

Operating Systems

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Memory Management

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Goals of memory management

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

Tools of memory management

- Base and limit registers
- Swapping
- Paging (and page tables and TLB's)
- Segmentation (and segment tables)
- Page faults => 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 – branches they never take, or data they never read/write)
 - 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 slow, so must be minimized!
 - Protection
 - Virtual memory **isolates** address spaces from each other
 - One process cannot name addresses visible to others; each process has its own isolated address space

VM requires hardware and OS support

- MMU's, TLB's, page tables, page fault handling, ...
- Typically accompanied by swapping, and at least limited segmentation

A trip down Memory Lane ...

- 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 portions of a virtual address space – 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!

- 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
 - bow wow wow ... but it worked!

- Then came multiprogramming
 - multiple processes/jobs in memory at once
 - to overlap I/O and computation between processes/jobs, easing the task of the application programmer
 - 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

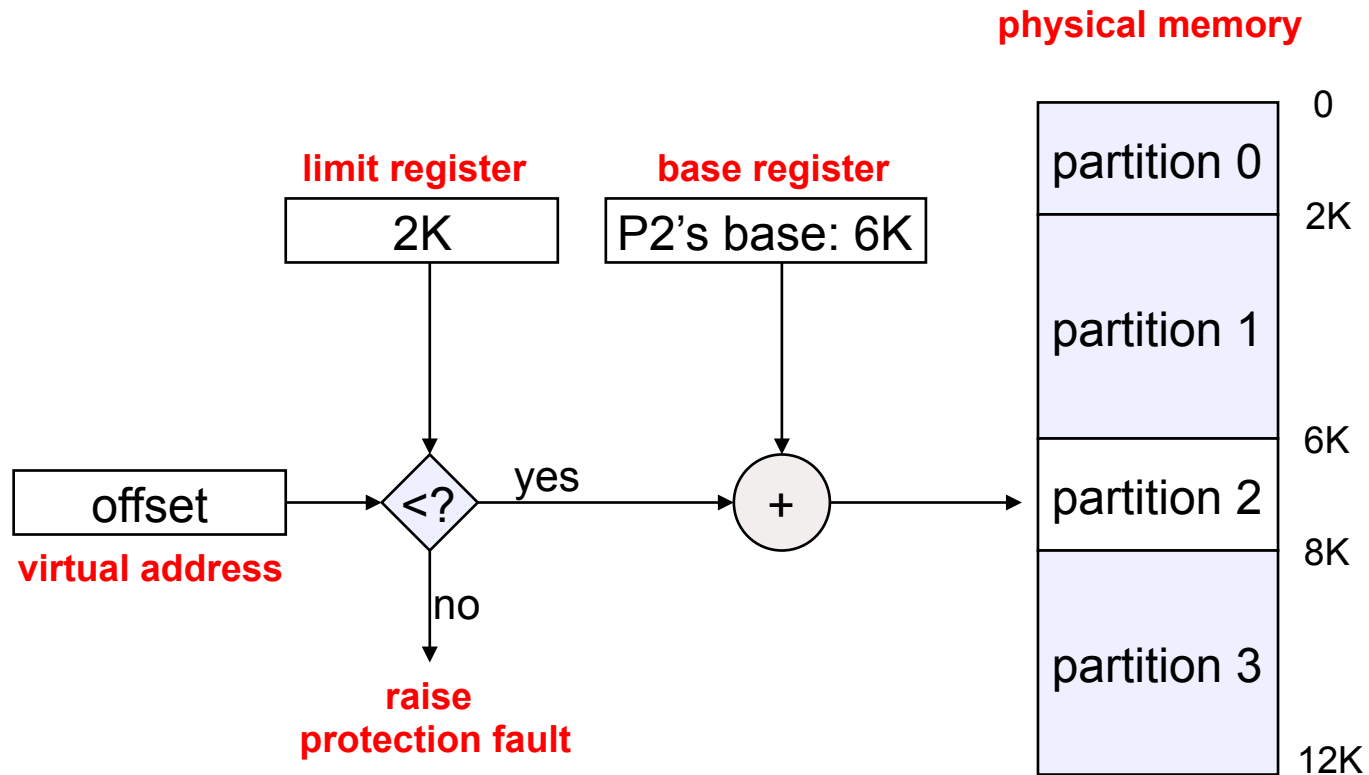
- To make it easier to manage memory of multiple processes, make processes use **virtual addresses** (which is *not* what we mean by “**virtual memory**” today!)
 - virtual addresses are independent of location in physical memory (RAM) where referenced data lives
 - OS determines location in physical 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
 - partitions may have different sizes, but 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 available partition is larger than what was requested
 - **external fragmentation**: two small partitions left, but one big job – what sizes should the partitions be??

