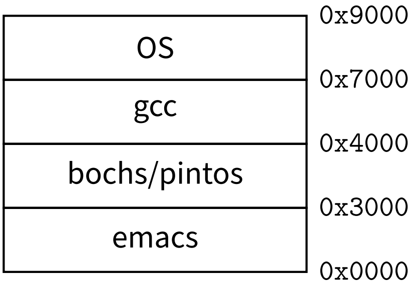
Administrivia

- **Lab 1 due Friday 3pm (5pm if you attend section)**
- **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 3:20pm to learn about lab 2**

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

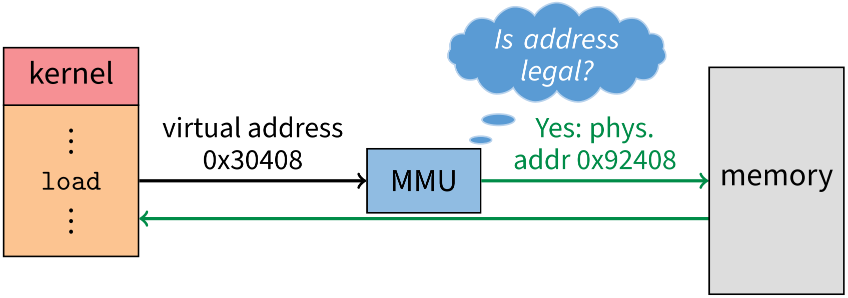


- **Consider multiprogramming on physical memory**
  - What happens if pintos needs to expand?
  - If emacs needs more memory than is on the machine?
  - If pintos has an error and writes to address 0x7100?
  - When does gcc have to know it will run at 0x4000?
  - What if emacs isn't using its memory?

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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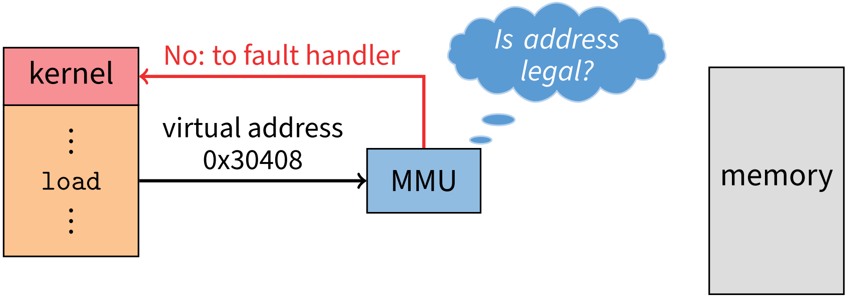

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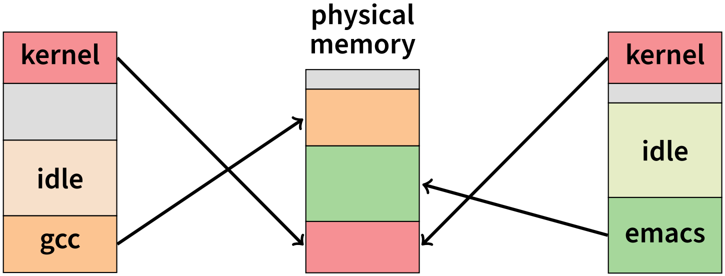
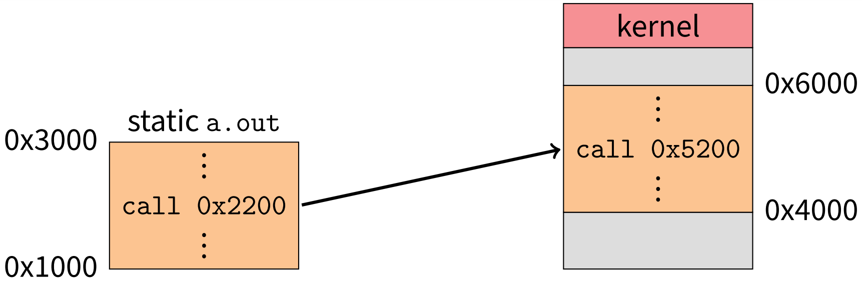
Virtual memory advantages

- **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: no hardware, load-time linking



- ***Linker*** **patches addresses of symbols like** `printf`
- **Idea: link when process executed, not at compile time**
  - Already have PIE (position-independent executable) for security
  - Determine where process will reside in memory at launch
  - Adjust all references within program (using addition)
- **Problems?**

