CS 261
Fall 2016

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Virtual Memory

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?

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  - 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

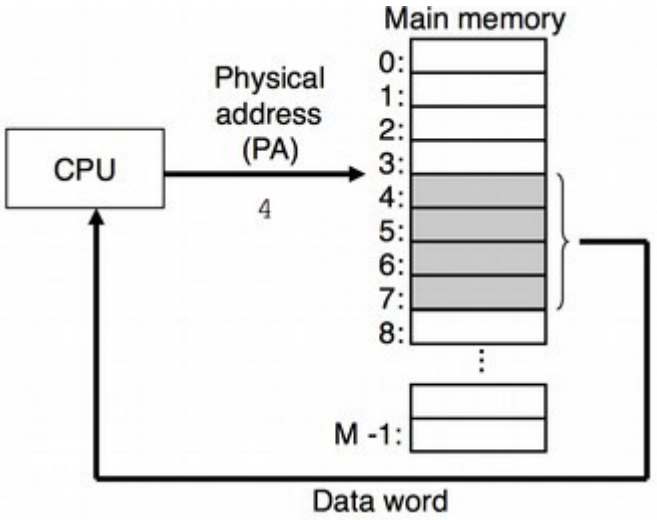
Tux

OS abstractions

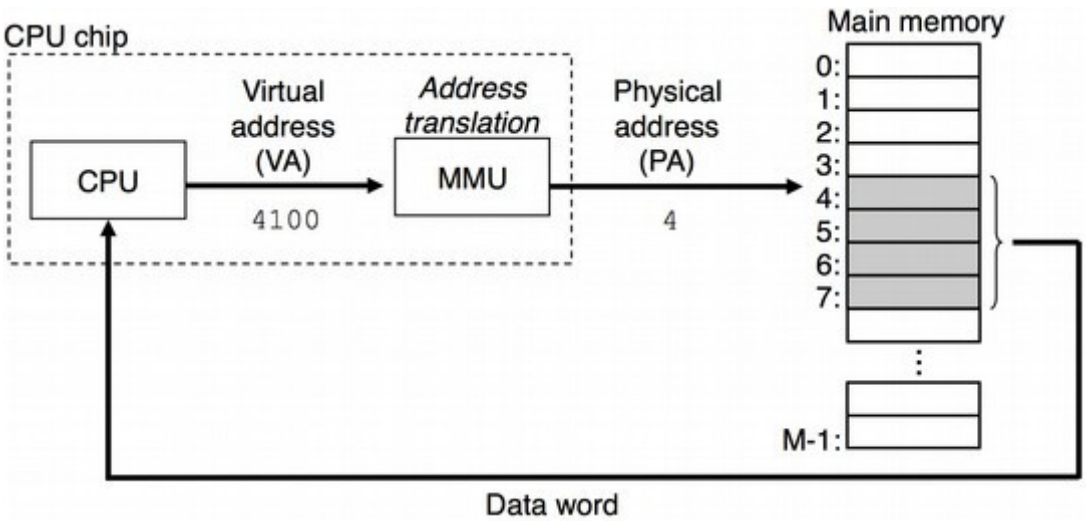
- The OS provides many useful abstractions so that programs don't need to handle hardware details
  - CS 450 covers operating systems in detail
- In this class:
  - Virtual memory: logical view of memory hierarchy
  - Process: logical view of a program running on a CPU
  - Thread: logical flow of execution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

