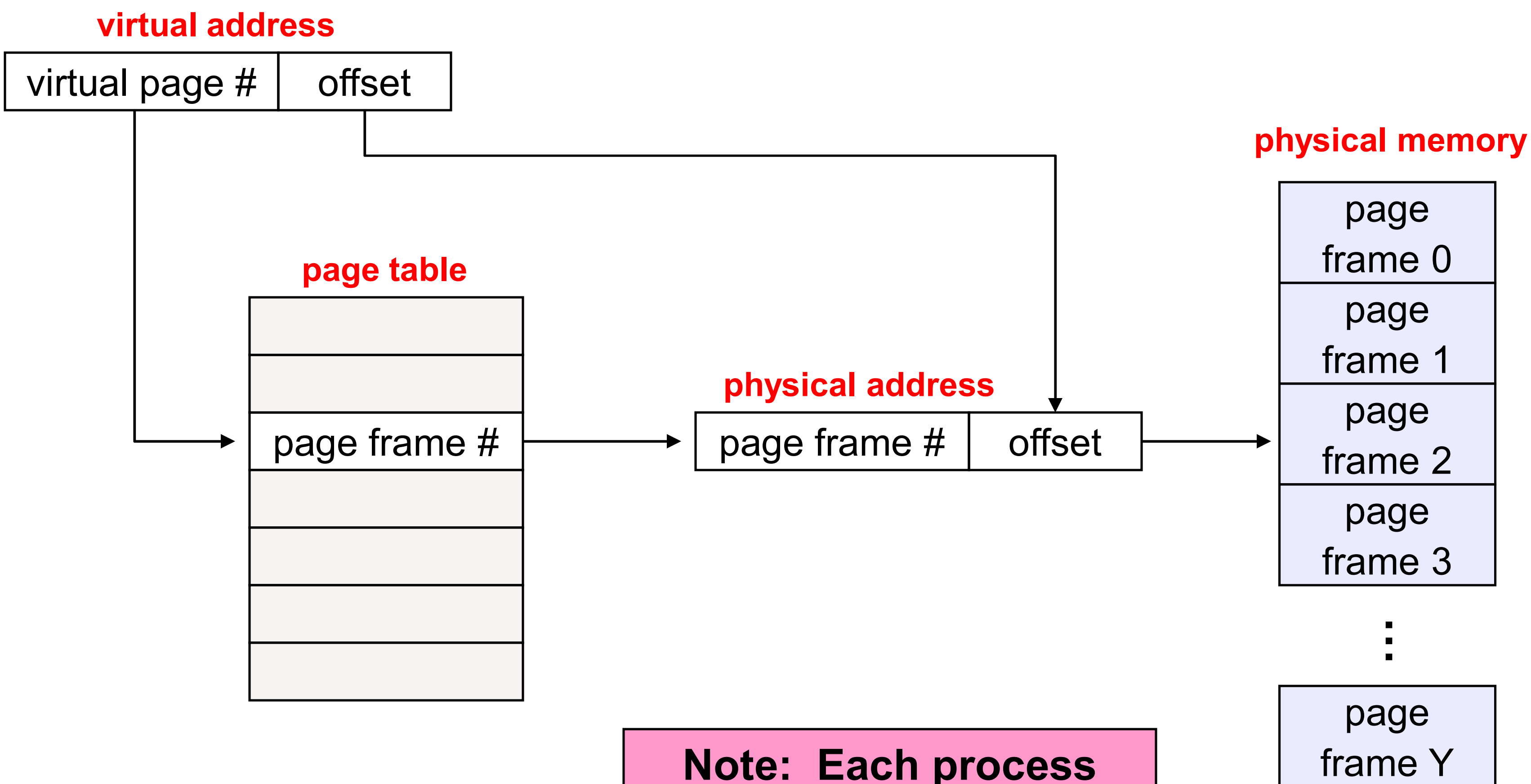
CSE 451: Operating Systems
Winter 2025

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

Gary Kimura

Reminder: Mechanics of address translation



Note: Each process has its own page table!

