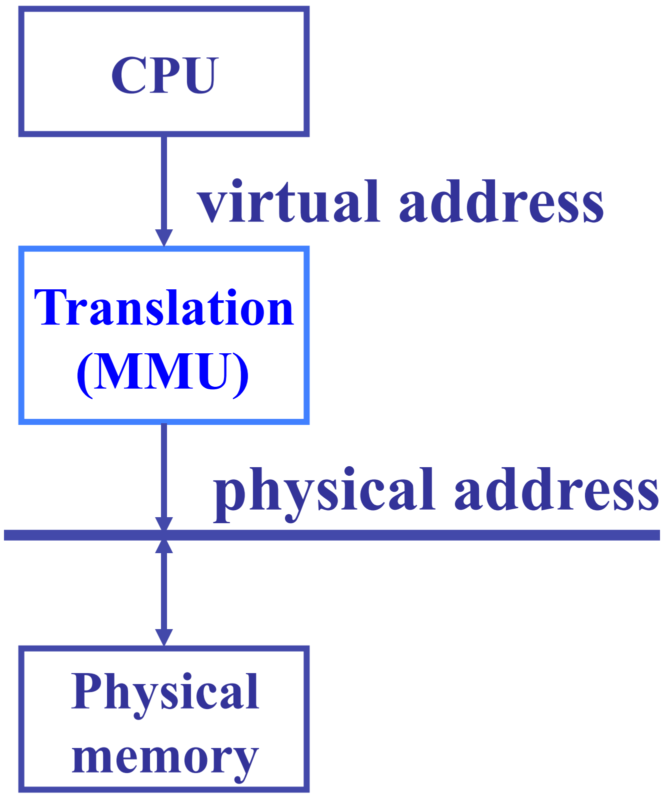
Virtual Addresses

- To make it easier to manage the memory of processes running in the system, we're going to make them use virtual addresses (logical addresses)
  - Virtual addresses are independent of the actual physical location of the data referenced
  - OS determines location of data in physical memory
  - Compiler+linker determines virtual memory. OS also allocates virtual memory (heap memory)
  - CPU executes instructions with virtual addresses
  - Virtual addresses are translated by hardware into physical addresses (with help from OS)
- The set of virtual addresses that can be used by a process comprises its virtual address space (VAS)
  - VAS often larger than physical memory (64-bit addresses)
  - But can also be smaller (32-bit VAS with 8 GB of memory)

The Big Picture

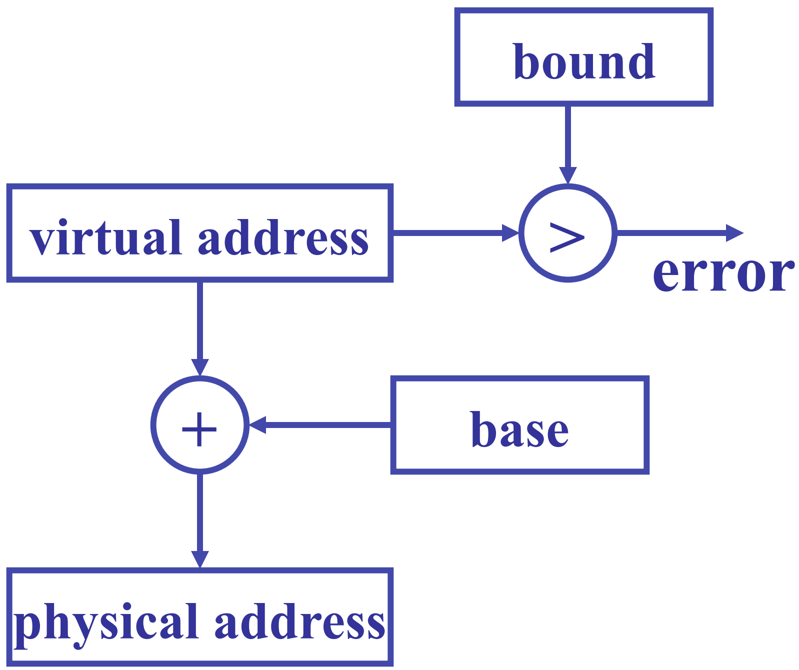


Translation overview



- Actual translation process is usually performed by hardware
- Translation table is set up by software
- CPU view
  - what program sees, virtual addresses
- Memory view
  - physical memory addresses

