CSE 120
Principles of Operating Systems

Fall 2014

Lecture 9: Memory Management

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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)

Lecture Overview

- Virtual memory warm-and-fuzzy
- Survey techniques for implementing virtual memory
  - Fixed and variable partitioning
  - Paging
  - Segmentation
- Focus on hardware support and lookup procedure
  - Next lecture we'll go into sharing, protection, efficient implementations, and other VM tricks and features

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 days of "second-generation" computers
  - Programs use physical addresses directly
  - 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

Virtual Addresses

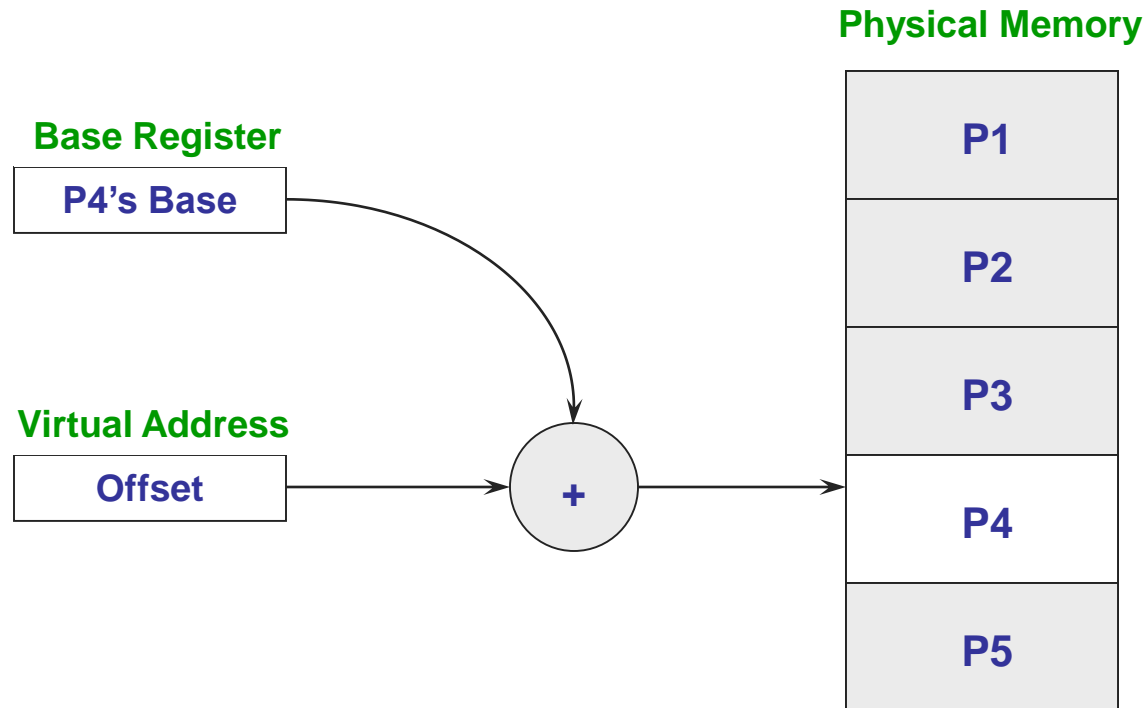| virtual addresses		physical addresses	
processor	➜	**mmu**	➜
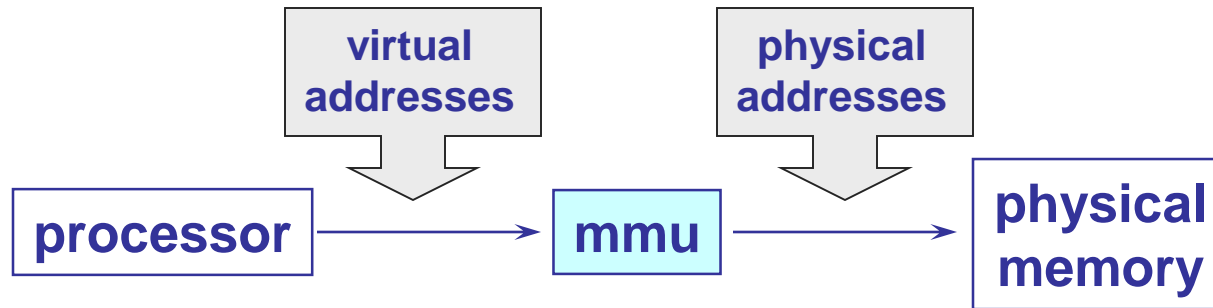
physical memory

- 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

Physical Memory

Base Register

P4's Base

Virtual Address

Offset

(+)

P1
P2
P3
P4
P5

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 exception fault
- Advantages
  - No internal fragmentation: allocate just enough for process
- Problems
  - External fragmentation: job loading and unloading produces empty holes scattered throughout memory

Variable Partitions

Base Register

P3's Base

Limit Register

P3's Limit

Virtual Address

Offset

$<$

Yes?

