CSE 451: Operating Systems
Spring 2010

Module 10
Memory Management

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Goals of memory management

- Allocate scarce memory resources among competing processes, maximizing memory utilization and system throughput
- Provide a convenient abstraction for programming (and for compilers, etc.)
- Provide isolation between processes
  - we have come to view "addressability" and "protection" as inextricably linked, even though they're really orthogonal

Tools of memory management

- Base and limit registers
- Swapping
- Paging (and page tables and TLBs)
- Segmentation (and segment tables)
- Page fault handling => Virtual memory
- The policies that govern the use of these mechanisms

Today's desktop and server systems

- The basic abstraction that the OS provides for memory management is virtual memory (VM)
  - Efficient use of hardware (real memory)
    - VM enables programs to execute without requiring their entire address space to be resident in physical memory
    - many programs don't need all of their code or data at once (or ever)
      - no need to allocate memory for it, OS should adjust amount allocated based on run-time behavior
  - Program flexibility
    - programs can execute on machines with less RAM than they "need"
      - On the other hand, paging is really, really slow...
  - Protection
    - virtual memory isolates address spaces from each other

VM Requires Hardware and OS Support

- Virtual memory requires hardware and OS support
  - MMU's, TLB's, page tables, page fault handling, …
- Typically accompanied by swapping, and at least limited segmentation
- Note: hardware is 64-bit, but software is still (mainly) 32-bit
  - Limits the size of the virtual address space of any individual process to 4GB

A Brief History of Memory Management

- Why?
  - Because it's instructive
  - Because embedded processors (98% or more of all processors) typically don't have virtual memory
  - Because some aspects are pertinent to allocating pieces of the virtual address space
    - i.e., e.g., malloc()
- First, there was job-at-a-time batch programming
  - programs used physical addresses directly
  - OS loads job (perhaps using a relocating loader to "offset" branch addresses), runs it, unloads it
  - what if the program wouldn't fit into memory?
    - manual overlays!
- An embedded system may have only one program!

Uniprogramming

- First, there was job-at-a-time batch programming
  - programs used physical addresses directly
  - OS loads job (perhaps using a relocating loader to "offset" branch addresses), runs it, unloads it
  - what if the program wouldn't fit into memory?
    - manual overlays!
- Swapping
  - save a program's entire state (including its memory image) to disk
  - allows another program to be run
  - first program can be swapped back in and re-started right where it was
- The first timesharing system, MIT's "Compatible Time Sharing System" (CTSS), was a uni-programmed swapping system
  - only one memory-resident user
  - upon request completion or quantum expiration, a swap took place
  - At least it worked...

Multiprogramming

- Then came multiprogramming
  - multiple processes/jobs in memory at once
    - to overlap I/O and computation
- Multiprogramming memory management requirements:
  - Protection
    - restrict which addresses processes can use, so they can't stomp on each other
  - fast translation
    - memory lookups must be fast, in spite of the protection scheme
  - fast context switching
    - when switching between jobs, updating memory hardware (protection and translation) must be quick

