CSE 120
Principles of Operating Systems

Fall 2022

Lecture 9: Memory Management

Geoffrey M. Voelker

Administrivia

- Project 2 released
  - This lecture gets you jumpstarted
- Homework 3 released
  - Do VM worksheet before part 2 of project 2

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 (1)
  - Techniques: partitioning, paging, segmentation (1)
  - Page table management, TLBs, VM tricks (2)
- Policies
  - Page replacement algorithms (3)

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 physical memory for it
  - OS will adjust amount of physical 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…

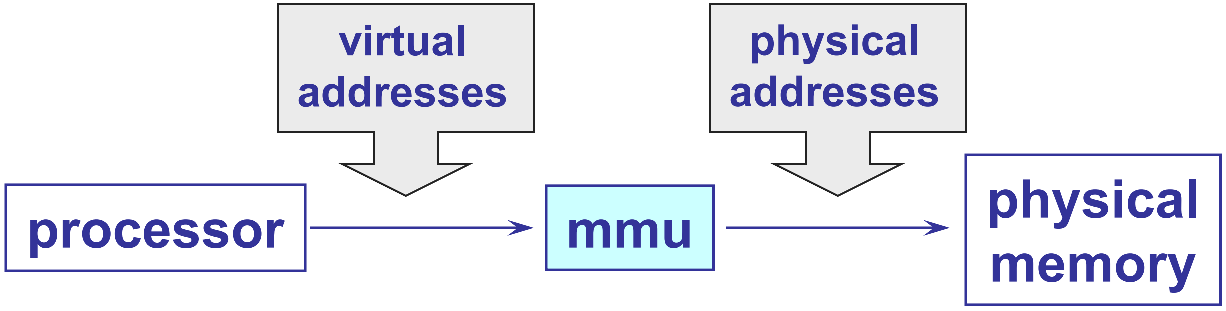
In the beginning...

- With early computers…
  - Programs used physical addresses directly (e.g., early PCs)
  - OS loads job, runs it, unloads it
- Multiprogramming changes all of this
  - Want multiple processes in memory at once
    - Overlap I/O and CPU of multiple jobs
  - Can do it a number of ways
    - Fixed and variable partitioning, paging, segmentation
  - Requirements
    - Need protection – restrict which addresses jobs can use
    - Fast translation – lookups need to be fast
    - Fast change – updating memory hardware on context switch

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
  - Instructions executed by the CPU issue 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 DRAM)