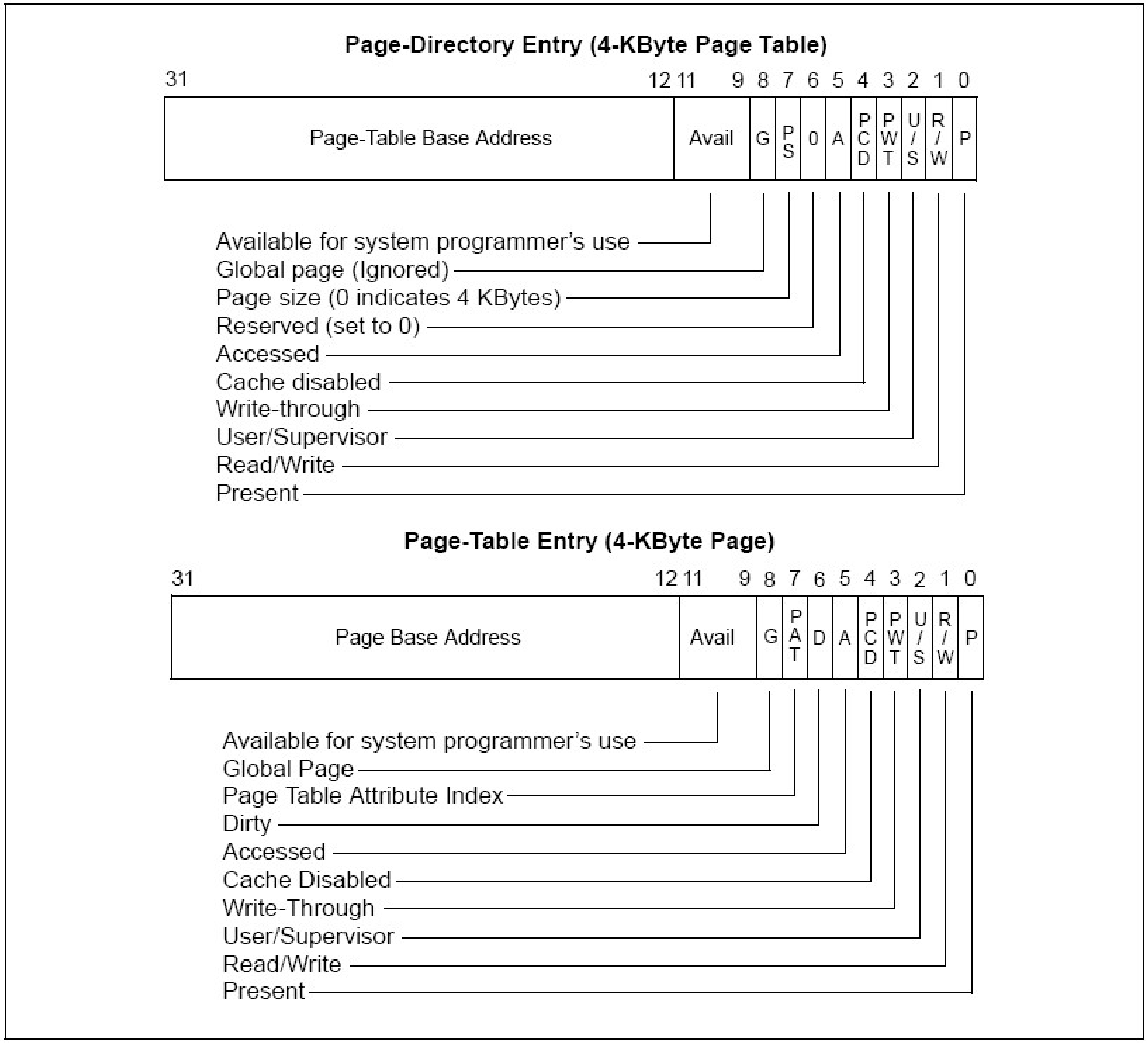
Reminder: Page Table Entries (PTEs)

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!

