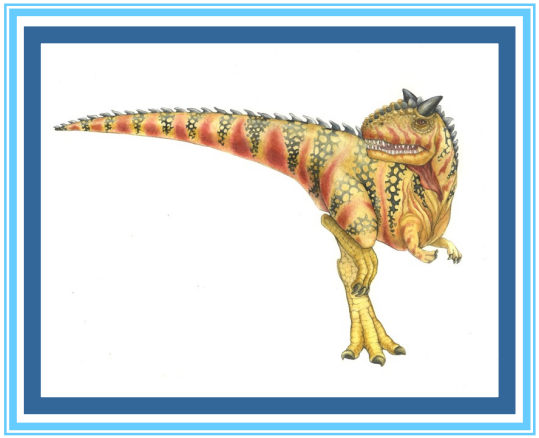
Chapter 10: Virtual Memory



Chapter 10: Virtual Memory

- Background
- Demand Paging
- Page Fault
- Copy-on-Write
- Page Replacement
- Thrashing
- Memory-Mapped Files
- Other Considerations

Objectives

- To describe the benefits of a virtual memory system
- To explain the concepts of demand paging, page-replacement algorithms, and allocation of page frames
- To discuss the principle of the working-set model
- To examine the relationship between shared memory and memory-mapped files

Review: Locality

- All paging schemes depend on locality
  - Processes reference pages in localized patterns
- Temporal locality
  - Locations referenced recently likely to be referenced again
- Spatial locality
  - Locations near recently referenced locations are likely to be referenced soon
- Although the cost of paging is high, if it is infrequent enough it is acceptable
  - Processes usually exhibit both kinds of locality during their execution, making paging practical

Background

- Code needs to be in memory to execute, but entire program rarely used
  - Error code, unusual routines, large data structures
- Entire program code not needed at same time
- Consider ability to execute partially-loaded program
  - Program no longer constrained by limits of physical memory
  - Each program takes less memory while running -> more programs run at the same time
    - Increased CPU utilization and throughput with no increase in response time or turnaround time
  - Less I/O needed to load or swap programs into memory -> each user program runs faster

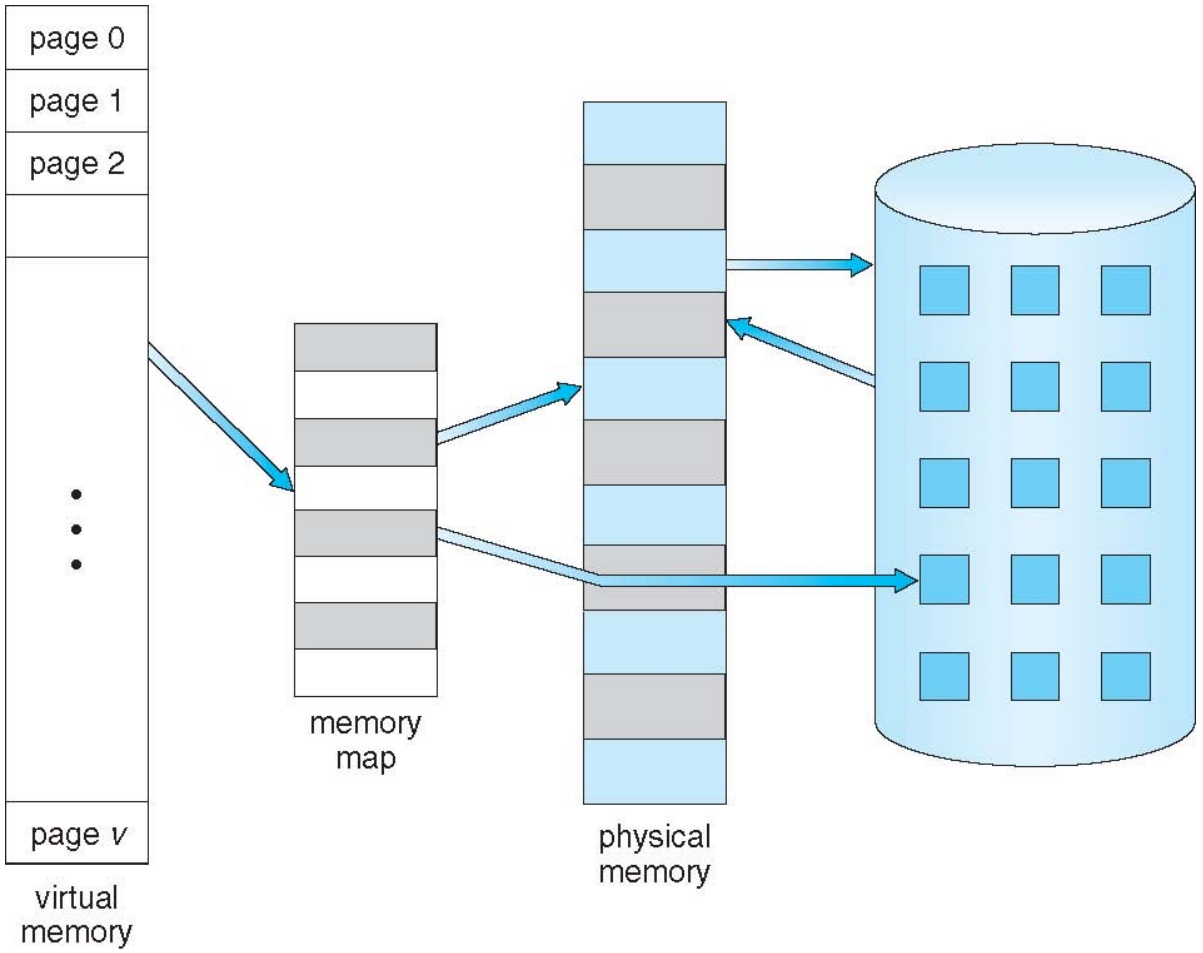
Background (Cont.)

- **Virtual memory** – separation of user logical memory from physical memory
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation
  - More programs running concurrently
  - Less I/O needed to load or swap processes

Background (Cont.)

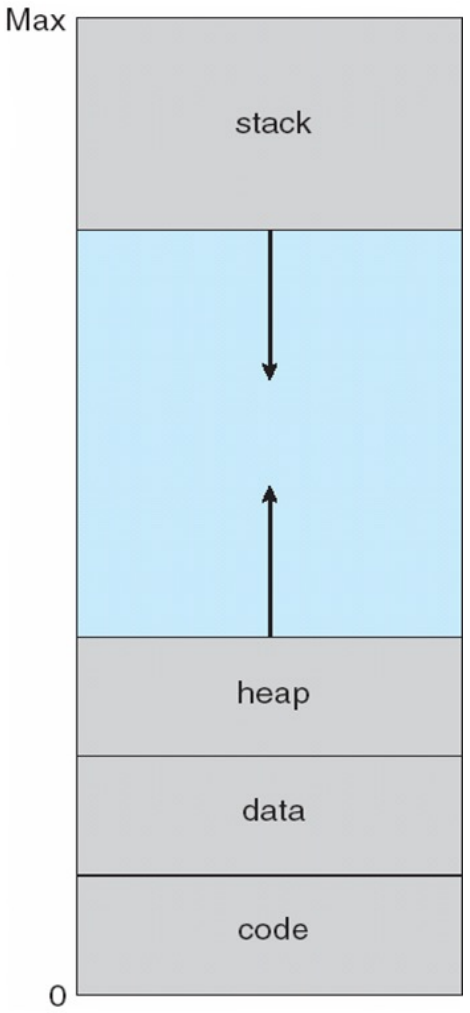
- **Virtual address space** – logical view of how process is stored in memory
  - Usually start at address 0, contiguous addresses until end of space
  - Meanwhile, physical memory organized in page frames
  - MMU must map logical to physical
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

