CS111, Lecture 25

Trust + assign6

😷 masks recommended

<u>Topic 4: Virtual Memory</u> - How can one set of memory be shared among several processes? How can the operating system manage access to a limited amount of system memory?

Learning Goals

- Reflect on aspects of trust, when we trust systems/others, and how we choose to trust systems/others
- Learn about examples of trust / isolation not being upheld in systems

Plan For Today

- **Recap:** Virtual Memory
- Trust Case Study: **Meltdown**
- assign6

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Virtual Memory

- Virtual memory is an example of "OS magic" – very powerful mechanism
- Virtualization: making one thing look like another – separation between appearance and reality
- OS can manage physical memory how it wants (e.g. swap to disk), invisible to user programs

Goals:

- **Multitasking** – allow multiple processes to be memory-resident at once
- **Transparency** – no process should need to know memory is shared. Each must run regardless of the number and/or locations of processes in memory.
- **Isolation** – processes must not be able to corrupt each other
- **Efficiency** (both of CPU and memory) – shouldn't be degraded badly by sharing

OS Execution

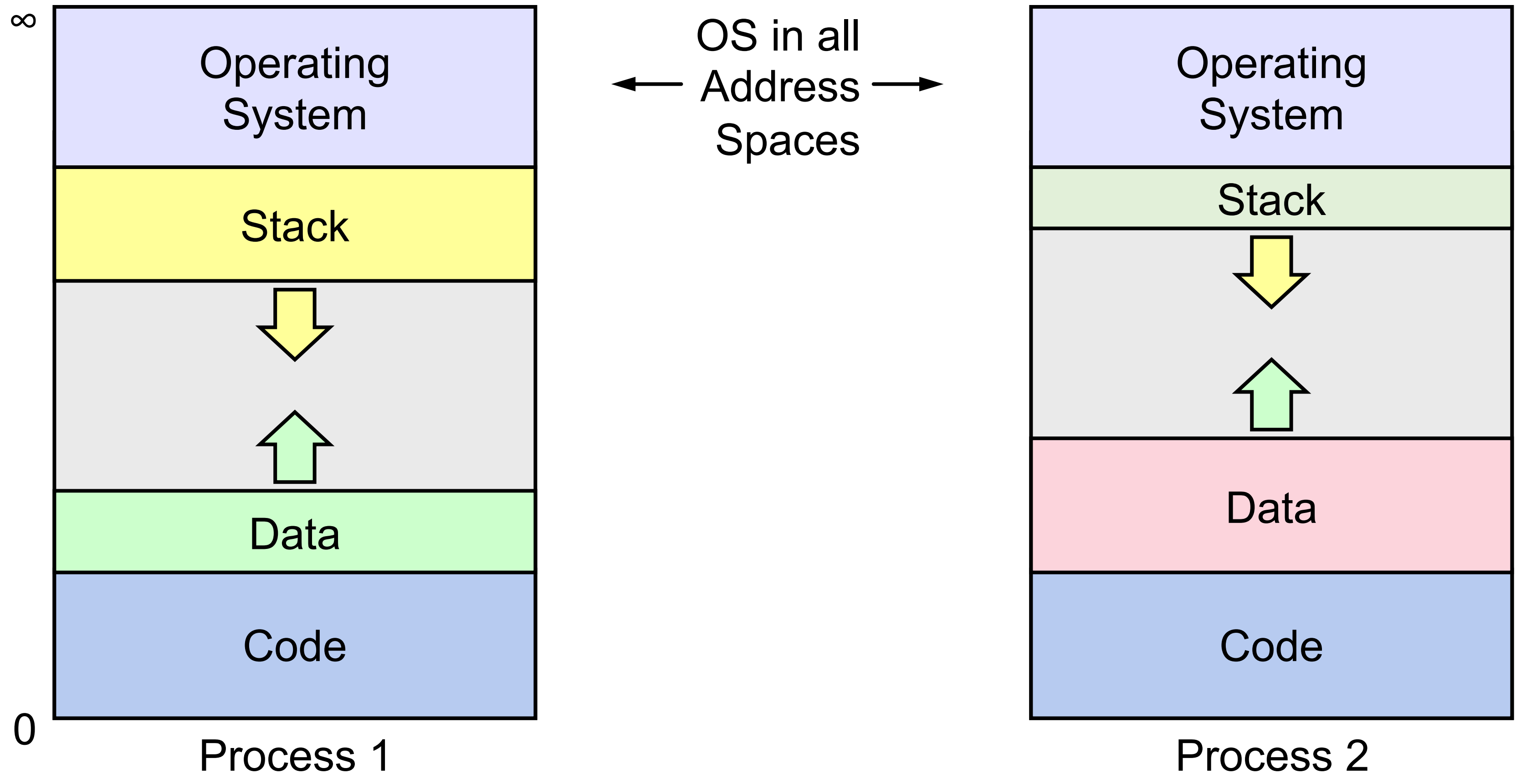
How does virtual memory work when the OS runs?