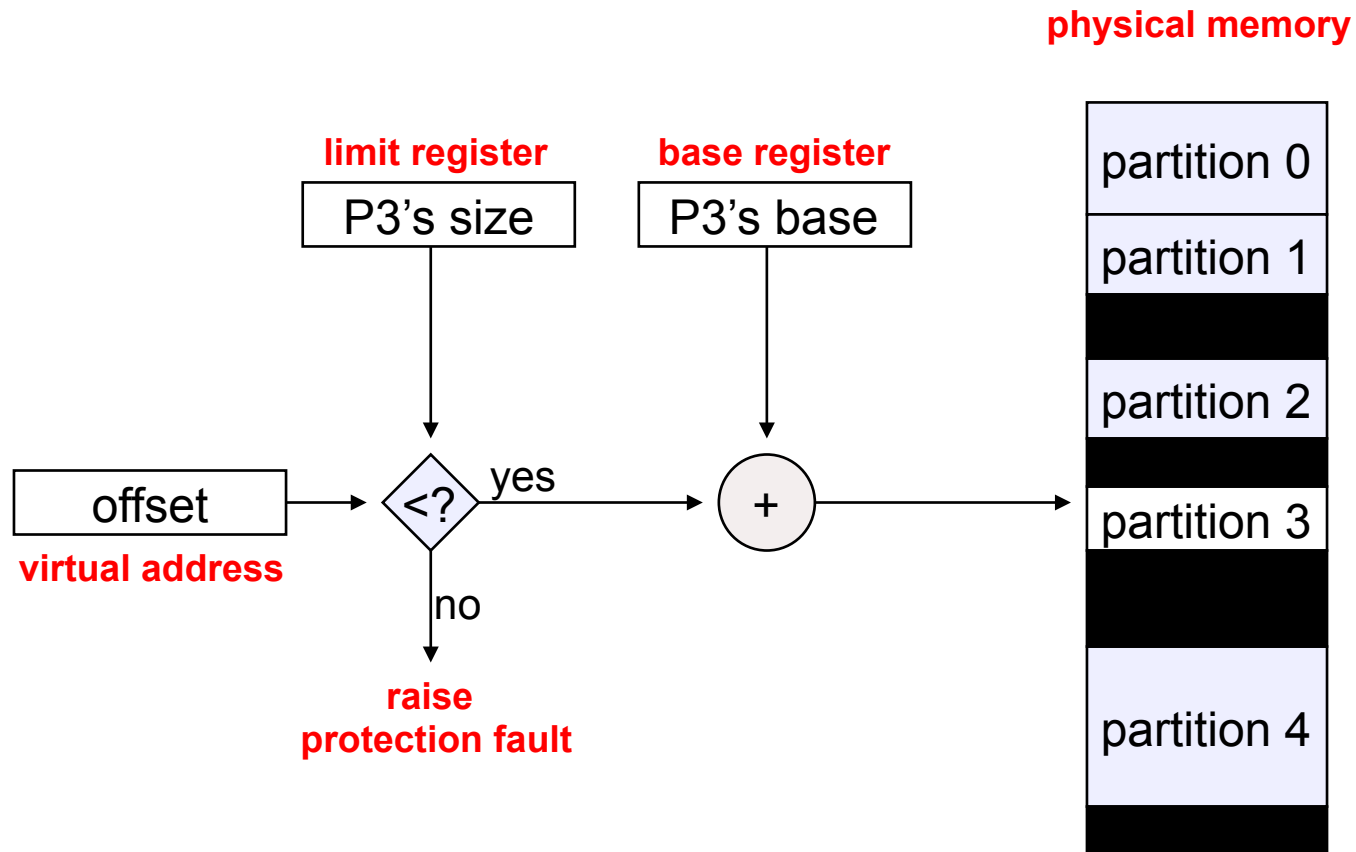
Mechanics of fixed partitions



Old technique #2: Variable partitions

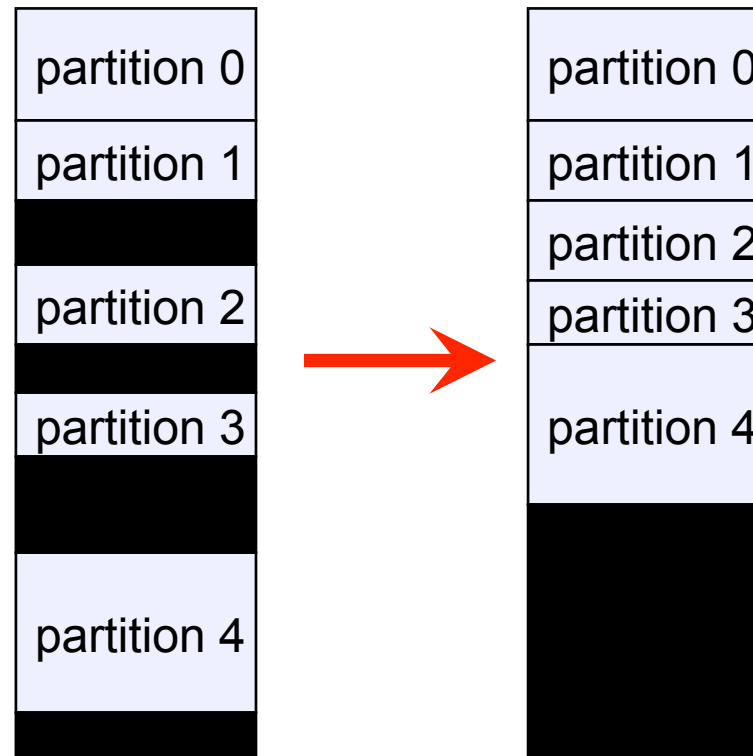
- Obvious next step: physical memory is broken up into partitions dynamically – partitions are tailored to programs
 - hardware requirements: **base register**, **limit register**
 - physical address = virtual address + base register