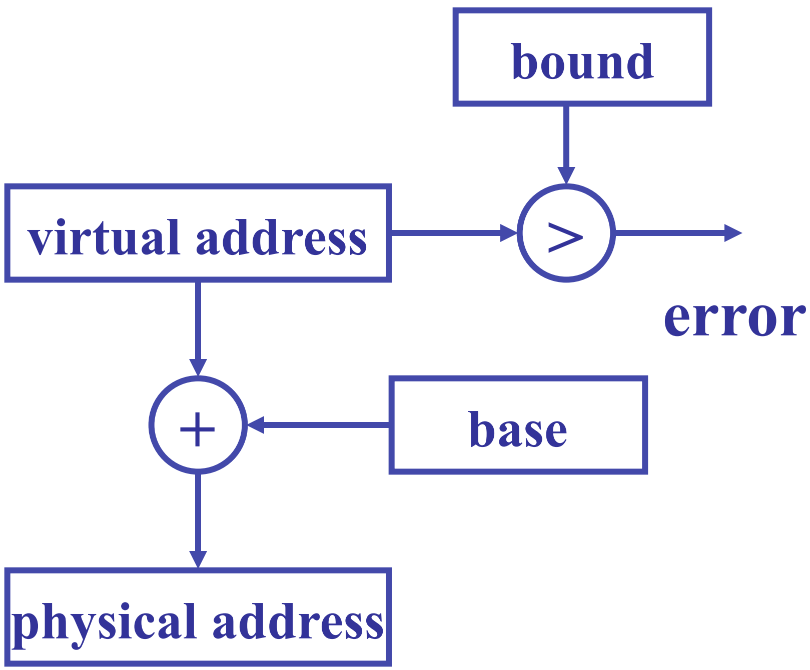
3.1 Base and bound



- Built in Cray-1 (1976)
- A program can only access physical memory in [base, base+bound]
- On a context switch: save/restore base, bound registers

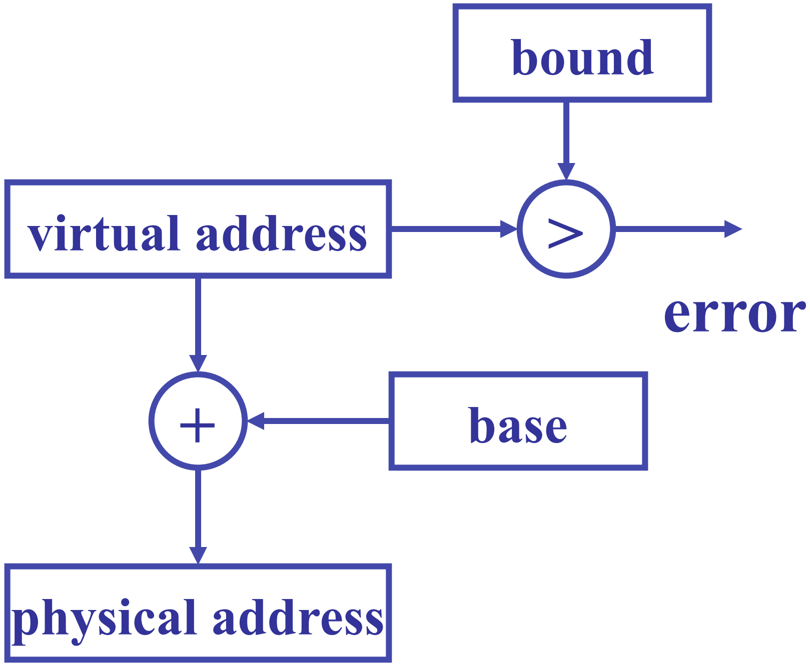
- Pros:
  - simple, fast translation, cheap
  - Can relocate segment at execution time

3.1 Base and bound



- The essence:
  - A level of indirection
  - Phy. Addr = Vir. Addr + base
- Why do we need the limit register? Protection
  - If (physical address > base + limit) then an exception will happen

3.1 Base and bound



- Cons:
  - Relocation requires moving the entire address space
  - Only one segment per process
  - How can two processes share code while keeping private data areas?
    - » Can it be done safely with a single-segment scheme?

What have we solved?

