But first, Combining segments and pages

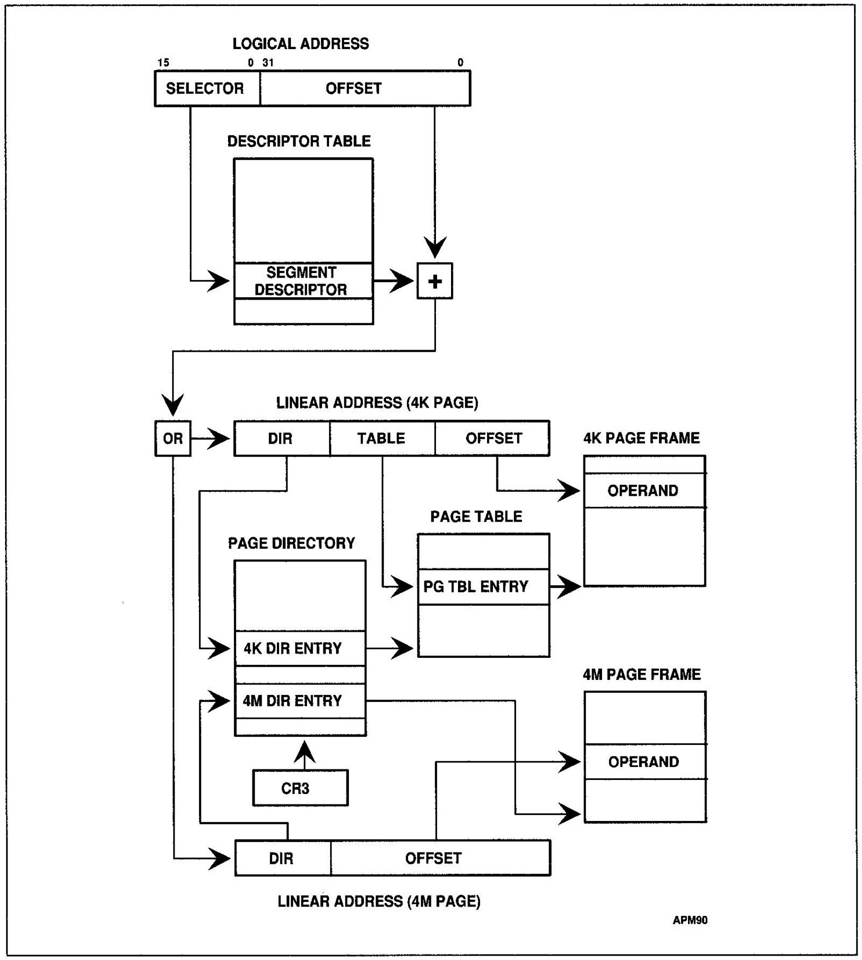

Figure 11-16. Combined Segment and Page Address Translation

Answer to mixing segments and pages

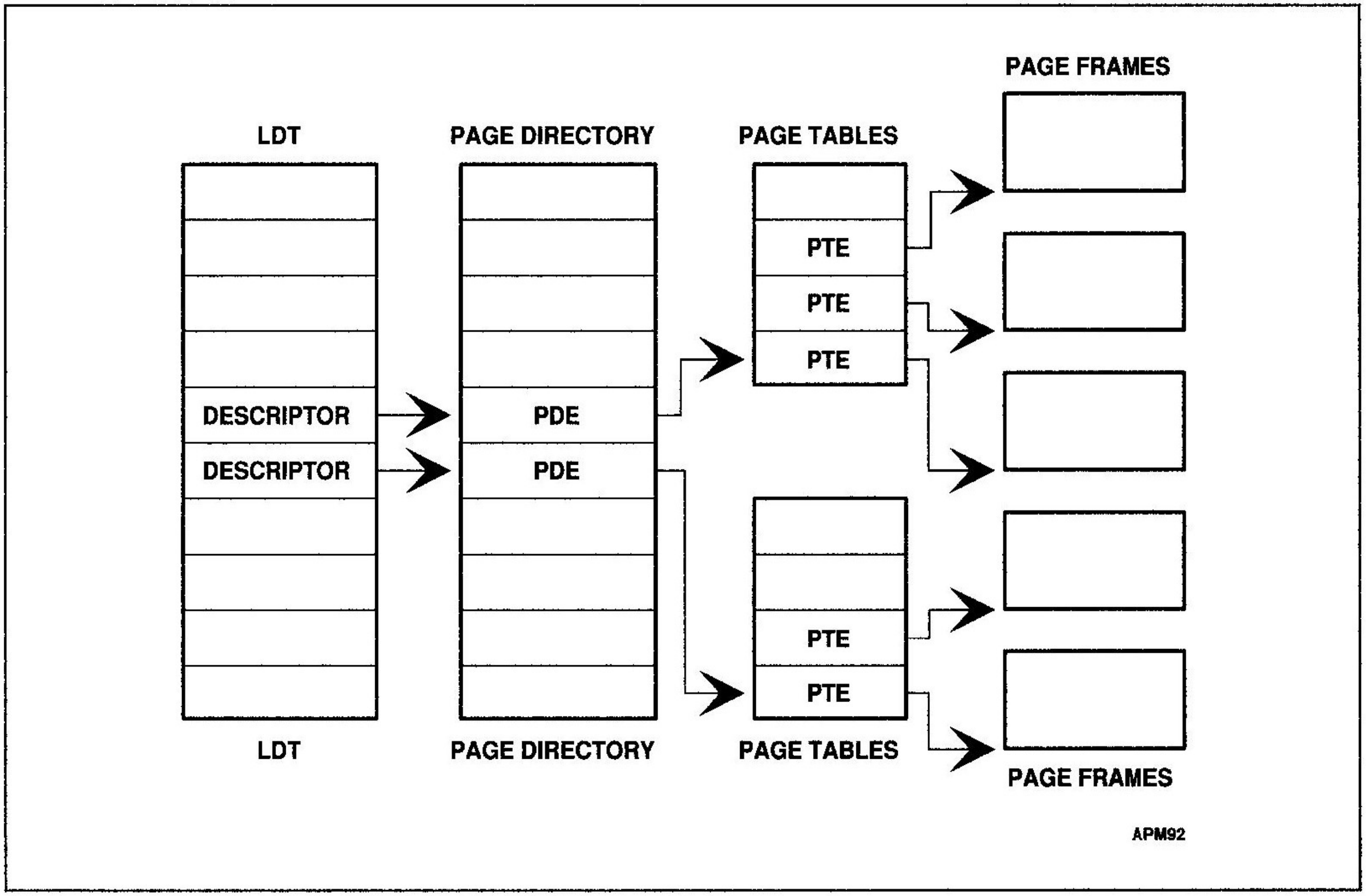

Figure 11-17. Each Segment Can Have Its Own Page Table