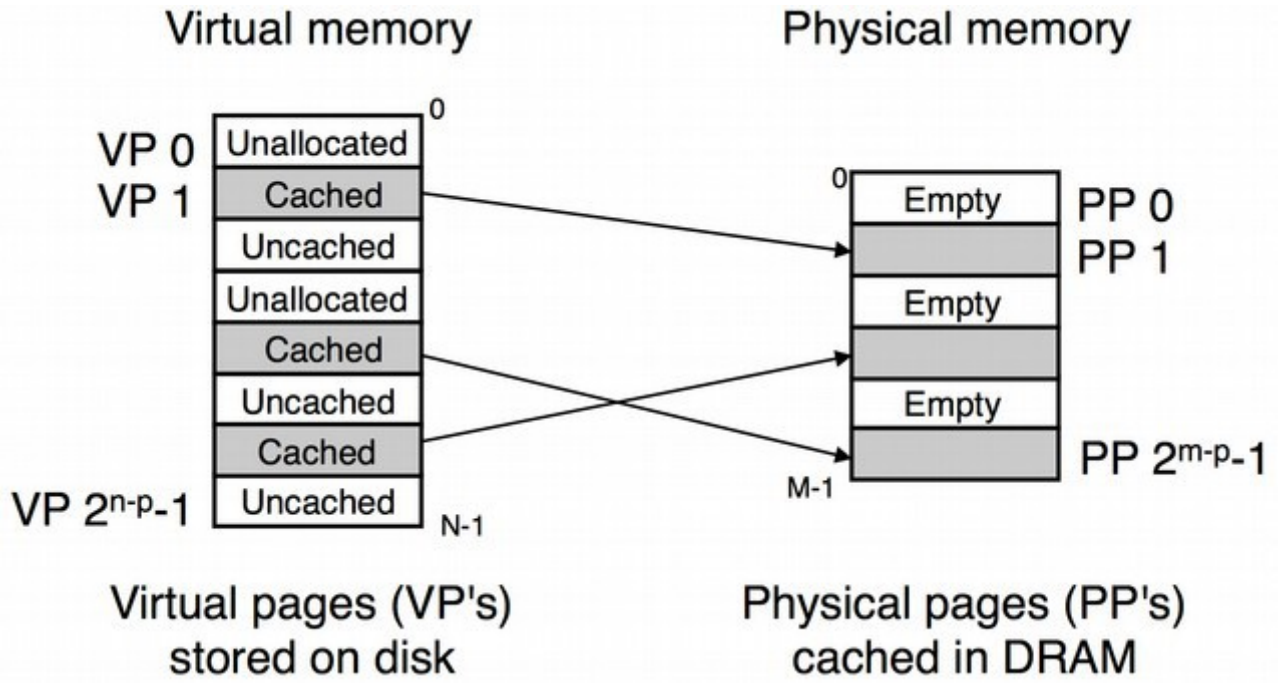
Example: Y86 programs have a virtual address space with addresses that range from `0x0` to `0x1000`, which is large enough to store 4K bytes

