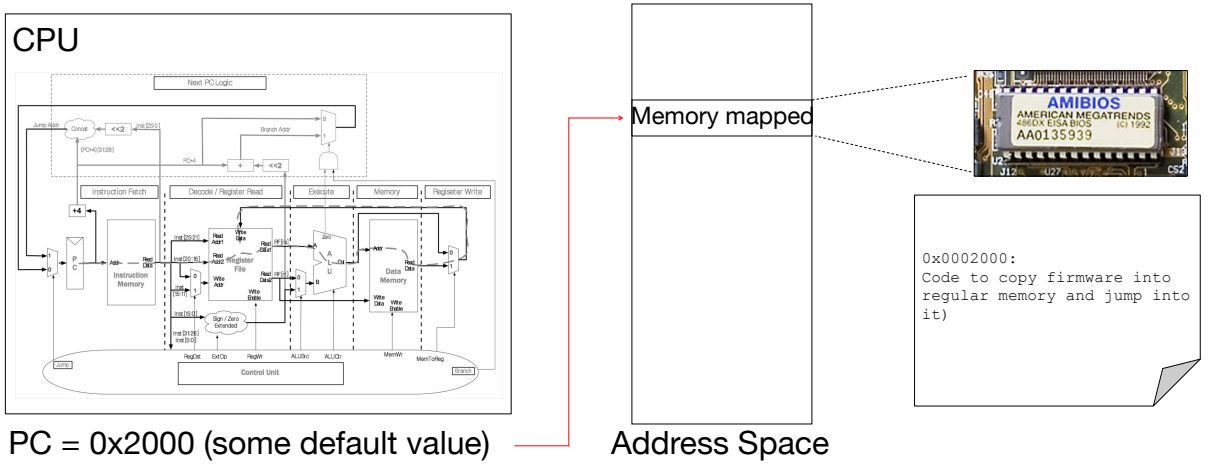
Virtual Memory

Administrivia

- Check-Ins Round 2
- Midterm regrade requests due Friday at 12PM Pacific
  - We plan to process all regrades by 4/12
- Project 3B due on 4/2 (tomorrow)
- Project 4 released: Try to complete tasks 1-3 by 4/9

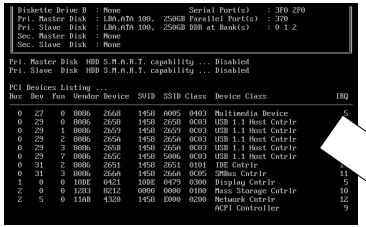
What Happens at Boot?

- When the computer switches on, it does the same as VENUS: the CPU executes instructions from some start address (stored in Flash ROM)

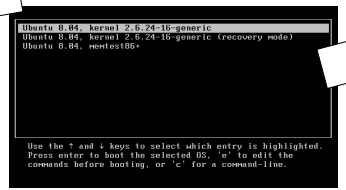


What Happens at Boot?

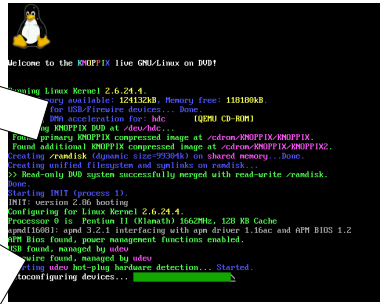
1. BIOS*: Find a storage device and load first sector (block of data)



2. Bootloader (stored on, e.g., disk): Load the OS *kernel* from disk into a location in memory and jump into it



4. Init: Launch an application that waits for input in loop (e.g., Terminal/Desktop/...



3. OS Boot: Initialize services, drivers, etc.

*BIOS: Basic Input Output System
also "EFI Firmware"

Launching Applications

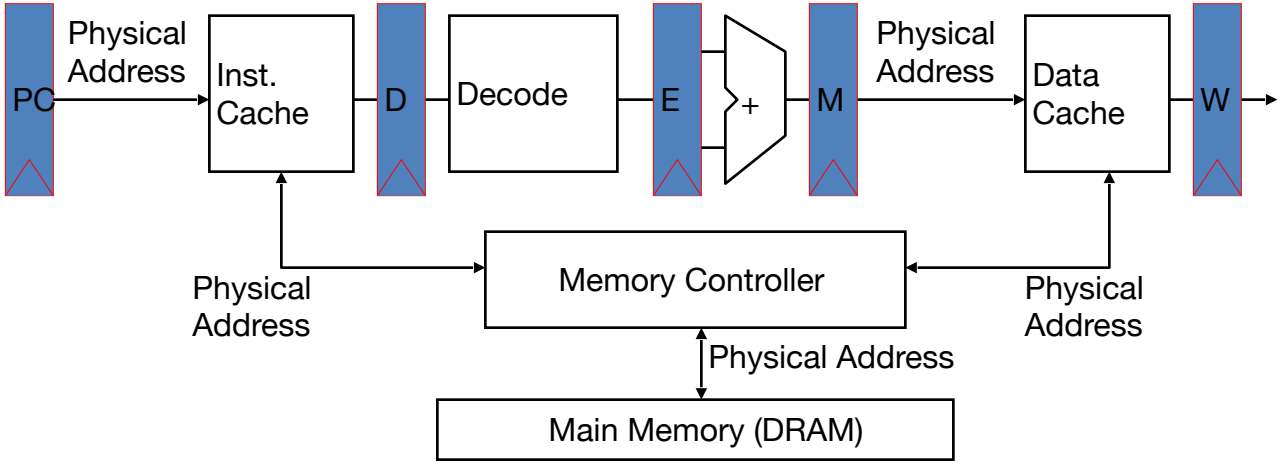
- Applications are called “processes” in most OSs
  - Each process has its own address space (so each process is **isolated**)
  - A process has one or more **threads** of execution
  - All threads in the system run (pseudo) simultaneously
  - Many user applications actually comprise multiple threads and/or processes (e.g., Chrome)
- Apps are started by another process (e.g., shell) calling an OS routine (This is a system call [“syscall”])
  - Depends on OS, but Linux uses fork to create a new process, and execve (execute file command) to load application
  - Under the hood these call something like `ecall`.
- Loads executable file from disk (using the file system service) and puts instructions & data into memory (.text, .data sections), prepares stack and heap
- Set argc and argv, jump to start of main
- Shell waits for main to return (wait)

Protection, Translation, Paging

- Supervisor mode alone is not sufficient to fully isolate applications from each other or from the OS
  - Application could overwrite another application's memory.
- Typically programs start at some fixed address, e.g. 0x8FFFFFFF
  - How can 100's of programs all share memory at location 0x8FFFFFFF?
- Also, may want to address more memory than we actually have (e.g., for sparse data structures)
- Solution: Virtual Memory
  - Gives each process the illusion of a full memory address space that it has completely for itself

