• Lab 1 due Friday 12pm (noon)
• We give short extensions to groups that run into trouble. But email us:
  - How much is done and left?
  - How much longer do you need?
• Attend section Friday at 1pm to learn about lab 2
• Came out of work in late 1960s by Peter Denning (lower right)
  - Established working set model
  - Led directly to virtual memory
Want processes to co-exist

<table>
<thead>
<tr>
<th>Process</th>
<th>Memory Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>0x9000</td>
</tr>
<tr>
<td>gcc</td>
<td>0x7000</td>
</tr>
<tr>
<td>bochs/pintos</td>
<td>0x4000</td>
</tr>
<tr>
<td>emacs</td>
<td>0x3000</td>
</tr>
</tbody>
</table>

- Consider multiprogramming on 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**
  - A bug in one process can corrupt memory in another
  - Must somehow prevent process A from trashing B’s memory
  - Also prevent A from even observing B’s memory (ssh-agent)

• **Transparency**
  - A process shouldn’t require particular physical memory bits
  - Yet processes often require large amounts of contiguous memory (for stack, large data structures, etc.)

• **Resource exhaustion**
  - Programmers typically assume machine has “enough” memory
  - Sum of sizes of all processes often greater than physical memory
Virtual memory goals

- Give each program its own *virtual* address space
  - At runtime, *Memory-Management Unit* relocates each load/store
  - Application doesn’t see *physical* memory addresses

- Also enforce protection
  - Prevent one app from messing with another’s memory

- And allow programs to see more memory than exists
  - Somehow relocate some memory accesses to disk
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Virtual memory advantages

- Can re-locate program while running
  - Run partially in memory, partially on disk
- Most of a process’s memory may be idle (80/20 rule).
  - Write idle parts to disk until needed
  - Let other processes use memory of idle part
  - Like CPU virtualization: when process not using CPU, switch (Not using a memory region? switch it to another process)

- Challenge: VM = extra layer, could be slow
Idea 1: load-time linking

- **Linker** patches addresses of symbols like `printf`
- **Idea:** link when process executed, not at compile time
  - Determine where process will reside in memory
  - Adjust all references within program (using addition)
- **Problems?**
Idea 1: load-time linking

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- **Idea**: link when process executed, not at compile time
  - Determine where process will reside in memory
  - Adjust all references within program (using addition)
- **Problems?**
  - How to enforce protection?
  - How to move once already in memory? (consider data pointers)
  - What if no contiguous free region fits program?
Idea 2: base + bound register

- Two special privileged registers: base and bound
- On each load/store/jump:
  - Physical address = virtual address + base
  - Check $0 \leq$ virtual address $< \text{bound}$, else trap to kernel
- How to move process in memory?
- What happens on context switch?
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  - Change base register
- **What happens on context switch?**
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- What happens on context switch?
  - OS must re-load base and bound register
Definitions

- Programs load/store to **virtual addresses**
- Actual memory uses **physical addresses**
- VM Hardware is Memory Management Unit (**MMU**)
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- Programs load/store to **virtual addresses**
- Actual memory uses **physical addresses**
- VM Hardware is Memory Management Unit (MMU)

- Usually part of CPU
- Configured through privileged instructions (e.g., load bound reg)
- Translates from virtual to physical addresses
- Gives per-process view of memory called **address space**
Base+bound trade-offs

- **Advantages**
  - Cheap in terms of hardware: only two registers
  - Cheap in terms of cycles: do add and compare in parallel
  - Examples: Cray-1 used this scheme

- **Disadvantages**
  - Growing a process is expensive or impossible
  - No way to share code or data (E.g., two copies of bochs, both running pintos)
  - One solution: Multiple segments
    - E.g., separate code, stack, data segments
    - Possibly multiple data segments

free space
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  - Possibly multiple data segments
Let processes have many base/bound regs

- Address space built from many segments
- Can share/protect memory at segment granularity