Virtual Memory That is Larger Than Physical Memory

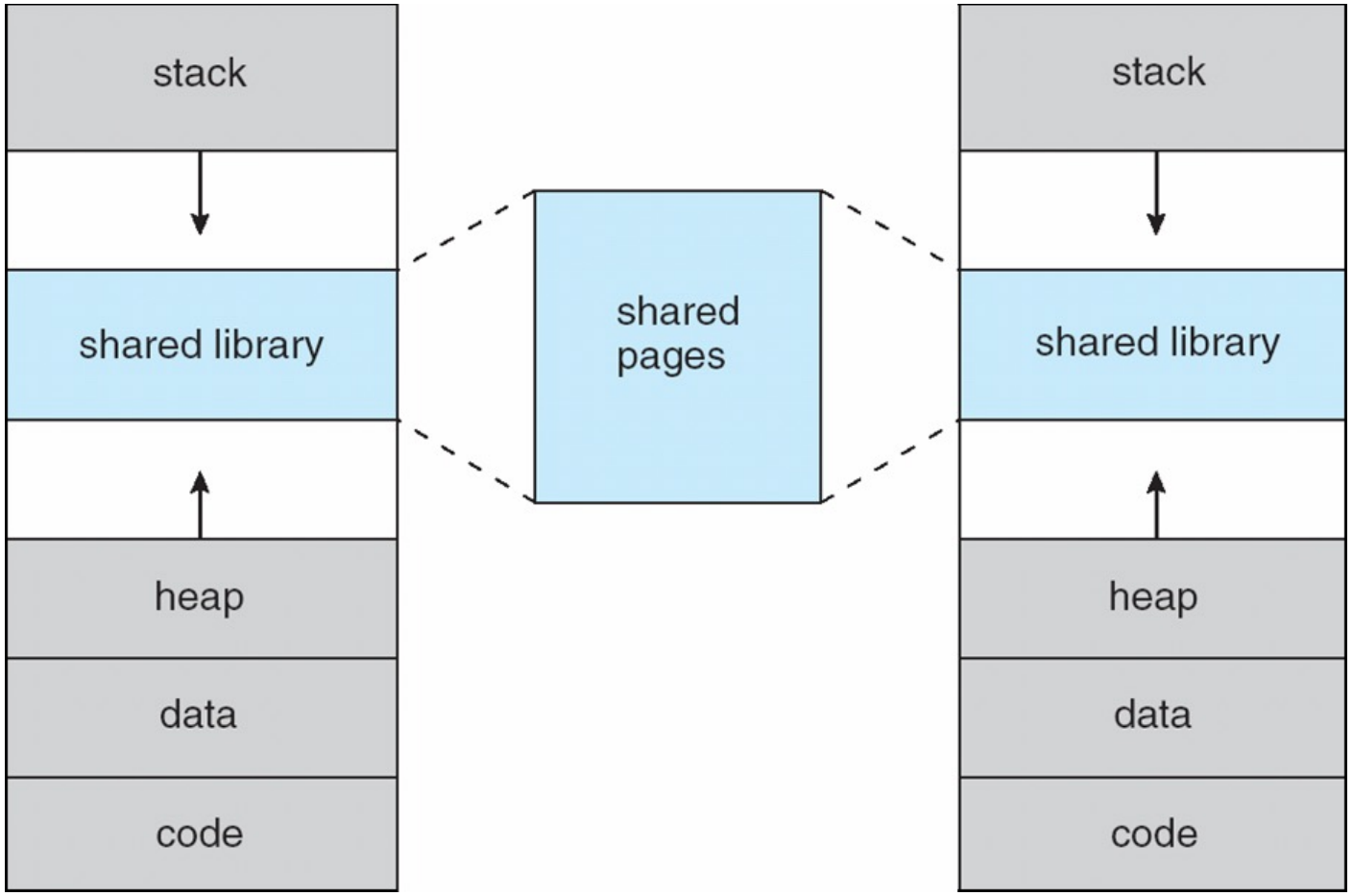


Virtual-address Space

- Usually design logical address space for stack to start at Max logical address and grow “down” while heap grows “up”
  - Maximizes address space use
  - Unused address space between the two is hole
    - No physical memory needed until heap or stack grows to a given new page
- Enables **sparse** address spaces with holes left for growth, dynamically linked libraries, etc
- System libraries shared via mapping into virtual address space
- Shared memory by mapping pages read-write into virtual address space
- Pages can be shared during `fork()`, speeding process creation



Shared Library Using Virtual Memory

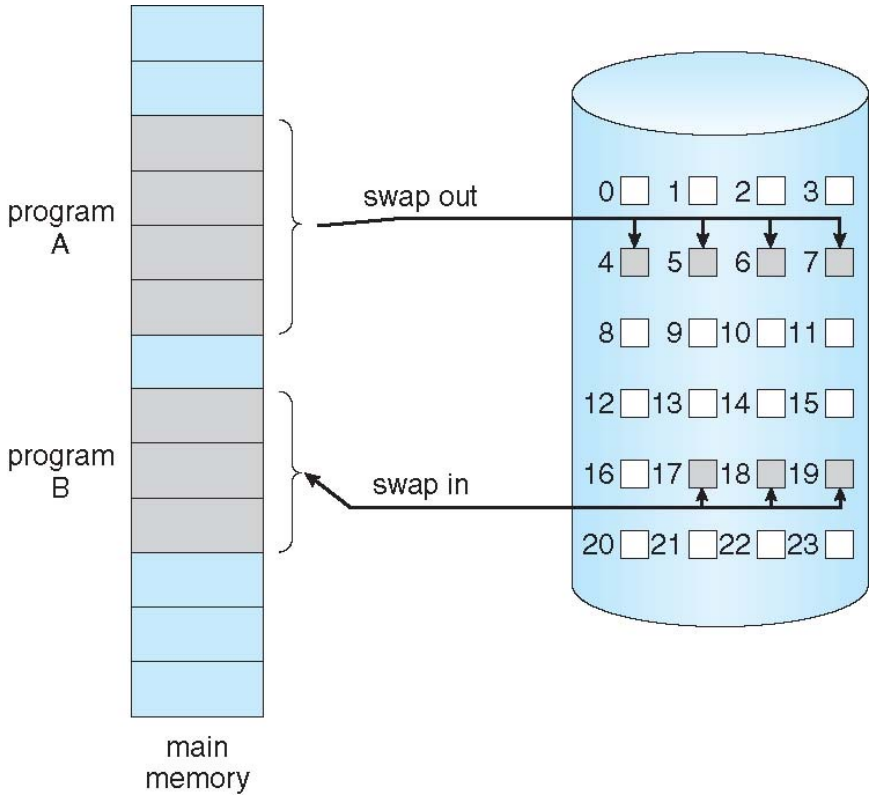


Paged Virtual Memory

- We've mentioned before that pages can be moved between memory and disk
  - This process is called demand paging
- OS uses main memory as a page cache of all the data allocated by processes in the system
  - Initially, pages are allocated from memory
  - When memory fills up, allocating a page in memory requires some other page to be evicted from memory
  - Evicted pages go to disk (where? the swap file/partition)
  - The movement of pages between memory and disk is done by the OS, and is transparent to the application

Demand Paging

- Could bring entire process into memory at load time
- Or bring a page into memory only when it is needed
  - Less I/O needed, no unnecessary I/O
  - Less memory needed
  - Faster response
  - More users
- Similar to paging system with swapping (diagram on right)
- Page is needed ⇒ reference to it
  - invalid reference ⇒ abort
  - not-in-memory ⇒ bring to memory



Demand Paging (OS)

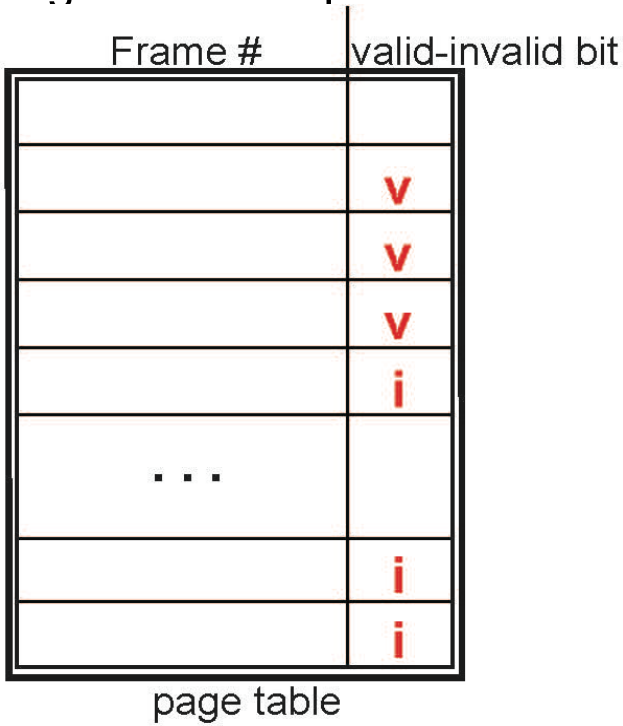
- Recall demand paging from the OS perspective:
  - Pages are evicted to disk when memory is full
  - Pages loaded from disk when referenced again
  - References to evicted pages cause a TLB miss » PTE was invalid, causes fault
  - OS allocates a page frame, reads page from disk
  - When I/O completes, the OS fills in PTE, marks it valid, and restarts faulting process
- Dirty vs. clean pages
  - Actually, only dirty pages (modified) need to be written to disk
  - Clean pages do not – but you need to know where on disk to read them from again

Demand Paging (Process)

- Demand paging is also used 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

