Precept 5: Virtual Memory

COS 318: Fall 2021

Project 5 Schedule

- **See website & Calendar 🤪**
- **Design Review 11/10/21 3-5, 8-10, 11/11/21 3-5**

Project 5 Overview

- **Goal:** Add memory management + virtual memory support to the kernel
- Read the project spec for more details
- Starter code can be found on the lab machines (/u/318/code/project5)
- Start early?

Done with Process Management

- Now: Can add new processes and kill them, and they can communicate through mailboxes
- TODO: each process is still in the same address space, so we would like to make it so that processes cannot interfere with each other (or with the kernel) by giving them their own virtual address space!

Project 5 Overview

- Add demand-paged VMM + restrict user processes from kernel level privileges
- Need to implement:
  - Virtual address spaces for user processes
  - Page allocation
  - Paging to & from disk
  - Page fault handler

Implementation Checklist

- **memory.h**
  - `page_map_entry_t`
- **memory.c**
  - `page_addr()`
  - `page_alloc()`
  - `init_mem()`
  - `setup_page_table()`
  - `page_fault_handler()`
  - `page_swap_in()`
  - `page_replacement_policy()`
  - `page_swap_out()`

Big Picture

- Set up kernel memory
- Set up VA to PA mapping for each process on creation
  - Processes now run in virtual memory
  - Hardware uses mapping when executing instructions
- Implement the page fault handler
  - If virtual page not in memory, page it in from disk and map it to a physical page

Address Translation Review

VA to PA Translation: Overview

- All addresses are virtual
  => must go through MMU
- MMU checks TLB first
- On miss: performs translation using page tables
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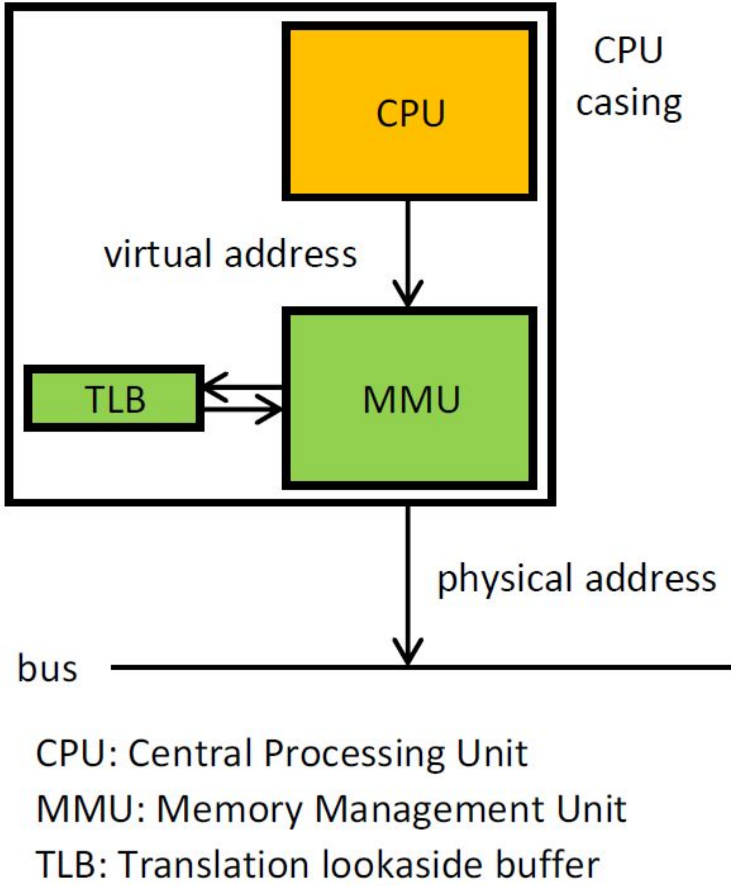
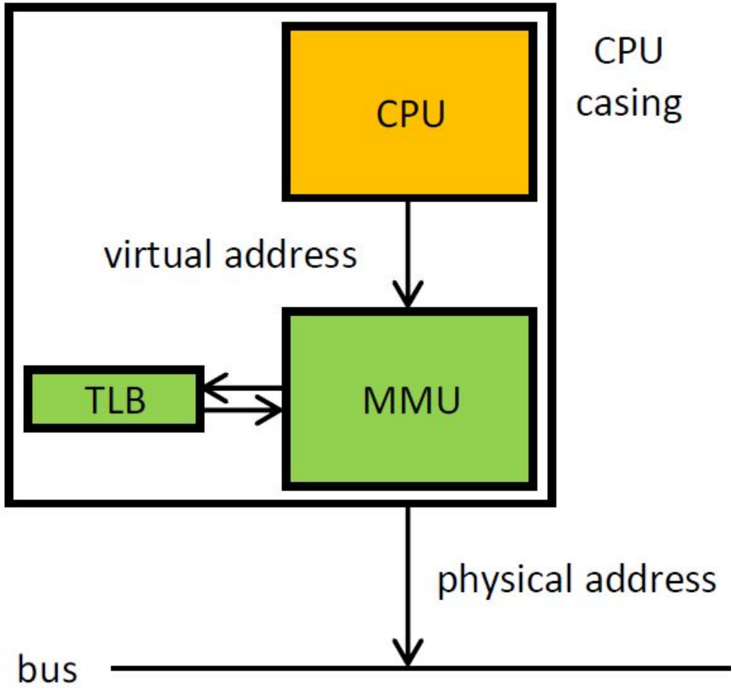