CSE 451: Operating Systems
Winter 2023

Module 12
Virtual Memory, Page Faults, Demand Paging, and Page Replacement

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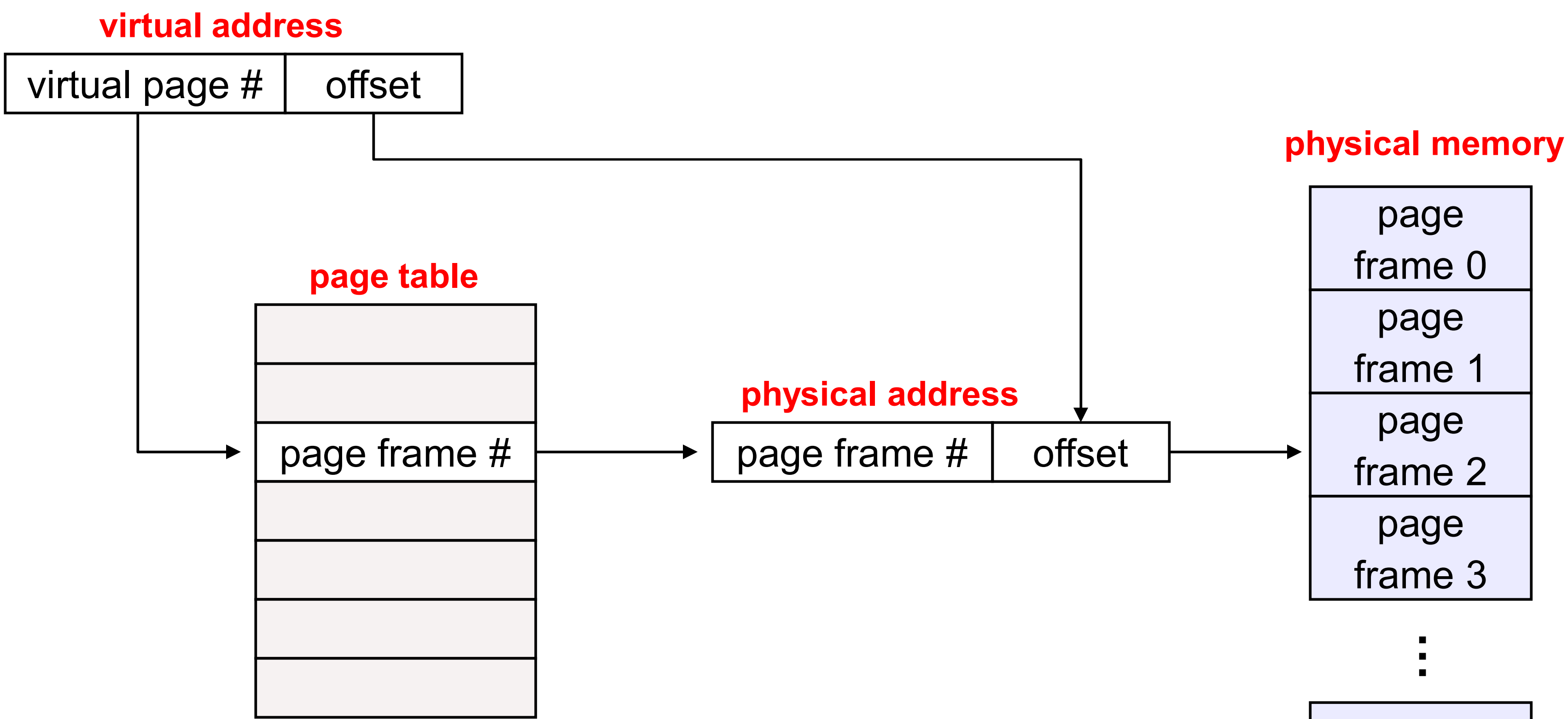
Reminder: Mechanics of address translation



