Announcements

- Midterm: this Friday, July 18th, in class
  - closed book/notes; covers through VM, Project 2
  - local SCPD: come to class
  - remote (e.g. Florida): posted on cs140.stanford.edu
- Testing today: remote questions via google talk
  - cs140sum08@gmail.com google.com/talk
- Poll: Project help session
- Today: Virtual Memory (major OS win, project #3)
- But first, a fun demo!
  - Christopher Anderson, pintos on "real" hardware

Lecture overview

- Virtual memory
  - Maps virtual addresses to physical pages & disk blocks
  - Like processes, a killer OS abstraction: ~40 years old.
  - Today: what it's good for, how it evolved,
  - how to implement it
- Readings:
  - Silberschatz 7th ed. Chapter 8
  - Silberschatz 6th ed. Chapter 9

Introduction: Virtual Memory

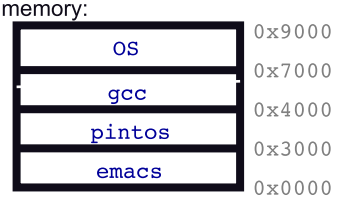
- Simple mapping of virtual (program) addresses to physical (DRAM) addresses

Virtual address	address
2000	0
1000	1000
9000	2000

- result: 2030->0030, 1248->1248, 90FF->20FF
- **Why?** What problem is this trying to solve?

Problem: we want processes to co-exist

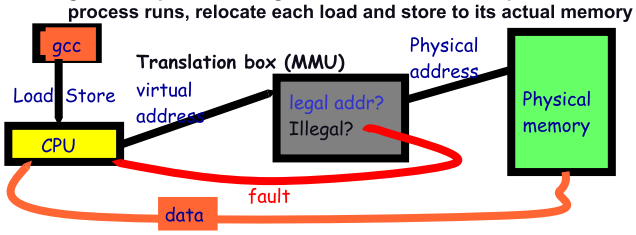
- Consider a primitive system running three processes in physical memory:



What happens if pintos needs to expand?
If emacs needs more memory than is on the machine??
If pintos has an error and writes to address 0x7100?
When does gcc have to know it will run at 0x4000?
What if emacs isn't using its memory?

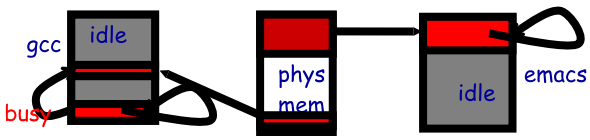
Issues in sharing physical memory

- **Protection**: errors in one process should only affect it
  - record process's legal address range(s), check that each load and store only references a legal address
- **Transparency**: a process should be able to run regardless of its location in or the size of physical memory
  - give each process a large, static "fake" address space; as process runs, relocate each load and store to its actual memory



Win: We (can) get both flexibility and speed!

- VM = indirection between apps and actual memory
  - Flexibility: process can be moved in memory as it executes, run partially in memory and on disk, …
  - Simplicity: drastically simplifies applications
  - Efficiency: most of a process's memory will be idle (80/20 rule).



Therefore, use fact that we can remap addresses to let other processes use idle parts. Makes memory seem much larger!
Similar to CPU virtualization: when process not using CPU, switch. When not using page, switch.

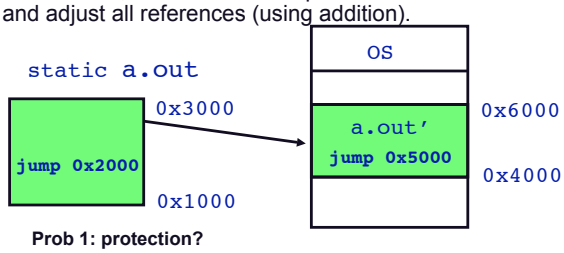
- Challenge: VM = extra layer. Careless = molasses slow.

Our main questions

- How is protection enforced?
- How are processes relocated?
- How is memory partitioned?