 - how do we provide protection?
 - if (physical address > base + limit) 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



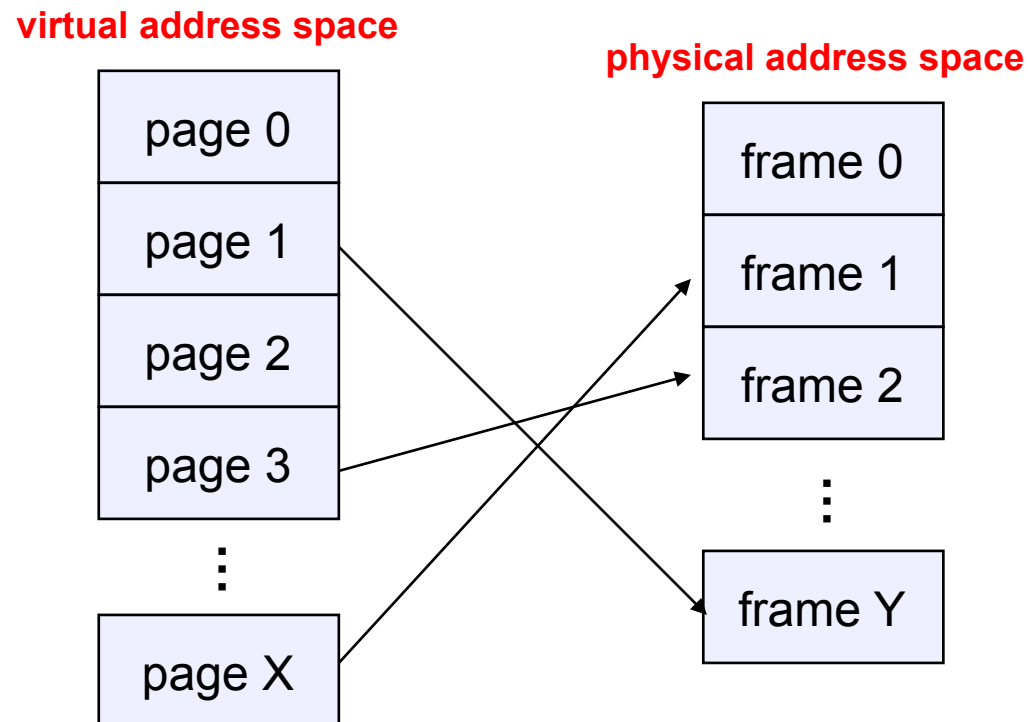
Dealing with fragmentation

- Compact memory by copying
 - Swap a program out
 - Re-load it, adjacent to another
 - Adjust its base register
 - “Lather, rinse, repeat”
 - Ugh