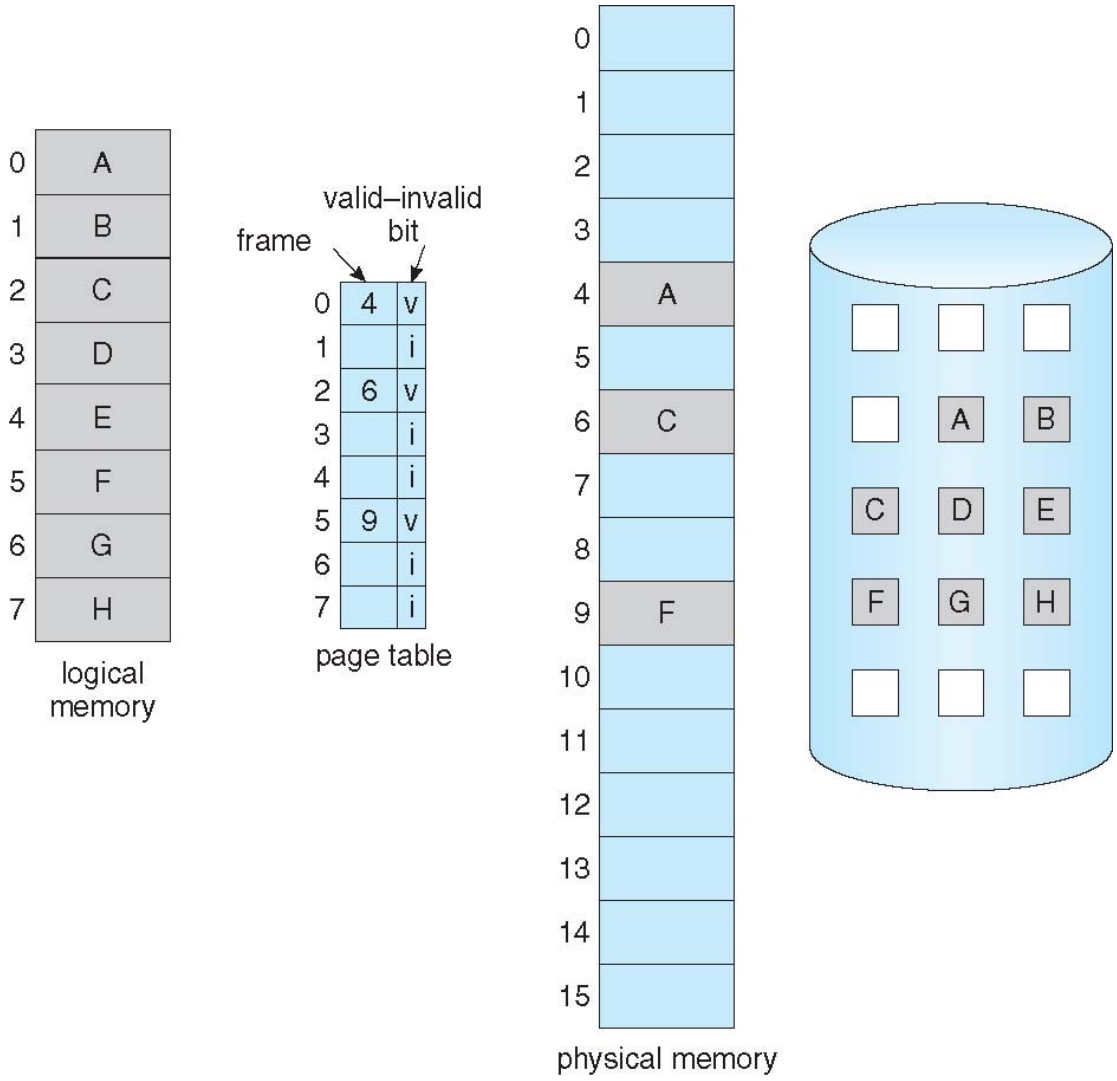
Valid-Invalid Bit

- With each page table entry a valid–invalid bit is associated (**v** ⇒ in-memory – **memory resident**, **i** ⇒ not-in-memory)
- Initially valid–invalid bit is set to **i** on all entries
- Example of a page table snapshot:



- During MMU address translation, if valid–invalid bit in page table entry is **i** ⇒ page fault

Page Table When Some Pages Are Not in Main Memory



Page Fault (I)

- If there is a reference to a page, first reference to that page will trap to operating system:

  page fault

1. Operating system looks at another table to decide:
   - Invalid reference ⇒ abort
   - Just not in memory
2. Find free frame
3. Swap page into frame via scheduled disk operation
4. Reset tables to indicate page now in memory
   Set validation bit = **v**
5. Restart the instruction that caused the page fault

Page Fault (II)

- What happens when a process accesses a page that has been evicted?

  1. When it evicts a page, the OS sets the PTE as invalid and stores the location of the page in the swap file in the PTE

  2. When a process accesses the page, the invalid PTE will cause a trap (page fault)

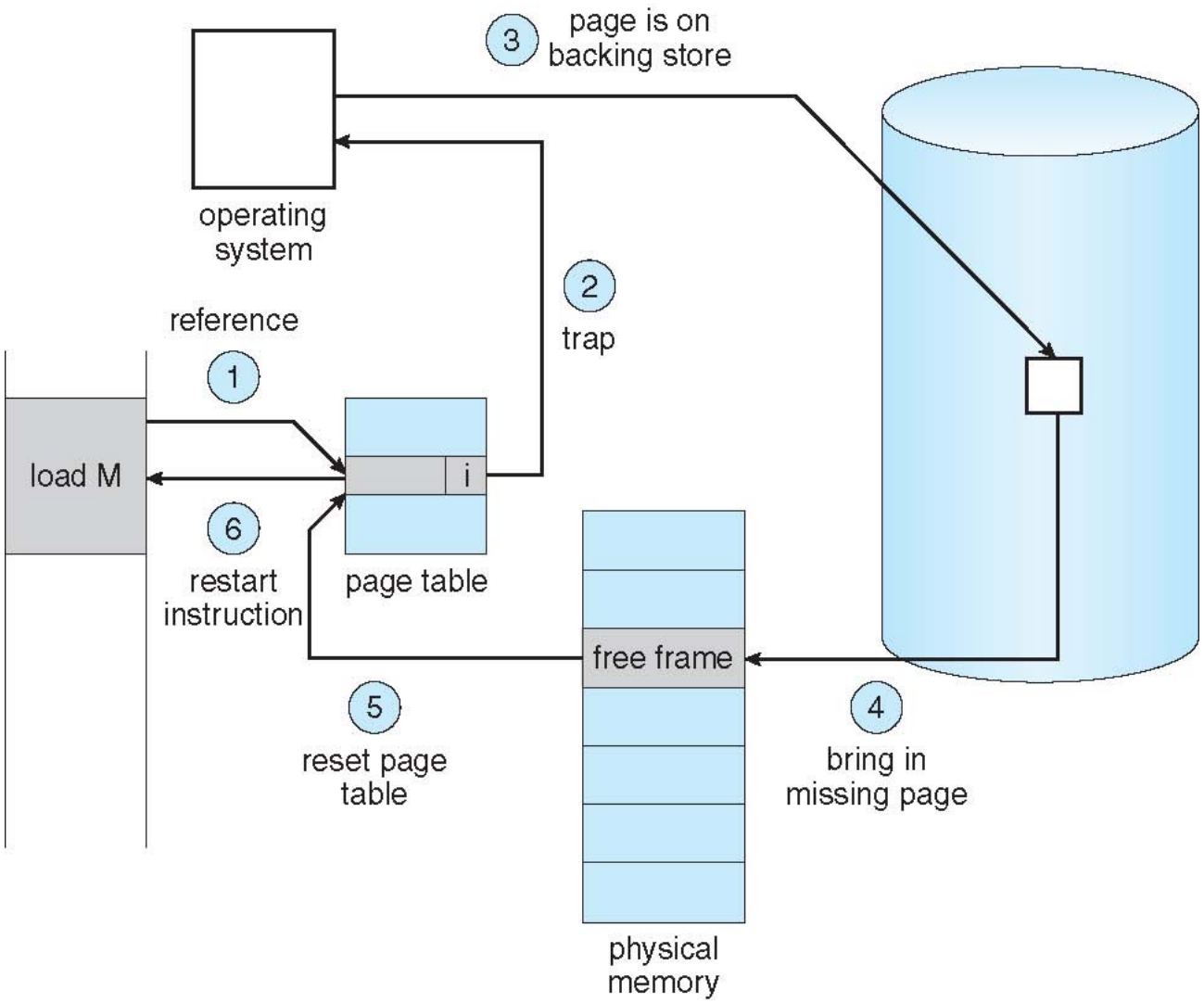
  3. The trap will run the OS page fault handler

  4. Handler uses the invalid PTE to locate page in swap file

  5. Reads page into a physical frame, updates PTE to point to it 6. Restarts process

- But where does it put it? Has to evict something else
  - OS usually keeps a pool of free pages around so that allocations do not always cause evictions

Steps in Handling a Page Fault



Aspects of Demand Paging

- Extreme case – start process with *no* pages in memory
  - OS sets instruction pointer to first instruction of process, non-memory-resident -> page fault
  - And for every other process pages on first access
  - **Pure demand paging**
- Actually, a given instruction could access multiple pages -> multiple page faults
  - Consider fetch and decode of instruction which adds 2 numbers from memory and stores result back to memory
  - Pain decreased because of **locality of reference**
- Hardware support needed for demand paging
  - Page table with valid / invalid bit
  - Secondary memory (**swap space, see Chapter11**)
  - Instruction restart

Performance of Demand Paging

- Stages in Demand Paging (worse case)

1. Trap to the operating system
2. Save the user registers and process state
3. Determine that the interrupt was a page fault
4. Check that the page reference was legal and determine the location of the page on the disk
5. Issue a read from the disk to a free frame:
    1. Wait in a queue for this device until the read request is serviced
    2. Wait for the device seek and/or latency time
    3. Begin the transfer of the page to a free frame
6. While waiting, allocate the CPU to some other user
7. Receive an interrupt from the disk I/O subsystem (I/O completed)
8. Save the registers and process state for the other user
9. Determine that the interrupt was from the disk
10. Correct the page table and other tables to show page is now in memory
11. Wait for the CPU to be allocated to this process again
12. Restore the user registers, process state, and new page table, and then resume the interrupted instruction

Performance of Demand Paging (Cont.)