Must specify segment as part of virtual address
Segmentation mechanics

- Each process has a segment table
- Each VA indicates a segment and offset:
  - Top bits of addr select segment, low bits select offset (PDP-10)
  - Or segment selected by instruction or operand (means you need wider “far” pointers to specify segment)
• 2-bit segment number (1st digit), 12 bit offset (last 3)
  - Where is 0x0240? 0x1108? 0x265c? 0x3002? 0x1600?
Segmentation trade-offs

**Advantages**
- Multiple segments per process
- Allows sharing! (how?)
- Don’t need entire process in memory

**Disadvantages**
- Requires translation hardware, which could limit performance
- Segments not completely transparent to program (e.g., default segment faster or uses shorter instruction)
- $n$ byte segment needs $n$ contiguous bytes of physical memory
- Makes *fragmentation* a real problem.
Fragmentation

- **Fragmentation** $\Rightarrow$ Inability to use free memory

- **Over time:**
  - Variable-sized pieces = many small holes (external fragmentation)
  - Fixed-sized pieces = no external holes, but force internal waste (internal fragmentation)
Alternatives to hardware MMU

- **Language-level protection (JavaScript)**
  - Single address space for different modules
  - Language enforces isolation
  - Singularity OS does this with C# [Hunt]

- **Software fault isolation**
  - Instrument compiler output
  - Checks before every store operation prevents modules from trashing each other
  - Google’s now deprecated Native Client does this for x86 [Yee]
  - Easier to do for virtual architecture, e.g., Wasm
Paging

• Divide memory up into small, equal-size pages
• Map virtual pages to physical pages
  - Each process has separate mapping
• Allow OS to gain control on certain operations
  - Read-only pages trap to OS on write
  - Invalid pages trap to OS on read or write
  - OS can change mapping and resume application
• Other features sometimes found:
  - Hardware can set “accessed” and “dirty” bits
  - Control page execute permission separately from read/write
  - Control caching or memory consistency of page
Paging trade-offs

- Eliminates external fragmentation
- Simplifies allocation, free, and backing storage (swap)
- Average internal fragmentation of .5 pages per “segment”
Allocate any physical page to any process

Can store idle virtual pages on disk
Paging data structures

- Pages are fixed size, e.g., 4 KiB
  - Least significant 12 ($\log_2 4$ Ki) bits of address are page offset
  - Most significant bits are page number

- Each process has a page table
  - Maps virtual page numbers (VPNs) to physical page numbers (PPNs)
  - Also includes bits for protection, validity, etc.

- On memory access: Translate VPN to PPN, then add offset
Example: Paging on PDP-11

- **64 KiB virtual memory, 8 KiB pages**
  - Separate address space for instructions & data
  - I.e., can’t read your own instructions with a load

- **Entire page table stored in registers**
  - 8 Instruction page translation registers
  - 8 Data page translations

- **Swap 16 machine registers on each context switch**
x86 Paging

- Paging enabled by bits in a control register (%cr0)
  - Only privileged OS code can manipulate control registers

- Normally 4 KiB pages

- %cr3: points to physical address of 4 KiB page directory
  - See `pagedir_activate` in Pintos

- Page directory: 1024 PDEs (page directory entries)
  - Each contains physical address of a page table

- Page table: 1024 PTEs (page table entries)
  - Each contains physical address of virtual 4K page
  - Page table covers 4 MiB of Virtual mem

- See [old intel manual](https://www.intel.com/content/dam/doc/advanced/64-arch-manuals/Volume_3A.pdf) for simplest explanation
  - Also volume 2 of [AMD64 Architecture docs](https://www.amd.com/en/technologies/amd64-architecture-manuals)
  - Also volume 3A of [latest intel 64 architecture manual](https://www.intel.com/content/dam/doc/advanced/64-arch-manuals/Volume_3A.pdf)
x86 page translation