Simple idea 1: load-time linking

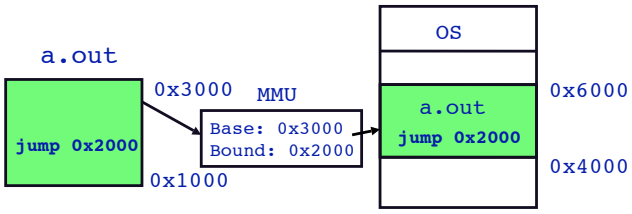
- Link as usual, but keep the list of references
- At load time, determine where process will reside in memory and adjust all references (using addition).



Prob 1: protection?
Prob 2: how to move in memory? (Consider: data pointers)
Prob 3: more than one segment?

Simple idea 2: base + bound register

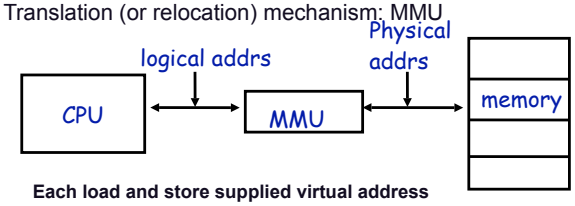
- Use hardware to solve problem: on every load and store
  relocation: physical addr = virtual addr + base register
  protection: check that address falls in [base, base+bound)



When process runs, base register = 0x3000, bounds register = 0x2000. Jump addr = 0x2000 + 0x3000 = 0x5000
How to move process in memory? What happens on process switch?

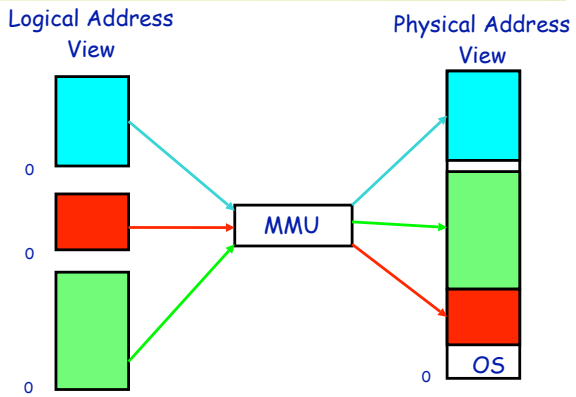
Some terminology

- Definitions:
  program addresses are called logical or virtual addresses
  actual addresses are called physical or real addresses
- Translation (or relocation) mechanism: MMU



Each load and store supplied virtual address translated to real address by MMU (memory management unit)
All other mechanisms for dynamic relocation use a similar organization. All lead to multiple (per process) views of memory, called address spaces

Address spaces

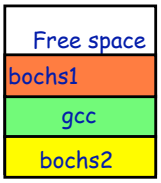


Protection mechanics

- How to prevent users from changing base/bound register?
- General mechanism: privileged instructions
  OS runs in privileged mode (set a bit in process status word)
  application processes run in user mode
  Certain instructions can only be issued in privileged mode (checked by hardware: illegal instruction trap)
- How to switch? ("usually" how its done, many variations)
  User->OS: application issues a system call, hardware then:
    sets program counter to known address (can't trust user to)
    updates process status word
    and disables relocation (OS has different address space)
  OS->User:
    OS sets base and bounds register (recall: relocation off)
    issues an instruction that simultaneously (1) sets pc to given address, (2) turns relocation back on, and (3) lowers privilege.

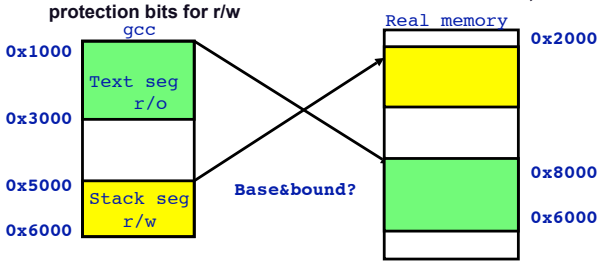
Base & bound trade-offs

- Pro:
  - **cheap in terms of hardware: only two registers**
  - **cheap in terms of cycles: do add and compare in parallel**
  - **examples: Cray-1**
- Con: only one segment
  - **prob 1: growing processes.**
  - **How to expand gcc?**
  - **prob 2: how to share code and data??**
  - **how can bochs copies share code?**
  - **prob 3: how to separate code and data?**
- A solution: multiple segments
  - "segmentation"