Virtual addresses for multiprogramming

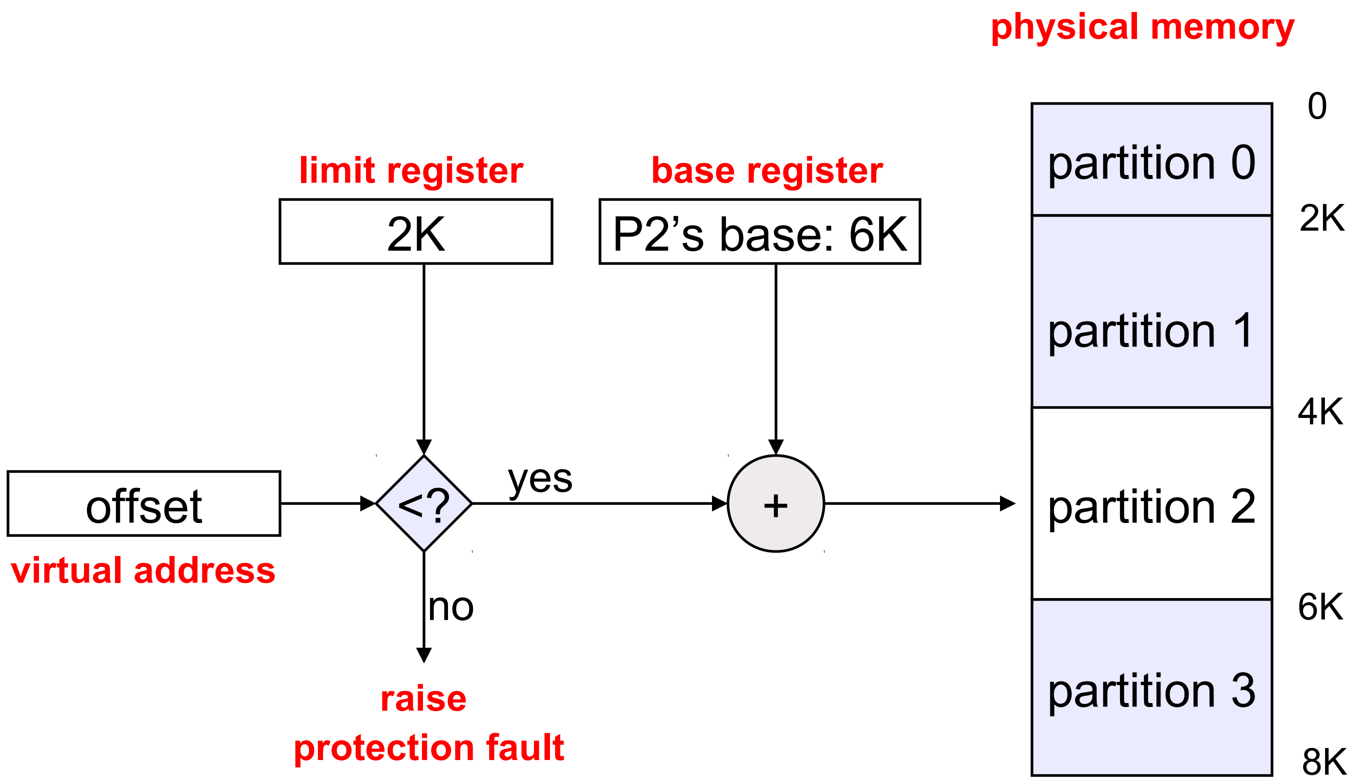
- To make it easier to manage memory of multiple processes, make processes use virtual addresses
  - virtual addresses are independent of location in physical memory (RAM) where referenced data lives
    - OS determines location in physical memory
  - instructions issued by CPU reference virtual addresses
    - e.g., pointers, arguments to load/store instructions, PC …
  - virtual addresses are translated by hardware into physical addresses (with some setup from OS)

- The set of virtual addresses a process can reference is its address space
  - many different possible mechanisms for translating virtual addresses to physical addresses
    - we'll take a historical walk through them, ending up with our current techniques
- Note: We are not yet talking about paging, or virtual memory
  - only that the program issues addresses in a virtual address space, and these must be translated to reference memory (the physical address space)
  - for now, think of the program as having a contiguous virtual address space that starts at 0, and a contiguous physical address space that starts somewhere else

Old technique #1: Fixed partitions

- Physical memory is broken up into fixed partitions
  - all partitions are equally sized, partitioning never changes
  - hardware requirement: base register, limit register
    - physical address = virtual address + base register
    - base register loaded by OS when it switches to a process
  - how do we provide protection?
    - if (physical address > base + limit) then… ?
- Advantages
  - Simple
- Problems
  - internal fragmentation: the fixed size partition is larger than what was requested
  - external fragmentation: two small partitions left, but one big job – what sizes should the partitions be??

