CS 261
Fall 2018

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Virtual Memory and Operating Systems

Topics

- Operating systems
- Address spaces
- Virtual memory
- Address translation
- Memory allocation

Lingering questions

- What happens when you call `malloc()`?
  - How exactly is memory allocated?
- What is the correspondence between addresses in machine code and physical memory cells?
  - Are Y86 operand addresses used by the hardware?
- *There's a gap here ...*
  - In early machines, there was no gap; the machine ran one program at a time and every program had complete control of the machine – there was no need for `malloc()`
  - Modern machines support multi-tasking, so this is not sufficient
  - What we need is some kind of system software to mediate between user programs and the hardware

Operating systems

- An operating system (OS) is systems software that provides essential / fundamental system services
  - Manages initialization (booting) and cleanup (shutdown)
  - Manages hardware/software interactions (I/O)
  - Manages running programs (scheduling)
  - Manages memory (virtual memory)
  - Manages data (file systems)
  - Manages external devices (drivers & interrupts)
  - Manages communication (networking)
  - Manages security (permissions)

Kernel

- The OS kernel is the core piece of software that has complete control over the system
  - Direct access to all hardware ("kernel mode")
    - All other software runs in user mode
  - Design philosophies: monolithic kernels vs. microkernels
    - Classic debate: Tanenbaum vs. Torvalds
  - Often designed to be small but extensible
    - Plugins are called drivers
  - Technically, "Linux" is a kernel
    - The operating system is "GNU/Linux"
    - Combination of Linux kernel and GNU userspace utilities

gnu

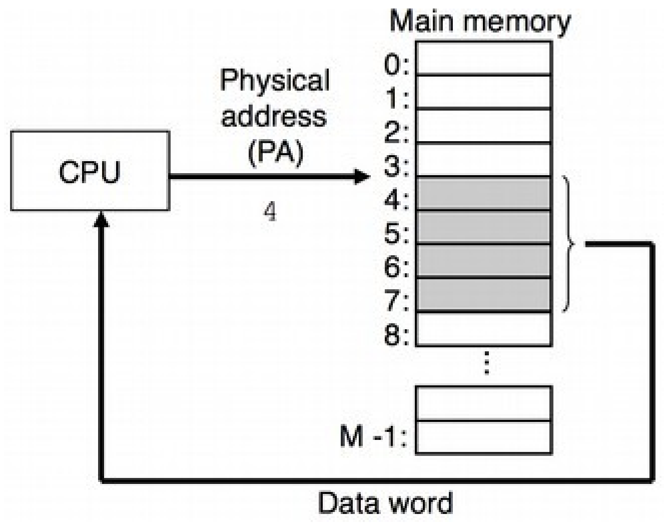
Tux

OS abstractions

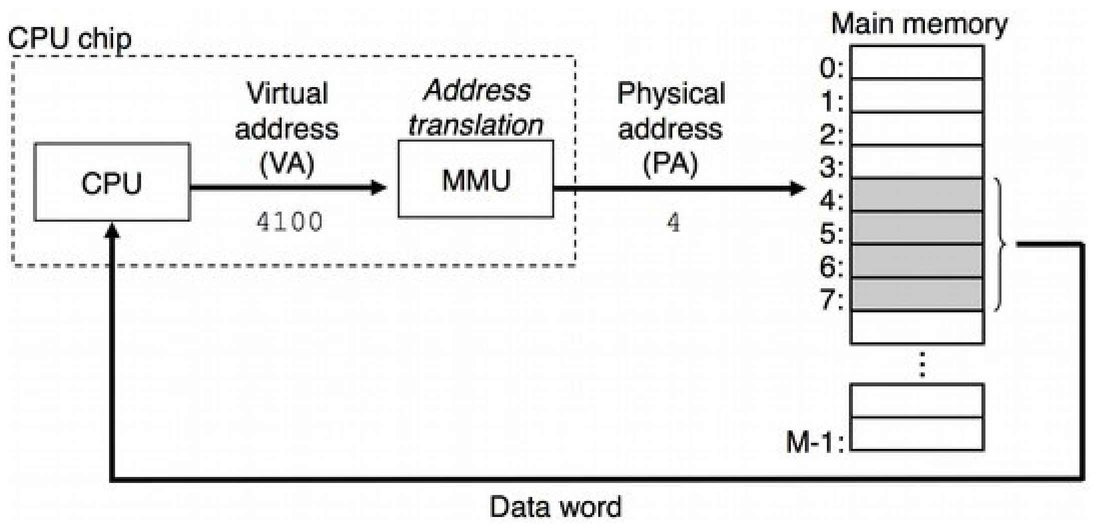
- The OS provides many useful abstractions so that programs don’t need to handle hardware details
  - CS 450 covers operating systems in detail
- In this class:
  - Virtual memory: logical view of memory hierarchy
  - Process: logical view of a program running on a CPU
  - Thread: logical flow of execution in a program
  - File: logical view of data on a disk

