PAGE REPLACEMENT

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Today's Topics

- What if the physical memory becomes full?
  - Page replacement algorithms

- How to manage memory among competing processes?

- Advanced virtual memory techniques
  - Shared memory
  - Copy on write
  - Memory-mapped files

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
- 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

Page Replacement

- Goal of page replacement algorithm is to reduce fault rate by selecting the best victim page to remove
- The best page to evict is the one never touched again
  - As process will never again fault on it
- “Never” is a long time, so picking the page closest to “never” is the next best thing
- Belady’s proof
  - Evicting the page that won’t be used for the longest period of time minimizes the number of page faults

Belady's Algorithm

- Optimal page replacement (OPT)
  - Replace the page that will not be used for the longest time in the future
  - Has the lowest fault rate for any page reference stream
  - Problem: have to predict the future
  - Why is Belady's useful? – Use it as a yardstick!
    - Compare other algorithms with the optimal to gauge room for improvement
    - If optimal is not much better, then algorithm is pretty good, otherwise algorithm could use some work.
    - Lower bound depends on workload, but random replacement is pretty bad

FIFO

- First-In First-Out
  - Obvious and simple to implement
    - Maintain a list of pages in order 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?
    - Maybe, it’s not the case
    - We don’t have any information either way
  - FIFO suffers from “Belady’s Anomaly”
    - The fault rate might increase when the algorithm is given more memory

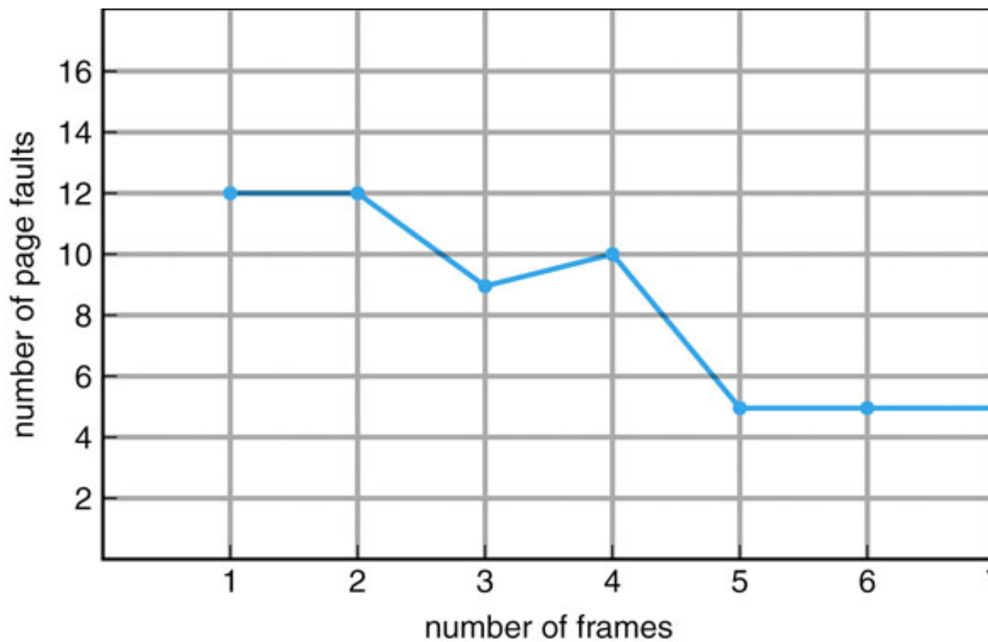
Belady's Anomaly

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames: 9 faults

1	4	5
2	1	3
3	2	4

- 4 frames: 10 faults

1	5	4
2	1	5
3	2	
4	3	



LRU

- Least Recently Used
- 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 has not been used for the longest time in the past
  - LRU looks at the past, Belady's wants to look at future
- Implementation
  - Counter implementation: put a timestamp
  - Stack implementation: maintain a stack
- Why do we need an approximation?

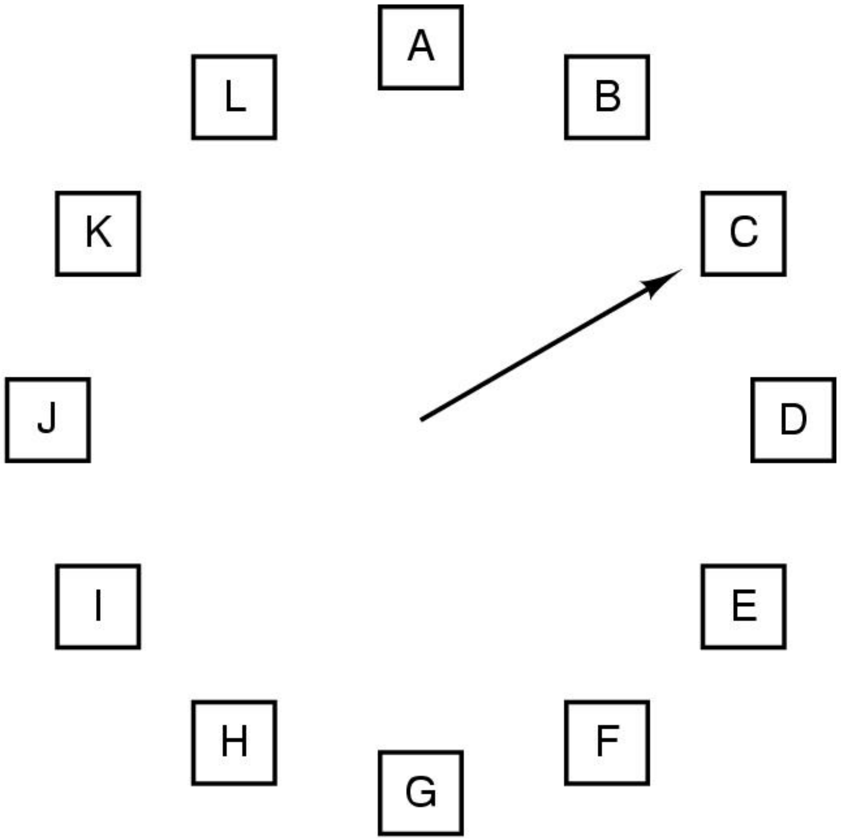
Approximating LRU

- Many LRU approximations use the PTE reference (R) bit
  - R bit is set whenever the page is referenced (read or written)
- Counter-based approach
  - Keep a counter for each page
  - At regular intervals, for every page, do:
    - If R = 0, increment the counter (hasn't been used)
    - If R = 1, zero the counter (has been used)
    - Zero the R 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