Slight diversion

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
  - 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

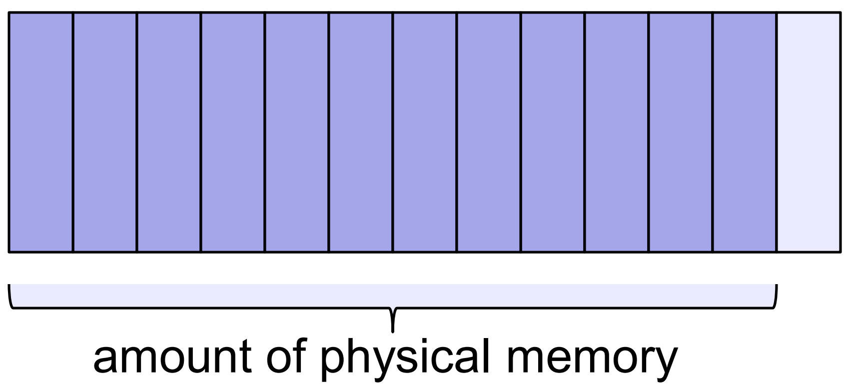
#2: FIFO

- 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

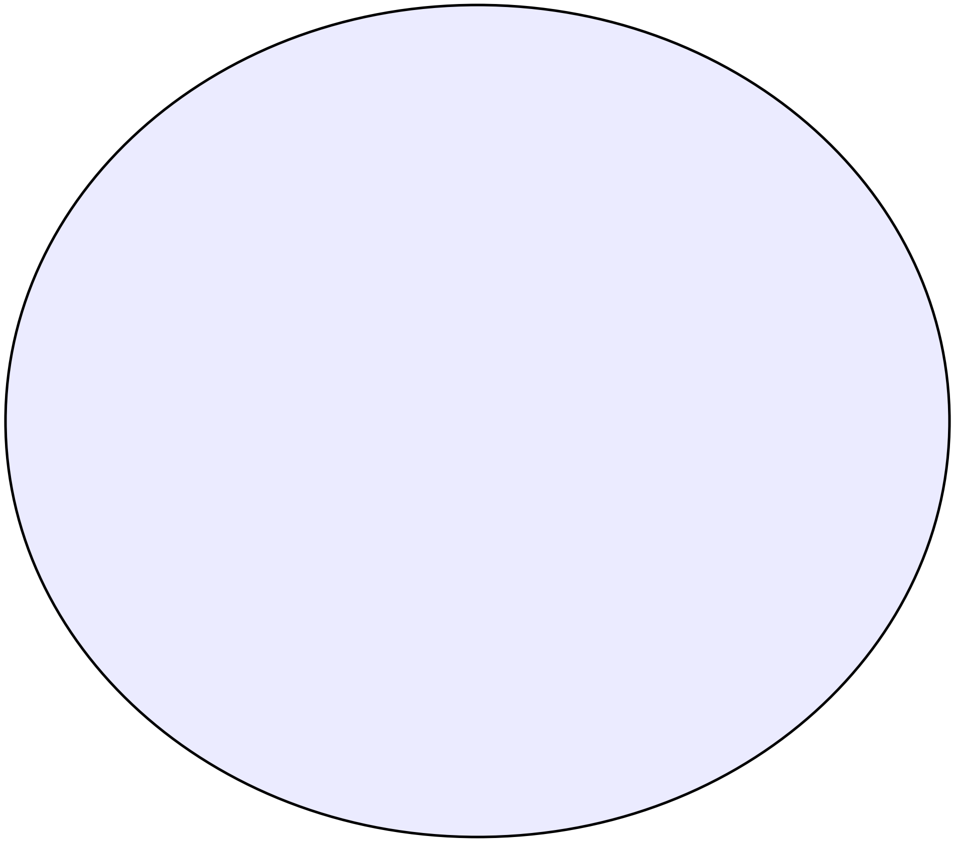
- Implementation
  - to be perfect, must grab a timestamp on every memory reference, put it in the PTE, order or search based on the timestamps …
  - way too $$ in memory bandwidth, algorithm execution time, etc.
  - so, we need a cheap approximation …

