W4118 Operating Systems

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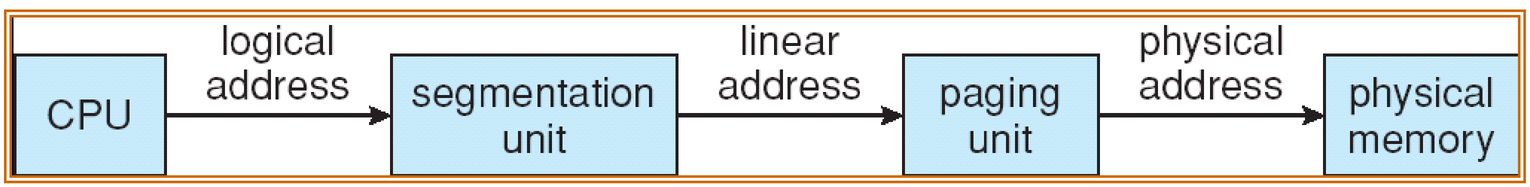
Outline

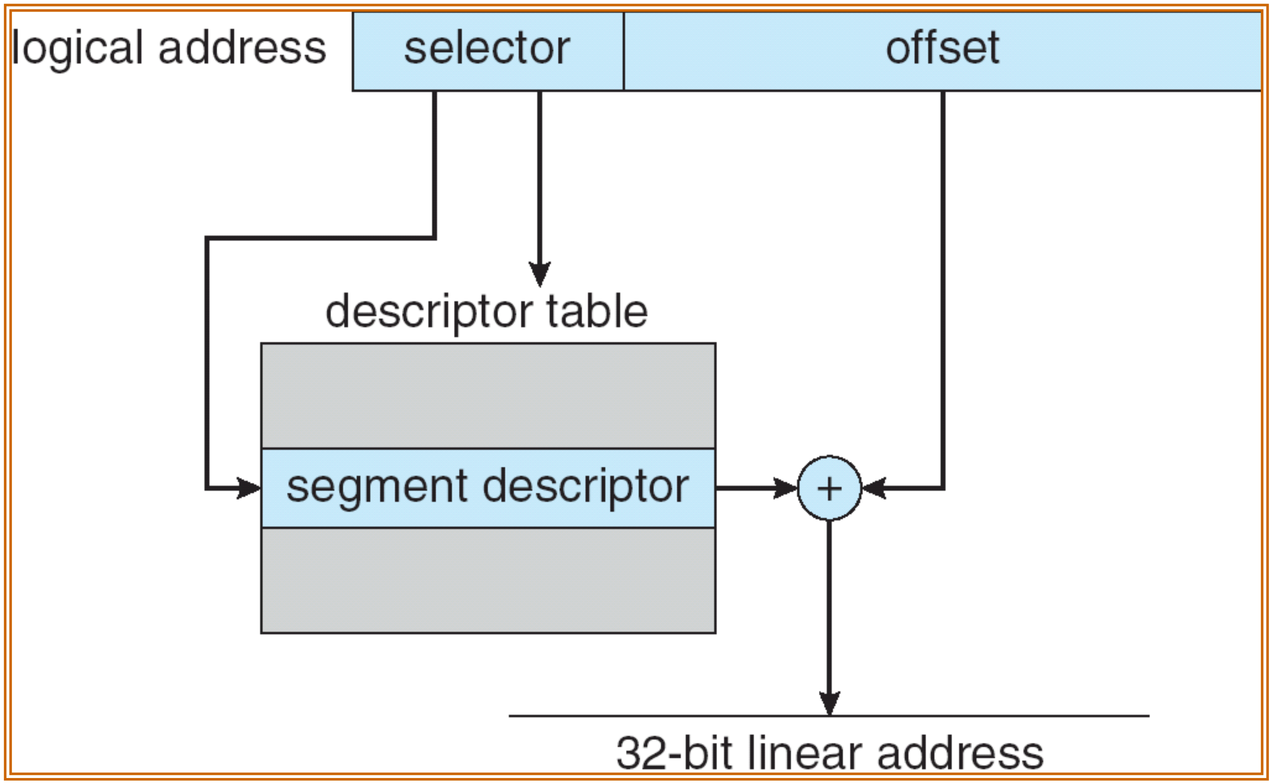
- x86 segmentation and paging hardware
- Linux address space translation
- Copy-on-write
- Linux page replacement algorithm
- Linux dynamic memory allocation

x86 segmentation and paging

- Using Pentium as example
- CPU generates virtual address (seg, offset)
  - Given to segmentation unit
    - Which produces linear addresses
  - Linear address given to paging unit
    - Which generates physical address in main memory
    - Paging units form equivalent of MMU