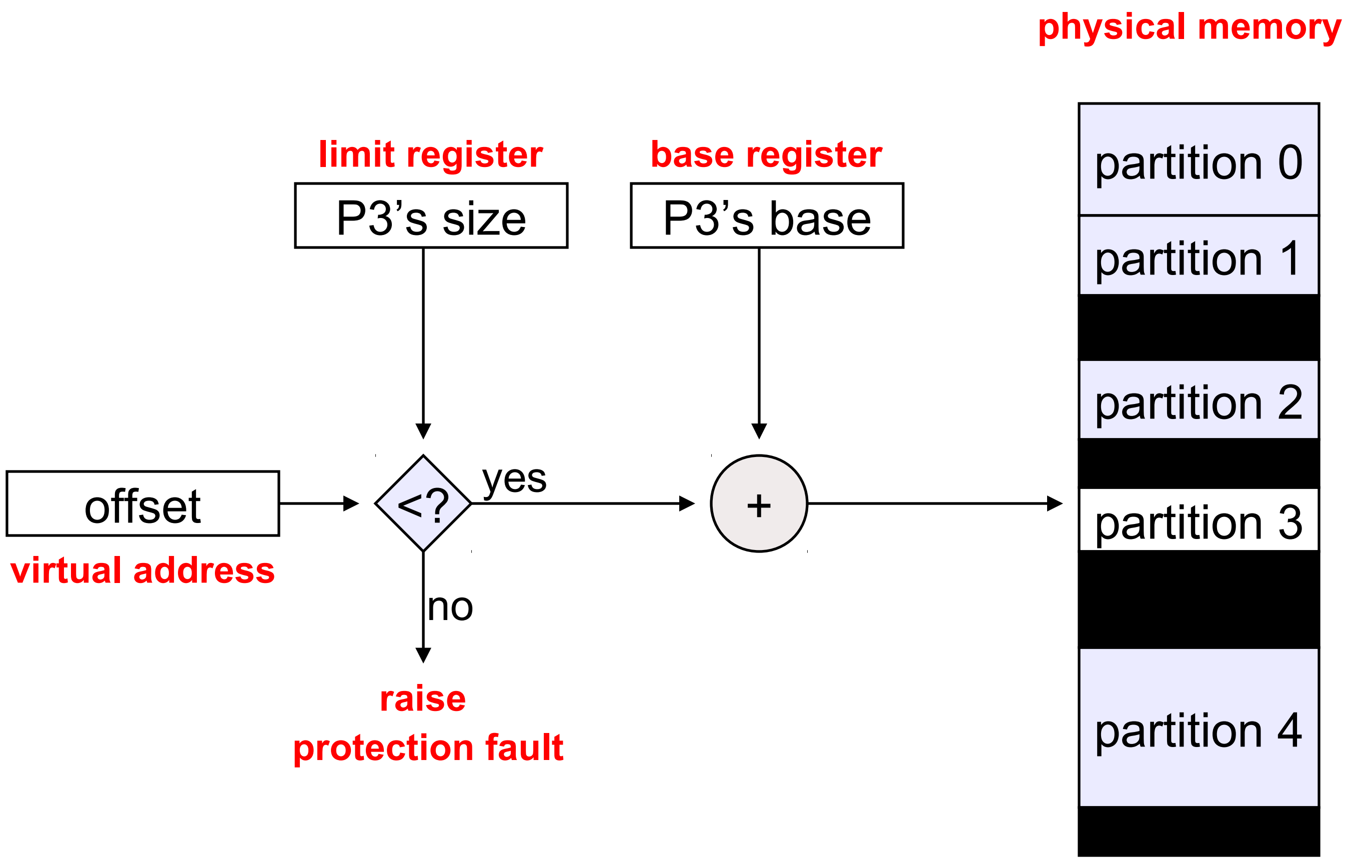
Mechanics of fixed partitions



Old technique #2: Variable partitions

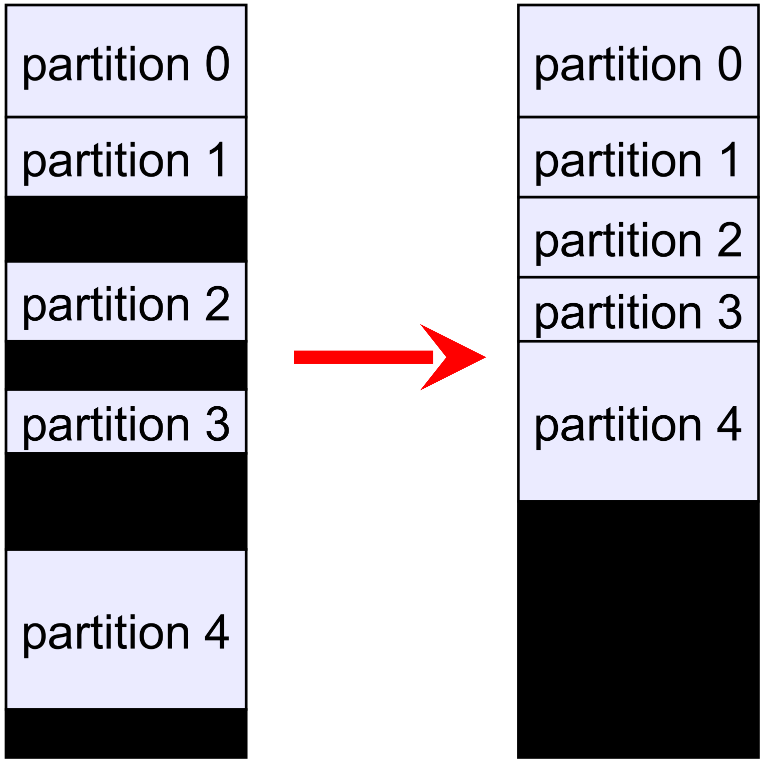
- Obvious next step: physical memory is broken up into variable-sized partitions
  - hardware requirements: base register, limit register
  - physical address = virtual address + base register
  - how do we provide protection?
    - if (physical address > base + limit) then… ?
- Advantages
  - no internal fragmentation
    - simply allocate partition size to be just big enough for process (assuming we know what that is!)