Note: Each process has its own page table!

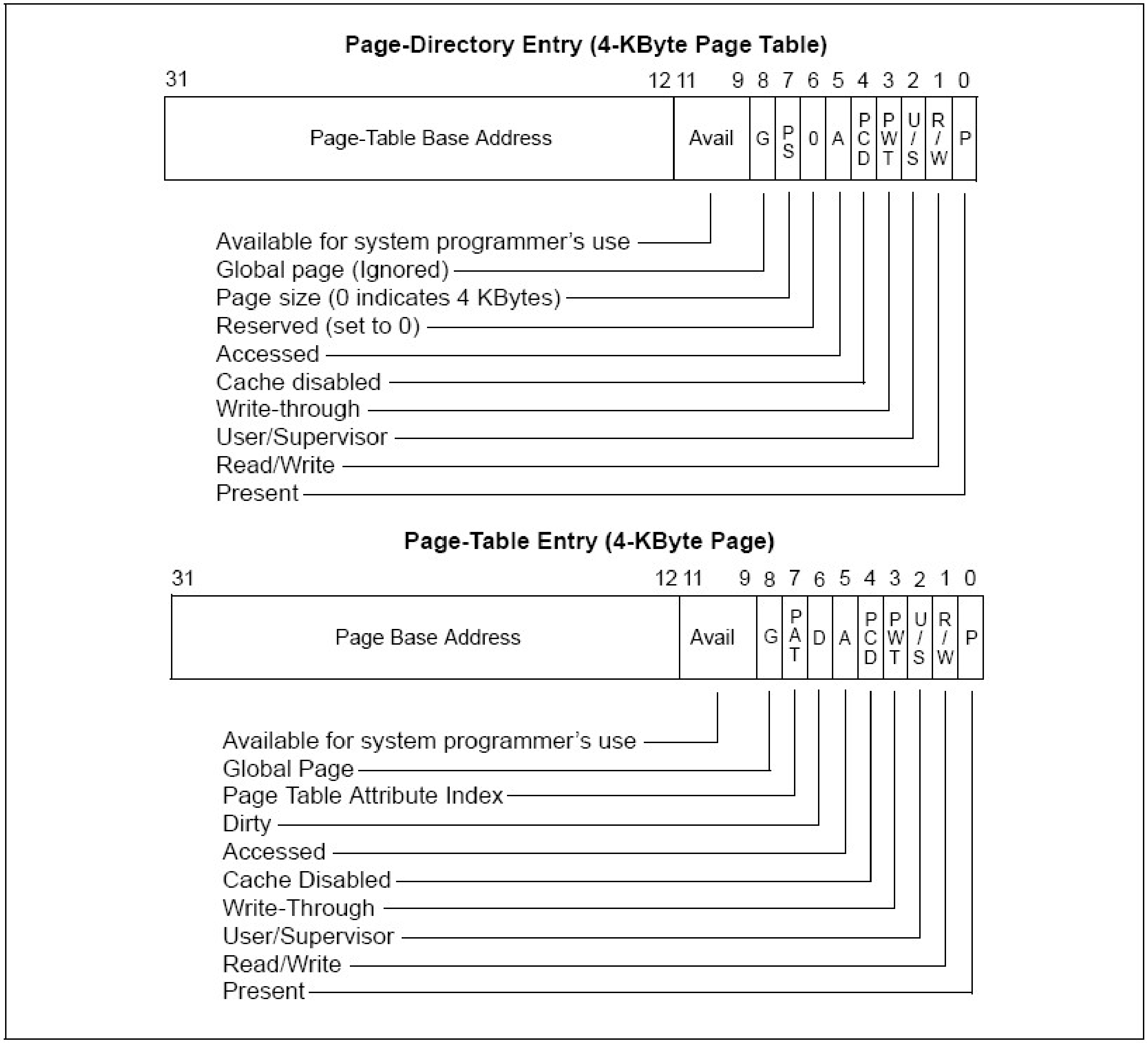
Reminder: Page Table Entries (PTEs)