*32 bits aligned onto a 4-KByte boundary

1024 PDE × 1024 PTE = 2^{20} Pages
### Page Directory Entry (4-KByte Page Table)

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>Page-Table Base Address</td>
</tr>
<tr>
<td>12-11</td>
<td>Available for system programmer’s use</td>
</tr>
<tr>
<td>9</td>
<td>Global page (Ignored)</td>
</tr>
<tr>
<td>8</td>
<td>Page size (0 indicates 4 KBytes)</td>
</tr>
<tr>
<td>7</td>
<td>Reserved (set to 0)</td>
</tr>
<tr>
<td>6</td>
<td>Accessed</td>
</tr>
<tr>
<td>5</td>
<td>Cache disabled</td>
</tr>
<tr>
<td>4</td>
<td>Write-through</td>
</tr>
<tr>
<td>3</td>
<td>User/Supervisor</td>
</tr>
<tr>
<td>2</td>
<td>Read/Write</td>
</tr>
<tr>
<td>1</td>
<td>Present</td>
</tr>
<tr>
<td>0</td>
<td>Present</td>
</tr>
</tbody>
</table>
**Page-Table Entry (4-KByte Page)**

<table>
<thead>
<tr>
<th>31</th>
<th>12 11 9 8 7 6 5 4 3 2 1 0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Page Base Address</td>
</tr>
</tbody>
</table>

- Available for system programmer’s use
- Global Page
- Page Table Attribute Index
- Dirty
- Accessed
- Cache Disabled
- Write-Through
- User/Supervisor
- Read/Write
- Present
x86 hardware segmentation

- **x86 architecture also supports segmentation**
  - Segment register base + pointer val = *linear address*
  - Page translation happens on linear addresses

- **Two levels of protection and translation check**
  - Segmentation model has four privilege levels (CPL 0–3)
  - Paging only two, so 0–2 = kernel, 3 = user

- **Why do you want *both* paging and segmentation?**
x86 hardware segmentation

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- **Why do you want both paging and segmentation?**

- **Short answer: You don’t – just adds overhead**
  - Most OSes use “flat mode” – set base = 0, bounds = 0xffffffff in all segment registers, then forget about it
  - x86-64 architecture removes much segmentation support

- **Long answer: Has some fringe/incidental uses**
  - Keep pointer to thread-local storage w/o wasting normal register
  - VMware runs guest OS in CPL 1 to trap stack faults
  - OpenBSD used CS limit for $W \land X$ when no PTE NX bit
Making paging fast

- x86 PTs require 3 memory references per load/store
  - Look up page table address in page directory
  - Look up physical page number (PPN) in page table
  - Actually access physical page corresponding to virtual address

- For speed, CPU caches recently used translations
  - Called a *translation lookaside buffer* or TLB
  - Typical: 64-2k entries, 4-way to fully associative, 95% hit rate
  - Modern CPUs add second-level TLB with ∼1,024+ entries; often separate instruction and data TLBs
  - Each TLB entry maps a VPN → PPN + protection information

- On each memory reference
  - Check TLB, if entry present get physical address fast
  - If not, walk page tables, insert in TLB for next time
    (Must evict some entry)
TLB details

- TLB operates at CPU pipeline speed ⇒ small, fast
- Complication: what to do when switching address space?
  - Flush TLB on context switch (e.g., old x86)
  - Tag each entry with associated process’s ID (e.g., MIPS)
- In general, OS must manually keep TLB valid
  - Changing page table in memory won’t affect cached TLB entry
- E.g., on x86 must use `invlpg` instruction
  - Invalidates a page translation in TLB
  - Note: very expensive instruction (100–200 cycles)
  - Must execute after changing a possibly used page table entry
  - Otherwise, hardware will miss page table change
- More Complex on a multiprocessor (TLB shootdown)
  - Requires sending an interprocessor interrupt (IPI)
  - Remote processor must execute `invlpg` instruction
x86 Paging Extensions

- **PSE: Page size extensions**
  - Setting bit 7 in PDE makes a 4 MiB translation (no PT)

- **PAE Page address extensions**
  - Newer 64-bit PTE format allows 36+ bits of physical address
  - Page tables, directories have only 512 entries
  - Use 4-entry Page-Directory-Pointer Table to regain 2 lost bits
  - PDE bit 7 allows 2 MiB translation

- **Long mode PAE (x86-64)**
  - In Long mode, pointers are 64-bits
  - Extends PAE to map 48 bits of virtual address (next slide)
  - Why are aren’t all 64 bits of VA usable?
x86 long mode paging

Virtual Address

Sign Extend

Page-Map Level-4 offset (PML4)

Page Directory-Pointer Offset

Page Directory Offset

Page-Table Offset

Physical-Page Offset

63 48 47 39 38 30 29 21 20 12 11 0

Page-Map Level-4 Table

Page-Directory Pointer Table

Page-Directory Table

Page Table

4-Kbyte Physical Page

Physical Address

Page-Map L4 Base Addr

CR3
Where does the OS live?

