Pintos Project #3
Virtual Memory

CS3204: Operating System
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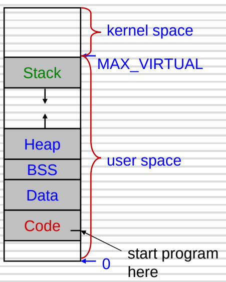
Outline

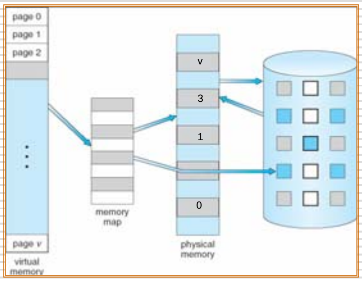
- Virtual memory concept
- Current pintos memory management
- Task
  - Lazy load
  - Stack growth
  - File memory mapping
  - Swapping
- Suggestion
  - How to start
  - Implementation order

Virtual Memory Concept



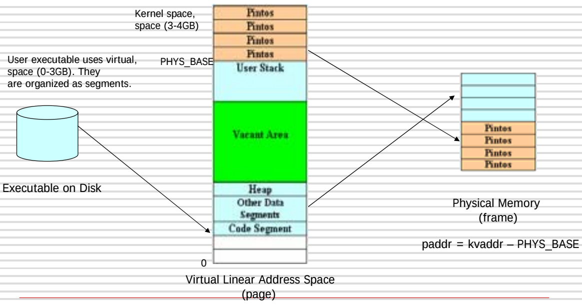
- VM is the logical memory layout for every process
  - It is divided into kernel space and user space
  - Kernel space is global (shared)
  - User space is local (individual)
- Different from physical memory
- Map to the physical memory
- How to do it? Paging!
  - Divide the VM of a process into small pieces (pages)– 4KB
  - "Randomly" permute their orders in PM

Virtual Memory Mapping



- Page
  - 4KB in VM
- Frame
  - 4KB in PM
- One to one mapping

Pintos Virtual Memory Management

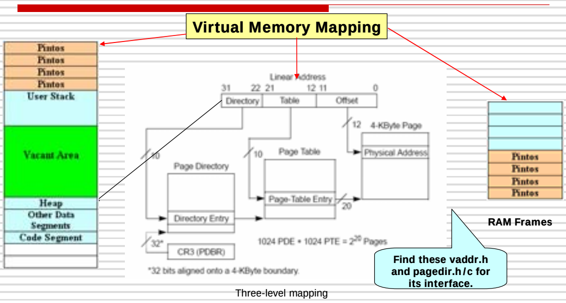


Pintos Virtual Memory Mapping

```
                        +----------+
       .--------------->|Page Table|-----------.
      /                 +----------+           |
  0   |  12 11 0                           0   V  12 11 0
 +---------+----+                          +---------+----+
 |Page Nr  | Ofs|                          |Frame Nr | Ofs|
 +---------+----+                          +---------+----+
  Virt Addr    |                            Phys Addr   ^
                \_______________________________________/
```

- Virtual address (31–12: page number, 11–0: offset)
- Physical address (31-12: frame number, 11-0: offset)
- Two-level mapping
  - Page number finds to the corresponding frame
  - Page offset finds to the corresponding byte in the frame

Pintos Virtual Memory Mapping…



Three-level mapping

Current Status (Before project 3)

- Support multiprogramming
- Load the entire data, code and stack segments into memory before executing a program (see load() in process.c)
- Fixed size of stack (1 page) to each process
- A restricted design!

Project 3 Requirement

- Lazy load
  - Do not load any page initially
  - Load one page from executable when necessary
- Stack growth
  - Allocate additional page for stack when necessary
- File memory mapping
  - Keep one copy of opened file in memory
  - Keep track of which memory maps to which file
- Swapping
  - If run out of frames, select one using frame
  - Swap it out to the swap disk
  - Return it as a free frame

Step 1: Frame "Table"

- Functionalities
  - Keep track all the frames of physical memory used by the user processes
  - Record the statuses of each frame, such as
    - Thread it belongs to (if any!)
    - Page table entry it corresponds to (if any!)
    - … (can be more)
- Implementations (two possible approaches)
  - 1. Modify current frame allocator "palloc_get_page(PAL_USER)"
  - 2. Implement your own frame allocator on top of "palloc_get_page(PAL_USER)" without modifying it. (Recommended)
  - Have a look at "init.c" and "palloc.c" to understand how they work
  - Not necessary to use hash table (need figure out by yourself)
- Usage
  - Frame table is necessary for physical memory allocation and is used to select victim when swapping.

Step 2: Lazy Loading

- How does pintos load executables?
  - Allocate a frame and load a page of executable from file disk into memory
- Before project 3
  - Pintos will initially load all pages of executable into physical memory
- After project 3
  - Load nothing except setup the stack at the beginning
  - When executing the process, a page fault occurs and the page fault handler checks where the expected page is: in executable file (i.e. hasn't loaded yet)? in swap disk (i.e. swapped out already)?
  - If in executable, you need to load the corresponding page from executable
  - If in swap disk, you need to load the corresponding page from swap disk
  - Page fault handler needs to resume the execution of the process after loading the page