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

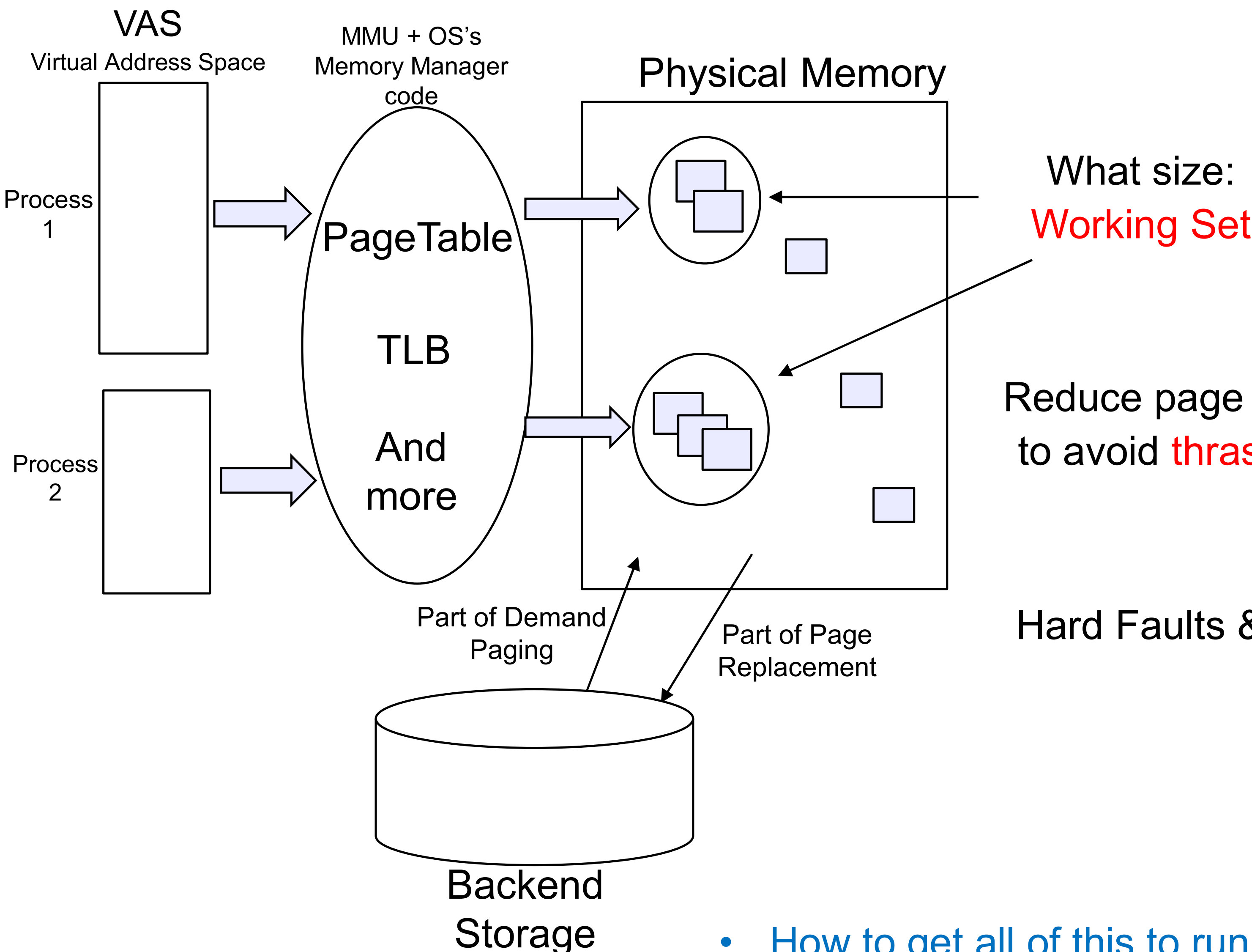
- AKA Not Recently Used (NRU) or Second Chance
  – replace page that is “old enough”
  – logically, arrange all physical page frames in a big circle (clock)
    - just a circular linked list
  – a “clock hand” is used to select a good LRU candidate
    - sweep through the pages in circular order like 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

