Virtual Memory III

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Today's Topics

What if the physical memory becomes full?

- Page replacement algorithms

How to manage memory among competing processes?

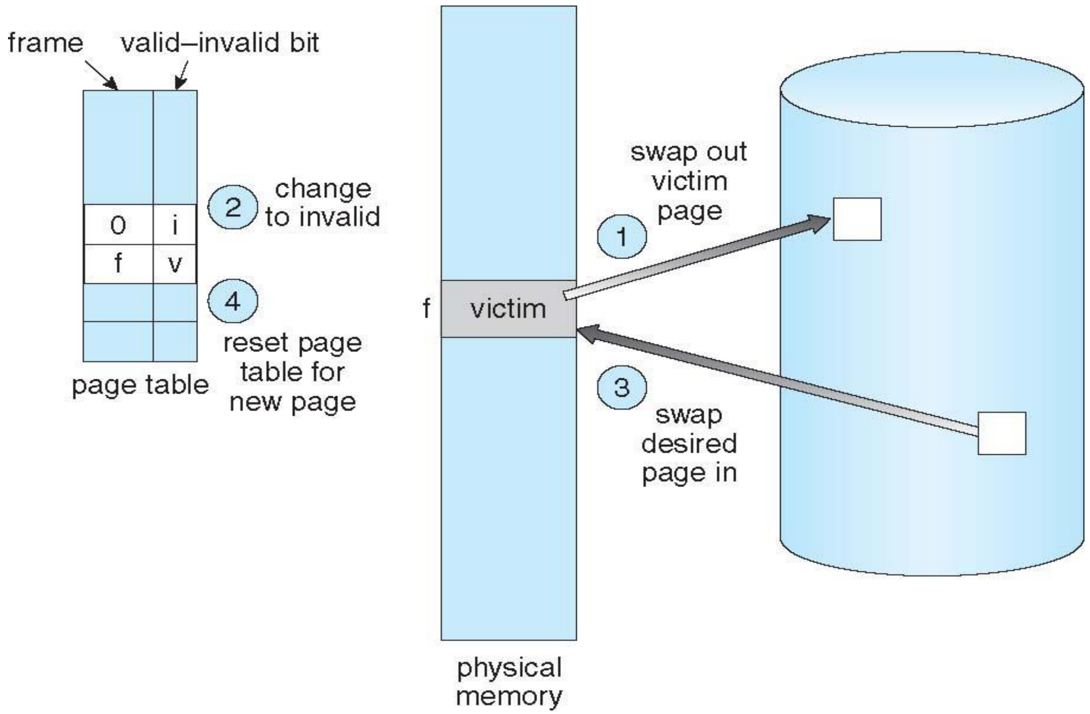
Advanced virtual memory techniques

- Shared memory
- Copy on write
- Memory-mapped files

Page Replacement (1)

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 (No free frame)
- 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 (2)

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
  - 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

- 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 be better
  - Lower bound depends on workload

FIFO (1)

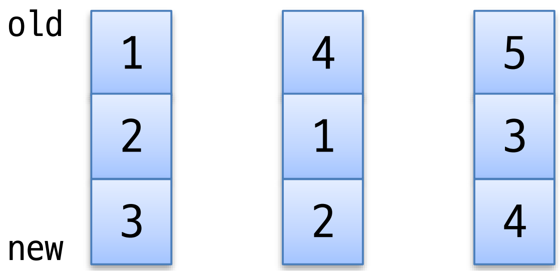
First-In First-Out

- 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

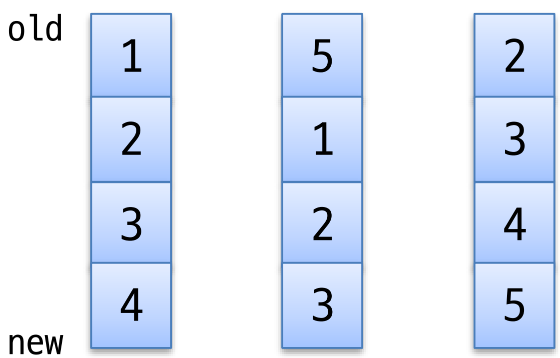
FIFO (2)

