UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

CS 202 Advanced Operating Systems

Virtual Memory (cont'd)

Elephant(s) in the room

- Problem 1: Translation is slow!
  - Many memory accesses for each memory access
  - Caches are useless!

- Problem 2: Page table can be gigantic!
- We need one for each process
- All your memory belongs to us!

"Unfortunately, there's another elephant in the room."

Speeding up Translation with a TLB

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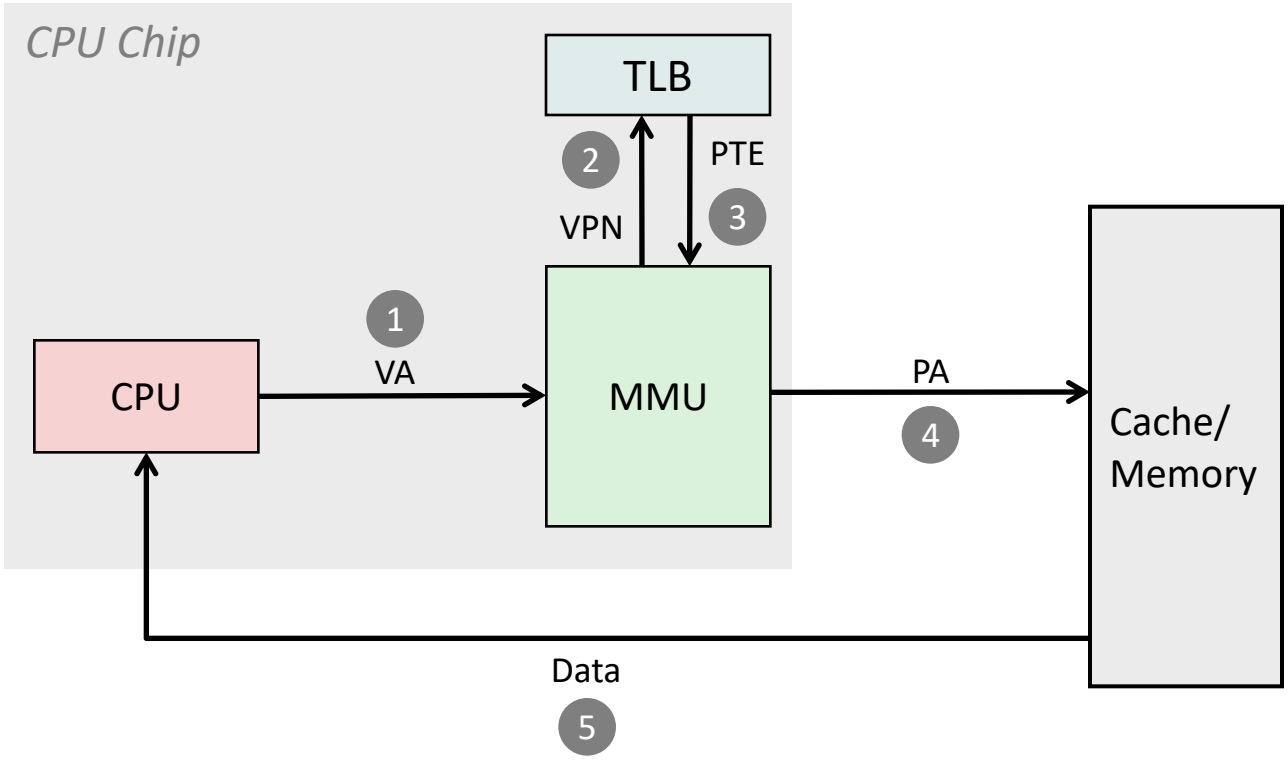
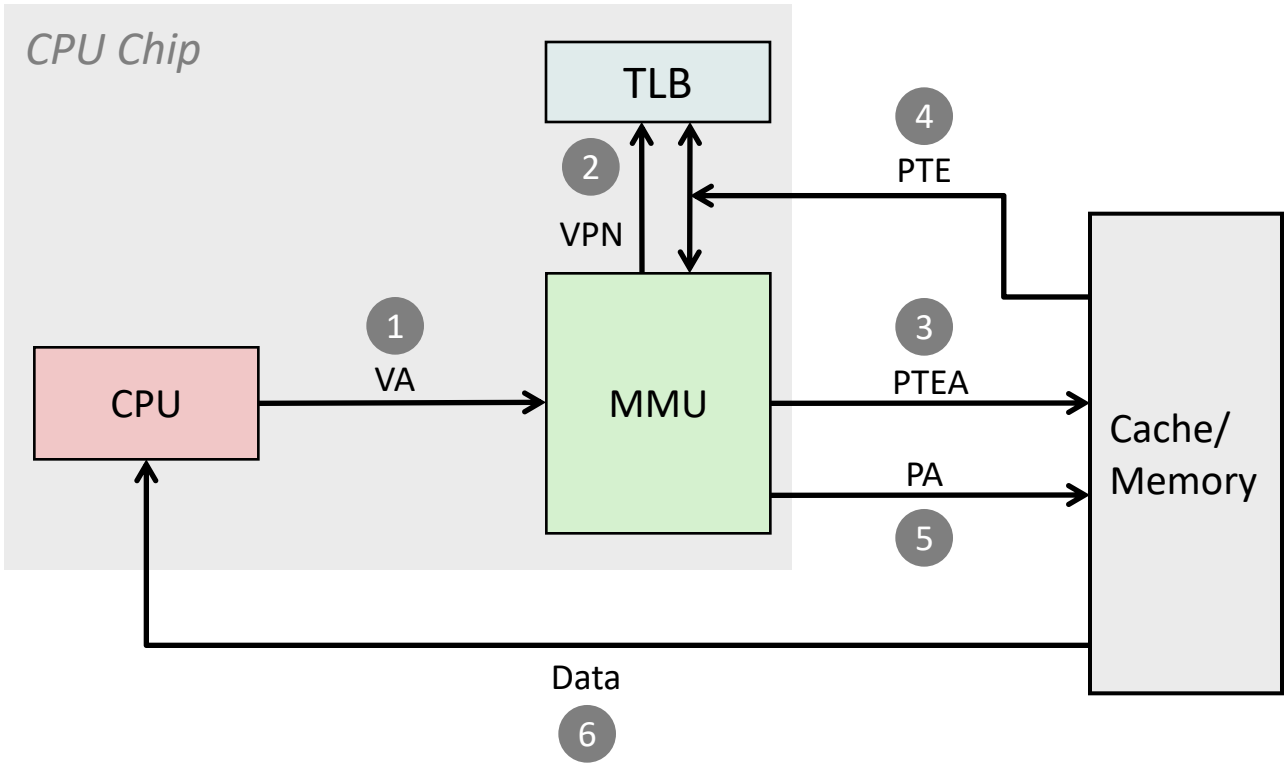
- Page table entries (PTEs) are cached in L1 like any other memory word
  - PTEs may be evicted by other data references
  - PTE hit still requires a small L1 delay
- Solution: *Translation Lookaside Buffer* (TLB)
  - Small hardware cache in MMU
  - Maps virtual page numbers to physical page numbers
  - Contains complete page table entries for small number of pages