Second Chance (or LRU Clock)

- FIFO with giving a second chance to a recently referenced page
- 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 R bit is off, it hasn't been used recently and we have a victim
  - If the R bit is on, turn it off and go to next page
- Arm moves quickly when pages are needed
  - Low overhead if we have plenty of memory
  - If memory is large, "accuracy" of information degrades

Second Chance (or LRU Clock)



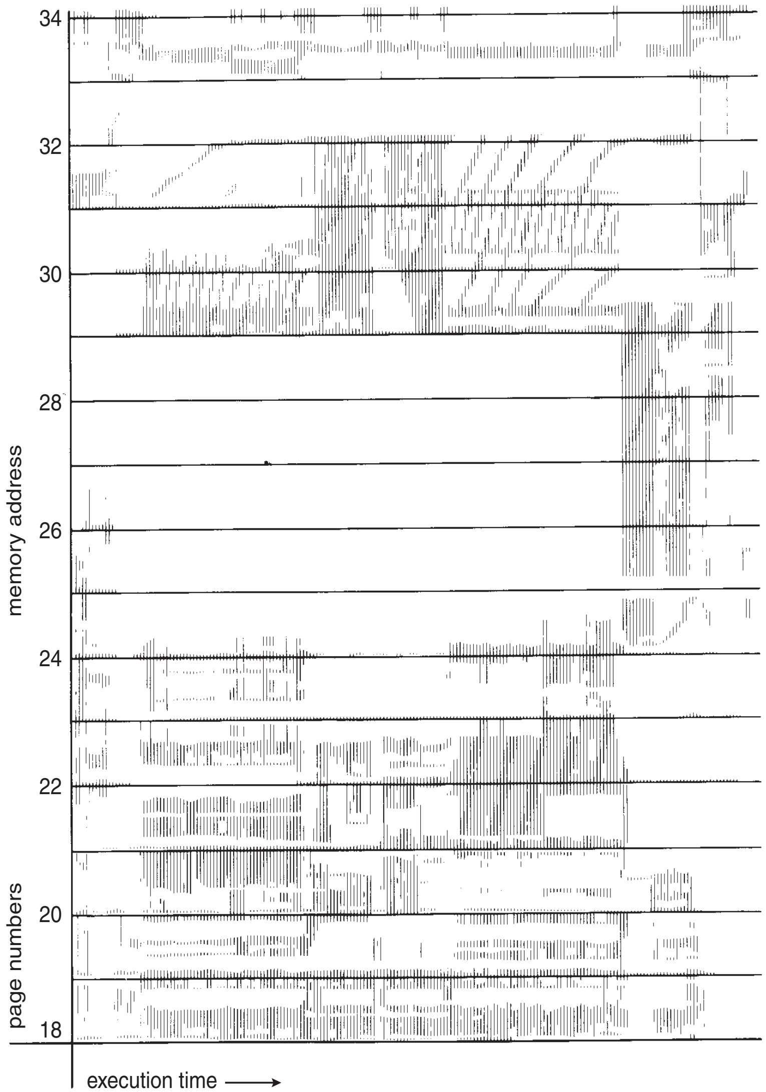
When a page fault occurs, the page the hand is pointing to is inspected. The action taken depends on the R bit:

R = 0: Evict the page
R = 1: Clear R and advance hand

Working Set Model

- Working set
  - A working set of a process is used to model the dynamic locality of its memory usage
    - i.e., working set = set of pages process currently “needs”
    - Peter Denning, 1968
  - Definition
    - WS(t,w) = {pages P such that P was referenced in the time interval (t, t-w)}
    - t: time, w: working set window size (measured in page references)
  - A page is in the working set only if it was referenced in the last w references

