CS 153
Design of Operating Systems

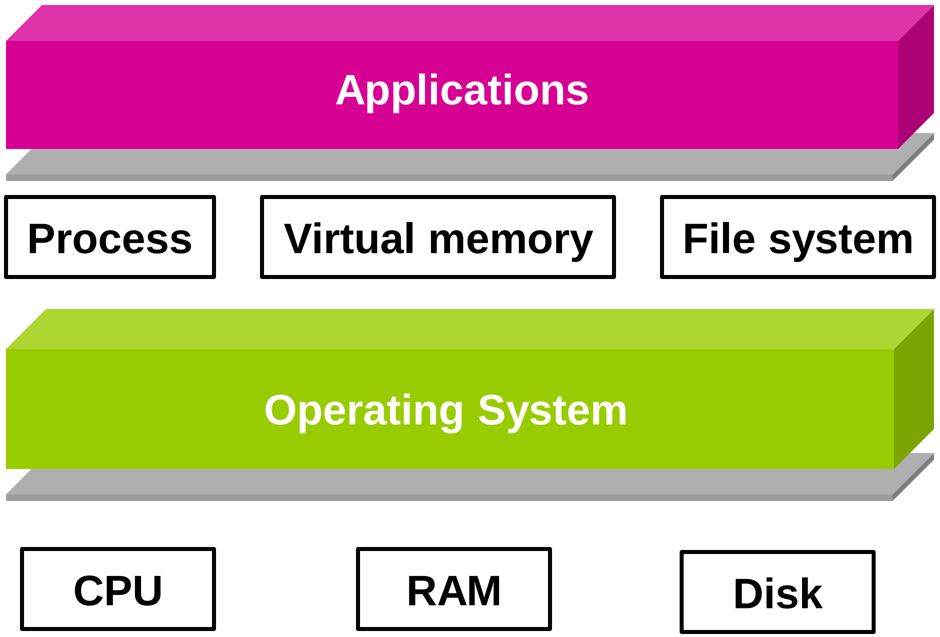
Winter 2016

Lecture 15: Memory Management

Announcements

- Get started on project 2 ASAP
- Please ask questions if unclear
  - REMINDER: 4% for class participation
  - Come to office hours

OS Abstractions



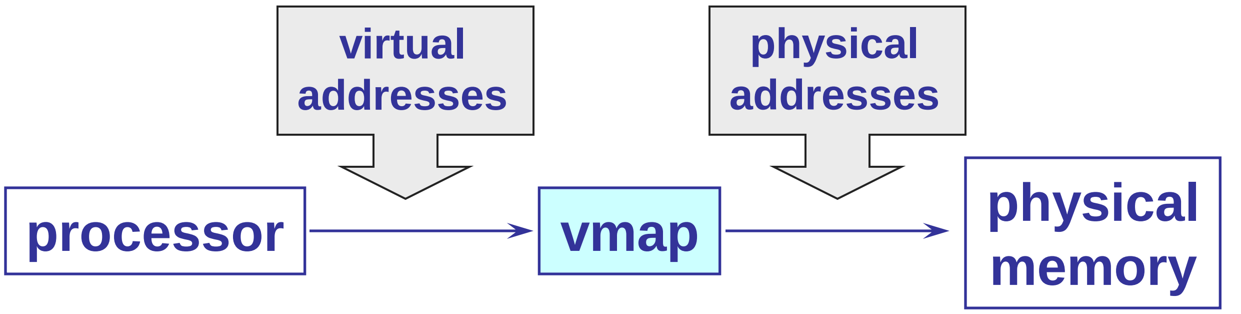
Need for Virtual Memory

- 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
  - How to share physical memory across multiple processes?
    - » Many programs do not need all of their code and data at once (or ever) – no need to allocate memory for it
    - » A program can run on machine with less memory than it “needs”
      - Run DOS games in Windows XP