- four drawbacks
  1. No protection
  2. Low utilization -- Cannot relocate dynamically
     - Cannot do anything about holes
  3. No sharing -- Single segment per process
     - Cannot share part of process address space (e.g. text)
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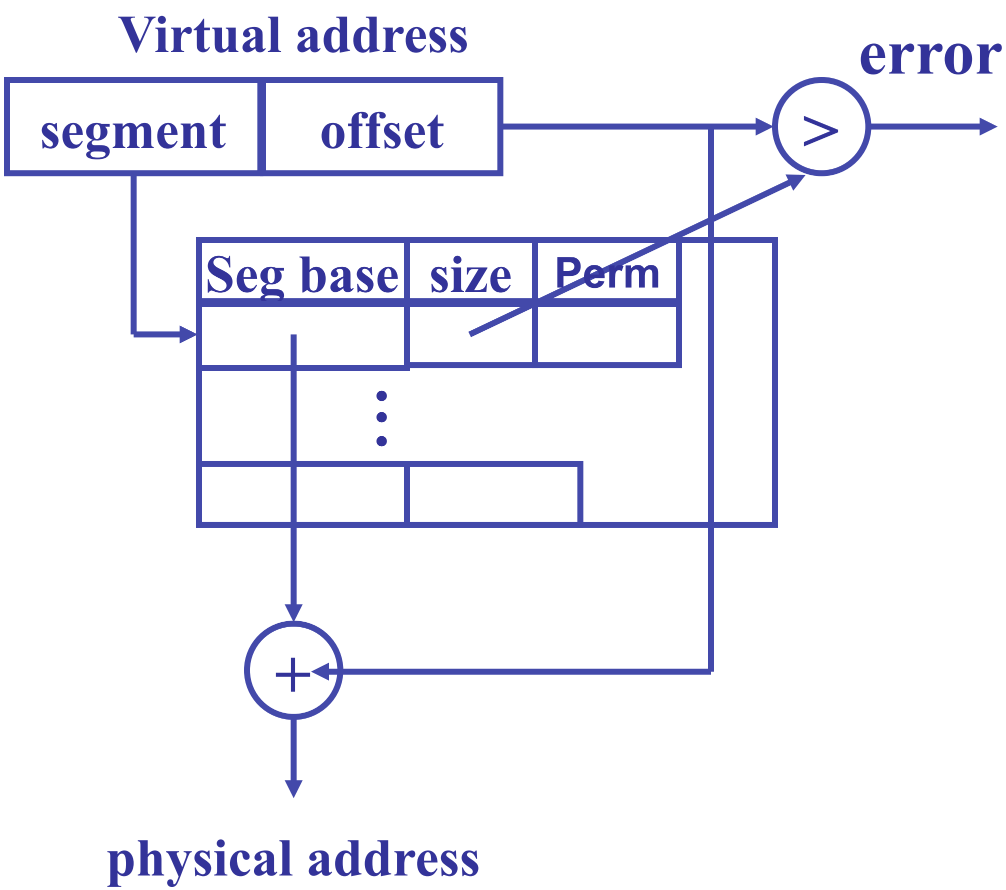
3.2 Multiple Segments

