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4. Project 3: Virtual Memory

By now you should have some familiarity with the inner workings of Pintos. Your OS can properly handle multiple threads of execution with proper synchronization, and can load multiple user programs at once. However, the number and size of programs that can run is limited by the machine's main memory size. In this assignment, you will remove that limitation.

You will build this assignment on top of the last one. Test programs from project 2 should also work with project 3. You should take care to fix any bugs in your project 2 submission before you start work on project 3, because those bugs will most likely cause the same problems in project 3.

You will continue to handle Pintos disks and file systems the same way you did in the previous assignment (see section 3.1.2 Using the File System).

4.1 Background

4.1.1 Source Files

You will work in the "vm" directory for this project. The "vm" directory contains only "Makefile"s. The only change from "userprog" is that this new "Makefile" turns on the setting "`-DVM`". All code you write will be in new files or in files introduced in earlier projects.

You will probably be encountering just a few files for the first time:

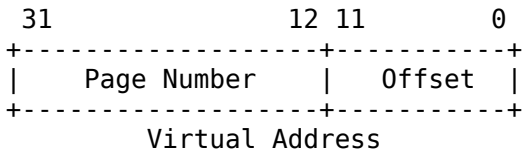
"devices/block.h"
"devices/block.c"
: Provides sector-based read and write access to block device. You will use this interface to access the swap partition as a block device.

4.1.2 Memory Terminology

Careful definitions are needed to keep discussion of virtual memory from being confusing. Thus, we begin by presenting some terminology for memory and storage. Some of these terms should be familiar from project 2 (see section 3.1.4 Virtual Memory Layout), but much of it is new.

4.1.2.1 Pages

A *page*, sometimes called a *virtual page*, is a continuous region of virtual memory 4,096 bytes (the *page size*) in length. A page must be *page-aligned*, that is, start on a virtual address evenly divisible by the page size. Thus, a 32-bit virtual address can be divided into a 20-bit *page number* and a 12-bit *page offset* (or just *offset*), like this:

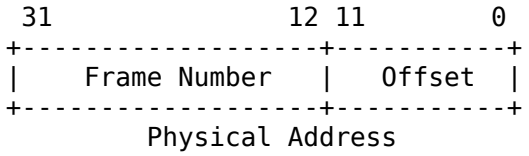


Each process has an independent set of *user (virtual) pages*, which are those pages below virtual address PHYS_BASE, typically 0xc0000000 (3 GB). The set of *kernel (virtual) pages*, on the other hand, is global, remaining the same regardless of what thread or process is active. The kernel may access both user and kernel pages, but a user process may access only its own user pages. See section 3.1.4 Virtual Memory Layout, for more information.

Pintos provides several useful functions for working with virtual addresses. See section A.6 Virtual Addresses, for details.

4.1.2.2 Frames

A *frame*, sometimes called a *physical frame* or a *page frame*, is a continuous region of physical memory. Like pages, frames must be page-size and page-aligned. Thus, a 32-bit physical address can be divided into a 20-bit *frame number* and a 12-bit *frame offset* (or just *offset*), like this:



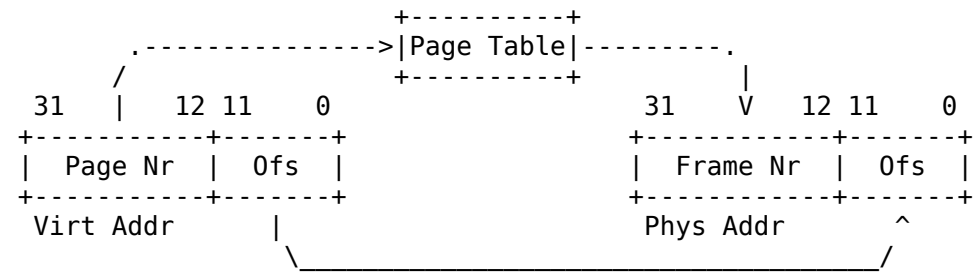
The 80*x*86 doesn't provide any way to directly access memory at a physical address. Pintos works around this by mapping kernel virtual memory directly to physical memory: the first page of kernel virtual memory is mapped to the first frame of physical memory, the second page to the second frame, and so on. Thus, frames can be accessed through kernel virtual memory.