“Bare” 5-Stage Pipeline

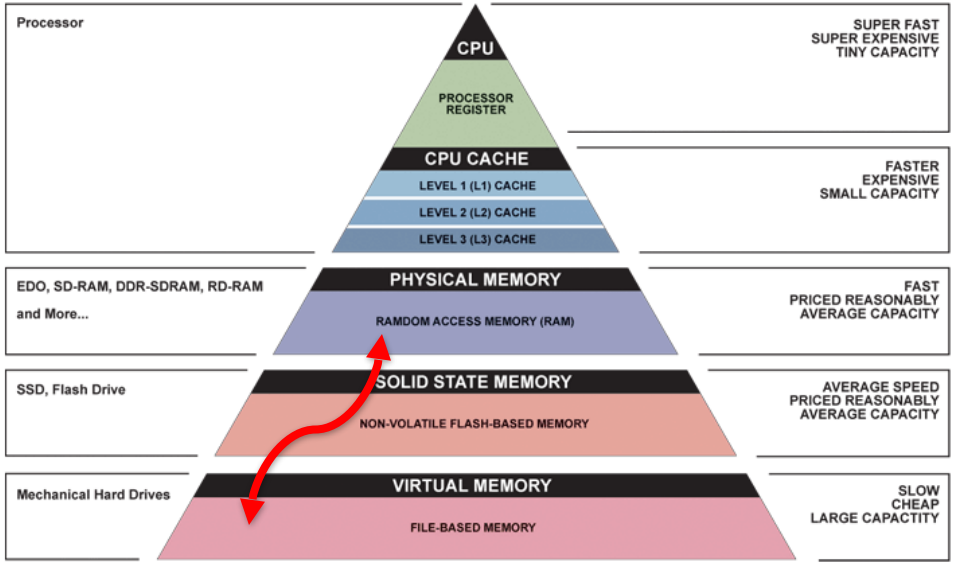
- In a bare machine, the only kind of address is a physical address



What do we need Virtual Memory for?
Reason 1: Adding Disks to Hierarchy

- Need to devise a mechanism to “connect” memory and disk in the memory hierarchy

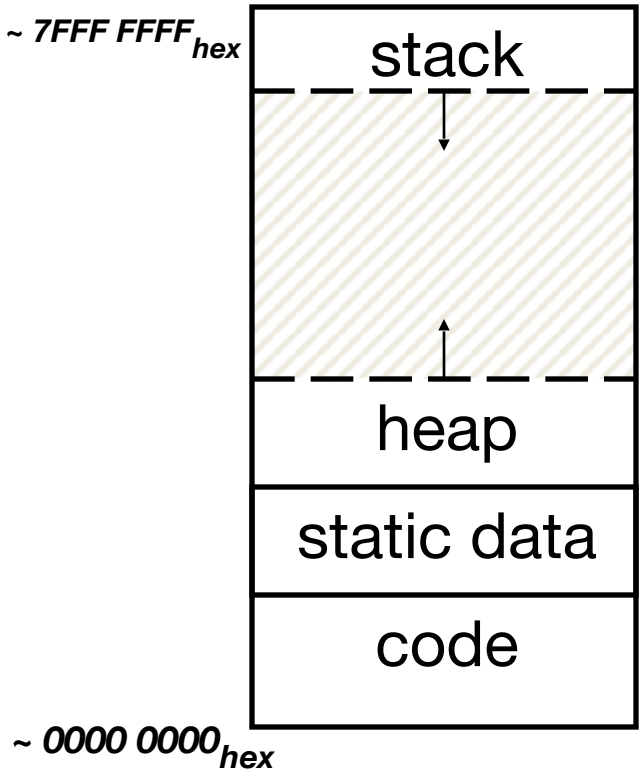
- Disk
  - Slow
  - But huge
  - How could we make use of its capacity (when running low on DRAM)?



▲ Simplified Computer Memory Hierarchy
Illustration: Ryan J. Leng

What do we need Virtual Memory for?
Reason 2: Simplifying Memory for Apps

- Processes should see the straightforward memory layout we saw earlier ->
- User-space applications should think they own all of memory
- So we give them a **virtual** view of memory



What do we need Virtual Memory for?
Reason 3: Protection Between Processes

- With a bare system, addresses issued with loads/stores are real physical addresses
- This means any process can issue any address, therefore can access any part of memory, even areas which it doesn't own
  - Ex: The OS data structures
- We should send all addresses through a mechanism that the OS controls, before they make it out to DRAM - a translation mechanism
  - Can check that process has permission to access a particular part of memory

Address Spaces

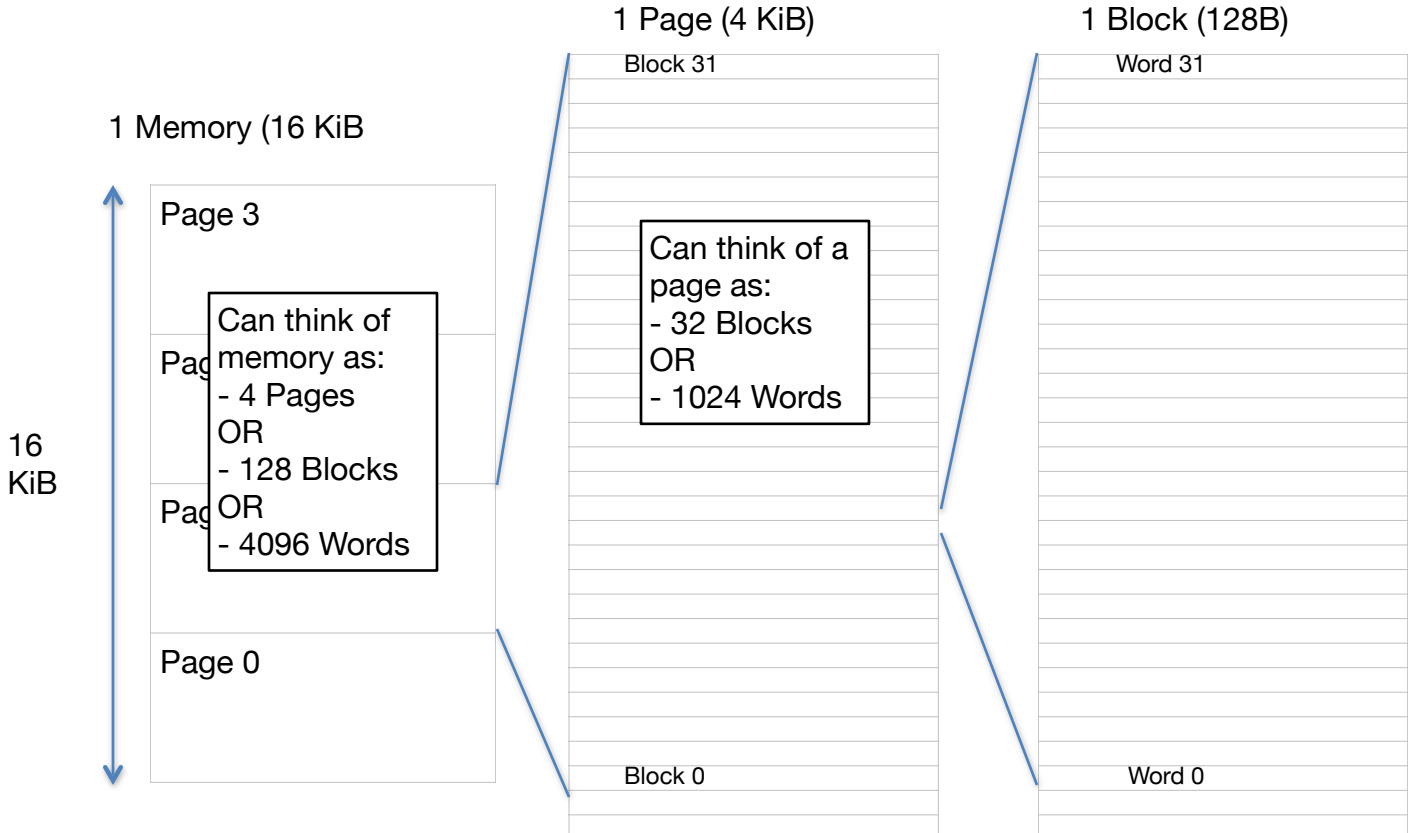
- Address space = set of addresses for all available memory locations
- Now, two kinds of memory addresses:
  - ***Virtual*** Address Space
    - Set of addresses that the user program knows about
  - ***Physical*** Address Space
    - Set of addresses that map to actual physical locations in memory
    - Hidden from user applications
- Memory manager maps between these two address spaces

Aside: Blocks vs. Pages

- In caches, we dealt with individual ***blocks***
  - Usually ~64-128B on modern systems
  - We “divide” memory into a set of blocks
- In VM, we deal with individual ***pages***
  - Usually ~4 KB on modern systems
  - Now, we’ll “divide” memory into a set of pages
- Common point of confusion: Bytes, Words, Blocks, Pages are all just different ways of looking at memory!