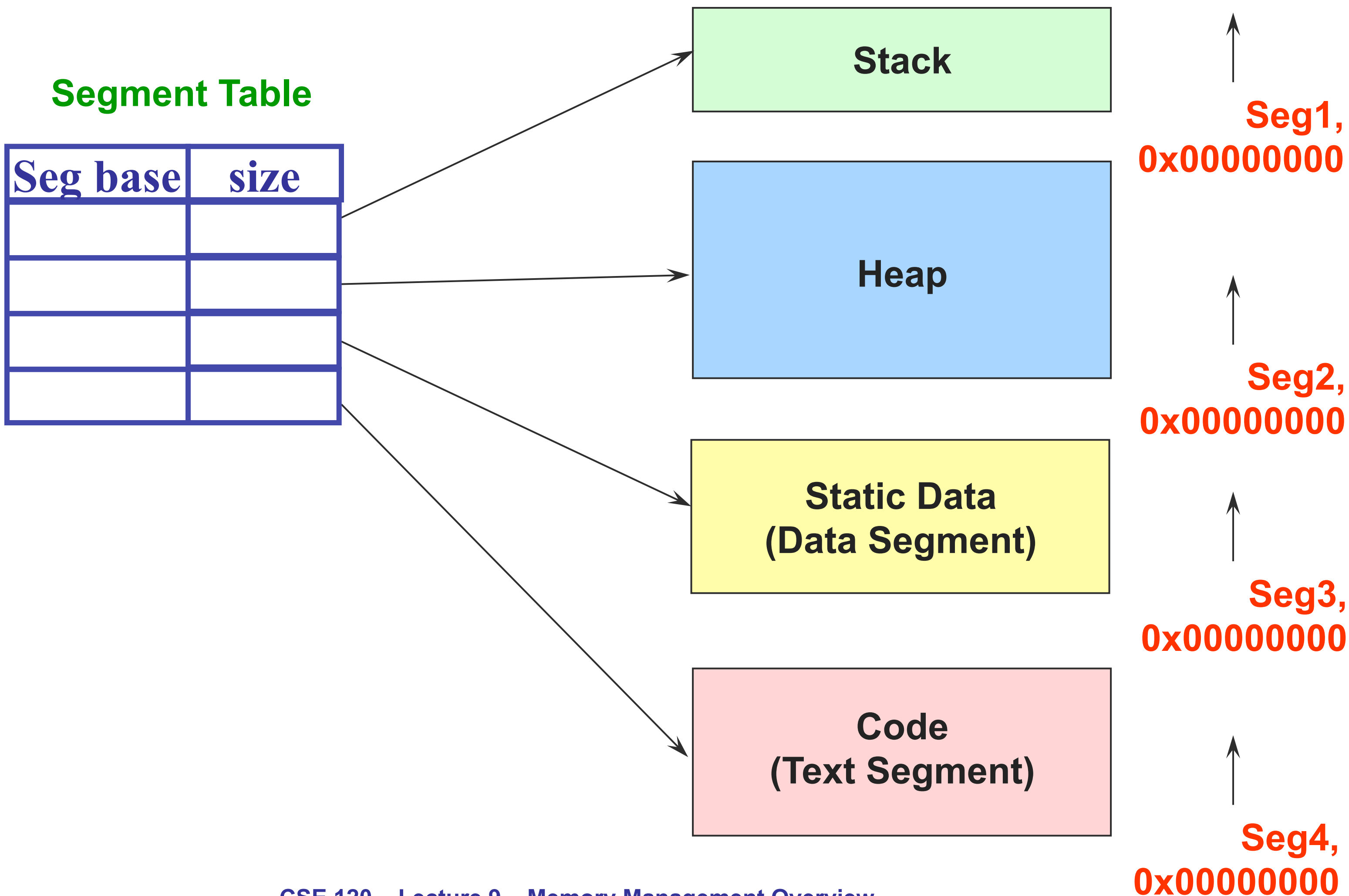


- Separate a virtual memory address space into multiple "segments"
- A hardware segment table of (seg base, size), each entry also has an associated permission (nil, read, write, exec)
- On a context switch: save/restore the table (or a pointer to the table) in kernel memory

Segmentation

- Segmentation is a technique that partitions memory into logically related data units
  - Module, procedure, stack, data, file, etc.
- Natural extension of base-and-bound
  - Base-and-bound: 1 segment/process
  - Segmentation: many segments/process

