CSE 120
Principles of Operating Systems

Spring 2018

Lecture 11: Page Replacement

Geoffrey M. Voelker

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)

Lecture Overview

- Review paging and page replacement
- Survey page replacement algorithms
- Discuss local vs. global replacement
- Discuss thrashing

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 TLB miss
    - PTE was invalid, causes fault
  - 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 brand 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 all necessary code and data pages are in memory
  - 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 this is done
  - And they come in all shapes and sizes

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

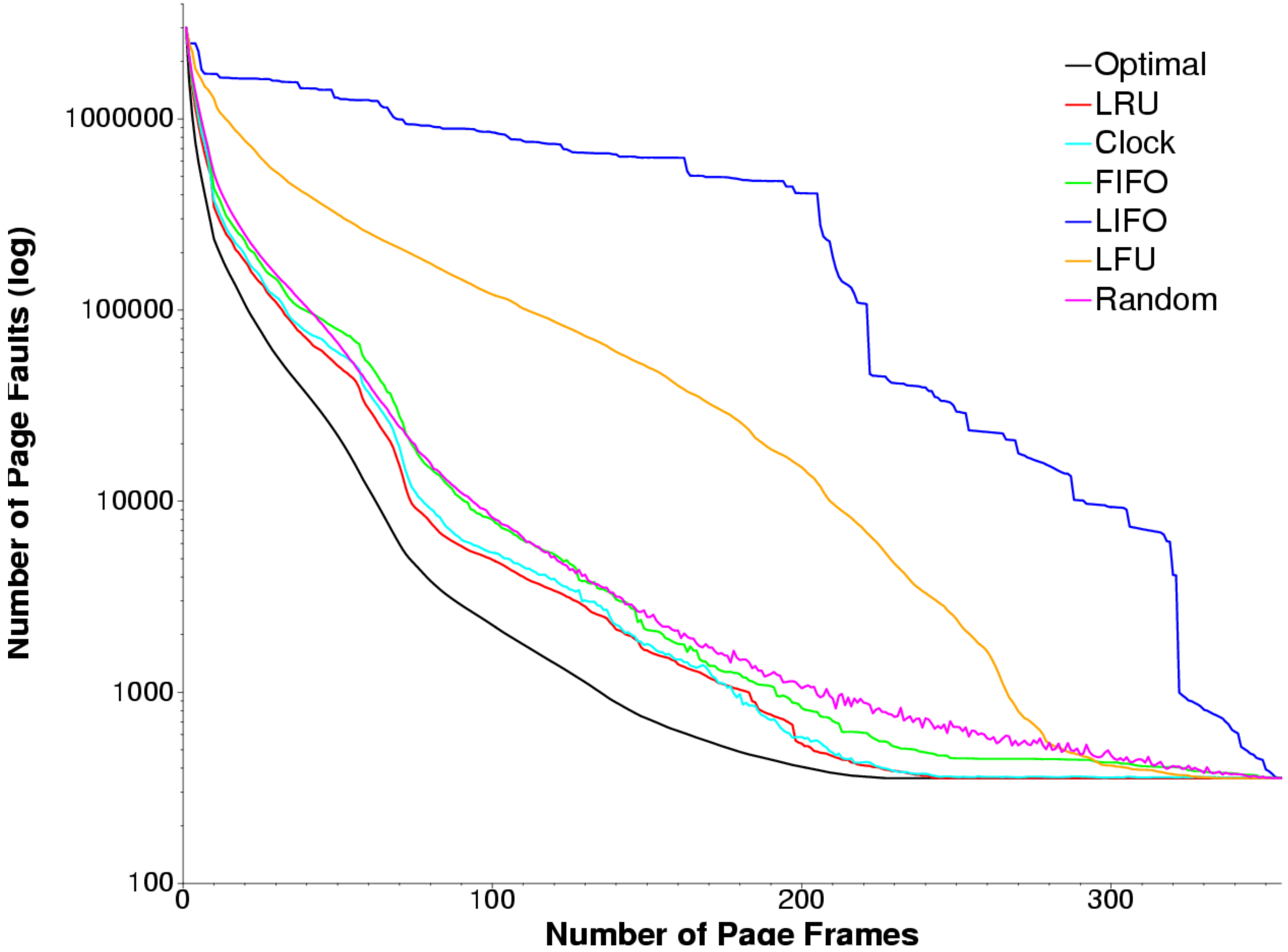
Approximating LRU

- LRU approximations use the PTE reference 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
- Some old architectures don’t have a reference bit
  - Can simulate reference bit using the valid bit to induce faults
  - What happens when we make a page invalid?

