Project 3: Virtual Memory

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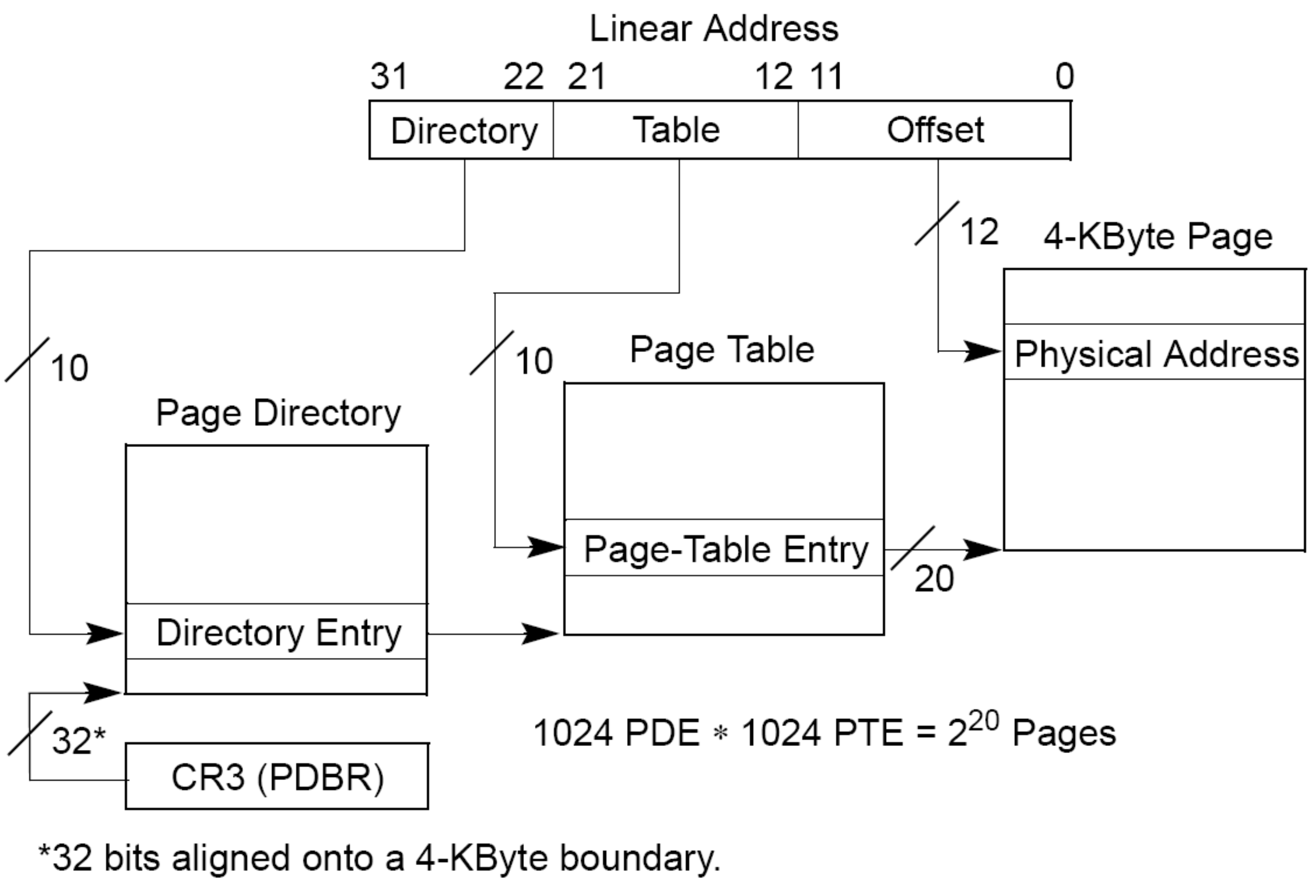
Introduction (1)

- **Paging in the x86 architecture**



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`)

Introduction (3)

- **Current Pintos VM implementation (cont'd)**
  - 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)