Segmentation

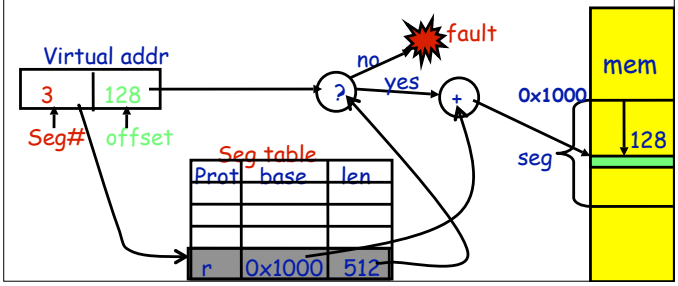
- Big idea: let processes have many base&bounds ranges
  - **Process address space built from multiple "segments". Each has its own base&bound values. Since we can now share, add protection bits for r/w**



  - **Big result: Lets processes be split across memory!**
- Problem: how to specify what segment address refers to?

Segmentation Mechanics

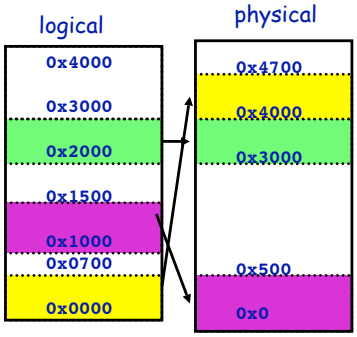
- Each process has an array of its segments (segment table)
- Each memory reference indicates a segment and offset:
  - **Top bits of addr select seg, low bits select offset (PDP-10)**
  - **Seg select by instruction, or operand (pc selects text)**



Segmentation example

- **2-bit segment number (1st digit), 12 bit offset (last 3)**

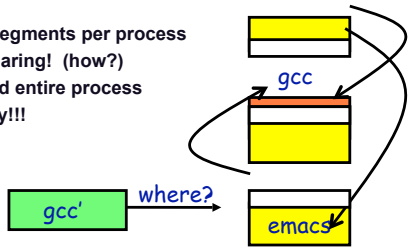
Seg	base	bounds	rw
0	0x4000	0x6ff	10
1	0x0000	0x4ff	11
2	0x3000	0xfff	11
3			00



- **where is 0x0240?**
- **0x1108?**
- **0x265c?**
- **0x3002?**
- **0x1600?**

Segmentation Tradeoffs

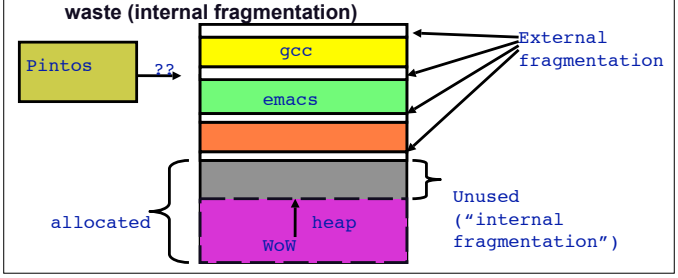
- Pro:
  - **Multiple segments per process**
  - **Allows sharing! (how?)**
  - **Don't need entire process in memory!!!**



- Con:
  - **Extra layer of translation**
    - **speed = hardware support**
  - **More subtle: an "n" byte segment requires n *contiguous* bytes of physical memory. (why?) Makes fragmentation a real problem.**

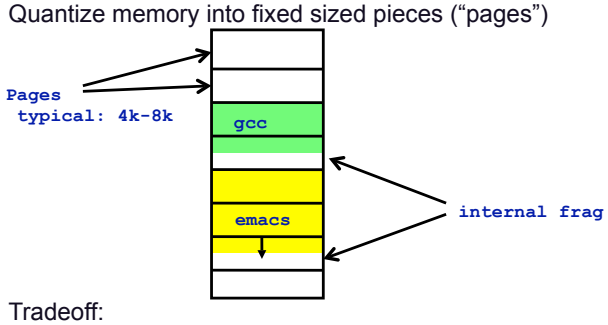
Fragmentation

- "The inability to use memory that is free".
- Over time:
  - **variable-sized pieces = many small holes (external frag.)**
  - **fixed-sized pieces = no external holes, but force internal waste (internal fragmentation)**