TLB Hit



A TLB hit eliminates a memory access

TLB Miss



A TLB miss incurs an additional memory access (the PTE)

Fortunately, TLB misses are rare. Why?

Reloading the TLB

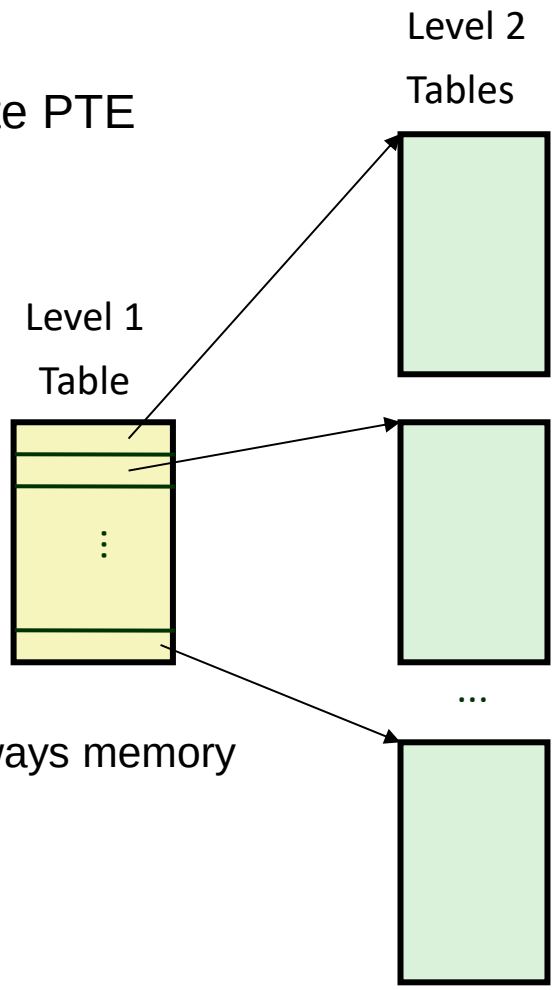
- If the TLB does not have mapping, two possibilities:
  1. MMU loads PTE from page table in memory
     - Hardware managed TLB, OS not involved in this step
     - OS has already set up the page tables so that the hardware can access it directly
  2. Trap to the OS
     - Software managed TLB, OS intervenes at this point
     - OS does lookup in page table, loads PTE into TLB
     - OS returns from exception, TLB continues
- A machine will only support one method or the other
- At this point, there is a PTE for the address in the TLB

Page Faults

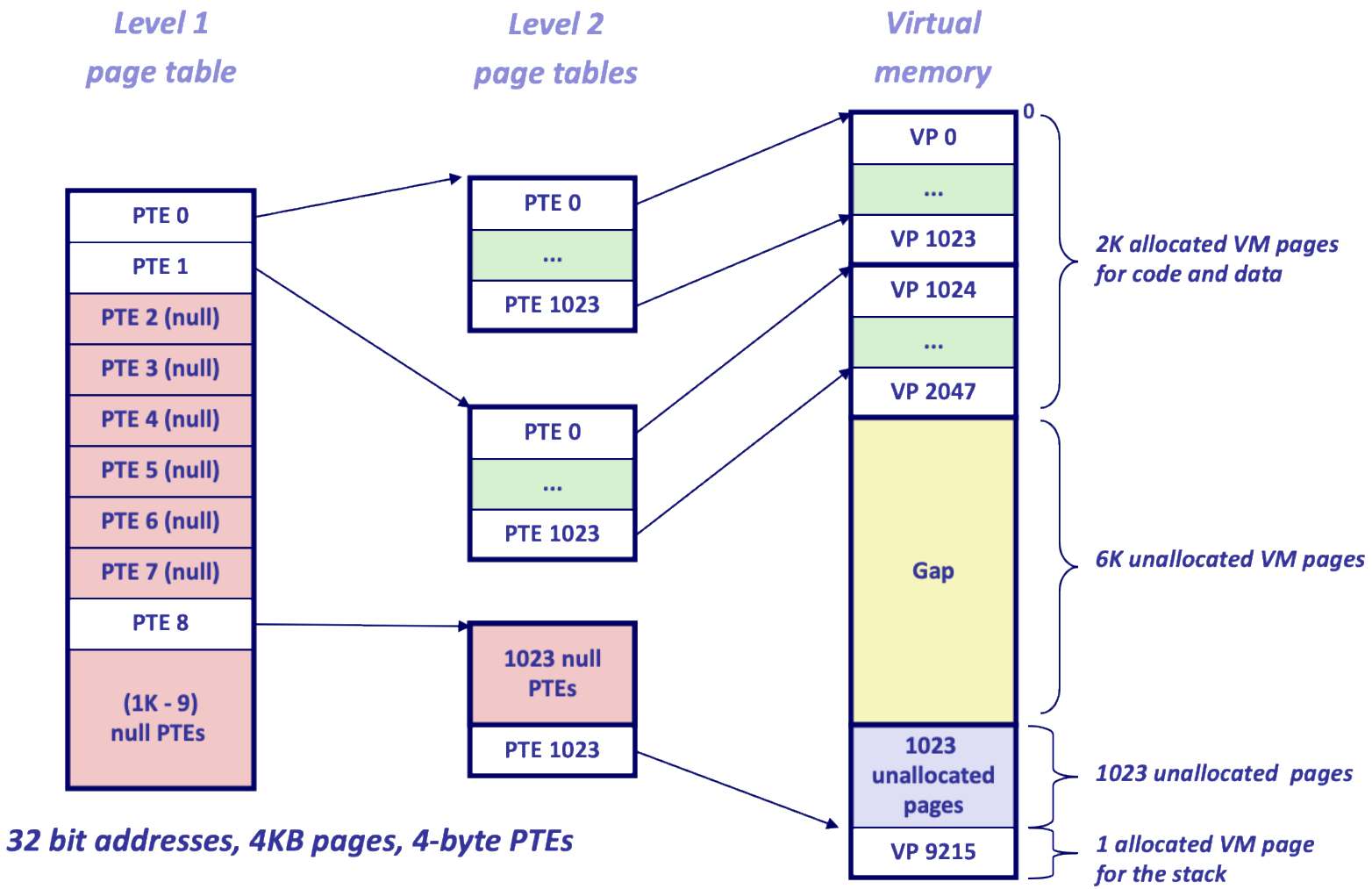
- PTE can indicate a protection fault
  - Read/write/execute – operation not permitted on page
  - Invalid – virtual page not allocated, or page not in physical memory
- TLB traps to the OS (software takes over)
  - R/W/E – OS usually will send fault back up to process, or might be playing games (e.g., copy on write, mapped files)
  - Invalid
    - Virtual page not allocated in address space
      - OS sends fault to process (e.g., segmentation fault)
    - Page not in physical memory
      - OS allocates frame, reads from disk, maps PTE to physical frame