No?

$+$

Protection Fault

P1

P2

P3
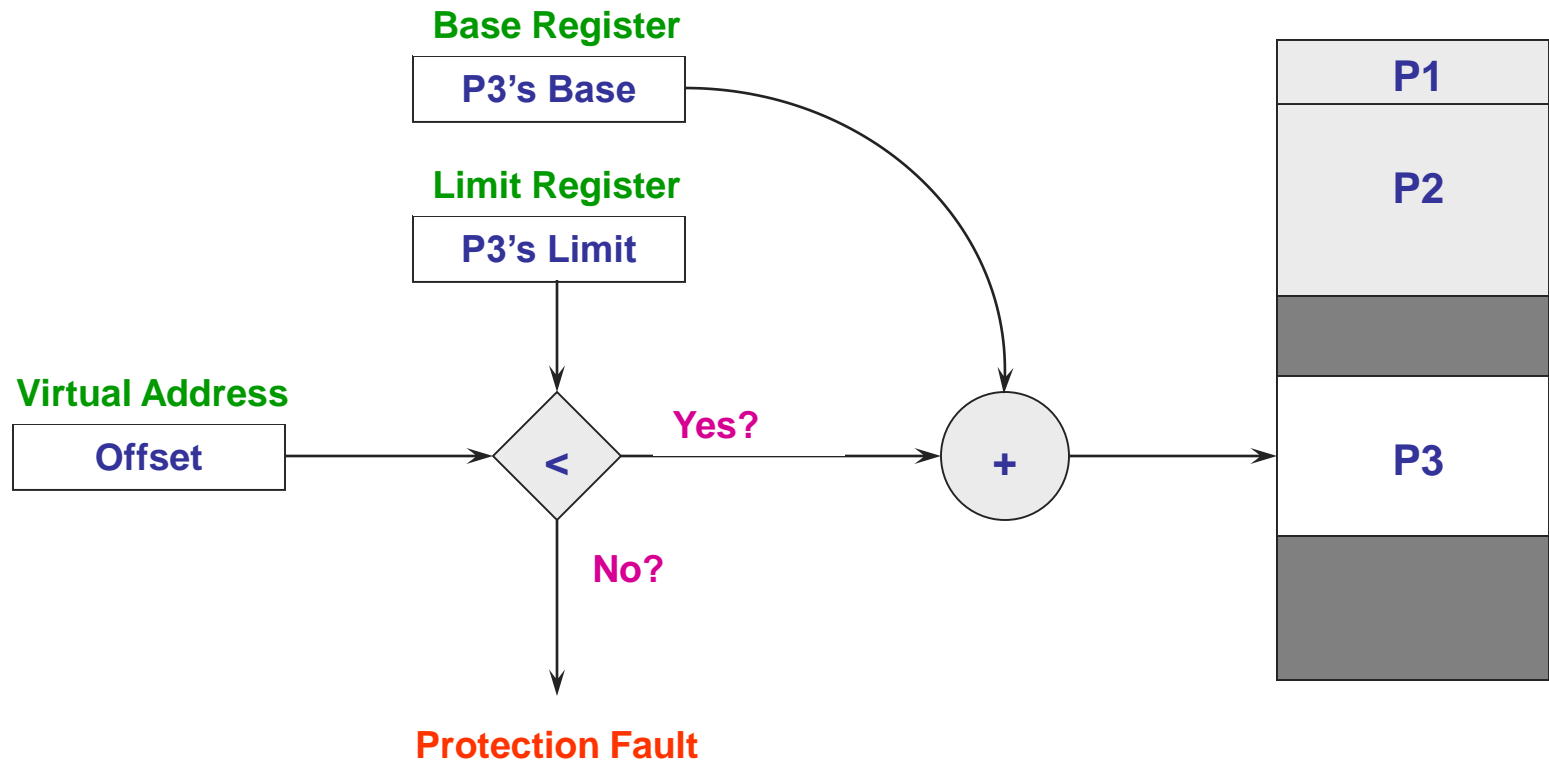
Paging

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

Physical Memory

Virtual Memory

| Page 0 |
|--------|
| Page 1 |
| Page 2 |

...