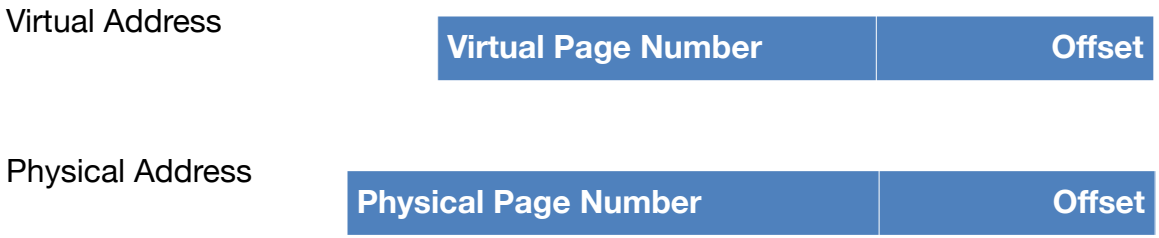
Bytes, Words, Blocks, Pages

Ex: 16 KiB DRAM, 4 KiB Pages (for VM), 128 B blocks (for caches), 4 B words (for lw/sw)

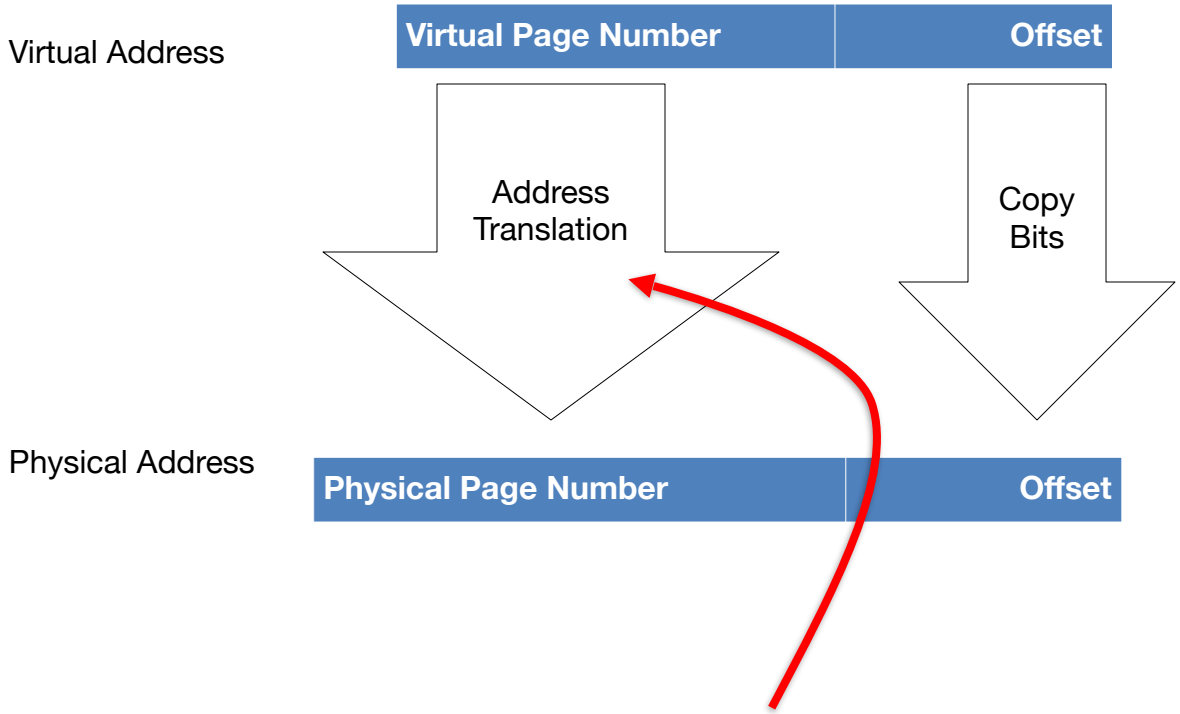


Address Translation

- So, what do we want to achieve at the hardware level?
  - Take a Virtual Address, that points to a spot in the Virtual Address Space of a particular program, and map it to a Physical Address, which points to a physical spot in DRAM of the whole machine



Address Translation



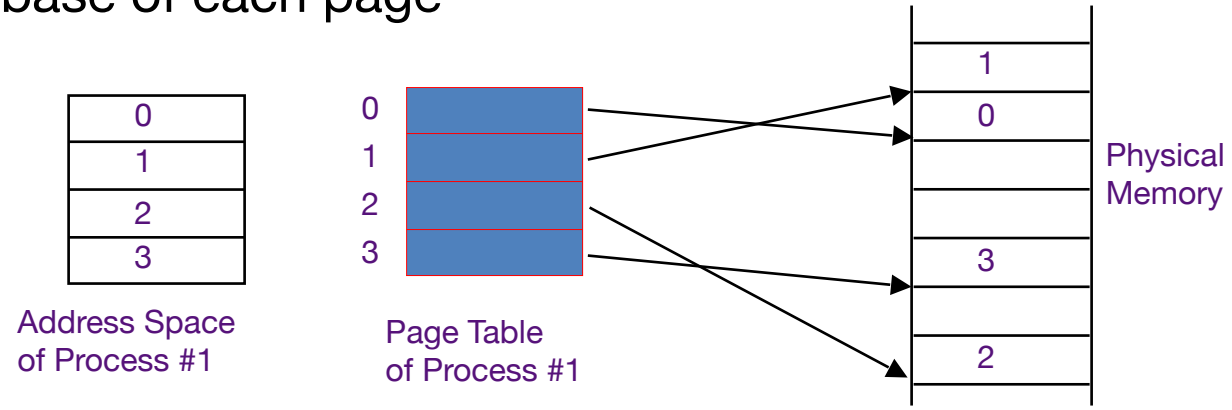
Rest of this lecture: How do we implement this?