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

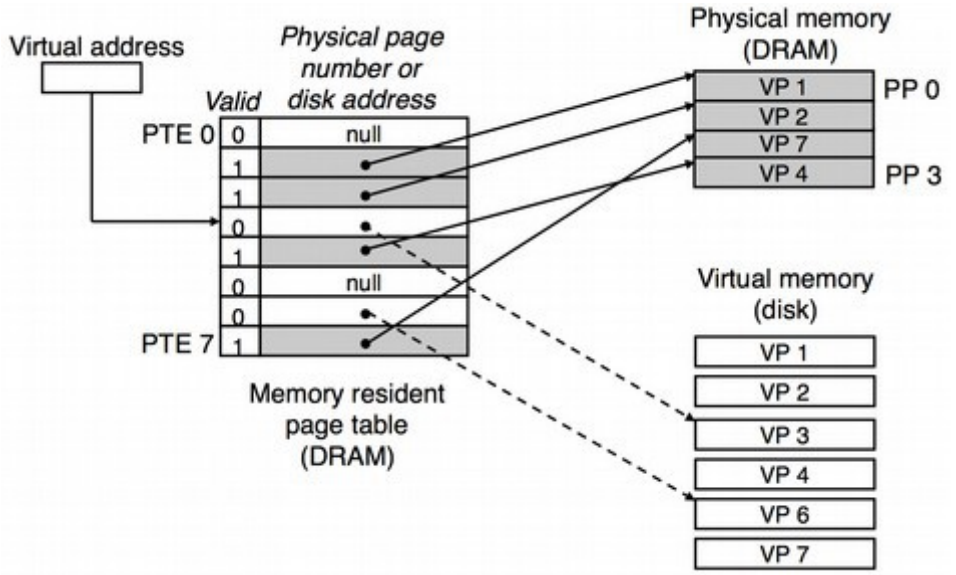
Virtual memory

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

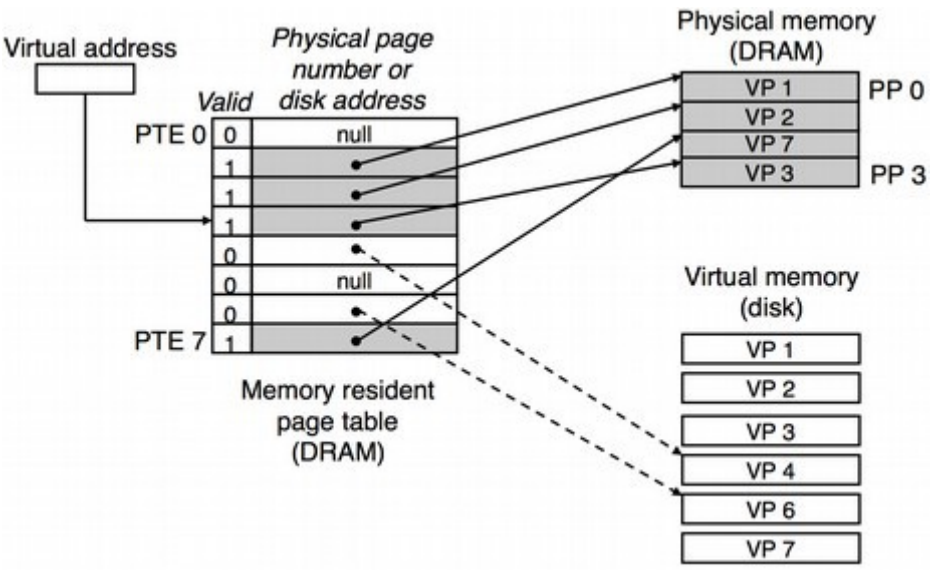


Page tables

- 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

- Memory management unit (MMU)
  - On-chip CPU component for address translation
  - Goal: perform translation as quickly as possible
- Translation lookaside buffer (TLB)
  - Small cache of PTEs in MMUs
  - Provides faster address translations (in most cases)
  - *It's caches all the way down …*

Virtual memory caveats

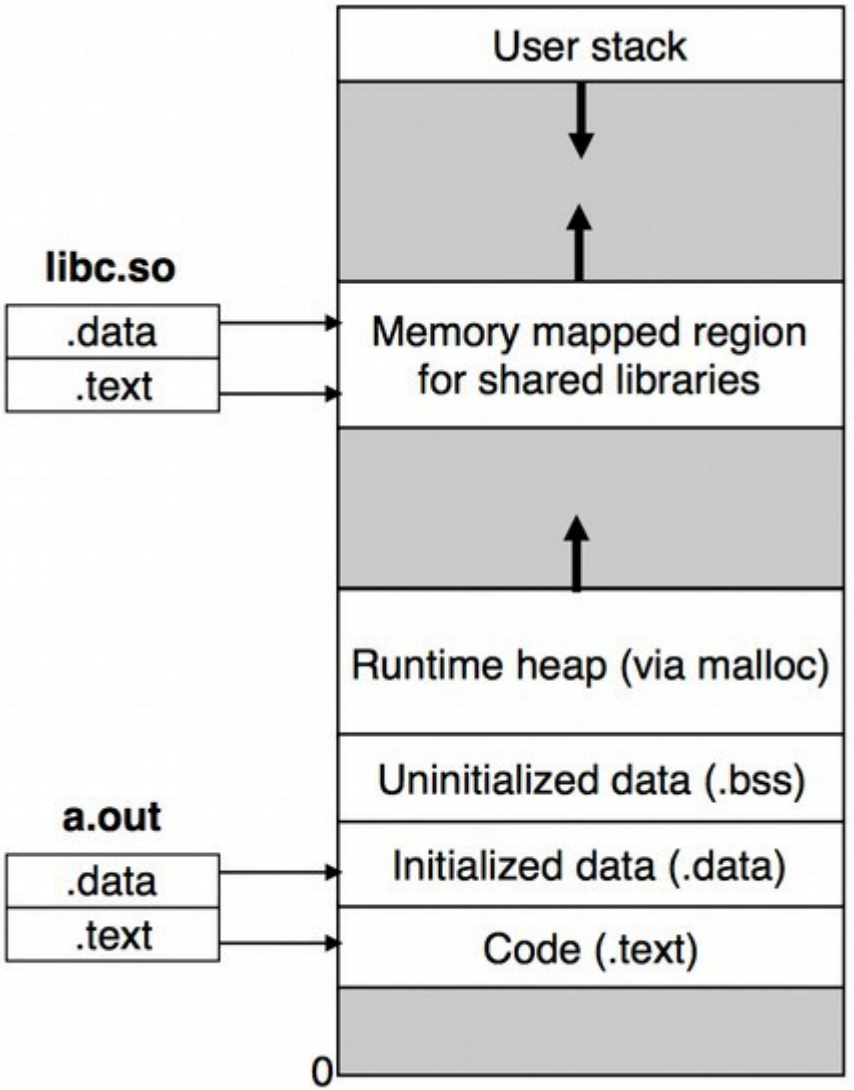
- Virtual memory works well **if a program has good locality**
  - Especially temporal locality
  - This is a compelling reason to design for good locality
- Virtual memory works well **if a program has a working set that fits in main memory**
  - If this is not true, the system may need to continuously 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



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

After the break

- We will continue discussing OS principles
  - Layers of abstraction that simplify development
  - Theme: *systems software is a foundation*
  - If you like this material, plan on taking **CS 450**