Multi-Level Page Tables

- Suppose:
  - 4KB (2^{12}) page size, 48-bit address space, 8-byte PTE
- Problem:
  - Would need a 512 GB page table!
    - $2^{48} * 2^{-12} * 2^{3} = 2^{39}$ bytes
- Common solution:
  - Multi-level page tables
  - Example: 2-level page table
    - Level 1 table: each PTE points to a page table (always memory resident)
    - Level 2 table: each PTE points to a page (paged in and out like any other data)



A Two-Level Page Table Hierarchy



Page Replacement

Mapped Files

- Mapped files enable processes to do file I/O using loads and stores
  - Instead of “open, read into buffer, operate on buffer, …”
- Bind a file to a virtual memory region (mmap() in Unix)
  - PTEs map virtual addresses to physical frames holding file data
  - Virtual address base + N refers to offset N in file
- Initially, all pages mapped to file are invalid
  - OS reads a page from file when invalid page is accessed
  - OS writes a page to file when evicted, or region unmapped
  - If page is not dirty (has not been written to), no write needed
    - Another use of the dirty bit in PTE

Demand Paging (OS)

- We use demand paging (similar to other caches):
  - Pages loaded from disk when referenced
  - Pages may be evicted to disk when memory is full
  - Page faults trigger paging operations
- What is the alternative to demand paging?
  - Some kind of prefetching
- Lazy vs. aggressive policies in systems

Demand Paging (Process)

- Demand paging 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 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 policy

- What we discussed so far (page faults, swap, page table structures, etc…) is mechanisms
- Page replacement policy: determine which page to remove when we need a victim
- Does it matter?
  - Yes! Page faults are super expensive
  - Getting the number down, can improve the performance of the system significantly

Evicting the Best Page

- Goal is to reduce the page fault rate
- 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 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
  - Idea: Replace the page that will not be used for the longest time in the future
  - Optimal? How would you show?
  - Problem: Have to predict the future
- Why is Belady's useful then?
  - Use it as a yardstick/upper bound
  - 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
  - What's a good lower bound?
    - 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