VA to PA Translation: Overview

- Page tables defined in software
- Use CR3 register to find root page table in RAM
- Checks page permissions - faults if invalid
- Image Source



CPU: Central Processing Unit
MMU: Memory Management Unit
TLB: Translation lookaside buffer

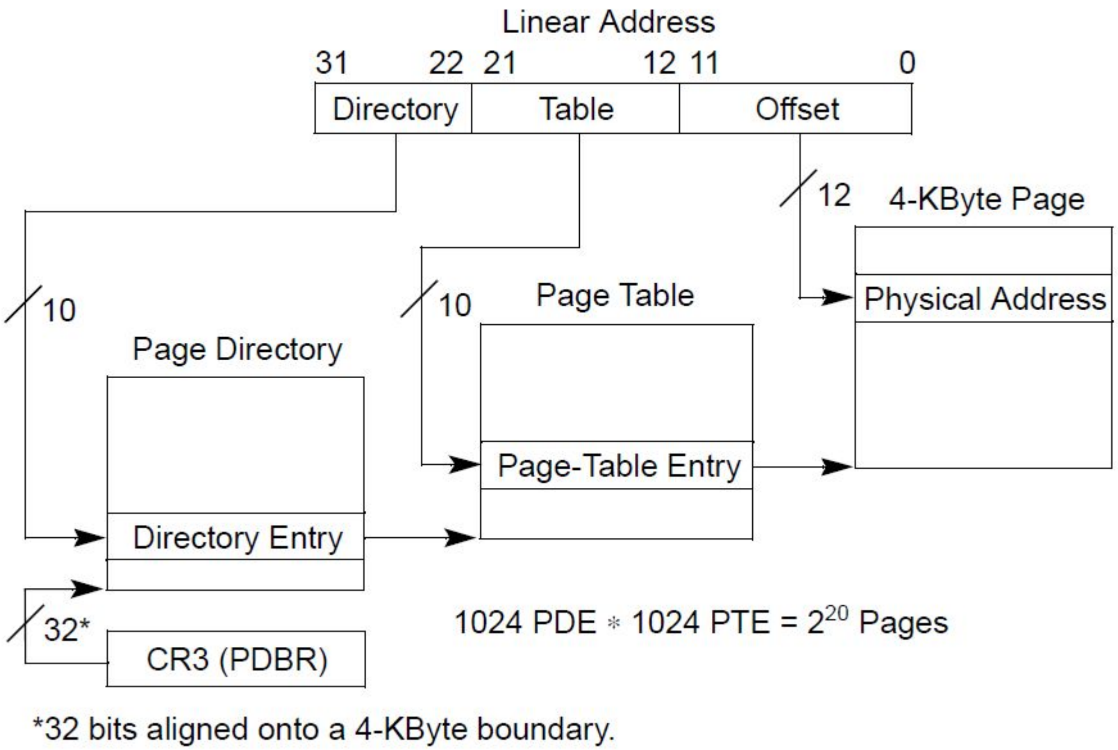
Paging System: Dir. / Table Entries

- Hierarchical System:
  - Directory Entries hold page table start address
  - Table Entries hold page start address
  - Page start address + offset = Physical address