Page N-1
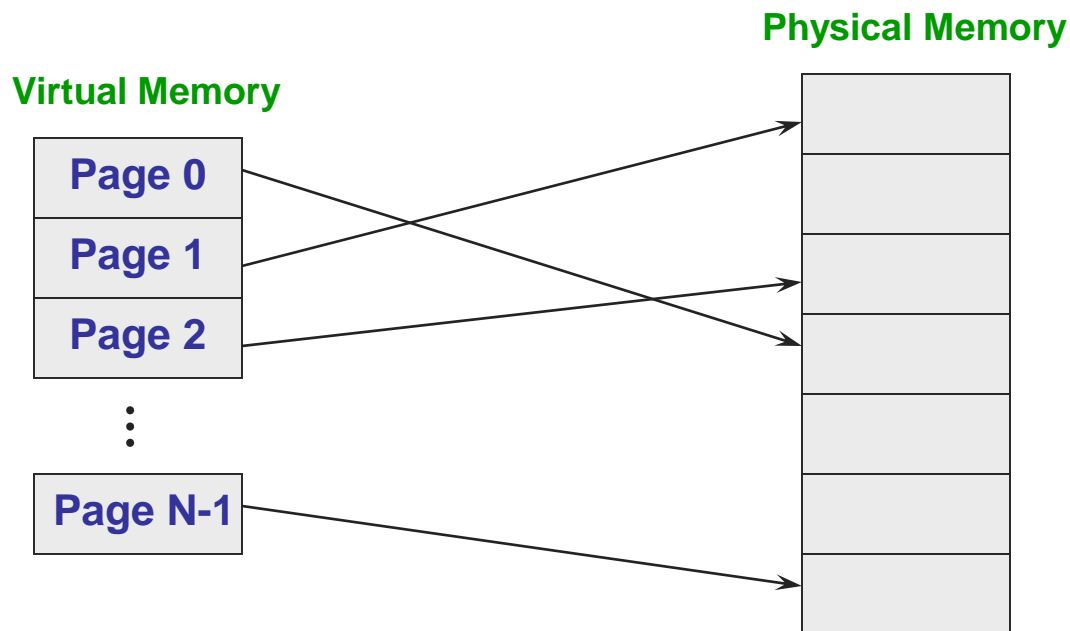
Programmer/Process View

- 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 storage
- The mapping is invisible to the program
- Protection is provided because a program 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
  - One page table entry (PTE) per page in virtual address space
    - Or, one PTE per VPN

