Operating Systems ECE344

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
- 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 will provide 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"
    - Many programs do not need all of their code and data at once (or ever) – no need to allocate memory for it
  - Processes cannot see the memory of others'
  - 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 old days (generally before 1970s)
  - 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

Remember this example?

```
int myval;
int main(int argc, char *argv[])
{
  myval = atoi(argv[1]);
  while (1)
   printf("myval is %d, loc 0x%lx\n", myval, (long) &myval);
}
```

- Now *simultaneously* start two instances of this program
  - Myval 5
  - Myval 6
  - What will the outputs be?

Default

```
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
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```

```
myval is 6, loc 0x2030
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myval is 6, loc 0x2030
```
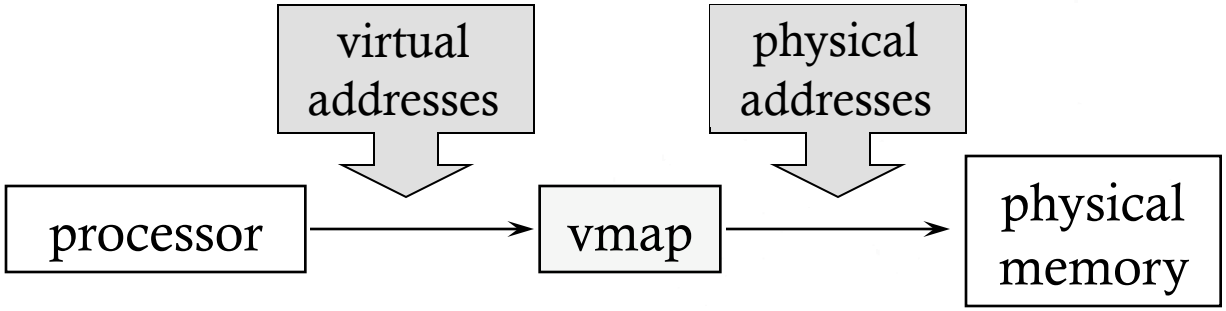

Virtual Addresses

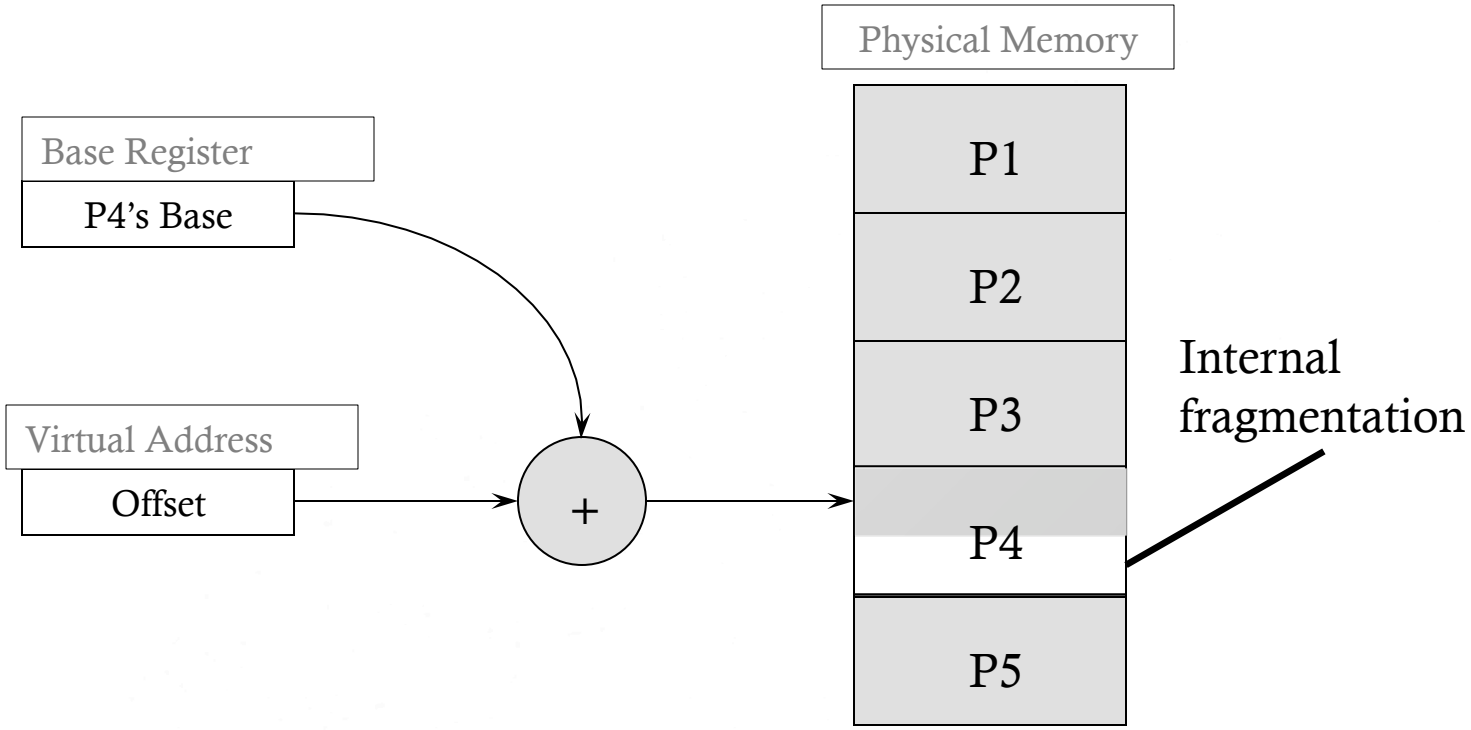


- Many ways to do this translation…
  - Start with old, simple ways, progress to current techniques

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?)