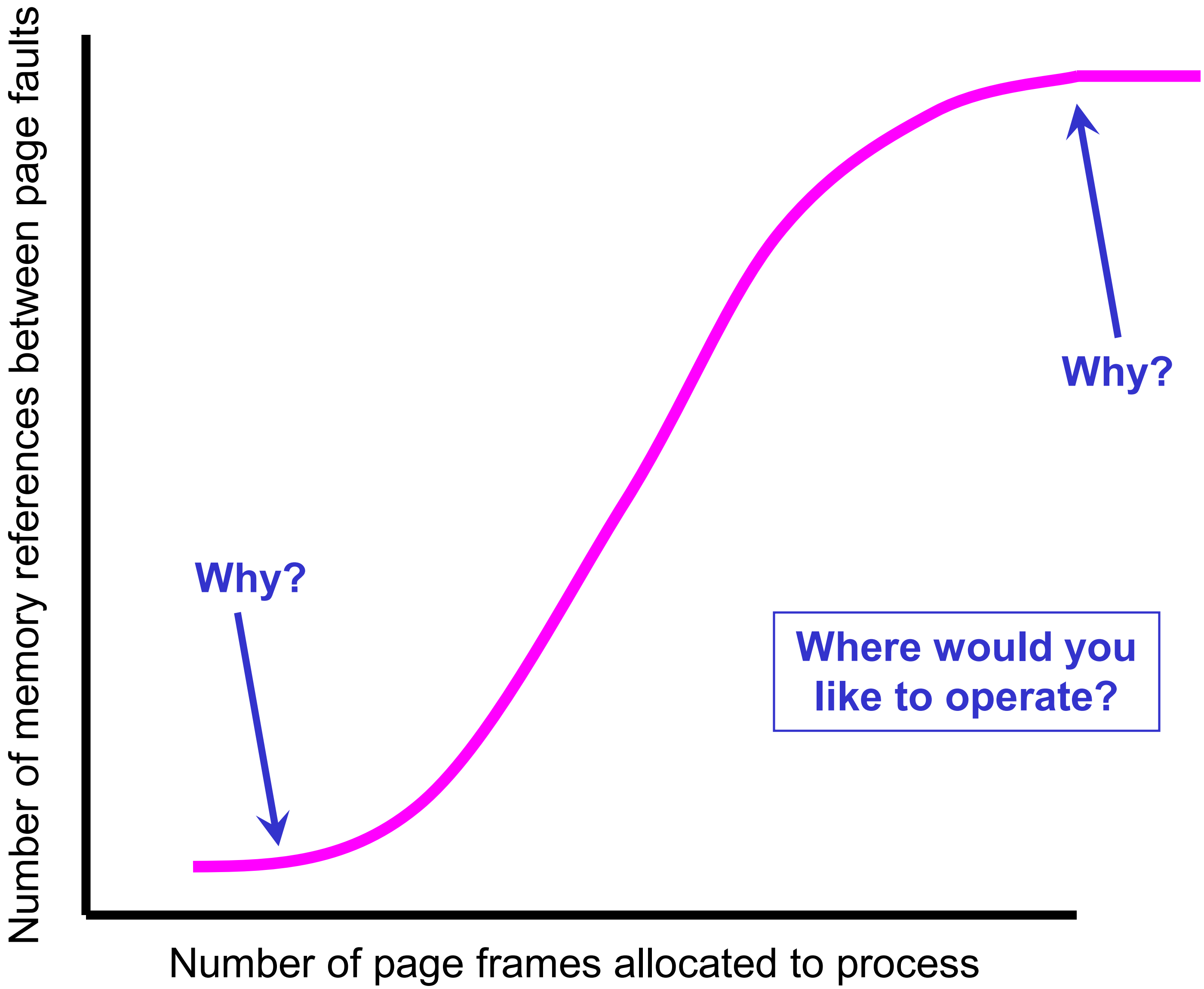
- Hybrid algorithms
  - local replacement
  - an explicit mechanism for adding or removing page frames