OS has space in every process’s virtual address space. (not duplicated – just maps itself into each virtual address space). This way OS doesn’t have to manually translate.

Problem: don’t want user program accessing OS pages.

Solution: new bit in page table that marks kernel-only pages. When in user mode, not accessible, but accessible when OS is running.

OS and User in Same Address Space



Plan For Today

- **Recap:** Virtual Memory
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Meltdown

Meltdown is a vulnerability publicly disclosed in 2018 that allows a program to access kernel-only pages. (https://meltdownattack.com)

"Meltdown is a novel attack that allows overcoming memory isolation completely by providing a simple way for any user process to read the entire kernel memory of the machine it executes on, including all physical memory mapped in the kernel region.“

- Hardware-level vulnerability
- hardware fixes in later processors, patches in some earlier ones (though concerns about performance penalties introduced), patched in OSes

Demo: https://www.youtube.com/watch?v=RbHbFkh6eeE

Discussion Question #1

How do we decide how / whether to fix a potential vulnerability / violation of trust? How do we evaluate tradeoffs in performance penalties, user convenience, and other factors?

- E.g. what if vulnerability is unlikely or difficult to exploit?
- E.g. what if fix causes a performance penalty or other user inconvenience?
- E.g. do we make any fix opt-out or opt-in?

Discussion Question #2

With potential vulnerabilities / violations of trust, how, if at all, do we hold parties accountable? Who holds them accountable? Examples of accountable parties could include:

- Hardware designers (e.g. Intel)
- OS designers (e.g. Microsoft Windows, Google Android, Apple iOS)
- App developers
- Users

Trust Overview

- Who/what do we trust?
- How do we decide who/what to trust?
- What do we do when that trust is not upheld?

Recap

- **Recap:** Virtual Memory
- Trust Case Study: **Meltdown**
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Lecture 25 takeaway: The Meltdown vulnerability is a great case study in when assumptions about systems are not upheld. When thinking about trust, we must think about who we trust, why, and what happens if that trust is not upheld.