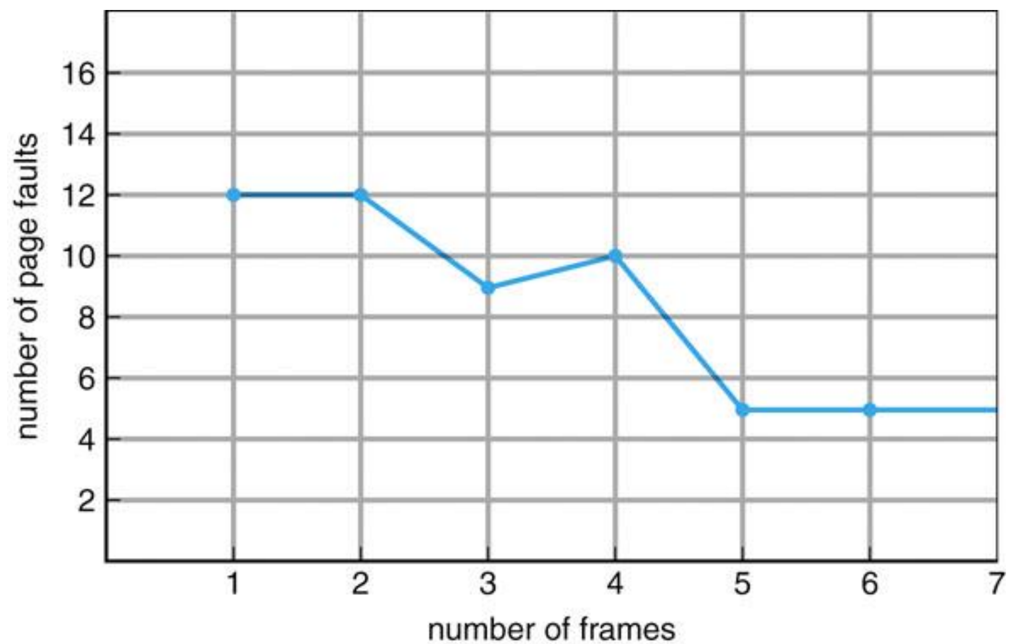
Example: Belady's anomaly

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



- 4 frames: 10 faults





LRU (1)

Least Recently Used

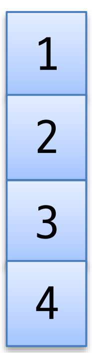
- LRU uses reference information for better replacement decision
  - Idea: past experience gives us a guess of future behavior
  - On replacement, evict the page that has not been used for the longest time in the past
  - LRU looks at the past, Belady's wants to look at future
- Implementation
  - Counter implementation: put a timestamp
  - Stack implementation: maintain a stack
- We need an approximation (heuristic)

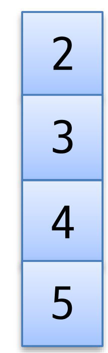
LRU (2)

Example:

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

- 4 frames: ?? faults





LRU (3)

Approximating LRU

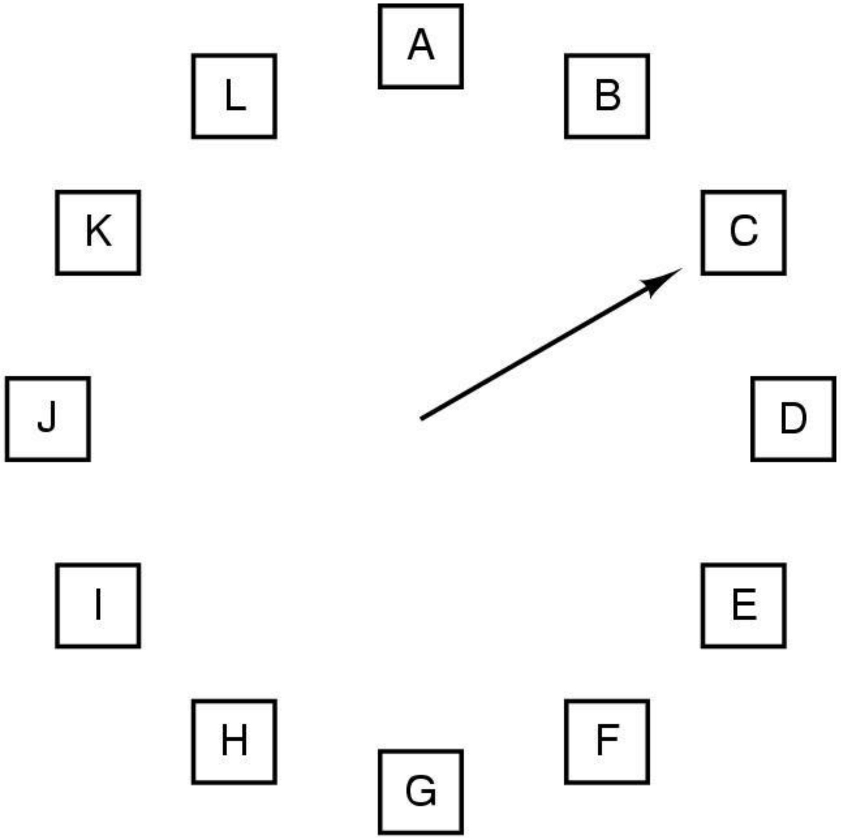
1	1	1	2	20
V	R	M	Prot	Page Frame Number (PFN)

- 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
  - 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 (1)

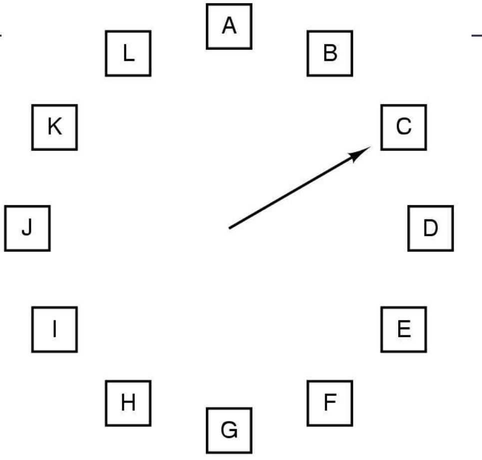
Second chance or LRU clock

- FIFO with giving a second chance to a recently referenced page
- Arrange all of physical page frames in a big circle (clock)



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

Second Chance (2)