- Problems
  - external fragmentation
    - as we load and unload jobs, holes are left scattered throughout physical memory
    - slightly different than the external fragmentation for fixed partition systems

Mechanics of variable partitions



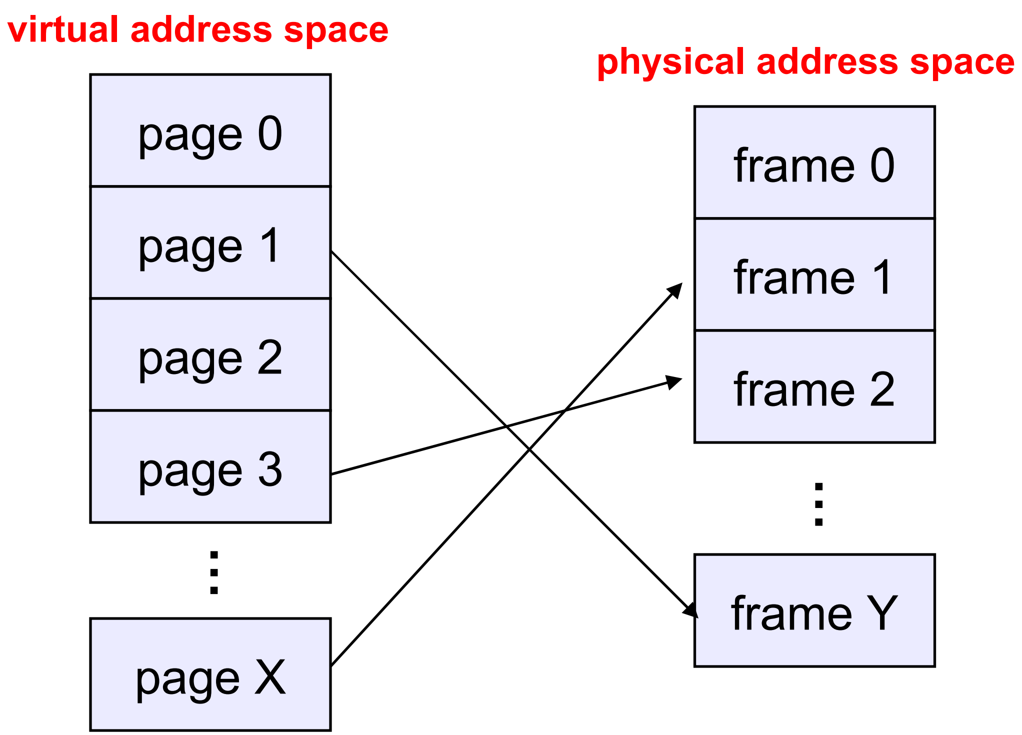
Dealing with fragmentation

- Compact memory by copying



Modern technique: Paging

- Solve the external fragmentation problem by using fixed sized units in both physical and virtual memory
- Solve the internal fragmentation problem by making the units small



