

CSE 120

Principles of Operating Systems

Fall 2025

Lecture 11: Page Replacement

Geoffrey M. Voelker

Administrivia

- Project 2 due Sat 11/15
 - ◆ Discussion slides on Piazza “Resources” page
 - ◆ Recordings on Canvas
- Homework 3 due Mon 11/17
 - ◆ Do VM worksheet when starting task 2 of project
 - ◆ VM worksheet solutions posted on main course page

Memory Management

Final lecture on memory management:

- Goals of memory management
 - ◆ To provide a convenient abstraction for programming
 - ◆ To allocate scarce memory resources among competing processes to maximize performance with minimal overhead
- Mechanisms
 - ◆ Physical and virtual addressing (1)
 - ◆ Techniques: Partitioning, paging, segmentation (1)
 - ◆ Page table management, TLBs, VM tricks (2)
- Policies
 - ◆ Page replacement algorithms (3)

Locality

- All paging schemes depend on locality
 - ◆ Processes reference pages in localized patterns
- **Temporal locality**
 - ◆ Locations referenced recently likely to be referenced again
- **Spatial locality**
 - ◆ Locations near recently referenced locations are likely to be referenced soon
- Although the cost of paging is high, if it is infrequent enough it is acceptable
 - ◆ Processes usually exhibit both kinds of locality during their execution, making paging practical

Demand Paging (OS)

- Recall demand paging from the OS perspective:
 - ♦ Pages are evicted to disk when memory is full
 - ♦ Pages loaded from disk when referenced again
 - ♦ References to evicted pages cause a page fault
 - » PTE is invalid when page contents are on disk
 - ♦ OS allocates a page frame, reads page from disk
 - ♦ When I/O completes, the OS fills in PTE, marks it valid, and restarts faulting process
- Dirty vs. clean pages
 - ♦ Actually, only dirty pages (modified) need to be written to disk
 - ♦ Clean pages do not – but you need to know where on disk to read them from again

Demand Paging (Process)

- Demand paging is also used when a process first starts up
- When a process is created, it has
 - ◆ A new page table with all valid bits off
 - ◆ No pages in physical memory
- When the process starts executing
 - ◆ Instructions fault on code and data pages
 - ◆ Faulting stops when no new code and data pages accessed
 - ◆ Only code and data needed by a process needs to be loaded
 - ◆ This, of course, changes over time...

Page Replacement

- When a page fault occurs, the OS loads the faulted page from disk into a page frame of memory
- At some point, the process has used all of the page frames it is allowed to use
 - ◆ This is likely (much) less than all of available memory
- When this happens, the OS must **replace** a page for each page faulted in
 - ◆ It must evict a page to free up a page frame
- The **page replacement algorithm** determines how
 - ◆ And they come in all shapes and sizes

Swapping to Disk

- Recall that the OS uses a **swap file** for storing data evicted from physical memory
 - ♦ Windows: c:\pagefile.sys
- Unix traditionally uses a **swap partition**
 - ♦ Region of disk just for evicting pages (no file system used)
 - » But can also use a file in a file system if desired
 - ♦ A separate disk can improve performance
 - » Disk I/O for paging does not interfere with disk I/O for files
 - » Not as critical today with large physical memories
- Size of swap file/partition determines # of processes
 - ♦ Run out of swap → no more processes can be created

Evicting the Best Page

- The goal of the replacement algorithm is to reduce the fault rate by selecting the best victim page to remove
- **The best page to evict is the one never touched again**
 - ◆ Will never fault on it
- Never is a long time, so picking the page closest to “never” is the next best thing
 - ◆ Evicting the page that won’t be used for the longest period of time minimizes the number of page faults
 - ◆ Proved by Belady
- We’re now going to survey various replacement algorithms, starting with Belady’s