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

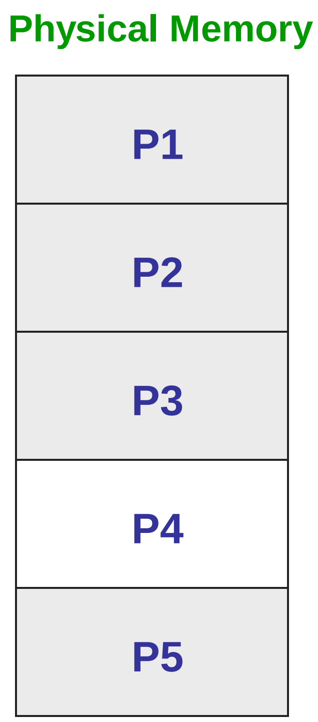
Virtual Addresses



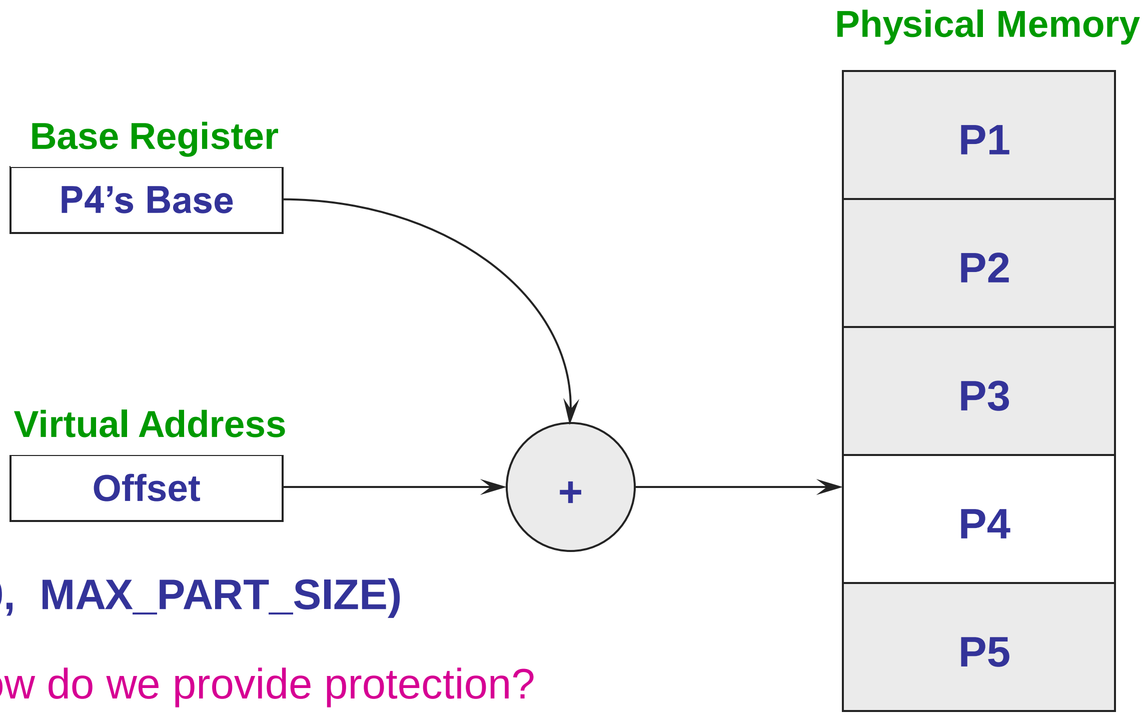
- Many ways to do this translation…
  - Need hardware support and OS management algorithms
- Requirements
  - Need protection – restrict which addresses jobs can use
  - Fast translation – lookups need to be fast
  - Fast change – updating memory hardware on context switch

First Try: Fixed Partitions

- Physical memory is broken up into fixed partitions
  - Size of each partition is the same and fixed
  - Hardware requirements: base register
  - Physical address = virtual address + base register
  - Base register loaded by OS when it switches to a process (part of PCB)



First Try: Fixed Partitions



[0, MAX_PART_SIZE)

How do we provide protection?