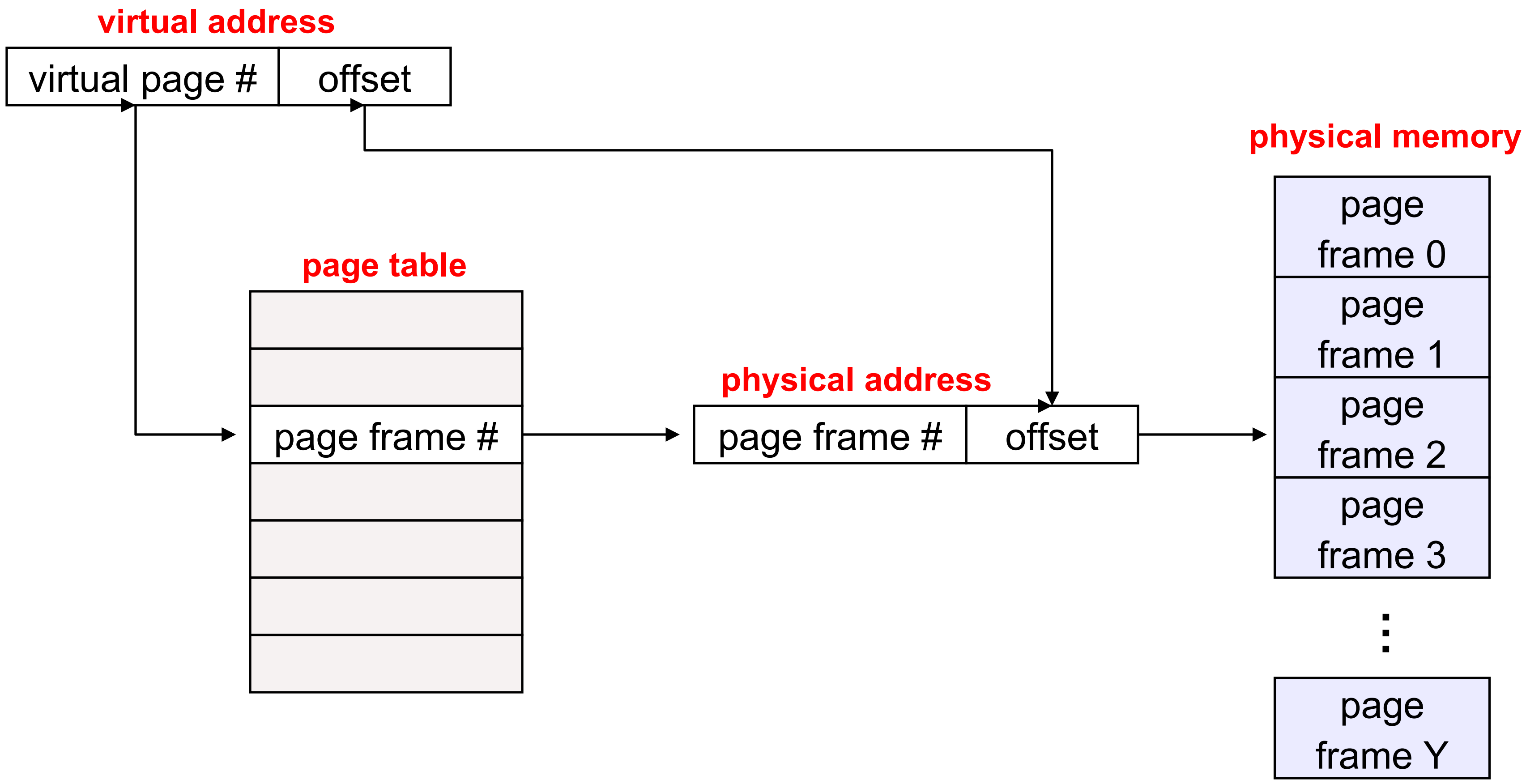
Life Is Easy…

- For developers:
  - Processes view memory as a contiguous address space from bytes 0 through N
  - N is independent of the actual hardware
- For the memory manager (OS):
  - Efficient use of memory, because very little internal fragmentation
  - Efficient use of the system because no external fragmentation at all
    - No need to copy big chunks of memory around to coalesce free space
- For the protection system (OS):
  - One process cannot name another process's memory, so there is complete isolation