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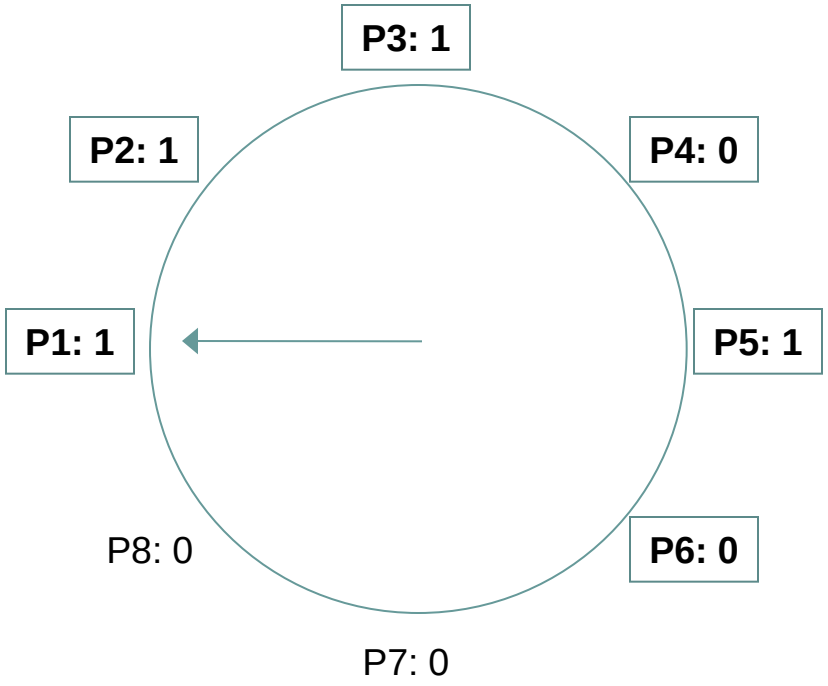
- LRU approximations use the PTE reference bit
  - Keep a counter for each page
  - At regular intervals, for every page do:
    - If ref bit = 0, increment counter
    - If ref bit = 1, zero the counter
    - Zero the reference bit
  - The counter will contain the number of intervals since the last reference to the page
  - The page with the largest counter is the least recently used
- Some architectures don't have a reference bit
  - Can simulate reference bit using the valid bit to induce faults

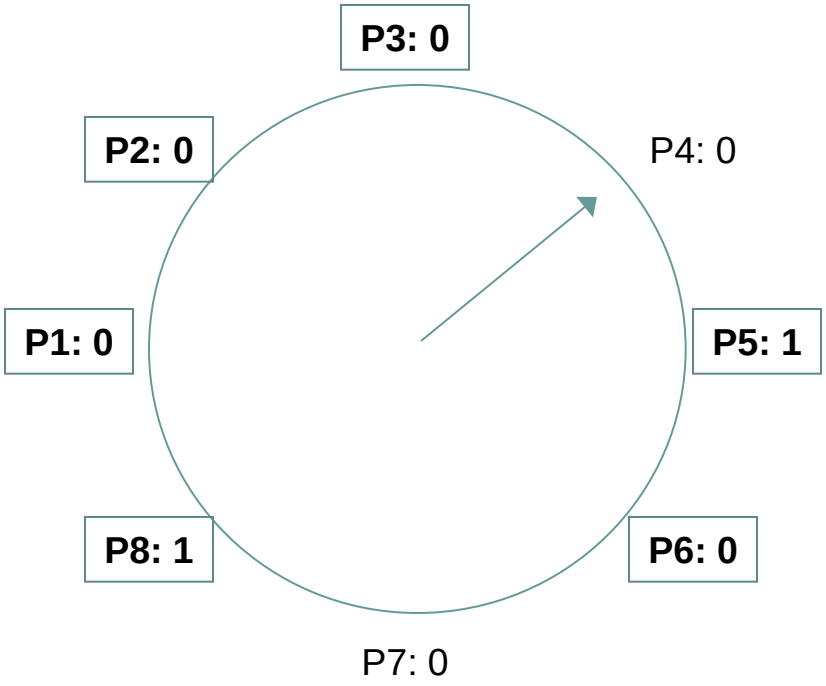
LRU Clock (Not Recently Used)