Virtual memory

- Kernel translates between virtual and physical addresses
- Goals:
  - Use main memory as a cache for disks
  - Provide every process with a uniform view of memory
  - Protect processes from interference



No virtual memory



With virtual memory

Address spaces

- An address space is an ordered set of non-negative integer addresses
  - Ex: { 0, 1, 2, 3, … , 499, 500 }
  - Linear address spaces don’t skip any addresses
  - Two address spaces: virtual and physical
  - Every byte has two addresses (virtual and physical)

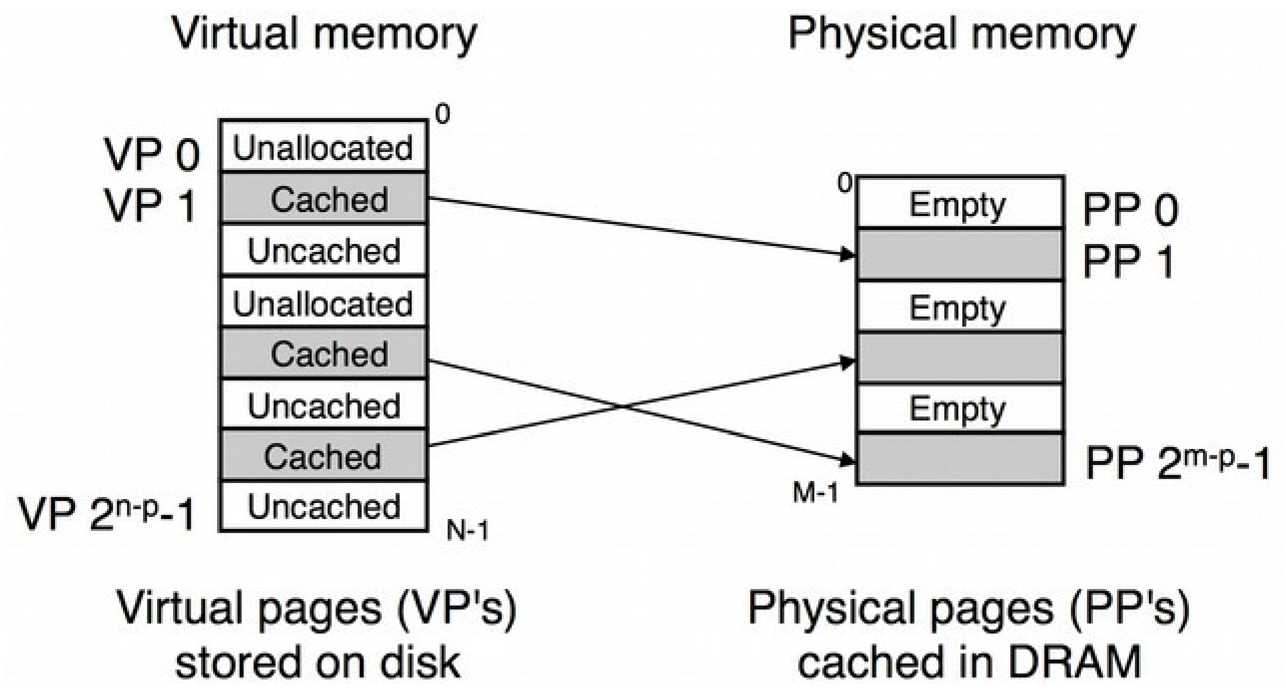
Example: Y86 programs have a virtual address space with addresses that range from `0x0` to `0x1000`, which is large enough to store 4K bytes

Virtual memory

- Fixed-sized memory partitioning
  - Virtual address space into virtual pages
  - Physical address space into physical pages (or frames)
  - Pages are usually relatively large (4 KB to 2 MB)
- Virtual memory uses RAM as a cache for pages
  - Process uses consistent virtual / logical addresses
  - OS translates these to physical addresses as necessary
    - Use a table for fast lookups!
  - We will assume hardware handles L1, L2, & L3 SRAM caches

