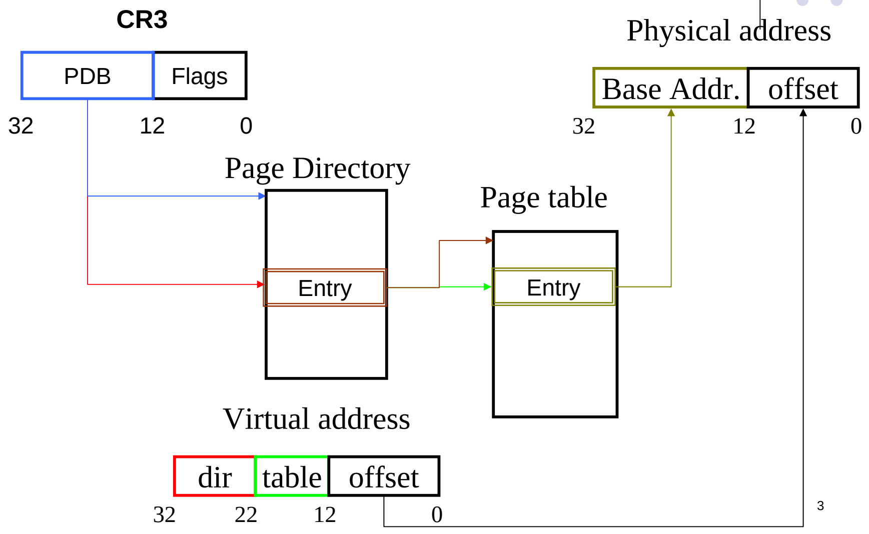
Project 5

Virtual Memory

Goals

- Two-level page tables
  - Setup Page Directory & Page Tables
  - Read Soft. Devel. Manual Vol. 3 (Ch 2-4)
- Page fault handler
  - Allocate physical page and bring in virtual page
- Physical page frame management
  - page allocation & replacement
  - swap in & out

Two Level Virtual Memory



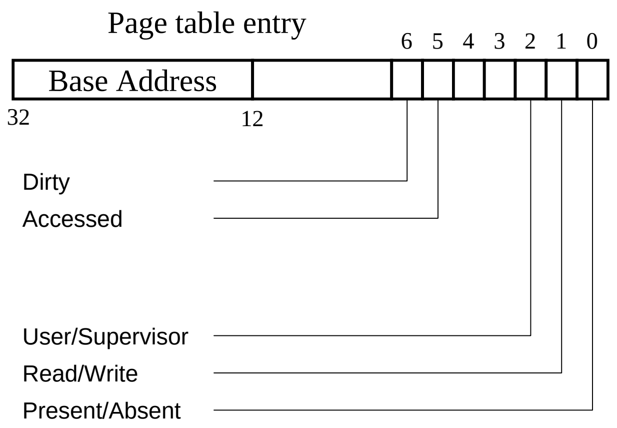
In Words…

- MMU uses CR3 and the first 10 bits of the virtual addr to index into the page directory and find the physical address of the page table we need.
- Then it uses the next 10 bits of the virtual addr to index into the page table, find the physical address of the actual page.
- The lowest 12 bits are used as the offset in the page.

Properties

- Size of one Page Directory or one Page Table or one Page is 4KB (2^12)
- Page Directory is a Page Table for the Page Tables
  - Avoids million entry page tables
- Each Entry is 4 bytes (32 bits)
  - So one page can have 2^10 entries!
- Each directory or table page is just a physical page which must also be page aligned

Two-Level Page Tables(cont'd)



Protection bits

- Present Bit (P)
  - If 1, then physical page is in memory
  - If 0, then other bits can be used to provide information to help the OS bring in the page
- Read/Write Bit (RW)
  - All pages can be read
  - If 1, page can be written to
- User/Supervisor Bit (US)
  - If 1, page can be accessed in kernel or user mode
  - If 0, page can only be accessed in kernel mode

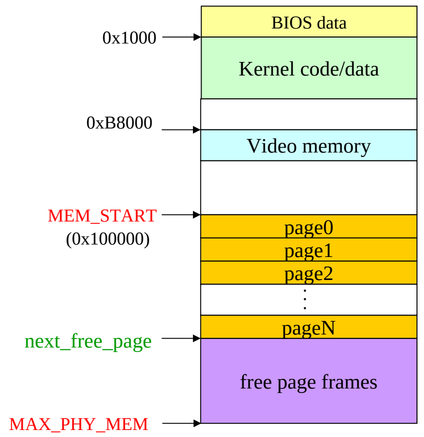
How are page tables used?