Locality In A Memory-Reference Pattern



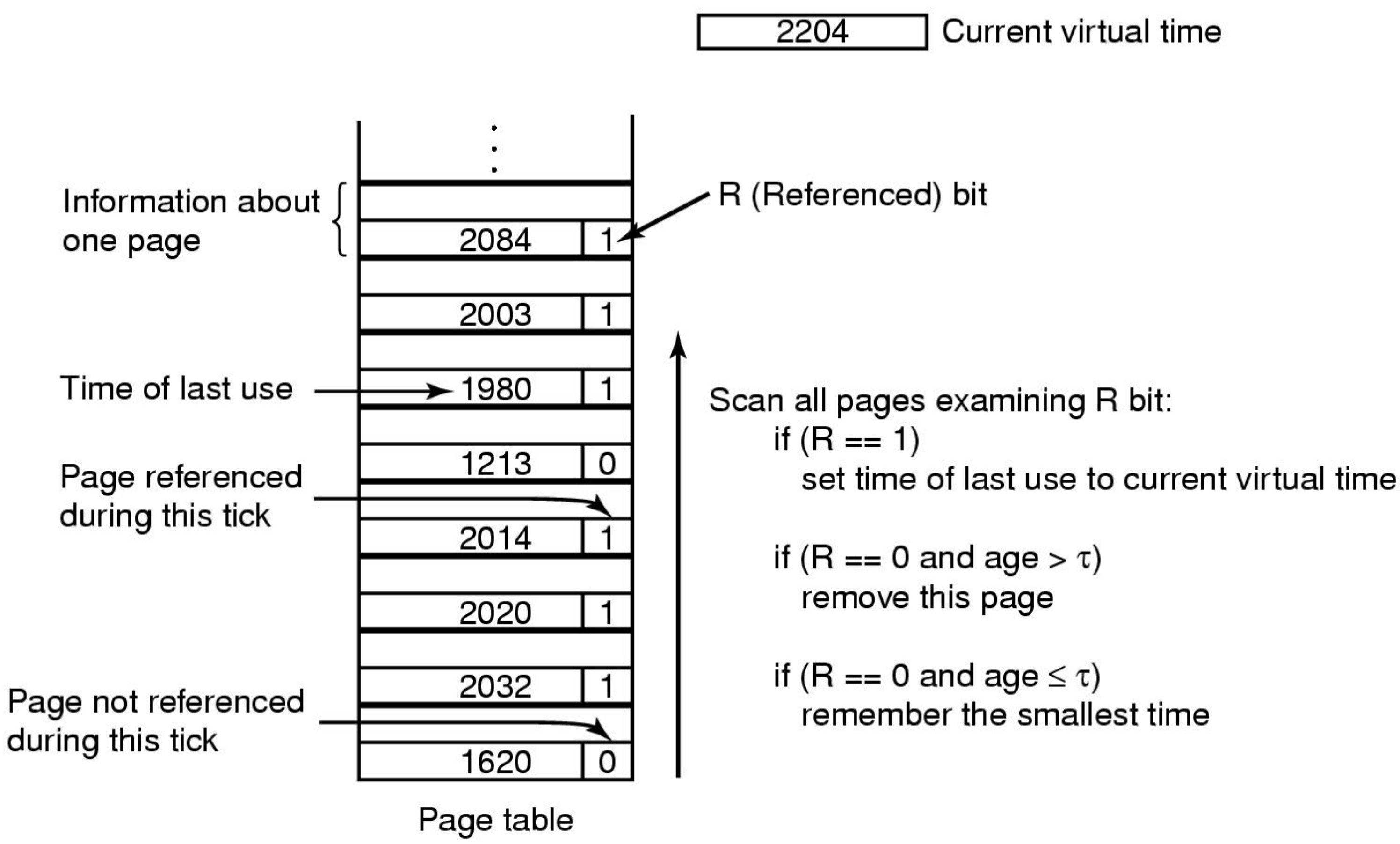
Working Set Size

- 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, more pages are referenced
  - Within that period of time, the working set size is larger
- Intuitively, working set must be in memory to prevent heavy faulting (thrashing)
- Controlling the degree of multiprogramming based on the working set
  - Associate parameter “wss” with each process
  - If the sum of “wss” exceeds the total number of frames, suspend a process
  - Only allow a process to start if its “wss”, when added to all other processes, still fits in memory
  - Use a local replacement algorithm within each process

Working Set Page Replacement

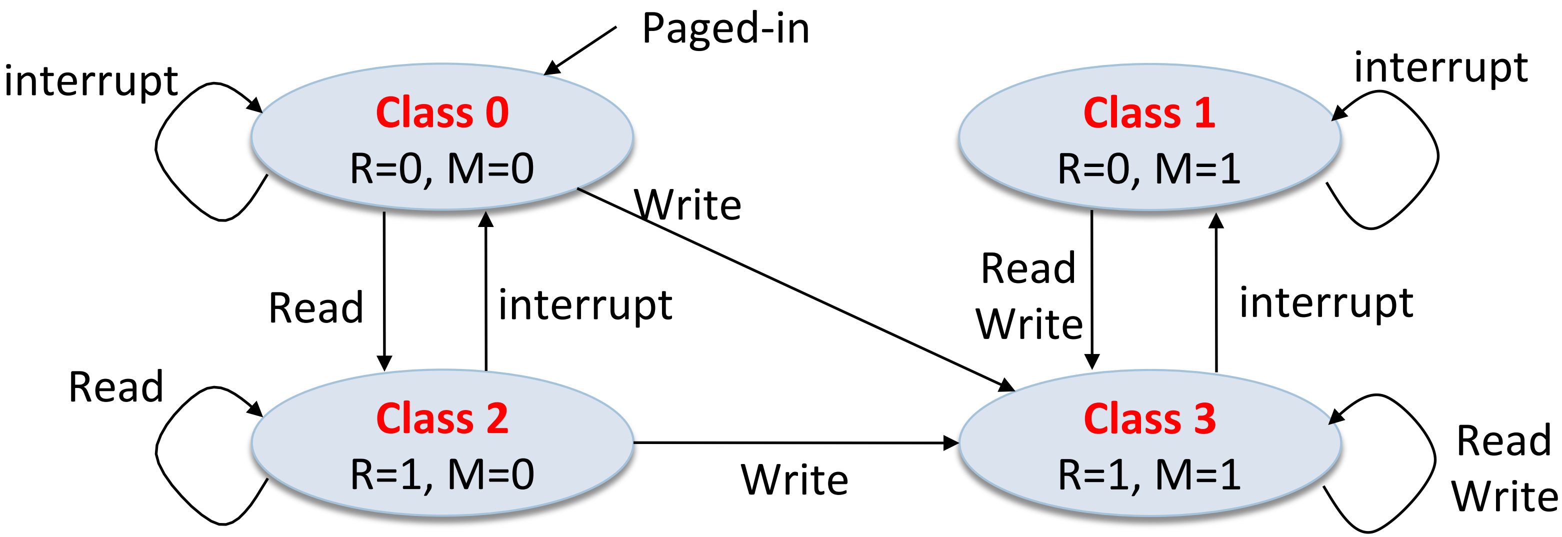
- Maintaining the set of pages touched in the last k references is expensive
- Approximate the working set as the set of pages used during the past time interval
  - Measured using the current virtual time: the amount of CPU time a process has actually used
- Find a page that is not in the working set and evict it
  - Associate the "Time of last use (T_{last})" field in each PTE
  - A periodic clock interrupt clears the R bit
  - On every page fault, the page table is scanned to look for a suitable page to evict
  - If R = 1, timestamp the current virtual time ($T_{last} \leftarrow T_{current}$)
  - If R = 0 and ($T_{current} - T_{last}$) > t, evict the page
  - Otherwise, remember the page with the greatest age

