Project 3: Virtual Memory

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Introduction (1)

- Paging in the x86 architecture

*32 bits aligned onto a 4-KByte boundary.
Introduction (2)

- Current Pintos VM implementation
  - Use paging
  - Page size: 4KB
  - Each process has its own page tables
    - The page directory is allocated when the process is created
      (pagedir_create() @ userprog/pagedir.c)
    - (struct thread *) t->pagedir points to the page directory
      (load() @ userprog/process.c)
    - The (secondary) page tables are dynamically created if necessary
      (lookup_page() @ userprog/pagedir.c)
    - For kernel region, processes have the same mapping
      (PHYS_BASE ~ 0xffffffff)
• No demand paging
  – When a process is created, all the contents of code and data
    segments are read into the physical memory
    (load_segment() @ userprog/process.c)

• Fixed stack size
  – Only one stack page is allocated to each process
    (setup_stack() @ userprog/process.c)

• No page faults in the user mode
  – Everything needed by each process is in the physical memory

• Page faults may occur only in the kernel mode
  – If you use the optimistic approach to accessing arguments
  – When invalid pointers are passed via system calls
Project 3 Overview

- **Requirements**
  - Lazy loading (or demand paging)
  - Swapping in/out pages from/to swap disk
  - Dynamic stack growth
  - Memory mapped files
Lazy Loading (1)

Why?

• An executable file holds code and data images
• A process will not need all the pages immediately

How to?

• Use the executable file as the backing store
  – Only when a page is needed at run time, load the corresponding code/data page into the physical memory
  – Loaded pages will have valid PTEs

• Handling page faults
  – Accesses to not-yet-loaded pages will cause page faults
  – Find the corresponding location in the executable file
  – Read in the page from the executable file
  – Setup the corresponding PTE
Lazy Loading (2)

- **Loading code/data from the executable file**
  - In `load_segment()` @ `userprog/process.c`
  - Each page is filled with data using “page_zero_bytes” and “page_read_bytes”
    - page_zero_bytes + page_read_bytes = PGSIZE
  - All zeroed page (page_zero_bytes == PGSIZE)
    - Allocate a new page and initialize it with zeroes
  - Full code/data page (page_read_bytes == PGSIZE)
    - Allocate a new page and read its contents from the executable file
  - Partial page (0 < page_read_bytes < PGSIZE)
    - Read page_read_bytes from the executable file and fill the rest of the page with zeroes
Lazy Loading (3)

- **The supplemental page table**
  - The page table with additional data about each page
  - Main purposes
    - On a page fault, find out what data should be there for the faulted virtual page
    - On a process termination, decide what resources to free
  - Possible organizations
    - Per-segment
    - Per-page
  - Implementation
    - You can use any data structure for the supplemental page table.
    - `<hash.h>` will be useful (lib/kernel/hash.[ch])
Lazy Loading (4)

- **Strategy**

  1. Get the information on the faulted page
  2. Allocate a new frame
  3. Read from the executable file
  4. Update information
  5. Install the new page
Swapping (1)

- Why?
  - You may run out of the physical memory
  - Your program’s memory footprint can be larger than the physical memory size

- How to?
  - Find a victim page in the physical memory
  - Swap out the victim page to the swap disk
  - Extend your supplemental page table to indicate the victim page has been swapped out
  - When the page is accessed later, swap in the page from the swap disk to the physical memory
### Swapping (2)

#### Swap disk

- Use the following command to create an 4 MB swap disk in the `vm/build` directory
  ```bash
  $ pintos-mkdisk swap.dsk 4
  ```
- Alternatively, you can tell Pintos to use a temporary 4-MB swap disk for a single run with `-swap-disk=4`
  - Used during "make check"
- A swap disk consists of swap slots
  - A swap slot is a continuous, page-size region of disk space on the swap disk

![Swap disk diagram](image)
Swapping (3)

- **Accessing swap disk**
  - The swap disk is automatically attached as hd1:1 when you run Pintos.
  - Use the disk interface in `devices/disk.h`
    - A size of a disk sector is 512 bytes
    - You can read or write one sector at a time

```c
struct disk *disk_get (int chan_no, int dev_no);
disk_sector_t disk_size (struct disk *);
void disk_read (struct disk *, disk_sector_t, void *);
void disk_write (struct disk *, disk_sector_t, const void *);
```
Swapping (4)

- Managing swap slots
  - Pick an unused swap slot for evicting a page from its from to the swap disk
  - Free a swap slot when its page is read back or the process is terminated
  - Allocate lazily, i.e., only when they are actually required by eviction

- The swap table
  - The swap table tracks in-use and free swap slots
  - `<bitmap.h>` will be useful (lib/kernel(bitmap.[ch]))
Swapping (5)

- Page replacement policy
  - You should implement a global page replacement algorithm that approximates LRU
    - Do not use FIFO or RANDOM
    - The “second chance” or “clock” algorithm is OK
    - Bonus if you implement your own page replacement policy better than the “second chance” algorithm
  - Get/Clear Accessed and Dirty bits in the PTE
    - pagedir_is_dirty(), pagedir_set_dirty()
    - pagedir_is_accessed(), pagedir_set_accessed()
  - Other processes should be able to run while you are performing I/O due to page faults
    - Some synchronization effort will be required
Swapping (6)