Virtual Addresses

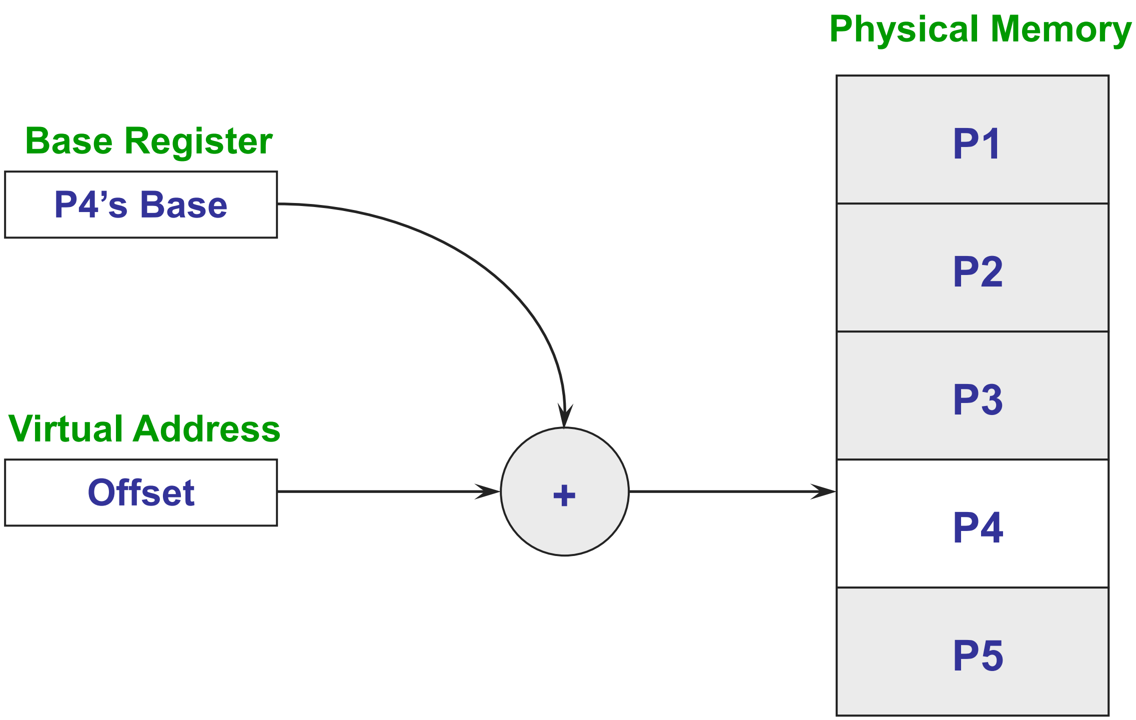


- Many ways to do this translation…
  - Start with old, simple ways, progress to current techniques

Fixed Partitions

- Physical memory is broken up into fixed partitions
  - Hardware requirements: base register
  - Physical address = virtual address + base register
  - Base register loaded by OS when it switches to a process
  - Size of each partition is the same and fixed
  - How do we provide protection?
- Advantages
  - Easy to implement, fast context switch
- Problems
  - Internal fragmentation: memory in a partition not used by a process is not available to other processes
  - Partition size: one size does not fit all (very large processes)