Paged Memory Systems

- Processor-generated address can be split into:

Virtual Page Number	Offset

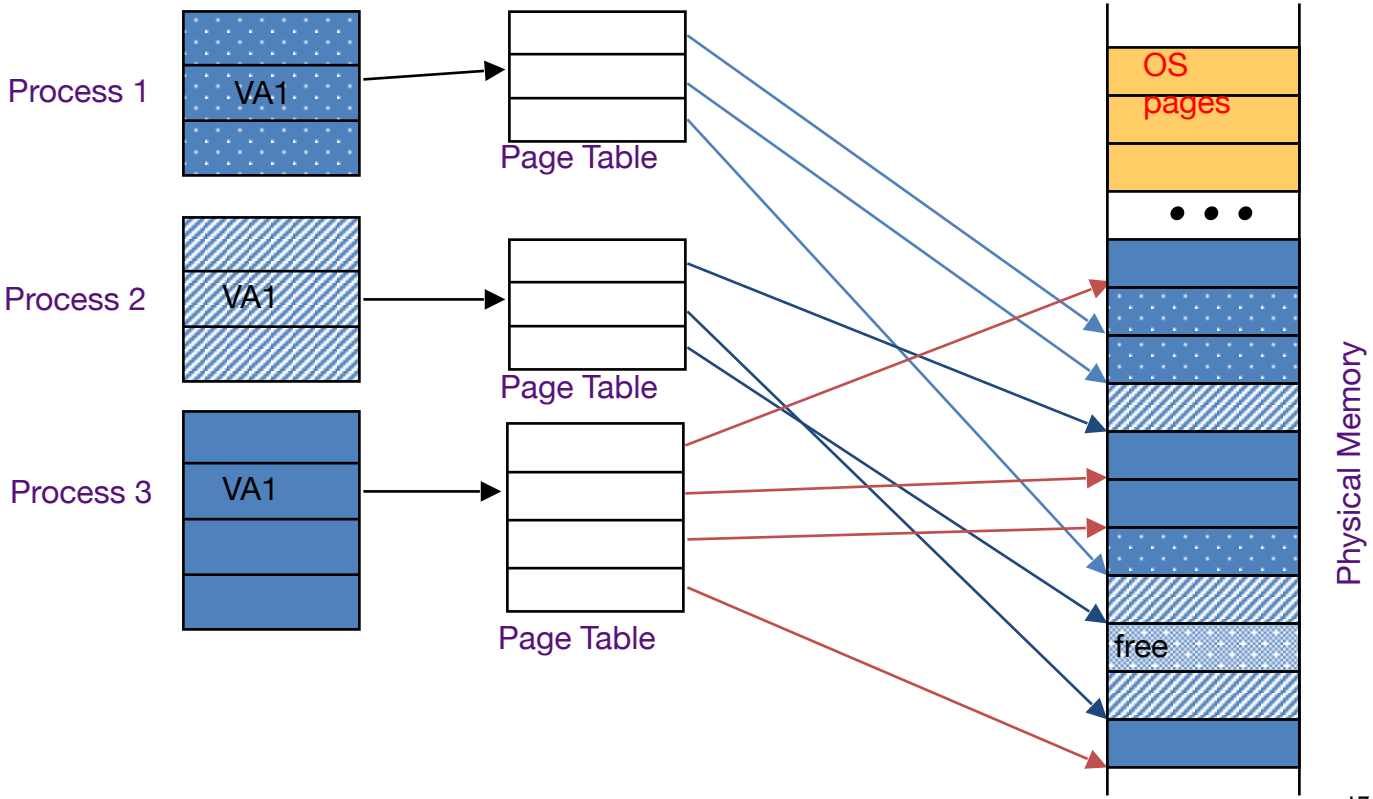
  - A *page table* contains the physical address of the base of each page



Page tables make it possible to store the pages of a process non-contiguously.

Private (Virtual) Address Space per Process

- Each process has a page table
- Page table contains an entry for each process page
- Physical Memory acts like a "cache" of pages for currently running programs. **Not recently used pages are stored in secondary memory, e.g. disk (in "swap partition")**



Where Should Page Tables Reside?

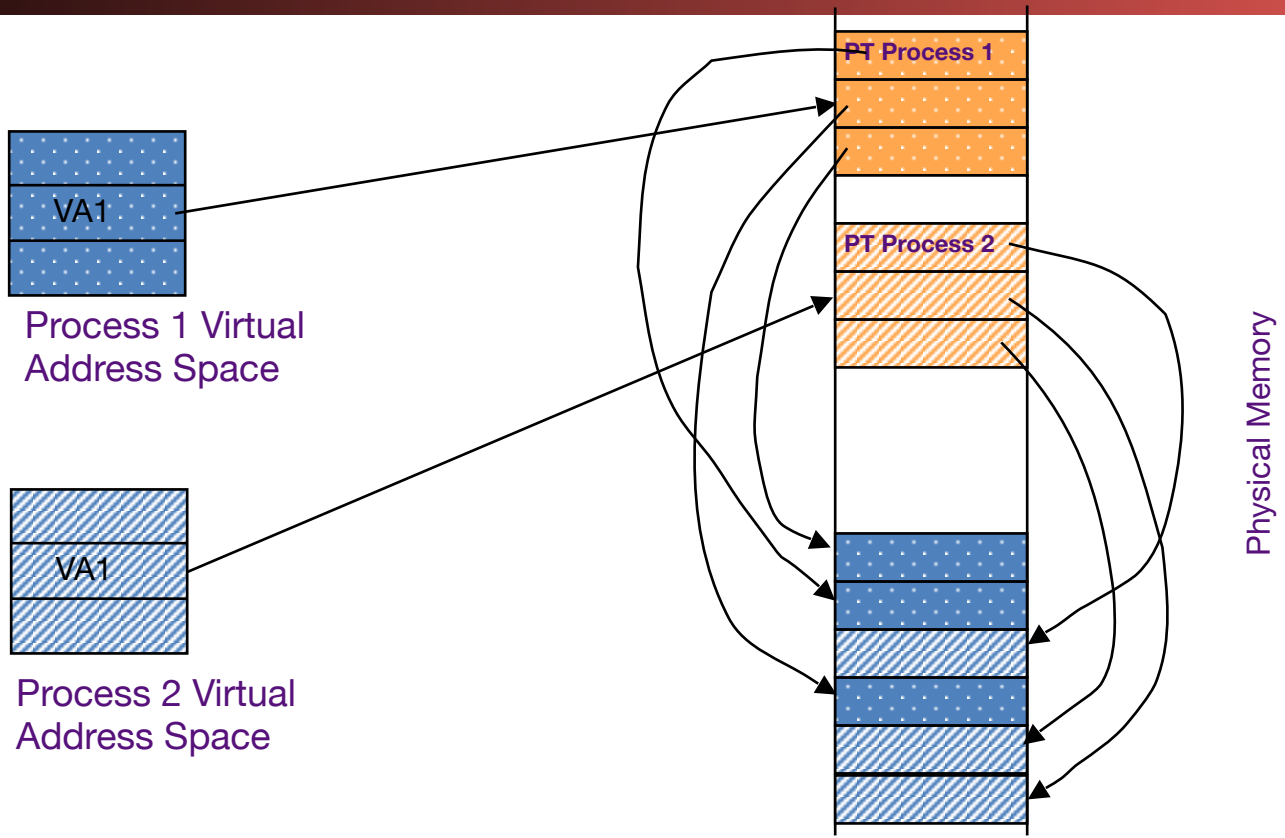
- Space required by the page tables (PT) is proportional to the address space, number of processes, ...