Pintos provides functions for translating between physical addresses and kernel virtual addresses. See section A.6 Virtual Addresses, for details.

4.1.2.3 Page Tables

In Pintos, a *page table* is a data structure that the CPU uses to translate a virtual address to a physical address, that is, from a page to a frame. The page table format is dictated by the 80*x*86 architecture. Pintos provides page table management code in "pagedir.c" (see section A.7 Page Table).

The diagram below illustrates the relationship between pages and frames. The virtual address, on the left, consists of a page number and an offset. The page table translates the page number into a frame number, which is combined with the unmodified offset to obtain the physical address, on the right.



4.1.2.4 Swap Slots

A *swap slot* is a continuous, page-size region of disk space in the swap partition. Although hardware limitations dictating the placement of slots are looser than for pages and frames, swap slots should be page-aligned because there is no downside in doing so.

4.1.3 Resource Management Overview

You will need to design the following data structures:

Supplemental page table

> Enables page fault handling by supplementing the hadrware page table. See section 4.1.4 Managing the Supplemental Page Table.

Frame table

> Allows efficient implementation of eviction policy. See section 4.1.5 Managing the Frame Table.

Swap table

> Tracks usage of swap slots. See section 4.1.6 Managing the Swap Table.

Table of file mappings

Processes may map files into their virtual memory space. You need a table to track which files are mapped into which pages.

You do not necessarily need to implement four completely distinct data structures: it may be convenient to wholly or partially merge related resources into a unified data structure.

For each data structure, you need to determine what information each element should contain. You also need to decide on the data structure's scope, either local (per-process) or global (applying to the whole system), and how many instances are required within its scope.

To simplify your design, you may store these data structures in non-pageable memory. That means that you can be sure that pointers among them will remain valid.

Possible choices of data structures include arrays, lists, bitmaps, and hash tables. An array is often the simplest approach, but a sparsely populated array wastes memory. Lists are also simple, but traversing a long list to find a particular position wastes time. Both arrays and lists can be resized, but lists more efficiently support insertion and deletion in the middle.

Pintos includes a bitmap data structure in "lib/kernel/bitmap.c" and "lib/kernel/bitmap.h". A bitmap is an array of bits, each of which can be true or false. Bitmaps are typically used to track usage in a set of (identical) resources: if resource *n* is in use, then bit *n* of the bitmap is true. Pintos bitmaps are fixed in size, although you could extend their implementation to support resizing.

Pintos also includes a hash table data structure (see section A.8 Hash Table). Pintos hash tables efficiently support insertions and deletions over a wide range of table sizes.

Although more complex data structures may yield performance or other benefits, they may also needlessly complicate your implementation. Thus, we do not recommend implementing any advanced data structure (e.g. a balanced binary tree) as part of your design.

4.1.4 Managing the Supplemental Page Table

The *supplemental page table* supplements the page table with additional data about each page. It is needed because of the limitations imposed by the page table's format. Such a data structure is often called a "page table" also; we add the word "supplemental" to reduce confusion.

The supplemental page table is used for at least two purposes. Most importantly, on a page fault, the kernel looks up the virtual page that faulted in the supplemental page table to find out what data should be there. Second, the kernel consults the supplemental page table when a process terminates, to decide what resources to free.

You may organize the supplemental page table as you wish. There are at least two basic approaches to its organization: in terms of segments or in terms of pages. Optionally, you may use the page table itself as an index to track the members of the supplemental page table. You will have to modify the Pintos page table implementation in "pagedir.c" to do so. We recommend this approach for advanced students only. See section A.7.4.2 Page Table Entry Format, for more information.

The most important user of the supplemental page table is the page fault handler. In project 2, a page fault always indicated a bug in the kernel or a user program. In project 3, this is no longer true. Now, a page fault might only indicate that the page must be brought in from a file or swap. You will have to implement a more sophisticated page fault handler to handle these cases. Your page fault handler, which you should implement by modifying page_fault() in "userprog/exception.c", needs to do roughly the following:

1. Locate the page that faulted in the supplemental page table. If the memory reference is valid, use the supplemental page table entry to locate the data that goes in the page, which might be in the file system, or in a swap slot, or it might simply be an all-zero page. If you implement sharing, the page's data might even already be in a page frame, but not in the page table.