Page based virtual memory

- Quantize memory into fixed sized pieces ("pages")



- Tradeoff:
  - pro: eliminates external fragmentation
  - pro: simplifies allocation, free and swapping

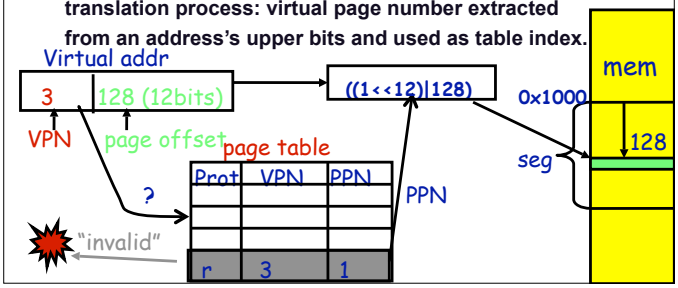
Page-based mechanics

memory is divided into chunks of the same size (pages)

each process has a table ("page table") that maps virtual page numbers to corresponding physical page numbers

PT entry also includes protection bits (r, w, valid)

translation process: virtual page number extracted from an address's upper bits and used as table index.



Page-based translation example

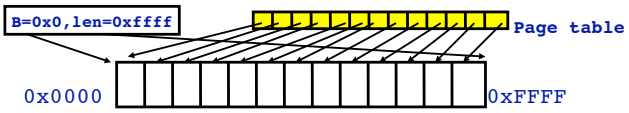
- MIPS R2000: 32 bit addr. space, 20-bit VPN and 12-bit offset:

Page number	page offset
20 bits	12 bits

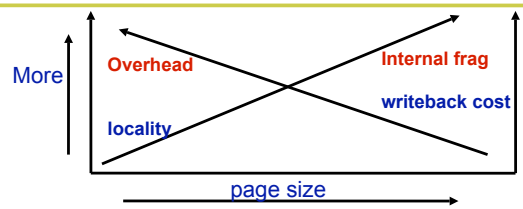
```
/* partial page table entry */
struct pte { unsigned ppn:20, valid:1, writeable:1…; };

/* given virtual address and r/w indication, return physical
   addr. Uses a simple "direct" page table (I.e., an array) with
   (conceptually) an entry for every possible vpn */
unsigned xlate(unsigned va, int wr) {
        struct pte *pte = &page_table[va >> 12];
        if(!pte->valid || (wr && !pte->writeable))
                raise address_fault;
        return (pte->ppn << 12) | (va & 0xfff);   }
```

Page tables vs. segmentation

- Good:
  - Easy to allocate: keep a free list of available pages and grab the first one
  - easy to swap since everything is the same size and since pages usually same size as disk blocks
- Bad:
  - size: PTs need one entry for each page-sized unit of virtual memory, vs one entry for every contiguous range.
    - e.g., given a range [0x0000, 0xffff] need one segment descriptor but, assuming 4K pages, 16 page table entries



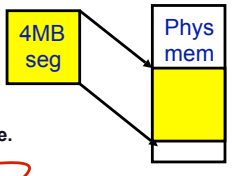
Page size tradeoffs



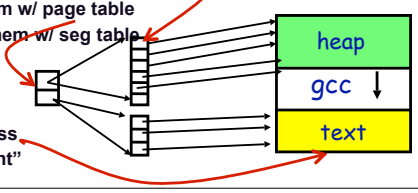
- Small page = large PT overhead:
  - 32-bit address space with 1K pages. How big PT?
- Large page = internal frag. (doesn't match info. size)
  - most Unix processes have few segments (code, data, stack, heap) so not much of a problem
  - (except for page table memory itself…)

Paging + segmentation: best of both?

- Dual problems:
  - Paged VM: simple page table = lots of storage
  - Segmentation: All bytes in segment must map to contiguous set of storage locations. Makes paging problematic: all of seg in mem or none.



