UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

Andrea C. Arpaci-Dusseau
Remzi H. Arpaci-Dusseau

VIRTUAL MEMORY

Questions answered in this lecture:

How to support processes when not enough physical memory?
When should a page be moved from disk to memory?
What page in memory should be **replaced**?
How can the LRU page be **approximated** efficiently?

ANNOUNCEMENTS

- P1: Will be graded by end of week (should be no surprises)
- Project 2: Available now
  - Due Friday, Oct 14th at 6pm; Watch discussion videos!
  - Shell (what is reasonable?) and Scheduler
  - Still a few partner match requests to handle
- Exam 1: Wednesday 10/5 7:15 – 9:15pm Bascom 272
  - Class time on Tuesday for review, plus Wed discussion section
  - Use form to send questions
  - Look at previous exam / simulations for sample questions
- Reading for today: Chapter 21 + 22

MOTIVATION

OS goal: Support processes when not enough physical memory

- Single process with very large address space
- Multiple processes with combined address spaces

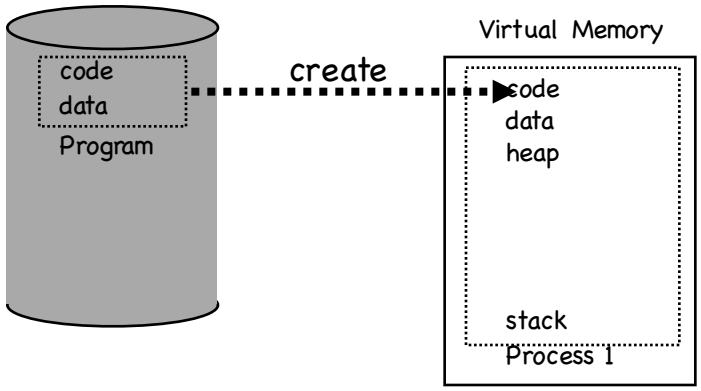
User code should be independent of amount of physical memory

- Correctness, if not performance

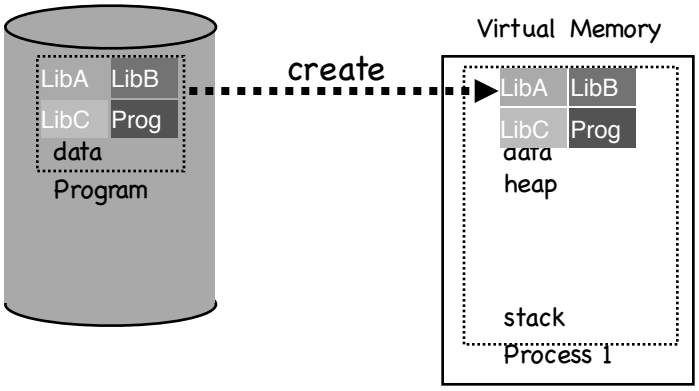
Virtual memory: OS provides illusion of more physical memory

Why does this work?

- Relies on key properties of user processes (workload) and machine architecture (hardware)