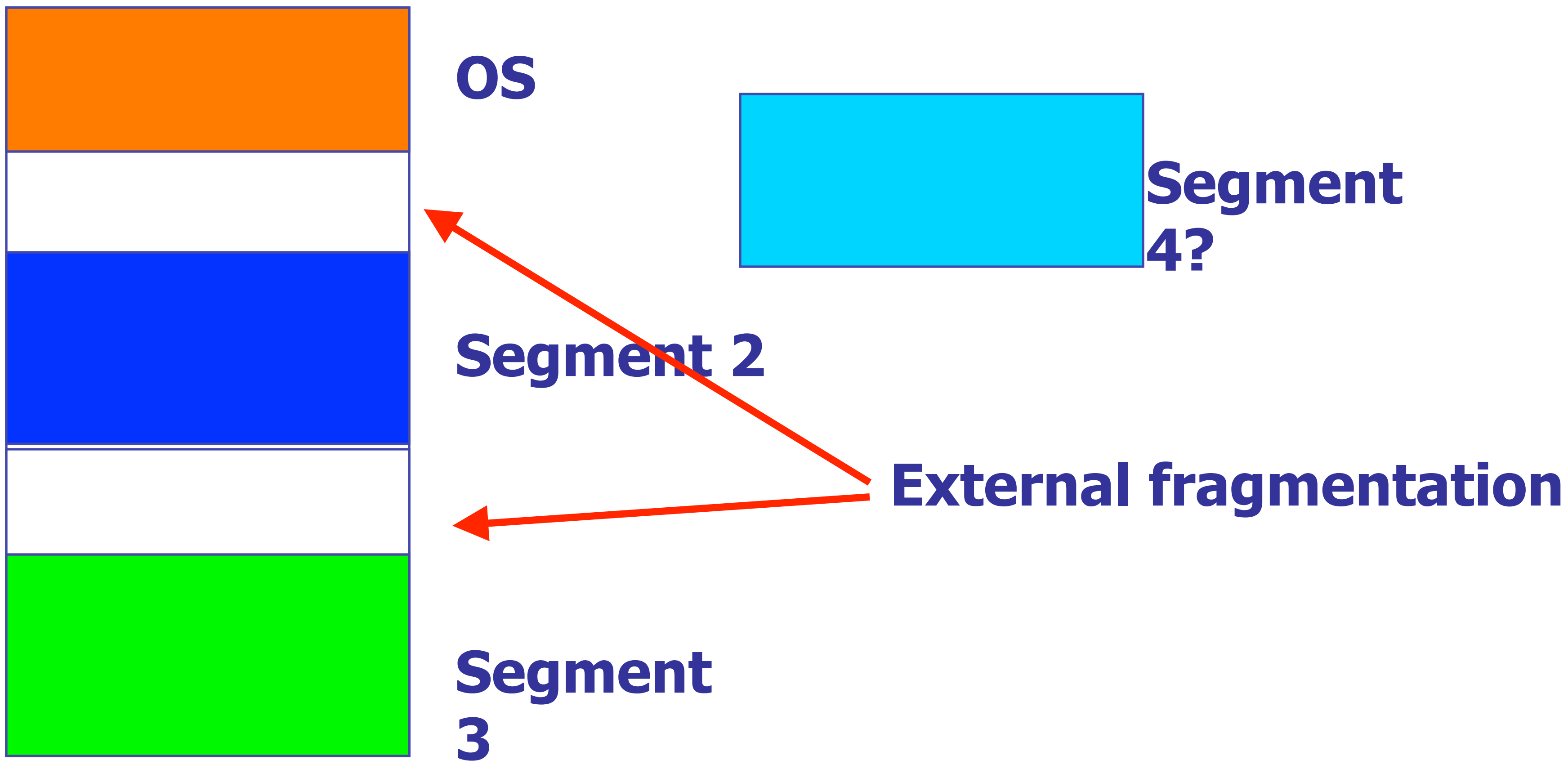
Segmented Address Space



Pros/cons of segmentation

- Pros:
  - Process can be split among several segments
    - Allows sharing
  - Segments can be assigned, moved, or swapped independently
- Cons:
  - External fragmentation: many holes in physical memory
    - Also happens in base and bound scheme

External fragmentation with segmentation



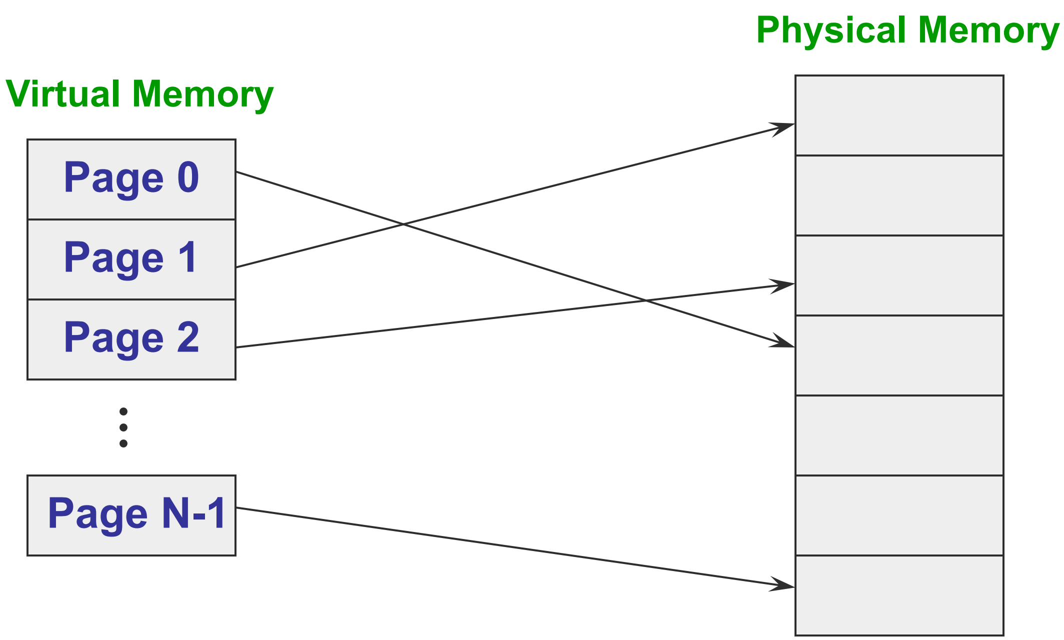
What fundamentally causes external fragmentation?

