**Administrivia**

- Lab 1 due Friday 12pm (noon)
- We give will 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 10:30am to learn about lab 2.
  - Saachi will grant a free extension to 5pm on lab 1 if attending section prevented you from completing the lab on time.

**Virtual memory**

- 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>OS</th>
<th>0x9000</th>
</tr>
</thead>
<tbody>
<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>
<tr>
<td></td>
<td>0x0000</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?
  - How to move process in memory?
  - How to enforce protection?
  - What if no contiguous free region fits program?

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

Idea 2: base + bound register

- Two special privileged registers: base and bound
  - Physical address = virtual address + base
  - Check 0 ≤ virtual address < bound, else trap to kernel
- 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 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

**Segmentation**

- 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)
Segmentation example

- 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 segmentation a real problem.

Fragmentation

- Fragmentation \(\implies\) 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

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”
### Simplified allocation

- 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 (log₂ 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

### 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

### x86 page directory entry

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

*32 bits aligned onto a 4–KByte boundary*
TLB details

- TLB operates at CPU pipeline speed \( \implies \) 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 (PI)
  - Remote processor must execute `invlpg` instruction

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?
  - 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 ∧ 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
  - Each TLB entry maps a VPN \( \rightarrow \) 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)

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 (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

<table>
<thead>
<tr>
<th>Sign Extend</th>
<th>Page-Map</th>
<th>Page Directory</th>
<th>Page Table</th>
<th>Physical Page Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>48</td>
<td>47</td>
<td>39 38</td>
<td>30 29 21 20 12 11 0</td>
</tr>
</tbody>
</table>

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)
- Hardware capabilities
  - 8KB, 64KB, 512KB, 4MB 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

Pintos memory layout

- Kernel/Pseudo-physical memory
- User stack
- BSS/Heap
- Data segment
- Code segment
- Invalid virtual addresses

PAL code interface details

- Examples of Digital Unix PAL code 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 → 2^4 pages have same translation
  - ASM - address space match → mapping applies in all processes

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

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 hander 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!
### 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?