Reduce page faults to avoid thrashing

Hard Faults & Soft Faults

- How to get all of this to run faster
- Additional features gained with paging


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

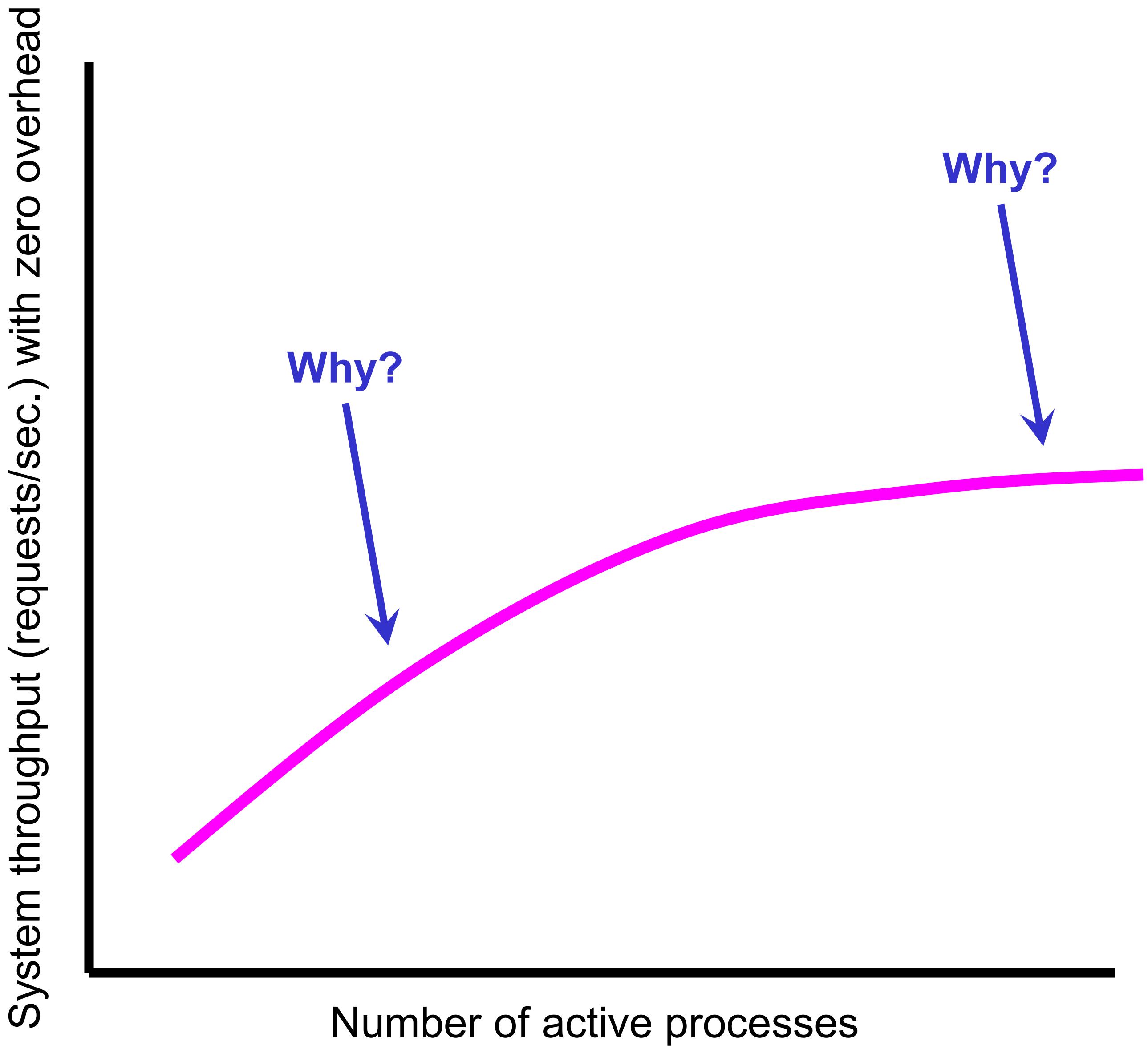
- Estimate |WS(0,w)| for a process
- Allow that process to start only if you can allocate it that many page frames
- Use a local replacement algorithm (LRU Clock?) make sure that “the right pages” (the working set) are occupying the process’s frames
- Track each process’s working set size, and re-allocate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