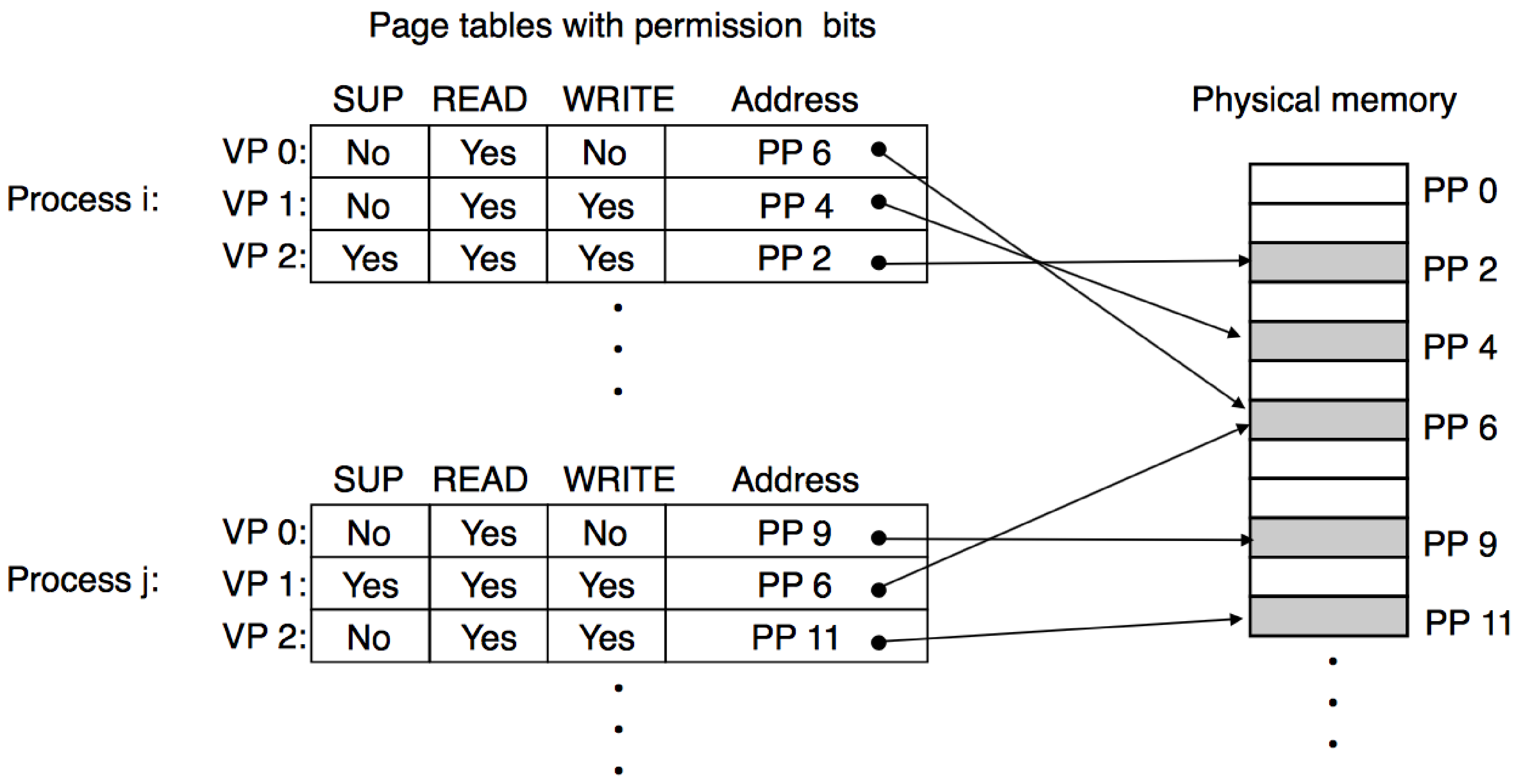
Virtual memory

- Virtual page groups:
  - Unallocated: uninitialized pages
  - Cached: allocated pages currently cached in physical memory
  - Uncached: allocated pages not currently cached



Virtual memory

- VM provides address space separation and page-level protection



Page tables with permission bits

Process i:

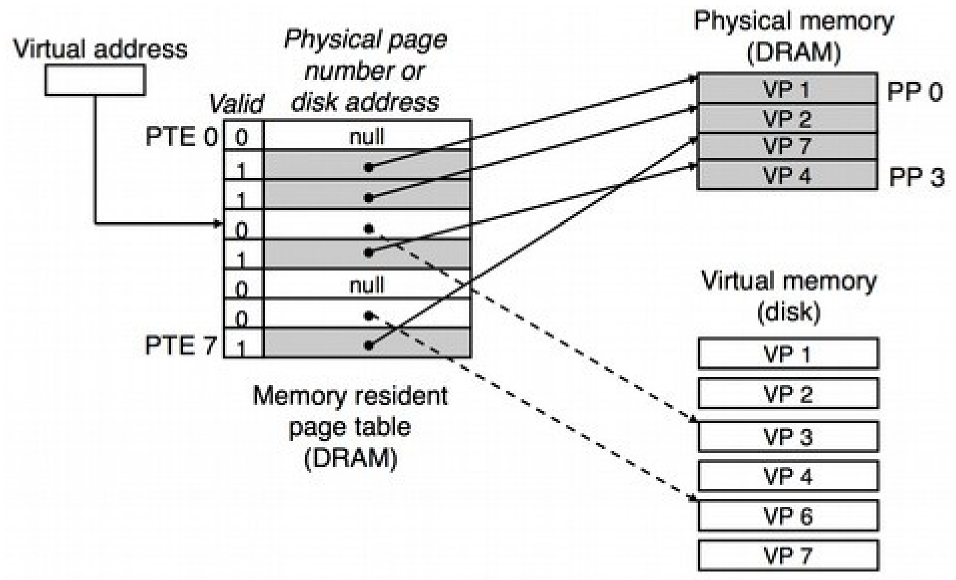
	SUP	READ	WRITE	Address
VP 0:	No	Yes	No	PP 6
VP 1:	No	Yes	Yes	PP 4
VP 2:	Yes	Yes	Yes	PP 2

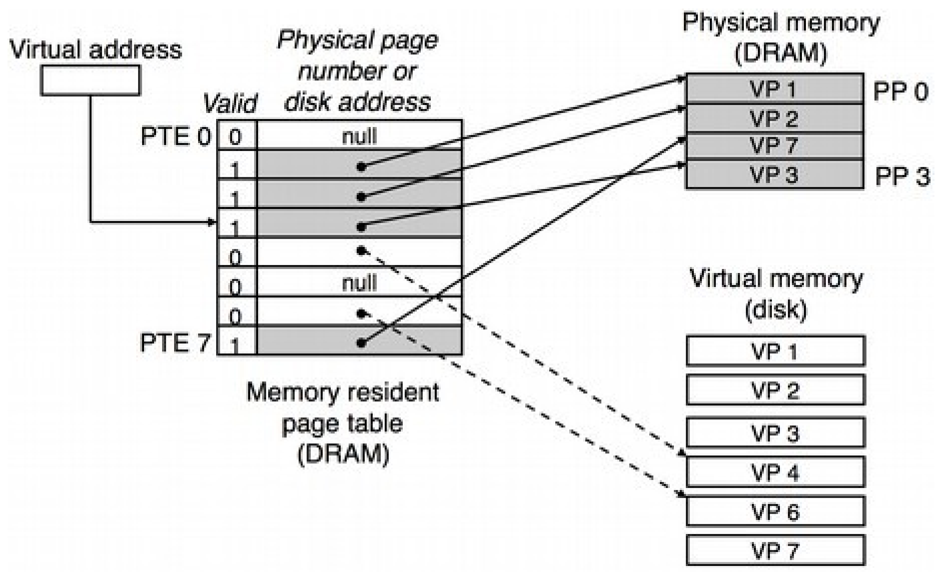
Process j:

	SUP	READ	WRITE	Address
VP 0:	No	Yes	No	PP 9
VP 1:	Yes	Yes	Yes	PP 6
VP 2:	No	Yes	Yes	PP 11

Page tables

- Page table: OS data structure for page lookups (array of page table entries)
- DRAM cache misses (called page faults) are very expensive
  - Disks are MUCH slower than DRAM
  - Transferring pages back and forth is called paging or swapping