- Three major activities
  - Service the interrupt – careful coding means just several hundred instructions needed
  - Read the page – lots of time
  - Restart the process – again just a small amount of time
- Page Fault Rate $0 \le p \le 1$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault
- Effective Access Time (EAT)

$$\begin{aligned} EAT = (1 - p) \times & \text{ memory access} \\ & + p \text{ (page fault overhead} \\ & \quad + \text{swap page out} \\ & \quad + \text{swap page in)} \end{aligned}$$

Demand Paging Example

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- EAT = (1 – p) x 200 + p (8 milliseconds)

  = (1 – p x 200 + p x 8,000,000

  = 200 + p x 7,999,800
- If one access out of 1,000 causes a page fault, then

  EAT = 8.2 microseconds.

  This is a slowdown by a factor of 40!!
- If want performance degradation < 10 percent
  - 220 > 200 + 7,999,800 x p
    20 > 7,999,800 x p
  - p < .0000025
  - < one page fault in every 400,000 memory accesses

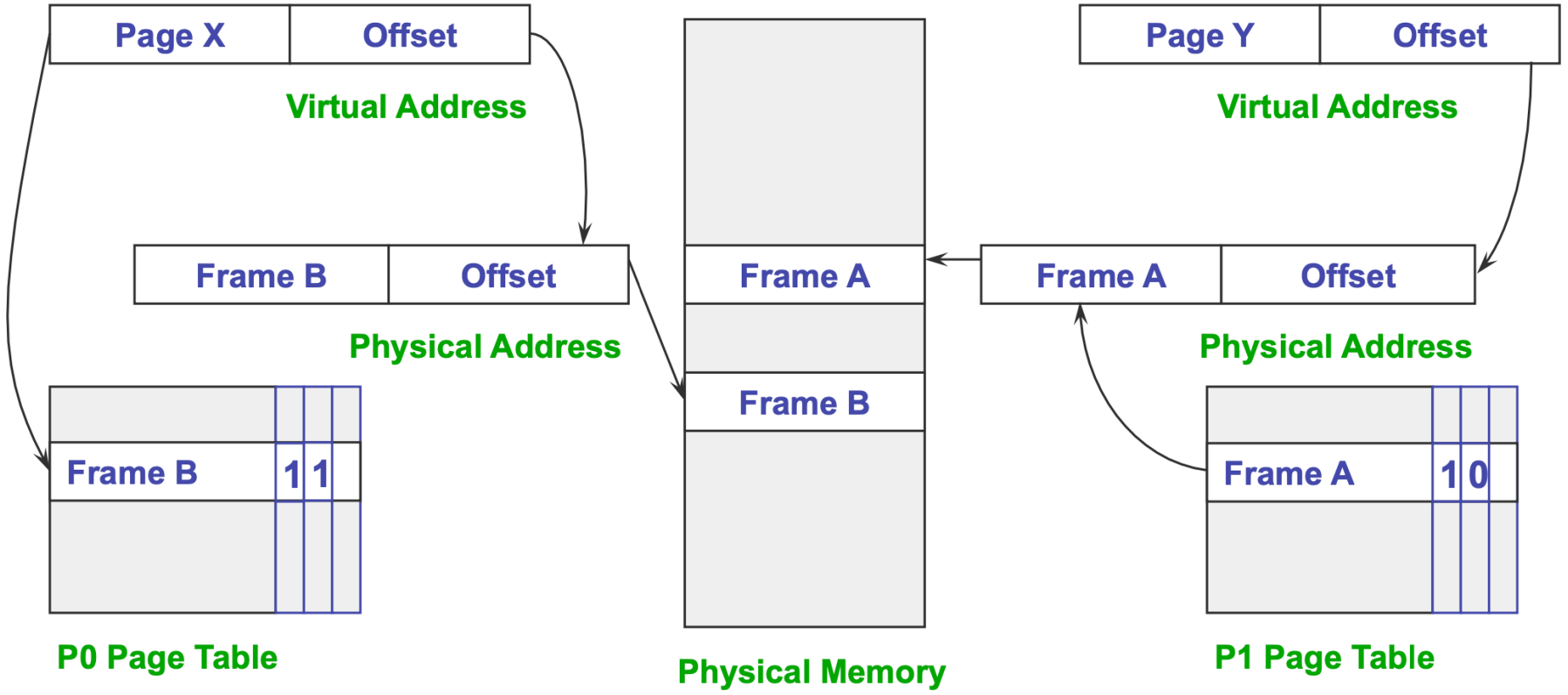
Copy on Write (I)

- OSes spend a lot of time copying data
  - System call arguments between user/kernel space
  - Entire address spaces to implement fork()
- Use Copy on Write (CoW) to defer large copies as long as possible, hoping to avoid them altogether
  - Instead of copying pages, create shared mappings of parent pages in child virtual address space
  - Shared pages are protected as read-only in child
    - Reads happen as usual
    - Writes generate a protection fault, trap to OS, copy page, change page mapping in client page table, restart write instruction
  - How does this help fork()? (Implemented as Unix vfork())

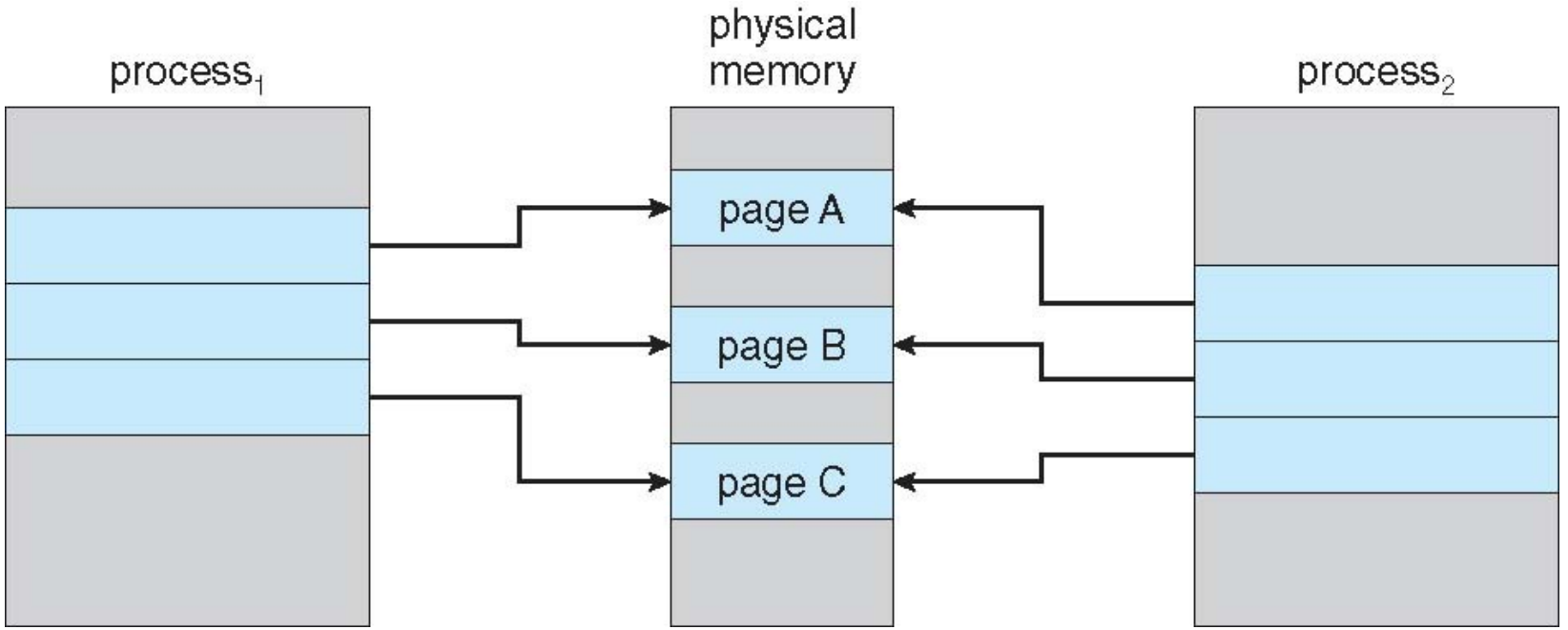
Copy-on-Write (II)

- **Copy-on-Write** (COW) allows both parent and child processes to initially ***share*** the same pages in memory
  - If either process modifies a shared page, only then is the page copied
- COW allows more efficient process creation as only modified pages are copied
- In general, free pages are allocated from a **pool** of **zero-fill-on-demand** pages
  - Pool should always have free frames for fast demand page execution
    - Don't want to have to free a frame as well as other processing on page fault
  - Why zero-out a page before allocating it?
- `vfork()` variation on `fork()` system call has parent suspend and child using copy-on-write address space of parent
  - Designed to have child call `exec()`
  - Very efficient