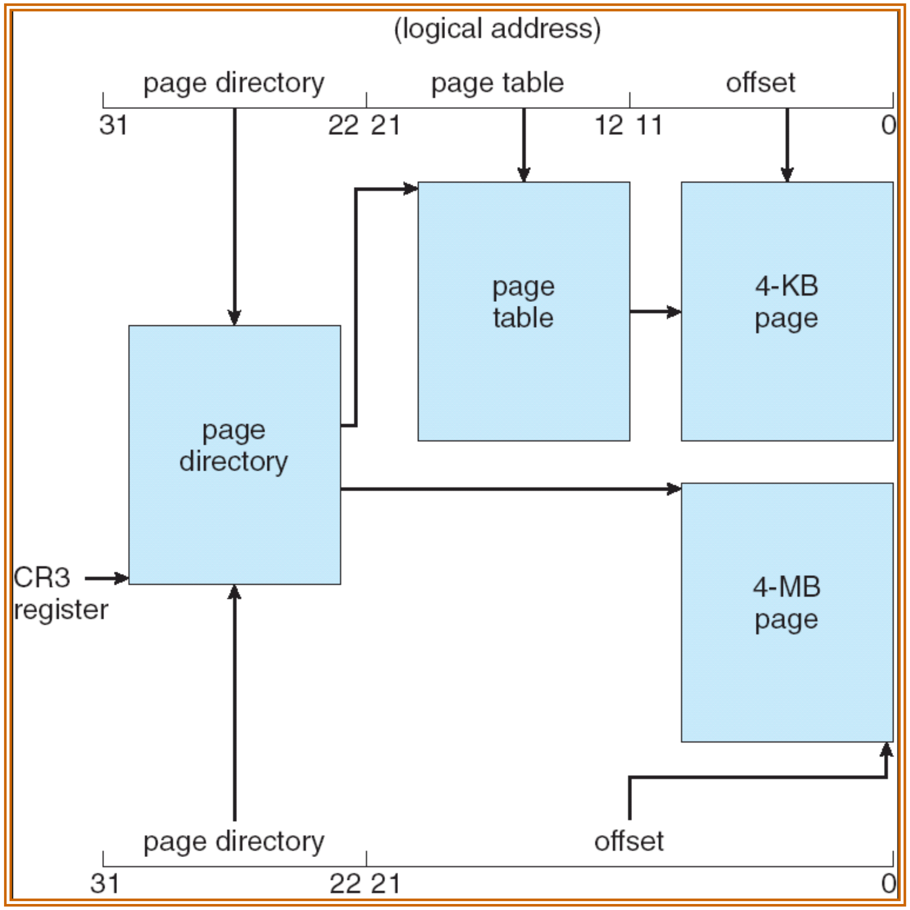
x86 segmentation hardware



Specifying segment selector

- virtual address: segment selector + offset
- Segment selector stored in segment registers (16-bit)
  - cs: code segment selector
  - ss: stack segment selector
  - ds: data segment selector
  - es, fs, gs
- Segment register can be implicitly or explicitly specified
  - Implicit by type of memory reference
    - jmp $8049780 // implicitly use cs
    - mov $8049780, %eax // implicitly use ds
  - Through special registers (cs, ss, es, ds, fs, gs on x86)
    - mov %ss:$8049780, %eax // explicitly use ss

x86 paging hardware



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Linux address translation

- Linux uses paging to translate virtual addresses to physical addresses
- Linux does not use segmentation
- Advantages
  - More portable since some RISC architectures don't support segmentation
  - Hierarchical paging is flexible enough

Linux segmentation

- Since x86 segmentation hardware cannot be disabled, Linux just uses NULL mappings
- Linux defines four segments
  - Set segment base to 0x00000000, limit to 0xffffffff
  - segment offset == linear addresses
  - User code (segment selector: __USER_CS)
  - User data (segment selector: __USER_DS)
  - Kernel code (segment selector: __KERNEL_CS)
  - Kernel data (segment selector: __KERNEL_DATA)
  - arch/i386/kernel/head.S

Segment protection

- Current Privilege level (CPL) specifies privileged mode or user mode
  - Stored in current code segment descriptor
  - User code segment: CPL = 3
  - Kernel code segment: CPL = 0
- Descriptor Privilege Level (DPL) specifies protection
  - Only accessible if CPL <= DPL
- Switch between user mode and kernel mode (e.g. system call and return)
  - Hardware load the corresponding segment selector (__USER_CS or __KERNEL_CS) into register cs

Paging

- Linux uses up to 4-level hierarchical paging
- A linear address is split into five parts, to seamlessly handle a range of different addressing modes
  - Page Global Dir
  - Page Upper Dir
  - Page Middle Dir
  - Page Table
  - Page Offset
- Example: 32-bit address space, 4KB page without physical address extension (hardware mechanism to extend address range of physical memory)
  - Page Global dir: 10 bits
  - Page Upper dir and Page Middle dir are not used
  - Page Table: 10 bits
  - Page Offset: 12 bits

Paging in 64 bit Linux

Platform	Page Size	Address Bits Used	Paging Levels	Address Splitting
Alpha	8 KB	43	3	10+10+10+13
IA64	4 KB	39	3	9+9+9+12
PPC64	4 KB	41	3	10+10+9+12
sh64	4 KB	41	3	10+10+9+12
X86_64	4 KB	48	4	9+9+9+9+12

Page table operations

- Linux provides data structures and operations to create, delete, read and write page directories
  - include/asm-i386/pgtable.h
  - arch/i386/mm/hugetlbpage.c