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 the programmer ...
 - Processes view memory as a contiguous address space from bytes 0 through N – a **virtual address space**
 - N is independent of the actual hardware
 - In reality, virtual pages are scattered across physical memory frames – not contiguous as earlier
 - Virtual-to-physical mapping
 - This mapping is **invisible** to the program
- For the memory manager ...
 - Efficient use of memory, because very little internal fragmentation
 - No external fragmentation at all
 - No need to copy big chunks of memory around to coalesce free space

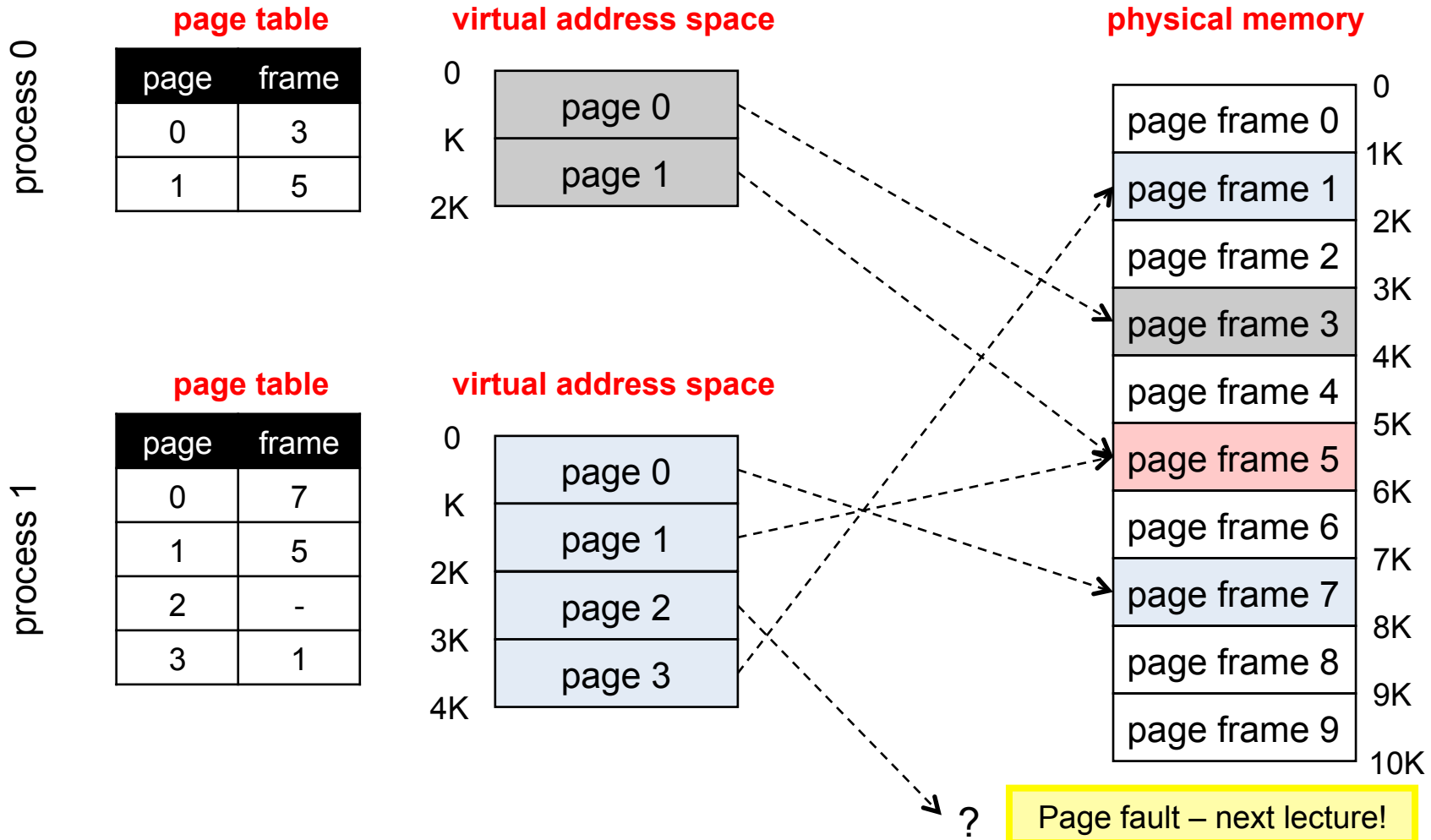
- For the protection system
 - One process cannot “name” another process’s memory – there is complete isolation
 - The virtual address 0xDEADBEEF maps to different physical addresses for different processes

