PROJECT 3B: PAGING – USER

Minimum Requirements: 7 public tests

TEST DISTRIBUTION

- Public tests – 9 tests | 42 points
- Release tests – 0 tests | 0 points
- Secret tests – 12 tests | 50 points

INTRO

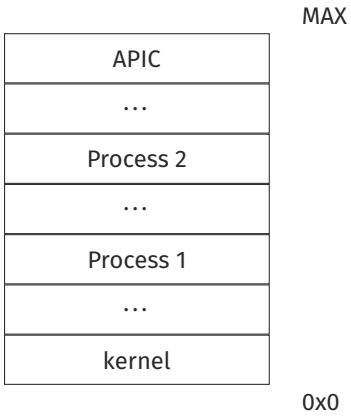
- In 3A:
  - We have already set up an identity mapping for kernel space.
  - But when setting up a user process, it still uses a kernel Malloc to malloc the user memory. (That is why VM_USER is set for kernel space in 3A, you need to unset it in 3B)
- In 3B:
  - Make each user process have its own linear address space, which means each user process is going to have its own page directory and page tables.
  - Implement demand paging and paging to disk.

VIRTUAL MEMORY

- Address translation: Virtual Addr →(segmentation address translation)→Linear Addr →(Paging address translation)→Physical Addr.
- Memory is divided into page frames. To run any program, we need to map the address of this page frames to the address space of that user process, and load the corresponding binary into the page frames.
- When the OS runs out of page frames, it can swap out some pages and store them in secondary storage. When some missing pages are accessed again, it can swap them in.
- Because of swapping, user space size is no longer limited by the physical memory size. Each user process can view its user address space from 0x0000 0000 to 0x6fff ffff, which translates into 0x8000 0000 to 0xefff ffff in kernel address. (Note: the upper limit can be different and it depends on your implementation)

LINEAR ADDRESS SPACE LAYOUT – BEFORE PAGING

- When GeekOS only works with segmentation (Linear address is the same as physical address)



LINEAR ADDRESS SPACE LAYOUT – AFTER PAGING

0xFFFF FFFF		Memory space ends
0xFEE0 0000	Kernel	APIC
0xFEC0 0000	Kernel	IOAPIC
0xF000 0000		User memory end
0xF000 0000 – argBlockSize	User	StackPointer
		Dynamically growing stack
		Heap, data, text
0x8000 1000	User	Text segment usually loaded here
0x8000 0000	User	User memory start, first page is unmapped
	Kernel	Kernel binary and gap
0x0000 0000	Kernel	Memory space start

The argument block should be placed so that it ends just before 0x70000000; the initial stack pointer should be the address of the argument block.

Notes:
0x7000 0000 is user address which corresponds to 0xF000 0000 in kernel space.

You don't actually need to put them in the exact position the spec mentions. The point here is
a) Argument block is at the bottom of the stack.
b) When the stack grows, it will not collide with APIC.
c) The stack can expand large enough to pass the tests.

But it is recommended to put it this way.

FILES TO MODIFY

- `Paging.c`
  - Map kernel space (3a)
  - Handle page fault (allocating a stack page or swapping)
  - Initialize page related data structures.
  - Manage paging file
- `uservm.c`
  - Replace userseg.c with uservm.c (replace segmentation with virtual memory).
  - All the functions implemented in userseg.c need to be re-implemented in uservm.c.
- `Mem.c`
  - Managing page frames.
- Corresponding headers
- `Main.c`
- `Makefile.common`

CHANGE MAKEFILE: MAKEFILE.COMMON

- There is a line which specifies which of userseg.c or uservm.c should be used. You can switch between them by `USER_IMP_C`.

INTRO

- Allocate page frames for the user process, fill in the two-level page tables for user processes. Load user programs into the page frames for the user processes.
- Make sure you understand the function in userseg.c before implementing its counterpart in uservm.c

USER_TO_KERNEL()

- No need to change this function, copy over from userseg. But you need to understand why it works.
- Use offset 0x8000 0000 (we will set `userContext->memory` to 0x8000 0000 in `create_user_context`).