- Each process (including the kernel) has its own page directory and a set of page tables.
- The address of page directory is in CR3 (page directory register) when the process is running
- CR3 is loaded with pcb->page_directory at context switch
  - Done for you in the given code

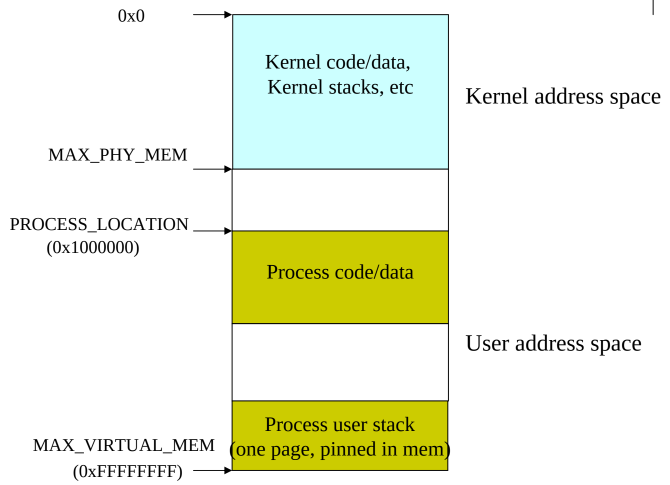
How are page tables used?(cont'd)

- Don't forget to mask off extra bits when using the base address from page table
  - PE_BASE_ADDR_MASK (see memory.h)

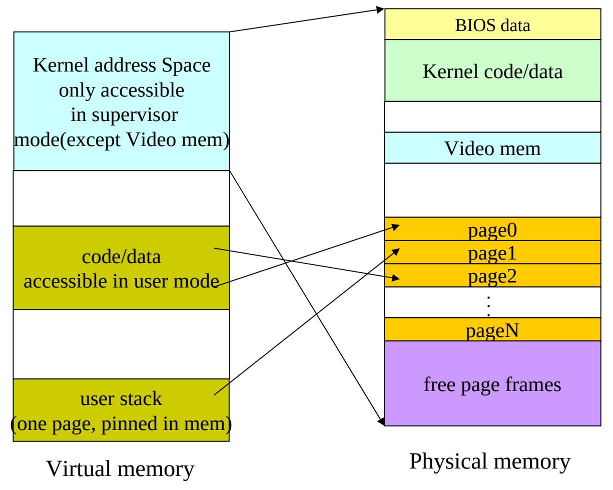
Physical Memory Layout



Virtual Memory (Process) Layout



Virtual-Physical Mapping



Virtual address Mapping

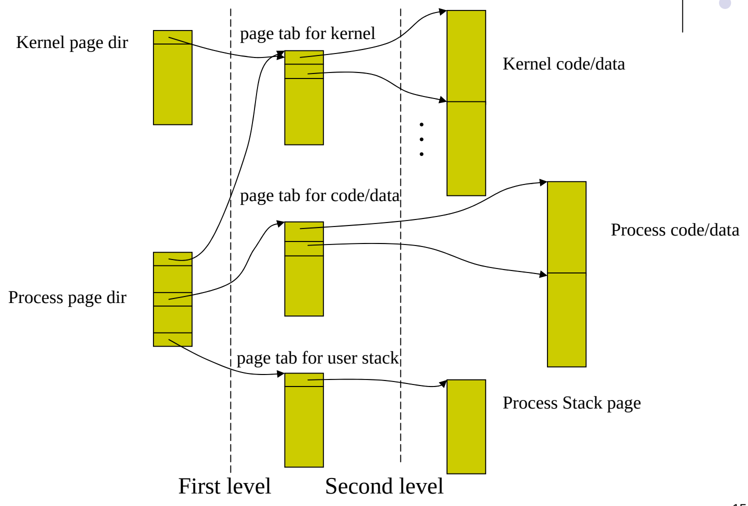
- Kernel addresses are mapped to exactly the same physical addresses
- All threads share the same kernel address space
- Each process has its own address space. It must also map the kernel address space to the same physical address space
  - Allows direct access to the video buffer

Virtual address Mapping

So what do we need to do?

- Setup kernel page tables that are shared by all the threads. (In init_memory())
- Setup process page tables when creating the process (In setup_page_table())
  - Note: create_thread() also calls setup_page_table

Kernel page tables and Process page tables



Some clarifications:

- It is OK to setup only one page table for each of the following:

  kernel, process' data/code and process' user-stack.
  (We assume that our data/code/stack size is not too big.)
- The page directories and page tables are themselves pages and must be allocated using page_alloc()

Setup Kernel Page Table

- Allocate and pin two physical pages: one for kernel page directory and the other for kernel page table
  - Do we need to allocate pages for kernel code/data?
- Fill in the kernel page table.
  - What value should be filled in the base_addr field and the protection bits?