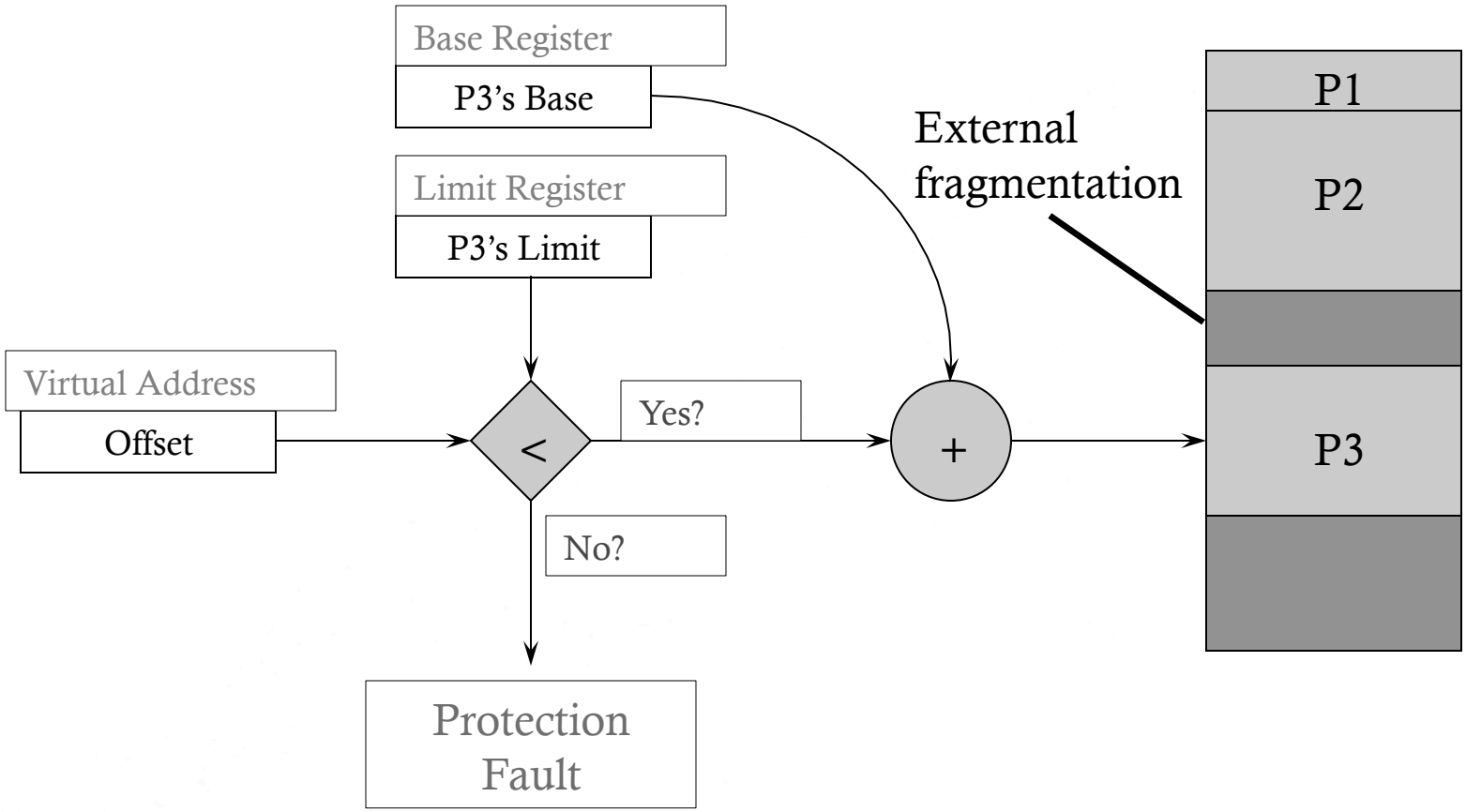
Fixed Partitions



Variable Partitions

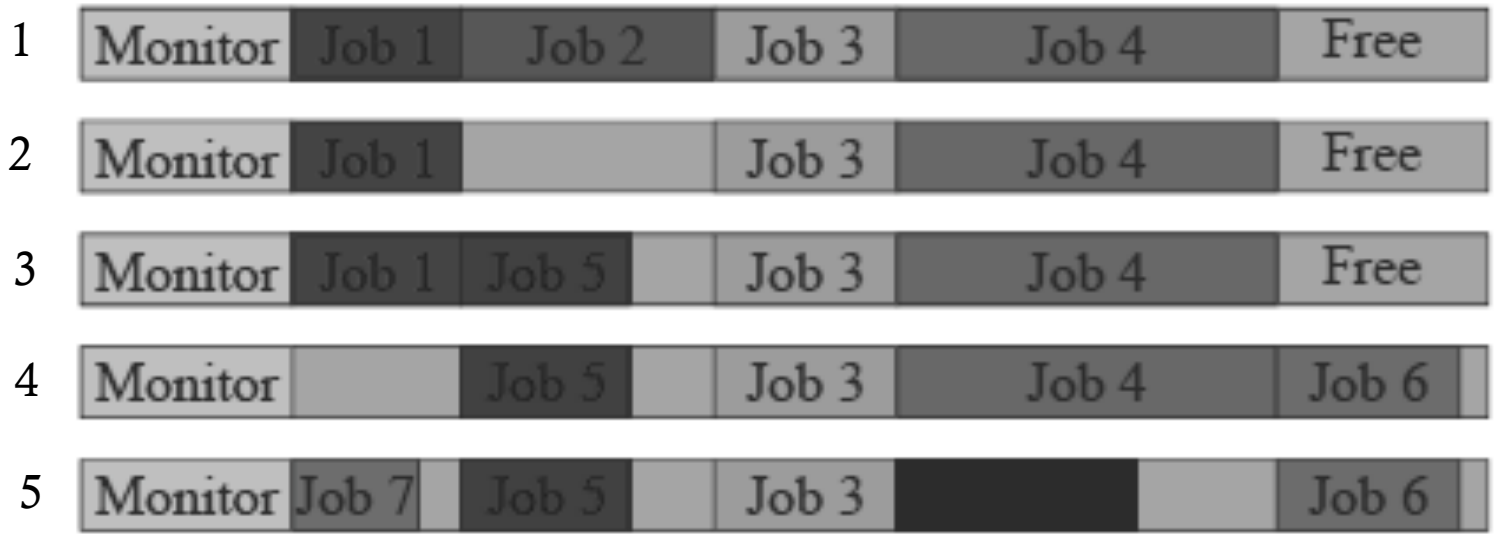
- Natural extension – physical memory is broken up into variable sized partitions
  - Hardware requirements: base register and limit register
  - Physical address = virtual address + base register
  - Why do we need the limit register? Protection
    - If (physical address > base + limit) then exception 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