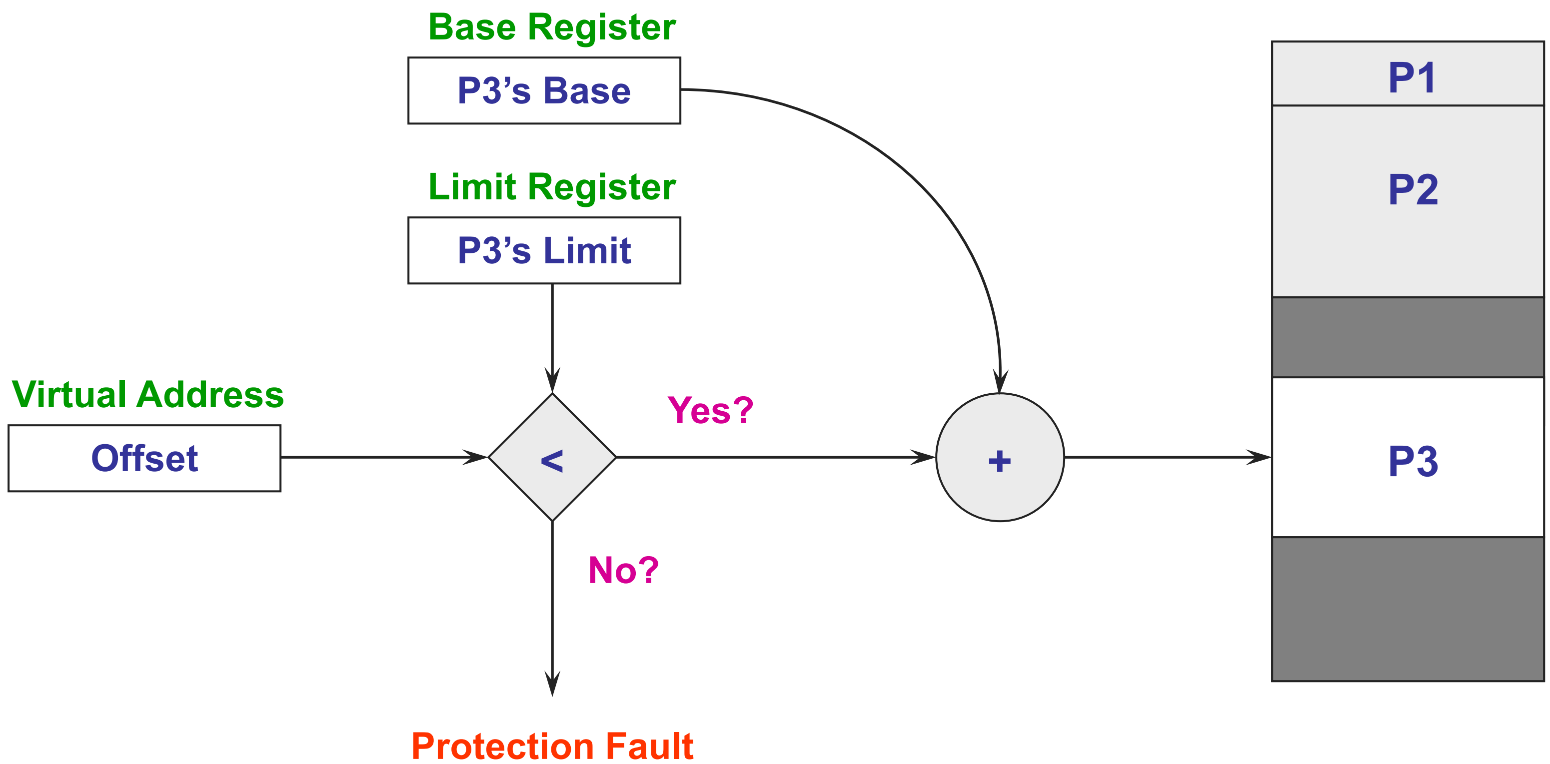
Fixed Partitions



Variable Partitions

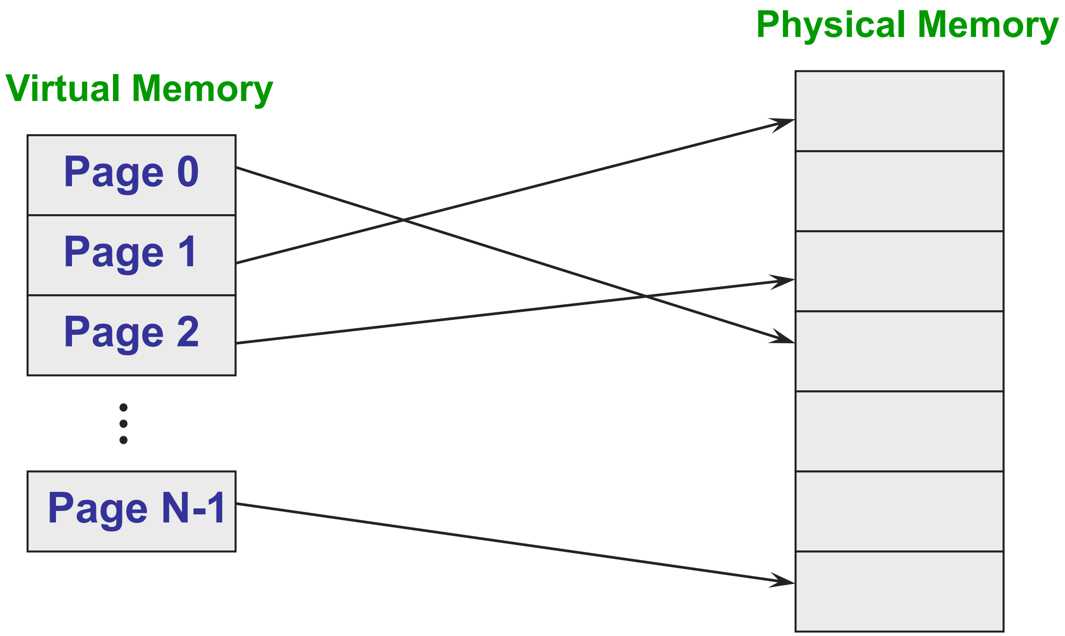
- Natural extension – physical memory is broken up into variable sized partitions
  - Hardware requirements: base register and limit register
  - Physical address = virtual address + base register
  - Why do we need the limit register? Protection
    - If (physical address > base + limit) then fault (exception)
- Advantages
  - No internal fragmentation: allocate just enough for process
- Problems
  - External fragmentation: process creation and termination produces empty holes scattered throughout memory