First Try: Fixed Partitions

- Advantages
  - Easy to implement
    - » Need base register
    - » Verify that offset is less than fixed partition size
  - Fast context switch

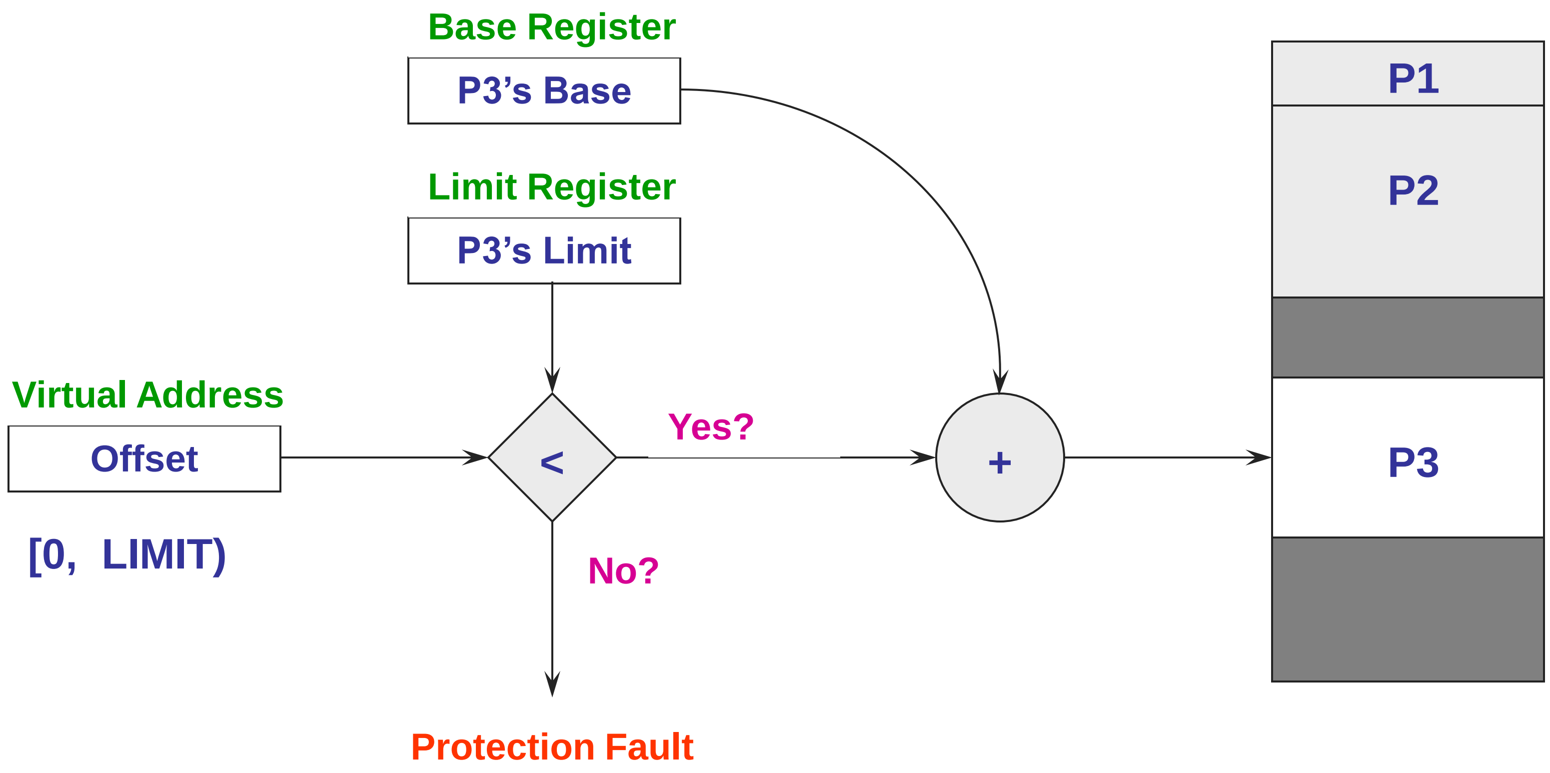
- Problems?
  - Internal fragmentation: memory in a partition not used by a process is not available to other processes
  - Partition size: one size does not fit all (very large processes?)