Variable Partitions and Fragmentation

Memory wasted by External Fragmentation

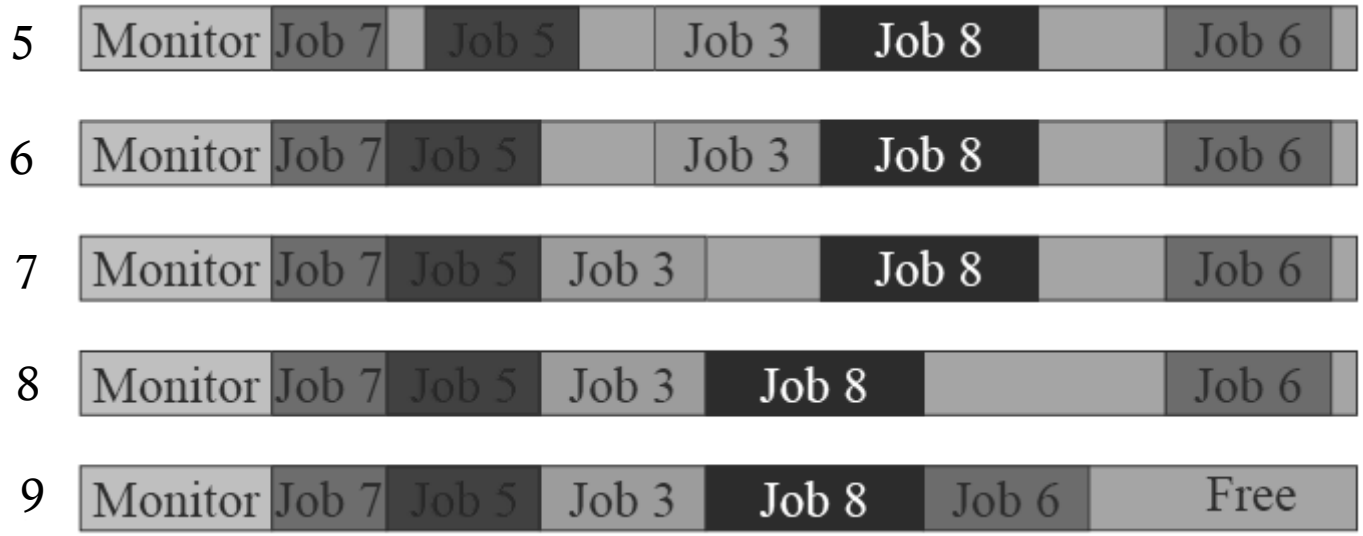


Do you know about disk de-fragmentation?

It can improve your system performance!

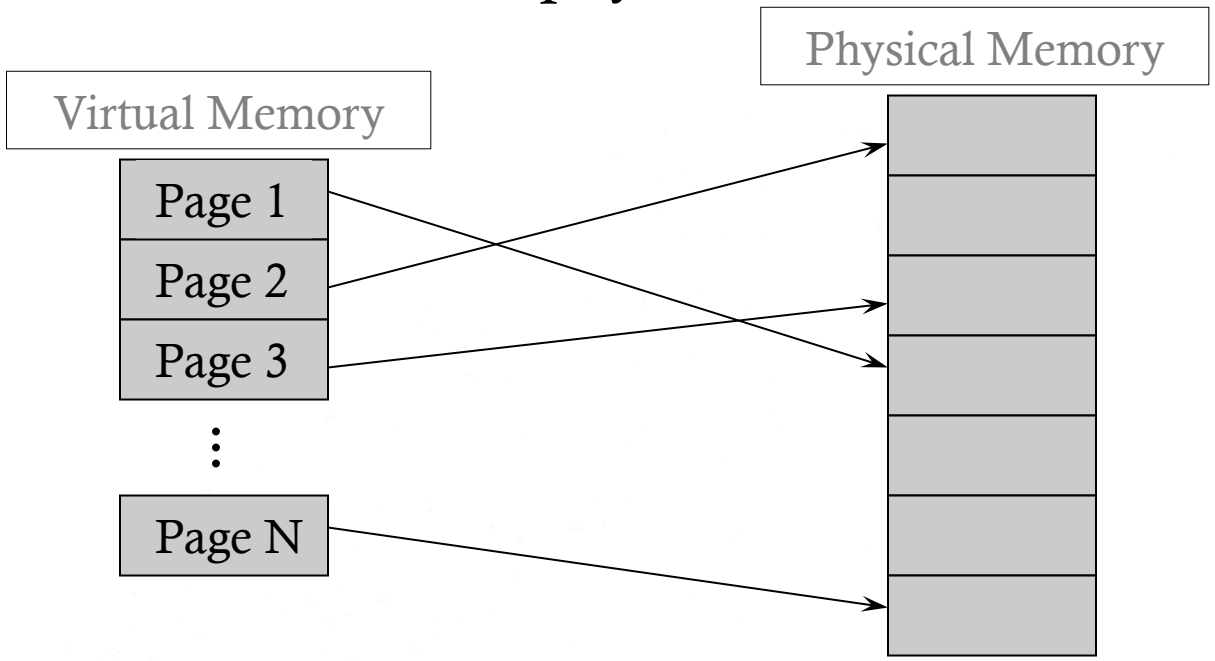
Compaction

- Processes must be suspended during compaction
- Need be done only when fragmentation gets very bad



Paging

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



Internal vs. External fragmentation

- How paging can solve fragmentation problems?