Working Set Model



Not Recently Used

- NRU or enhanced second chance
  - Use R (reference) and M (modify) bits
    - Periodically, (e.g., on each clock interrupt), R is cleared, to distinguish pages that have not been referenced recently from those that have been



Not Recently Used

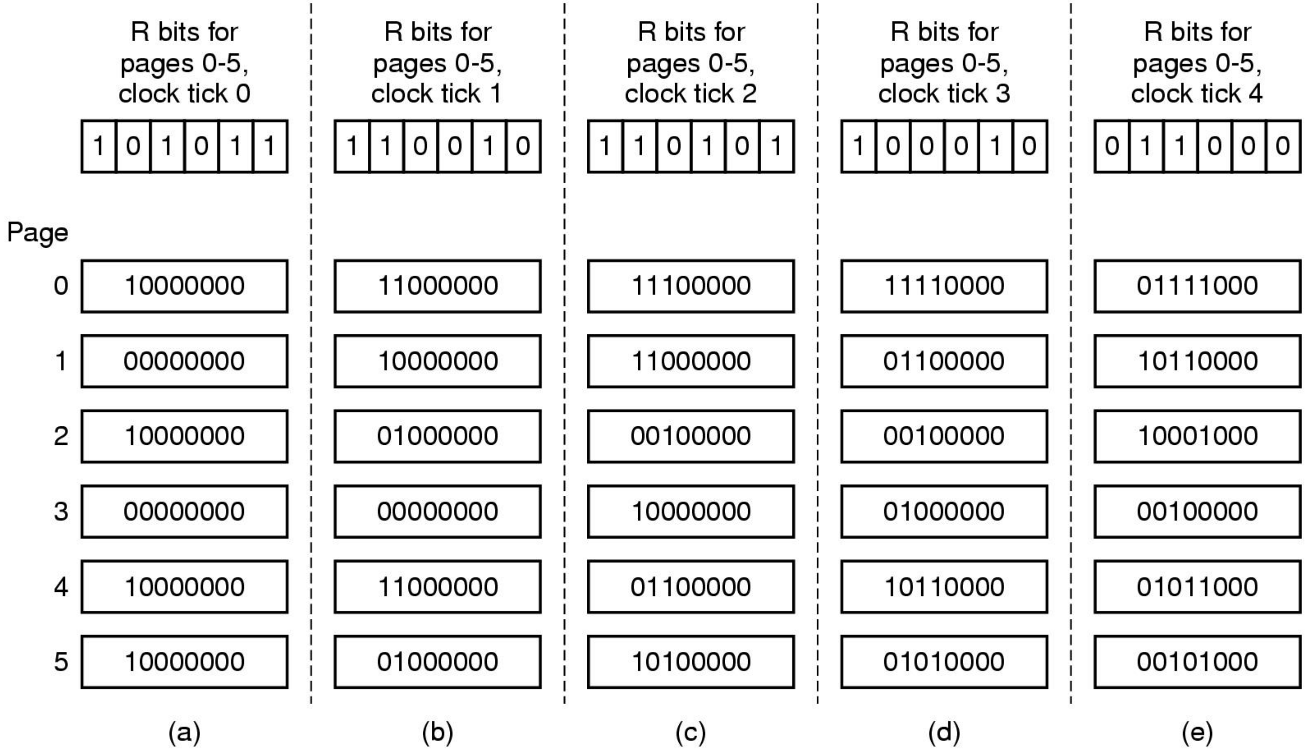
- Algorithm
  - Removes a page at random from the lowest numbered nonempty class
  - It is better to remove a modified page that has not been referenced in at least one clock tick than a clean page that is in heavy use
  - Used in Macintosh
- Advantages
  - Easy to understand
  - Moderately efficient to implement
  - Gives a performance that, while certainly not optimal, may be adequate

Least Frequently Used

- Counting-based page replacement
  - A software counter is associated with each page
  - At each clock interrupt, for each page, the R bit is added to the counter
    - The counters denote how often each page has been referenced
- Least frequently used (LFU)
  - The page with the smallest count will be replaced
  - (cf.) Most frequently used (MFU) page replacement
    - The page with the largest count will be replaced
    - Based on the argument that the page with the smallest count was probably just brought in and has yet to be used
  - It never forgets anything
    - A page may be heavily used during the initial phase of a process, but then is never used again

Least Frequently Used

- Aging
  - The counters are shifted right by 1 bit before the R bit is added to the leftmost



Allocation of Frames

- Problem
  - In a multiprogramming system, we need a way to allocate physical memory to competing processes
    - What if a victim page belongs to another process?
    - 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 its limit, it replaces from its own pages
    - Local replacement: some process may do well, others suffer
  - Variable space algorithms
    - Processes' set of pages grows and shrinks dynamically
    - Global replacement: one process can ruin it for the rest (Linux)