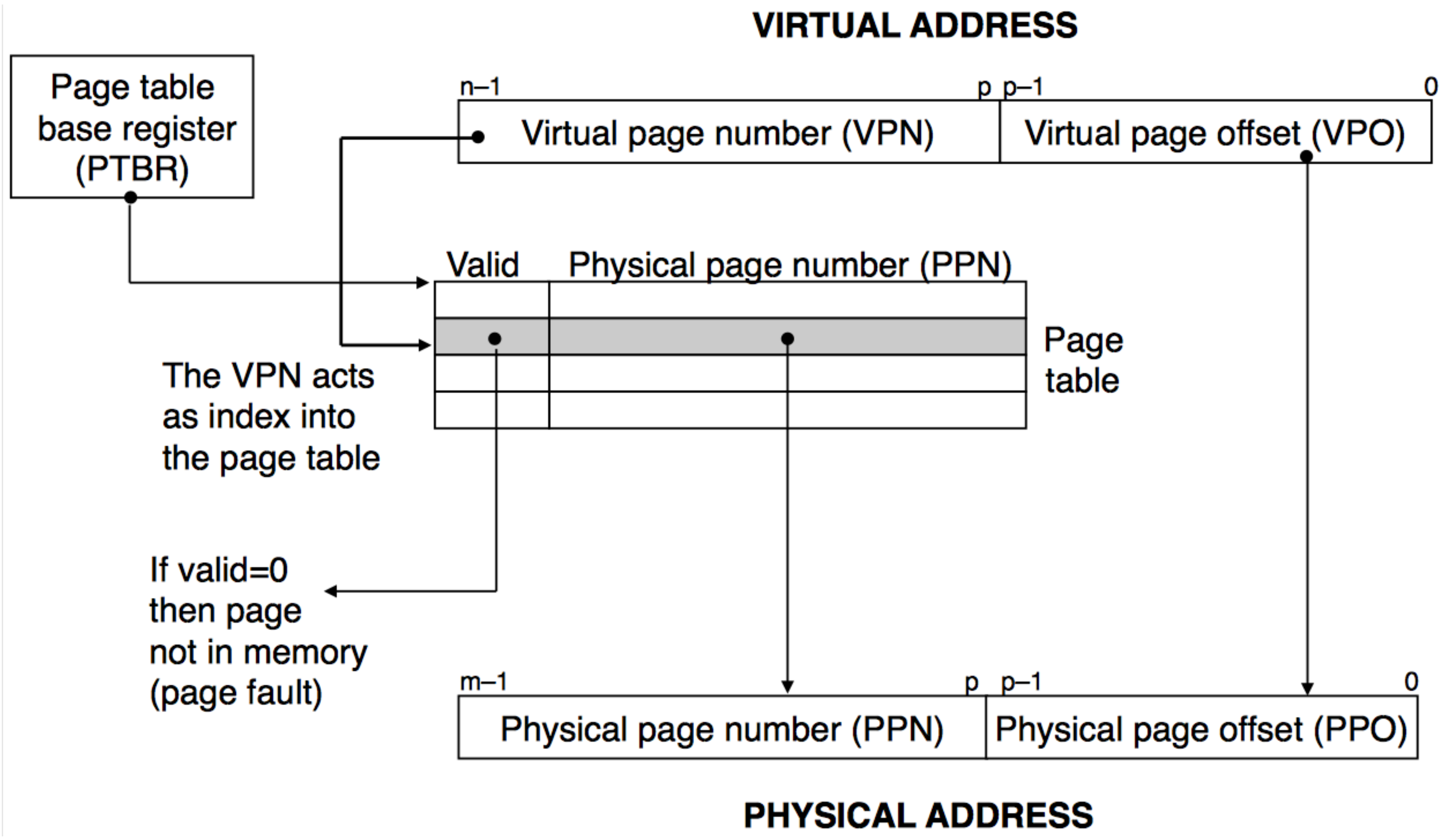




before page fault on VP 3 **after page fault on VP 3**

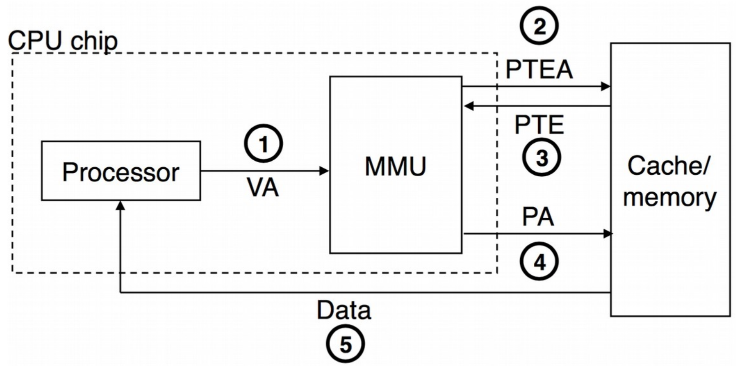
Address translation

- n-bit virtual address space => m-bit physical address space
- p-bit page offsets (page size is 2^p)