- Idea: use paging + segmentation!
  - Map program mem w/ page table
  - Map page table mem w/ seg table



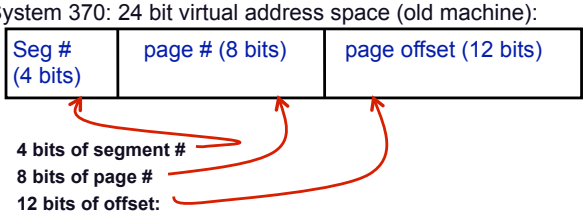
Call virtual address chunk a "segment"

Paging + segmentation tradeoffs

- Page-based virtual memory lets segments come from non-contiguous memory
  - **makes allocation flexible**
  - **portion of segment can be on disk!**
- Segmentation = way to keep page table space manageable
  - **Page tables correspond to logical units (code, stack). Often relatively large.**
  - **(But what happens if page tables really large?)**
- Going from paging to P+S is like going from single segment to multiple segments, except at a higher level.
  - **Instead of having a single page table, have many page tables with base and bound for each.**

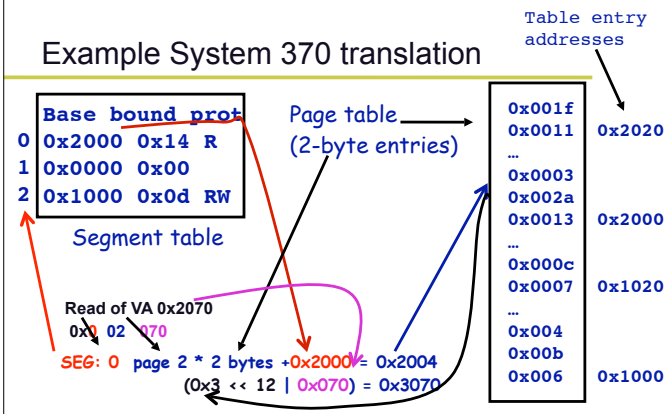
Example: IBM System 370

- System 370: 24 bit virtual address space (old machine):



- The mappings:
  - **Segment table: maps segment number to physical address & size of that segment's page table.**
  - **Page table maps virtual page to 12 bit physical page #, which is concatenated to the 12 bit offset to get a 24 bit address**

Example System 370 translation



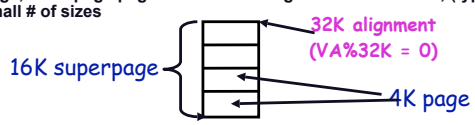
0x202016 read? 0x104c84 read?

P+S discussion

- If segment not used then no need to have page table for it
- Can share at two levels:
  - **single page or single segment (whole page table)**
- Pages eliminate external fragmentation and make it possible for segments to grow, page without shuffling
- If page size small compared to most fragments then internal fragmentation not too bad (.5 of page per seg)
- User not given write access to page tables
  - **read access can be quite useful (e.g., to let garbage collectors see dirty bits), but only experimental OSes provide this…**
- If translation tables kept in main memory, overhead high
  - **1 or 2 overhead reference for every real ref (I.e., mem op)**
- Other example systems: VAX, Multics, x86, …

Who won?

- Simplicity = good (and fast): Most new architectures have gone with pages
  - **Examples: MIPS, SPARC, Alpha.**
  - And many old architectures have added paging even if they started with segmentation!
- But: to efficiently map large regions (both in page table and to save TLB entries) many new machines backsliding into "super pages"
  - **large, multi-page pages: have strict alignment restrictions; (typically) small # of sizes**



inflexibility = speed, but handles 80% of the cases we want (e.g. that 8 MB frame buffer!)

Virtual memory summary

- VM gives
  - **flexibility + protection + speed (if clever)**
- Base & bounds = simple relocation + protection
  - **Pro: simple, fast**
  - **Con: inflexible**
- Segmentation = generalization of base & bounds.
  - **Pro: Gives more flexible sharing and space usage**
  - **Con: segments need contiguous physical memory ranges**
- Paging: instead of using extents, use fixed sized units
  - **Quantize memory into pages & use (page) table to map virtual to physical pages**