Paging System: Dir. / Table Entries

- Dirs and Tables must fit onto a 4KB page!
  - Therefore, the lower 12 bits of the start address are always 0
- Higher 20 bits hold start address, lower 12 bits store permissions / status

Paging System: Linear to Physical



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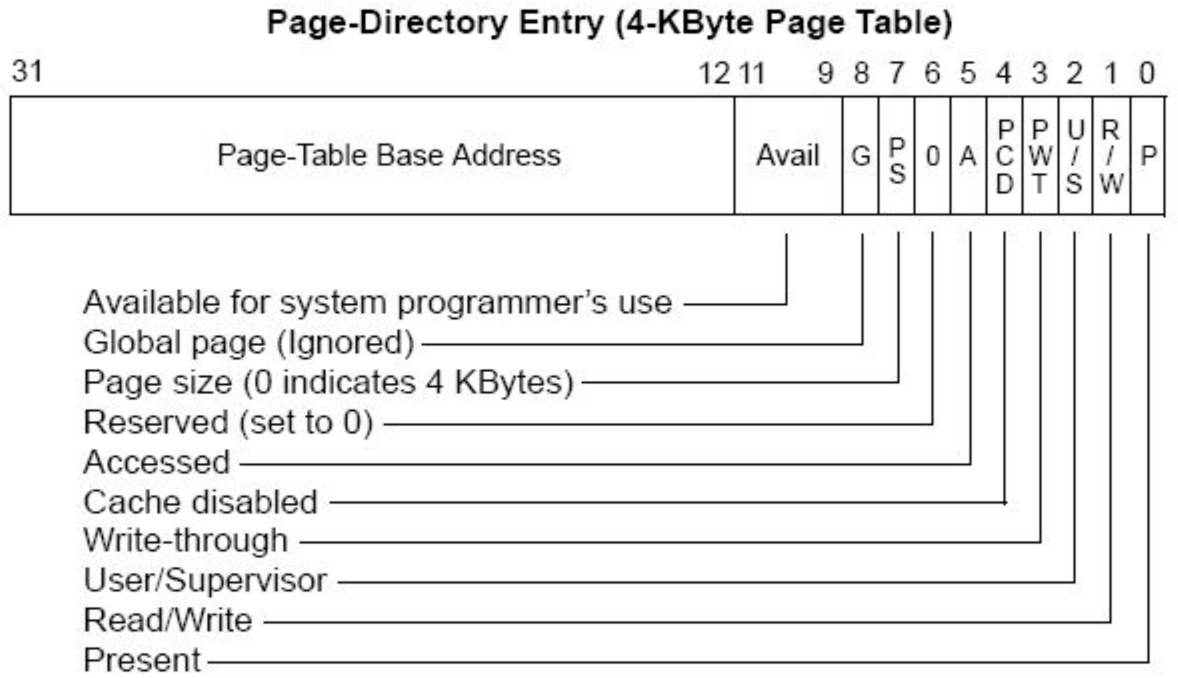
Paging System: Directory Entries