Plan For Today

- **Recap:** Virtual Memory
- Trust Case Study: **Meltdown**
- **assign6**

CS 111 Project 6: Virtual Memory

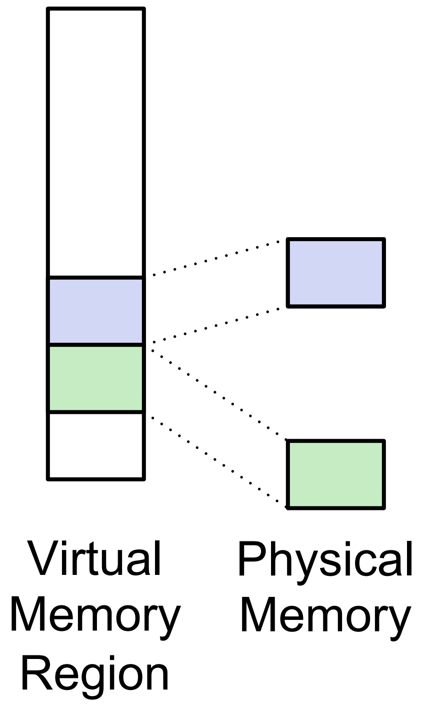
Briana Berger & Anjali Ragupathi

Overview

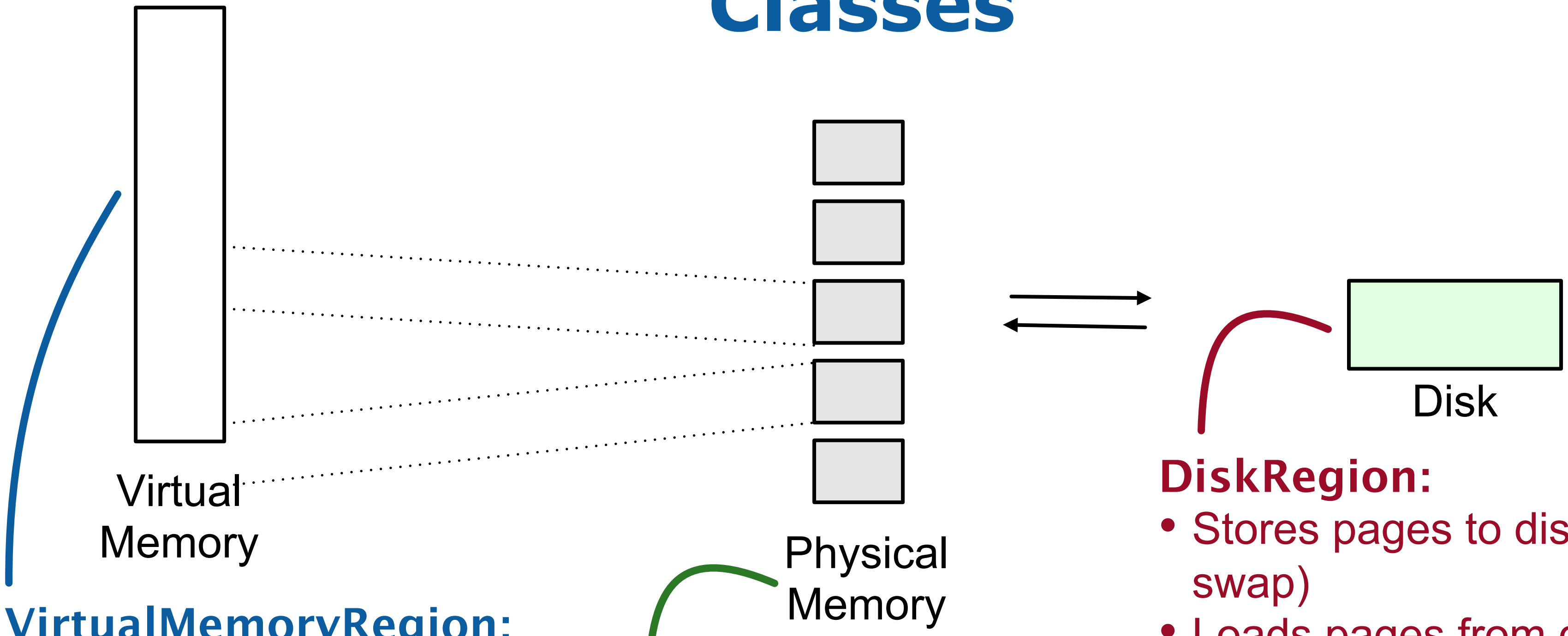
Part 1: implement paging (no demand paging - assuming sufficient physical pages)

Part 2: add demand paging with the clock algorithm (physical memory might fill up, and pages must be swapped to disk)

- Write code in **VirtualMemoryRegion** to manage a virtual address space and a page map.
- Write code in **PhysicalMemory** to give physical pages and run the clock algorithm to kick pages to disk.



Classes



VirtualMemoryRegion:
- Allocates virtual memory
- Catch page faults
- Map/unmap pages
- Maintain a page map

PhysicalMemory:
- Manages pool of physical pages
- Runs clock algorithm

DiskRegion:
- Stores pages to disk (e.g. swap)
- Loads pages from disk (e.g. swap, code)

Assignment Structure

Slightly modified mechanism for implementing virtual memory (due to not writing OS code):

- **VirtualMemoryRegion** models a virtual address space of a specified size
- Processes don’t request pages – we assume entire region is ok to access, but not actually mapped until used
- *Page fault* if process accesses unmapped address – runs **handle_fault**, which should add mapping.
- Accessing again in the same way doesn’t run your code – you just handle new accesses.

Helpful Assignment Types/Functions

VPage – type that represents start of a virtual page (really just a pointer)

PPage – type that represents start of a physical page (really just a pointer)

get_page_size() – returns page size in bytes (guaranteed to be power of 2)

Test Harness

test_harness.cc is the provided testing program – it can run *script* .txt files in a special format to test your code. The script specifies what code of yours to run and how. Each sanity check test is a script file.

```
./test_harness somescript.txt
```

Example: samples/scripts/one_page_read.txt:

```
# Make a VMRegion with 1 page, and read it
1
INIT 1 1
READ 1 0
```

See spec for more details on script file format.