Second Try: 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

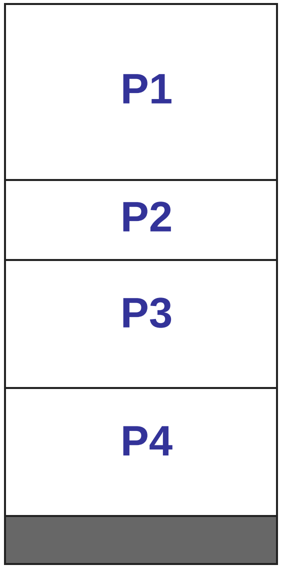
- Why do we need the limit register?
  - Protection: if (virtual address > limit) then fault

Second Try: Variable Partitions



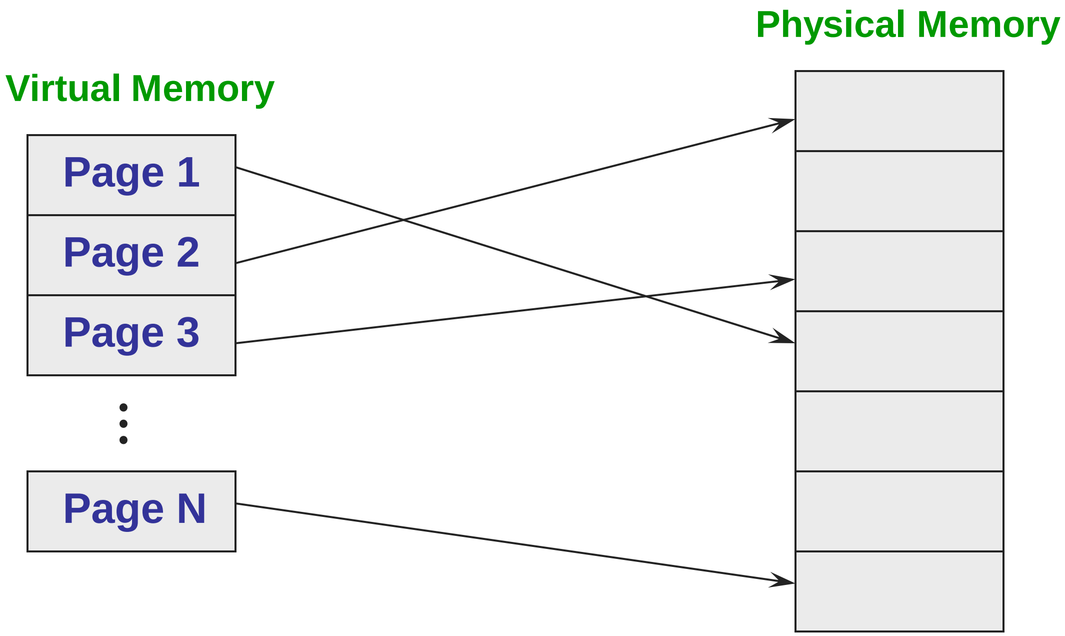
Variable Partitions

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



State-of-the-Art: Paging