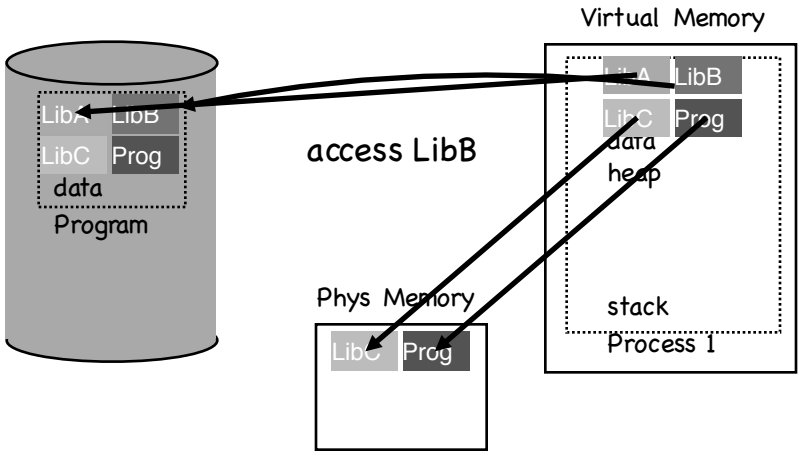


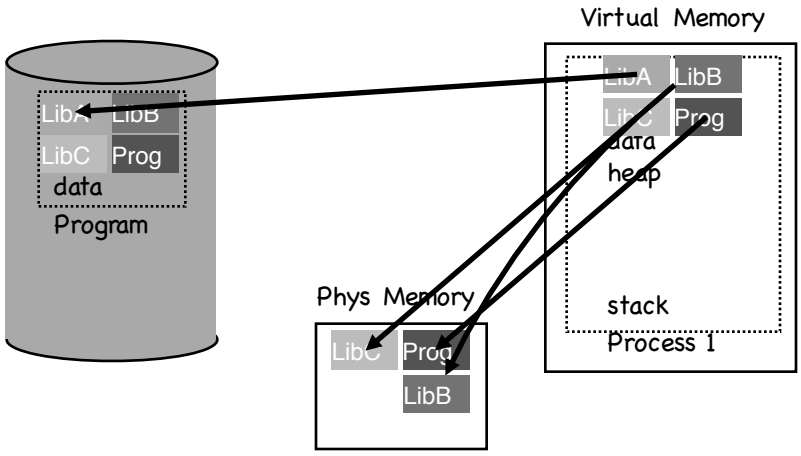
what's in code?



Code: many large libraries, some of which are rarely/never used

How to avoid wasting physical pages to store rarely used virtual pages?





copy (or move) to RAM

Called "**paging**" in

LOCALITY OF REFERENCE

Why does this give good performance?

Leverage locality of reference within processes

- Spatial: reference memory addresses **near** previously referenced addresses
- Temporal: reference memory addresses that have referenced in the past
- Processes spend majority of time in small portion of code
  - Estimate: 90% of time in 10% of code

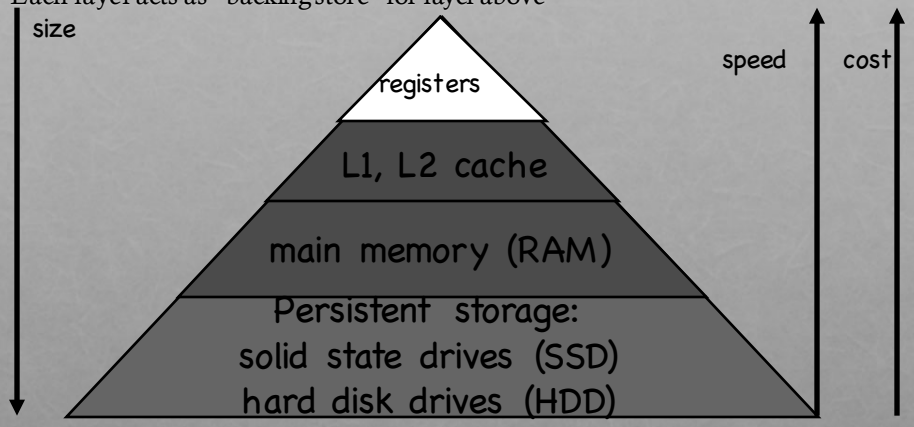
Implication:

- Process only uses small amount of address space at any moment
- Only small amount of address space must be resident in physical memory

MEMORY HIERARCHY

Leverage memory hierarchy of machine architecture

Each layer acts as "backing store" for layer above



Which entity controls each layer?