SWITCH_TO_ADDRESS_SPACE()

- In addition to the original function, which sets segment registers, invoke `Set_PDBR` to use the page directory of the current process (`userContext->pageDir`, which will be initialized in `create_user_context`)

CREATE_USER_CONTEXT()

- Initialize the fields of `User_Context` considering paging.
- Most parts should be the same as in userseg.
- Instead of Malloc, `context->memory` should now point to the start of user address in linear address space. (spec: Set the beginning of the segments for user processes to be 0x80000000.) The size should also be changed to the size of the entire user address space in linear address space.
- Add a page directory for each user process. The page directory for a user process will contain entries that maps user linear memory to physical memory, but it will also contain entries to address the kernel memory. (The first half of the user page directory should be the same as the kernel page directory, as well as the entry for APIC and IOAPIC. You don't need to worry about the user space part here because you will map this part in `Load_User_Program`)

CREATE_USER_CONTEXT()

- Notes about LDT: since different user processes have the same value for `context->memory`, the LDTs are initialized the same way for different user processes (check the original `create_user_context` if you don't understand). You can now choose to have one global LDT for all user processes, or you can choose to preserve the one ldt-per-process approach, but now they are identical. (Refer to the LDT section in the spec.)

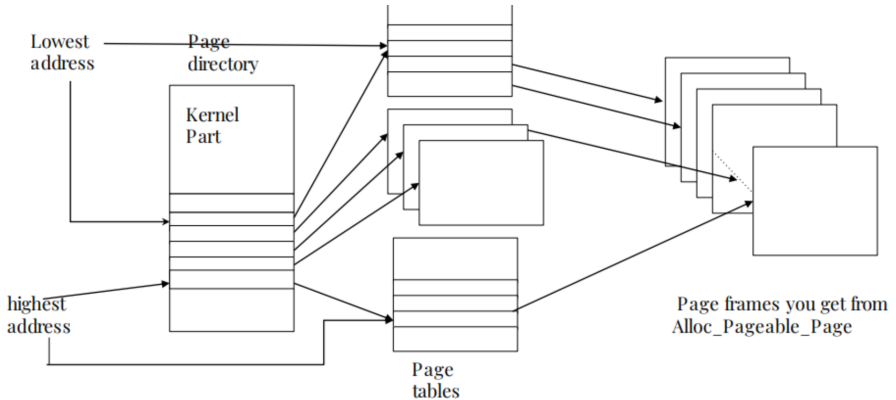
LOAD_USER_PROGRAM()

- Load the user program binary into memory and establish an address mapping.
- Go through the `Load_User_Program` in userseg.c, pay attention to how each segment is loaded into the main memory and how the argument block is formatted.
- Fill in the page table entries for the user process's text, data, and stack regions.
  - Each of these regions will consist of some number of pages allocated by the routine `Alloc_Pageable_Page`. (Hint: we need to use `Alloc_Pageable_Page` in order to fill in the baseAddress in the second level page table here, which is different from 3a where we can calculate the base address directly).
  - This routine differs from `Alloc_Page` in that the allocated page it returns will have a special flag `PAGE_PAGEABLE` set in the flags field of its entry in the struct Page data structure (see mem.h). This marks the page as eligible for being stolen and paged out to disk by the kernel when a page of memory is needed elsewhere but no free pages are available.
- Map the memory for the argument block.
- Map 2 more pages beyond argument block for the initial stack region.

LOAD_USER_PROGRAM()

- Load the binary segments into the memory.
  - Option 1: You can copy the image page by page into the physical page frames you got from last step. (NOT recommended)
  - You can follow the instruction for `Copy_To_User` except that the PDBR should be set to `userContext->pageDir` here.
- Format the argument block, it should be copied to the address as the picture of linear address space layout indicates. (Hint: you might want to look at the definition of `Format_Argument_Block`.)
- When initializing `userContext->argBlockAddr`, `userContext->stackPointerAddr`, you need to notice that they refer to user addresses.
- If (`segment->protFlags & VM_WRITE`) == 0, do not give writing permission to the pages for that segment, for protection reasons.
- If you changed PDBR in this function, reset it to the original one.
- `Round_Up_To_Page()`, `Round_Down_To_Page()` in mem.h might be useful.