  - External fragmentation: can be solved by re-mapping between VA and PA
  - Internal fragmentation: can be solved if the page size is relatively small

User/Process Perspective

- Users (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
  - Different from variable partition, where the physical memory for each process is contiguously allocated
- 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

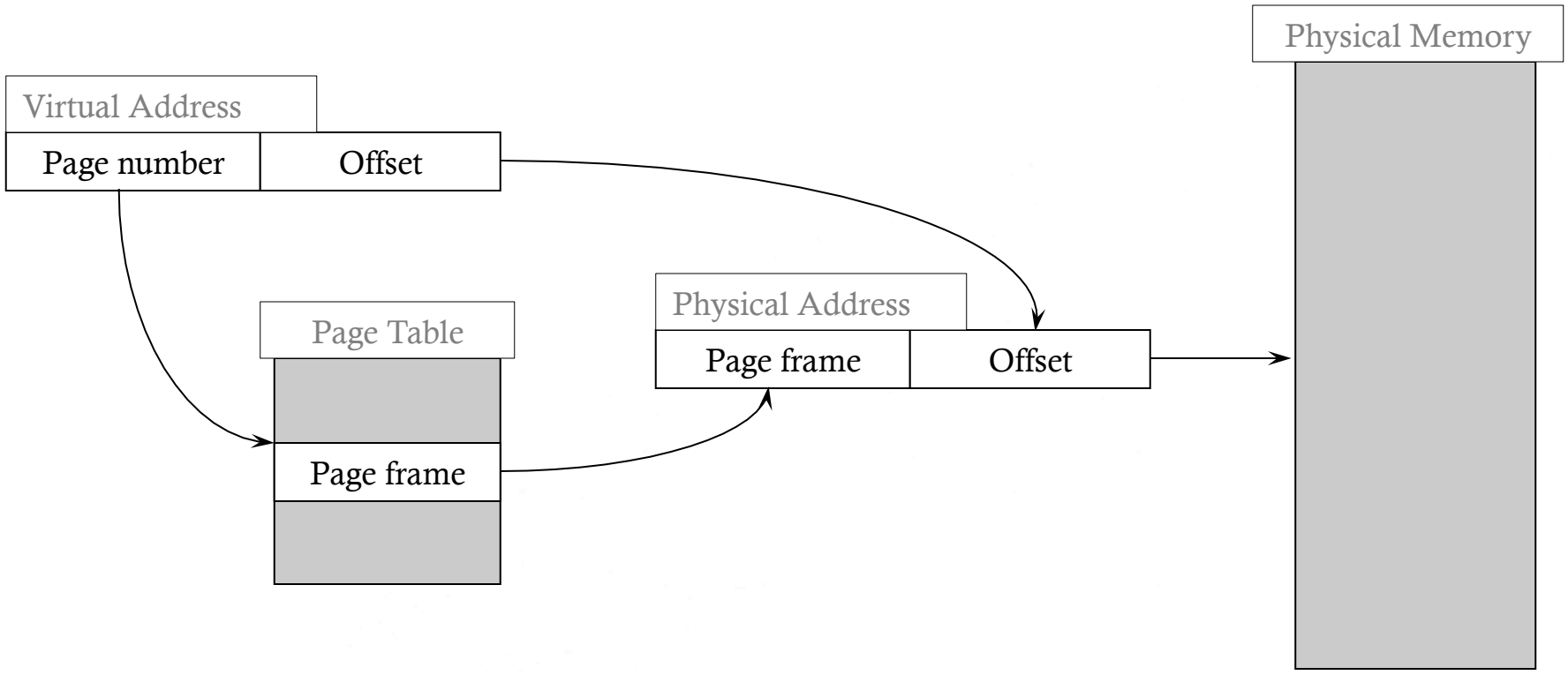
Question

- Page size is always a power of 2
  - Examples: 4096 bytes = 4KB, 8192 bytes = 8KB
  - Why?
  - Why not 1000 or 2000?

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
- 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

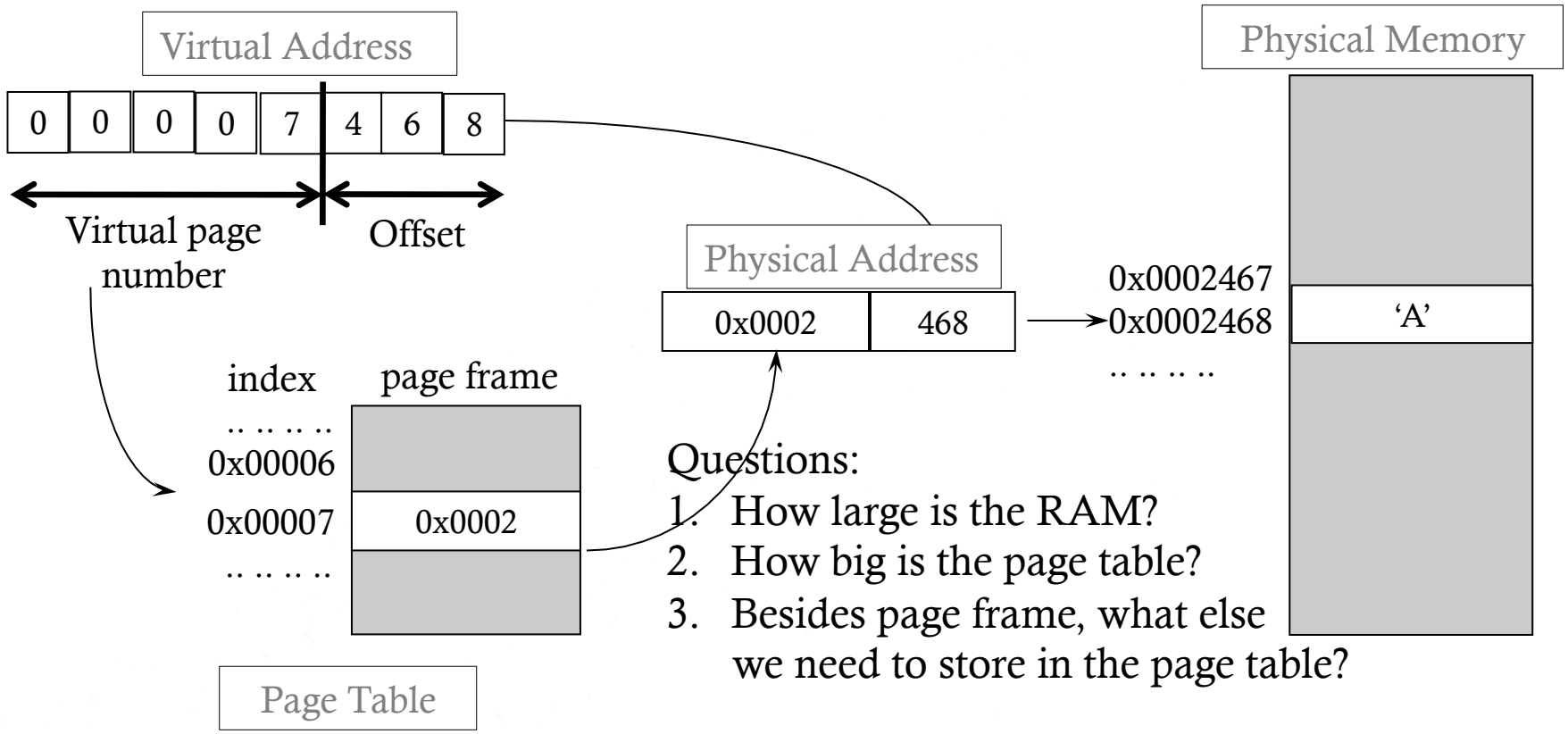


Paging Example

- Pages are 4K (Linux default)
  - VPN is 20 bits (2^{20} VPNs), offset is 12 bits
- Virtual address is 0x7468 (hexadecimal)
  - 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 Lookups

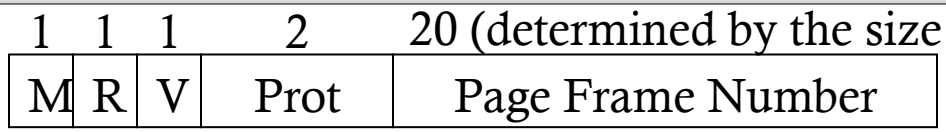
Example: how do we 'load 0x00007468'?