Setup Kernel Page Table(cont'd)

- Set US bit for video memory area (SCREEN_ADDR in common.h)
  - User process' require direct access
  - One page is enough
- Don't forget to map kernel page table into kernel page directory
- For threads, just store the address of the kernel page directory into the pcb

Set up a Process' Page Tables

- Allocate and pin four physical pages for each of the following:
  - Page directory, page table for code/data, page table for stack, and stack page
- Page Table entries in the Page Directory that point to kernel page tables should be user accessible
  - However, the kernel pages themselves should not be user accessible, except for video memory

Set up a Process' Page Tables(cont'd)

- Map the page tables into the page directory
- Fill in the page table for code/data pages
  - Which bits should be set?
- Fill in the page table for user stack page
  - Which bits should be set here?
- Don't forget to store the physical address of the page directory into
  - pcb->page_directory

Paging Mechanism

- After init_memory(), the kernel enables paging mode by setting CR0[PG] to one
  - Done in kernel.c
- In dispatch(), the kernel load CR3 register with current_running->page_directory
  - Done in scheduler.c

Paging Mechanism(Cont'd)

- When the physical page of a virtual address is not present in memory(the P bit is not set), the MMU hardware will trigger a page fault interrupt (int 14).
- The exception handler saves the faulting virtual address in *current_running->fault_addr*

  and then calls page_fault_handler()
  - done in interrupt.c

Page Fault Handler

- That's what you are to implement
- Only code/data pages will incur page fault
  - all other pages (page directory, page tables, stack page) are pinned in memory
- So assume the page table is always there and go directly to find the corresponding entry for the faulting virtual address
  - You should never page fault on a page directory or page table access

Page Fault Handler(Cont'd)

- Allocate a physical page
  - Swap out another page if no free page is available
- Fill in the page_map structure
  - Discussed in more detail later
- Swap in the page from disk and map the virtual page to the physical page
  - Similar to last assignment, use USB disk as backing store

Physical Page Management—The page_map structure

- Defined in memory.c
- An array that maintains the management information of each physical page. All physical pages are indexed by a page #
- Fields in each page_map structure
  - The pcb that owns the page
  - Page_aligned virtual address of the page
  - The page table entry that points to this page
  - Pinned or not

Page Allocation

- Implement page_alloc() in memory.c
- A simple page allocation algorithm

```
If (there is a free page)
   allocate it
Else
   swap out a page and allocate it
```

Page Allocation(Cont’d)

- How do we know whether there is a free page and where it is?
- If no free pages, which page to swap out?
  - Completely at your discretion
- Be careful not to swap out a pinned page

Swap in and Swap out

- From where and to where?
  - The process’ image is on the USB disk
  - Location and size are stored in pcb->swap_loc and pcb->swap_size
  - Note: swap_loc, swap_size is in term of sectors!
- The read()/write() utilities will be useful (usb functions)
- If the dirty bit (D bit) of the page table entry is clear, do you still need to write the page back?

Swap in and Swap out(Cont'd)

- Be careful when reading or writing
  - The images on disk are sector-aligned (512 bytes) not page-aligned (4KB)
  - Only swap in the data belonging to this process
  - Be careful not to overwrite other process's image when swapping out
  - Example: Swapping in a page of process 1, but the page on the disk actually contains 3 sectors of process 1 followed by 5 sectors of process 2
  - Don't forget to modify the protection bits of the corresponding page table entry after swapping in or swapping out

Swap in and Swap out (Cont'd)

- Invalidate TLB entry when swapping out a page.
  - Use invalidate_page() which is done in memory.c
- Note: we do not have different swap space for different instances of same process. When we swap a page out for a process, that page will be written to the space allocated to store that process on disk.
- So in our implementation, each process can only be started once.

Synchronization Issue

- The page map array is accessed and modified by multiple processes during setup_page_table() and page_fault_handler().
- So what should we do?

Some clarifications:

- Only the process' code/data pages could be swapped in or out. The following pages are allocated for once and pinned in memory for ever:

  Page directories, page tables, user stack pages
- It is OK not to reclaim the pages when a process exits

Summary

- You need to implement the following three functions in memory.c:

  init_memory(), setup_page_table(pcb_t *), page_fault_handler()

- You need also implement the following auxiliary functions and use them in the above three functions:

  page_alloc(), page_replacement_policy(), page_swap_out(), page_swap_in()

- Add whatever other auxiliary functions you need to make your code more readable

Extra Credit

- FIFO replacement policy
  - Queue structure
- FIFO with second chance
  - Use accessed bit
- You may need to modify the page_map structure we discussed here

About design review

Do you prefer:

- Submit a write up of your design via email only.
- Signup for individual review with TA. (You would still need to do the writeup).

- If we decide to use email, we can still arrange individual group to do review with TA if your group wants to.