Note: Assume for now that all pages of the address space are resident in memory – no “page faults”

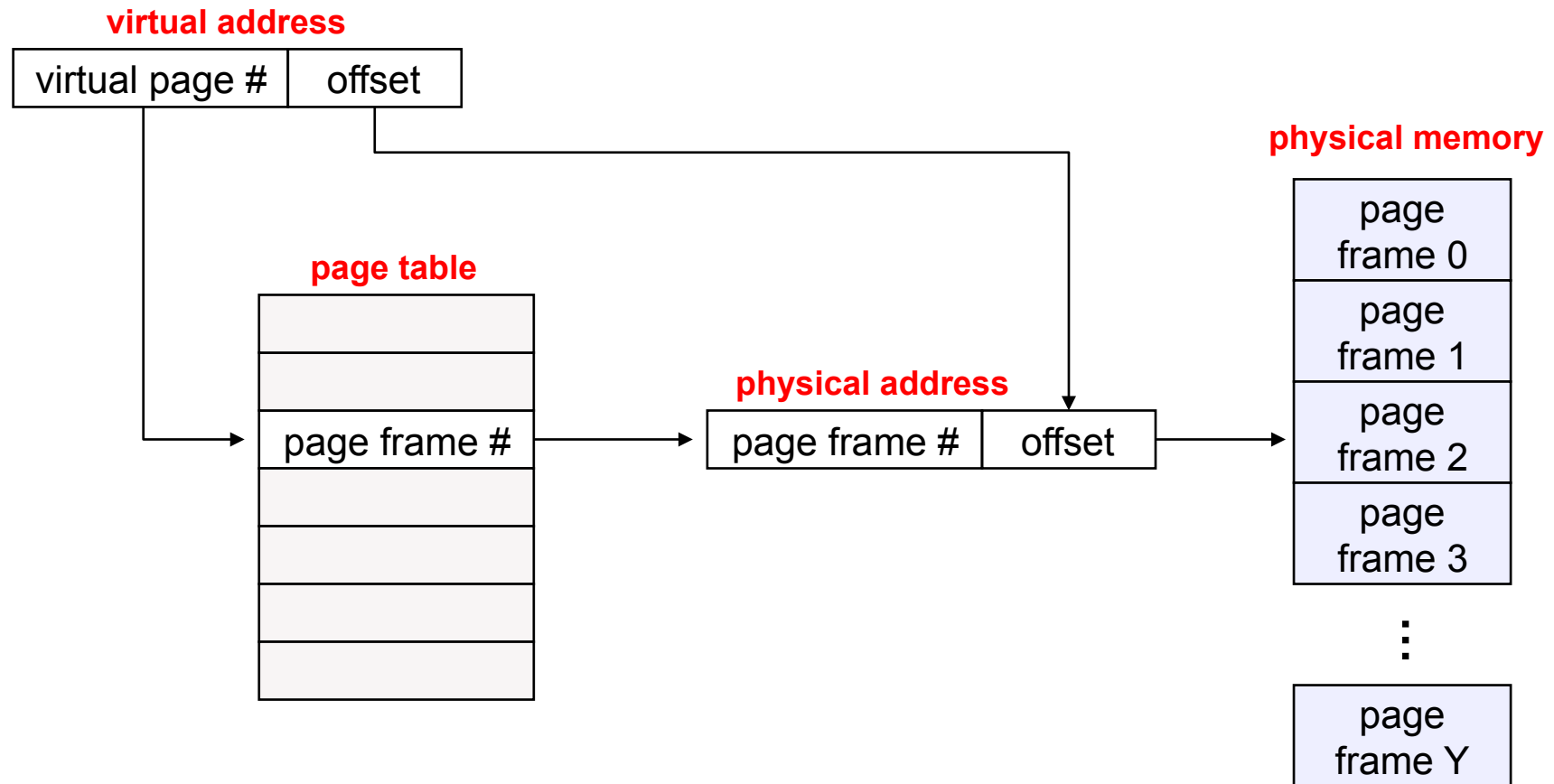
Address translation

- 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
 - map virtual page number (VPN) to page frame number (PFN)
 - VPN is simply an index into the page table