Part 1: Paging

Milestone 1: Read-only pages -> get free ppage, map it to accessed vpage.

Milestone 2: Reading from disk -> does the mapped page have initial contents on disk?

Milestone 3: Read/Write pages -> Process might write to a page

Milestone 4: Destructor -> Remove mappings, free physical pages

You will write code only in virtualmemoryregion.hh/cc.

VirtualMemoryRegion

void handle_fault(char *fault_addr);

Private - called when a page fault occurs – passed virtual address that was accessed

~VirtualMemoryRegion()

Destructor – called when a region goes away (must unmap / free pages)

void map(VPage va, PPage pa, Prot prot);

Private - implemented for you – you must call when you want to add/update a mapping

void unmap(VPage va);

Private - implemented for you – you must call when you want to remove a mapping

VirtualMemoryRegion

Two already-initialized private instance variables:

PhysicalMemory *physical_memory_;

- Use to get and return physical pages

DiskRegion *disk_;

- Use to store and load saved data from disk

PhysicalMemory

PPage get_new_ppage(VPage mapped_page, VirtualMemoryRegion *owner);

- Call to get physical page

void page_free(PPage p)

- Call to free physical page

DiskRegion

bool is_page_stored_on_disk(const VPage vpage);

Returns whether there is data for this virtual page stored on disk

void load_page_from_disk(const VPage vpage, PPage dst);

Reads data from disk for this virtual page into specified physical page

Protections

How do we know whether a page should be read-only or read/write?

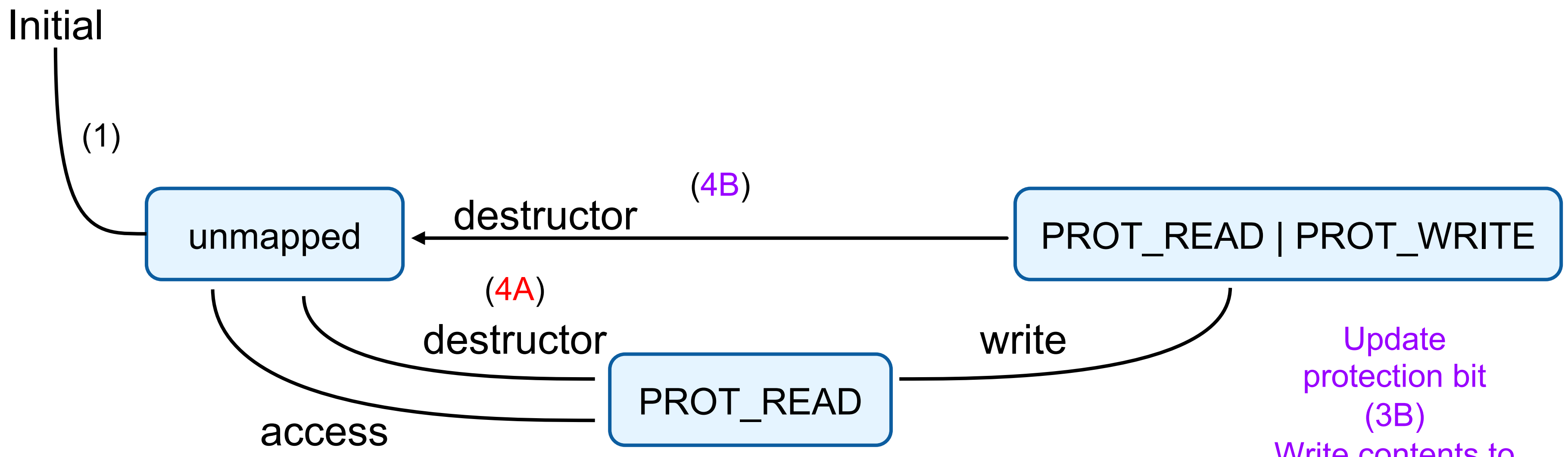
- Set all new mappings to be read-only (PROT_READ)
- If process writes to that page, it will trigger another page fault; use that as an indicator that the page should be read-write, and update its protections to read-write (PROT_READ | PROT_WRITE)

Page Map

You will need to maintain a <u>page map instance variable</u> starting in milestone 3.