If the supplemental page table indicates that the user process should not expect any data at the address it was trying to access, or if the page lies within kernel virtual memory, or if the access is an attempt to write to a read-only page, then the access is invalid. Any invalid access terminates the process and thereby frees all of its resources.

2. Obtain a frame to store the page. See section 4.1.5 Managing the Frame Table, for details.

   If you implement sharing, the data you need may already be in a frame, in which case you must be able to locate that frame.

3. Fetch the data into the frame, by reading it from the file system or swap, zeroing it, etc.

   If you implement sharing, the page you need may already be in a frame, in which case no action is necessary in this step.

4. Point the page table entry for the faulting virtual address to the physical page. You can use the functions in "userprog/pagedir.c".

4.1.5 Managing the Frame Table

The *frame table* contains one entry for each frame that contains a user page. Each entry in the frame table contains a pointer to the page, if any, that currently occupies it, and other data of your choice. The frame table allows Pintos to efficiently implement an eviction policy, by choosing a page to evict when no frames are free.

The frames used for user pages should be obtained from the "user pool," by calling palloc_get_page(PAL_USER). You must use PAL_USER to avoid allocating from the "kernel pool," which could cause some test cases to fail unexpectedly (see Why PAL_USER?). If you modify "palloc.c" as part of your frame table implementation, be sure to retain the distinction between the two pools.

The most important operation on the frame table is obtaining an unused frame. This is easy when a frame is free. When none is free, a frame must be made free by evicting some page from its frame.

If no frame can be evicted without allocating a swap slot, but swap is full, panic the kernel. Real OSes apply a wide range of policies to recover from or prevent such situations, but these policies are beyond the scope of this project.

The process of eviction comprises roughly the following steps:

1. Choose a frame to evict, using your page replacement algorithm. The "accessed" and "dirty" bits in the page table, described below, will come in handy.

2. Remove references to the frame from any page table that refers to it.

   Unless you have implemented sharing, only a single page should refer to a frame at any given time.

3. If necessary, write the page to the file system or to swap.

The evicted frame may then be used to store a different page.

4.1.5.1 Accessed and Dirty Bits

80*x*86 hardware provides some assistance for implementing page replacement algorithms, through a pair of bits in the page table entry (PTE) for each page. On any read or write to a page, the CPU sets the *accessed bit* to 1 in the page's PTE, and on any write, the CPU sets the *dirty bit* to 1. The CPU never resets these bits to 0, but the OS may do so.

You need to be aware of *aliases*, that is, two (or more) pages that refer to the same frame. When an aliased frame is accessed, the accessed and dirty bits are updated in only one page table entry (the one

for the page used for access). The accessed and dirty bits for the other aliases are not updated.

In Pintos, every user virtual page is aliased to its kernel virtual page. You must manage these aliases somehow. For example, your code could check and update the accessed and dirty bits for both addresses. Alternatively, the kernel could avoid the problem by only accessing user data through the user virtual address.

See section A.7.3 Accessed and Dirty Bits, for details of the functions to work with accessed and dirty bits.

4.1.6 Managing the Swap Table

The swap table tracks in-use and free swap slots. It should allow picking an unused swap slot for evicting a page from its frame to the swap partition. It should allow freeing a swap slot when its page is no longer needed (such as when the process owning the page is terminated).

You may use the BLOCK_SWAP block device for swapping, obtaining the struct block that represents it by calling block_get_role(). From the "vm/build" directory, use the command pintos-mkdisk swap.dsk --swap-size=*n* to create an disk named "swap.dsk" that contains a *n*-MB swap partition. Afterward, "swap.dsk" will automatically be attached as an extra disk when you run pintos. Alternatively, you can tell pintos to use a temporary *n*-MB swap disk for a single run with "`--swap-size=n`".

Swap slots should be allocated lazily, that is, only when they are actually required by eviction. Reading data pages from the executable and writing them to swap immediately at process startup is not lazy. Swap slots should not be reserved to store particular pages.

4.1.7 Managing Memory Mapped Files

The file system is most commonly accessed with read and write system calls. A secondary interface is to "map" the file into virtual pages, using the mmap system call. The program can then use memory instructions directly on the file data.