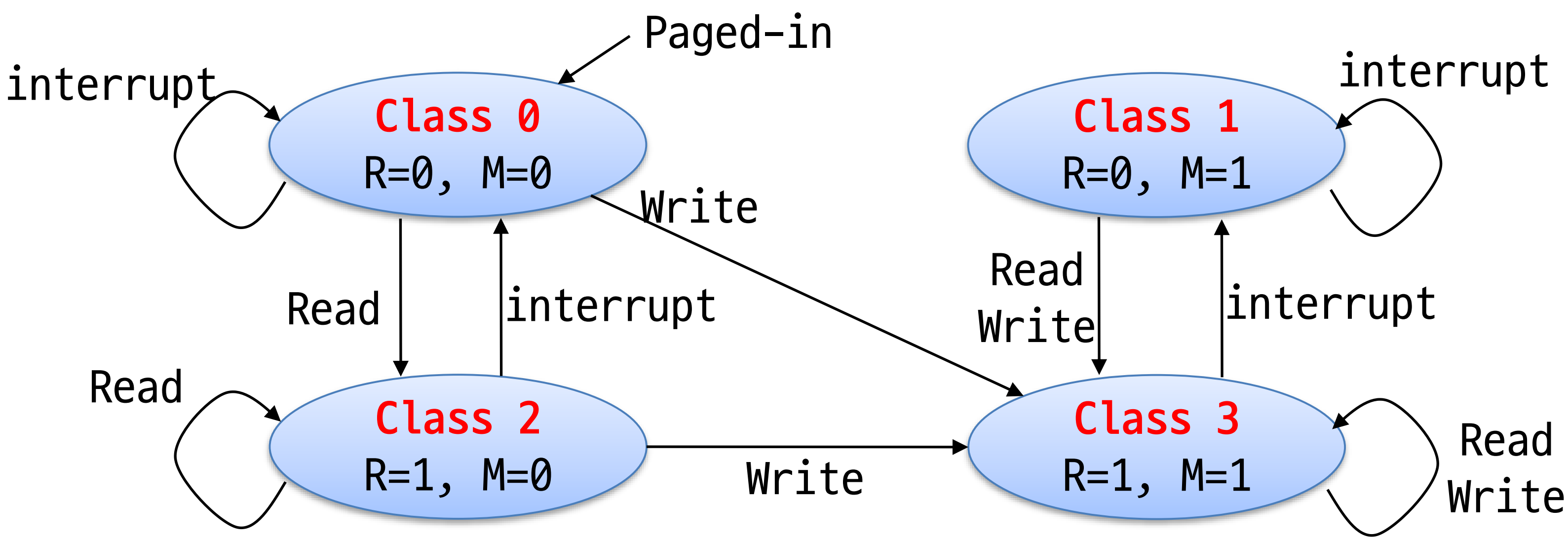
Second chance or LRU clock

- 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

Not Recently Used (1)

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
  - Considering modification of a page



Not Recently Used (2)

Algorithm

- Removes a page at random from the lowest numbered nonempty class
- It is better to keep a modified page that has not been referenced in at least one clock tick than a clean page
- Used in Macintosh

Advantages

- Easy to understand
- Moderately efficient to implement
- Gives a performance that, while certainly not optimal, may be adequate

LFU (1)

Counting-based page replacement

- A software counter 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

Most frequently used (MFU)

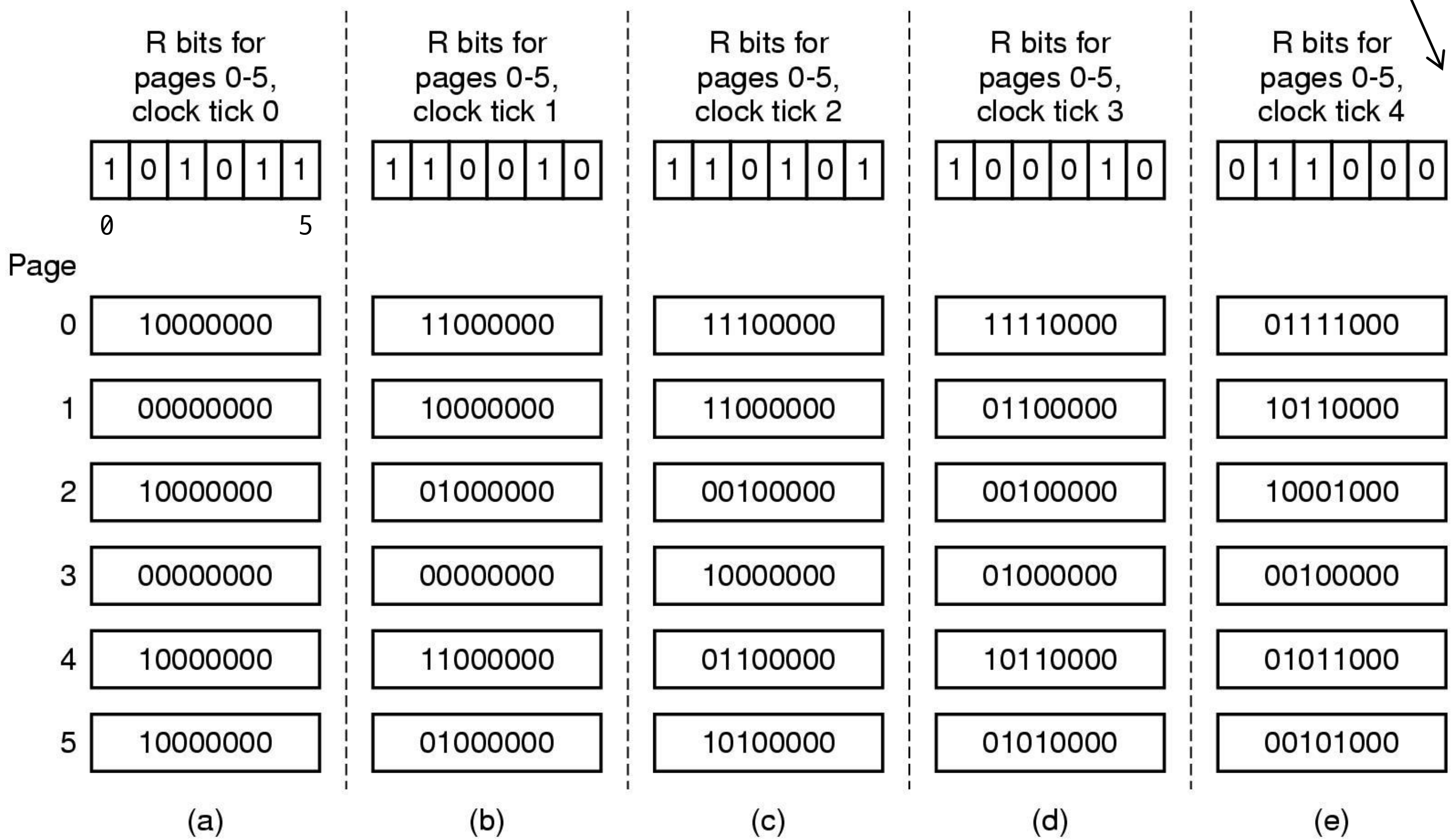
- The page with the largest count will be replaced
- The page with the smallest count was probably just brought in and has yet to be used
- A page may be heavily used during the initial phase of a process, but then is never used again