Questions:

1. How large is the RAM?
2. How big is the page table?
3. Besides page frame, what else we need to store in the page table?

Page Table Entries (PTEs)

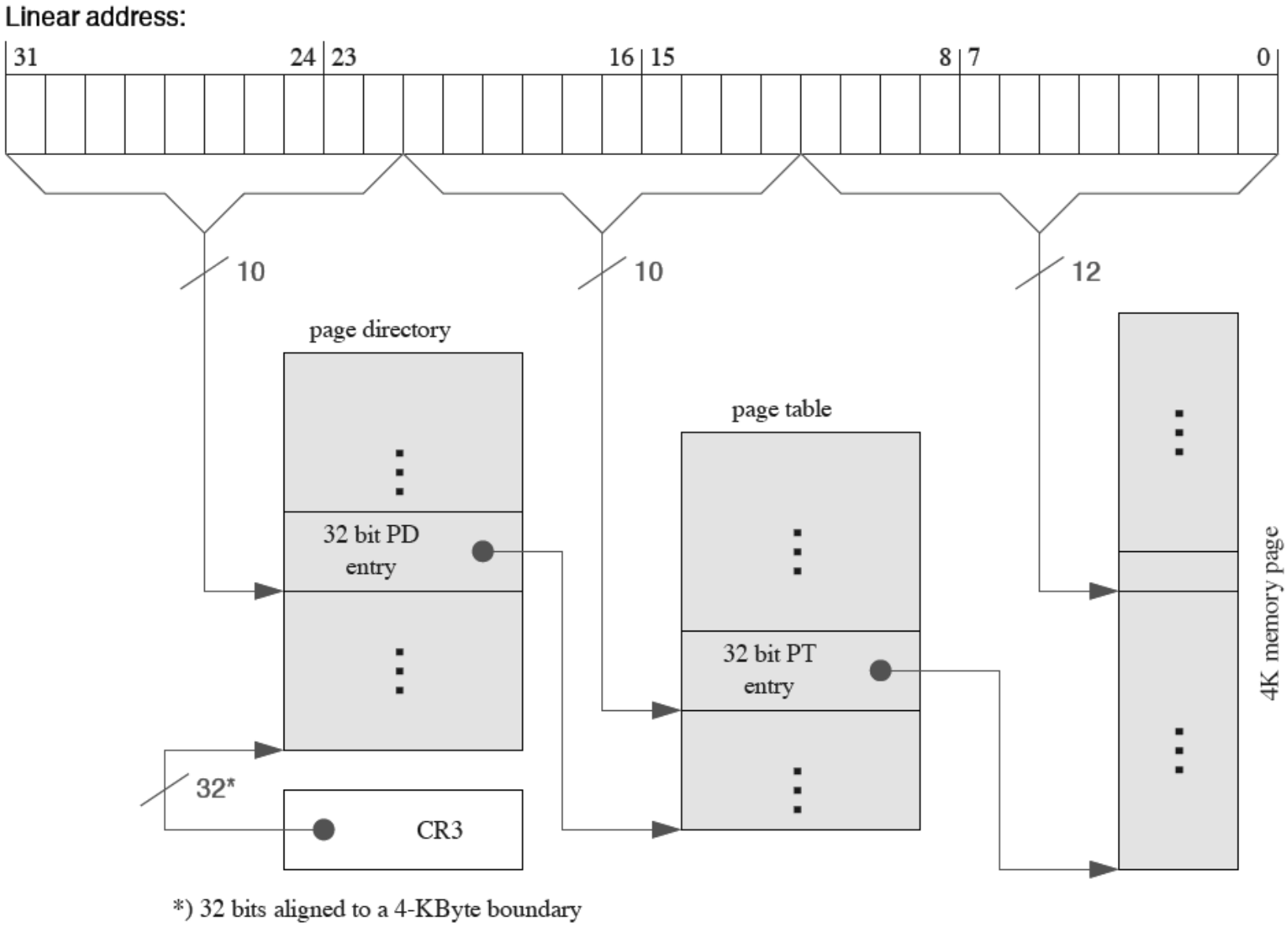


- Page table entries control mapping
  - The Modify bit says whether or not the page has been written
    - It is set when a write to the page occurs
  - The Reference bit says whether the page has been accessed
    - It is set when a read or write to the page occurs
  - The Valid bit says whether or 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
  - If you're interested: watch the OS lecture scene from "The Social Network" again, see if now you can understand

http://www.youtube.com/watch?v=-3Rt2_9d7Jg

2-level page table

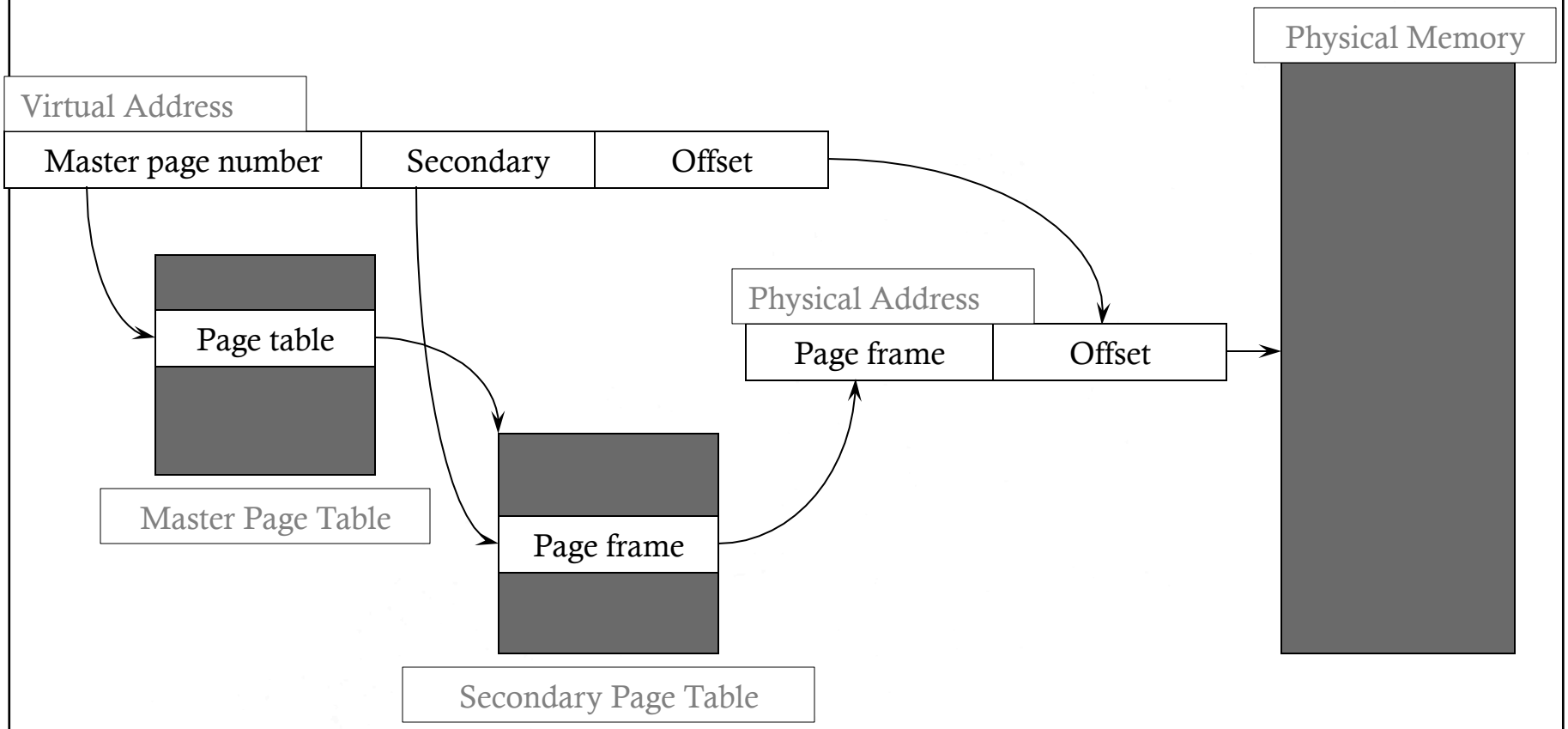
- Single level page table size is too large
  - 4KB page, 32 bit virtual address, 1M entries per page table!


Linear address:
31
24
23
16
15
8
7
0
10
10
12
page directory
32 bit PD
entry
page table
32 bit PT
entry
4K memory page
32*
CR3
*) 32 bits aligned to a 4-KByte boundary

Two-Level Page Tables

- Two-level page tables
  - Virtual addresses (VAs) have three parts:
    - Master page number, secondary page number, and offset
  - Master page table maps VAs to secondary page table
  - Secondary page table maps page number to physical page