Variable Partitions



Paging

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



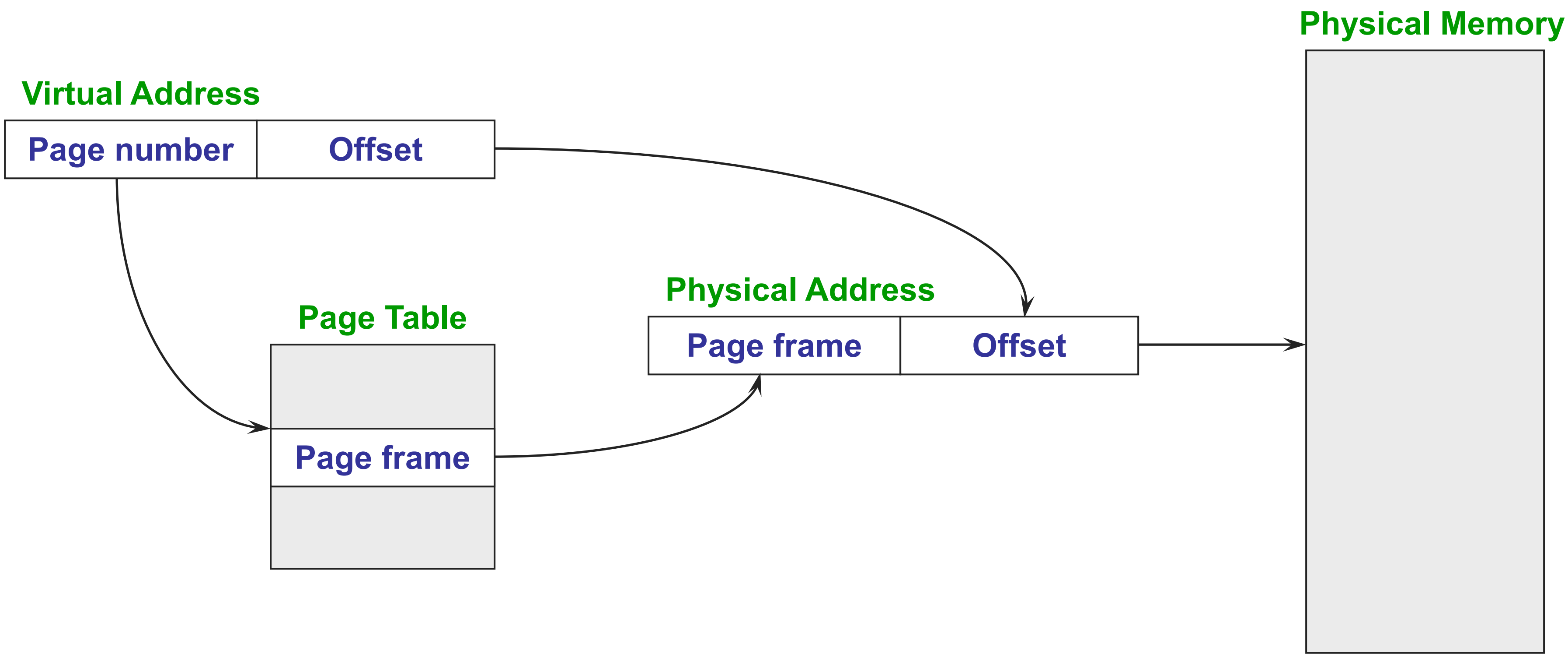
Programmer/Process View

- Programmers (and processes) view memory as one contiguous address space from 0 through N
  - Virtual address space (VAS)
- In reality, pages are scattered throughout physical memory
  - The mapping is invisible to the process
- Protection is provided because a process cannot reference memory outside of its VAS
  - The address “0x1000” maps to different physical addresses in different processes

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
    - Will also refer to PFN as "physical page number"
  - One page table entry (PTE) per page in virtual address space
    - Or, one PTE per VPN