VIRTUAL MEMORY INTUITION

Idea: OS keeps unreferenced (or rarely referenced) pages on disk

- Slower, cheaper backing store than memory

Process can run when not all pages are loaded into main memory

OS and hardware cooperate to provide illusion of large disk as fast as main memory

- Same correctness as if all of address space in main memory
- Hopefully have similar performance

Requirements:

- OS must have **mechanism** to identify location of each page in address space → in memory or on disk
- OS must have **policy** for determining which pages live in memory and which on disk

VIRTUAL ADDRESS SPACE MECHANISMS

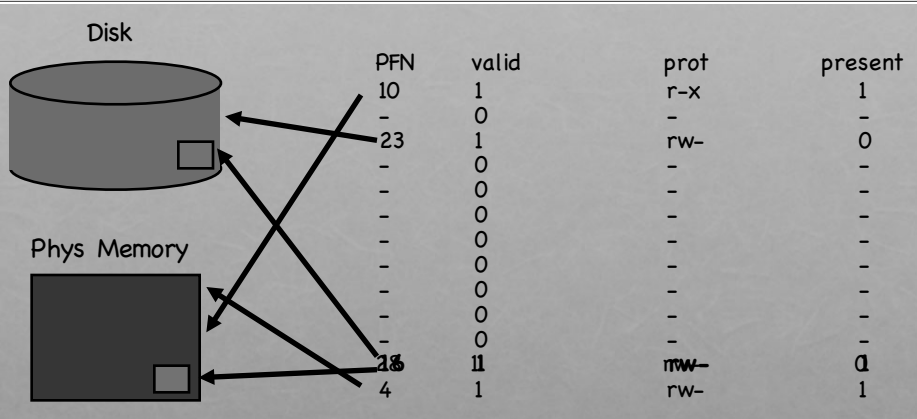
Each page in virtual address space maps to one of three:

- Nothing (error): Free
- Physical main memory: Small, fast, expensive
- Disk (persistent storage): Large, slow, cheap

Extend page tables with an extra bit: `present`

- `permissions (r/w), valid, present`
- Page in memory: `present` bit set in PTE, hold PPN
- Page on disk: `present` bit cleared
  - PTE points to **block address on disk**
  - Causes trap into OS when page is referenced
  - **Trap: page fault**

PRESENT BIT



What if access vpn 0xb?

VIRTUAL MEMORY MECHANISMS

Hardware and OS cooperate to translate addresses

First, hardware checks TLB for virtual address
- if TLB hit, address translation is done; page in physical memory

If TLB miss…
- Hardware or OS walk page tables
- If PTE indicates page is present, then page in physical memory; load TLB with vpn->ppn mapping

If page fault (i.e., `present` bit is cleared)
- Trap into OS (not handled by hardware)
- Find **free** page in physical memory
  - OS selects victim page in memory to replace
  - Write victim page out to disk if modified (add `dirty` bit to PTE)
- OS reads referenced page from disk into memory
- Page table is updated with mapping to ppn, `present` bit is set
- Process continues execution

What should scheduler do?

Faulting process not READY
Pick a READY process to run

MECHANISM FOR CONTINUING A PROCESS

Continuing process after page fault is tricky
- Want page fault to be transparent to user
- Page fault may have occurred in middle of instruction
  - When instruction is being fetched
  - When data is being loaded or stored
- Requires hardware support
  - precise interrupts: stop CPU pipeline such that instructions before faulting instruction have completed, and those after can be restarted

Complexity depends upon instruction set
- Can faulting instruction be restarted from beginning?
  - Example: `move +(SP), R2`
  - Must track side effects so hardware can undo

VIRTUAL MEMORY POLICIES

Goal: Minimize number of page faults

- Page faults require milliseconds to handle (reading from disk)
- Implication: Plenty of time for OS to make good decision

OS has two decisions

- Page selection
  - **When** should a page (or pages) on disk be **brought into** memory?
- Page replacement
  - **Which r**esident page (or pages) in memory should be **thrown out** to disk?

PAGE SELECTION

When should a page be brought from disk into memory?