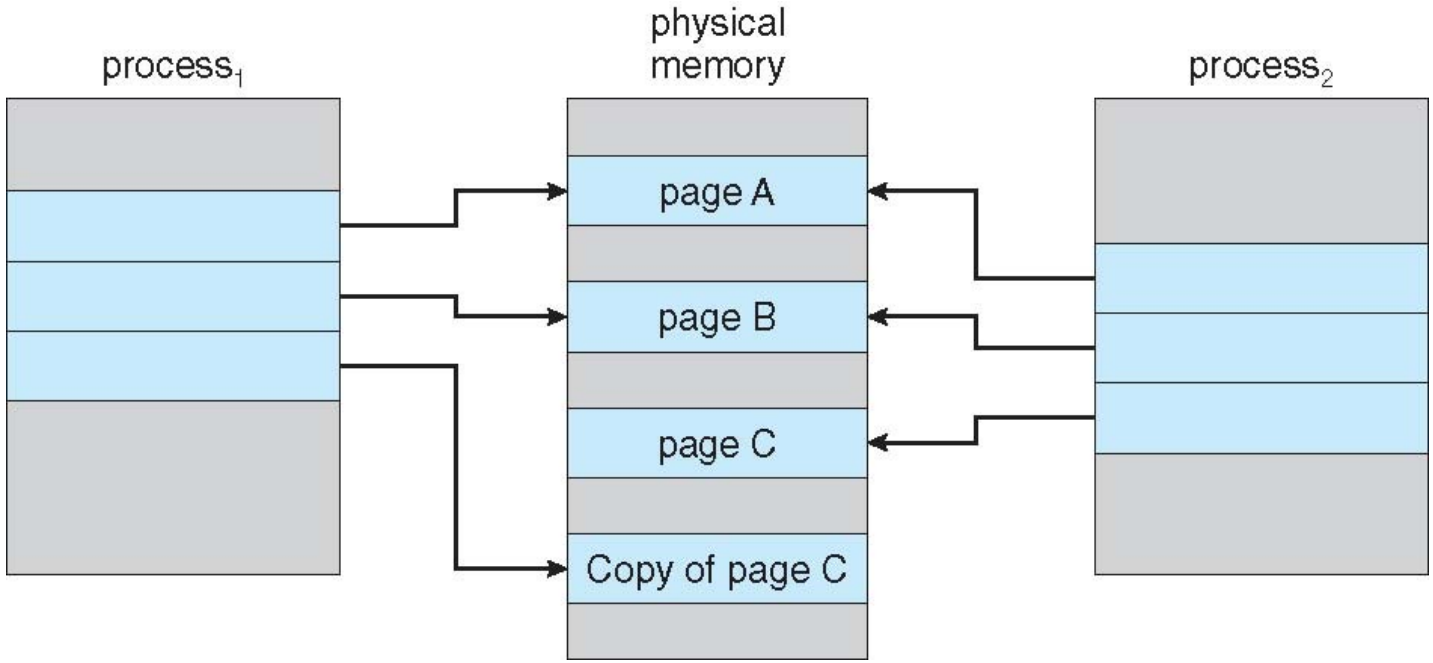
Exclusive Page on Write



Before Process 1 Modifies Page C



After Process 1 Modifies Page C



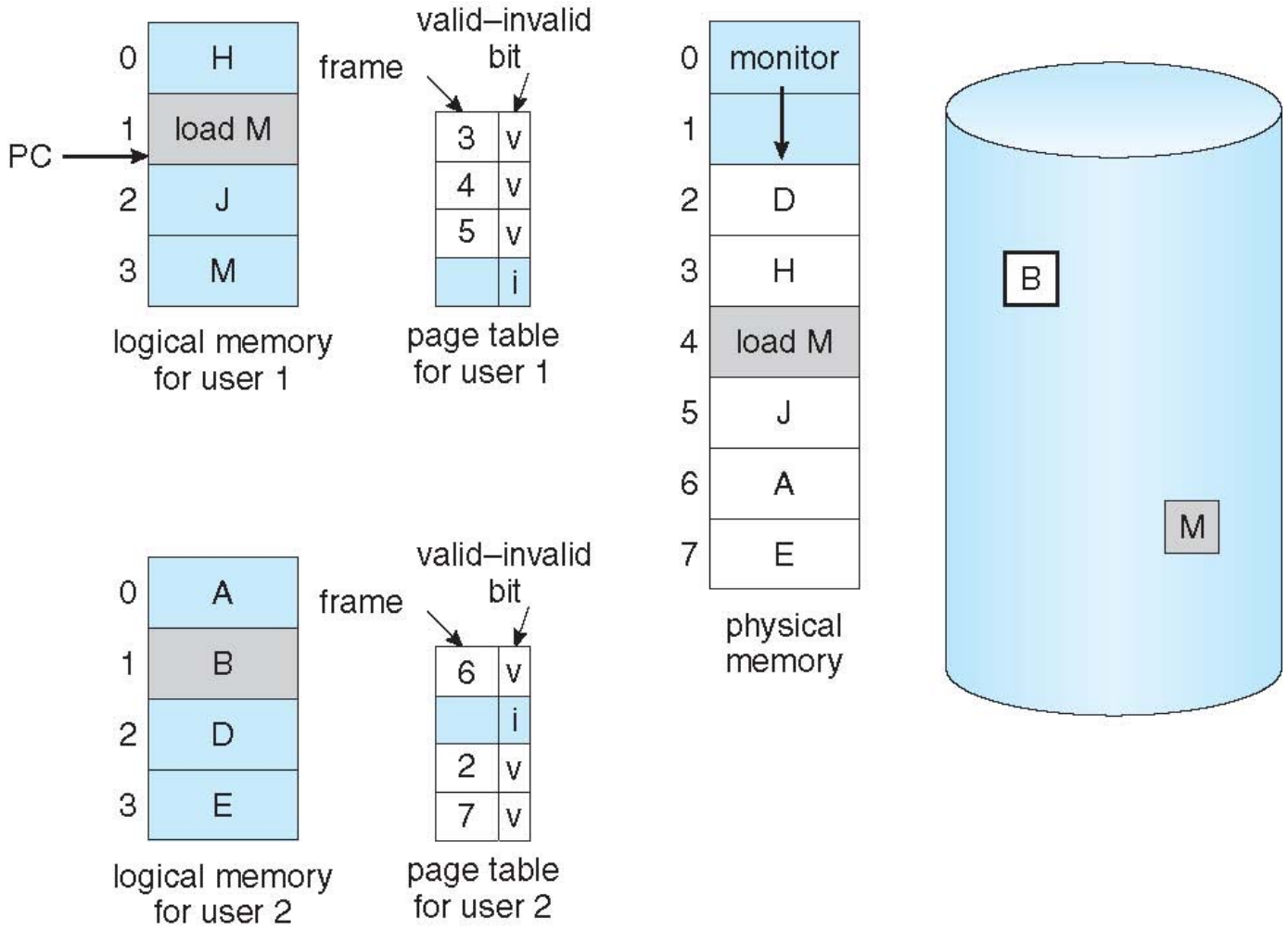
What Happens if There is No Free Frame?

- Used up by process pages
- Also in demand from the kernel, I/O buffers, etc
- How much to allocate to each?
- Page replacement – find some page in memory, but not really in use, page it out
  - Algorithm – terminate? swap out? replace the page?
  - Performance – want an algorithm which will result in minimum number of page faults
- Same page may be brought into memory several times

Page Replacement

- Prevent **over-allocation** of memory by modifying page-fault service routine to include page replacement
- Use **modify** (**dirty**) **bit** to reduce overhead of page transfers – only modified pages are written to disk
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory

Need For Page Replacement



Basic Page Replacement

1. Find the location of the desired page on disk

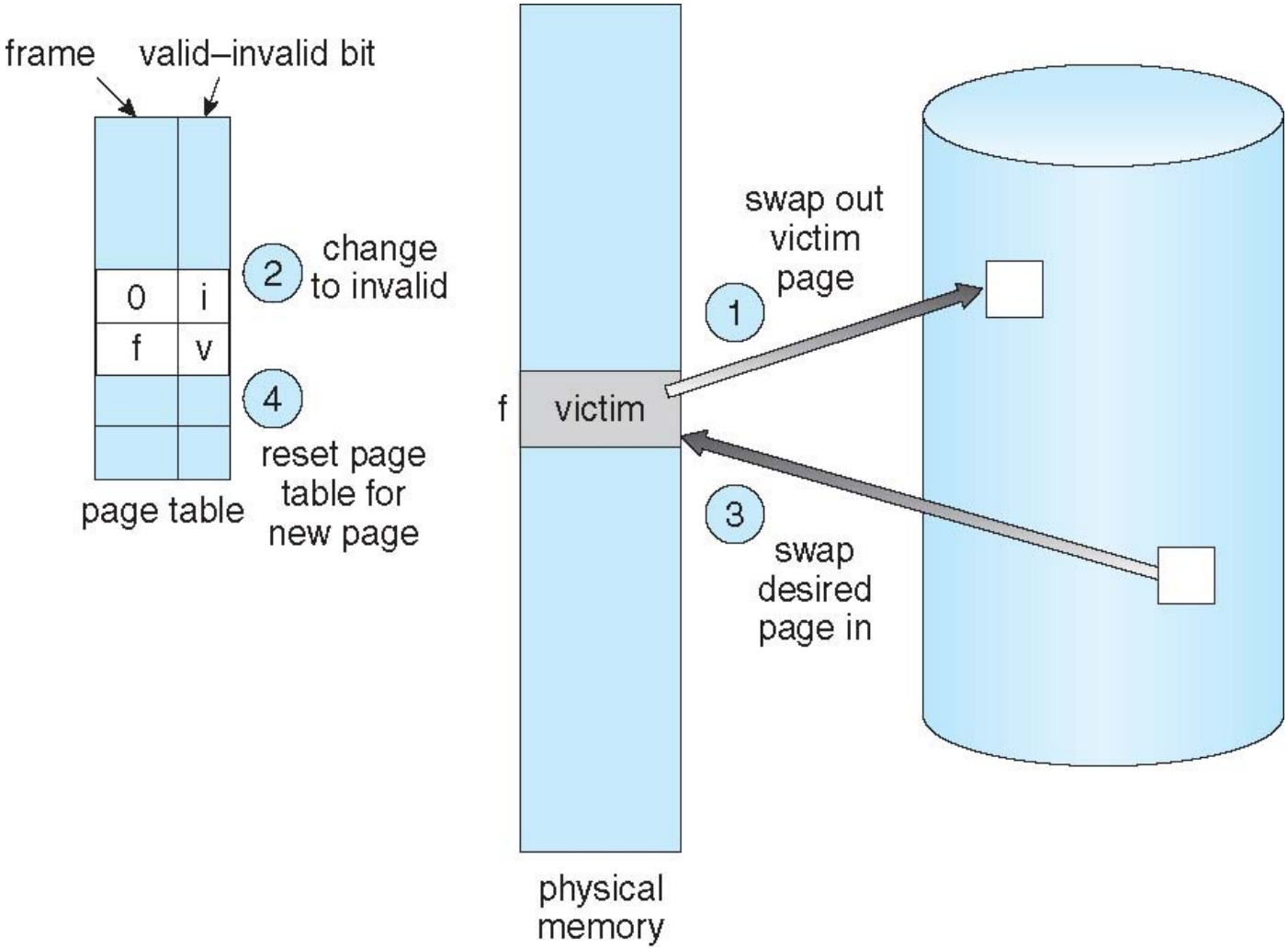
2. Find a free frame:
   - If there is a free frame, use it
   - If there is no free frame, use a page replacement algorithm to select a **victim frame**
     - Write victim frame to disk if dirty