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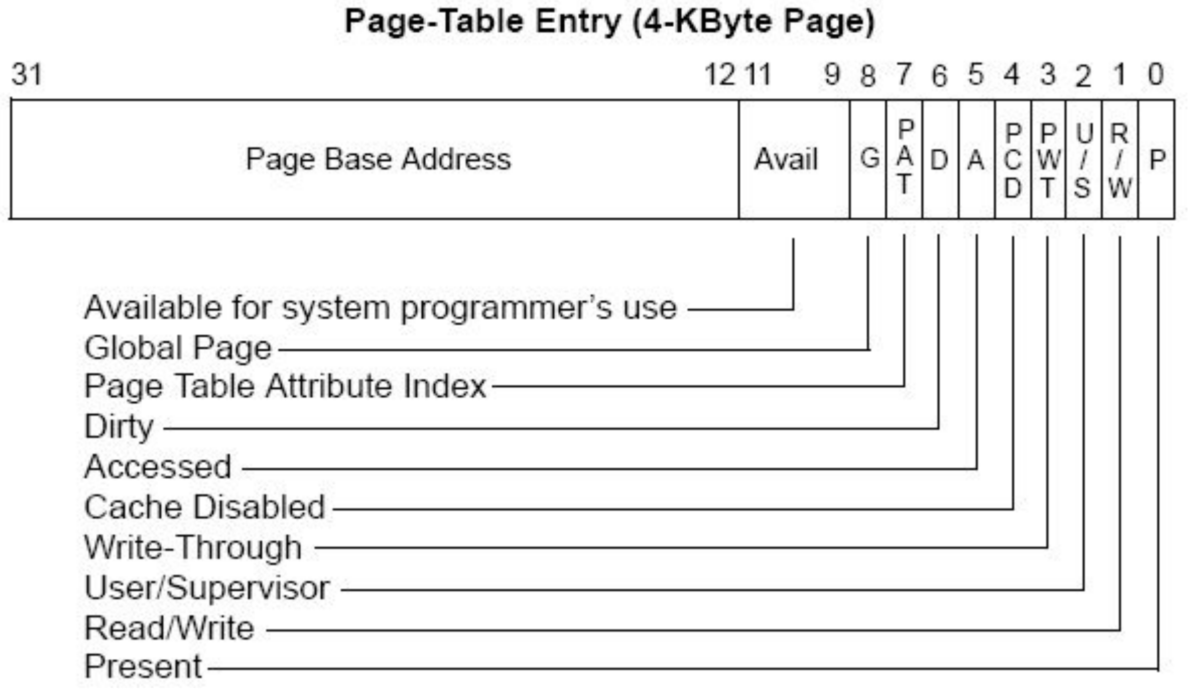
Paging System: Table Entries



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Check: VA Space = Paging Space

- We use 32-bit (4-byte) VAs, 4KB pages, and a two level page table system
    - 4KB per page / 4 bytes per entry= 2^10 entries
- 2^10 (p.d.e) * 2^10 (p.t.e) * 2^12 (bytes per page) = 2^32 addressable bytes
- 32 bits can address 2^32 locations

Project Description

Initializing Kernel Memory

- Allocate page directory
- Allocate N_KERNEL_PTS (page tables)
- Setup each page table, mapping pages until you reach MAX_PHYSICAL_MEMORY
- **physical addr=virtual addr** for the kernel (identity map)
- Set the correct flags (i.e. give user the permission to use the memory pages associated with the screen)

Initializing User Memory

- User processes need four types of pages (page directory, page table, stack page table, and stack pages)
- PROCESS_START (virtual addr. of code + data):
  - Use one page table and set entries relative to process address space
  - Each process needs pcb->swap_size memory
- PROCESS_STACK (virtual addr. of top of stack):
  - Allocate N_PROCESS_STACK_PAGES for each process

Page Faults

- A page fault occurs when we access a virtual page that is not currently present in physical memory.
- How does the hardware know that a page fault occurred?
- Keep track of metadata of physical page frames:
  - Free or not?
  - Information to implement a replacement algorithm (FIFO is sufficient)
  - Pinned or not? When would you want to pin a physical page frame?

Page Faults

- You need to write `page_fault_handler()`:
  - Find the faulting page in the page directory and page table
  - Allocate a page frame of physical memory
  - Load the contents of the page from the appropriate swap location on the USB disk (think about how to figure out the swap location)
  - Update the page table of the process

Paging From Disk

- To resolve a page fault, you might need to evict the contents of a physical page frame to disk
- Use a USB disk image for swap storage (usb/scsi.h)
- Use scsi_write() and scsi_read(), which have already been implemented
- Assume that processes do not change size (no dynamic memory allocation)
- Update page tables
- Decide if you need to flush TLB

