**Administrivia**

- Lab 1 due Friday 12pm.
- **We give will give short extensions to groups that run into trouble. But email us:**
  - How much is done & left?
  - How much longer do you need?
- **Attend section Friday at 2:15pm to learn about lab 2.**
## Want processes to co-exist

<table>
<thead>
<tr>
<th></th>
<th>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
  - Yes 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 run time, Memory-Management Unit relocates each load, store to actual memory... App doesn’t see physical memory

- 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
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

- **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**?
  - 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:
  - Physical address = virtual address + base
  - Check $0 \leq \text{virtual address} < \text{bound}$, else trap to kernel
- How to move process in memory?
- What happens on context switch?
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- How to move process in memory?
  - Change base register

- What happens on context switch?
  - OS must re-load base and bound register
Definitions

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

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

• Advantages
  - Cheap in terms of hardware: only two registers
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• 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
• 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
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** ⇒ 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 (Java)**
  - Single address space for different modules
  - Language enforces isolation
  - Singularity OS does this [Hunt]

- **Software fault isolation**
  - Instrument compiler output
  - Checks before every store operation prevents modules from trashing each other
  - Google *Native Client* does this with only about 5% slowdown [Yee]
Paging

- Divide memory up into small *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., 4K
  - Least significant 12 (log_2 4K) 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

![Diagram showing paging data structures](image-url)
Example: Paging on PDP-11

- 64K virtual memory, 8K 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 4KB pages
- %cr3: points to 4KB 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 MB of Virtual mem
- See old intel manual for simplest explanation
  - Also volume 2 of AMD64 Architecture docs
  - Also volume 3A of latest Pentium Manual
**x86 page translation**

- Linear Address
  - 31 22 21 12 11 0
  - Directory Table Offset

- Page Directory
  - Page Table
  - Page-Table Entry
  - Physical Address

- CR3 (PDBR)
  - 32*

- 1024 PDE × 1024 PTE = $2^{20}$ Pages

*32 bits aligned onto a 4-KByte boundary
# x86 page directory entry

**Page–Directory Entry (4-KByte Page Table)**

|       | Avail | G | P | S | 0 | A | P | C | D | P | W | T | U | S | R | W | P |
|-------|-------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Page–Table Base Address** |       |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

**Available for system programmer’s use**

**Global page (Ignored)**

**Page size (0 indicates 4 KBytes)**

**Reserved (set to 0)**

**Accessed**

**Cache disabled**

**Write–through**

**User/Supervisor**

**Read/Write**

**Present**
# x86 page table entry

The x86 page table entry is a 4-KByte page that contains various attributes and flags to manage memory access and protection.

## Page-Table Entry (4-KByte Page)

<table>
<thead>
<tr>
<th>Bit Position</th>
<th>Bit Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>Page Base Address</td>
<td>The base address of the page.</td>
</tr>
<tr>
<td>12:11</td>
<td>Available</td>
<td>Indicates whether the page is available.</td>
</tr>
<tr>
<td>9:8</td>
<td>Global Page</td>
<td>Determines if the page is a global page.</td>
</tr>
<tr>
<td>7:6</td>
<td>Page Table Attribute Index</td>
<td>Specifies the attributes of the page.</td>
</tr>
<tr>
<td>5</td>
<td>Dirty</td>
<td>Indicates if the page is dirty.</td>
</tr>
<tr>
<td>4:3</td>
<td>Accessed</td>
<td>Indicates if the page has been accessed.</td>
</tr>
<tr>
<td>2:1</td>
<td>Cache Disabled</td>
<td>Determines if cache access is disabled.</td>
</tr>
<tr>
<td>0</td>
<td>Present</td>
<td>Indicates if the page is present.</td>
</tr>
<tr>
<td>11</td>
<td>Write-Through</td>
<td>Determines if write-through is enabled.</td>
</tr>
<tr>
<td></td>
<td>User/Supervisor</td>
<td>Determines if user or supervisor mode.</td>
</tr>
<tr>
<td></td>
<td>Read/Write</td>
<td>Determines if read or write access is allowed.</td>
</tr>
</tbody>
</table>
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

• **x86 architecture *also* supports segmentation**
  - Segment register base + pointer val = *linear address*
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• **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?**

• **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**
  - 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 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
  - 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 switch 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
- E.g., x86 `invlpg` instruction
  - Invalidates a page translation in TLB
  - Must execute after changing a possibly used page table entry
  - Otherwise, hardware will miss page table change
- More Complex on a multiprocessor (TLB shootdown)
x86 Paging Extensions

- **PSE: Page size extensions**
  - Setting bit 7 in PDE makes a 4MB 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 2MB translation

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

- **Sign Extend**
- **Page–Map Level–4 offset (PML4)**
- **Page Directory–Pointer Offset**
- **Page Directory Offset**
- **Page–Table Offset**
- **Physical–Page Offset**

### Diagram

- **Virtual Address**
- **CR3**
- **Page–Map L4 Base Addr**
- **Physical Address**
- **4–Kbyte Physical Page**
- **PML4E**
- **PDPE**
- **PDE**
- **PTE**
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
# 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>

- **Kernel/ Pseudo-physical memory**: `0xffffffff`
- **User stack**: `0xc0000000` (PHYS_BASE)
- **BSS / Heap**: `0x08048000`
- **Data segment**: `0x00000000`
- **Code segment**: `0x08048000`
- **Invalid virtual addresses**: `0x00000000`
Very different MMU: MIPS

- Hardware has 64-entry TLB
  - 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
  - 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

- Software managed TLB (like MIPS)
  - 8KB, 64KB, 512KB, 4MB pages all available
  - TLB supports 128 instruction/128 data entries of any size

- But TLB miss handler not part of OS
  - Processor ships with special “PAL code” in ROM
  - Processor-specific, but provides uniform interface to OS
  - Basically firmware that runs from main memory like OS

- Various 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
PAL code interface details

• 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 → $2^N$ pages have same translation
  - ASM - address space match → 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?