Belady's Algorithm

- Belady's algorithm is known as the optimal page replacement algorithm because it has the lowest fault rate for any page reference stream
 - ♦ Idea: Replace the page that will not be used for the longest time in the future
 - ♦ Problem: Have to predict the future
- Why is Belady's useful then? Use it as a yardstick
 - ♦ Compare implementations of page replacement algorithms with the optimal to gauge room for improvement
 - ♦ If optimal is not much better, then algorithm is pretty good
 - ♦ If optimal is much better, then algorithm could use some work
 - » Random replacement is often the lower bound

First-In First-Out (FIFO)

- FIFO is an obvious algorithm and simple to implement
 - ◆ Maintain a list of pages in order in which they were paged in
 - ◆ On replacement, evict the one brought in longest time ago
- Why might this be good?
 - ◆ Maybe the one brought in the longest ago is not being used
- Why might this be bad?
 - ◆ Then again, maybe it's not
 - ◆ We don't have any info to say one way or the other
- FIFO suffers from “Belady’s Anomaly”
 - ◆ The fault rate might actually **increase** when the algorithm is given more memory (**very bad**)

Least Recently Used (LRU)

- LRU uses reference information to make a more informed replacement decision
 - ◆ Idea: We can't predict the future, but we can make a guess based upon past experience
 - ◆ On replacement, evict the page that has not been used for the longest time in the past (Belady's: future)
 - ◆ When does LRU do well? When does LRU do poorly?
- Implementation
 - ◆ To be perfect, need to time stamp every reference (or maintain a stack) – much too costly
 - ◆ So we need to approximate it