Suppose file "foo" is 0x1000 bytes (4 kB, or one page) long. If "foo" is mapped into memory starting at address 0x5000, then any memory accesses to locations 0x5000...0x5fff will access the corresponding bytes of "foo".

Here's a program that uses mmap to print a file to the console. It opens the file specified on the command line, maps it at virtual address 0x10000000, writes the mapped data to the console (fd 1), and unmaps the file.

```
#include <stdio.h>
#include <syscall.h>
int main (int argc UNUSED, char *argv[])
{
  void *data = (void *) 0x10000000;     /* Address at which to map. */

  int fd = open (argv[1]);              /* Open file. */
  mapid_t map = mmap (fd, data);        /* Map file. */
  write (1, data, filesize (fd));       /* Write file to console. */
  munmap (map);                         /* Unmap file (optional). */
  return 0;
}
```

A similar program with full error handling is included as "mcat.c" in the "examples" directory, which also contains "mcp.c" as a second example of mmap.

Your submission must be able to track what memory is used by memory mapped files. This is necessary to properly handle page faults in the mapped regions and to ensure that mapped files do not overlap any other segments within the process.

4.2 Suggested Order of Implementation

We suggest the following initial order of implementation:

1. Frame table (see section 4.1.5 Managing the Frame Table). Change "process.c" to use your frame table allocator.

   Do not implement swapping yet. If you run out of frames, fail the allocator or panic the kernel.

   After this step, your kernel should still pass all the project 2 test cases.

2. Supplemental page table and page fault handler (see section 4.1.4 Managing the Supplemental Page Table). Change "process.c" to record the necessary information in the supplemental page table when loading an executable and setting up its stack. Implement loading of code and data segments in the page fault handler. For now, consider only valid accesses.

   After this step, your kernel should pass all of the project 2 functionality test cases, but only some of the robustness tests.

From here, you can implement stack growth, mapped files, and page reclamation on process exit in parallel.

The next step is to implement eviction (see section 4.1.5 Managing the Frame Table). Initially you could choose the page to evict randomly. At this point, you need to consider how to manage accessed and dirty bits and aliasing of user and kernel pages. Synchronization is also a concern: how do you deal with it if process A faults on a page whose frame process B is in the process of evicting? Finally, implement a eviction strategy such as the clock algorithm.

4.3 Requirements

This assignment is an open-ended design problem. We are going to say as little as possible about how to do things. Instead we will focus on what functionality we require your OS to support. We will expect you to come up with a design that makes sense. You will have the freedom to choose how to handle page faults, how to organize the swap partition, how to implement paging, etc.

4.3.1 Design Document

Before you turn in your project, you must copy the project 3 design document template into your source tree under the name "pintos/src/vm/DESIGNDOC" and fill it in. We recommend that you read the design document template before you start working on the project. See section D. Project Documentation, for a sample design document that goes along with a fictitious project.

4.3.2 Paging

Implement paging for segments loaded from executables. All of these pages should be loaded lazily, that is, only as the kernel intercepts page faults for them. Upon eviction, pages modified since load (e.g. as indicated by the "dirty bit") should be written to swap. Unmodified pages, including read-only pages, should never be written to swap because they can always be read back from the executable.

Implement a global page replacement algorithm that approximates LRU. Your algorithm should perform at least as well as the simple variant of the "second chance" or "clock" algorithm.

Your design should allow for parallelism. If one page fault requires I/O, in the meantime processes that do not fault should continue executing and other page faults that do not require I/O should be able to complete. This will require some synchronization effort.

You'll need to modify the core of the program loader, which is the loop in load_segment() in "userprog/process.c". Each time around the loop, page_read_bytes receives the number of bytes to read from the executable file and page_zero_bytes receives the number of bytes to initialize to zero following the bytes read. The two always sum to PGSIZE (4,096). The handling of a page depends on these variables' values:

- If page_read_bytes equals PGSIZE, the page should be demand paged from the underlying file on its first access.

- If page_zero_bytes equals PGSIZE, the page does not need to be read from disk at all because it is all zeroes. You should handle such pages by creating a new page consisting of all zeroes at the first page fault.