  - Offset indicates where in physical page address is located
- Example
  - 4K pages, 4 bytes/PTE
  - How many bits in offset? 4K = 12 bits
  - Want master page table in one page: 4K/4 bytes = 1K entries
  - Hence, 1K secondary page tables. How many bits?
  - Master (1K) = 10, offset = 12, inner = 32 – 10 – 12 = 10 bits

Two-Level Page Tables



What is the problem with 2-level page table?

- Hints:
  - Programs only know virtual addresses
  - Each virtual address must be translated
    - Each program memory access requires several actual memory accesses
    - Will discuss solution in the next lecture

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

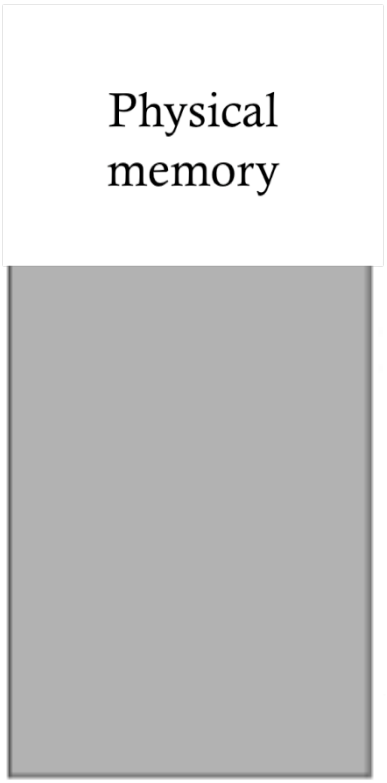
Paging Limitations

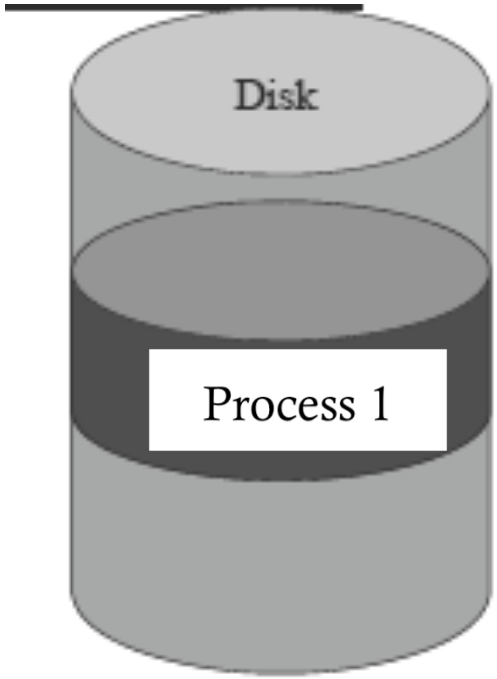
- Can still have internal fragmentation
  - Process may not use memory in multiples of a page
- Memory reference overhead
  - 2 references per address lookup (page table, then memory)
    - Even more for two-level page tables!
  - Solution – use a hardware cache of lookups (more later)
- Memory required 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!
    - Remember: each process has its own page table!
  - Solution – 2-level page tables

What if a process requires more memory than physical memory?