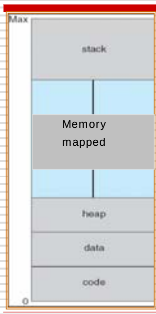
Step 3: Supplemental Page Table

- Functionalities
  - Your "s-page table" must be able to decide where to load executable and which corresponding page of executable to load
  - Your "s-page table " must be able to decide how to get swap disk and which part (in sector) of swap disk stores the corresponding page
- Implementation
  - Use hash table (recommend)
- Usage
  - Rewrite load_segment() (in process.c) to populate s-page table without loading pages into memory
  - Page fault handler then loads pages after consulting s-page table

Step 4: Stack Growth

- Functionalities
  - Before project 3: user stack is fixed with size of 1 page, i.e. 4KB
  - After project 3: user stack is allows to allocate additional pages as necessary
- Implementation
  - If the user program exceeds the stack size, a page fault will occur
  - Catch the stack pointer, esp, from the interrupt frame
  - In page fault handler, you need to determine whether the faulted address is "right below" the current end of the stack
    - Whether page fault is for lazy load or stack growth
    - Don't consider fault addresses less than esp - 32
  - Calculate how many additional pages need to be allocated for stack; or just allocated faulting page.
  - You must impose an absolute limit on stack size, STACK_SIZE
    - Consider potential for stack/heap collisions

Step 5: File Memory Mapping



- Functionalities
  - Make open files accessible via direct memory access – "map" them
    - Storing data will write to file
    - Read data must come from file
  - If file size is not multiple of PGSIZE—sticks-out, may cause partial page – handle this correctly
  - Reject mmap when: zero address or length, overlap, or console file (tell by fd)

Step 5: File Memory Mapping…

- Implementations
  - Use "fd" to keep track of the open files of a process
  - Design two new system calls: mapid_t mmap(fd, addr) and void munmap(mapid_t)
  - Mmap() system call also populates the s-page table
  - Design a data structure to keep track of these mappings (need figure out by yourself)
  - We don't require that two processes that map the same file see the same data
  - We do require that mmap()'ed pages are
    - Loaded lazily
    - Written back only if dirty
    - Subject to eviction if physical memory gets scarce

Step 6: Swap "table"

- Functionalities
  - When out of free frames, evict a page from its frame and put a copy of into swap disk, if necessary, to get a free frame — "swap out"
  - When page fault handler finds a page is not memory but in swap disk, allocate a new frame and move it to memory — "swap in"
- Implementation
  - Need a method to keep track of whether a page has been swapped and in which part of swap disk a page has been stored if so
  - Not necessary to use hash table (need figure out by yourself)
  - Key insights: (1) only owning process will ever page-in a page from swap; (2) owning process must free used swap slots on exit

Step 7: Frame Eviction

- Implementations
  - The main purpose of maintaining frame table is to efficiently find a victim frame for swapping
  - Choose a suitable page replacement algorithm, i.e. eviction algorithm, such as second chance algorithm, additional reference bit algorithm etc. (See 9.4 of textbook)
  - Select a frame to swap out from frame table
    - **Unfortunately, frame table entry doesn't store access bits**
    - Refer frame table entry back to the page table entry (PTE)
    - Use accessed/dirty bit in PTE (must use pagedir_* function here to get hardware bit.)
  - Send the frame to swap disk
    - Prevent changes to the frame during swapping first
  - Update page tables (both s-page table and hardware page table via pagedir_* functions) as needed

Step 8: On Process Termination

- Resource Management
  - Destroy your supplemental page table
  - Free your frames, freeing the corresponding entries in the frame table
  - Free your swap slots (if any) and delete the corresponding entries in the swap table
  - Close all files: if a file is mmapped + dirty, write the dirty mmapped pages from memory back to the file disk

Important Issues

- Synchronization
  - Allow parallelism of multiple processes
  - Page fault handling from multiple processes must be possible in parallel
  - For example, if process A's page fault needs I/O (swapping or lazy load); and if process B's page fault does not need I/O (stack growth or all '0' page), then B should go ahead without having to wait for A.

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Implementation Order Suggestions

- Pre-study
  - Understand memory & virtual memory (Lecture slides and Ch 8 & 9 of the textbook)
  - Understand project specification (including Appendix A.6, A.7 and A.8)
  - Understand the important pieces of source code (process.c: load_segment(), exception.c: page_fault())
- Try to pass all the test cases of project 2
  - At least, argument passing and system call framework should work
- Frame table management

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Implementation Order Suggestions…

- Supplemental page table management
- Run regression test cases from project 2
  - They are already integrated in the P3 test cases
  - You kernel with lazy load should pass all the regression test cases at this point
- Implement stack growth and file memory mapping in parallel
- Swapping
  - Implement the page replacement algorithm
  - Implement "swap out" & "swap in" functionality

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Other Suggestions

- Working the VM directory
  - Create your page.h, frame.h, swap.h as well as page.c, frame.c, swap.c in VM directory
  - Add your additional files to the makefile: Makefile.build
- Keep an eye on the project forum
- Start the design document early
  - It counts 50% of your project scores!
  - Its questions can enlighten your design!
  - Is shared this time (1 per group)

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Design Milestone

- Decide on the data structures
  - Data structures for s-page table entry, frame table entry, swap table entry
  - Data structures for the "tables" (not necessary a table) such as hash table? array? list? Or bitmap?
  - Should your "tables" be global or per-process?
- Decide the operations for the data structures
  - How to populate the entries of your data structures
  - How to access the entries of your data structures
  - How many entries your data structure should have
  - When & how to free or destroy your data structure
- Deadline
  - October 24th 11:59pm, no extensions

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End

- Questions?
- Good luck!

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