This is an idealized generic PTE

1	1	1	2	20
V	R	M	prot	page frame number

- PTE's control mapping
  - the valid bit says whether or not the PTE can be used
    - says whether or not a virtual address is valid
    - it is checked each time a virtual address is used
  - the referenced bit says whether the page has been accessed
    - it is set when a page has been read or written to
  - the modified bit says whether or not the page is dirty
    - it is set when a write to the page has occurred
  - the protection bits control which operations are allowed
    - read, write, execute
  - the page frame number determines the physical page
    - physical page start address = PFN

Here is an actual PTE



Paged virtual memory

- We've hinted that all the pages of an address space do not need to be resident in memory
  - the full (used) address space exists on secondary storage (disk) in page-sized blocks
  - the OS uses main memory as a (page) cache
  - a page that is needed is transferred to a free page frame
  - if there are no free page frames, a page must be evicted
    - evicted pages go to disk (only need to write if they are dirty)
  - all of this is transparent to the application (except for performance …)
    - managed by hardware and OS
- Traditionally called paged virtual memory

Page faults

- What happens when a process references a virtual address in a page that has been evicted (or never loaded)?
  - when the page was evicted, the OS set the PTE as invalid and noted the disk location of the page in a data structure (that looks like a page table but holds disk addresses)
  - when a process tries to access the page, the invalid PTE will cause an exception (page fault) to be thrown
    - Can a single instruction have multiple faults?
  - the OS will run the page fault handler in response
    - handler uses the “like a page table” data structure to locate the page on disk
    - handler reads page into a physical frame, updates PTE to point to it and to be valid
    - OS restarts the faulting process
    - **there are a million and one details …**

Demand paging

- Pages are only brought into main memory when they are referenced
  - only the code/data that is needed (demanded!) by a process needs to be loaded
    - What's needed changes over time, of course…
  - Hence, it's called demand paging
- Few systems try to anticipate future needs
  - OS crystal ball module notoriously ineffective
- But it's not uncommon to cluster pages
  - OS keeps track of pages that should come and go together
  - bring in all when one is referenced
  - interface may allow programmer or compiler to identify clusters

Page replacement

- When you read in a page, where does it go?
  - if there are free page frames, grab one
    - what data structure might support this?
  - if not, must evict something else
  - this is called page replacement
- Page replacement algorithms
  - try to pick a page that won't be needed in the near future
  - try to pick a page that hasn't been modified (thus saving the disk write)
  - OS typically tries to keep a pool of free pages around so that allocations don't inevitably cause evictions
  - OS also typically tries to keep some "clean" pages around, so that even if you have to evict a page, you won't have to write it
    - accomplished by pre-writing when there's nothing better to do
  - *Much* more on this later!

How do you “load” a program?

- Create process descriptor (process control block)
- Create page table
- Put address space image on disk in page-sized chunks
- Build page table (pointed to by process descriptor)
  - all PTE valid bits ‘false’
  - an analogous data structure indicates the disk location of the corresponding page
  - when process starts executing:
    - instructions immediately fault on both code and data pages
    - faults taper off, as the necessary code/data pages enter memory

Oh, man, how can any of this possibly work?

- Locality!
  - temporal locality
    - locations referenced recently tend to be referenced again soon
  - spatial locality
    - locations near recently references locations are likely to be referenced soon (think about why)
- Locality means paging can be infrequent
  - once you've paged something in, it will be used many times
  - on average, you use things that are paged in
  - but, this depends on many things:
    - degree of locality in the application
    - page replacement policy and application reference pattern
    - amount of physical memory vs. application "footprint" or "working set"

Evicting the best page

- The goal of the page replacement algorithm:
  - reduce fault rate by selecting best victim page to remove
    - "system" fault rate or "program" fault rate??
  - the best page to evict is one that will never be touched again
    - duh …
  - "never" is a long time
    - Belady's proof: evicting the page that won't be used for the longest period of time minimizes page fault rate
- Rest of this module:
  - survey a bunch of page replacement algorithms
  - for now, assume that a process pages against itself, using a fixed number of page frames

#1: Belady's Algorithm

- Provably optimal: lowest fault rate (remember SJF?)
  - evict the page that won't be used for the longest time in future
  - problem: impossible to predict the future
- Why is Belady's algorithm useful?
  - as a yardstick to compare other algorithms to optimal
    - if Belady's isn't much better than yours, yours is pretty good
      - how could you do this comparison?
- Is there a best practical algorithm?
  - no; depends on workload
- Is there a worst algorithm?
  - no, but random replacement does pretty badly
    - don't laugh – there are some other situations where OS's use near-random algorithms quite effectively!