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



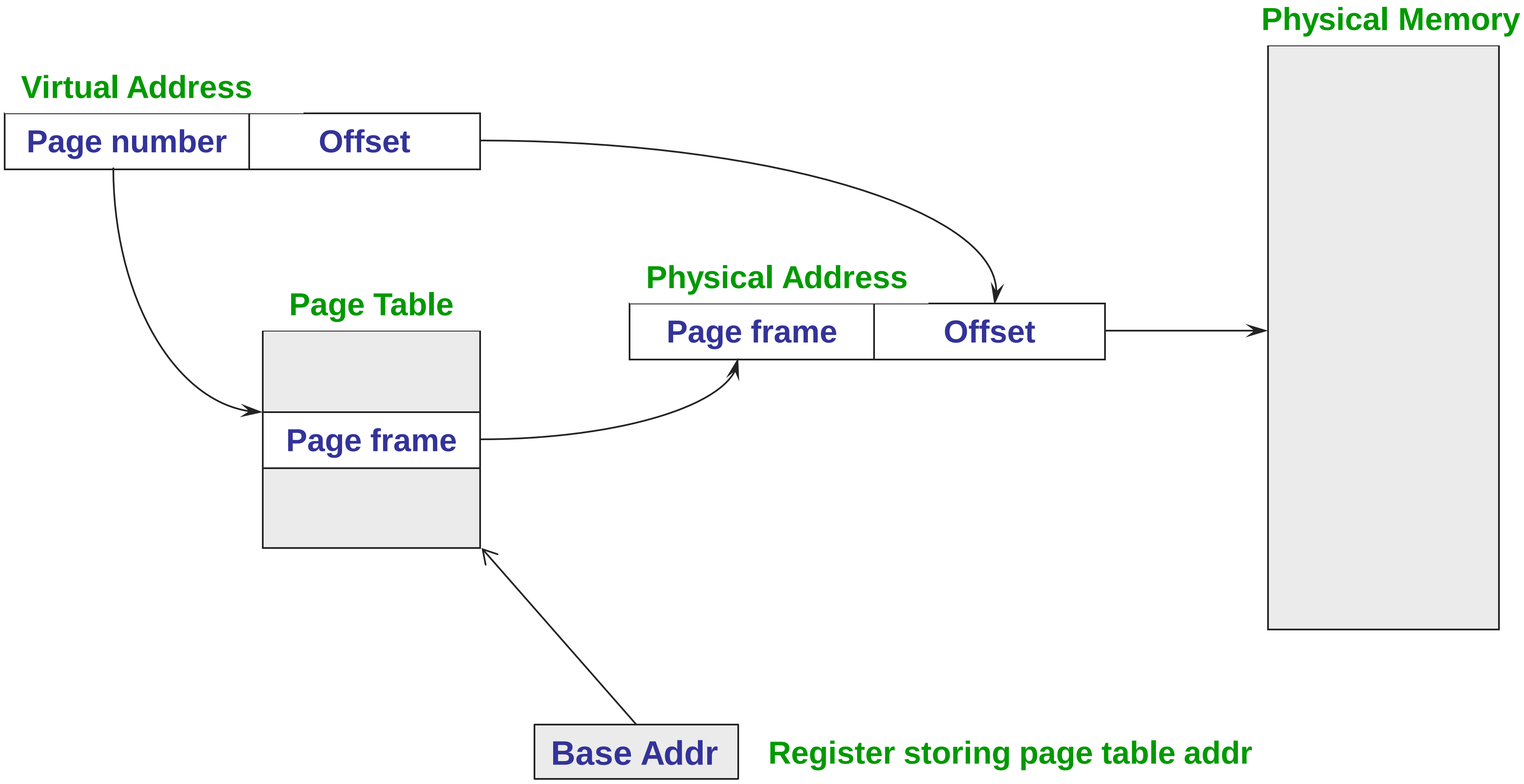
Process Perspective

- Processes view memory as one contiguous address space from 0 through N (N = 2^32 on 32-bit arch.)
  - Virtual address space (VAS)
- In reality, pages are scattered throughout physical memory
- 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