1. Segments of many different sizes
2. Each has to be allocated contiguously

- "Million-dollar" question:
  Physical memory is precious.
  Can we limit the waste to a single hole of X bytes?

Paging

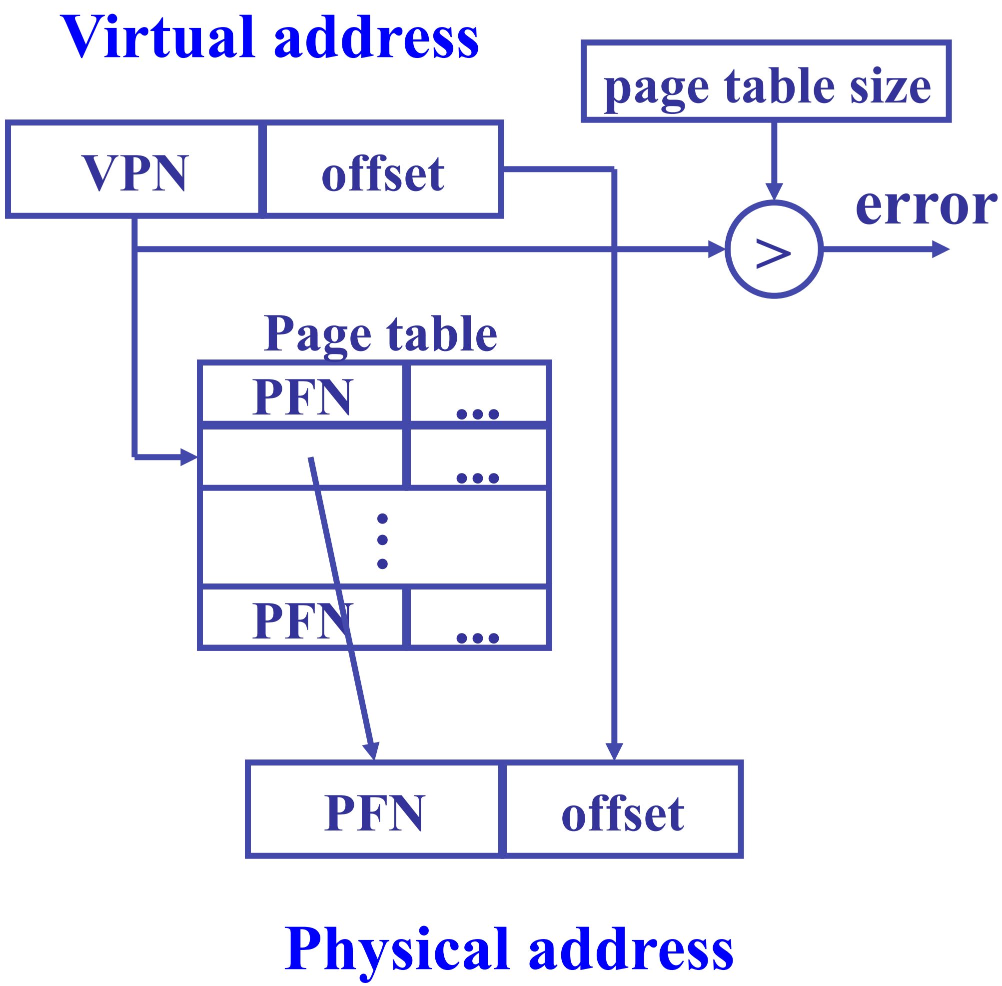
- Paging solves the external fragmentation problem by using fixed sized units in both physical and virtual memory