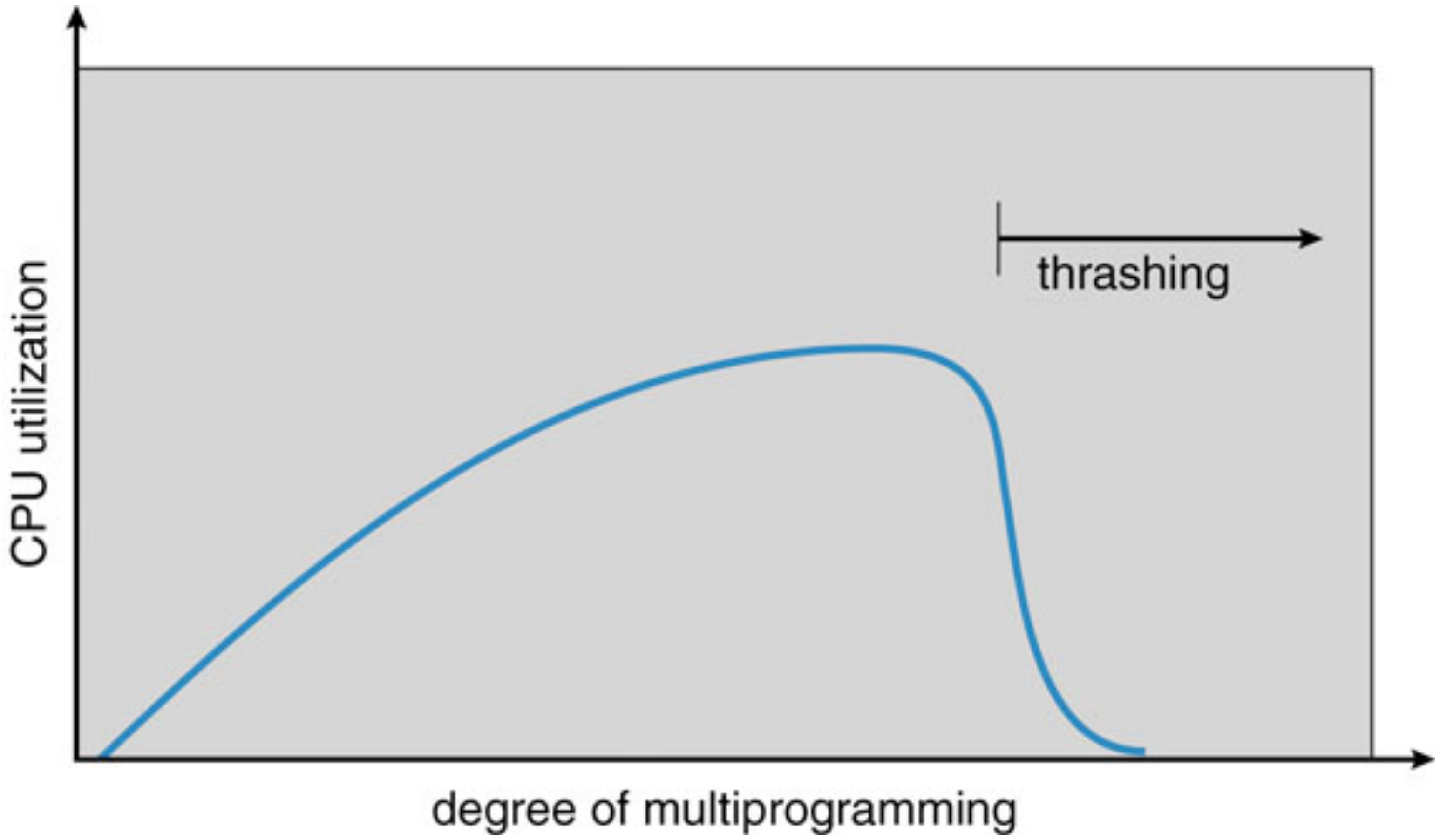
Global vs. Local Allocation

- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
  - But then process execution time can vary greatly
  - But greater throughput so more common
- **Local replacement** – each process selects from only its own set of allocated frames
  - More consistent per-process performance
  - But possibly underutilized memory

Thrashing

- What OS does if page replacement algorithms fail
- Most of the time is spent by an OS paging data back and forth from disk
  - No time is spent doing useful work
  - The system is overcommitted
  - No idea which pages should be in memory to reduce faults
  - Could be that there just isn't enough physical memory for all processes
- Possible solutions
  - Swapping – write out all pages of a process
  - Buy more memory