LFU (2)

At this time,
which one should be evicted?

Aging (counting)

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

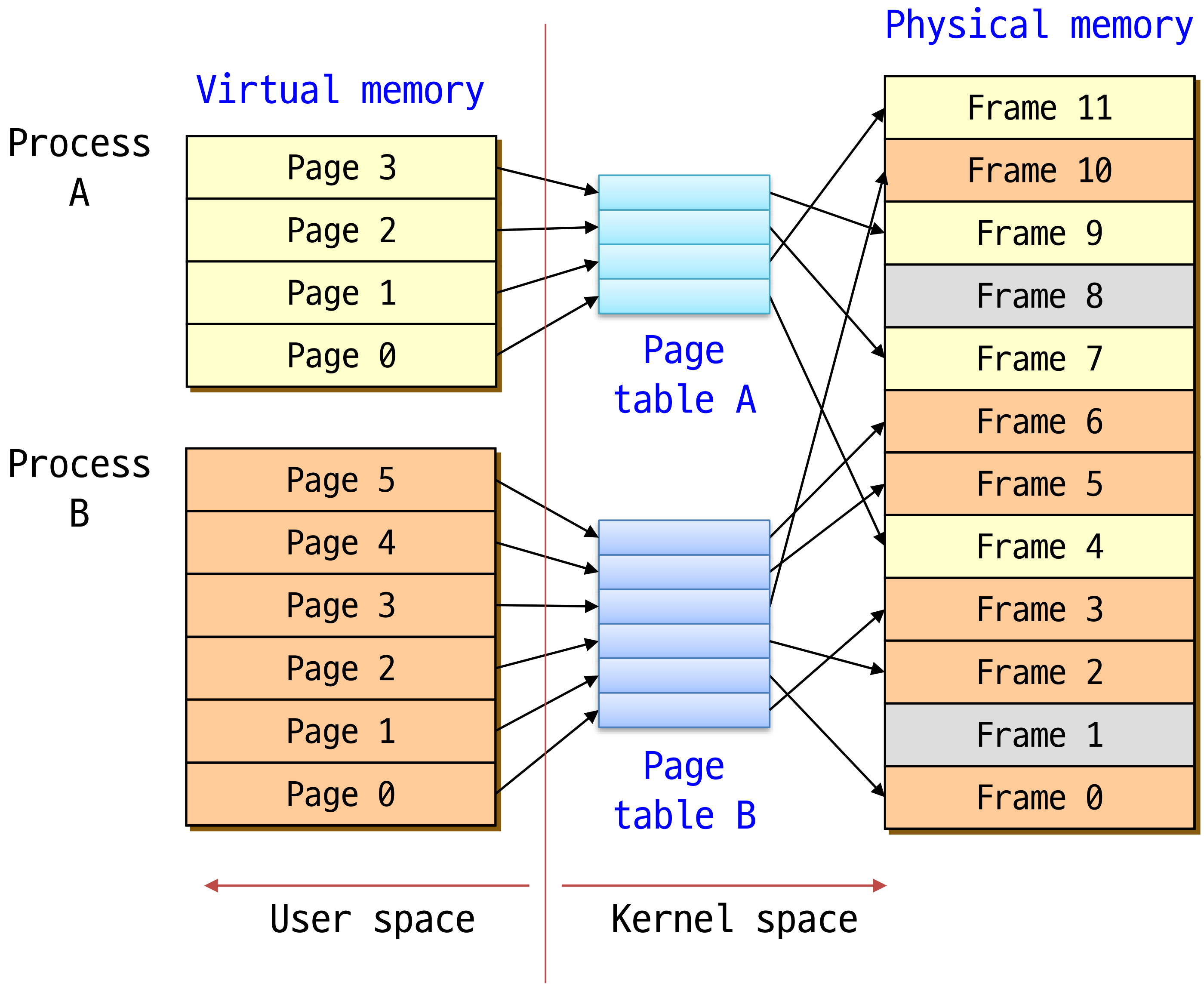


Allocation of Frames

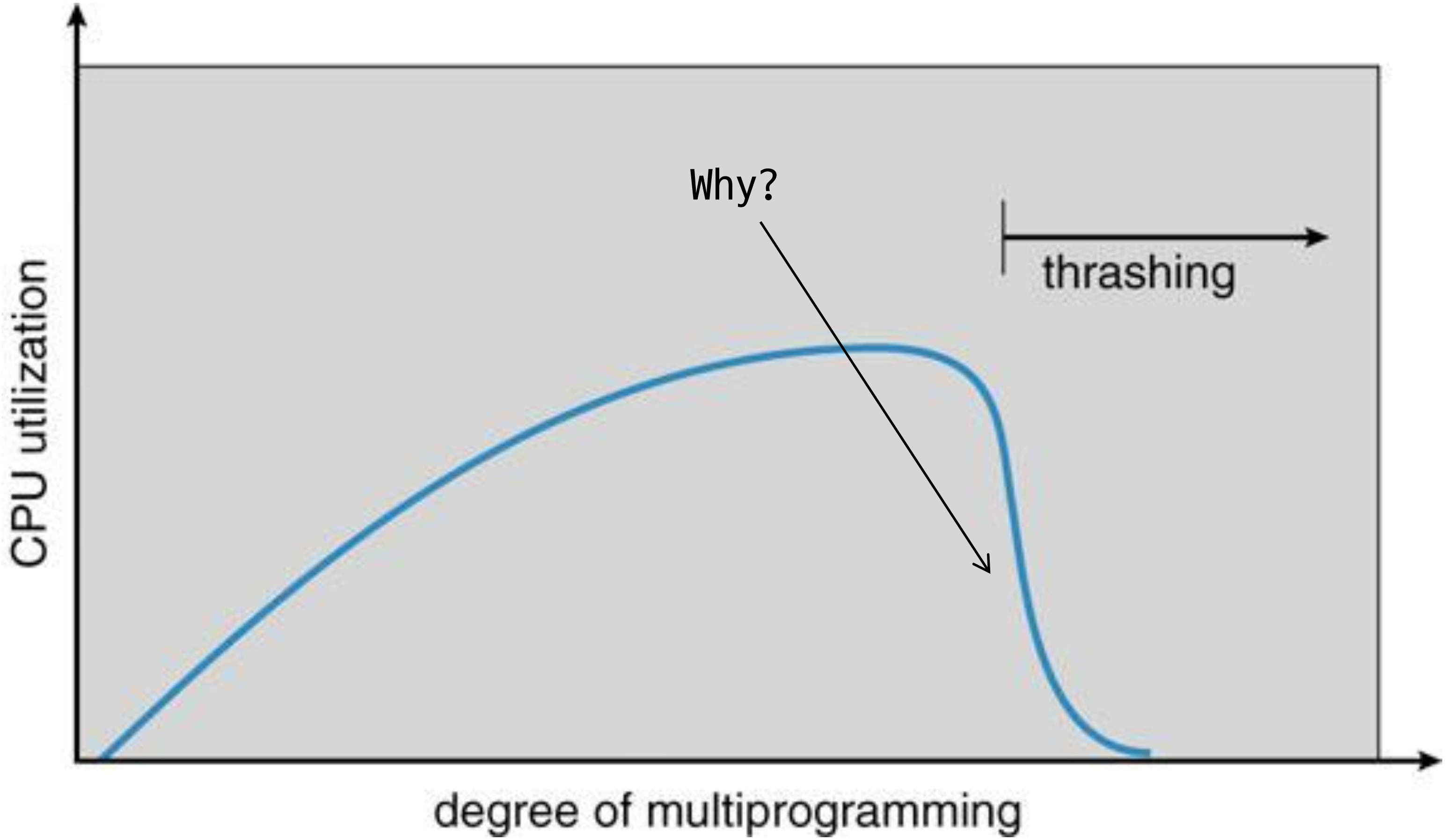
Problem

- 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)

Allocation of Frames



Thrashing (1)



Why?
thrashing
CPU utilization
degree of multiprogramming

Thrashing (2)

Thrashing

- Most of the time is spent by an OS paging data back and forth from disk (heavy page fault)
  - 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
  - Write out all pages of a process
  - Buy more memory

Working Set Model (1)

Working set: The set of pages process currently "needs"

- Peter Denning, 1968
- A working set of a process is used to model the dynamic locality of its memory usage

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

Working Set Model (2)

Working set size (WSS)

- 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:

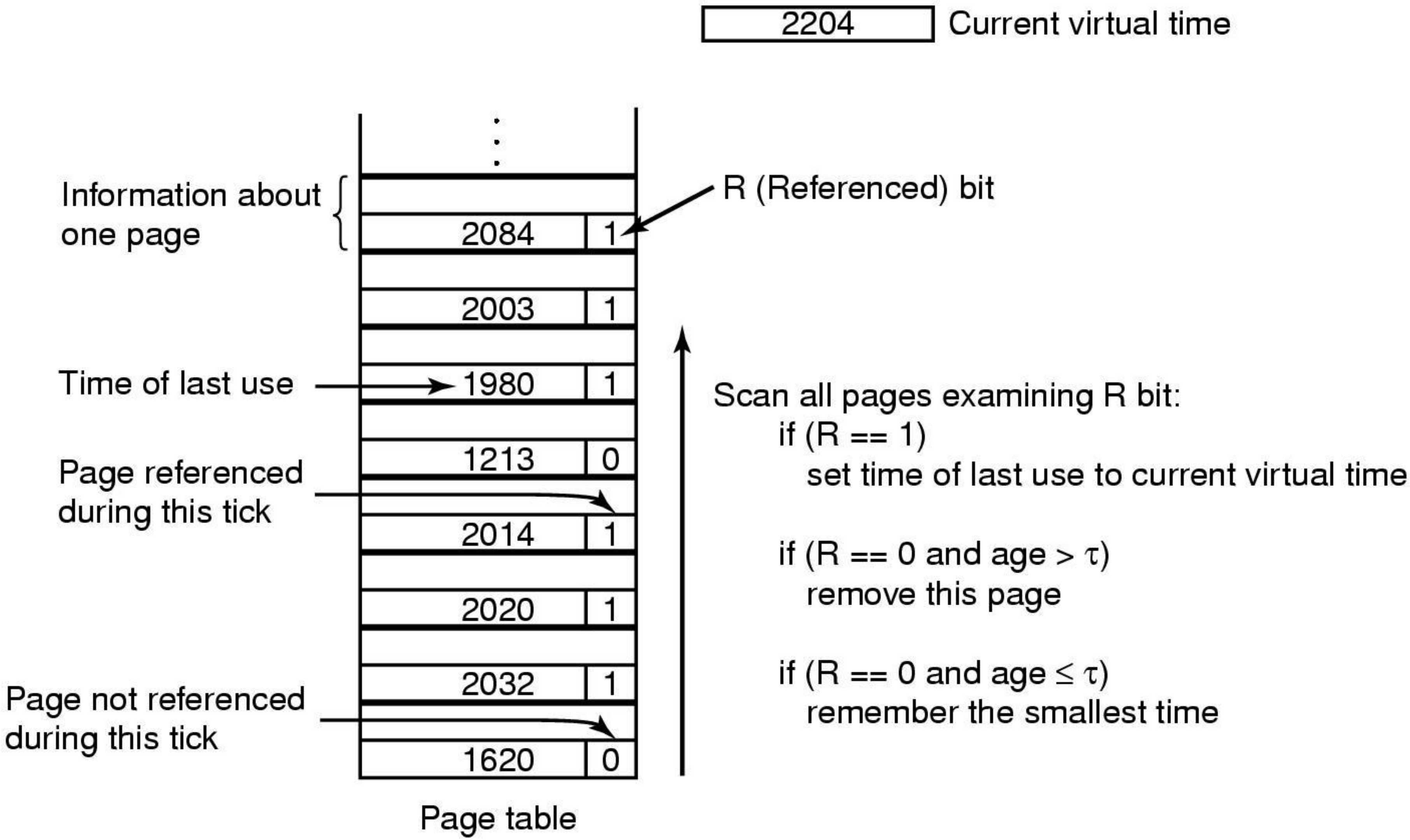
- Associate parameter WSS with each process
- If the sum of WSS exceeds the total number of frames, suspend a process
- Only allow a process to start if its WSS still fits in memory

Working Set Model (3)

Working set page replacement

- Maintaining the set of pages touched in the last k references
- Approximate the working set
  - 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 (Tlast)" 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 (Tlast = Tcurrent)
  - If R = 0 and (Tcurrent – Tlast) > t, evict the page

Working Set Model (4)