3. Bring the desired page into the (newly) free frame; update the page and frame tables

4. Continue the process by restarting the instruction that caused the trap

Note now potentially 2 page transfers for page fault – increasing EAT

Page Replacement (I)



Page Replacement (II)

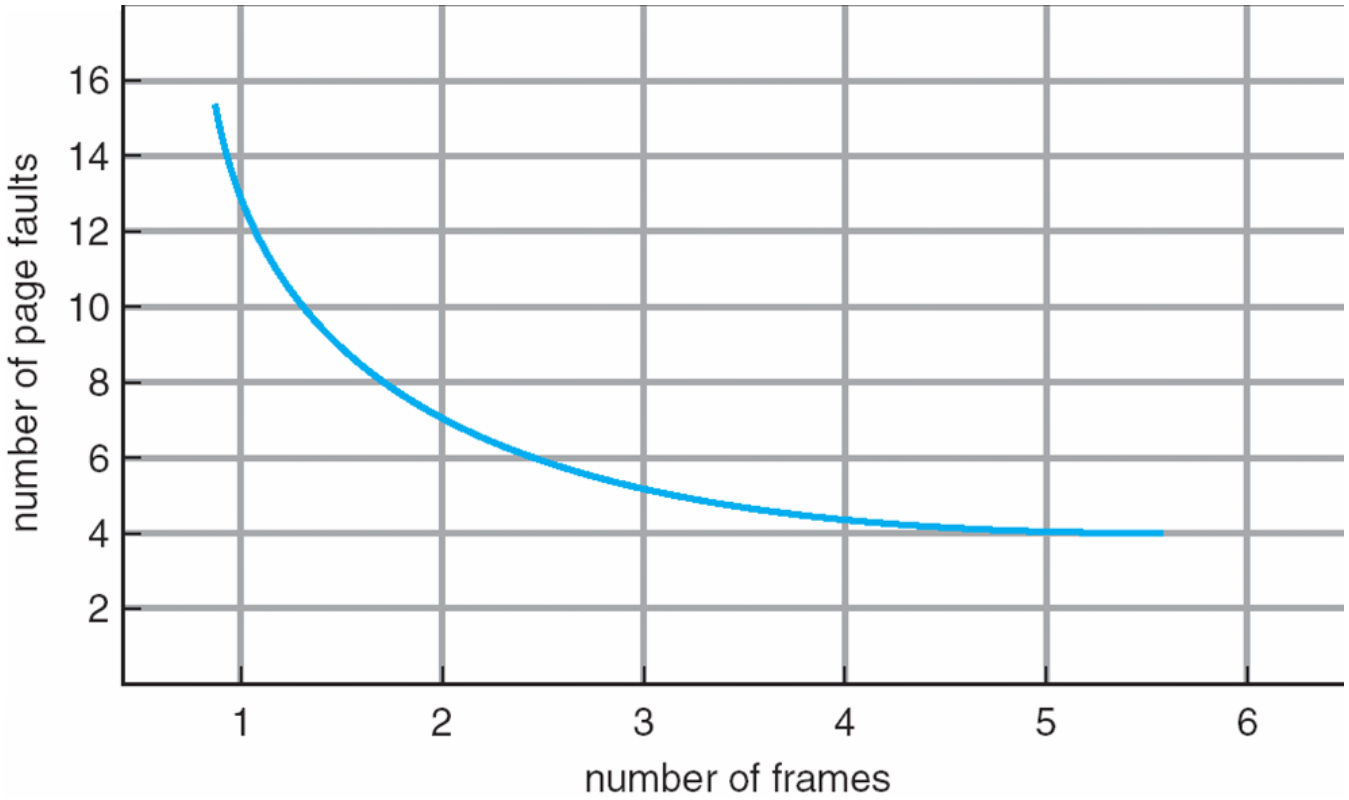
- When a page fault occurs, the OS loads the faulted page from disk into a page frame of memory
- At some point, the process has used all of the page frames it is allowed to use
  - This is likely less than all of available memory
- When this happens, the OS must replace a page for each page faulted in
  - It must evict a page to free up a page frame

Page and Frame Replacement Algorithms

- **Frame-allocation algorithm** determines
  - How many frames to give each process
  - Which frames to replace
- **Page-replacement algorithm**
  - Want lowest page-fault rate on both first access and re-access
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
  - String is just page numbers, not full addresses
  - Repeated access to the same page does not cause a page fault
  - Results depend on number of frames available
- In all our examples, the **reference string** of referenced page numbers is

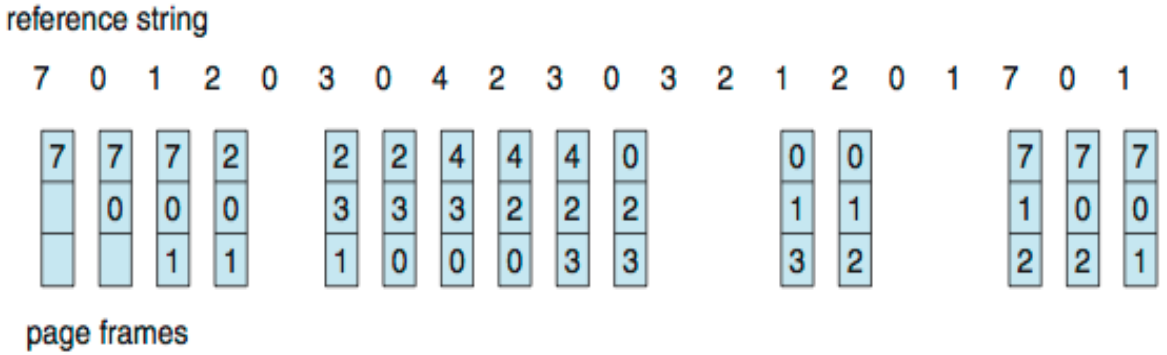
7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1