UCR

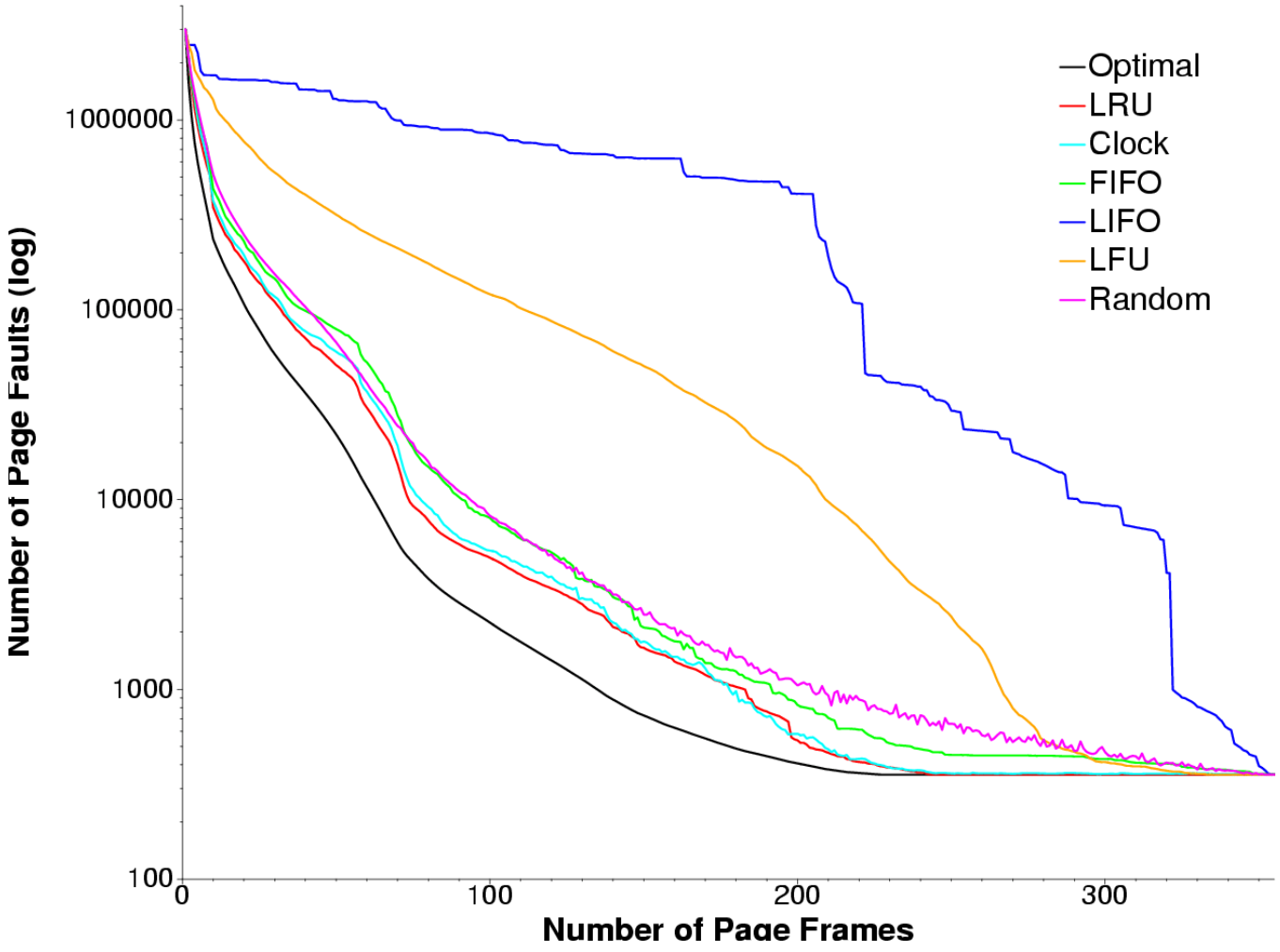
- Not Recently Used (NRU) – Used by Unix
  - Replace page that is “old enough”
  - Arrange all of physical page frames in a big circle (clock)
  - A clock hand is used to select a good LRU candidate
    - Sweep through the pages in circular order like a clock
    - If the ref bit is off, it hasn’t been 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)