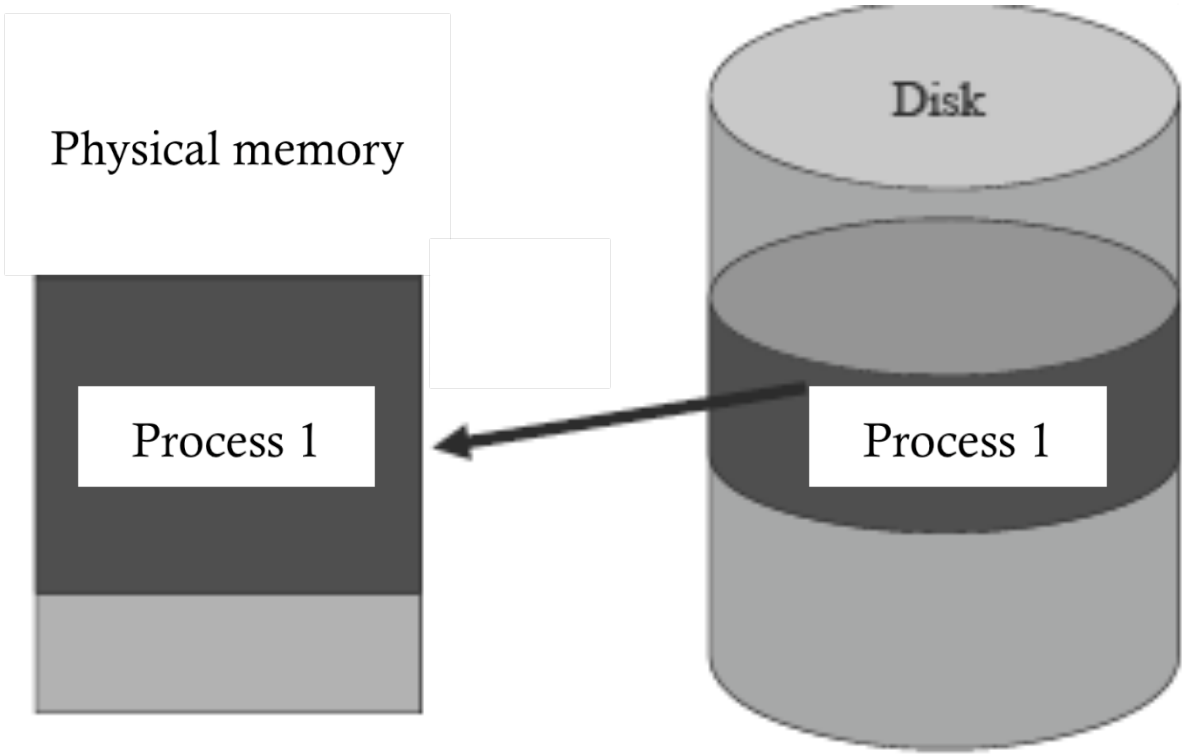
- Swapping
  - Move one/several/all pages of a process to disk
    - Free up physical memory
    - "Page" is the unit of swapping
  - The freed physical memory can be mapped to other pages
  - Processes that use large memory can be swapped out (and later back in)
- Real life analogy?
  - Putting things from your shelf to your parents' house

Swapping

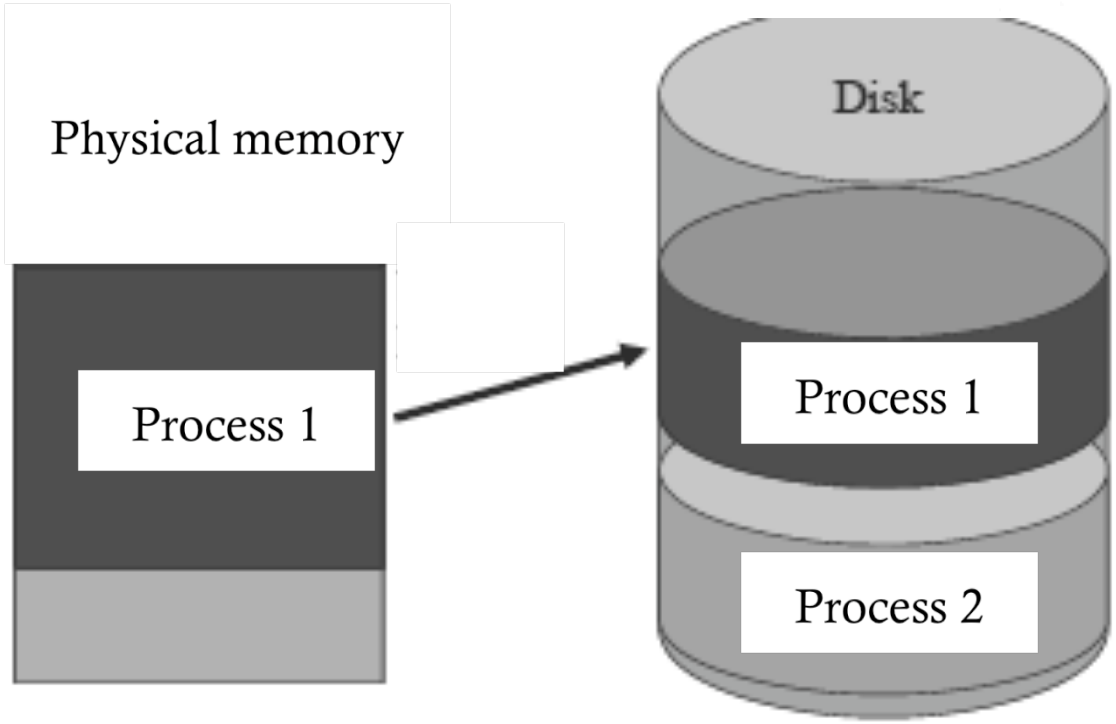




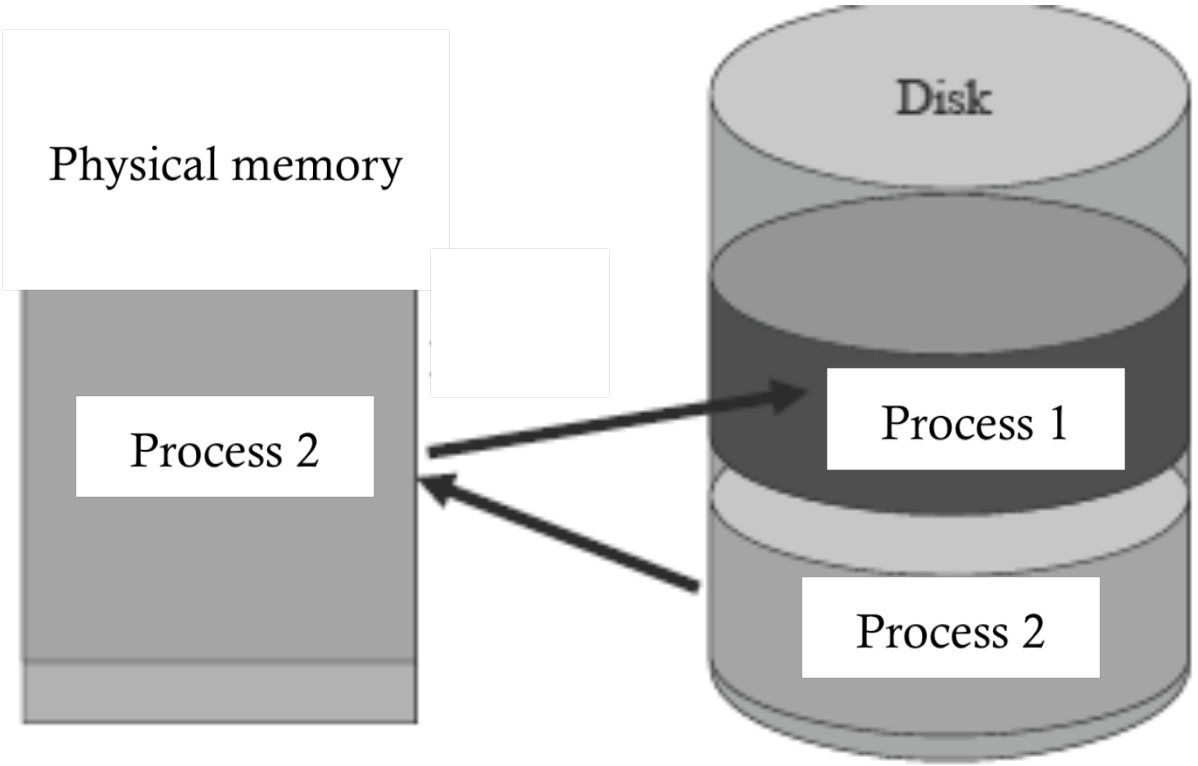
Swapping process 1's data into memory



Swapping



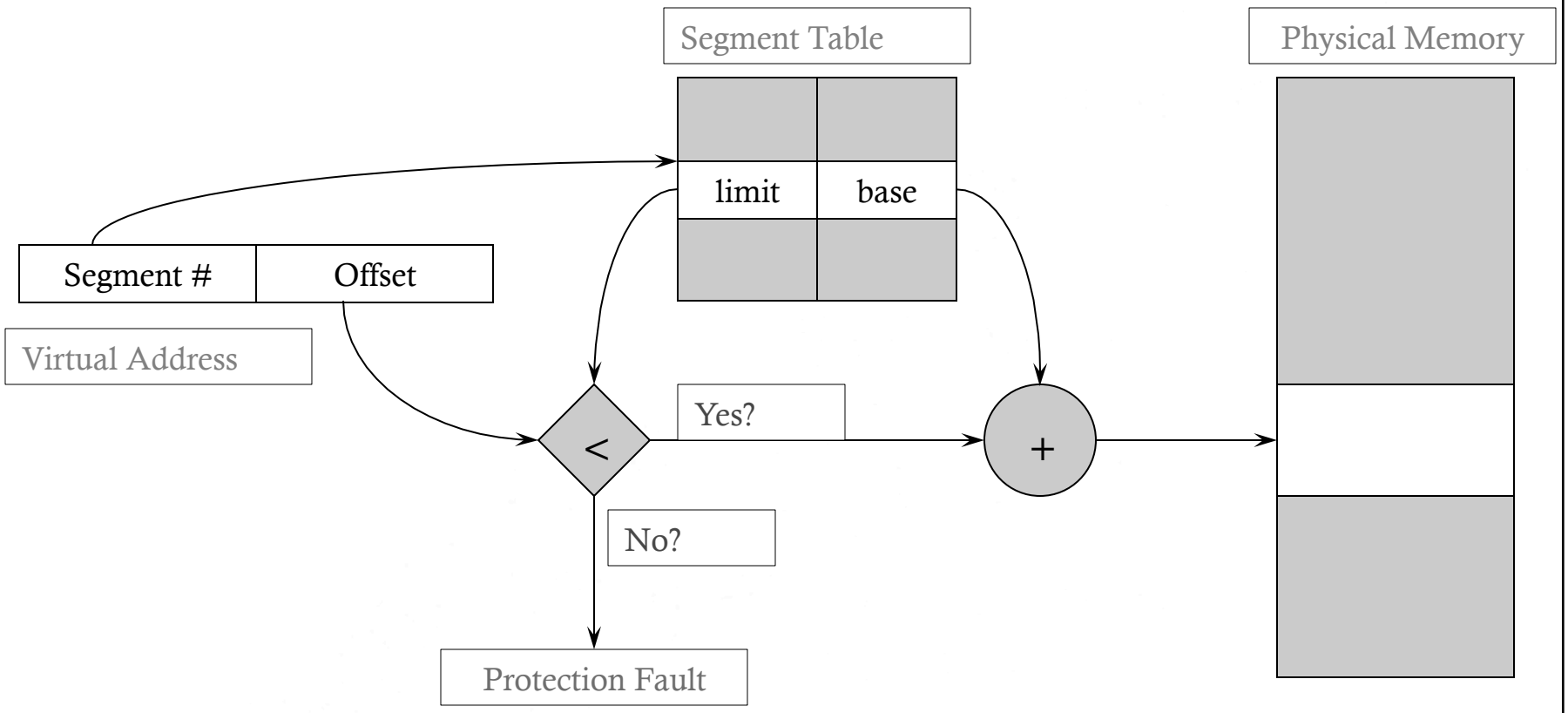
Swapping



A variation of paging: Segmentation

- Segmentation is a technique that partitions memory into logically related data units
  - Module, procedure, stack, data, file, etc.
  - Virtual addresses become <segment #, offset>
  - Units of memory from user'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

- Extensions
  - Can have one segment table per process
    - Segment #s are then process-relative
  - Can easily share memory
    - Put same translation into base/limit pair
    - Can share with different protections (same base/limit, diff prot)
- Problems
  - 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