Graph of Page Faults Versus The Number of Frames



First-In-First-Out (FIFO) Algorithm

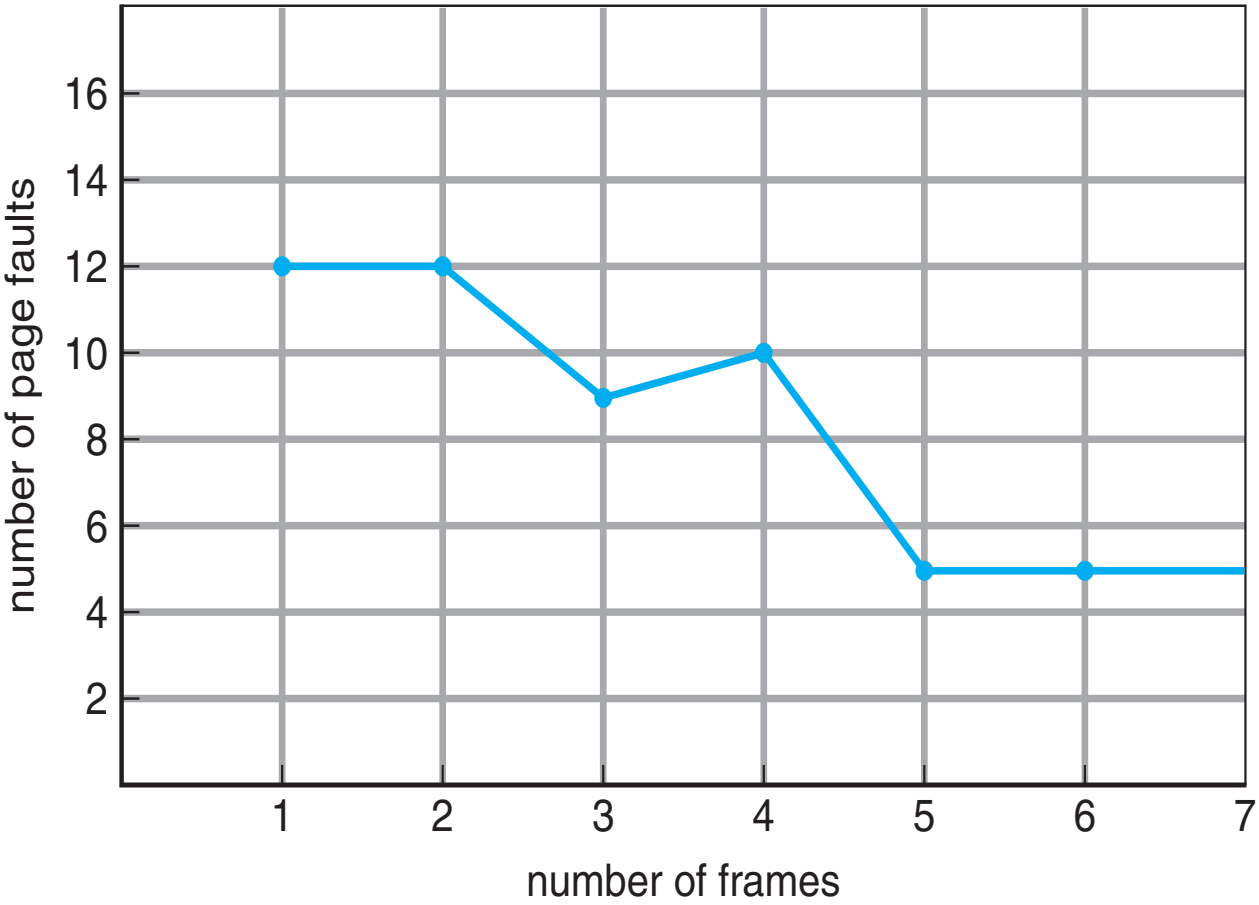
- Reference string: **7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1**
- 3 frames (3 pages can be in memory at a time per process)



15 page faults

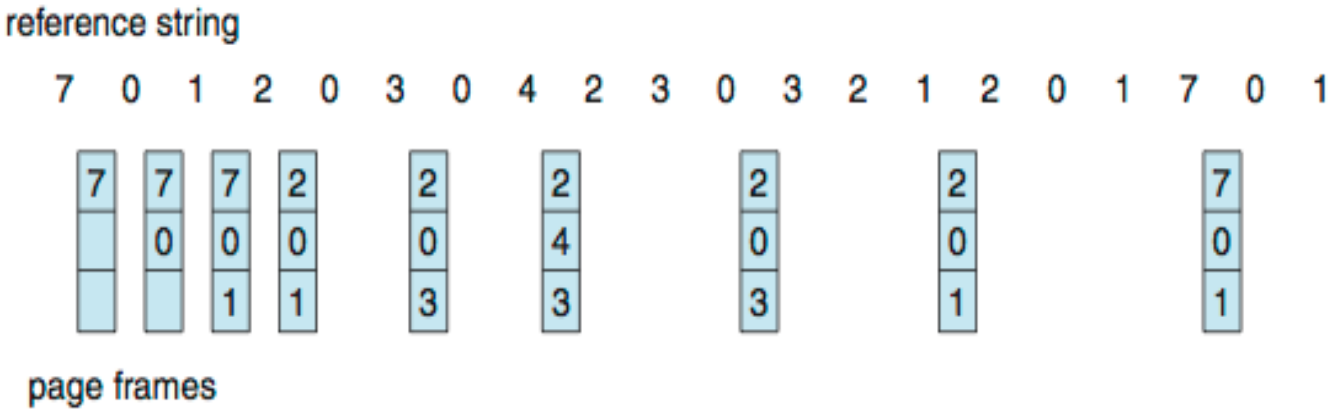
- Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5
  - Adding more frames can cause more page faults!
    - **Belady's Anomaly**
- How to track ages of pages?
  - Just use a FIFO queue

FIFO Illustrating Belady's Anomaly



Optimal Algorithm

- Replace page that will not be used for longest period of time
  - 9 is optimal for the example
- How do you know this?
  - Can't read the future
- Used for measuring how well your algorithm performs

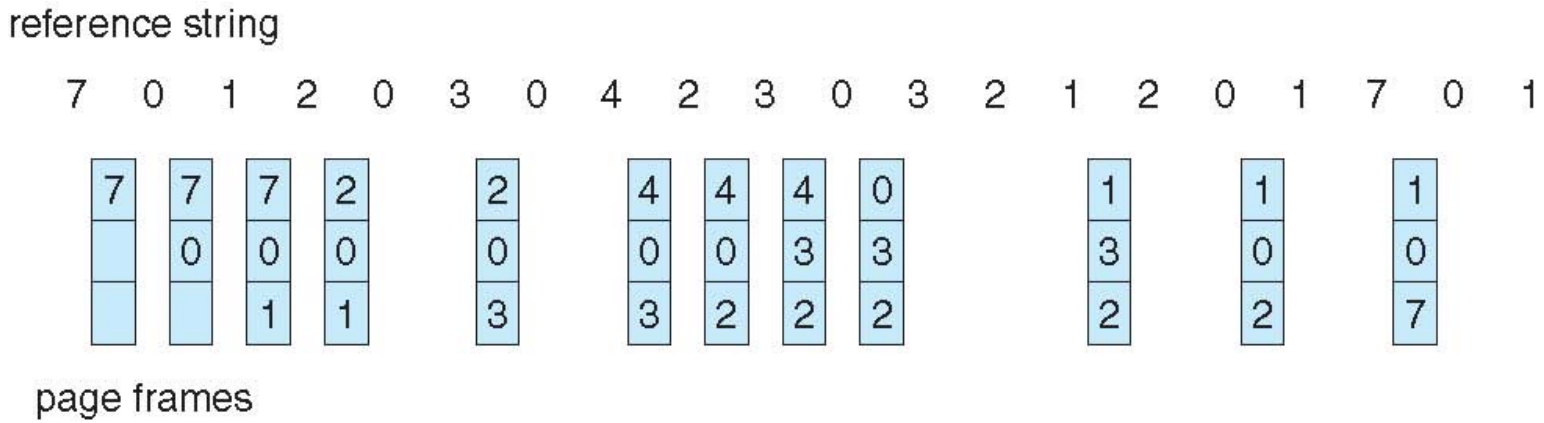


Belady's Algorithm

- Belady's algorithm is known as the optimal page replacement algorithm because it has the lowest fault rate for any page reference stream
  - Idea: Replace the page that will not be used for the longest time in the future
  - Problem: Have to predict the future
- Why is Belady's useful then? Use it as a yardstick
  - 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
  - If optimal is much better, then algorithm could use some work
    - Random replacement is often the lower bound

Least Recently Used (LRU) Algorithm

- Use past knowledge rather than future
- Replace page that has not been used in the most amount of time
- Associate time of last use with each page

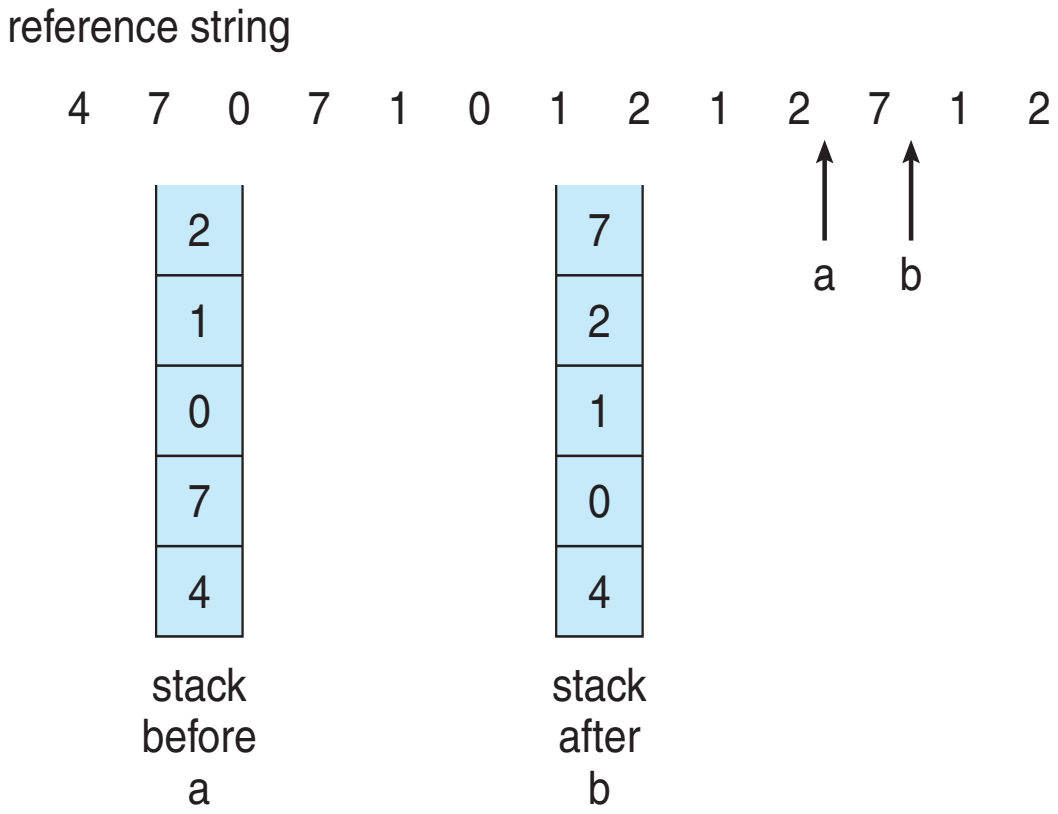


- 12 faults – better than FIFO but worse than OPT
- Generally good algorithm and frequently used
- But how to implement?