- The frame table
  - Allows efficient implementation of eviction policy
  - One entry for each frame that contains a user page
    - Each entry contains a pointer to the page, if any, that currently occupies it, and other data of your choice
  - Use the frame table while you choose a victim page to evict when no frames are free

- Code pages can be shared among those processes created from the same executable file (optional)
Swapping (7)

- **User pool vs. kernel pool**
  - The physical memory is divided into the user pool and the kernel pool
    - Running out of pages in the user pool just causes user programs to page
    - Running out of pages in the kernel pool means a disaster
    - The size of the user pool can be limited (–ul option)
  - The frames used for user pages should be obtained from the “user pool”
    - By calling `palloc_get_page` (PAL_USER)
Swapping (8)

- **Frame allocation**
  - On top of the current page allocator (threads/palloc.c)
    - `palloc_get_page()`, `palloc_free_page()`
  - If there are free frames in the user pool, allocate one by calling `palloc_get_page()`
  - If none is free
    - Choose a victim page using your page replacement policy
    - Remove references to the frame from any page table that refers to it
    - If the frame is modified, write the page to the file system or to the swap disk
    - Return the frame
Stack Growth (1)

- Growing the stack segment
  - Allocate additional pages as necessary
  - Devise a heuristic that attempts to distinguish stack accesses from other accesses
    - Bug if a program writes to the stack below the stack pointer
    - However, in x86, it is possible to fault 4 ~ 32 bytes below the stack pointer
  - You may impose some absolute limit on stack size
  - The first stack page need not be allocated lazily
    - The page is initialized with the command line arguments
  - All stack pages should be candidates for eviction
    - An evicted stack page should be written to swap
Stack Growth (2)

- How to obtain the user stack pointer?
  - You need the current value of the user program’s stack pointer on page fault
    - Compare it with the faulted address
  - When the page fault occurred in the user mode
    - Use (struct intr_frame *) f->esp
  - When the page fault occurred in the kernel mode
    - struct intr_frame is not saved by the processor
    - (struct intr_frame *) f->esp yields an undefined value
    - Save esp into struct thread on the initial transition from user to kernel mode
Memory Mapped Files (1)

- **Example**
  - Writes the contents of a file to the console

```c
#include <stdio.h>
#include <syscall.h>
int main (int argc, char *argv[])
{
    void *data = (void *) 0x10000000;

    int fd = open (argv[1]);
    mapid_t map = mmmap (fd, data);
    write (1, data, filesize(fd));
    munmap (map);
    return 0;
}
```
Memory Mapped Files (2)

- System calls to implement

```c
mapid_t mmap (int fd, void *addr);
void munmap (mapid_t mapping);
```

- mmap() fails if
  - fd is 0 or 1
  - The file has a length of zero bytes
  - addr is 0
  - addr is not page-aligned
  - The range of pages mapped overlaps any existing set of mapped pages

- All mappings are implicitly unmapped when a process exits
Managing mapped files

- Lazily load pages in mmap regions
  - For the final mapped page, set the bytes beyond the end of the file to zero
- Use the mmap’d file itself as backing store for mapping
  - All pages written to by the process are written back to the file
- Closing or removing a file does not unmap any of its mappings
  - Once created, a mapping is valid until munmap() is called or the process exits
Summary (1)

- Pages
  - Code page (clean)
  - Data page (clean/dirty)
  - Stack page (dirty)
  - mmaped page (clean/dirty)
Summary (2)

- **When you attach a new frame,**
  - It may be just initialized to zero
  - It may be read from a file
  - It may be read from a swap slot

- **When you evict a frame,**
  - It may be just dropped
  - It may be swapped out to a swap slot
  - It may be written to a file
Tips (1)

- **Suggested order of implementation**
  - Lazy loading
    - Modify `load_segment()` and `page_fault()`
    - Construct the supplemental page table
    - You should be able to run all user programs of Project 2
  - Frame allocation/deallocation layer
    - Add a new interface that can allocate or free a frame
    - Construct the frame table as you allocate a new frame
    - Assume there is enough physical memory
      - No eviction is necessary
    - You should be able to run all user programs of Project 2
Tips (2)

- **Suggested order of implementation (cont’d)**
  - **Page replacement policy**
    - Develop your own page replacement policy
    - Need to interact with the supplemental page table and the frame table
    - First, try to evict read-only pages and make sure it has no problem
    - And then, implement the swap table and test your code to access the swap disk
    - Finally, implement the full-fledged page replacement policy
  - **Stack growth**
    - Extend your page fault handler
  - **Memory mapped files**
Tips (3)

- No files in the vm directory
  - You should add your files in the directory
  - The Pintos documentation says...

```
    vm/frame.c | 162 ++++++++  
    vm/frame.h |  23 +      
    vm/page.c  | 297 ++++++++++++++++++++  
    vm/page.h  |  50 ++      
    vm/swap.c  |   85 +++     
    vm/swap.h  |     11     
```

- Adding your own source files (src/Makefile.build)
Submission

- **Due**
  - December 12, 11:59PM
  - Fill out the design document (vm.txt) and put it in your source tree (pintos/src/vm)
  - Tar and gzip your Pintos source codes
    
    ```bash
    $ cd pintos
    $ (cd src/vm; make clean)
    $ tar cvzf TeamName.tar.gz ./src
    ```
  - Send it to the instructor via e-mail (gkm2164@gmail.com)
  - Hand in printed version of design document (vm.txt) on December 14(TUE)