- In its own address space?
  - Can’t do this on most hardware (e.g., syscall instruction won’t switch address spaces)
  - Also would make it harder to parse syscall arguments passed as pointers
- So in the same address space as process
  - Use protection bits to prohibit user code from writing kernel
- Typically all kernel text, most data at same VA in every address space
  - On x86, must manually set up page tables for this
  - Usually just map kernel in contiguous virtual memory when boot loader puts kernel into contiguous physical memory
  - Some hardware puts physical memory (kernel-only) somewhere in virtual address space
  - Typically kernel goes in high memory; with signed numbers, can mean small negative addresses (small linker relocations)
## Pintos memory layout

<table>
<thead>
<tr>
<th>Kernel/ Pseudo-physical memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>User stack</td>
</tr>
<tr>
<td>BSS / Heap</td>
</tr>
<tr>
<td>Data segment</td>
</tr>
<tr>
<td>Code segment</td>
</tr>
<tr>
<td>Invalid virtual addresses</td>
</tr>
</tbody>
</table>

- 0xffffffff
- 0xc0000000 (PHYS_BASE)
- 0x08048000
- 0x00000000
Very different MMU: MIPS

- Hardware checks TLB on application load/store
  - References to addresses not in TLB trap to kernel

- Each TLB entry has the following fields:
  Virtual page, Pid, Page frame, NC, D, V, Global

- Kernel itself unpaged
  - All of physical memory contiguously mapped in high VM (hardwired in CPU, not just by convention as with Pintos)
  - Kernel uses these pseudo-physical addresses

- User TLB fault handler very efficient
  - Two hardware registers reserved for it
  - utlb miss handler can itself fault—allow paged page tables

- OS is free to choose page table format!
DEC Alpha MMU

- **Firmware managed TLB**
  - Like MIPS, TLB misses handled by software
  - Unlike MIPS, TLB miss routines ship with machine in ROM (but copied to main memory on boot—so can be overwritten)
  - Firmware known as “PAL code” (privileged architecture library)

- **Hardware capabilities**
  - 8 KiB, 64 KiB, 512 KiB, 4 MiB pages all available
  - TLB supports 128 instruction/128 data entries of any size

- **Various other events vector directly to PAL code**
  - `call_pal` instruction, TLB miss/fault, FP disabled

- **PAL code runs in special privileged processor mode**
  - Interrupts always disabled
  - Have access to special instructions and registers
Examples of Digital Unix PALcode entry functions
- `callsys/retsys` - make, return from system call
- `swpctx` - change address spaces
- `wrvptptr` - write virtual page table pointer
- `tbi` - TBL invalidate

Some fields in PALcode page table entries
- `GH` - 2-bit granularity hint $\rightarrow 2^N$ pages have same translation
- `ASM` - address space match $\rightarrow$ mapping applies in all processes
Example: Paging to disk

- gcc needs a new page of memory
- OS re-claims an idle page from emacs
- If page is clean (i.e., also stored on disk):
  - E.g., page of text from emacs binary on disk
  - Can always re-read same page from binary
  - So okay to discard contents now & give page to gcc
- If page is dirty (meaning memory is only copy)
  - Must write page to disk first before giving to gcc
- Either way:
  - Mark page invalid in emacs
  - emacs will fault on next access to virtual page
  - On fault, OS reads page data back from disk into new page, maps new page into emacs, resumes executing
Paging in day-to-day use

- Demand paging
- Growing the stack
- BSS page allocation
- Shared text
- Shared libraries
- Shared memory
- Copy-on-write (fork, mmap, etc.)
- Q: Which pages should have global bit set on x86?