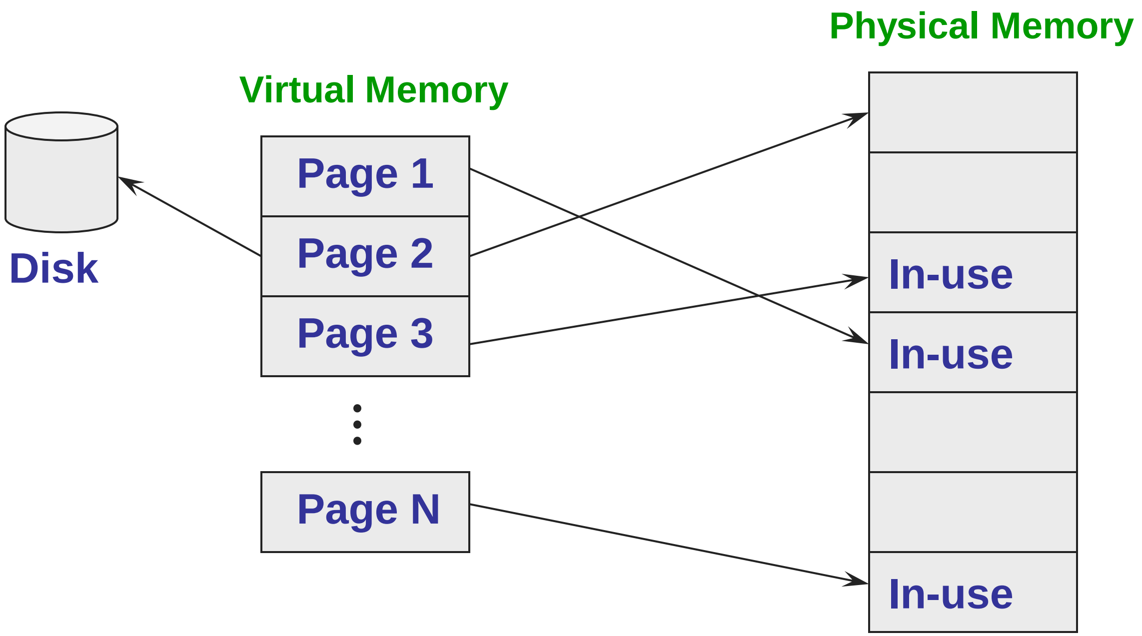
- Translating addresses
  - Virtual address has two parts: virtual page number and offset
  - Virtual page number (VPN) is an index into a page table
  - Page table determines page frame number (PFN)
  - Physical address is PFN::offset
- Page tables
  - Map virtual page number (VPN) to page frame number (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
  - Where is page table stored? Kernel or user space?

Page Lookups



Page out (the cold pages)

- What if we run short on physical memory? Well, we transfer a page worth of physical memory to disks