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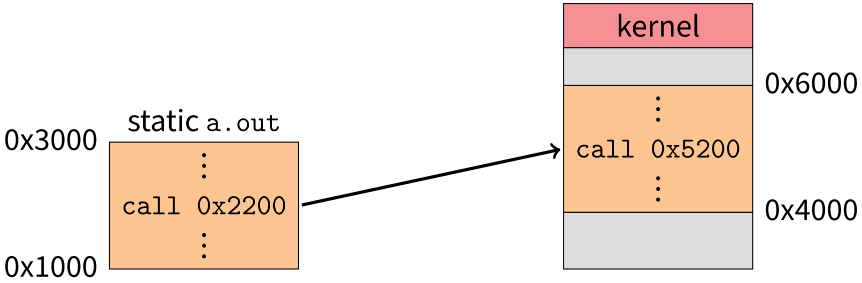

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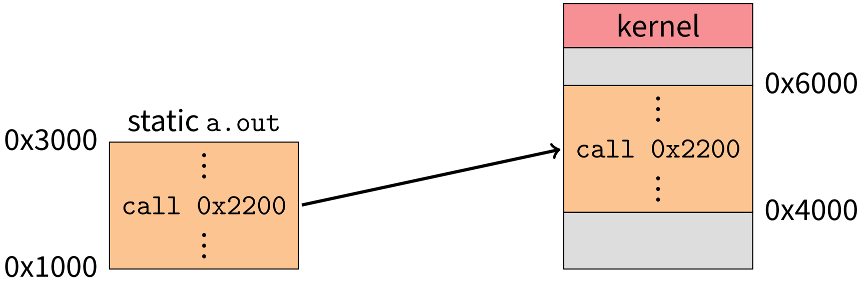
- **Problems?**
  - How to enforce protection?
  - How to move once already in memory? (consider data pointers)
  - What if no contiguous free region fits program?

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 $<$ bound, else trap to kernel
- **How to move process in memory?**
- **What happens on context switch?**

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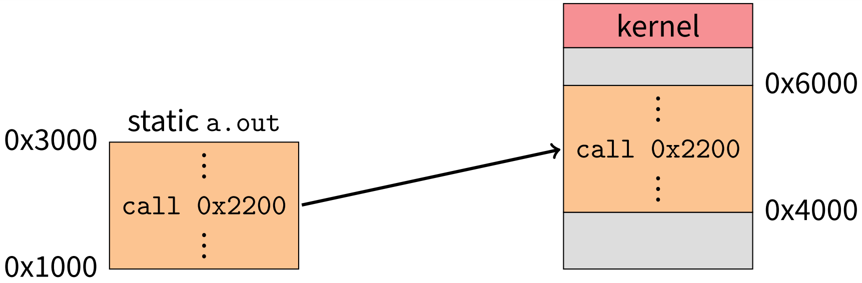

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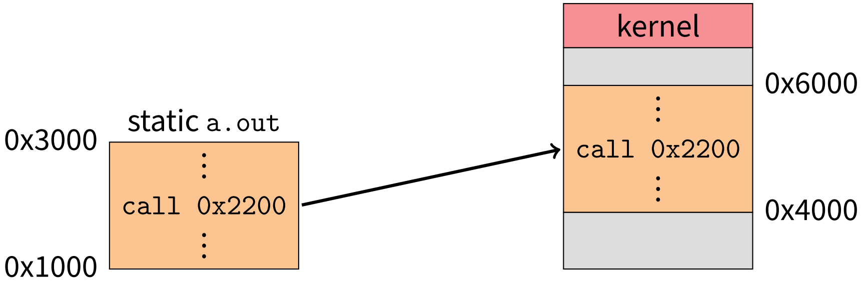

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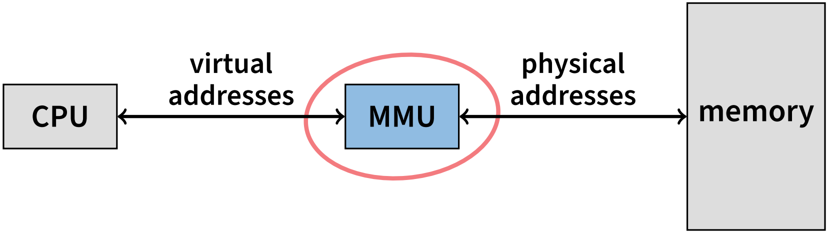
  - Change base register
- **What happens on context switch?**
  - Kernel must re-load base and bound registers