LOAD_USER_PROGRAM()



Hint: a helper function that maps one page at a time is useful

DESTROY_USER_CONTEXT()

- In addition to the original implementation in userseg.c, you need to free all the things you allocated (e.g. all the user pages (for now) and pages on the paging file (after implementing swapping)).
- Useful functions: `Free_Page`
- Clean up the paging file

COPY_FROM_USER() & COPY_TO_USER()

- Set PDBR to `CURRENT_THREAD->userContext->pageDir`, so that cpu can access the user address space.
- Write a helper function to lock all the pages you are going to access (hint: clear the `PAGE_PAGEABLE` bit of `struct page::flags`), must be done with interrupts disabled or using synchronization tools to prevent the pages to be swapped out. If the page is not in memory, you need to bring it back into the memory and lock it. (You don't need to worry about this part now, you can complete this part after finishing paging to file and page replacement.)
- Use memcpy to copy from source to destination, be careful about kernel address and user address.
- Reset the `PAGE_PAGEABLE` bit. (hint: useful function `Get_Page( )`)

TEST YOUR CODE!!!

- At this point, you should be able to boot up and run shell in your GeekOS.
- Make a submission, you should be able to pass all public tests except public test 7 – rec1000.

DEMAND PAGING

- A nice benefit of paging is that it is straightforward to dynamically allocate physical memory to processes. For example, you can allow the process's stack to grow beyond its initial allocation.
- To implement stack growth, you need to modify the default page fault handler from 3a. The fault handler reads register cr2 to determine the faulting address. It also prints the errorCode defined in `InterruptState` and the fault defined in the struct `faultcode_t` in paging.h.

PAGE_FAULT_HANDLER() – STACK GROWING

- Implement demand paging based on the original function.
- Use `state->errorCode` to determine the type of page fault.
- If the address is within one page of the current stack limit, allocate a new physical page frame, map the appropriate virtual page (which expands the stack) to this physical page frame; and return normally from the handler.
- Current stack limit: you need to keep track of this.

PAGE_FAULT_HANDLER() – PAGE ON DISK

- Implement this after paging to disk is implemented.
- If it is a page that is swapped out to disk (`pte->kernelInfo == KINFO_PAGE_ON_DISK`), you need to bring it back from disk.
- Function might be useful: `GET_PDBR`, `Get_Page`, `Free_Space_On_Paging_File`
- Enable interrupts before `Alloc_Pageable_Page`/`Read_From_Paging_File`.
  - If it is disabled, it will not be able to do IO, and cannot swap in/out pages if there are no more free page frames.
- If you want to swap in a page, first you need to `Alloc_Pageable_Page`, before `Read_From_Paging_File`, you need to set the `PAGE_PAGEABLE` bit to 0, because this page could potentially get swapped out while you are writing stuff into this page. The last step is to `Free_Space_On_Paging_File` and fill in the page table entries for the page you brought in.

PAGE_FAULT_HANDLER() – PAGE ON DISK

- Allocate a new page (`Alloc_Pageable_Page`)
- Read the contents of the indicated block of space in the paging file into the allocated page (`Read_From_Paging_File`)
- Update the relevant page table entry
- Free the page-sized chunk of disk space in the paging file (`Free_Space_On_Paging_File`)

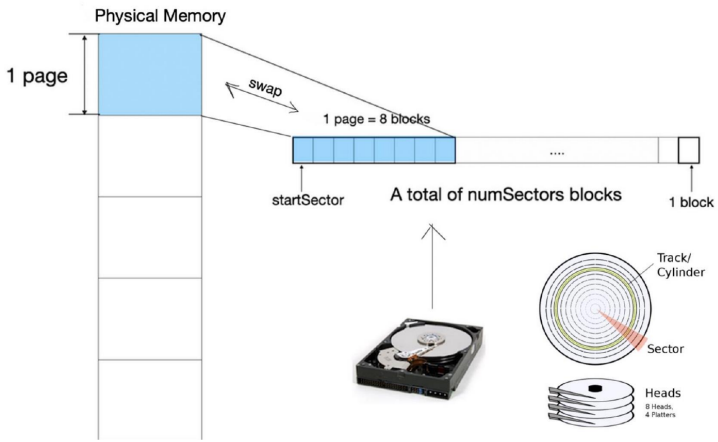
PAGE_FAULT_HANDLER() – SUMMARY

Cause	Indication	Action
Stack growing to new page	Fault is within one page of the current stack limit	Allocate a new page can continue.
Fault for page on disk	Bits in the page table indicate page is on disk	Read page from paging device and continue.
Fault for invalid address	None of the above is true	Terminate this user process.