  ⇒ *Too large to keep in registers inside CPU*

- Idea: Keep page tables in the main memory
  - Needs one reference to retrieve the page physical address and another to access the data word

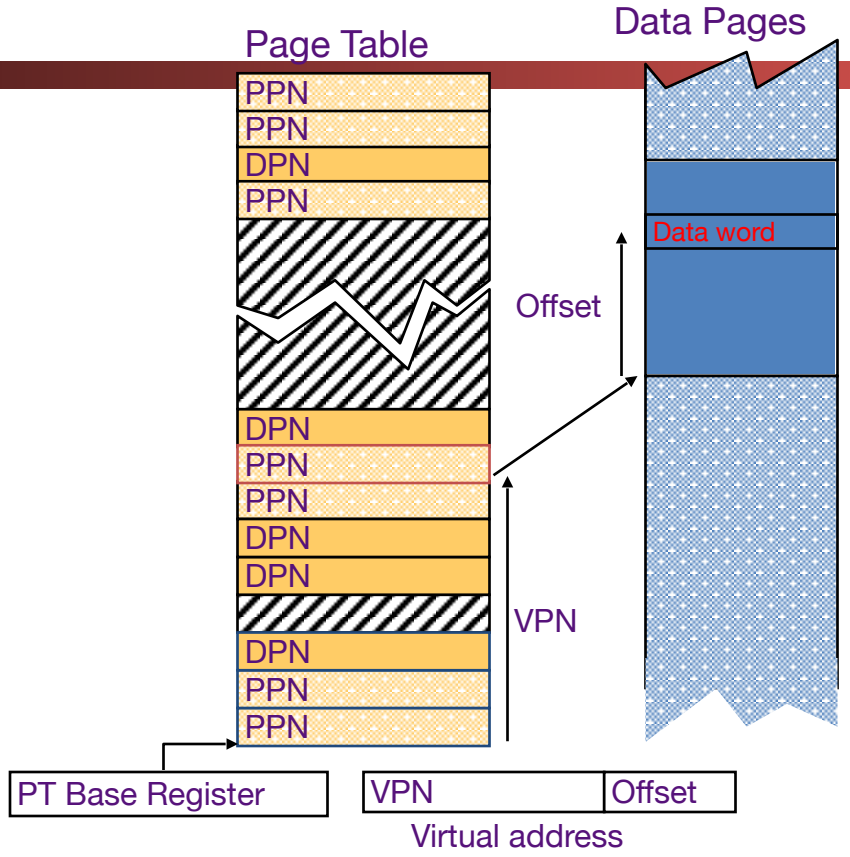
    ⇒ *doubles the number of memory references! (but we can fix this using something we already know about…)*

Page Tables in Physical Memory



Linear (simple) Page Table

- Page Table Entry (PTE) contains:
  - 1 bit to indicate if page exists
  - And either PPN or DPN:
  - PPN (physical page number) for a memory-resident page
  - DPN (disk page number) for a page on the disk
  - Status bits for protection and usage (read, write, exec)
- OS sets the Page Table Base Register whenever active user process changes



Suppose an instruction references a memory page that isn't in DRAM?

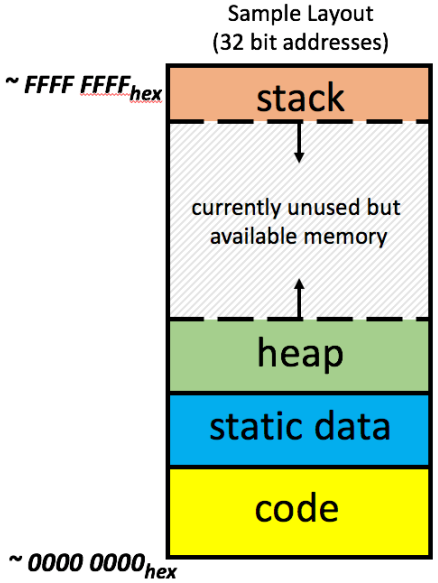
- We get a exception of type "***page fault***"
- Page fault handler (yet another function of the interrupt/trap handler) does the following:
  - If no unused page is available, a page currently in DRAM is selected to be replaced
    - The replaced page is written (back) to disk,
      page table entry that maps that VPN->PPN is marked with DPN
  - If virtual page doesn't yet exist, assign it an unused page in DRAM
  - If page exists but was on disk…
    - Initiate transfer of the page contents we're requesting from disk to DRAM, assigning to an unused DRAM page
  - Page table entry of the (virtual) page we're requesting is updated with a (now) valid PPN
- Following the page fault, re-execute the instruction

Size of Linear Page Table

With 32-bit memory addresses, 4-KB pages:

$\Rightarrow 2^{32} / 2^{12} = 2^{20}$ virtual pages per user, assume 4-Byte PTEs,

$\Rightarrow 2^{20}$ PTEs, 2^{22} bytes required: 4 MB page table per process!



Larger pages?

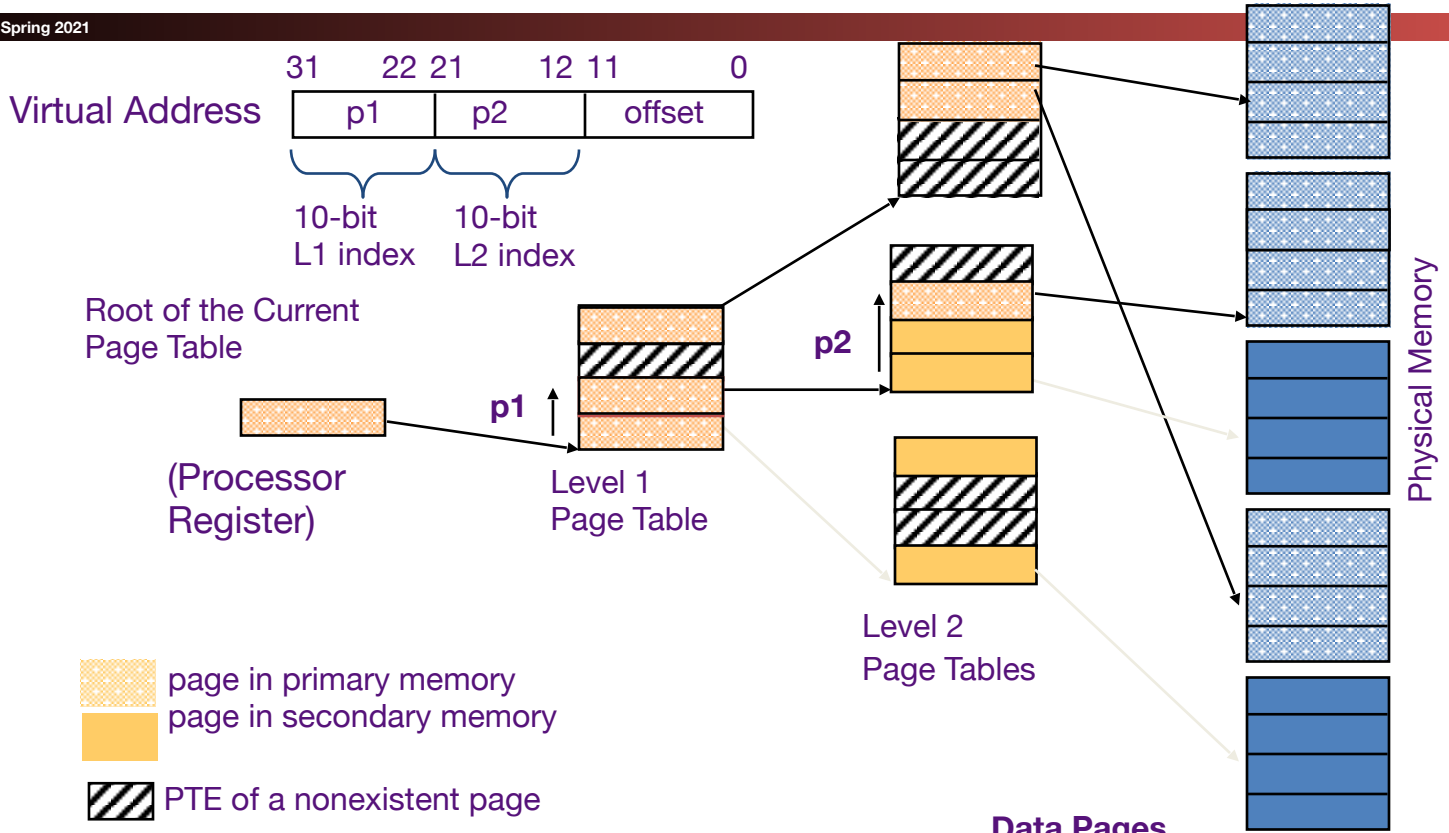
- Internal fragmentation (Not all memory in page gets used)
- Larger page fault penalty (more time to read from disk)

What about 64-bit virtual address space???