Definitions

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



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

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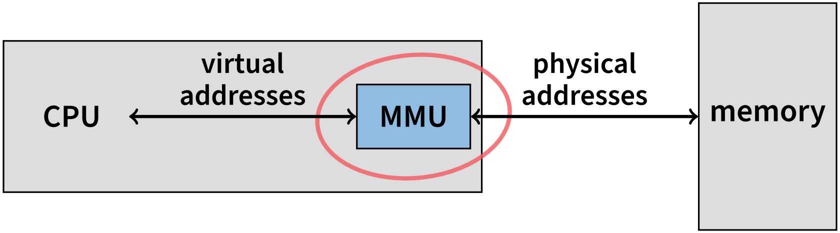

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Base+bound trade-offs

- **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

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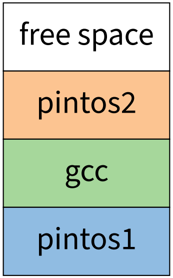
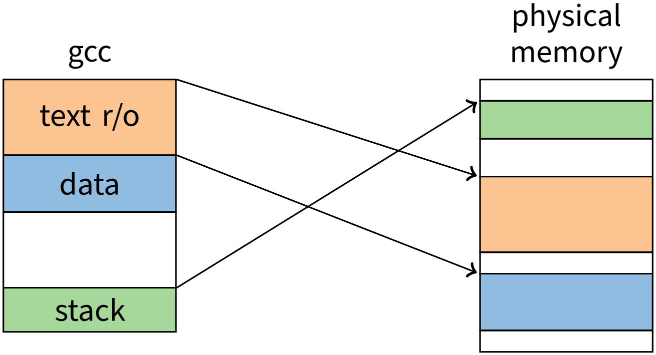
  - Examples: Cray-1 used this scheme
- **Disadvantages**
  - Growing a process is expensive or impossible
  - No way to share code or data (E.g., two copies of bochs, both running pintos)
- **One solution: Multiple segments**
  - E.g., separate code, stack, data segments
  - Possibly multiple data segments

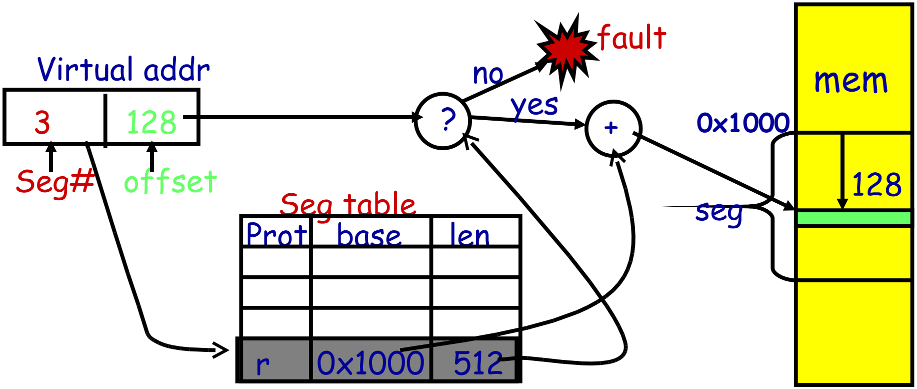


Segmentation



- **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**

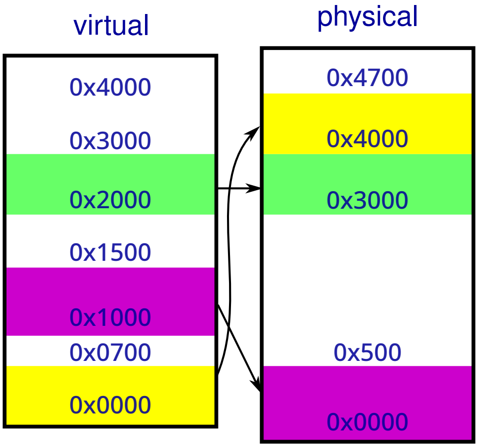
Segmentation mechanics



- **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

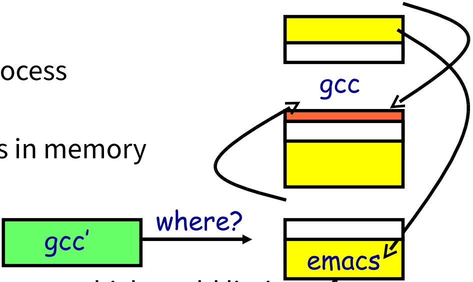
Seg	base	bounds	rw
0	0x4000	0x6ff	10
1	0x0000	0x4ff	11
2	0x3000	0xfff	11
3			00



- **2-bit segment number (1st digit), 12 bit offset (last 3)**
  - Where is 0x0240? 0x1108? 0x265c? 0x3002? 0x1600?