Page Lookups

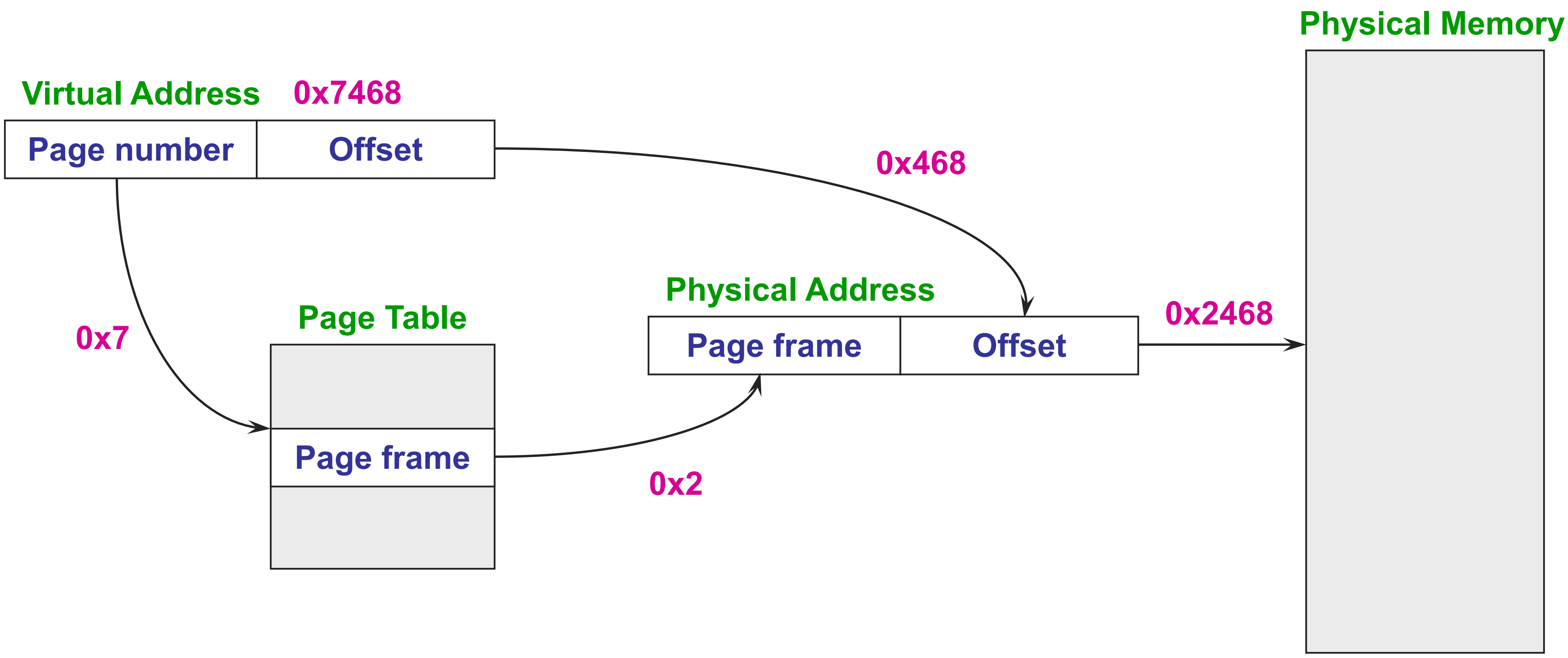


(Simple page table used by Nachos)

Paging Example

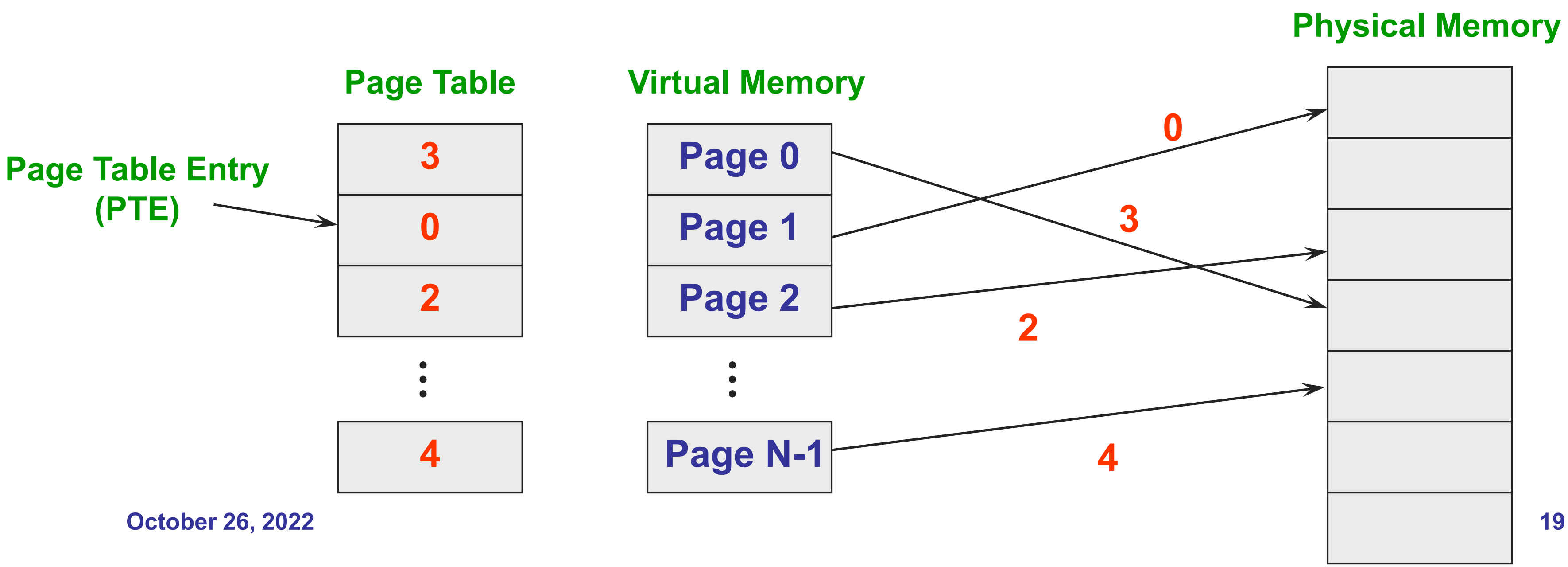
- Pages are 4K
  - 4K → offset is 12 bits → VPN is 20 bits (2^{20} VPNs)
- Virtual address is 0x7468
  - Virtual page is 0x7, offset is 0x468 (lowest 12 bits of address)
- Page table entry 0x7 contains 0x2
  - Page frame number is 0x2
  - Virtual page 0x7 is at address 0x2000 (physical page 2)
- Physical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