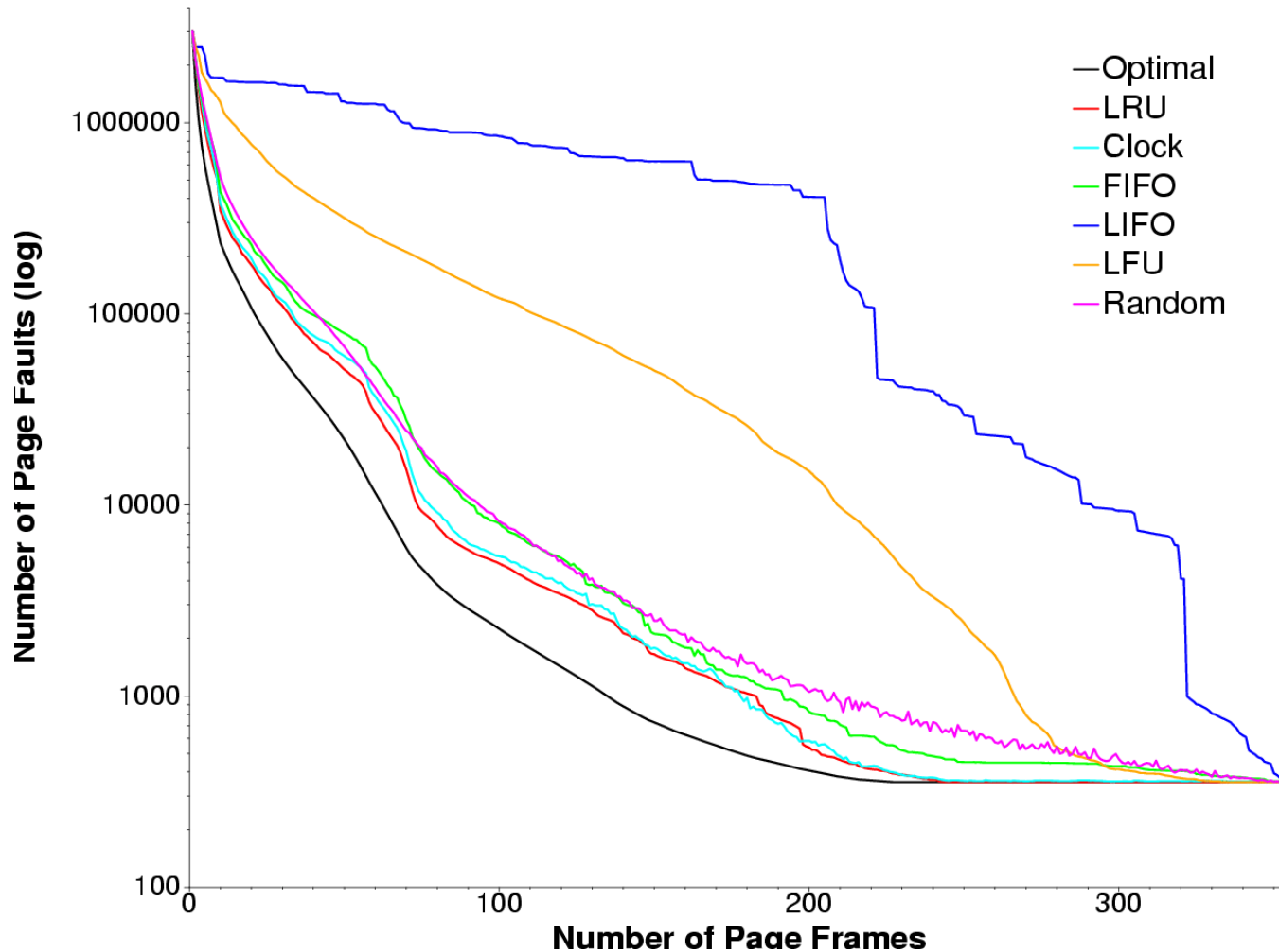
Approximating LRU

- LRU approximations use the PTE reference/used bit
 - ◆ Keep a counter for each page
 - ◆ At regular intervals, for every page do:
 - » If ref bit = 0, increment counter
 - » If ref bit = 1, zero the counter