Segmentation trade-offs

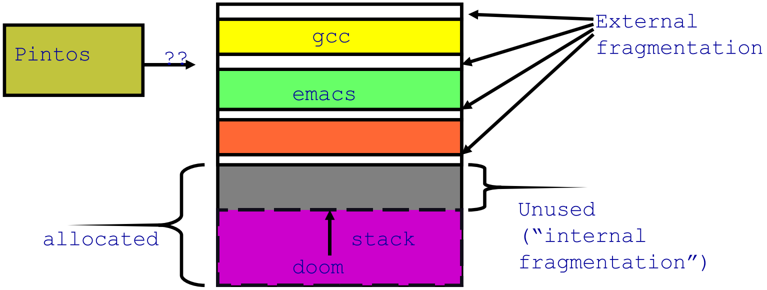
- **Advantages**
  - Multiple segments per process
  - Allows sharing! (how?)
  - Don't need entire process in memory



- **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 $\Longrightarrow$ 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)



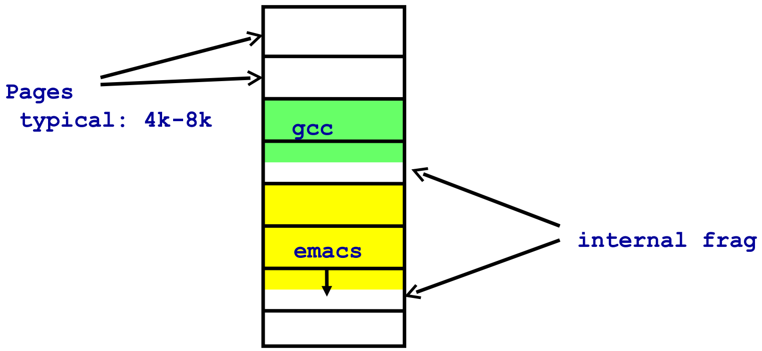
Alternatives to hardware MMU

- **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
  - Works really well on ARM64 [Yedidia'24]

Paging

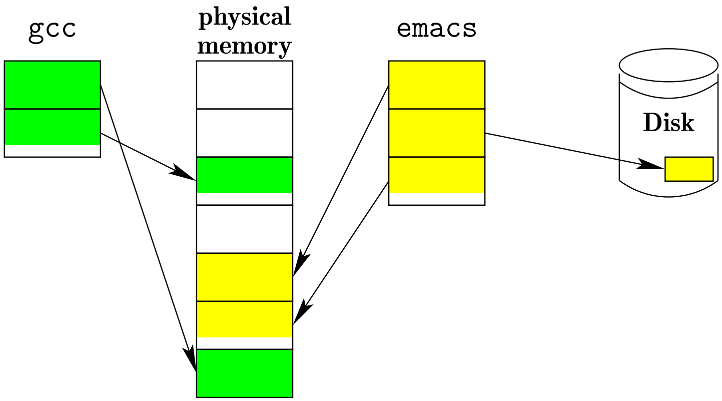
- **Divide memory up into small, equal-size *pages***
- **Map virtual pages to physical pages**
  - Each process has separate mapping
- **Allow OS to gain control on certain operations**
  - Read-only pages trap to OS on write
  - Invalid pages trap to OS on read or write
  - OS can change mapping and 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”

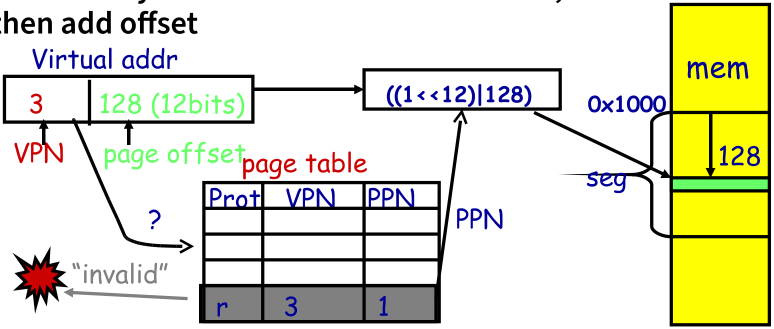
Simplified allocation



- Allocate any physical page to any process
- Can store idle virtual pages on disk