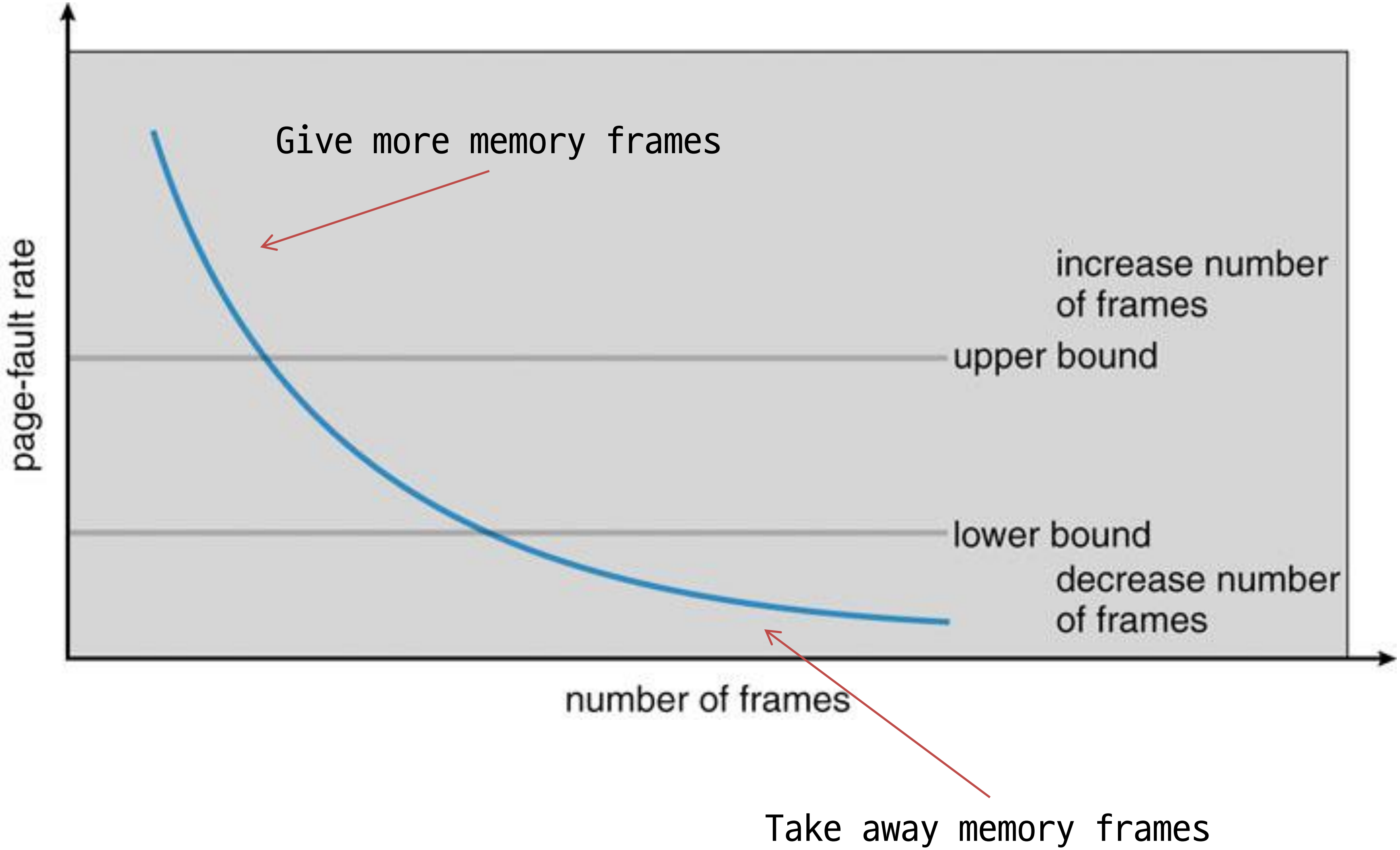
Let's assume t is 600. Then, which page should be evicted?

PFF (1)

Page Fault Frequency

- Monitor the fault rate for each process
- If the fault rate is above a high threshold(upper bound)
  - Give it more memory, so that it faults less
  - But not always valid – FIFO, Belady's anomaly
- If the fault rate is below a low threshold(lower bound)
  - Take away memory
- If the PFF increases and no free frames are available
  - Select some process and suspend it

PFF (2)



Give more memory frames
increase number of frames
upper bound
page-fault rate
lower bound
decrease number of frames
number of frames
Take away memory frames

Advanced VM Functionality

Virtual memory tricks

- Shared memory
- Copy on write
- Memory-mapped files

Shared Memory (1)

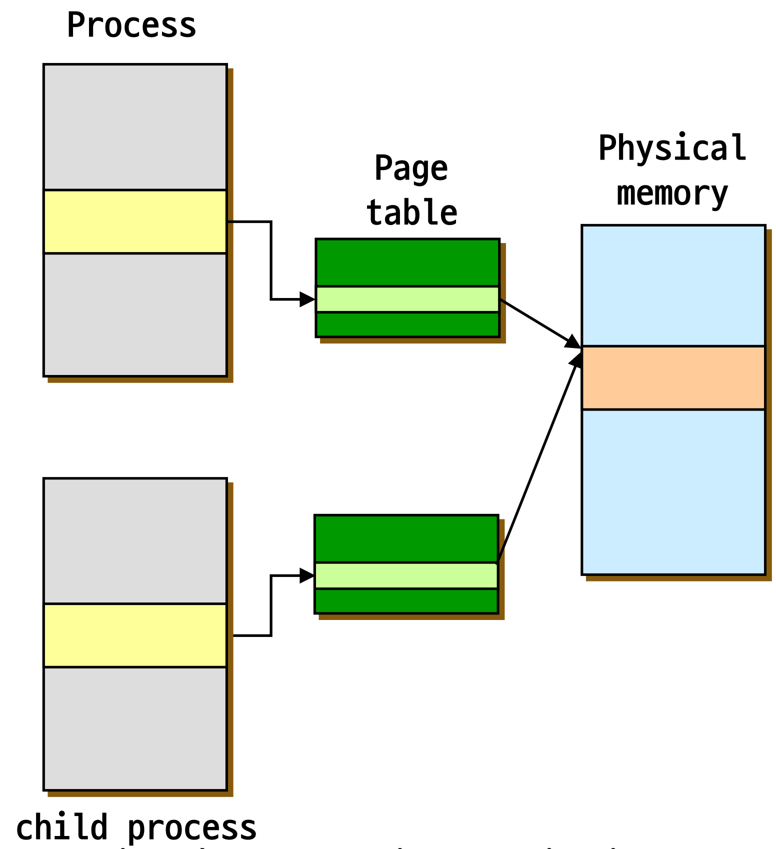
Shared memory

- 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 (2)

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



Copy On Write (1)