 - » Zero the reference bit
 - ◆ The counter will contain the number of **intervals** since the last reference to the page
 - ◆ The page with the largest counter is the least recently used

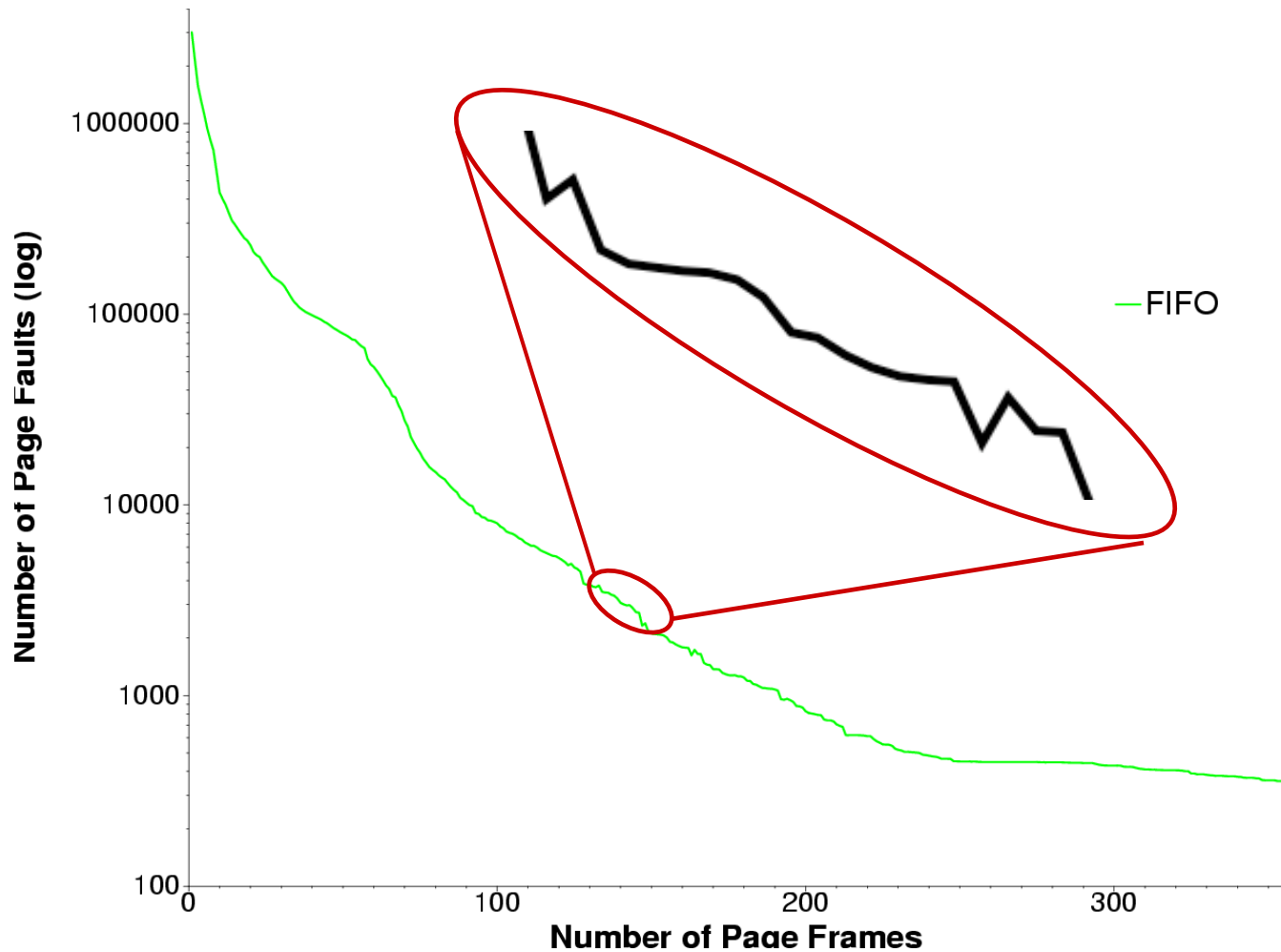
LRU Clock (Not Recently Used)