Paging data structures

- **Pages are fixed size, e.g., 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**



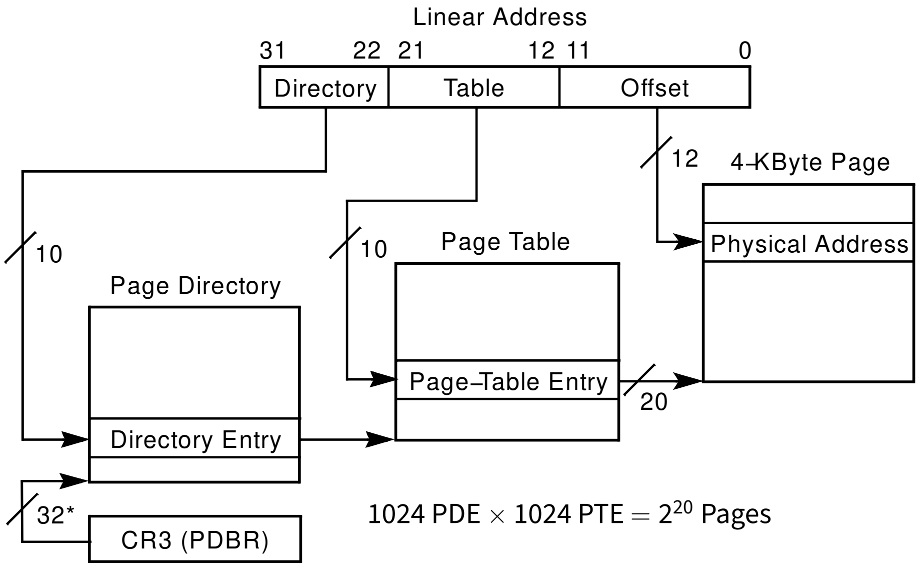
Example: Paging on PDP-11

- **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 for simplest explanation**
  - Also volume 2 of AMD64 Architecture docs
  - Also volume 3A of latest intel 64 architecture manual