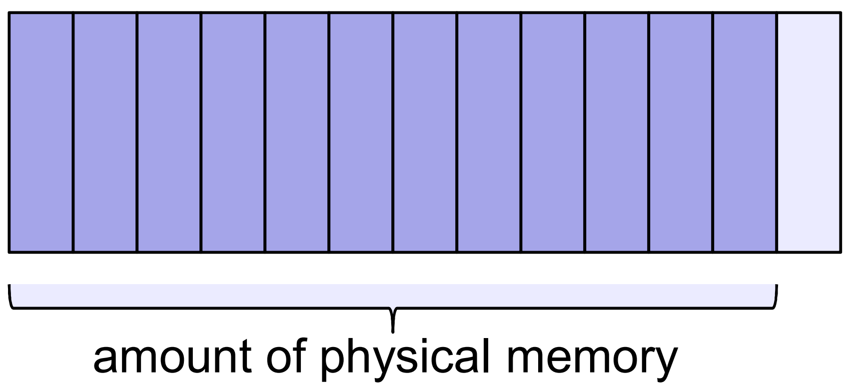
#2: FIFO

- FIFO is obvious, and simple to implement
  - when you page in something, put it on the tail of a list
  - evict page at the head of the list
- Why might this be good?
  - maybe the one brought in longest ago is not being used
- Why might this be bad?
  - then again, maybe it *is* being used
  - have absolutely no information either way
- In fact, FIFO's performance is typically lousy
- In addition, FIFO suffers from Belady's Anomaly
  - there are reference strings for which the fault rate *increases* when the process is given more physical memory

#3: Least Recently Used (LRU)

- LRU uses reference information to make a more informed replacement decision
  - idea: past experience gives us a guess of future behavior
  - on replacement, evict the page that hasn't been used for the longest amount of time
    - LRU looks at the past, Belady's wants to look at future
    - *How is LRU different from FIFO?*
  - when does LRU do well?
    - when is it lousy?

Example bad case: looping through array



#3: LRU continued

- Implementation
  - to be perfect, must grab a timestamp on every memory reference, put it in the PTE, order or search based on the timestamps …
  - way too $$ in memory bandwidth, algorithm execution time, etc.
  - so, we need a cheap approximation …

Approximating LRU

- Many approximations, all use the PTE's referenced bit
  - keep a counter for each page
  - at some regular interval, for each page, do:
    - if ref bit = 0, increment the counter (hasn't been used)
    - if ref bit = 1, zero the counter (has been used)
    - regardless, zero ref bit
  - the counter will contain the # of intervals since the last reference to the page
    - page with largest counter is least recently used
- Some architectures don't have PTE reference bits
  - can simulate reference bit using the valid bit to induce faults
    - hack, hack, hack