- Naming convention
  - pgd: Page Global Directory
  - pmd: Page Middle Directory
  - pud: Page Upper Directory
  - pte: Page Table Entry
  - Example: mk_pte(p, prot)

TLB operations

- x86 uses hardware TLB
  - OS does not manage TLB

- Only operation: flush TLB entries
  - include/asm-i386/tlbflush.h
  - movl %0 cr3: flush all TLB entries
  - invlpg addr: flush a single TLB entry
    - More efficient than flushing all TLB entries

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A cool trick: copy-on-write

- In fork(), parent and child often share significant amount of memory
  - Expensive to copy all pages
- COW Idea: exploit VA to PA indirection
  - Instead of copying all pages, share them
  - If either process writes to shared pages, only then is the page copied
  - How to detect page write?
    - Mark pages as read-only in both parent and child address space
    - On write, page fault occurs

Share pages

- copy_process() in kernel/fork.c
-     copy_mm()
-         dup_mmap() // copy page tables
-             copy_page_range() in mm/memory.c
-                 copy_pud_range()
-                     copy_pmd_range()
-                         copy_pte_range()
-                             copy_one_pte() // mark readonly

Copy page on page fault

- set_intr_gate(14, &page_fault) in arch/i386/kernel/traps.c
- ENTRY(page_fault) calls do_page_fault in arch/i386/kernel/entry.s

- do_page_fault in arch/i386/mm/fault.c
-     cr2 stores faulting virtual address
-     handle_mm_fault in mm/memory.c
-         handle_pte_fault in mm/memory.c
-             if(write_access)
-                 do_wp_page()

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Linux page replacement algorithm

- Two lists in *struct zone*
  - active_list: hot pages
  - inactive_list: cold pages
- Two bits in *struct page*
  - PG_active: is page on active list?
  - PG_referenced: has page been referenced recently?
- Approximate LRU algorithm
  - Replace a page in inactive list
  - Move from active to inactive under memory pressure
  - Need two accesses to go from inactive to active

Functions for page replacement

- lru_cache_add*(): add to inactive or active list
- mark_page_accessed(): called twice to move a page from inactive to active
- page_referenced(): test if a page is referenced
- refill_inactive_zone(): move pages from active to inactive

How to swap out page

- free_more_memory() in fs/buffer.c called
-     try_to_free_pages in mm/vmscan.c
-         shrink_caches
-             shrink_zone
-                 refill_inactive_zone
-                 shrink_cache
-                     shrink_list
-                         if(PageDirty(page))
-                             pageout()

How to load page

- On page fault, cr2 stores faulting virtual address
- handle_mm_fault() in mm/memory.c
- handle_pte_fault()
- if(!pte_present(entry))
- do_no_page() // anonymous page
- do_file_page() // file mapped page
- do_swap_page() // swapped out page

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Dynamic memory allocation

- How to allocate pages?
  - Data structures for page allocation
  - Buddy algorithm for page allocation
- How to allocate objects?
  - Slab allocation

Page descriptor

- Keep track of the status of each physical page
  - *struct page,* include/linux/mm.h
- All stored in mem_map array
- Simple mapping between a page and its descriptor
  - Nth page's descriptor is mem_map[N]
  - virt_to_page
  - page_to_pfn

Memory zone

- Keep track of pages in different zones
  - *struct zone*, include/linux/mmzone.h
  - ZONE_DMA: <16MB
  - ZONE_NORMAL: 16MB-896MB
  - ZONE_HIGHMEM: >896MB

Linux page allocator

- Linux use a buddy allocator for page allocation
  - Fast, simple allocation for blocks that are 2^n bytes [Knuth 1968]

- Idea: a free list for each size of block users want to allocate

- __page_alloc() in mm/page_alloc.c

Linux buddy allocator implementation

- Data structure
  - 11 free lists of blocks of pages of size 2^0, 2^1, …, 2^10
- Allocation restrictions: 2^n pages, 0<= n <= 10
- Allocation of 2^n pages:
  - Search free lists (n, n+1, n+2, …) for appropriate size
    - Recursively divide larger blocks until reach block of correct size
    - Insert "buddy" blocks into free lists
- Free
  - Recursively coalesce block with buddy if buddy free

Pros and cons of buddy allocator

- Advantages
  - Fast and simple compared to general dynamic memory allocation
  - Avoid external fragmentation by keeping free physical pages contiguous
- Disadvantages
  - Internal fragmentation
    - Allocation of block of k pages when k != 2^n

Slab allocator

- For objects smaller than a page
- Implemented on top of page allocator
- Memory managed by slab allocator is called cache

- Two types of slab allocator
  - Fixed-size slab allocator: cache contains objects of same size
    - for frequently allocated objects
  - General-purpose slab allocator: caches contain objects of size 2^n
    - for less frequently allocated objects
    - For allocation of object with size k, round to nearest 2^n

- _kmem_cache_create() and _kmalloc() in mm/slab.c

Pros and cons of slab allocator

- Advantages
  - Reduce internal fragmentation: many objects in one page
  - Fast
- Disadvantages
  - Memory overhead for bookkeeping
  - Internal fragmentation for general-purpose slab allocator