Page Lookups

Physical Memory

Virtual Address

Page number	Offset

Page Table

Page frame

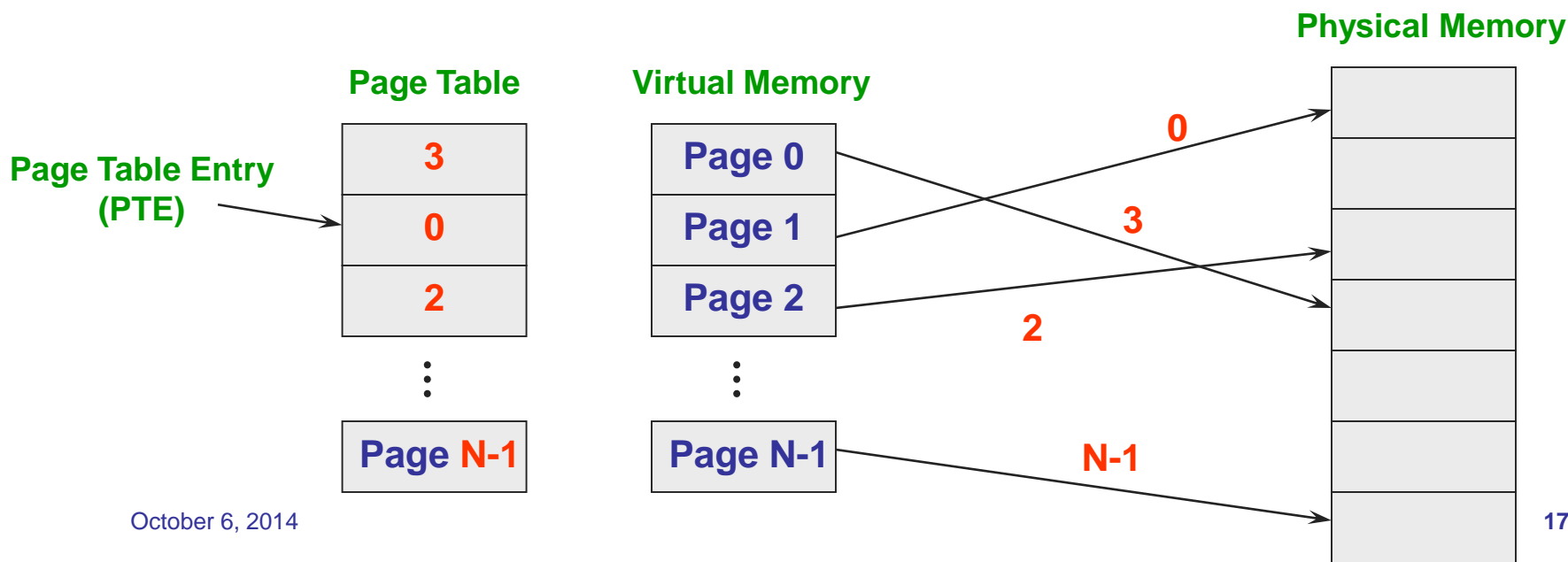**Physical Address**
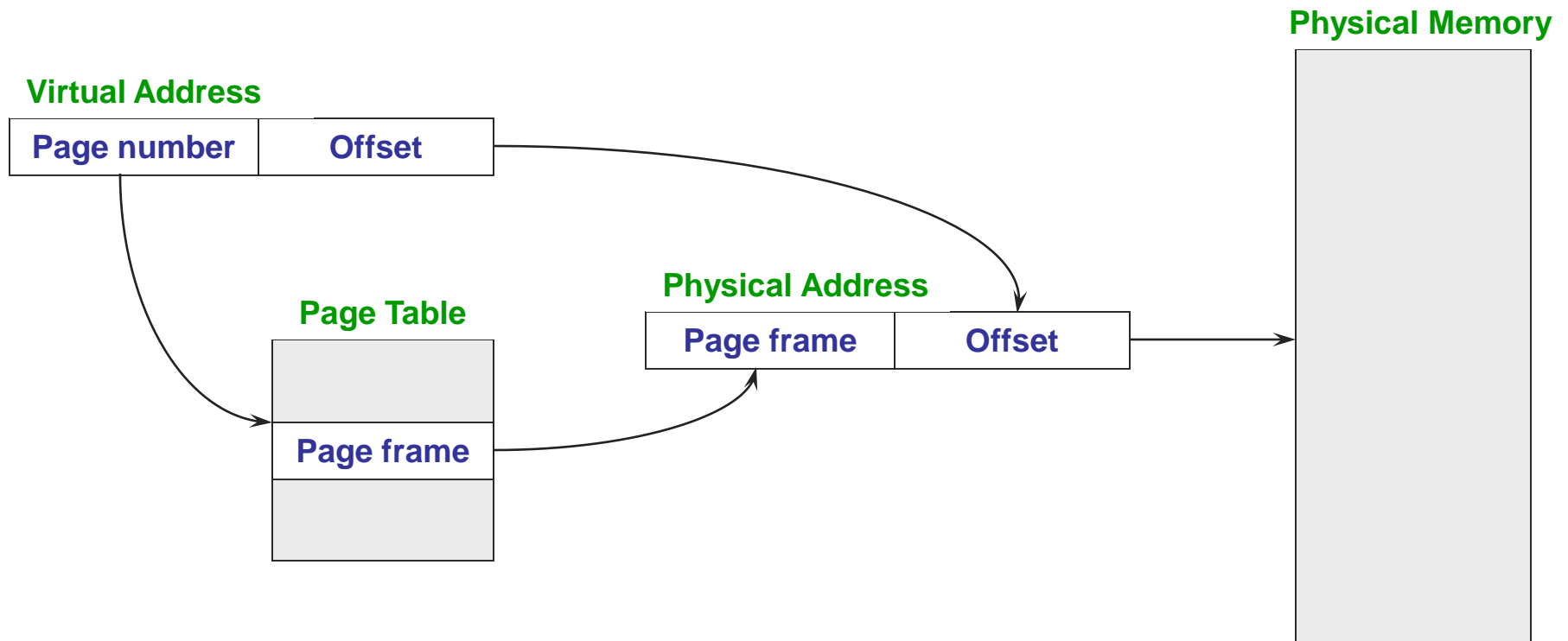
Page frame	Offset

Paging Example

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

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

Physical Memory

Page Table　　　**Virtual Memory**

Page Table Entry (PTE)

Page Table
3
0
2
⋮
Page N-1

Virtual Memory
Page 0
Page 1
Page 2
⋮
Page N-1

0

3

2

N-1

Page Table Entries (PTEs)

1	1	1	2	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
  - The page frame number (PFN) determines physical page