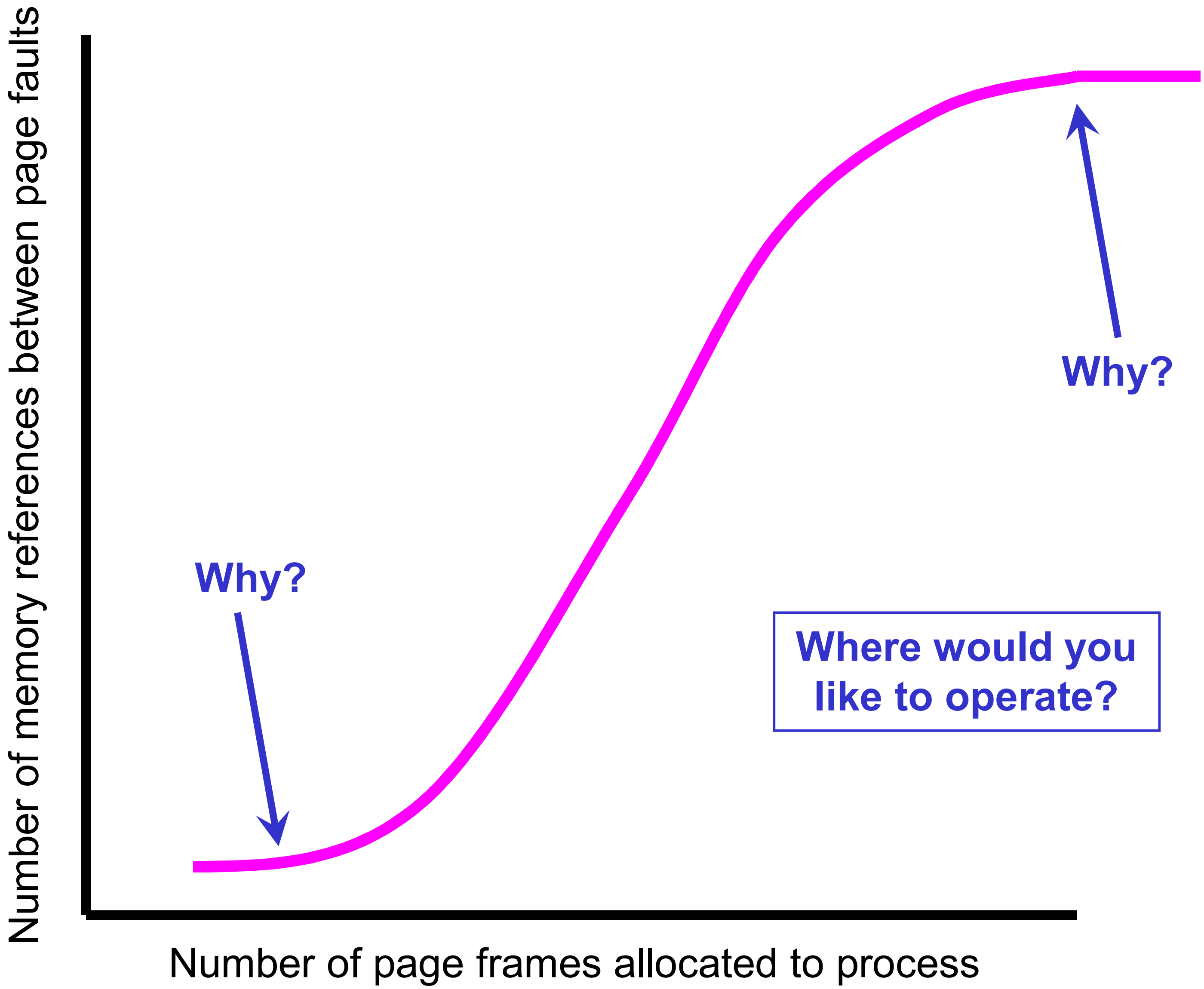
#4: LRU Clock

- AKA Not Recently Used (NRU) or Second Chance
  - replace page that is “old enough”
  - logically, arrange all physical page frames in a big circle (clock)
    - just a circular linked list
  - a “clock hand” is used to select a good LRU candidate
    - sweep through the pages in circular order like a clock
    - if ref bit is off, it hasn’t been used recently, we have a victim
      - so, what is 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 if have plenty of memory
  - if memory is large, “accuracy” of information degrades
    - add more hands to fix

Allocation of frames among processes

- FIFO and LRU Clock each can be implemented as either local or global replacement algorithms
  - local
    - each process is given a limit of pages it can use
    - it "pages against itself" (evicts its own pages)
  - global
    - the "victim" is chosen from among all page frames, regardless of owner
    - processes' page frame allocation can vary dynamically
- Issues with local replacement?
- Issues with global replacement?
  - Linux uses global replacement

- Hybrid algorithms
  - local replacement
  - an explicit mechanism for adding or removing page frames


Number of memory references between page faults
Why?
Why?
Where would you like to operate?
Number of page frames allocated to process

The *working set model of program behavior*

- The working set of a process is used to model the dynamic locality of its memory usage
  - working set = set of pages process currently “needs”
  - formally defined by Peter Denning in the 1960’s
- 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
  - obviously the working set (the particular pages) varies over the life of the program
  - so does the working set size (the number of pages in the WS)

Working set size

- The working set size, |WS(t,w)|, changes with program locality
  - during periods of poor locality, more pages are referenced
  - within that period of time, the working set size is larger
- Intuitively, the working set must be in memory, otherwise you'll experience heavy faulting (thrashing)
  - when people ask "How much memory does Firefox need?", really they're asking "what is Firefox's average (or worst case) working set size?"