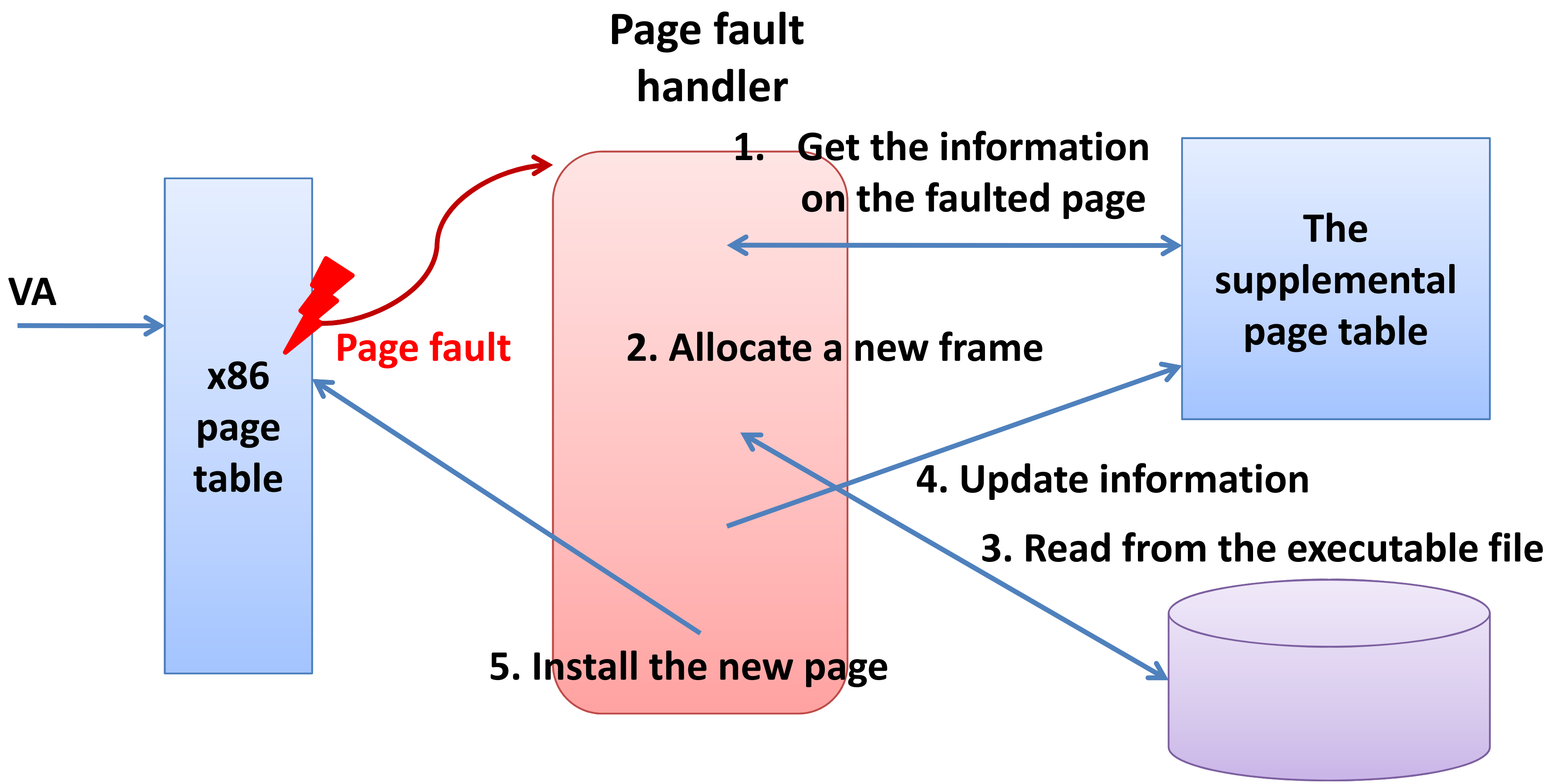
- **Loading code/data from the executable file**
  - In `load_segment() @ userprog/process.c`
  - Each page is filled with data using "`page_zero_bytes`" and "`page_read_bytes`"
    - `page_zero_bytes + page_read_bytes = PGSIZE`
  - All zeroed page (`page_zero_bytes == PGSIZE`)
    - Allocate a new page 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



Swapping (1)

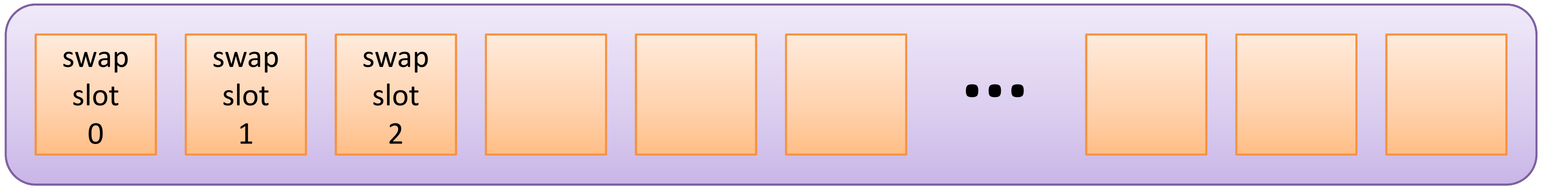
- **Why?**
  - You may run out of the physical memory
  - Your program's memory footprint can be larger than the physical memory size
- **How to?**
  - Find a victim page in the physical memory
  - Swap out the victim page to the swap disk
  - Extend your supplemental page table to indicate the victim 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

```
$ 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



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

```
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

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

    int fd = open (argv[1]);
    mapid_t map = mmap (fd, data);
    write (1, data, filesize(fd));
    munmap (map);
    return 0;
}
```

Memory Mapped Files (2)

- **System calls to implement**

```
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 exisitng set of mapped pages
- All mappings are implicitly unmapped when a process exits

Memory Mapped Files (3)

- **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`)

```
userprog_SRC += userprog/gdt.c          # GDT initialization.
userprog_SRC += userprog/tss.c          # TSS management.

# No virtual memory code yet.
vm_SRC += vm/page.c                     # Some file.
vm_SRC += vm/frame.c
vm_SRC += vm/swap.c

Filesystem code.
"Makefile.build" 107 lines --59%--                    64,1          56%
```

Submission

- **Due**
  - December 15, 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

```
$ cd pintos
$ (cd src/vm; make clean)
$ tar cvzf TeamName.tar.gz ./src
```

  - Send it to the instructor via e-mail (NOT to the GoogleGroups!!)
  - Hand in the printed version of your design document during the demo session (after final exam)