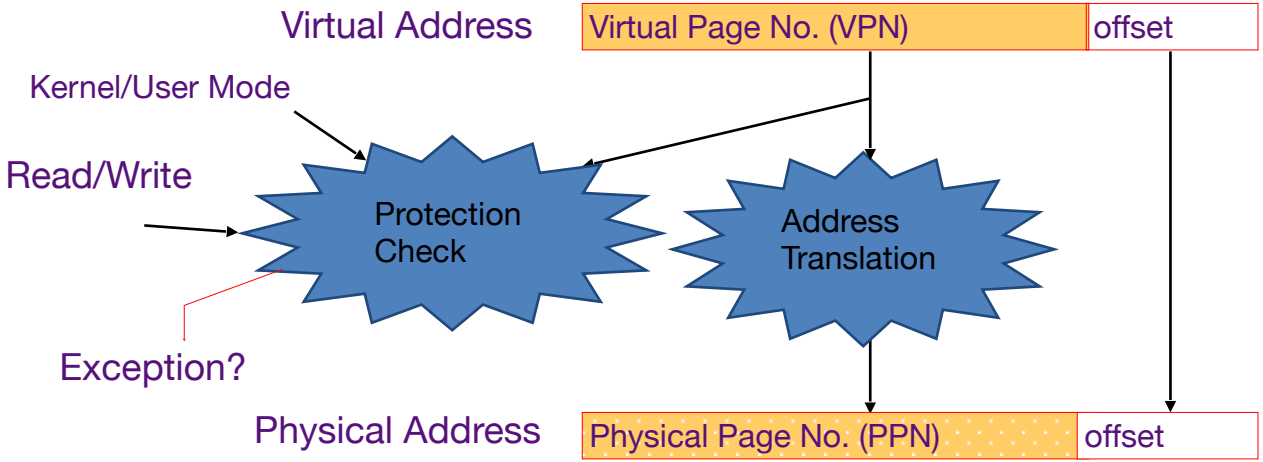
- Even 1MB pages would require 2^{44} 8-Byte PTEs (35 TB!)

What is the "saving grace" ? Most processes only use a set of high address (stack), and a set of low address (instructions, heap)

Hierarchical Page Table – exploits sparsity of virtual address space use



Address Translation & Protection



- Every instruction and data access needs address translation and protection checks

A good VM design needs to be fast (~ one cycle) and space efficient

Translation Lookaside Buffers (TLB)

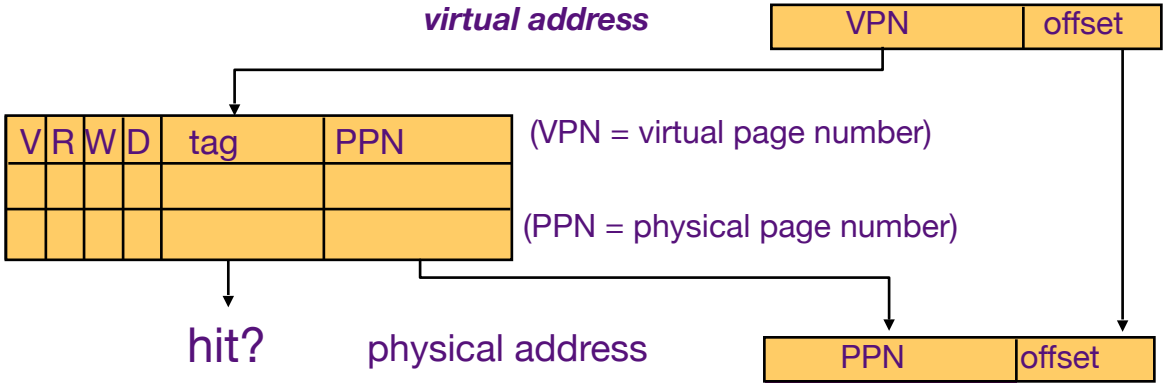
Address translation is very expensive!

In a two-level page table, each reference becomes several memory accesses

Solution: ***Cache some translations in TLB***

TLB hit ⇒ ***Single-Cycle Translation***

TLB miss ⇒ ***Page-Table Walk to refill***



TLB Designs

- Typically 32-128 entries, sometimes fully associative
  - Each entry maps a large page, hence less spatial locality across pages => more likely that two entries conflict
  - Sometimes larger TLBs (256-512 entries) are 4-8 way set-associative
  - Larger systems sometimes have multi-level (L1 and L2) TLBs
- Random or FIFO replacement policy
- "TLB Reach": Size of largest virtual address space that can be simultaneously mapped by TLB

Example: 64 TLB entries, 4KB pages, one page per entry

TLB Reach = _____?

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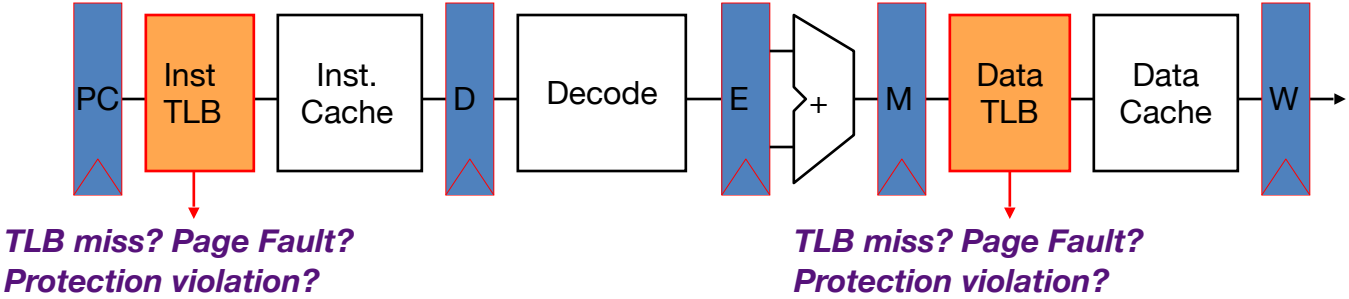
TLB Reach = 64 Entries * 4KB/Entry = 256 KB