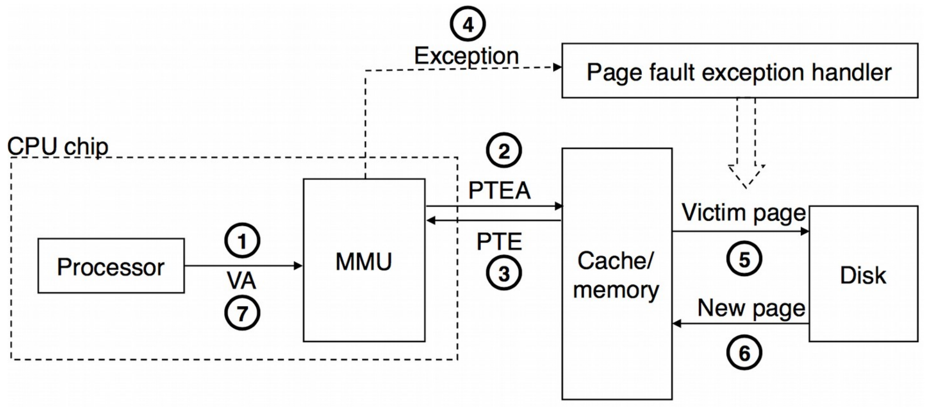

VIRTUAL ADDRESS
Page table base register (PTBR)
n–1
p
p–1
0
Virtual page number (VPN)
Virtual page offset (VPO)
Valid
Physical page number (PPN)
Page table
The VPN acts as index into the page table
If valid=0 then page not in memory (page fault)
m–1
p
p–1
0
Physical page number (PPN)
Physical page offset (PPO)
PHYSICAL ADDRESS

Address translation

- Memory management unit (MMU)
  - On-chip CPU component for address translation
  - Goal: perform translation as quickly as possible



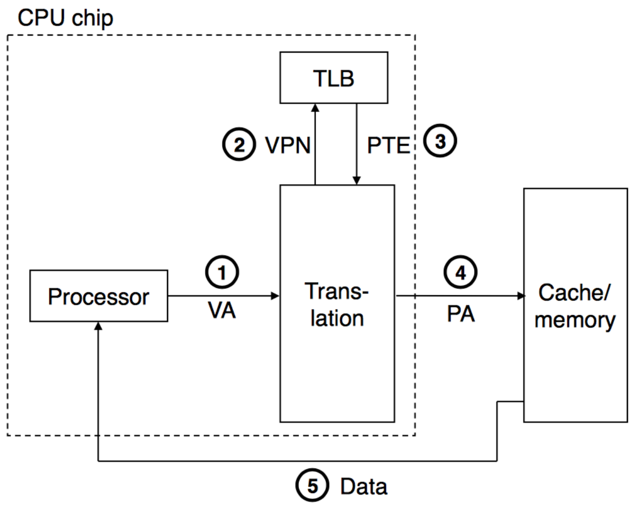
Page hit



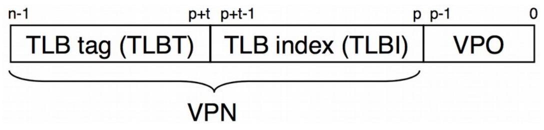
Page miss

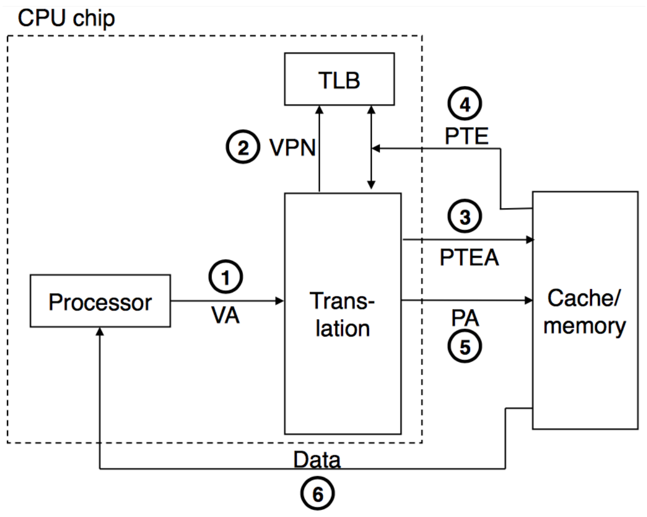
Address translation

- Translation lookaside buffer (TLB)
  - Small cache of page table entries (PTEs) in MMUs
  - Provides faster address translations (in most cases)
  - *It's caches all the way down …*