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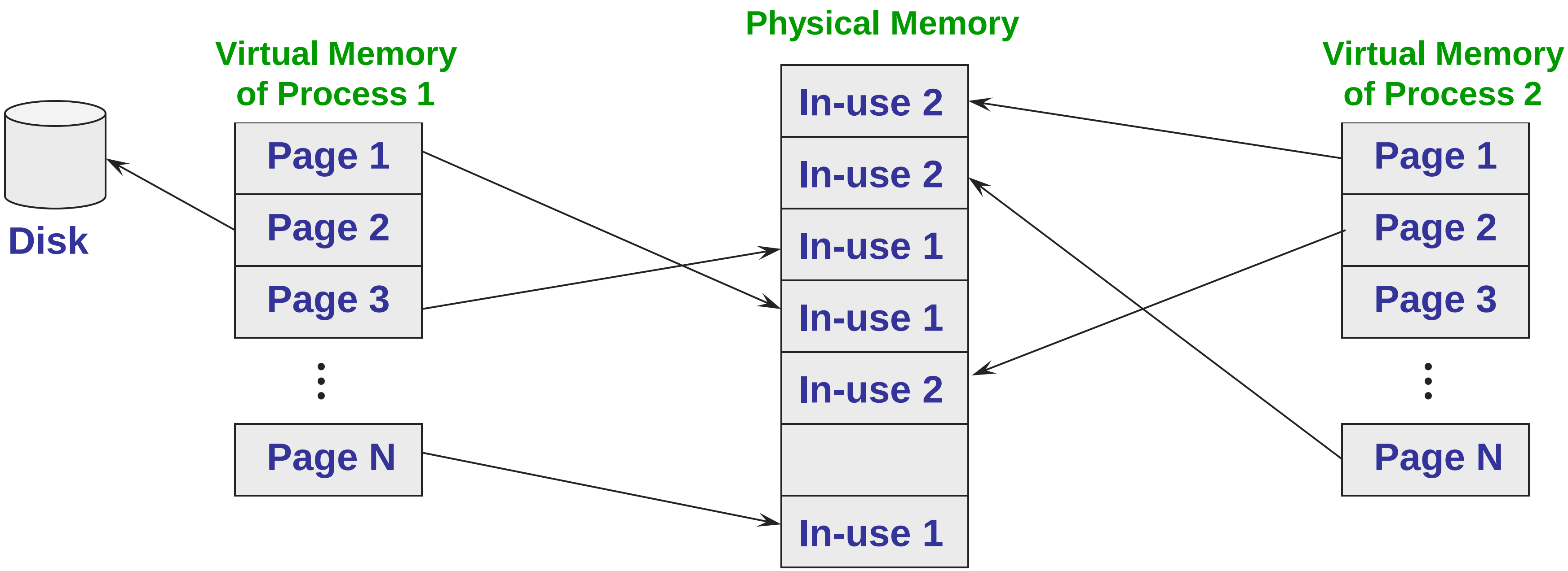
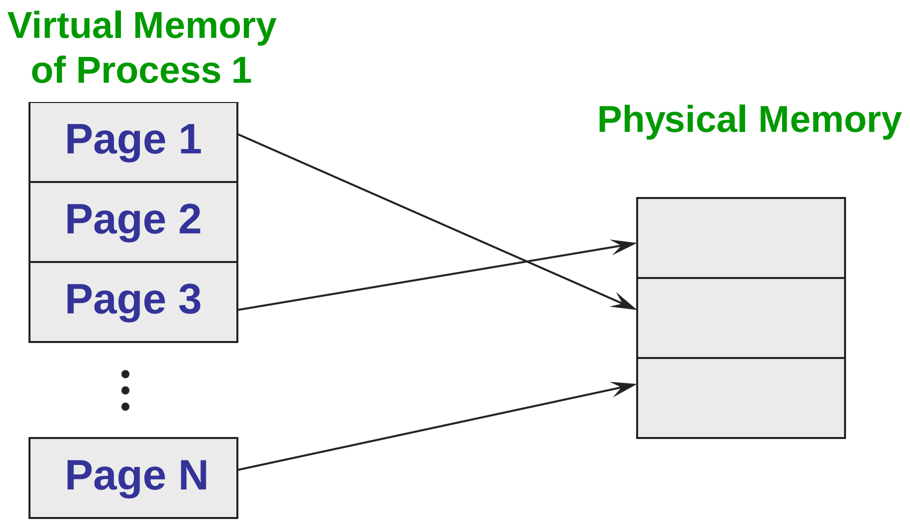


Paging question

- Can we serve a process asking for more memory than we physically have?



Paging Example

- Pages are 4KB
  - Offset is 12 bits (because 4KB = 2^{12} bytes)
  - VPN is 20 bits (32 bits is the length of every virtual address)
- 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 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 (Why?)
  - The Protection bits say what operations are allowed on page
    - » Read, write, execute (Why do we need these?)
  - 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
    - » All pages of the same size
- 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
    - » 4KB vs. 512 bytes

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)

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

Next time...

- Read chapters 8 and 9 in either textbook