- Otherwise, neither page_read_bytes nor page_zero_bytes equals PGSIZE. In this case, an initial part of the page is to be read from the underlying file and the remainder zeroed.

4.3.3 Stack Growth

Implement stack growth. In project 2, the stack was a single page at the top of the user virtual address space, and programs were limited to that much stack. Now, if the stack grows past its current size, allocate additional pages as necessary.

Allocate additional pages only if they "appear" to be stack accesses. Devise a heuristic that attempts to distinguish stack accesses from other accesses.

User programs are buggy if they write to the stack below the stack pointer, because typical real OSes may interrupt a process at any time to deliver a "signal," which pushes data on the stack.(4) However, the 80*x*86 PUSH instruction checks access permissions before it adjusts the stack pointer, so it may cause a page fault 4 bytes below the stack pointer. (Otherwise, PUSH would not be restartable in a straightforward fashion.) Similarly, the PUSHA instruction pushes 32 bytes at once, so it can fault 32 bytes below the stack pointer.

You will need to be able to obtain the current value of the user program's stack pointer. Within a system call or a page fault generated by a user program, you can retrieve it from the esp member of the struct intr_frame passed to syscall_handler() or page_fault(), respectively. If you verify user pointers before accessing them (see section 3.1.5 Accessing User Memory), these are the only cases you need to handle. On the other hand, if you depend on page faults to detect invalid memory access, you will need to handle another case, where a page fault occurs in the kernel. Since the processor only saves the stack pointer when an exception causes a switch from user to kernel mode, reading esp out of the struct intr_frame passed to page_fault() would yield an undefined value, not the user stack pointer. You will need to arrange another way, such as saving esp into struct thread on the initial transition from user to kernel mode.

You should impose some absolute limit on stack size, as do most OSes. Some OSes make the limit user-adjustable, e.g. with the ulimit command on many Unix systems. On many GNU/Linux systems, the default limit is 8 MB.

The first stack page need not be allocated lazily. You can allocate and initialize it with the command line arguments at load time, with no need to wait for it to be faulted in.

All stack pages should be candidates for eviction. An evicted stack page should be written to swap.

4.3.4 Memory Mapped Files

Implement memory mapped files, including the following system calls.

System Call: mapid_t **mmap** (int *fd*, void **addr*)

Maps the file open as *fd* into the process's virtual address space. The entire file is mapped into consecutive virtual pages starting at *addr*.

Your VM system must lazily load pages in mmap regions and use the mmaped file itself as backing store for the mapping. That is, evicting a page mapped by mmap writes it back to the file it was mapped from.

If the file's length is not a multiple of PGSIZE, then some bytes in the final mapped page "stick out" beyond the end of the file. Set these bytes to zero when the page is faulted in from the file system, and discard them when the page is written back to disk.

If successful, this function returns a "mapping ID" that uniquely identifies the mapping within the process. On failure, it must return -1, which otherwise should not be a valid mapping id, and the process's mappings must be unchanged.

A call to mmap may fail if the file open as *fd* has a length of zero bytes. It must fail if *addr* is not page-aligned or if the range of pages mapped overlaps any existing set of mapped pages, including the stack or pages mapped at executable load time. It must also fail if *addr* is 0, because some Pintos code assumes virtual page 0 is not mapped. Finally, file descriptors 0 and 1, representing console input and output, are not mappable.

System Call: void **munmap** (mapid_t *mapping*)

Unmaps the mapping designated by *mapping*, which must be a mapping ID returned by a previous call to mmap by the same process that has not yet been unmapped.

All mappings are implicitly unmapped when a process exits, whether via exit or by any other means. When a mapping is unmapped, whether implicitly or explicitly, all pages written to by the process are written back to the file, and pages not written must not be. The pages are then removed from the process's list of virtual pages.

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, following the Unix convention. See Removing an Open File, for more information. You should use the file_reopen function to obtain a separate and independent reference to the file for each of its mappings.

If two or more processes map the same file, there is no requirement that they see consistent data. Unix handles this by making the two mappings share the same physical page, but the mmap system call also has an argument allowing the client to specify whether the page is shared or private (i.e. copy-on-write).