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

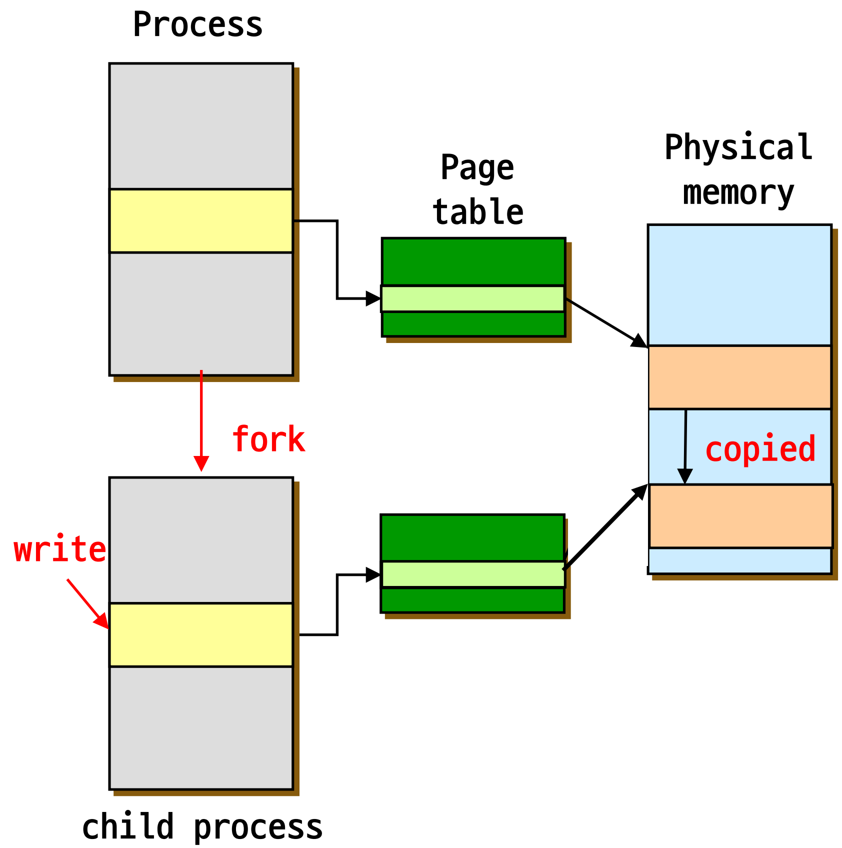
Solution 2: Use vfork() system call

- 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 (2)

Solution 3: Copy On Write (COW)

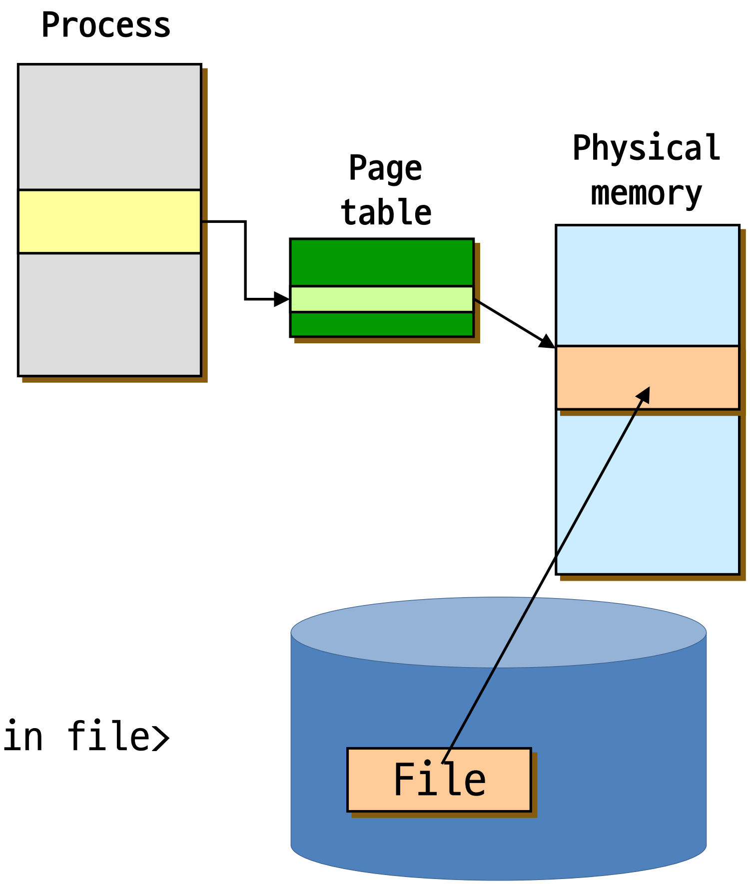
- Instead of copying all pages, create shared mappings of parent pages in child address space
- Shared pages are protected as read-only in child
  - Reads happen as usual
  - Writes generate a protection fault, trap to OS, and OS copies the page, changes page mapping in client page table, restarts write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



Memory-Mapped Files (1)

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> = <offset N in file>
- Initially, all pages in mapped region marked as invalid
  - Whenever invalid page is accessed, OS reads a page from file
  - When evicted from physical memory, OS writes a page to file
  - If page is not dirty, no write needed



Memory-Mapped Files (2)

Example

```
if ((fd = open("test.txt", O_RDWR)) == -1) {
   perror("open");
   exit(1);
}

addr = mmap(NULL, statbuf.st_size, PROT_READ|PROT_WRITE,
   MAP_SHARED, fd, (off_t)0);
if (addr == MAP_FAILED) {
   perror("mmap");
   exit(1);
}
close(fd);

printf("%s", addr);
strcpy(addr, buf);
sprintf(addr, "%s to modify some text ", buf);
...
...
```

Memory-Mapped Files (3)

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.)

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(page)"

Summary (1)

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 (2)

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