Paging

- Translating addresses
  - Virtual address has two parts: virtual page number and offset
  - Virtual page number (VPN) is an index into a page table
  - Page table determines page frame number (PFN)
  - Physical address is PFN::offset ("::" means concatenate)
- Page tables
  - Map virtual page number (VPN) to page frame number (PFN)
    - VPN is the index into the table that determines PFN
  - One page table entry (PTE) per page in virtual address space
    - Or, one PTE per VPN

Paging



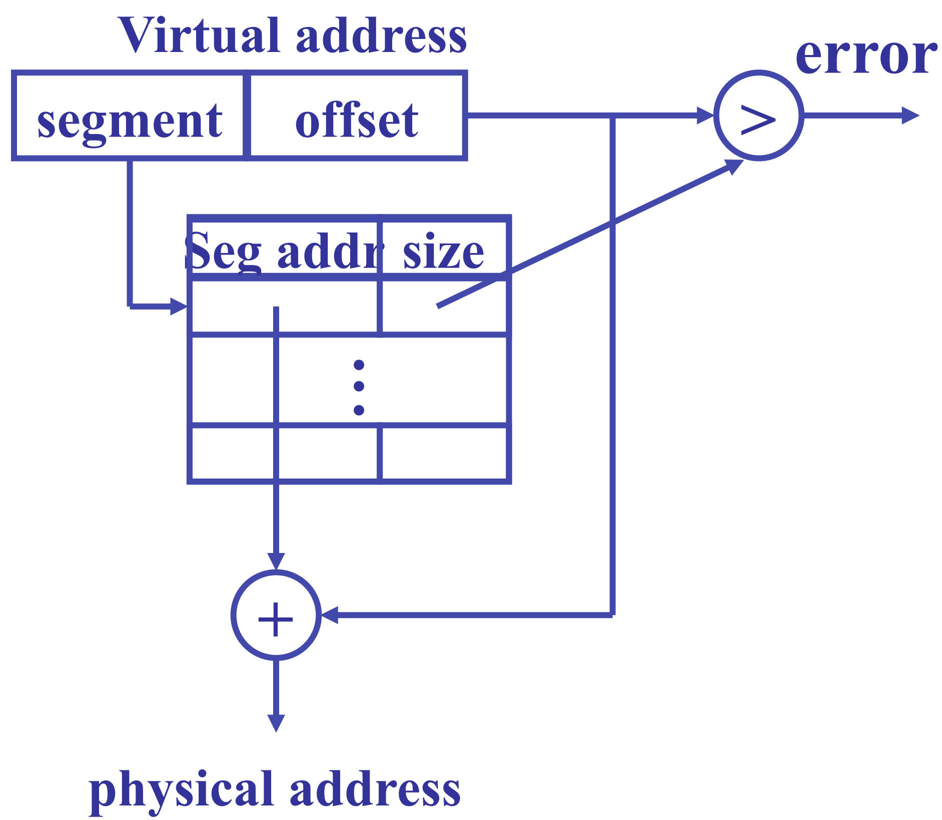
- Context switch
  - similar to the segmentation scheme
- Pros:
  - easy to allocate memory
  - easy to swap
  - easy to share

Paging Example

- Pages are 4K
  - ♦ 4K → offset is 12 bits → VPN is 20 bits (2^{20} VPNs), assuming 32bit system
- Virtual address is 0x7468
  - ♦ Virtual page is 0x7, offset is 0x468 (lowest 12 bits of address)
- Page table entry 0x7 contains 0x2
  - ♦ Page frame number is 0x2
  - ♦ Seventh virtual page is at address 0x2000 (physical page 2)
- Physical address = 0x2000 :: 0x468 = 0x2468

Deep thinking: Paging implementation

- Translation: table lookup and bit substitution
- Why is this possible?
- Why can't we do the same in segmentation?



Summary

- Virtual memory
  - Processes use virtual addresses
  - Hardware translates virtual address into physical addresses with OS support
- Evolution of techniques
  - Single, fixed physical segment per process (no virt mem)
  - Single segment per process, static relocation (no virt mem)
  - Base-and-bound – dynamic relocating whole process
  - Segmentation – multiple (variable-size) segments with dynamic relocation
  - Paging – small, fixed size pages

Next time…

- Chapters 18, 19, 20