Page Lookups



Page Tables

- Page tables completely define the mapping between virtual pages and physical pages for an address space
- Each process has an address space, so each process has a page table
- Page tables are data structures maintained in the OS



Page Table Entries (PTEs)

1	1	1	3	20
M	**R**	**V**	**Prot**	**Page Frame Number**

- Page table entries control mapping
  - The Modify bit says whether or not the page has been written
    - It is set when a write to the page occurs
  - The Reference bit says whether the page has been accessed
    - It is set when a read or write to the page occurs
  - The Valid bit says whether or not the PTE can be used
    - It is checked each time the virtual address is used
  - The Protection bits say what operations are allowed on page
    - Read, write, execute
    - PTE for page 0 often set no-read, no-write, no-execute
  - The page frame number (PFN) determines physical page

Paging Advantages

- Easy to allocate memory
  - Memory comes from a free list of fixed-sized chunks
  - Allocating a page is just removing it from the list
  - External fragmentation not a problem
- Easy to swap out chunks of a program
  - All chunks are the same size
  - Use valid bit to detect references to swapped pages
  - Pages are a convenient multiple of the disk block size

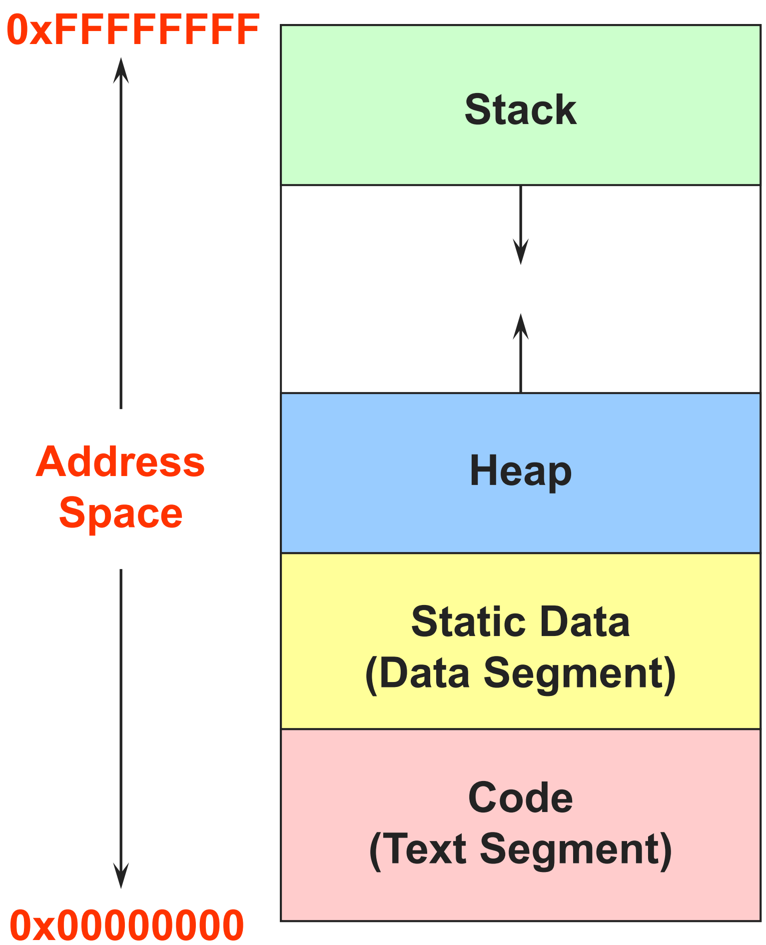
Paging Limitations

- Can still have internal fragmentation
  - Process may not use memory in multiples of a page
- Memory reference overhead
  - 2 references per address lookup (page table, then memory)
  - Solution – use a hardware cache of lookups (more later)
- Memory required to hold page table can be significant
  - Need one PTE per page
  - 32 bit address space w/ 4KB pages = 2^{20} PTEs
  - 4 bytes/PTE = 4MB/page table
  - 25 processes = 100MB just for page tables!
  - Solution – hierarchical page tables (more later)