Demand paging: Load page only when page fault occurs

- Intuition: Wait until page must absolutely be in memory
- When process starts: No pages are loaded in memory
- Problems: Pay cost of page fault for every newly accessed page

Prepaging (anticipatory, prefetching): Load page before referenced

- OS predicts future accesses (oracle) and brings pages into memory early
- Works well for some access patterns (e.g., sequential)
- Costs of guessing wrong?

Hints: Combine above with user-supplied hints about page references

- User specifies: may need page in future, don't need this page anymore, or sequential access pattern, …
- Example: `madvise()` in Unix

BREAK

- Will the Badgers or the Wolverines prevail on Saturday?
- If it isn't football, what is your favorite spectator sport?

PAGE REPLACEMENT

Which page in main memory should selected as victim?

- Write out victim page to disk if modified (dirty bit set)
- If victim page is not modified (clean), just discard

OPT: Replace page not used for longest time in future

- Advantages: Guaranteed to minimize number of page faults
- Disadvantages: Requires OS to predict the future; Not practical, but good for comparison

FIFO: Replace page that has been in memory the longest

- Intuition: First referenced long time ago, done with it now
- Advantages: Fair: All pages receive equal residency; Easy to implement (circular buffer)
- Disadvantage: Some pages may always be needed

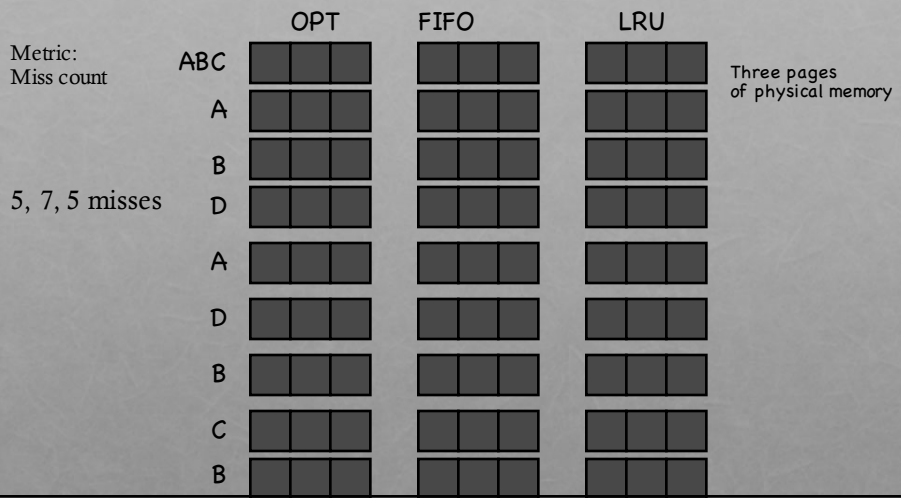
LRU: Least-recently-used: Replace page not used for longest time in past

- Intuition: Use past to predict the future
- Advantages: With locality, LRU approximates OPT
- Disadvantages:
  - Harder to implement, must track which pages have been accessed
  - Does not handle all workloads well

Random?

PAGE REPLACEMENT EXAMPLE

Page reference string: ABCABDADBCB



PAGE REPLACEMENT COMPARISON

Add more physical memory, what happens to performance?

- **LRU, OPT**
  - More memory → **guaranteed** fewer (or same number of) page faults
  - Smaller memory guaranteed to contain subset of larger memory
  - Stack property: smaller cache always subset of bigger
- **FIFO**:
  - More memory → **usually** fewer page faults
  - Belady's anomaly: May actually have more page faults!

FIFO PERFORMANCE MAY DECREASE!

Consider access stream: ABCDABEABCDE

Consider physical memory size: 3 pages vs. 4 pages

How many misses with FIFO?