Address translation

- Translating virtual addresses
  - a virtual address has two parts: virtual page number & offset
  - virtual page number (VPN) is index into a page table
  - page table entry contains page frame number (PFN)
  - physical address is PFN::offset
- Page tables
  - managed by the OS
  - one page table entry (PTE) per page in virtual address space
    - i.e., one PTE per VPN

Mechanics of address translation



PTE's: An Opportunity

- So long as there's a PTE lookup per memory reference, we might as well add some functionality
  - We can add protection
    - A virtual page can be read-only, and result in a fault if a store to it is attempted
    - Some pages may not map to anything
      - E.g., page 0
  - We can add some “accounting information”
    - Can't do anything fancy, as address translation has to be fast
    - Can keep track of whether or not a virtual page is being used, though
      - (This is intended primarily to help the paging algorithm, once we get to paging)

Page Table Entries (PTEs)

1	1	1	2	20
V	R	M	prot	page frame number

-
  - the valid bit says whether or not the PTE can be used
    - says whether or not a virtual address is valid
    - it is checked each time a virtual address is used
  - the referenced bit says whether the page has been accessed
    - it is set when a page has been read or written to
  - the modified bit says whether or not the page is dirty
    - it is set when a write to the page has occurred
  - the protection bits control which operations are allowed
    - read, write, execute
  - the page frame number determines the physical page
    - physical page start address = PFN

Paging Pros/Cons

- Pros:
  - Easy to allocate physical memory
  - Leads naturally to virtual memory
- Cons:
  - Address translation time
    - 2 references per load/store
      - Solution: caching
  - Page tables can be large:
    - 32-bit AS w/ 4KB pages = 2^{20} PTEs = 1,048,576 PTEs
    - 64-bit address space: !!!

Segmentation
(We will be back to paging soon!)

- Paging
  - view an address space as a linear array of bytes
- Segmentation
  - partition an address space into *logical* units
    - E.g., stack, code, heap, subroutines, …
  - a virtual address is <segment #, offset>

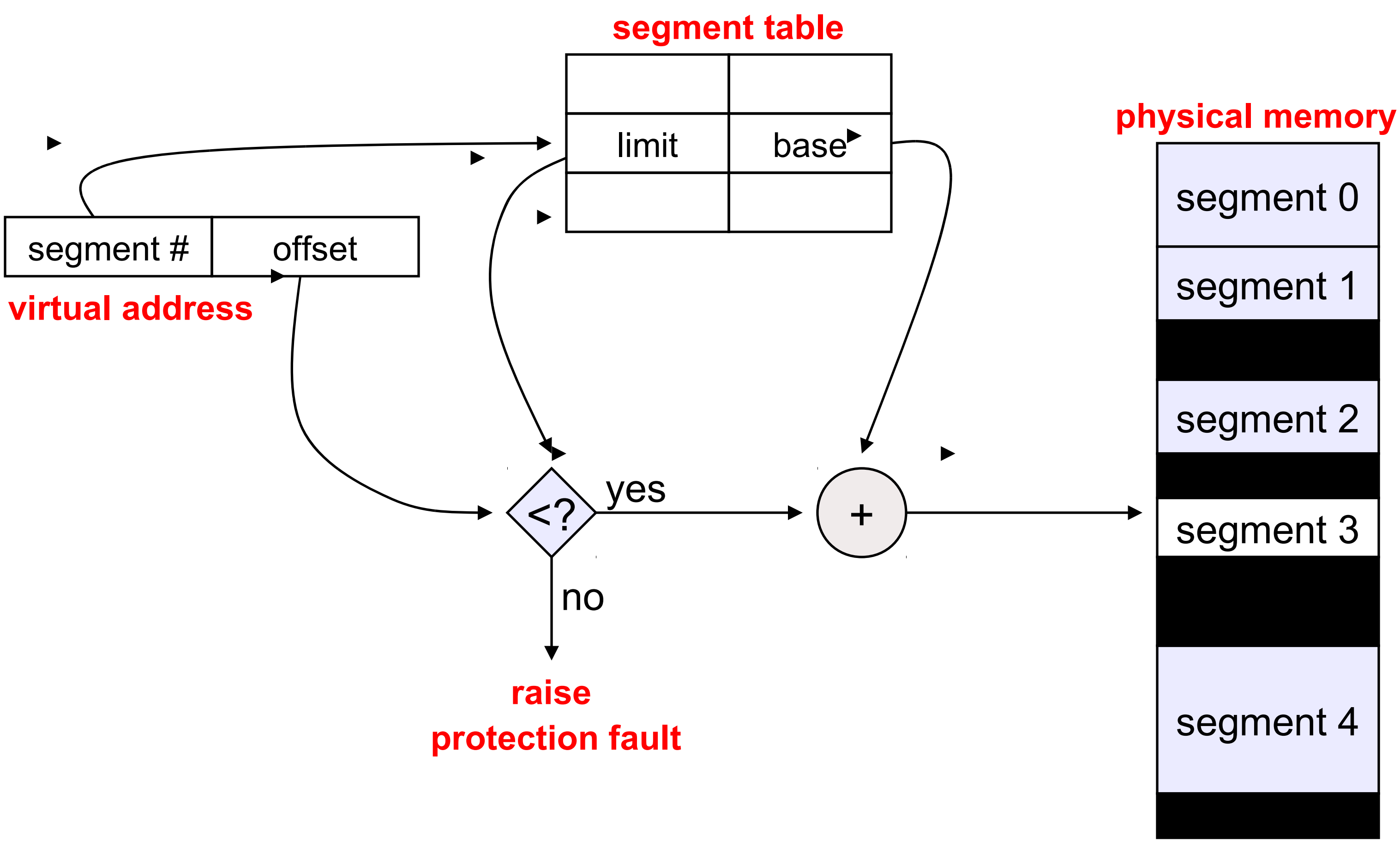
What's the point?