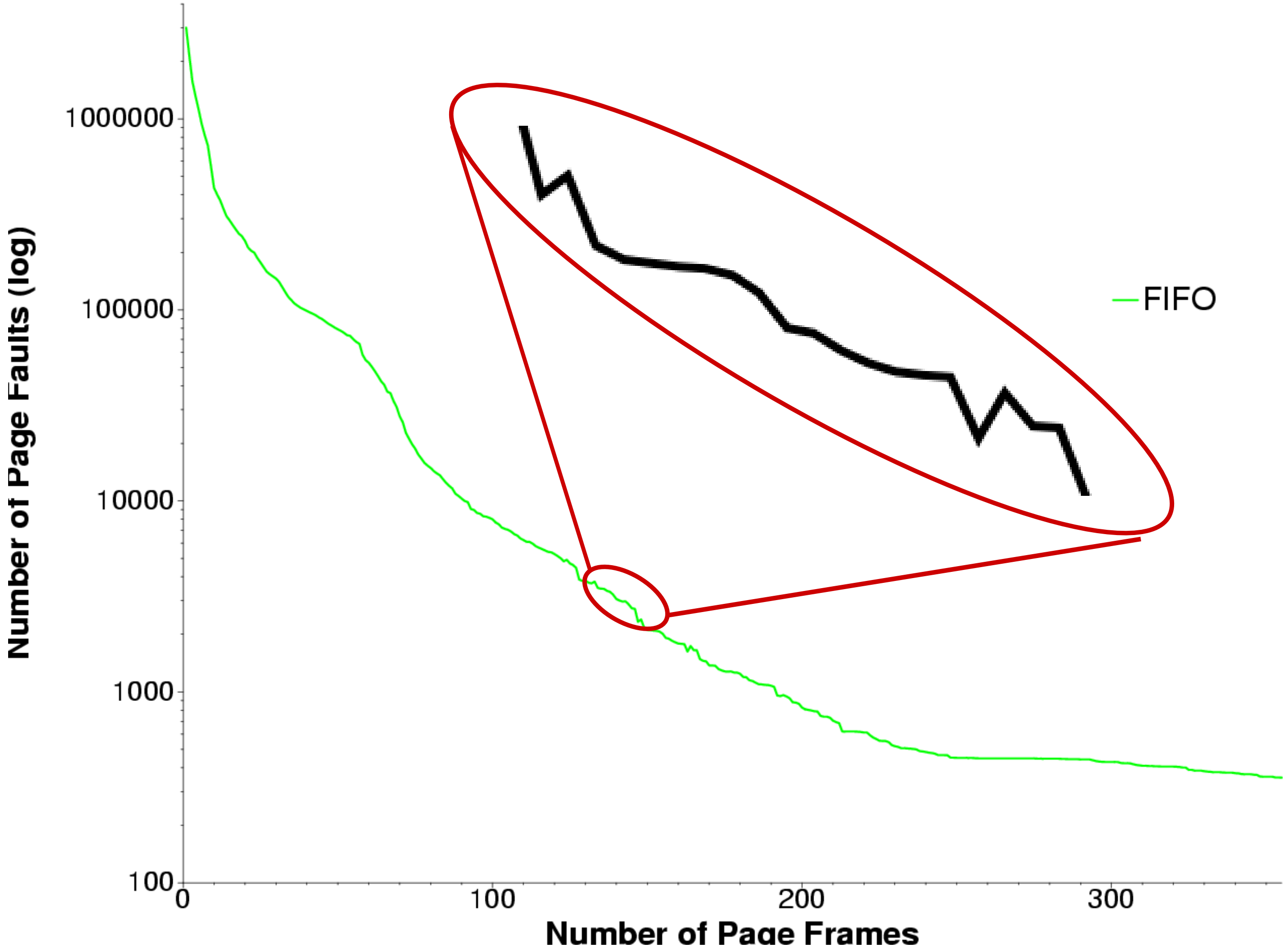
LRU Clock (Not Recently Used)