Paging (K-byte pages)



Mechanics of address translation



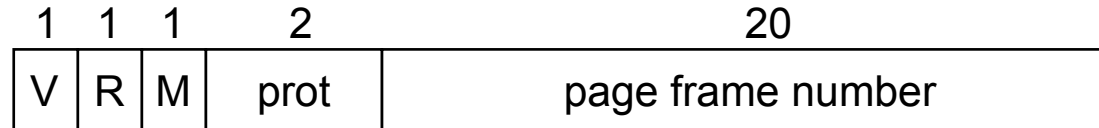
Example of address translation

- Assume 32 bit addresses
 - assume page size is 4KB (4096 bytes, or 2^{12} bytes)
 - VPN is 20 bits long (2^{20} VPNs), offset is 12 bits long
- Let's translate virtual address 0x13325328
 - VPN is 0x13325, and offset is 0x328
 - assume page table entry 0x13325 contains value 0x03004
 - page frame number is 0x03004
 - VPN 0x13325 maps to PFN 0x03004
 - physical address = PFN::offset = 0x03004328

Page Table Entries – an opportunity!

- As 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 – a fault will occur if a reference is attempted
 - We can add some “**accounting information**”
 - Can't do anything fancy, since address translation must be fast
 - Can keep track of whether or not a virtual page is being used, though
 - This will help the paging algorithm, once we get to paging

Page Table Entries (PTE's)



- PTE's control mapping
 - 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 advantages

- Easy to allocate physical memory
 - physical memory is allocated from free list of frames
 - to allocate a frame, just remove it from the free list
 - external fragmentation is not a problem
 - managing variable-sized allocations is a huge pain in the neck
 - “buddy system”
- Leads naturally to virtual memory
 - entire program need not be memory resident
 - take page faults using “valid” bit
 - all “chunks” are the same size (page size)
 - but paging was originally introduced to deal with external fragmentation, not to allow programs to be partially resident

Paging disadvantages

- Can still have internal fragmentation
 - Process may not use memory in exact multiples of pages
 - But minor because of small page size relative to address space size
- Memory reference overhead
 - 2 references per address lookup (page table, then memory)
 - Solution: use a hardware cache to absorb page table lookups
 - translation lookaside buffer (TLB) – next class
- Memory required to hold page tables can be large
 - need one PTE per page in virtual address space
 - 32 bit AS with 4KB pages = 2^{20} PTEs = 1,048,576 PTEs
 - 4 bytes/PTE = **4MB per page table**
 - OS's have separate page tables per process
 - 25 processes = 100MB of page tables
 - Solution: page the page tables (!!!)
 - (ow, my brain hurts...more later)

Segmentation

(We will be back to paging soon!)

- Paging
 - mitigates various memory allocation complexities (e.g., fragmentation)
 - view an address space as a linear array of bytes
 - divide it into pages of equal size (e.g., 4KB)
 - use a page table to map virtual pages to physical page frames
 - page (*logical*) => page frame (*physical*)
- Segmentation
 - partition an address space into *logical* units
 - stack, code, heap, subroutines, ...
 - a virtual address is **<segment #, offset>**