4.3.5 Accessing User Memory

You will need to adapt your code to access user memory (see section 3.1.5 Accessing User Memory) while handling a system call. Just as user processes may access pages whose content is currently in a file or in swap space, so can they pass addresses that refer to such non-resident pages to system calls. Moreover, unless your kernel takes measures to prevent this, a page may be evicted from its frame even while it is being accessed by kernel code. If kernel code accesses such non-resident user pages, a page fault will result.
While accessing user memory, your kernel must either be prepared to handle such page faults, or it must prevent them from occurring. The kernel must prevent such page faults while it is holding resources it would need to acquire to handle these faults. In Pintos, such resources include locks acquired by the device driver(s) that control the device(s) containing the file system and swap space. As a concrete example, you must not allow page faults to occur while a device driver accesses a user buffer passed to file_read, because you would not be able to invoke the driver while handling such faults.

Preventing such page faults requires cooperation between the code within which the access occurs and your page eviction code. For instance, you could extend your frame table to record when a page contained in a frame must not be evicted. (This is also referred to as "pinning" or "locking" the page in its frame.) Pinning restricts your page replacement algorithm's choices when looking for pages to evict, so be sure to pin pages no longer than necessary, and avoid pinning pages when it is not necessary.

4.4 FAQ

How much code will I need to write?

Here's a summary of our reference solution, produced by the diffstat program. The final row gives total lines inserted and deleted; a changed line counts as both an insertion and a deletion.

This summary is relative to the Pintos base code, but the reference solution for project 3 starts from the reference solution to project 2. See section 3.4 FAQ, for the summary of project 2.

The reference solution represents just one possible solution. Many other solutions are also possible and many of those differ greatly from the reference solution. Some excellent solutions may not modify all the files modified by the reference solution.

```
Makefile.build       |    4
devices/timer.c      |   42 ++
threads/init.c       |    5
threads/interrupt.c  |    2
threads/thread.c     |   31 +
threads/thread.h     |   37 +-
userprog/exception.c |   12
userprog/pagedir.c   |   10
userprog/process.c   |  319 +++++++++++++-----
userprog/syscall.c   |  545 ++++++++++++++++++++++++++++++-
userprog/syscall.h   |    1
vm/frame.c           |  162 +++++++++
vm/frame.h           |   23 +
vm/page.c            |  297 ++++++++++++++++
vm/page.h            |   50 ++
vm/swap.c            |   85 ++++
vm/swap.h            |   11
17 files changed, 1532 insertions(+), 104 deletions(-)
```

Do we need a working Project 2 to implement Project 3?

Yes.

How do we resume a process after we have handled a page fault?

Returning from page_fault() resumes the current user process (see section A.4.2 Internal Interrupt Handling). It will then retry the instruction to which the instruction pointer points.

Why do user processes sometimes fault above the stack pointer?

You might notice that, in the stack growth tests, the user program faults on an address that is above the user program's current stack pointer, even though the PUSH and PUSHA instructions would cause faults 4 and 32 bytes below the current stack pointer.

This is not unusual. The PUSH and PUSHA instructions are not the only instructions that can trigger user stack growth. For instance, a user program may allocate stack space by decrementing the stack pointer using a SUB $n, %esp instruction, and then use a MOV ..., m(%esp) instruction to write to a stack location within the allocated space that is *m* bytes above the current stack pointer. Such accesses are perfectly valid, and your kernel must grow the user program's stack to allow those accesses to succeed.

Does the virtual memory system need to support data segment growth?

No. The size of the data segment is determined by the linker. We still have no dynamic allocation in Pintos (although it is possible to "fake" it at the user level by using memory-mapped files). Supporting data segment growth should add little additional complexity to a well-designed system.

Why should I use PAL_USER for allocating page frames?

Passing PAL_USER to palloc_get_page() causes it to allocate memory from the user pool, instead of the main kernel pool. Running out of pages in the user pool just causes user

programs to page, but running out of pages in the kernel pool will cause many failures because so many kernel functions need to obtain memory. You can layer some other allocator on top of palloc_get_page() if you like, but it should be the underlying mechanism.

Also, you can use the "`-ul`" kernel command-line option to limit the size of the user pool, which makes it easy to test your VM implementation with various user memory sizes.

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