- Not Recently Used (NRU) – Traditional Approach
 - ◆ Idea: Replace page that is “old enough”
 - ◆ Arrange all of physical page frames in a big circle (clock)
 - ◆ A clock hand is used to select a good LRU candidate
 - » Sweep through the pages in circular order like a clock
 - » If the ref bit is off, it hasn’t been used recently
 - What is the minimum “age” if ref bit is off?
 - » If the ref bit is on, turn it off and go to next page
 - ◆ Arm moves quickly when pages are needed
 - ◆ Low overhead when plenty of memory
 - ◆ If memory is large, “accuracy” of information degrades
 - » One fix: use two hands (leading erase hand, trailing select hand)
 - » Hands have a fixed “angle” and move at the same time

Example: gcc Page Replace



Example: Belady's Anomaly



Eviction in Practice

- We have described eviction on the critical path of handling a page fault
 - ♦ In practice, we want to avoid this to reduce page fault time
- Instead, maintain a list of free physical pages
 - ♦ Grab from this list whenever the OS needs physical pages
- Do it in the background, off the page fault critical path
 - ♦ Page/swap daemon runs occasionally, executing the page replacement algorithm (kswapd on Linux)
 - ♦ When list reaches a “low water mark”, run daemon
 - ♦ When list reaches a “high water mark”, stop
 - ♦ Enables daemon to evict many dirty pages at once to amortize

Second Chance

- Maintaining a list of free physical pages enables another important optimization
- Recall that the page replacement algorithm is a rough approximation of LRU
 - ◆ Can certainly make mistakes
 - ◆ LRU does not necessarily work well for all program behaviors
- Idea: If a page is on the free list, and it is accessed by a process before being reallocated, rescue it from the free list and give it back to the process
 - ◆ Called “second chance”
 - ◆ Recovers from poor choices made by replacement algorithm