VM-related exceptions in pipeline



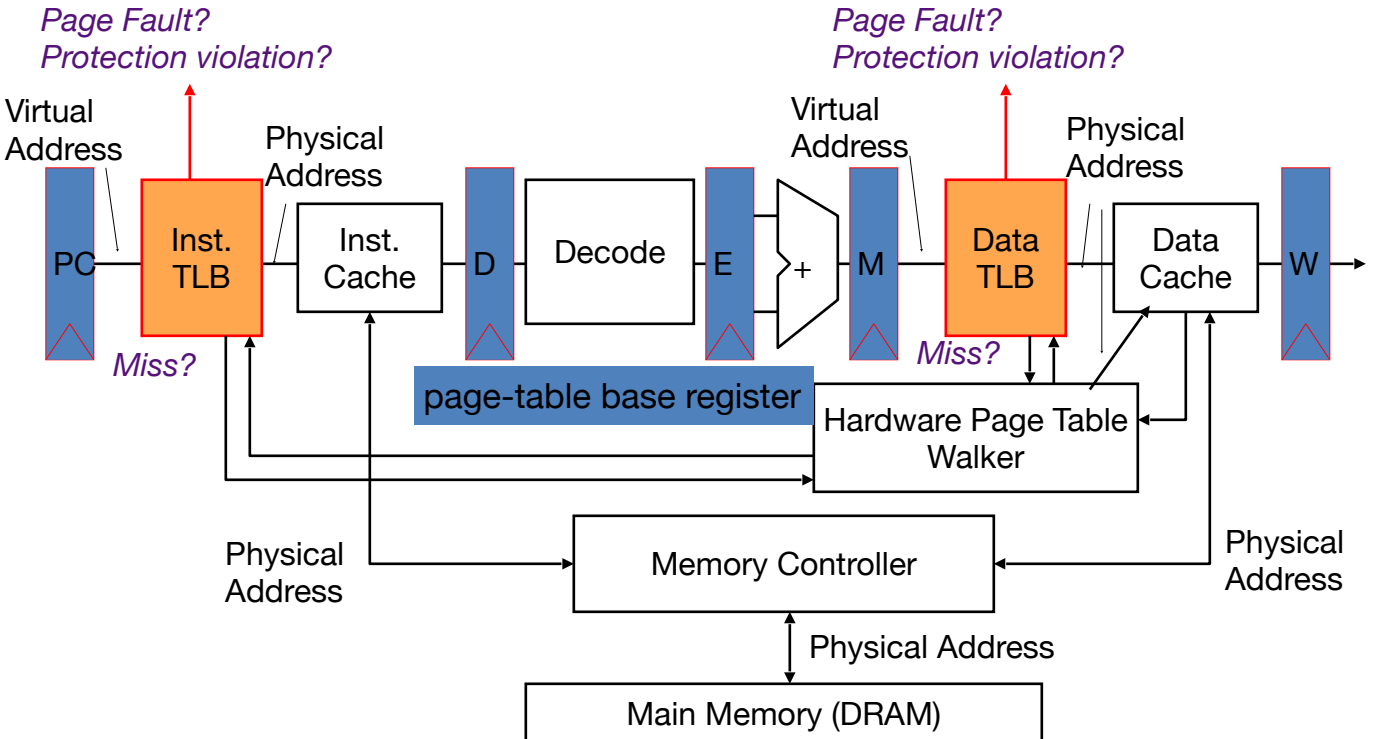
- Handling a TLB miss needs a hardware or software mechanism to refill TLB
  - Usually done in hardware now (x86, typically RISC-V)
- Handling a page fault (e.g., page is on disk) needs a *precise* trap so software handler can easily resume after retrieving page
- Handling protection violation may abort process

Using the TLB...

- Option 1: MIPS style
  - The TLB is the only translation in the hardware
  - Whenever you get a TLB miss, you jump to the page fault handler
- Option 2: x86
  - The page table has a defined structure
  - In the event of a TLB miss, the ***hardware*** walks the page table
    - Only if the page is unavailable do you jump to the page fault handler
- RISC-V prefers #2,
  but you can build a compliant RISC-V with #1
  - You just need to include the page-walking trap handler.
  - After the trap handler updates the page table for a process needs to call a special instruction to flush the TLB

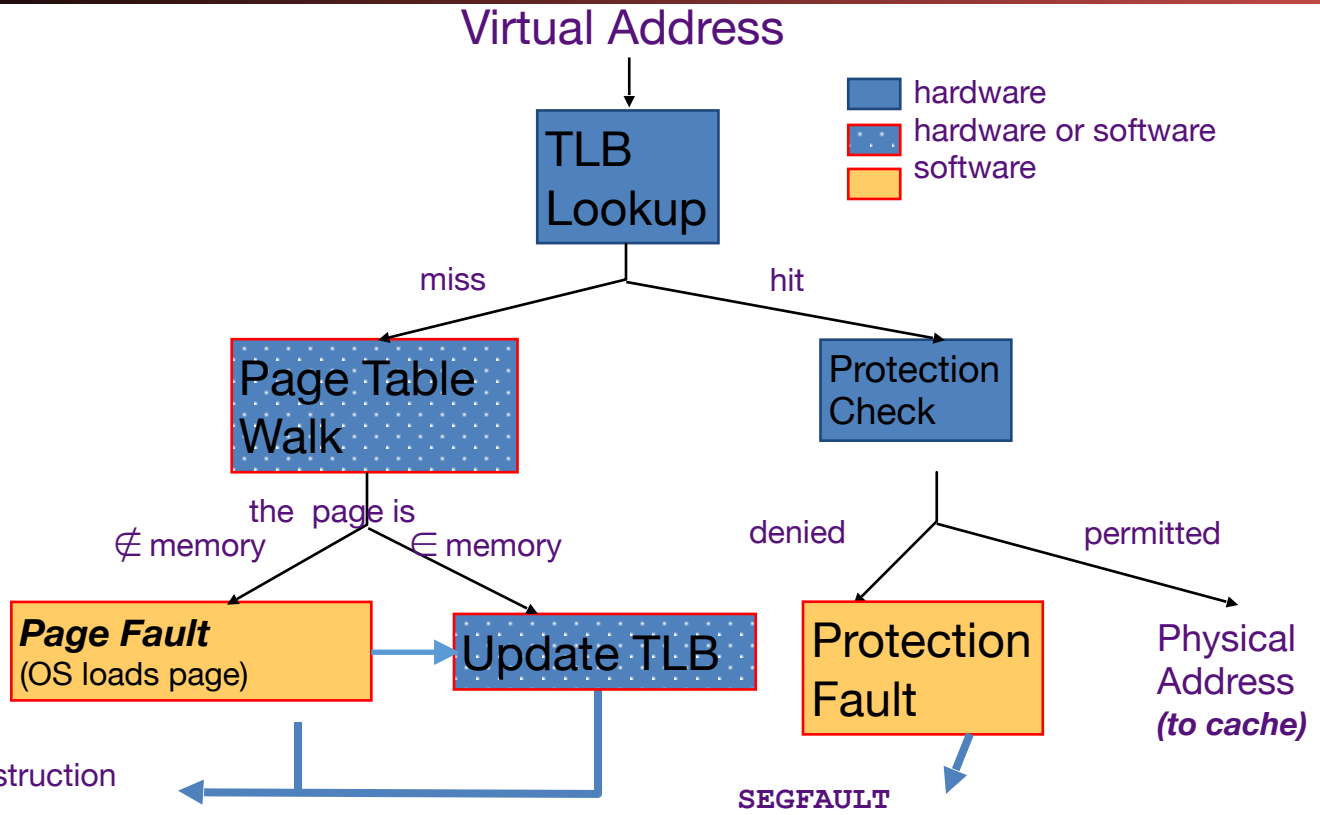
Page-Based Virtual-Memory Machine
(Hardware Page-Table Walk)

- Assumes page tables held in untranslated physical memory



Address Translation:

putting it all together



Summary: Virtual Memory Systems

Illusion of a large, private, uniform store

Protection & Privacy

several users, each with their private address space and one or more shared address spaces

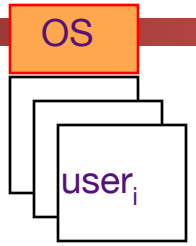
page table ≡ name space

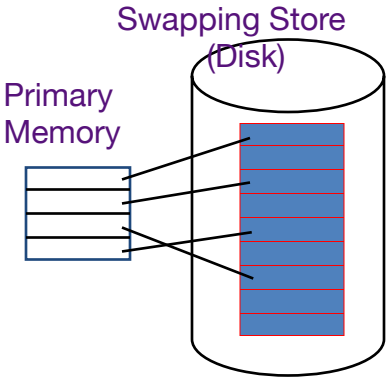
Demand Paging

Provides the ability to run programs larger than the primary memory

Hides differences in machine configurations

The price is address translation on each memory reference





Virtual Memory Paging As A Cache...