- Tracks information about mappings across calls to **handle_fault**
- Model as a map data structure (**unordered_map**) that contains only present pages
- You will update the design of your page map over time as you implement more functionality; only add what you need at each milestone.

State of a VPage



if first time access, page fault (2)

if not first time access (Read) -> read page contents

if not first time access (Write), page fault and go to (3B)

set protection bit to PROT_READ initially (3A)

Update protection bit (3B)

Write contents to page

Part 2: Demand Paging

Milestone 1: clock_sweep

Milestone 2: clock_should_remove

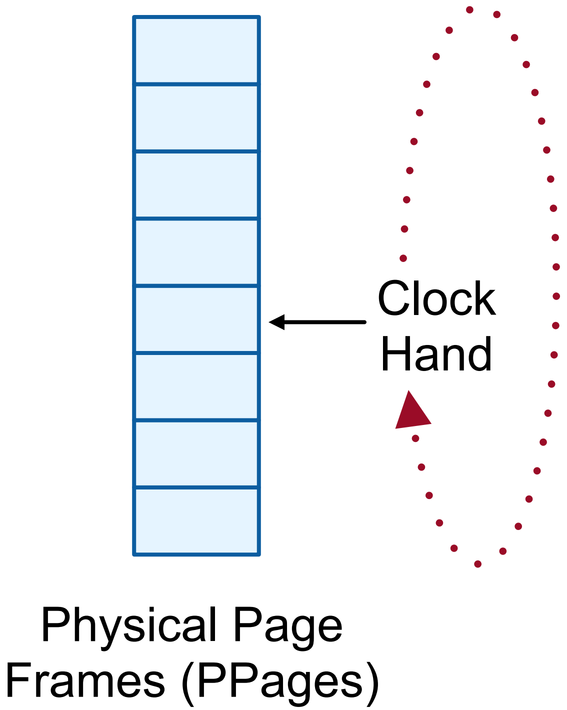
Milestone 3: clock_remove

Milestone 4: Dirty Pages

Milestone 5: Clock Algorithm

You will write more code in virtualmemoryregion.hh/cc and write code in physicalmemory.hh/cc for the clock algorithm.

The Clock Algorithm



If need PPage but all in use:

- **Check if hand is pointing to removal candidate**
- **Not candidate?**
  - Indicate swept over
  - Advance hand, try next page
- **Candidate? Kick out:**
  - Indicate kicked out
  - Advance hand, stop
- **Then get new PPage from pool**

VirtualMemoryRegion Part 2

void clock_sweep(VPage vp)

For clock algorithm, called when clock hand sweeps over page and marks unreferenced

bool clock_should_remove(VPage vp)

For clock algorithm, should return whether page is unreferenced

void clock_remove(VPage vp)

For clock algorithm, should mark page as kicked to disk

Referenced Bit

From lecture: when clock algorithm sweeps over a page, if referenced = 1, set it to 0 and continue. If referenced = 0, pick it to swap to disk.

For this assignment, instead of referenced bit, we will use page protections.

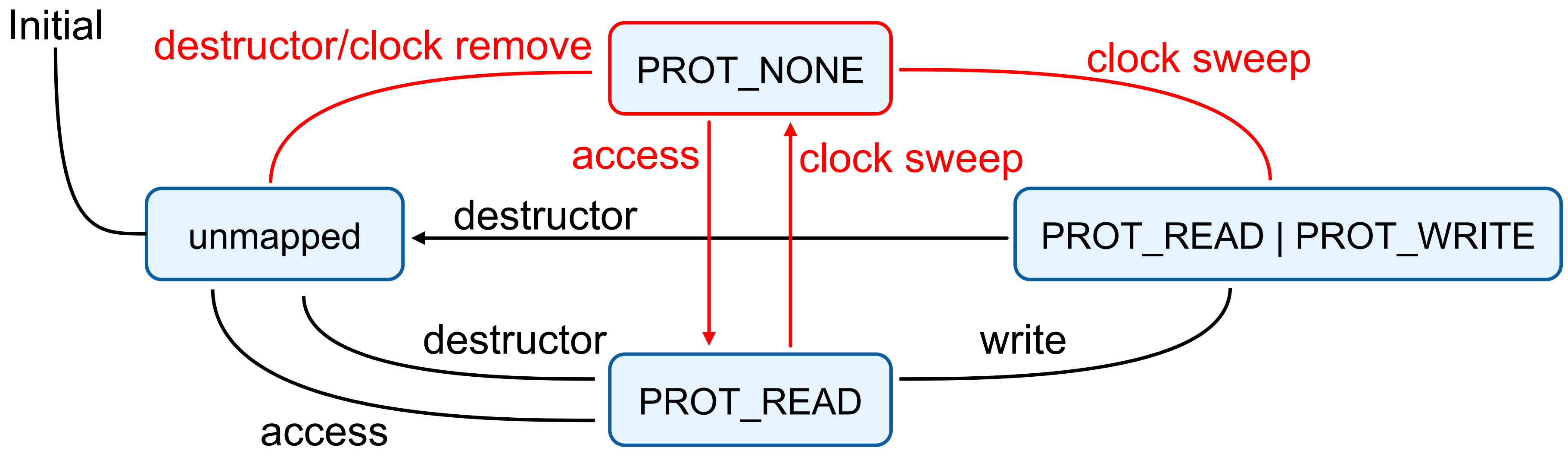
PROT_READ or **PROT_READ | PROT_WRITE** means referenced = 1