3 pages: 9 misses
4 pages: 10 misses

PROBLEMS WITH LRU-BASED REPLACEMENT

Previous lecture (TLBS): LRU poor when working set > available resources

LRU does not consider **frequency** of accesses

- Is a page accessed **once** in the past equal to one accessed **N** times?
- Common workload problem:
  - Scan (sequential read, never used again) one large data region flushes memory

Solution: Track frequency of accesses to page

Pure LFU (Least-frequently-used) replacement

- Problem: LFU can never forget pages from the far past

Examples of other more sophisticated algorithms:

- LRU-K and 2Q: Combines recency and frequency attributes
- Expensive to implement, LRU-2 used in databases

Similar policies used for replacing blocks in file buffer cache

IMPLEMENTING LRU (CONCEPTUALLY)

Software Perfect LRU

- OS maintains ordered list of physical pages by reference time
- When page is referenced: Move page to front of list
- When need victim: Pick page at back of list

Hardware Perfect LRU

- Associate timestamp with each page
- When page is referenced: Record timestamp for page
- When need victim: Scan through timestamps to find oldest
- Trade-off: Fast on memory reference, slow on replacement (especially as size of memory grows)

In practice, do not implement Perfect LRU

- LRU is approximation anyway, so approximate more
- Goal: Find an old page, but not necessarily the very oldest

CLOCK ALGORITHM

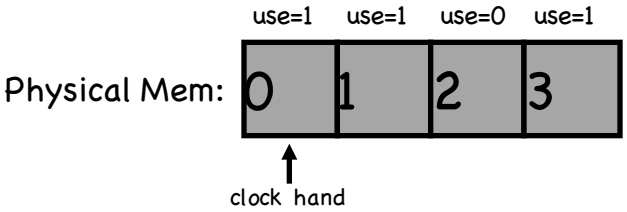
Hardware

- Associate `use` (or `reference`) bit for each page frame
- When page is referenced: set `use` bit

Operating System

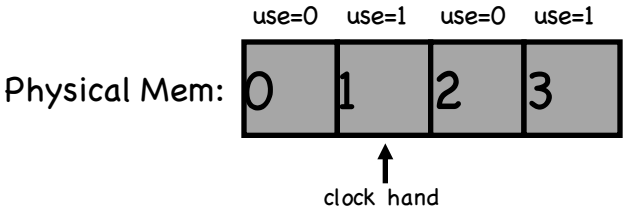
- Page replacement: Look for page with `use` bit cleared (has not been referenced for awhile)
- Implementation
  - Keep pointer to last examined page frame
  - Traverse pages in circular buffer
  - Clear `use` bits as search
  - Stop when find page with cleared `use` bit, replace this page

CLOCK: LOOK FOR A PAGE



Running process accesses page on disk; must page it in
Need to find page to replace; which will OS pick?

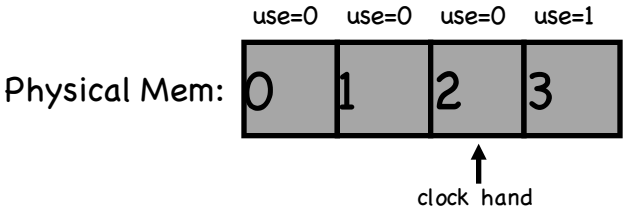
CLOCK: LOOK FOR A PAGE



Need to find page to replace; which will OS pick?

Clear use bit for page 0 and advance clock hand…

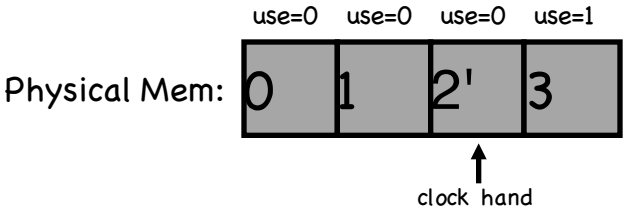
CLOCK: LOOK FOR A PAGE



Need to find page to replace; which will OS pick?

Clear use bit for page 1 and advance clock hand…

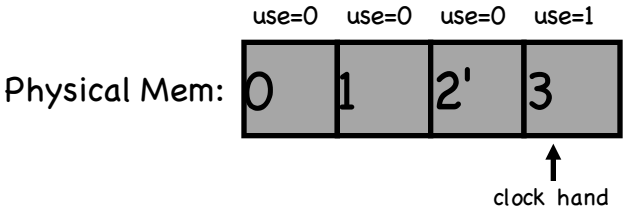
CLOCK: LOOK FOR A PAGE



Need to find page to replace; which will OS pick?