- Not Recently Used (NRU) – Used by Unix
  - 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
    - What does it degrade to?
    - One fix: use two hands (leading erase hand, trailing select hand)

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

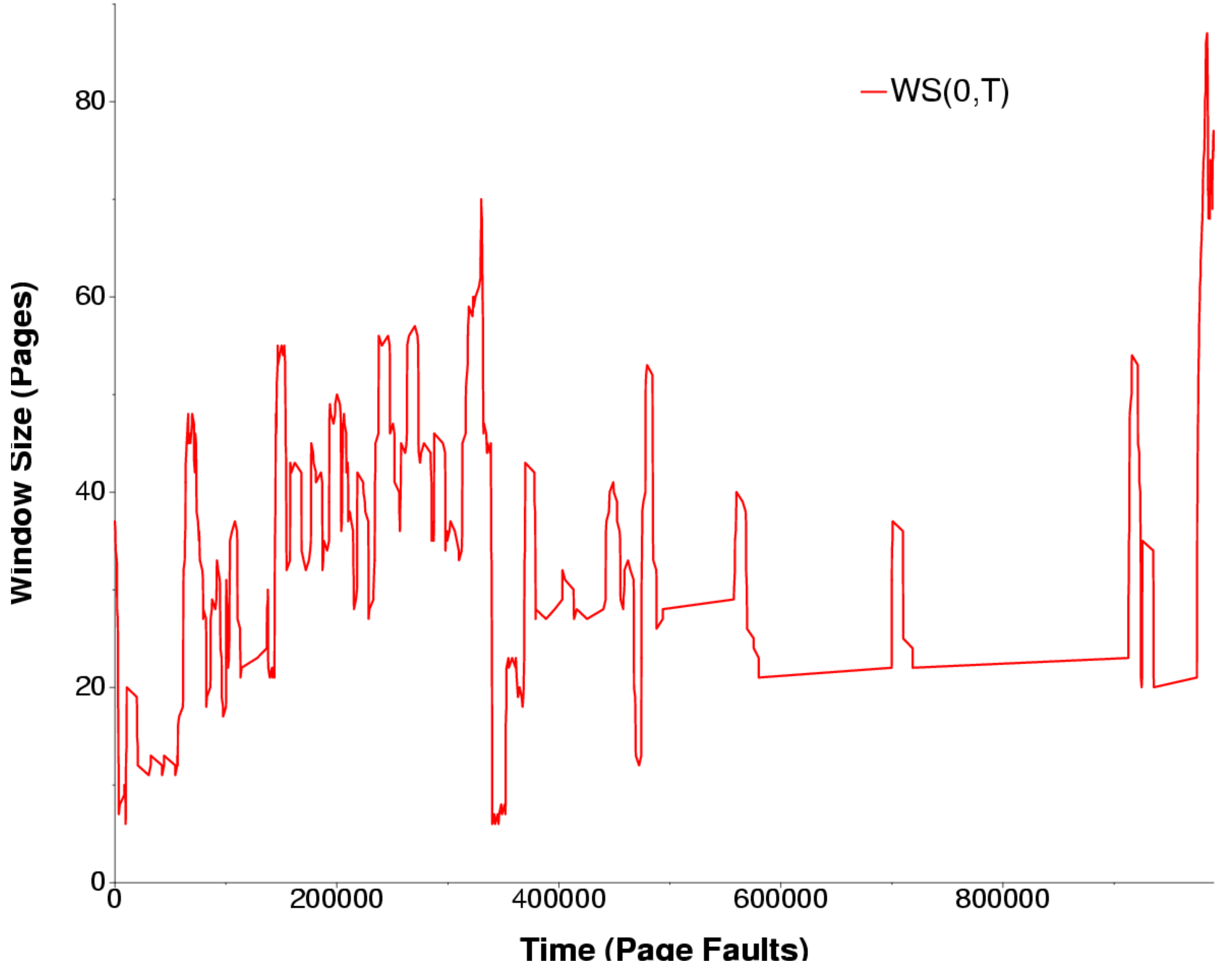
Working Set Model

- 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) = {pages P such that P 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 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

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

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, 40