Thrashing



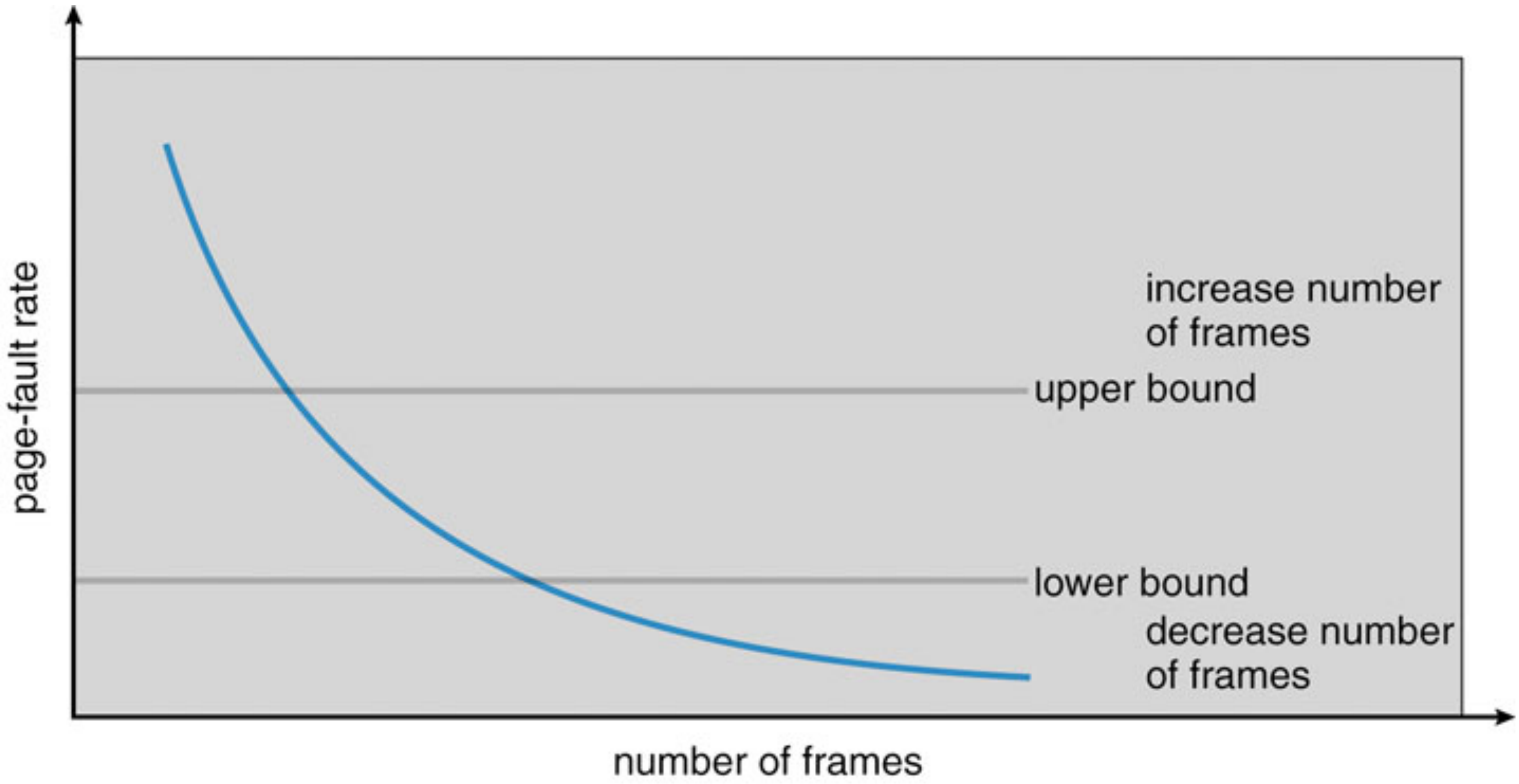
Demand Paging and Thrashing

- Why does demand paging work?
  - **Locality model**
  - Process migrates from one locality to another
  - Localities may overlap
- Why does thrashing occur?
  Σ size of locality > total memory size
  - Limit effects by using local or priority page replacement

Page Fault Frequency

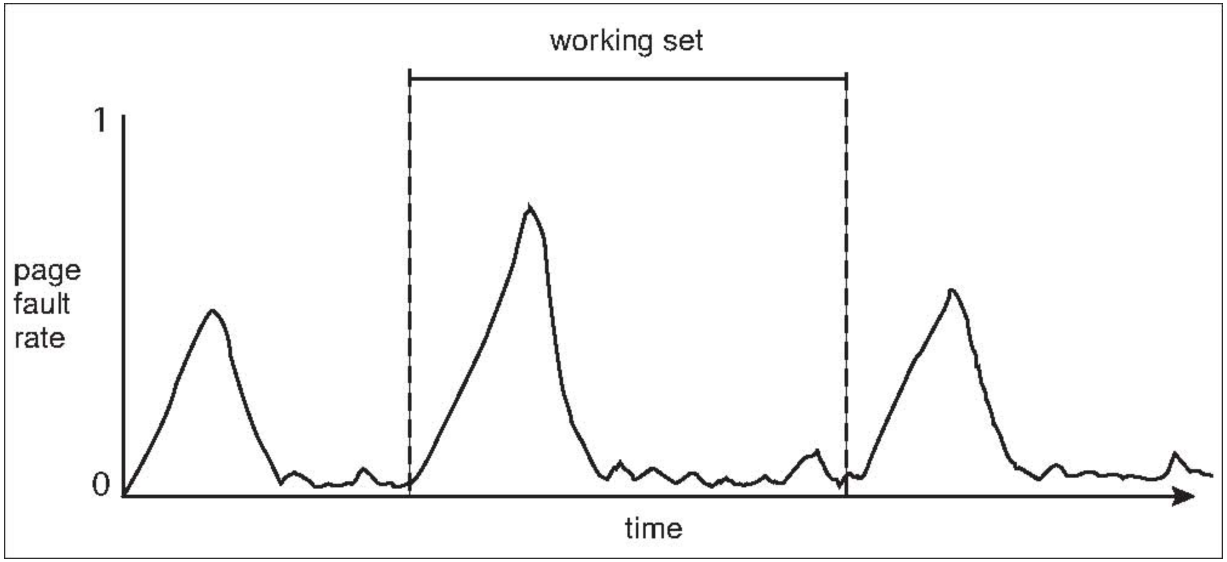
- A variable space algorithm that uses a more ad-hoc approach
  - Monitor the fault rate for each process.
  - If the fault rate is above a high threshold, give it more memory, so that it faults less (but not always – FIFO, Belady’s anomaly)
  - If the fault rate is below a low threshold, take away memory (again, not always)
- If the PFF increases and no free frames are available, we must select some process and suspend it

Page Fault Frequency



Working Sets and Page Fault Rates

- Direct relationship between working set of a process and its page-fault rate
- Working set changes over time
- Peaks and valleys over time