#5: Hypothetical Working Set algorithm

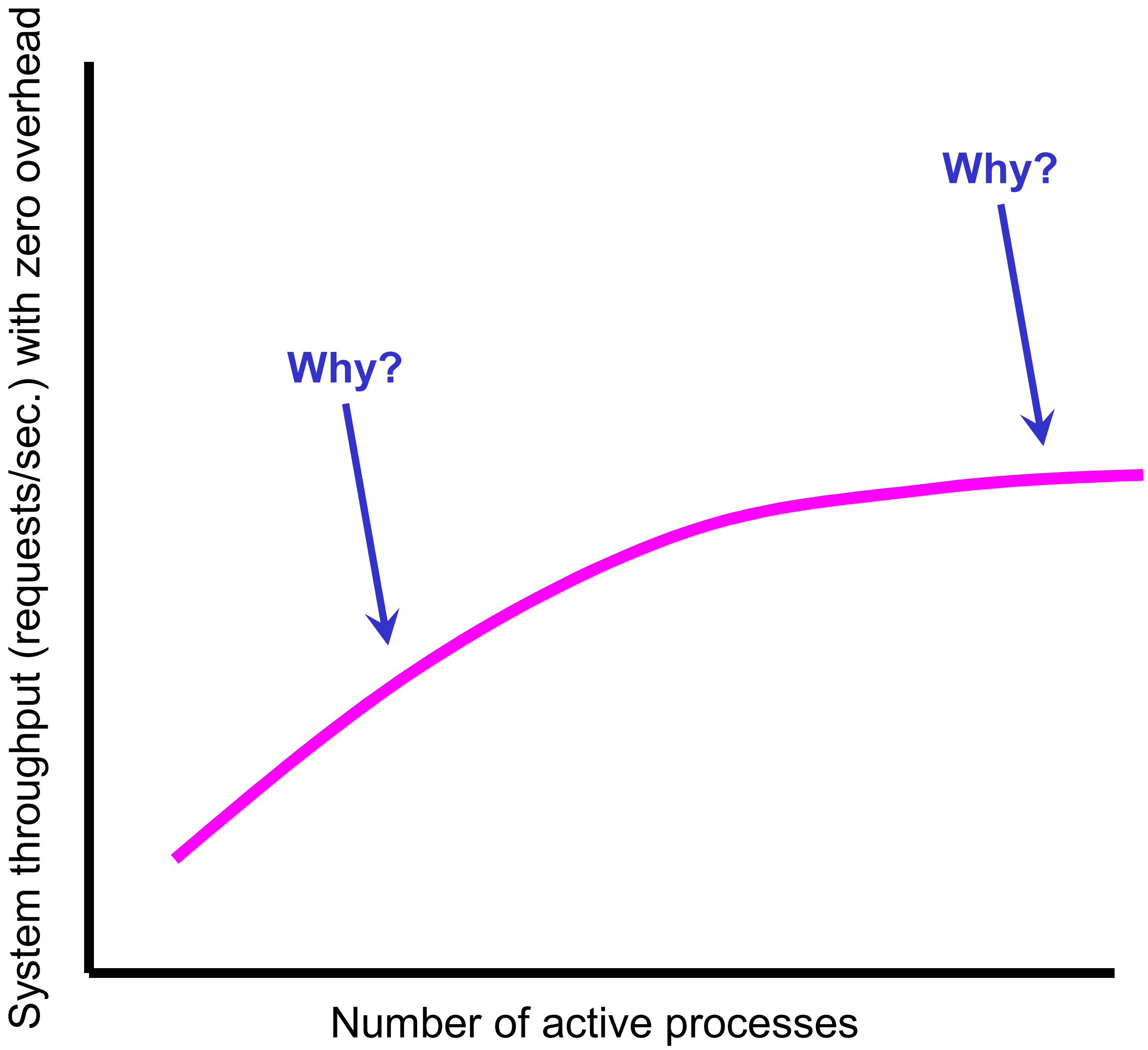
- Estimate |WS(0,w)| for a process
- Allow that process to start only if you can allocate it that many page frames
- Use a local replacement algorithm (LRU Clock?) make sure that "the right pages" (the working set) are occupying the process's frames
- Track each process's working set size, and re-allocate page frames among processes dynamically
- Problem? Solution?
- What the heck is w?