Evict **page 2** because it has not been recently used
Load physical page 2 with new contents from disk

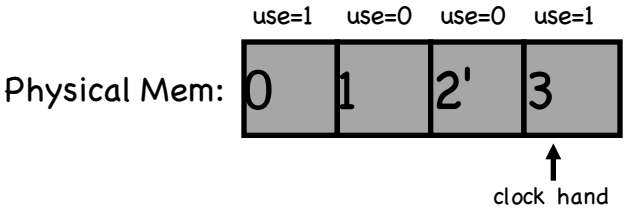
CLOCK: LOOK FOR A PAGE



Continue the running process

Imagine **page 0** is accessed…

CLOCK: LOOK FOR A PAGE

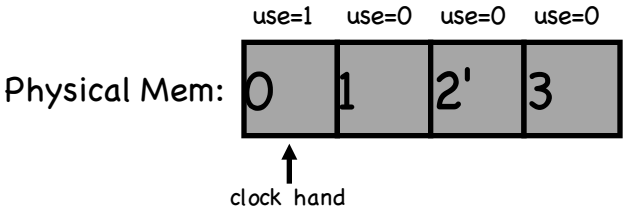


Continue the running process

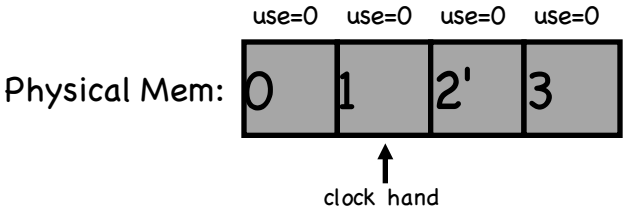
Set use bit for page 0

Process accesses page on disk; need to find another victim page

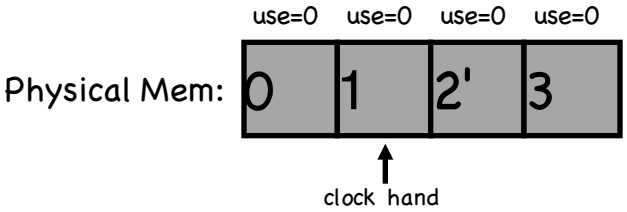
CLOCK: LOOK FOR A PAGE



CLOCK: LOOK FOR A PAGE



CLOCK: LOOK FOR A PAGE



Evict **page 1** because it has not been recently used

CLOCK EXTENSIONS

Replace multiple pages at once

- Intuition:
  Expensive to run replacement algorithm and to write single block to disk
- Find multiple victims each time and track free list

Add software counter ("`chance`")

- Intuition: Better ability to differentiate across pages (how much they are being accessed)
- Increment `chance` software counter if `use` bit is 0
- Replace when `chance` exceeds some specified limit

Use dirty bit to give preference to dirty pages

- Intuition: More expensive to replace dirty pages
  - Dirty pages must be written to disk, clean pages do not
- Replace pages that have `use` bit and `dirty` bit cleared

WHAT IF NO HARDWARE SUPPORT?

What can the OS do if hardware does not have `use` bit (or `dirty` bit) (and hardware-filled TLB)?

- Can the OS "emulate" these bits?

Leading question:

- How can the OS get control (i.e., generate a trap) every time `use` bit should be set? (i.e., when a page is accessed?)

CONCLUSIONS

Illusion of virtual memory:
Processes can run when:
sum of virtual address spaces > amount of physical memory

Mechanism:

- Extend page table entry with "present" bit
- OS handles page faults (or page misses) by reading in desired page from disk

Policy:

- Page selection – demand paging, prefetching, hints
- Page replacement – OPT, FIFO, LRU, others

Implementations (clock) perform approximation of LRU