Tips + Other Notes

Some Tips

- One page table is enough for process memory space
- Some functions (i.e. page fault handler) can be interrupted
    - Use synchronization primitives!
- Some pages don't need to be swapped out
    - Kernel pages, process page directory, page tables, stack page tables, and stack pages

Some Tips

- Test first with kernel threads
    - Implement `page_addr()`
    - Partially implement `page_alloc()` (assume number of pages is smaller than PAGEABLE_PAGES)
    - Implement `init_memory()`
    - Partially implement `setup_page_table()` (kernel threads only)
    - Comment out the loader thread in kernel.c and fix the value of NUM_THREADS in kernel.h

Some Tips

- After kernel threads are working
  - Finish the implementation of `setup_page_table()` (deal with processes)
  - Implement `page_fault_handler()`
  - Implement `page_swap_in()`
  - Uncomment the loader thread in kernel.c
- You should see a shell on the screen

Some Tips

- After the shell is working
  - Finish the implementation of `page_alloc()`
  - Implement `page_replacement_policy()`
  - Implement `page_swap_out()`
- Use the provided `bochs` executable in /u/318/code/project5/bin and NOT in /u/318/bin for testing

`bochs-gdb` vs `bochsdbg`

- `bochsdbg` does not work on this assignment!
- Use `bochs-gdb` instead:
  - Uncomment line 9 in `bochsrc` (set port to free value)
  - Run `bochs-gdb`, then `gdb` in another window
  - Run `target remote localhost:<port>`
  - Run `file kernel`, then `break kernel_start` (up to you)
  - Continue, then debug with standard gdb commands

Design Review

Page Table + Page Faults

Explain how virtual addresses are translated to physical addresses on i386. When are page faults triggered? How are you going to figure out what address a fault occurred on?

Page Map

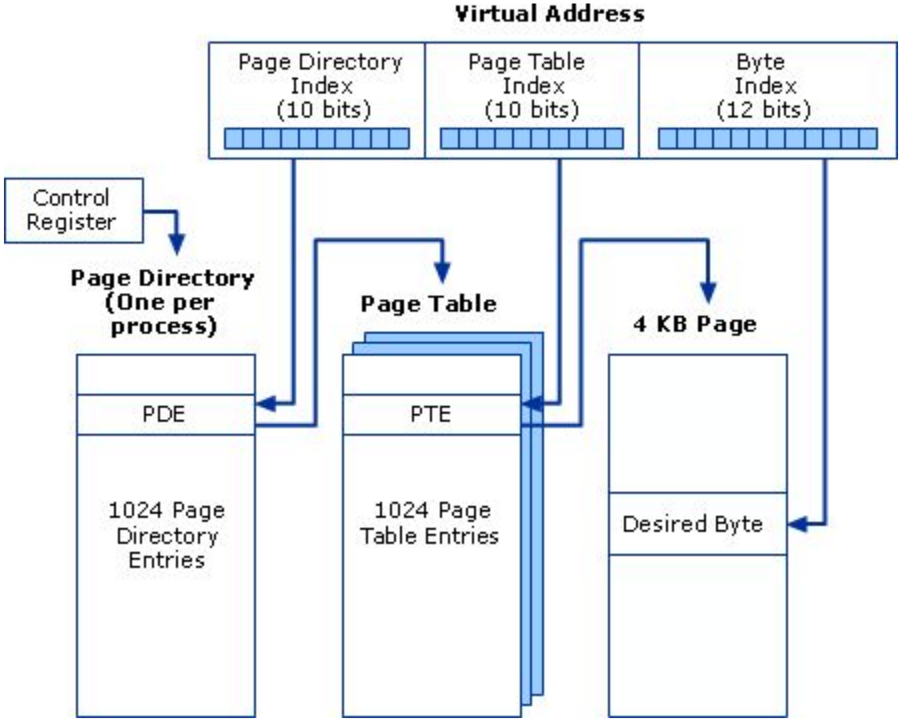
You're going to need a data structure to track information about pages. What information should you track?

Calling Relationships

For the functions `page_alloc`, `page_swap_in`, `page_swap_out`, and `page_fault_handler`, please describe the caller-callee relationship graph

Questions?

Paging System: VA Structure



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