LRU Clock

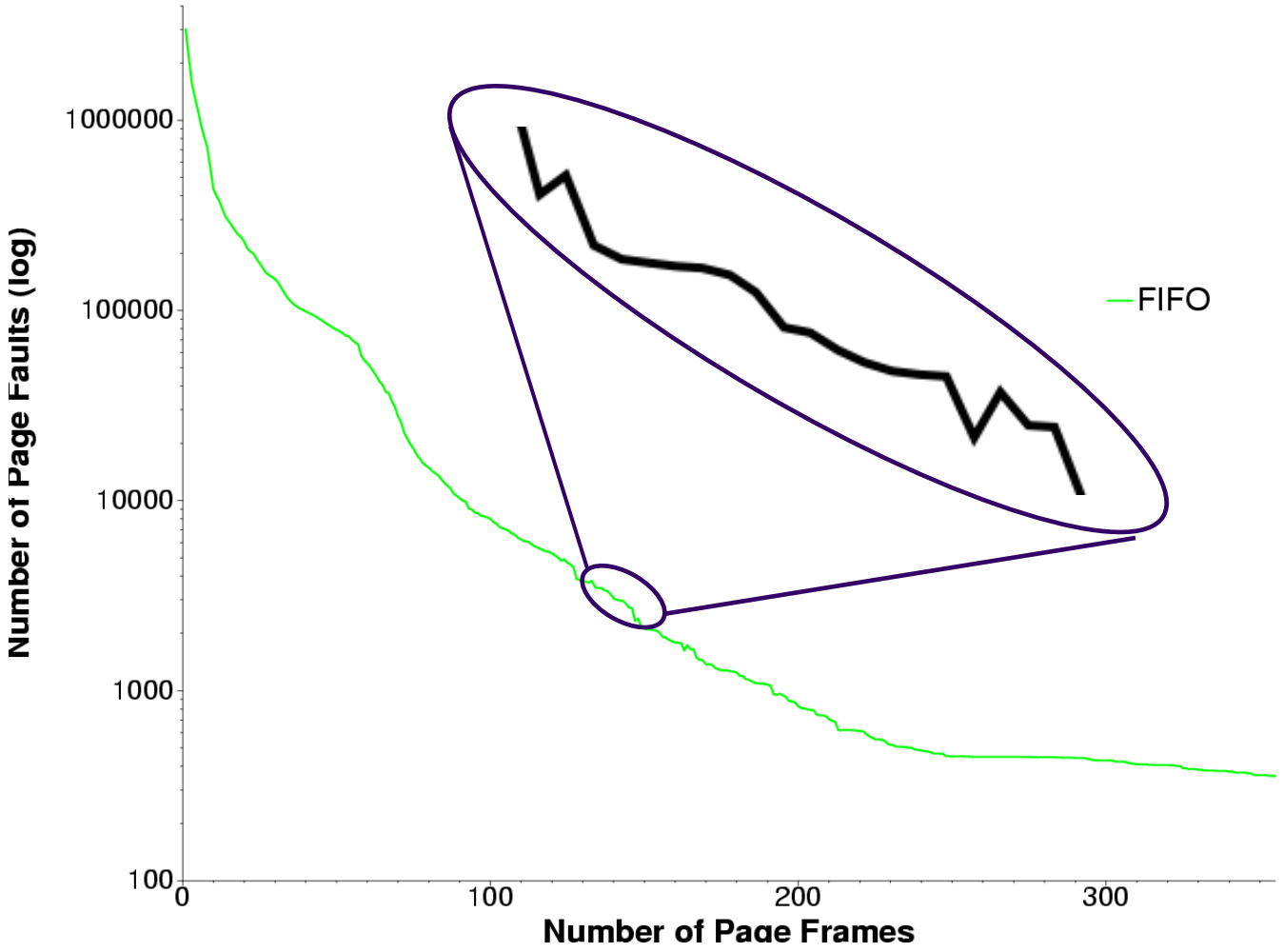




Example: gcc Page Replace



Example: Belady's Anomaly



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

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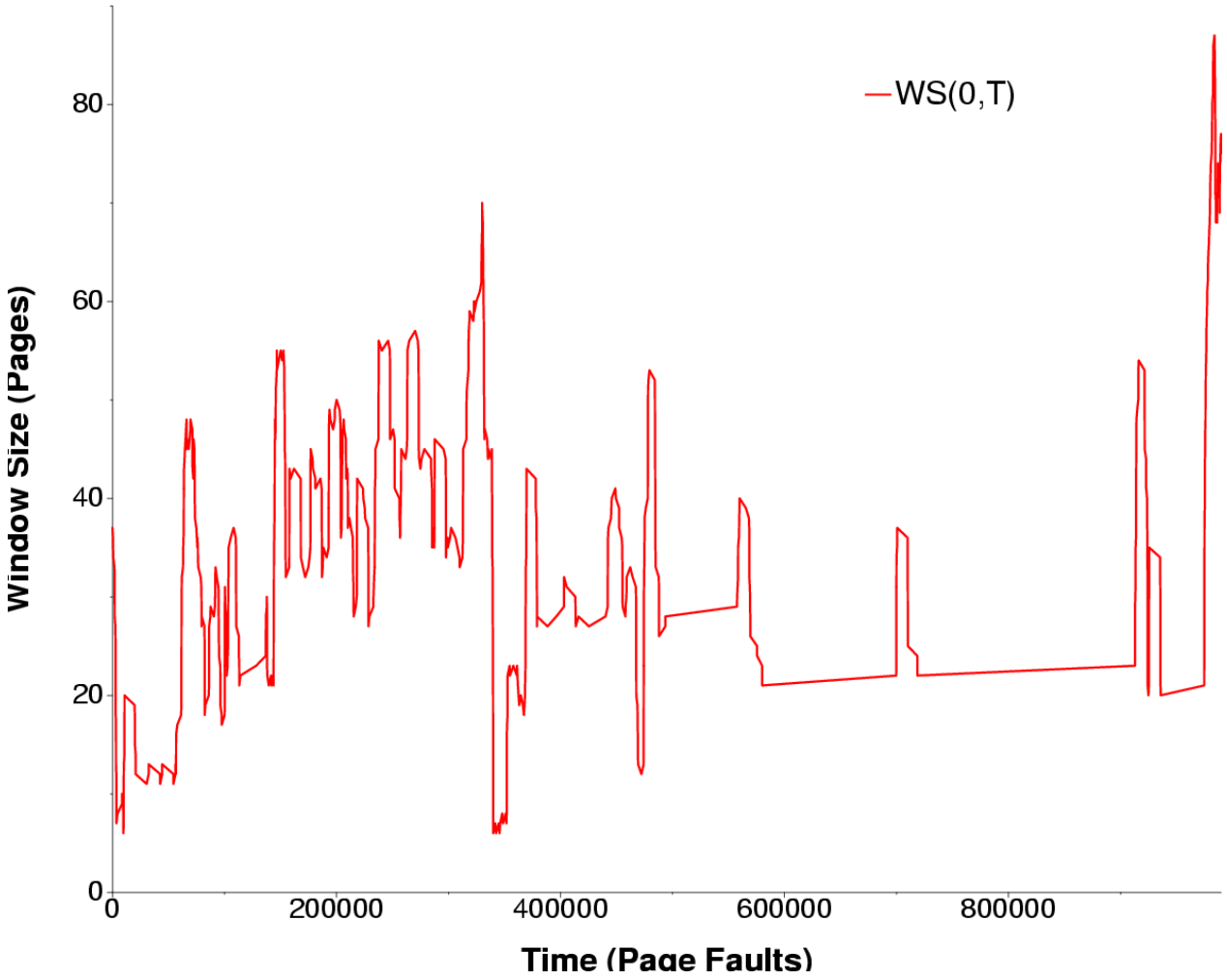
- A working set of a process is used to model the dynamic locality of its memory usage
  - Defined by Peter Denning in 60s
- Definition
  - WS(t,w) = {set of pages P, such that every page in P was referenced in the time interval (t, t-w)}
  - t – time, w – working set window (measured in page refs)
-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

Thrashing

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- Page replacement algorithms avoid thrashing
  - When most of the time is spent by the OS in paging data back and forth from disk
  - No 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?