Fixed vs. Variable Space

- In a multiprogramming system, we need a way to allocate memory to competing processes
- Problem: How to determine how much memory to give to each process?
 - ♦ Fixed space algorithms
 - » Each process is given a limit of pages it can use
 - » When it reaches the limit, it replaces from its own pages
 - » Local replacement
 - Some processes may do well while others suffer
 - ♦ Variable space algorithms
 - » Process' set of pages grows and shrinks dynamically
 - » Global replacement
 - One process can ruin it for the rest

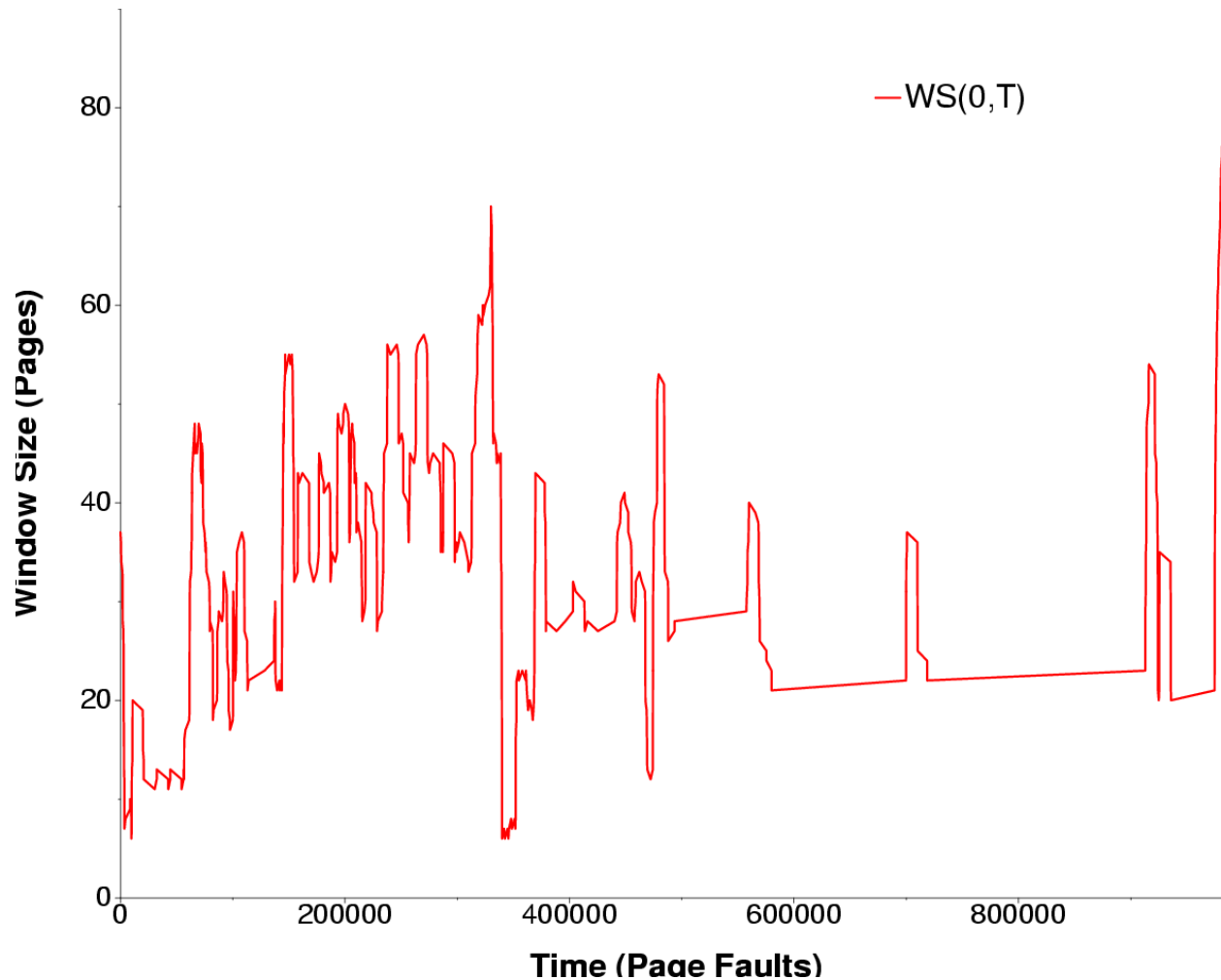
Working Set Model

- A working set of a process is used to model the dynamic locality of its memory usage
 - ◆ Defined by Peter Denning in 60s
- Definition
 - ◆ $WS(t,w) = \{\text{pages } P \text{ such that } P \text{ was referenced in the time interval } (t, t-w)\}$
 - ◆ t – time, w – working set window (measured in page refs)
- A page is in the working set (WS) only if it was referenced in the last w references

Working Set Size

- The working set size is the number of unique pages in the working set
 - ◆ The number of unique pages referenced in the interval $(t, t-w)$
- The working set size changes with program locality
 - ◆ During periods of poor locality, you reference more pages
 - ◆ Within that period of time, the working set size is larger
- Intuitively, want the working set to be the set of pages a process needs in memory to prevent heavy faulting
 - ◆ Each process has a parameter w that determines a working set with few faults
 - ◆ Denning: Don't run a process unless working set is in memory

Example: gcc Working Set



Working Set Problems

- Problems
 - ◆ How do we determine w ?
 - ◆ How do we know when the working set changes?
- Too hard to answer
 - ◆ So, working set is not used in practice as a page replacement algorithm
- However, it is still used as an abstraction
 - ◆ The intuition is still valid
 - ◆ When people ask, “How much memory does Firefox need?”, they are in effect asking for the size of Firefox’s working set

Page Fault Frequency (PFF)

- Page Fault Frequency (PFF) is a variable space algorithm that uses a more ad-hoc approach
 - ♦ Monitor the fault rate for each process
 - ♦ If the fault rate is above a high threshold, give it more memory
 - » So that it faults less
 - » But not always (FIFO, Belady's Anomaly)
 - ♦ If the fault rate is below a low threshold, take away memory
 - » Should fault more
 - » But not always
- Hard for PFF to distinguish between changes in locality and changes in size of working set
 - ♦ Page faults can increase for both reasons, PFF cannot distinguish between the two

Thrashing

- Page replacement algorithms avoid **thrashing**
 - ♦ When most of the time is spent by the OS in paging data back and forth from disk
 - ♦ Little time spent doing useful work (making progress)
 - ♦ In this situation, the system is **overcommitted**
 - » No idea which pages should be in memory to reduce faults
 - » Could just be that there isn't enough physical memory for all of the processes in the system
 - » Ex: Running Windows95 with 4 MB of memory...
 - ♦ Possible solutions
 - » **Swapping** – write out all pages of a process
 - » Buy more memory

Suspending the OS

- Swapping a process suspends it and saves it to disk
 - ◆ What about the entire system?
- Sleep mode
 - ◆ System suspends, but no data from memory saved to disk
 - ◆ Use power to refresh DRAM to maintain contents of memory
 - ◆ Resume on an interrupt (fast), but can lose data if power lost
- Hibernation
 - ◆ Save contents of physical memory to disk, suspend system
 - ◆ Resume on an interrupt, restore contents of physical memory
 - ◆ Slower, but does not require power (e.g., battery can run out)
- Hybrid: do both, combine advantages of both

Summary

- Page replacement algorithms
 - ♦ Belady's – optimal replacement (minimum # of faults)
 - ♦ FIFO – replace page loaded furthest in past
 - ♦ LRU – replace page referenced furthest in past
 - » Approximate using PTE reference bit
 - ♦ LRU Clock – replace page that is “old enough”
 - ♦ Working Set – keep the set of pages in memory that has minimal fault rate (the “working set”)
 - ♦ Page Fault Frequency – grow/shrink page set as a function of fault rate
- Multiprogramming
 - ♦ Should a process replace its own page, or that of another?

Next time...

- Read Chapters 37, 39