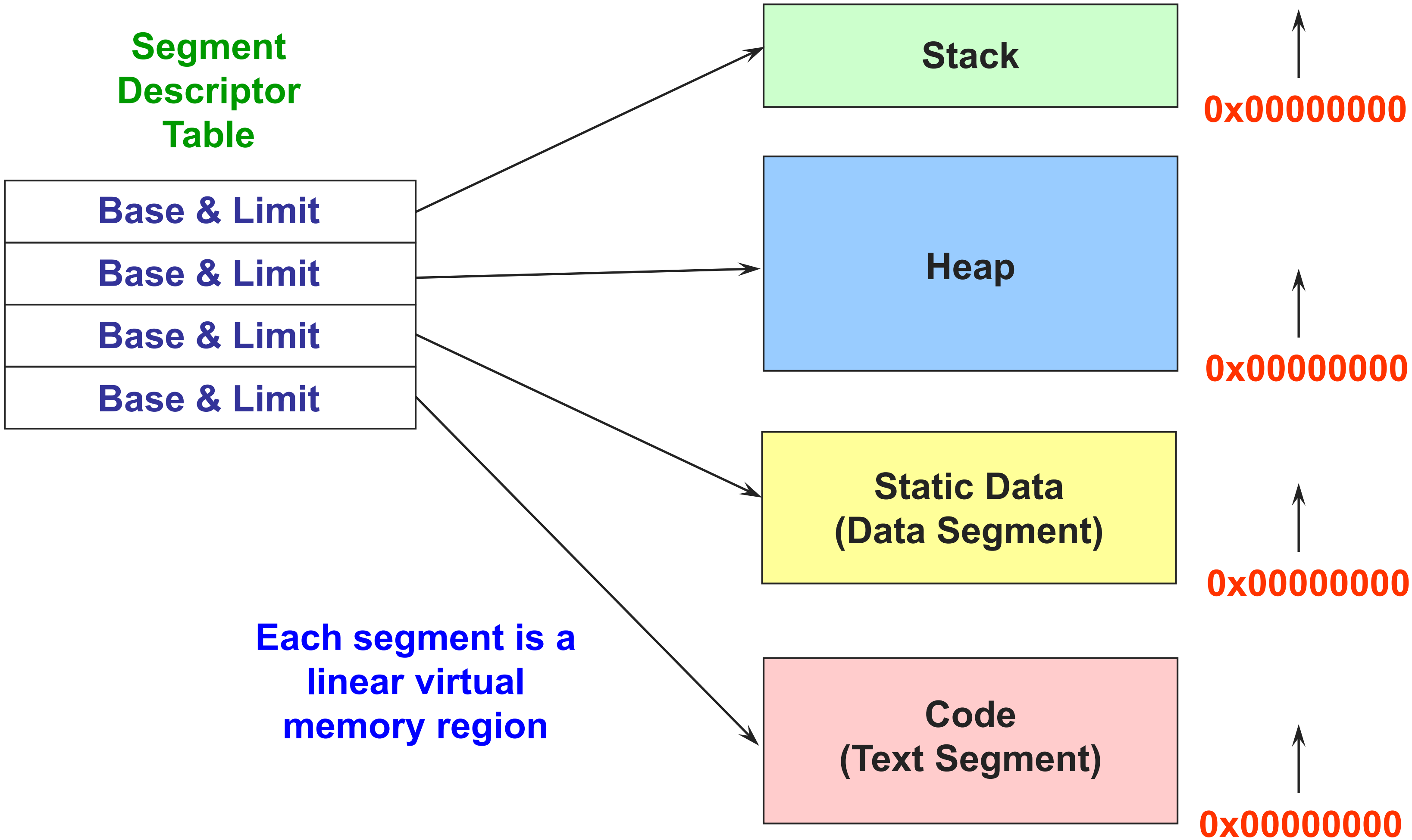
Segmentation

- Segmentation is a technique that partitions memory into logically related data units
  - Module, procedure, stack, data, file, etc.
  - Virtual addresses become <segment #, offset>
    - x86 stores segment #s in registers (CS, DS, SS, ES, FS, GS)
  - Units of memory from programmer's perspective
- Natural extension of variable-sized partitions
  - Variable-sized partitions = 1 segment/process
  - Segmentation = many segments/process
- Hardware support
  - Multiple base/limit pairs, one per segment (segment table)
  - Segments named by #, used to index into table