PROT_NONE (new – means no read, no write) means referenced = 0

E.g. in **clock_sweep**, you must update the corresponding virtual page to have protection **PROT_NONE**.

If the virtual page is accessed again, we get a page fault and we should upgrade to **PROT_READ**.

State of a VPage



Dirty Pages

If a page is kicked out of memory, we need to swap it to disk only if it’s dirty (has been modified since being mapped).

We will assume any page that the process attempts to write to is dirty.

NOTE: a PROT_NONE page could be dirty! E.g. page written to, then clock hand sweeps over.

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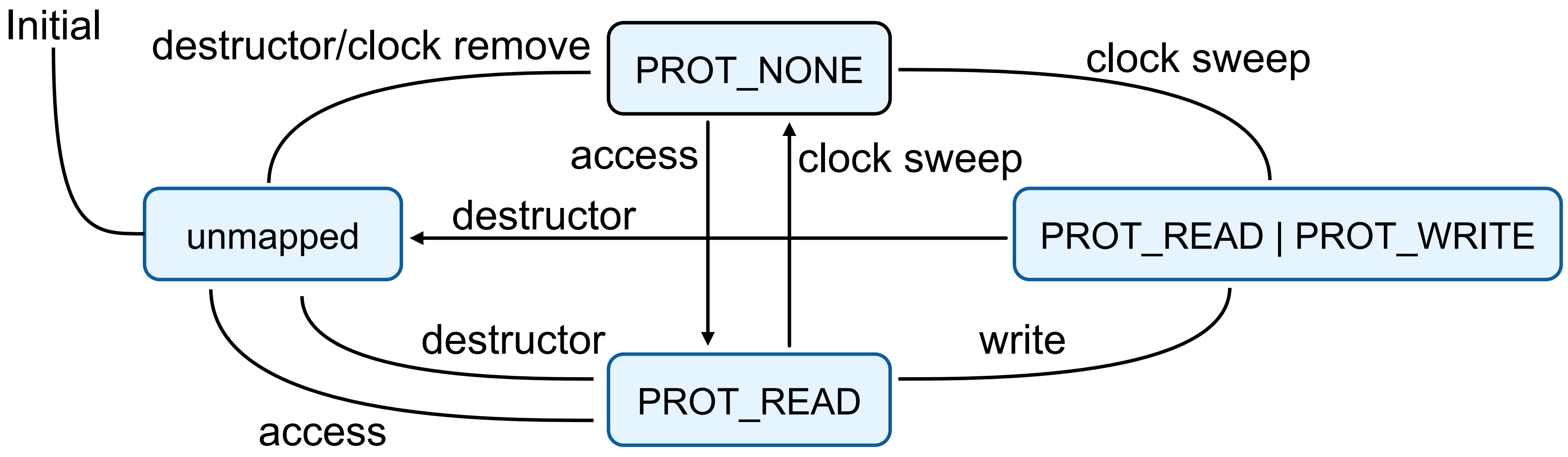
How do we track dirty state? **Hint**: what stores information about the pages?