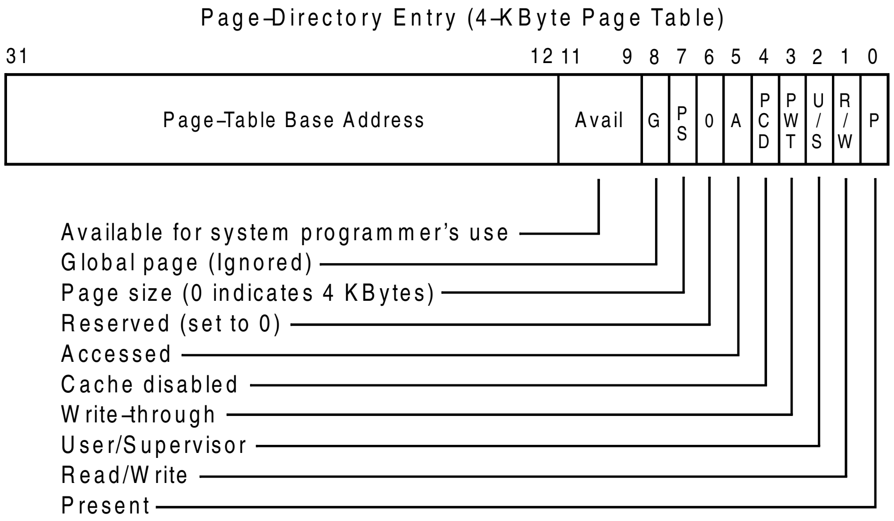
x86 page translation



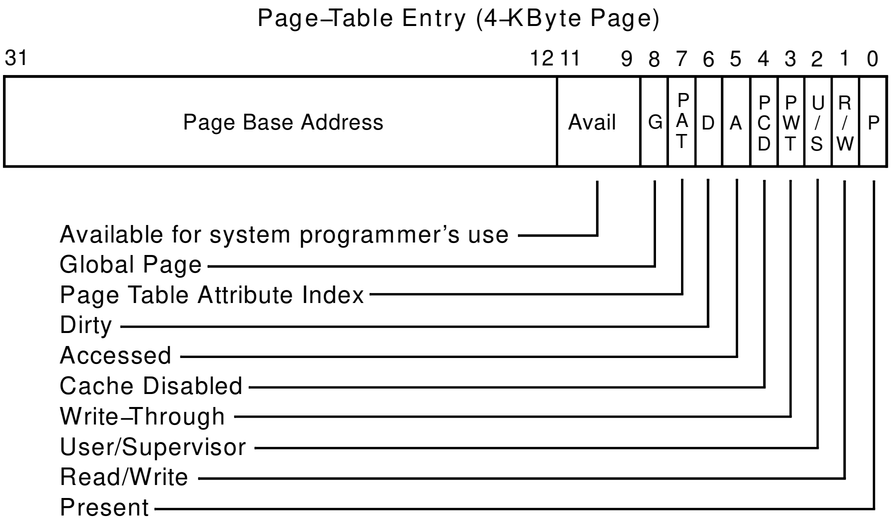
$1024 \text{ PDE} \times 1024 \text{ PTE} = 2^{20}$ Pages

*32 bits aligned onto a 4–KByte boundary

x86 page directory entry



x86 page table entry



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?**

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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
  - 32-bit VMware runs guest OS in CPL 1 to trap stack faults
  - OpenBSD used CS limit for $W \wedge X$ 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 $\sim$1,024+ entries; often separate instruction and data TLBs
  - 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)

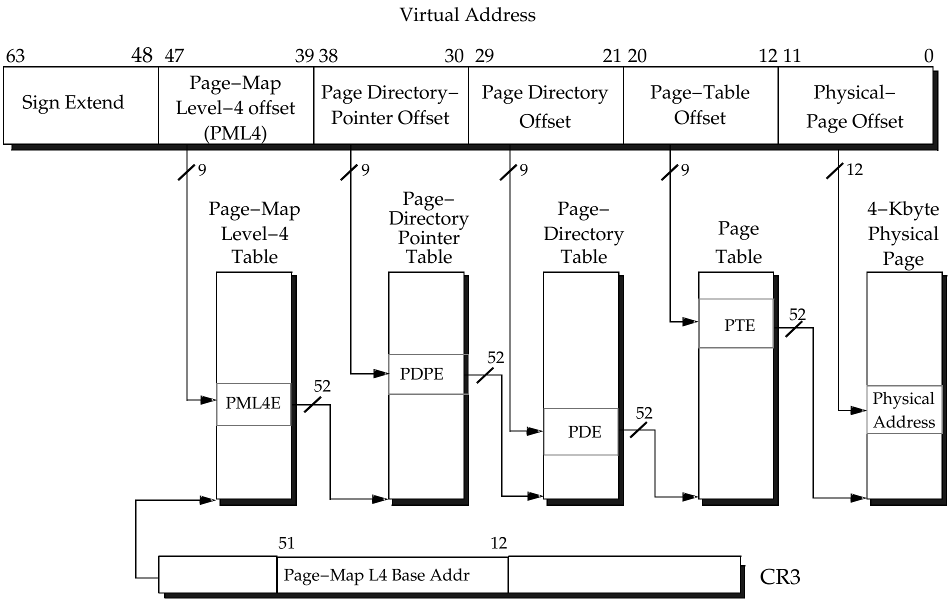
TLB details

- **TLB operates at CPU pipeline speed $\Longrightarrow$ 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?

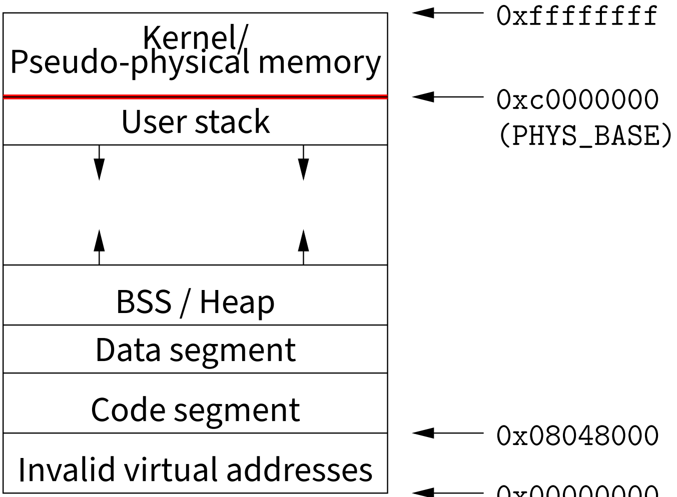
x86 long mode paging



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



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!**

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

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` - TLB 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?