PAGING TO DISK & PAGE REPLACEMENT

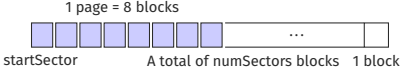
- In paging.c
  - `Init_Paging`
  - `Find_Space_On_Paging_File`
  - `Free_Space_On_Paging_File`
  - `Write_To_Paging_File`
  - `Read_From_Paging_File`
- In mem.c
  - `Alloc_Or_Reclaim_Page`
  - `Find_Page_To_Page_Out`
- In main.c
  - Add `Init_Paging`
- Also, anywhere you may want to use `KINFO_PAGE_ON_DISK` to check if the page is on disk

PAGING TO DISK & PAGE REPLACEMENT



PAGING TO DISK

- If it is a page that is swapped out to disk (`pte->kernelInfo == KINFO_PAGE_ON_DISK`), you need to bring it back from disk.
- How are paging files stored on disk?
  - The paging file consists of a group of consecutive disk blocks of size `SECTOR_SIZE` bytes.
  - Each page will consume 8 consecutive disk blocks.
  - Call `Get_Paging_Device()` will return a `Paging_Device` structure, which contains `startSector`, `numSectors` you can use.
- Disk read/write is block by block. (`Block_Write()` and `Block_Read()` in GeekOS)
- How to manage the paging files is up to you. A possible way is to make an array of pages on the disk.



PAGE OUT A PAGE

- The code to page out a page is partially implemented for you in `Alloc_Pageable_Page` in mem.c, and works as follows:
  - Find a page to page out using `Find_Page_To_Page_Out` which you will implement in mem.c. (This function relies on the clock field in the Page structure which you must manage)
  - Find space on the paging file using `Find_Space_On_Paging_File` which you will implement in paging.c
  - Write the page to the paging file using `Write_To_Paging_File` which you will implement in paging.c
  - Update the page table entry for the page to clear present bit.
  - Update the `pageBaseAddr` in the page table entry to be the first disk block that contains the page.
  - Update the `kernelInfo` bits (3 bits holding a number from 0-7) in the page table entry to be `KINFO_PAGE_ON_DISK` (used to indicate that the page is on disk rather than not valid).
  - Flush the TLB using `Flush_TLB` from lowlevel.asm.

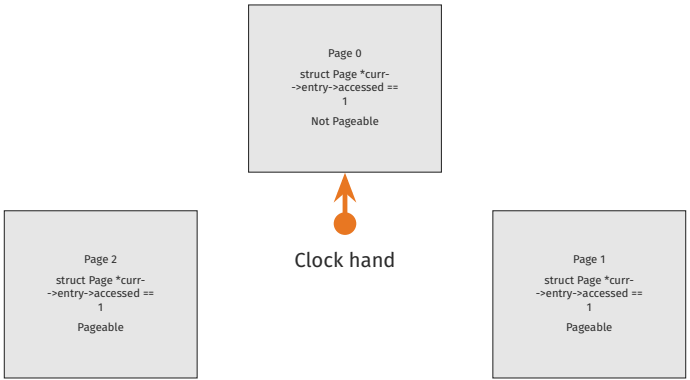
PAGING TO DISK

- In paging.c:
  - `Init_Paging`
    - Initialize your paging file structure with `Get_Paging_Device()` and the variables (`numSectors`) in the `Paging_Device` structure. The structure can simply be an int/boolean array, representing if a page on disk is free or not.
  - `Find_Space_On_Paging_File`
    - Use the paging file structure you defined above to find a free page on disk.
  - `Free_Space_On_Paging_File`
    - Use the paging file structure you defined above to mark the page on disk as free.
  - `Write_To_Paging_File`
    - Use `Block_Write` to write contents in the physical memory to disk blocks. Remember disk read/write is block by block.
  - `Read_From_Paging_File`
    - Similar with `Write_To_Paging_File`, but use `Block_Read`
- In main.c
  - Call `Init_paging()`