Advanced VM Functionality

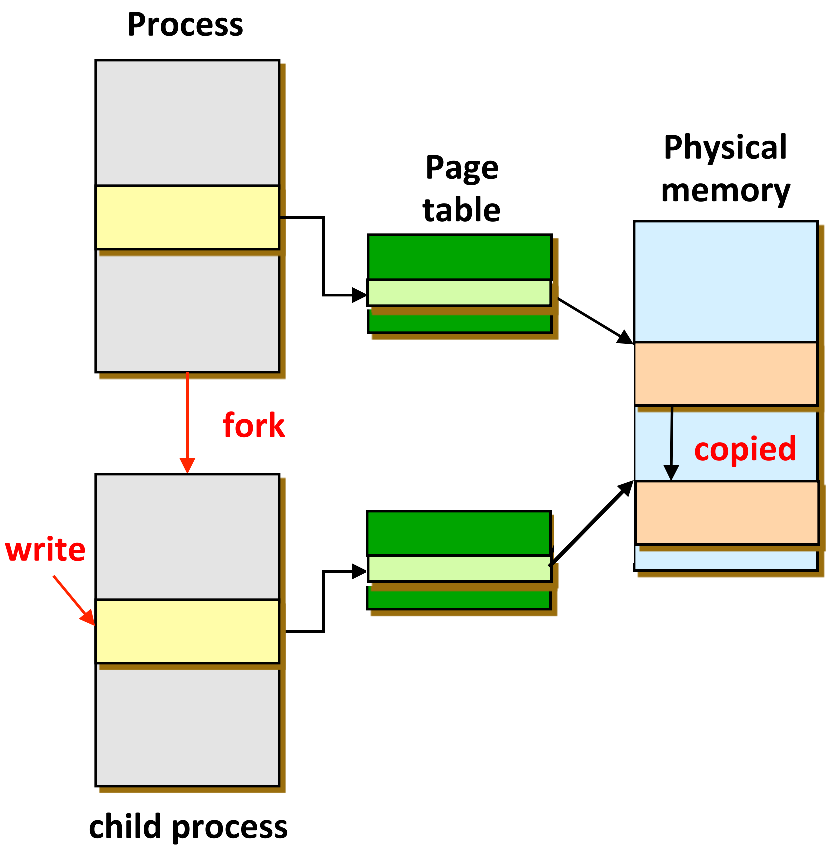
- Virtual memory tricks
  - Copy-on-Write
  - Shared memory
  - Memory-mapped files

Copy On Write

- Process creation
  - requires copying the entire address space of the parent process to the child process
  - Very slow and inefficient
- Solution 1: Use threads
  - Sharing address space is free
- Solution 2: Use vfork() system call
  - vfork() creates a process that shares the memory address space of its parent
  - To prevent the parent from overwriting data needed by the child, the parent's execution is blocked until the child exits or executes a new program
  - Any change by the child is visible to the parent once it resumes
  - Useful when the child immediately executes exec()

Copy On Write

- Solution 3: Copy On Write (COW)
  - Instead of copying all pages, create shared mappings of parent pages in child address space
  - Shared pages are protected as read-only in child
    - Reads happen as usual
    - Writes generate a protection fault, trap to OS, and OS copies the page, changes page mapping in client page table, restarts write instruction



Shared Memory

- Private virtual address spaces protect applications from each other
- But this makes it difficult to share data
  - Parents and children in a forking Web server or proxy will want to share an in-memory cache without copying
  - Read/Write (access to share data)
  - Execute (shared libraries)
- We can use shared memory to allow processes to share data using direct memory reference
  - Both processes see updates to the shared memory segment
  - How are we going to coordinate access to shared data?