- Can think of virtual memory's demand paging aspect as a simple cache
- Your program is given the illusion of as much RAM as it wants...
  - But this breaks things unless it doesn't really want all of it!
- Idea: Virtual memory can copy "pages" between RAM and disk
  - The main memory thus acts as a cache for the disk...

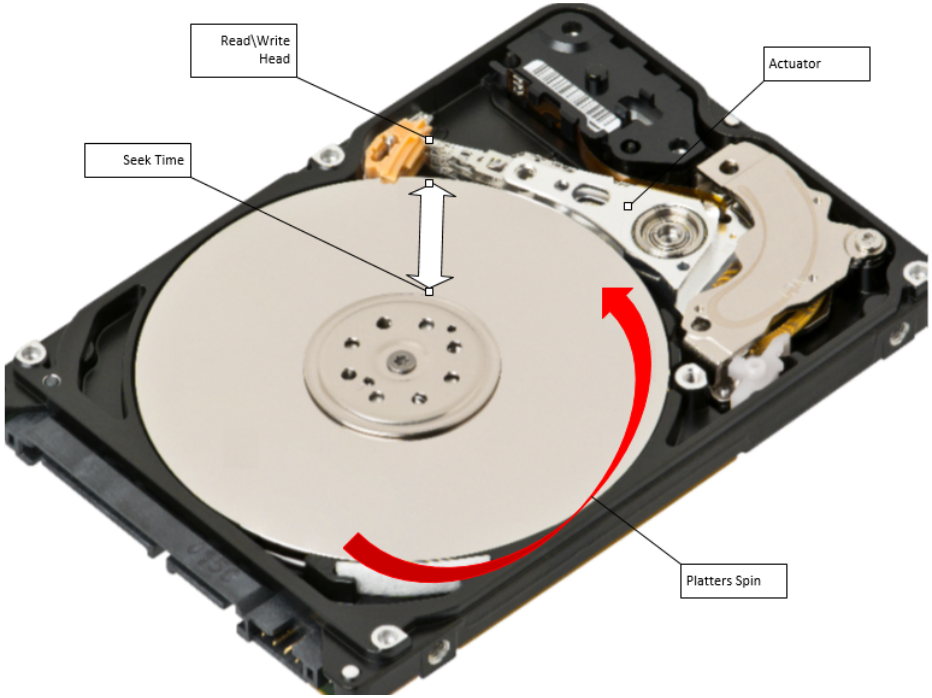
Virtual Memory's "Cache" Properties

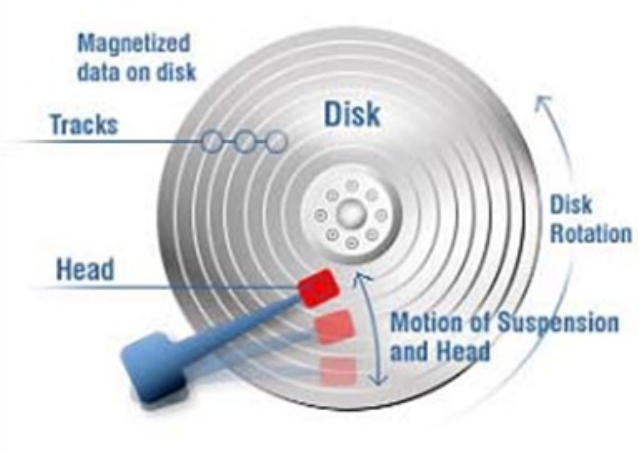
- Associativity: Effectively fully associative
- Replacement policy: Approximate LRU
- Block size: 4kB or more
  - The size of a page!
- Miss penalty...
  - Latency to get a block from disk: 1ms or so for an SSD...
    Or put in clock terms, a 1 GHz clock -> 1,000,000 clock cycles!
  - Or if you have a spinning disk: 10ms or so...
    So ***10,000,000 clock cycles***!
- We **really** don't want misses
  - Worth it to use sophisticated replacement policy

Implications

- As long as you don't really use full capacity, Virtual Memory is great...
  - Basically as long as your ***working set*** fits in physical memory, virtual memory is great at handling a little extra...
- But as soon as your working set exceeds physical memory, your performance falls of a cliff
  - The system starts ***thrashing***: Repeatedly needing to copy data to and from disk…
  - Similar to ***thrashing the cache*** when your working set exceeds cache capacity (but the cliff here is much steeper!)

Aside … Why are Disks So Slow?

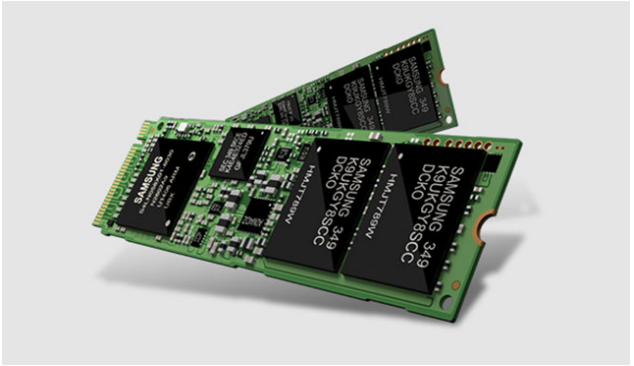




- 10,000 rpm (revolutions per minute)
- 6 ms per revolution
- Average random access time: 3 ms

What About SSD?

- Made with transistors -
  same technology as Flash memory
- Nothing mechanical that turns
- Like “Ginormous” DRAM
  - Except “nonvolatile” - holds contents when power is off
- Fast access to all locations, regardless of address
- Still much slower than register, caches, DRAM
  - Read/write blocks, not bytes
- Plus unusal requirements:
  - You can't erase single bits (set to 0), but only entire blocks
  - So to update a block, you copy everything to a new location that was erased with all 0



VM Tricks:
Copy-On-Write Duplication

- You split a process and now have two copies
  - The classic `fork()` operation
- Just copy the page table and registers...
  - And then mark both the original and copy's memory as ***read-only***!
- Every-time either process wants to write a page...
  - It traps to the protection fault handler...
  - Which copies the page
  - And then updates both page-tables to allow writing
  - And then returns
- Now you only copy memory when you first write to it

More VM Tricks: Shared Memory Communication

- Program A and B exist in their own separate little worlds
  - And of course, they are not supposed to inadvertently interfere with each other...
- But what if they want to share information?
  - We could just write and read to disk...
    But that is slow...
- Hey, we have this cool virtual memory system...
  - Who says that the same physical page can't be pointed to multiple times!
  - Can save us memory when multiple processes want to use same dynamically linked library!

Even More Memory Tricks: Memory Mapped files...

- Conventional file reading is slow...
  - You're reading things a line at a time...
  - And keep asking the OS for data...
- Can be way more overhead than you need...
- What you commonly want:
  - "Just load the entire file into a contiguous block of memory"
- So why not get the VM system to do that?

Memory Mapped I/O

- Program traps to the operating system for the **`mmap`** sys call
  - "Hey, I just want to read this file"
- OS sets the page table entries to point to disk
  - Just into the particular file instead of a "swap file"
- OS returns a pointer to the start of that virtual memory
- And the program just happily reads away...
- When the program actually reads...
  - Generates a page fault exception to the OS which loads the page into memory
  - Which then retries the faulting instruction and its like the file is just in memory
- Most page tables also support a "dirty" bit...
  - So if we need to swap out that page, if its dirty write it out...
    But if not, just discard it... We can reload again from disk!