- More "logical"
  - absent segmentation, a linker takes a bunch of independent modules that call each other and linearizes them
  - they are really independent; segmentation treats them as such
- Facilitates sharing and reuse
  - a segment is a natural unit of sharing – a subroutine or function
- A natural extension of variable-sized partitions
  - variable-sized partition = 1 segment/process
  - segmentation = many segments/process

Hardware support

- Segment table
  - multiple base/limit pairs, one per segment
  - segments named by segment #, used as index into table
    - a virtual address is <segment #, offset>
  - offset of virtual address added to base address of segment to yield physical address

Segment lookups

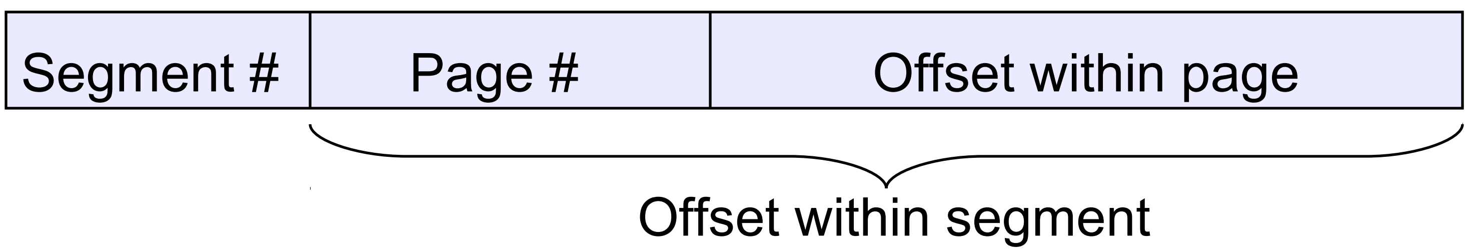


Pros and cons

- Yes, it's "logical" and it facilitates sharing and reuse
- But it has all the horror of a variable partition system
  - except that linking is simpler, and the "chunks" that must be allocated are smaller than a "typical" linear address space
- What to do?

Combining segmentation and paging

- Can combine these techniques
  - x86 architecture supports both segments and paging
- Use segments to manage logical units
  - segments vary in size, but are typically large (multiple pages)
- Use pages to partition segments into fixed-size chunks
  - each segment has its own page table
    - there is a page table per segment, rather than per user address space
  - memory allocation becomes easy once again
    - no contiguous allocation, no external fragmentation



- Linux:
  - 1 kernel code segment, 1 kernel data segment
  - 1 user code segment, 1 user data segment
  - all of these segments are paged
- Note: this is a very limited/boring use of segments!