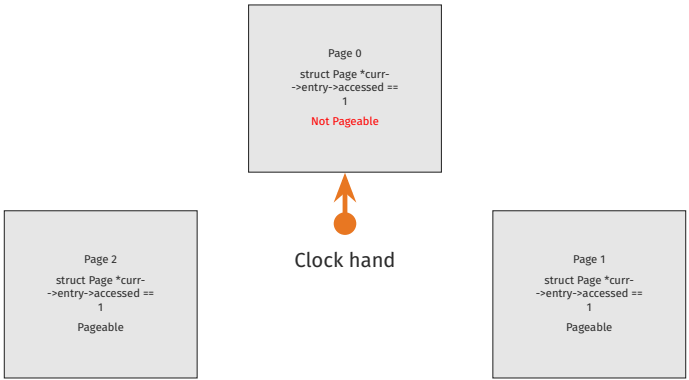
PAGE REPLACEMENT

- In mem.c:
  - `Alloc_Or_Reclaim_Page`
    - The routine is on page 27
  - `Find_Page_To_Page_Out`
    - The clock algorithm.
    - `g_pageList` contains all pages in the system.
    - Clock hand is incremented as long as the page table entry that the Page structure refers to has the accessed bit set or the page is not pageable.
    - Add a new field to userContext and mark how many pages the context has in memory. If less than 10 pages, don't page out its own pages; if more than 1000 pages, don't page out another process' pages.