Linear Address Space

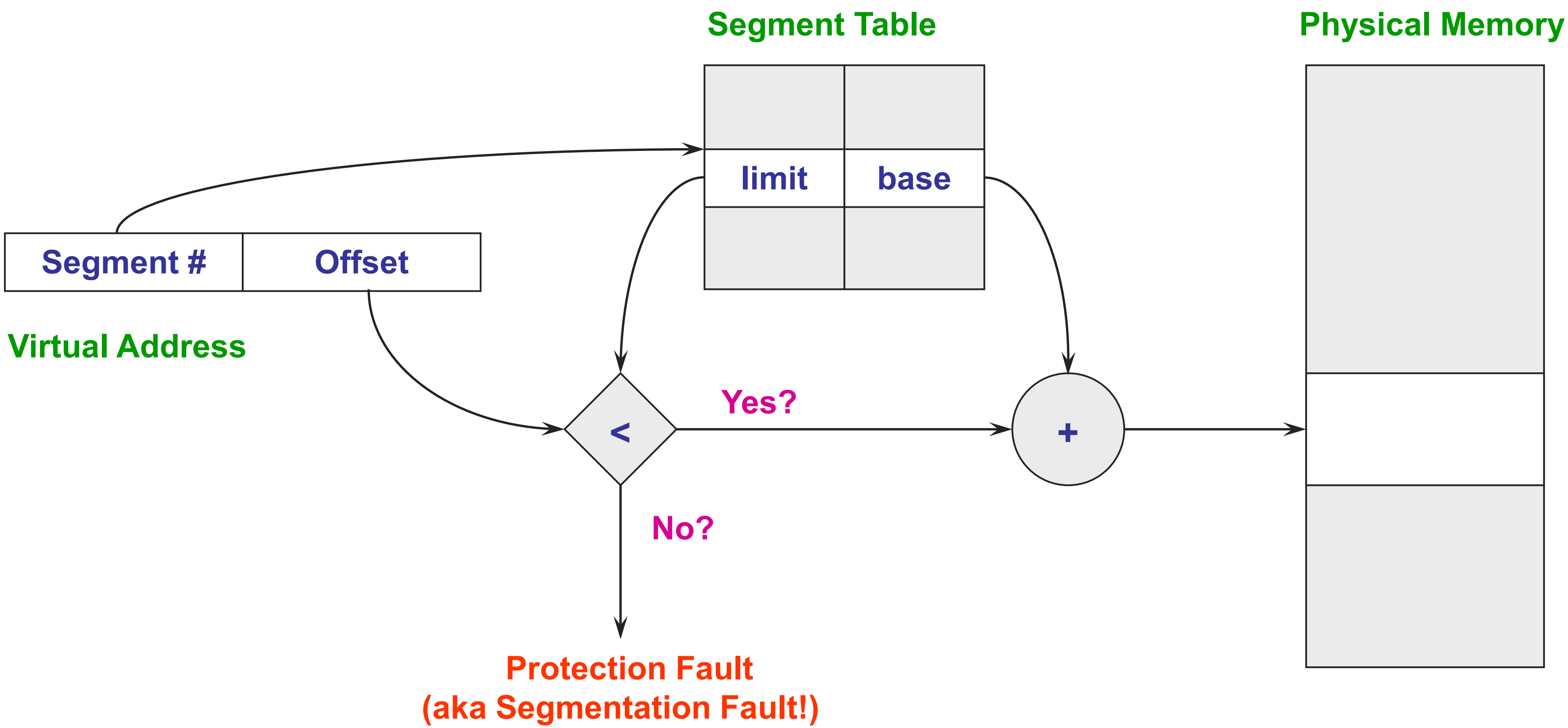


Segmented Address Space



Each segment is a linear virtual memory region

Segment Lookups



Segmentation and Paging

- Can combine segmentation and paging
  - x86 in 32-bit mode supports segments and paging
- Use segments to manage logically related units
  - Segments vary in size, but usually large (many pages)
- Use pages to partition segments into fixed-size chunks
  - Makes segments easier to manage within physical memory
    - Segments become "pageable" – rather than moving segments into and out of memory, just move page portions of segment
  - Need to allocate page table entries only for those pieces of the segments that have themselves been allocated
- Tends to be complex
  - Need both segment tables *and* page tables

Summary

- Virtual memory
  - Processes use virtual addresses
  - Hardware translates virtual address into physical addresses with OS support
- Various techniques
  - Fixed partitions – easy to use, but internal fragmentation
  - Variable partitions – more efficient, but external fragmentation
  - Paging – use small, fixed size chunks, efficient for OS
  - Segmentation – manage from programmer's perspective
  - Combine paging and segmentation to get benefits of both

Next time...

- Chapters 19, 20