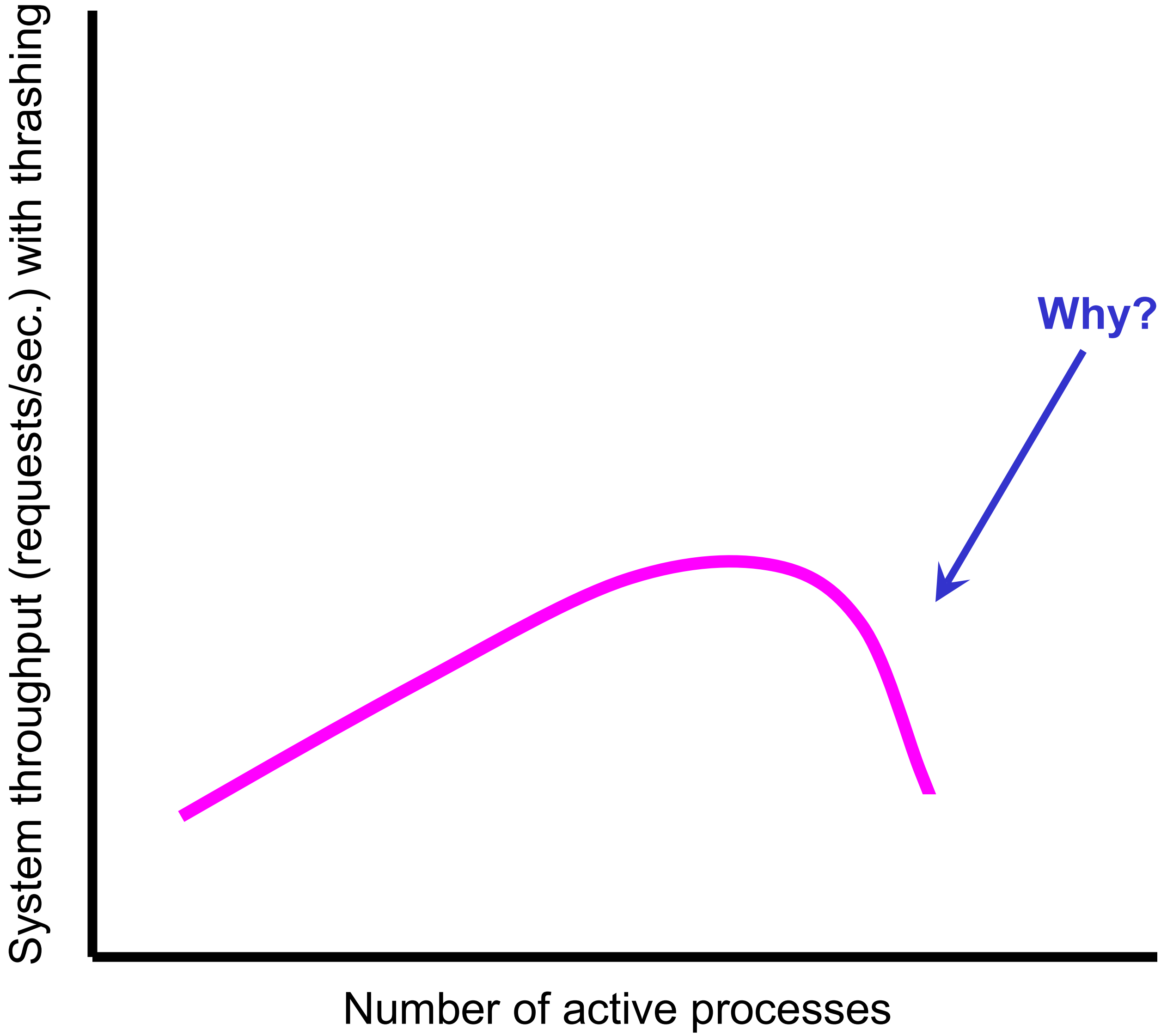
#6: Page Fault Frequency (PFF)

- 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


Why?
Why?
System throughput (requests/sec.) with zero overhead
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