DiskRegion Part 2

void store_page_to_disk(const VPage vpage, const PPage src);

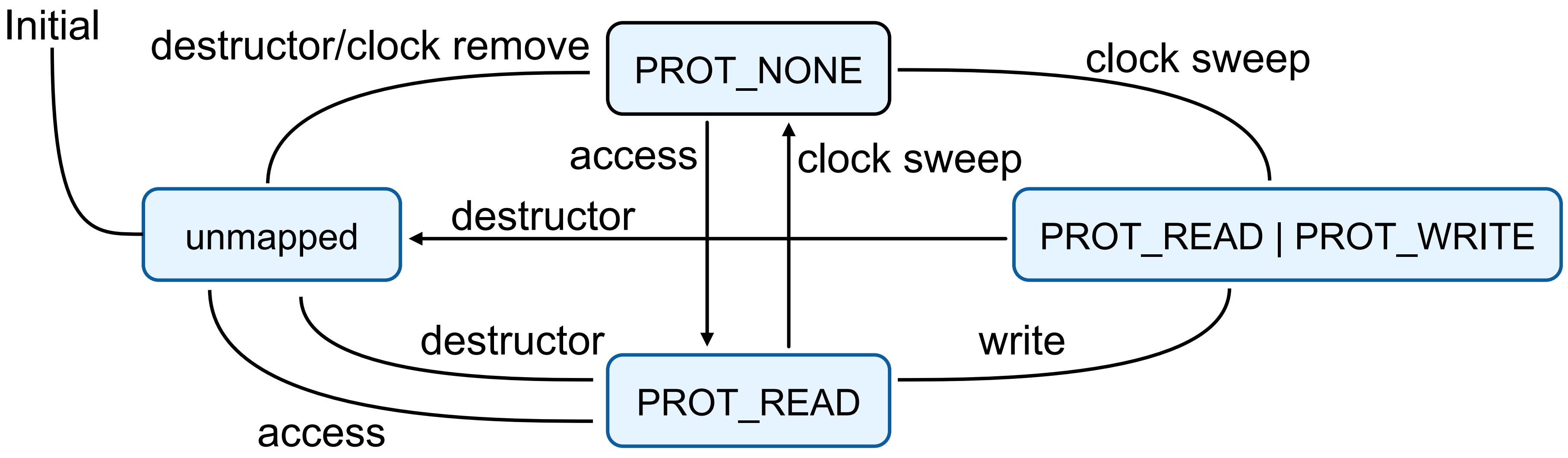
Stores physical page contents to disk, labeled as for the given virtual page.

State of a VPage



- **How do you keep track of whether a page is dirty?**
  - Hint: what stores information about the pages?
- **In which states can the page be dirty?**
- **Which arrows check/update the dirty state?**

State of a VPage



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  - clock_remove: You write a page to disk if it's dirty.

Clock Algorithm

Write code in PhysicalMemory::get_new_ppage() to check if there are more physical pages, and if not, run the clock algorithm to kick one out.

PhysicalMemory should maintain a fixed-size vector instance variable with info about each physical page – needed to loop over pages in clock algorithm.

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- **The index of the vector represents physical page numbers**
  - e.g. index 2 means physical page #2
  - how do you get from PPage to physical page number?
- **What information do you need for each physical page?**

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    - What VM object owns the Ppage? What VM object is the mapping to the Ppage?

Clock Algorithm

Write code in PhysicalMemory::get_new_ppage() to check if there are more physical pages, and if not, run the clock algorithm to kick one out.

PhysicalMemory can access "pool" of unallocated pages by:

std::size_t nfree()

Returns number of pages in unallocated pool

PPage page_alloc()

Call within get_new_ppage to get a fresh physical page if available

void page_free(PPage p)

Returns page to unallocated pool.

Clock Algorithm

```
PPage get_new_ppage(VPage mapped_page, VirtualMemoryRegion *owner) {
        // check if pages in unallocated pool
        // if not, run clock algorithm to free up page, you will call the clock_ methods that you implemented previously.
    //      a.) If it's been accessed recently, mark as unaccessed and continue
    //      b.) Otherwise, throw it out - this should return a page to the pool
        // now get a page from the unallocated pool
}
```

Final Tips

- Make sure to keep your page map updated
- Make sure to call map() whenever you change protections
- See spec for how to run in GDB
- write your own custom script files for testing (at least 2 required)

- There isn't much code! Huge emphasis on reading everything and being detail-oriented

Thank you!
Any questions?