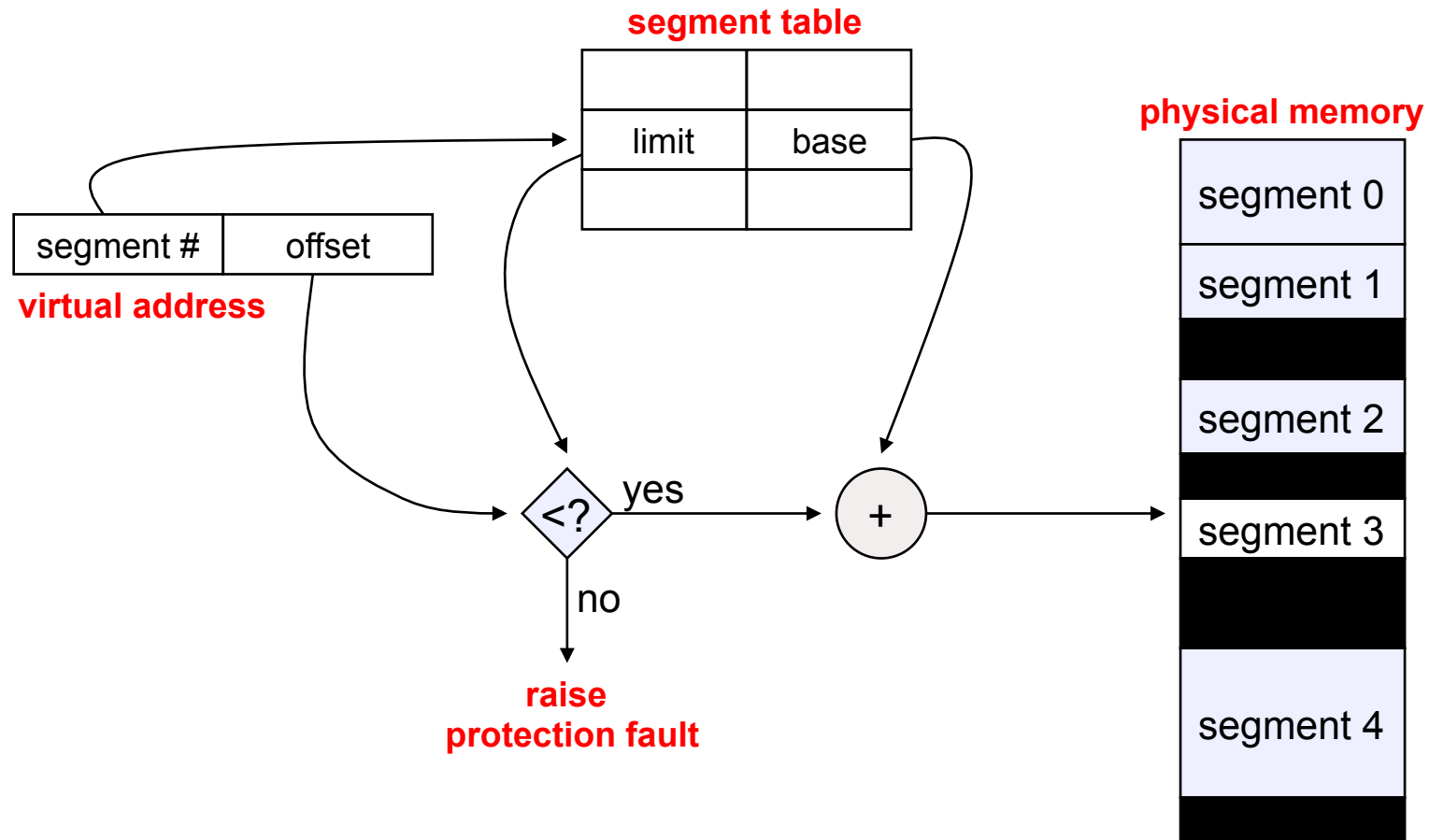
What's the point?

- 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

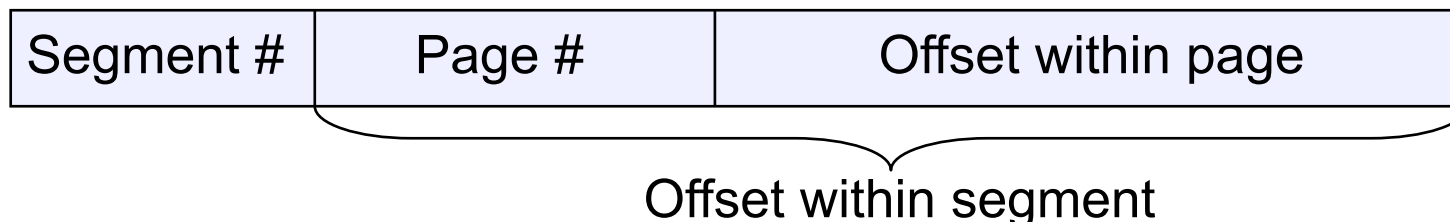


Pros and cons

- 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!