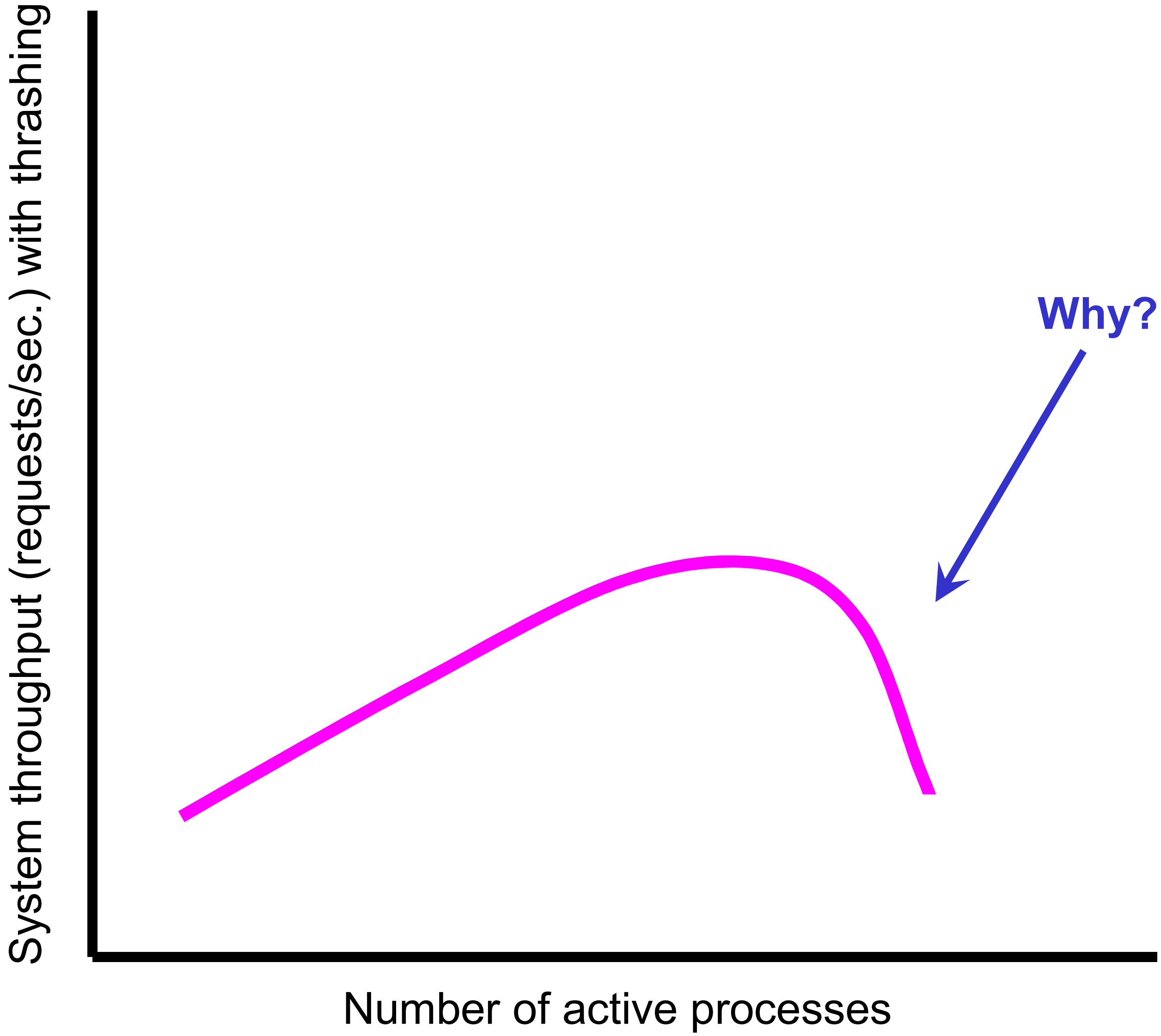
#6: Page Fault Frequency (PFF)

- PFF is a variable-space algorithm that uses a more *ad hoc* approach
- Attempt to equalize the fault rate among all processes, and to have a “tolerable” system-wide fault rate
  - monitor the fault rate for each process
  - if fault rate is above a given threshold, give it more memory
    - so that it faults less
  - if the fault rate is below threshold, take away memory
    - should fault more, allowing someone else to fault less

Thrashing

- Thrashing is when the system spends most of its time servicing page faults, little time doing useful work
  - could be that there is enough memory but a lousy replacement algorithm (one incompatible with program behavior)
  - could be that memory is over-committed
    - too many active processes


System throughput (requests/sec.) with zero overhead
Why?
Why?
Number of active processes


System throughput (requests/sec.) with thrashing
Why?
Number of active processes

Where is life interesting?

- Not if system has too much memory
  - page replacement algorithm doesn't much matter (over-provisioning)
- Not if system has too little memory
  - page replacement algorithm doesn't much matter (over-committed)
- Life is only interesting on the border between over-provisioned and over-committed
- Networking analogies
  - Aloha Network as an example of thrashing
  - over-provisioning as an alternative to Quality of Service guarantees

Summary

- Virtual memory
- Page faults
- Demand paging
  - don’t try to anticipate
- Page replacement
  - local, global, hybrid
- Locality
  - temporal, spatial
- Working set
- Thrashing

- Page replacement algorithms
  - #1: Belady's – optimal, but unrealizable
  - #2: FIFO – replace page loaded furthest in the past
  - #3: LRU – replace page referenced furthest in the past
    - approximate using PTE reference bit
  - #4: LRU Clock – replace page that is "old enough"
  - #5: Working Set – keep the working set in memory
  - #6: Page Fault Frequency – grow/shrink number of frames as a function of fault rate