Paging Advantages

- Easy to allocate memory

  - Memory comes from a free list of fixed size 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
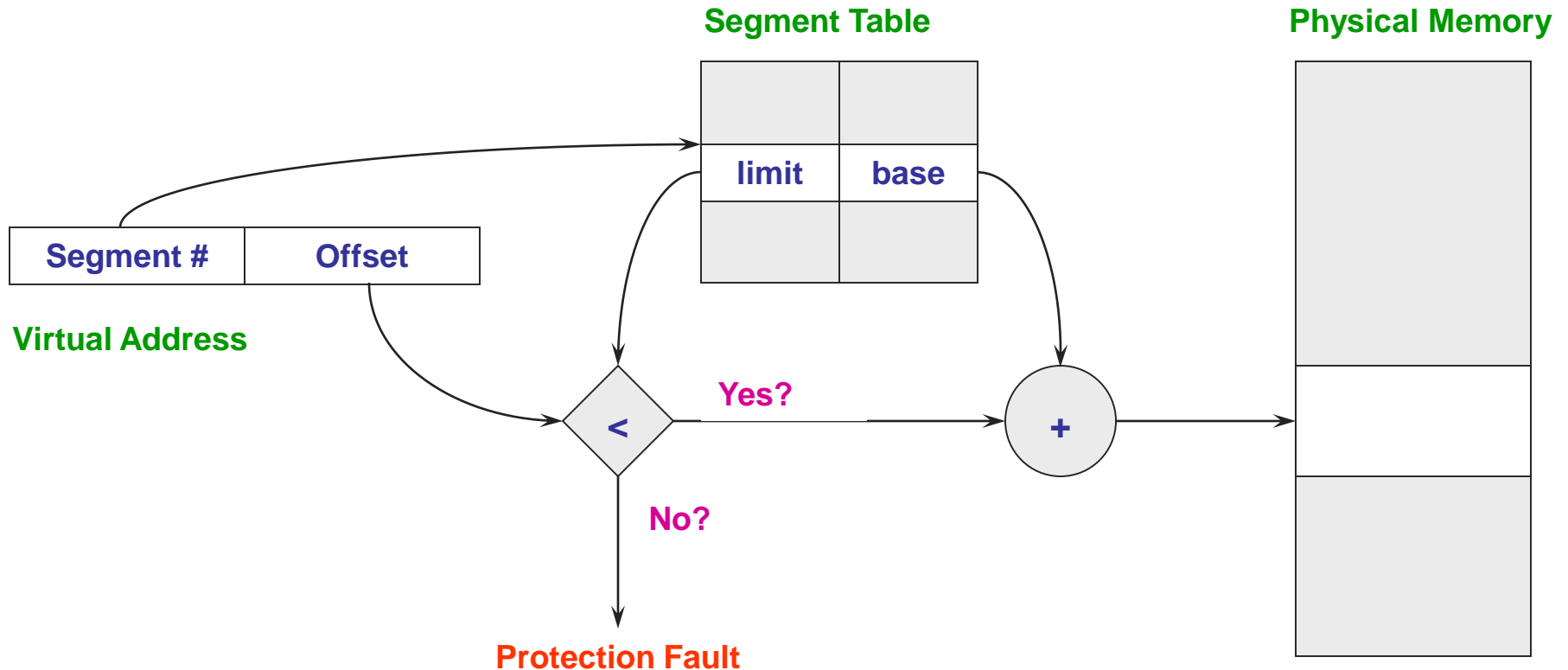 - Pages are a convenient multiple of the disk block size

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 – page the 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
  - 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

Segment Lookups

Segment Table

Physical Memory

limit	**base**

Segment #	**Offset**

Virtual Address

<

Yes?

+

No?

Protection Fault

Segment Table

- Extensions
  - Can have one segment table per process
    - » Segment #s are then process-relative (why do this?)
  - Can easily share memory
    - » Put same translation into base/limit pair
    - » Can share with different protections (same base/limit, diff prot)
- Problems
  - Cross-segment addresses
    - » Segments need to have same #s for pointers to them to be shared among processes
  - Large segment tables
    - » Keep in main memory, use hardware cache for speed
  - Large segments
    - » Internal fragmentation, paging to/from disk is expensive

Segmentation and Paging

- Can combine segmentation and paging
  - The x86 supports segments and paging
- Use segments to manage logically related units
  - Module, procedure, stack, file, data, etc.
  - Segments vary in size, but usually large (multiple 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…

Summary

- Virtual memory
  - Processes use virtual addresses
  - OS + hardware translates virtual address into physical addresses

- 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 in chunks from user's perspective
  - Combine paging and segmentation to get benefits of both

Next time...

- Chapter 9.6