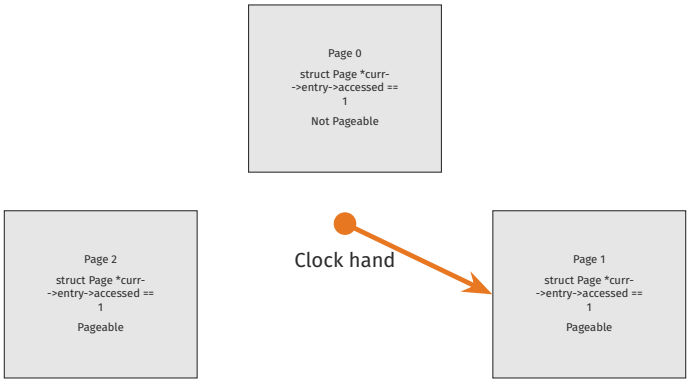
CLOCK ALGORITHM



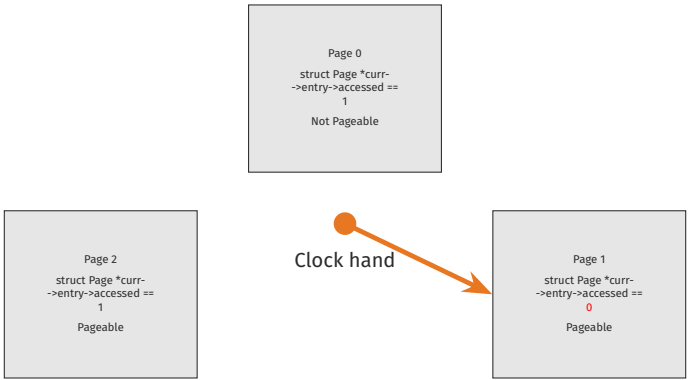
CLOCK ALGORITHM



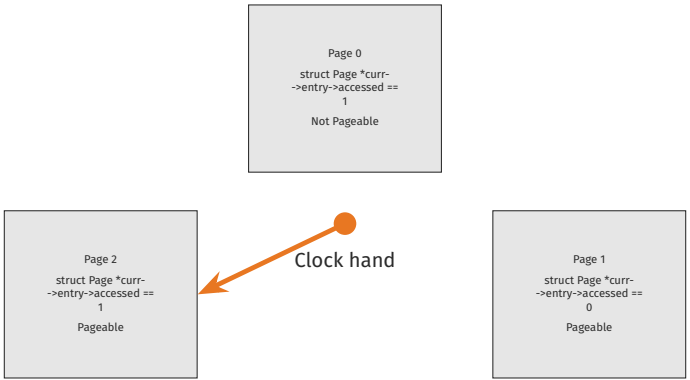
CLOCK ALGORITHM



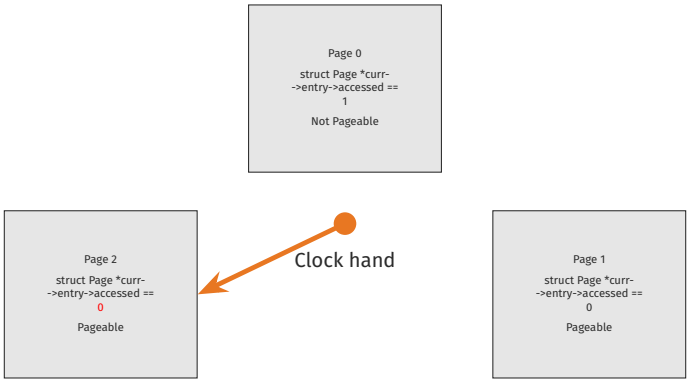
CLOCK ALGORITHM



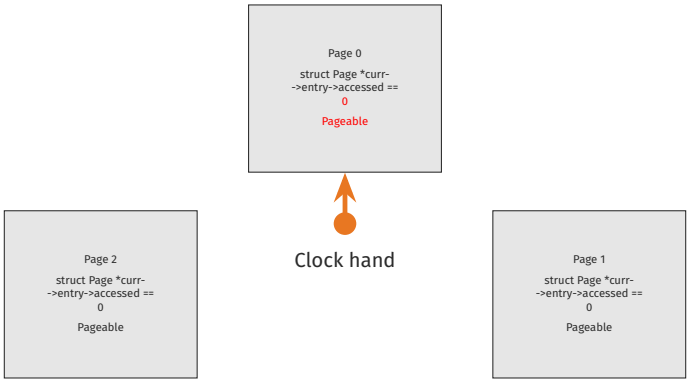
CLOCK ALGORITHM



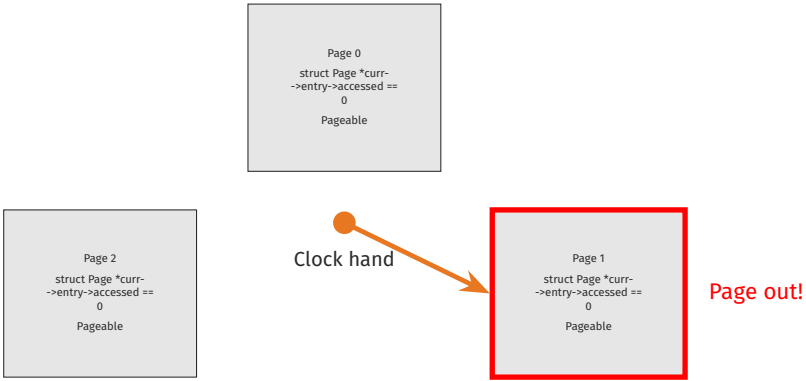
CLOCK ALGORITHM



CLOCK ALGORITHM



CLOCK ALGORITHM

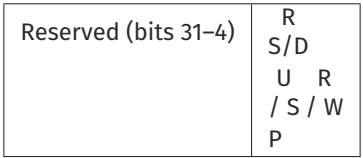


HINT

- There are many ways to finish this project as long as you can implement a VM system. And they might need fewer lines of code. No worries if you didn't follow the slides strictly.

PAGE FAULT ERROR CODES

Interrupt 14—Page-Fault Exception (#PF) (Continued)



P 0 The fault was caused by a non-present page.
1 The fault was caused by a page-level protection violation.

W/R 0 The access causing the fault was a read.
1 The access causing the fault was a write.

U/S 0 The access causing the fault originated when the processor was executing in supervisor mode.
1 The access causing the fault originated when the processor was executing in user mode.

RSVD 0 The fault was not caused by reserved bit violation.
1 The fault was caused by reserved bits set to 1 in a page directory.