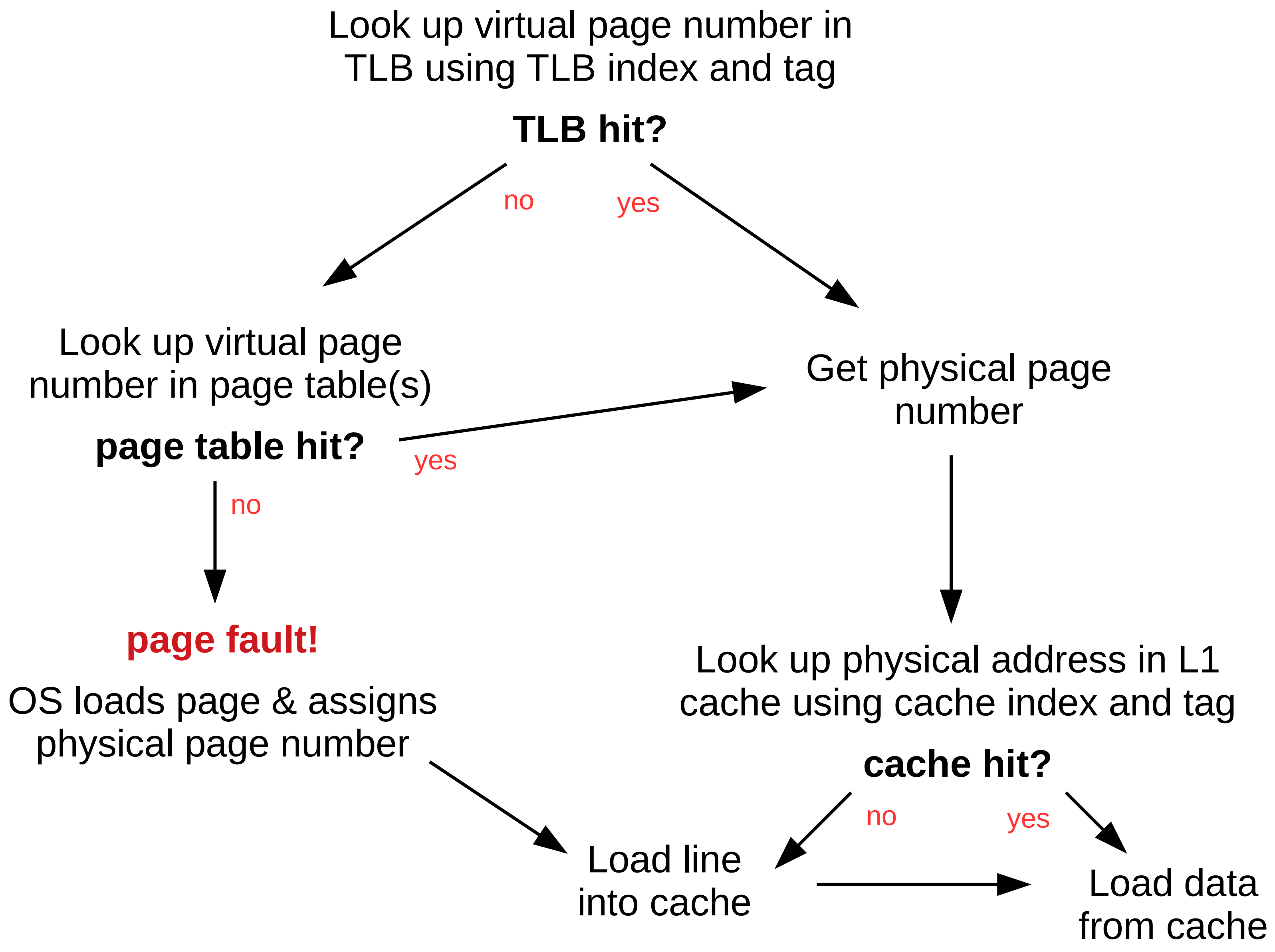
Page hit





Page miss

Address translation w/ L1 cache


Look up virtual page number in TLB using TLB index and tag
TLB hit?
no
yes
Look up virtual page number in page table(s)
page table hit?
yes
no
Get physical page number
page fault!
OS loads page & assigns physical page number
Look up physical address in L1 cache using cache index and tag
cache hit?
no
yes
Load line into cache
Load data from cache

Address translation w/ L1 cache

1) Convert hex virtual address to binary representation
   - Fill in virtual address bits from RIGHT TO LEFT (extra is zeros on left)
2) Extract page number (VPN) and page offset (VPO) from virtual address
3) Extract TLB index and TLB tag from virtual address
4) In TLB, look up TLB index and tag to find PPN
   - If not valid: TLB miss!
5) If not in TLB look up VPN in page table to find PPN
   - If not in page table: page fault!
6) Assemble physical address from page number (PPN) and page offset (PPO)
   - Physical page offset (PPO) is the same as the virtual page offset (VPO)
7) Extract cache index and cache tag from physical address
8) In cache, look up cache index and tag
   - If not found, cache miss!
   - If found, return data