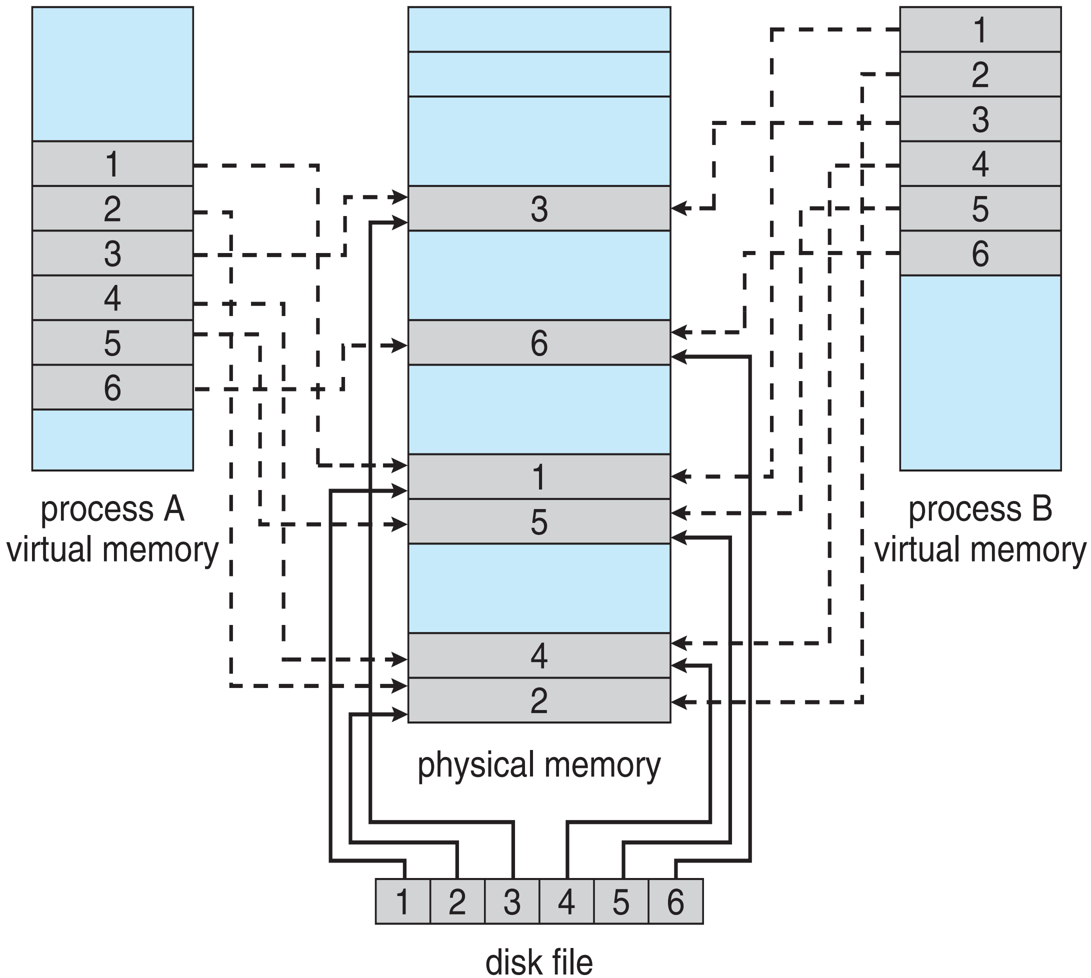
Shared Memory

- Implementation
  - How can we implement shared memory using page tables?
    - Have PTEs in both tables map to the same physical frame
    - Each PTE can have different protection values
    - Must update both PTEs when page becomes invalid
  - Can map shared memory at same or different virtual addresses in each process' address space
    - Different: Flexible (no address space conflicts), but pointers inside the shared memory segment are invalid
    - Same: Less flexible, but shared pointers are valid

Memory-Mapped Files

- Memory-mapped files
  - Mapped files enable processes to do file I/O using memory references
    - Instead of open(), read(), write(), close()
  - mmap(): bind a file to a virtual memory region
    - PTEs map virtual addresses to physical frames holding file data
    - <Virtual address base + N> refers to offset N in file
  - Initially, all pages in mapped region marked as invalid
    - OS reads a page from file whenever invalid page is accessed
    - OS writes a page to file when evicted from physical memory
    - If page is not dirty, no write needed

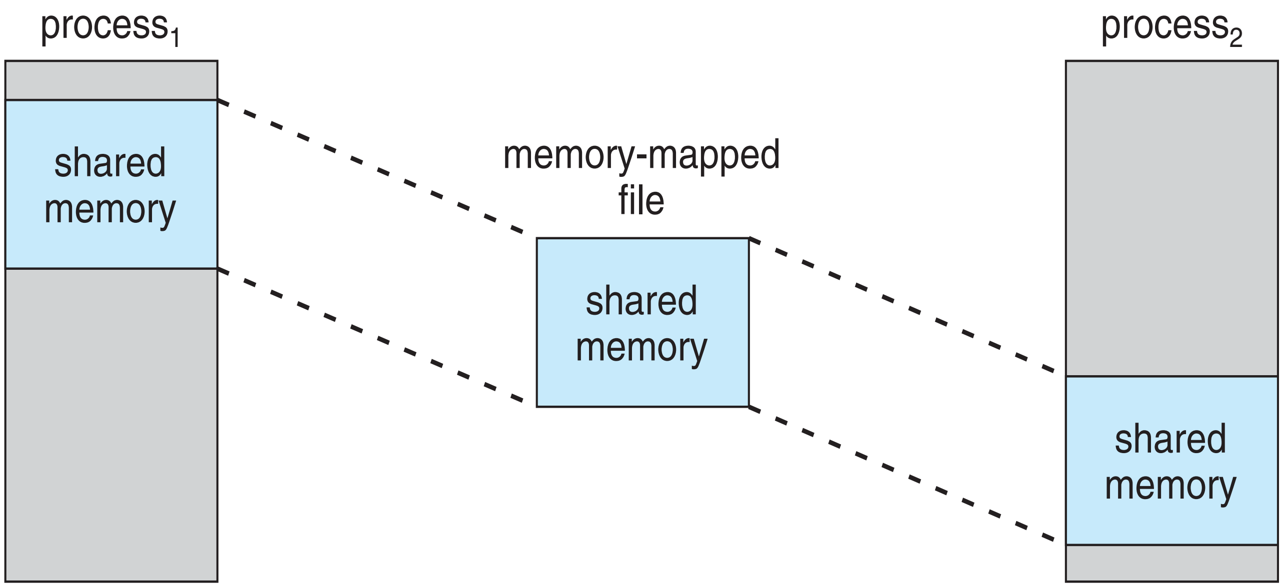
Memory Mapped Files



Memory-Mapped Files

- Note:
  - File is essentially backing store for that region of the virtual address space (instead of using the swap file)
  - Virtual address space not backed by “real” files also called “anonymous VM”
- Advantages
  - Uniform access for files and memory (just use pointers)
  - Less copying
  - Several processes can map the same file allowing the pages in memory to be shared
- Drawbacks
  - Process has less control over data movement
  - Does not generalize to streamed I/O (pipes, sockets, etc.)

Shared Memory via Memory-Mapped I/O



Summary

- VM mechanisms
  - Physical and virtual addressing
  - Partitioning, Paging, Segmentation
  - Page table management, TLBs, etc.
- VM policies
  - Page replacement algorithms
  - Memory allocation policies
- VM requires hardware and OS support
  - MMU (Memory Management Unit)
  - TLB (Translation Lookaside Buffer)
  - Page tables, etc.

Summary

- VM optimizations
  - Demand paging (space)
  - Managing page tables (space)
  - Efficient translation using TLBs (time)
  - Page replacement policy (time)
- Advanced functionality
  - Sharing memory
  - Copy on write
  - Mapped files