Virtual memory caveats

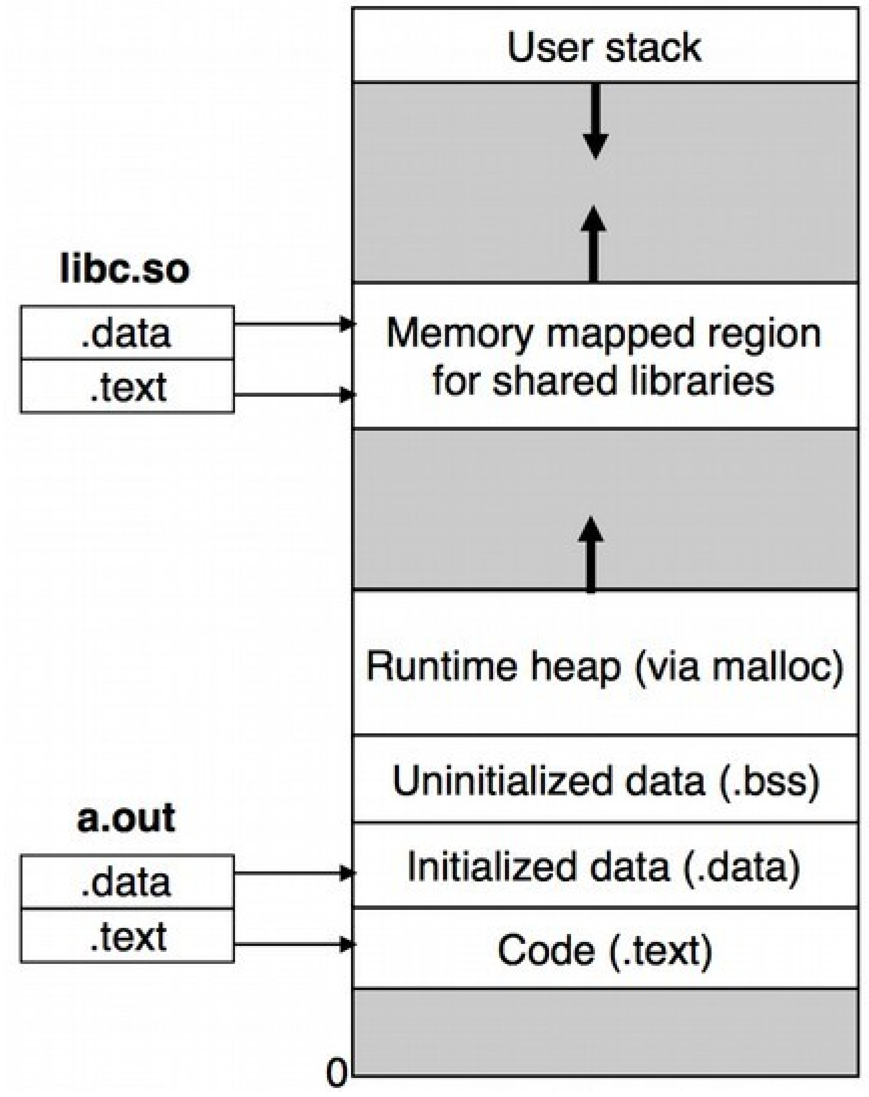
- Virtual memory works well **if a program has good locality**
  - Especially temporal locality
  - This is a compelling reason to design for good locality
- Virtual memory works well **if a program has a working set that fits in main memory**
  - If this is not true, the system may need to continuously swap pages in and out
  - This is called thrashing, and is a significant cause of poor program performance
  - Can be detected by profilers (via counting page faults)

Memory management

- Operating system provides memory allocation service
  - `mmap` system call (`malloc` uses this)
  - Creates virtual memory allocation
  - Private regions: changes are only seen by owner
    - Private, variable-sized region called the heap
  - Shared regions: changes are seen by all processes
    - Usually between heap and stack
    - Multiple virtual addresses map to the same physical address
    - Changes are seen by all processes
    - Usually a read-only region for shared library code

Process address spaces

Kernel uses higher addresses


User stack
libc.so
.data
.text
Memory mapped region for shared libraries
Runtime heap (via malloc)
Uninitialized data (.bss)
a.out
.data
.text
Initialized data (.data)
Code (.text)
0

Typical Linux process address space

Process address spaces

- OSes maintain a separate page table for every process
  - Provides program **linking consistency**
    - E.g., code always begins at 0x400000
  - Simplifies **efficient loading**
    - Don't actually load data from disk until needed (more efficient than P2!)
  - Streamlines **library sharing**
    - Keep one physical copy with multiple virtual mappings
  - Simplifies **memory allocation**
    - `malloc()` doesn't need to find contiguous physical memory
  - Improves **security**
    - Processes can't see/edit each others' address spaces

Memory allocation

- Explicit memory allocation
  - Programmer must allocate and deallocate manually
  - Example: malloc and free in C
- Implicit memory allocation
  - Programmers allocate manually, then a garbage collector determines when memory can be de-allocated safely
  - Approaches: reference counting and mark & sweep

Our final module

- For the rest of the semester, we will continue discussing operating systems principles
  - Layers of abstraction that simplify development
  - Theme: *systems software is a foundation*
  - If you like this material, plan on taking **CS 450**