LRU Algorithm (Cont.)

- Counter implementation
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter
  - When a page needs to be changed, look at the counters to find smallest value
    - Search through table needed
- Stack implementation
  - Keep a stack of page numbers in a double link form:
  - Page referenced:
    - move it to the top
    - requires 6 pointers to be changed
  - But each update more expensive
  - No search for replacement
- LRU and OPT are cases of **stack algorithms** that don't have Belady's Anomaly

Use of A Stack to Record Most Recent Page References



Another approach to implementing LRU replacement is to keep a stack of page numbers. Whenever a page is referenced, it is removed from the stack and put on the top. In this way, the most recently used page is always at the top of the stack, and the least recently used page is always at the bottom.

LRU Algorithm

- 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)
- Implementation
  - To be perfect, need to time stamp every reference (or maintain a stack) – much too costly
  - So we need to approximate it
  - Some architectures don't have a reference bit
    - Can simulate reference bit using the valid bit to induce faults
    - What happens when we make a page invalid?

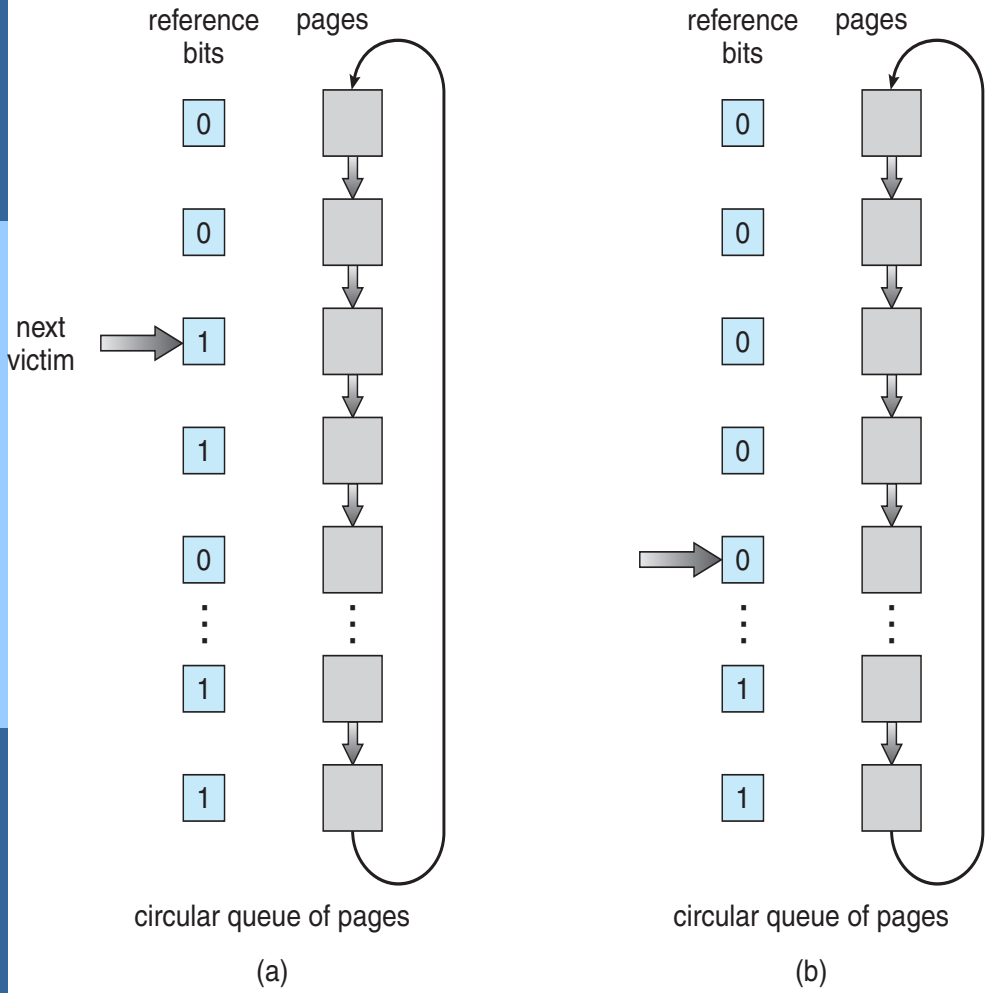
Approximating LRU

- 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

LRU Approximation Algorithms

- **Reference bit**
  - With each page associate a bit (counter), initially = 0
  - When page is referenced bit (counter) set to 1
  - 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
  - Replace any with reference bit = 0 (if one exists)
    - We do not know the order, however
- **Second-chance algorithm**
  - Generally FIFO, plus hardware-provided reference bit
  - **Clock** replacement
  - If page to be replaced has
    - Reference bit = 0 -> replace it
    - reference bit = 1 then:
      - set reference bit 0, leave page in memory
      - replace next page, subject to same rules

Second-Chance (clock) Page-Replacement Algorithm



A bit is associated with each page. It's initially set to 0, and when the page is referenced, it's set to 1.

Starting from the current pointer, if there is a need to replace a page to bring a new frame, the reference bit is checked. If reference bit = 0, that page is replaced. Otherwise, the bit is set to 0, the page is left in the memory, and the pointer is incremented.

Example –
Let's say the reference string is **0 4 1 4 2 4 3 4 2 4 0 4 1 4 2 4 3 4** and we have **3** frames. Let's see how the algorithm proceeds by tracking the second chance bit and the pointer.

- Initially, all frames are empty so after first 3 passes they will be filled with {0, 4, 1} and the second chance array will be {0, 0, 0} as none has been referenced yet. Also, the pointer will cycle back to 0.
- **Pass-4:** Frame={0, 4, 1}, second_chance = {0, 1, 0} [4 will get a second chance], pointer = 0 (No page needed to be updated so the candidate is still page in frame 0), pf = 3 (No increase in page fault number).
- **Pass-5:** Frame={2, 4, 1}, second_chance= {0, 1, 0} [0 replaced; it's second chance bit was 0, so it didn't get a second chance], pointer=1 (updated), pf=4
- **Pass-6:** Frame={2, 4, 1}, second_chance={0, 1, 0}, pointer=1, pf=4 (No change)
- **Pass-7:** Frame={2, 4, 3}, second_chance= {0, 0, 0} [4 survived but it's second chance bit became 0], pointer=0 (as element at index 2 was finally replaced), pf=5
- **Pass-8:** Frame={2, 4, 3}, second_chance= {0, 1, 0} [4 referenced again], pointer=0, pf=5
- **Pass-9:** Frame={2, 4, 3}, second_chance= {1, 1, 0} [2 referenced again], pointer=0, pf=5
- **Pass-10:** Frame={2, 4, 3}, second_chance= {1, 1, 0}, pointer=0, pf=5 (no change)
- **Pass-11:** Frame={2, 4, 0}, second_chance= {0, 0, 0}, pointer=0, pf=6 (2 and 4 got second chances)
- **Pass-12:** Frame={2, 4, 0}, second_chance= {0, 1, 0}, pointer=0, pf=6 (4 will again get a second chance)
- **Pass-13:** Frame={1, 4, 0}, second_chance= {0, 1, 0}, pointer=1, pf=7 (pointer updated, pf updated)
- **Page-14:** Frame={1, 4, 0}, second_chance= {0, 1, 0}, pointer=1, pf=7 (No change)
- **Page-15:** Frame={1, 4, 2}, second_chance= {0, 0, 0}, pointer=0, pf=8 (4 survived again due to 2nd chance!)
- **Page-16:** Frame={1, 4, 2}, second_chance= {0, 1, 0}, pointer=0, pf=8 (2nd chance updated)
- **Page-17:** Frame={3, 4, 2}, second_chance= {0, 1, 0}, pointer=1, pf=9 (pointer, pf updated)
- **Page-18:** Frame={3, 4, 2}, second_chance= {0, 1, 0}, pointer=1, pf=9 (No change)

https://www.geeksforgeeks.org/second-chance-or-clock-page-replacement-policy/

In this example, second chance algorithm does as well as the LRU method, which is much more expensive to implement in hardware.

Enhanced Second-Chance Algorithm

- Improve algorithm by using reference bit and modify bit (if available) in concert
- Take ordered pair (reference, modify)

1. (0, 0) neither recently used not modified – best page to replace
2. (0, 1) not recently used but modified – not quite as good, must write out before replacement
3. (1, 0) recently used but clean – probably will be used again soon
4. (1, 1) recently used and modified – probably will be used again soon and need to write out before replacement

- When page replacement called for, use the clock scheme but use the four classes replace page in lowest non-empty class
  - Might need to search circular queue several times

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

- 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) = { 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

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 of time, 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

Working Set Size

- 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

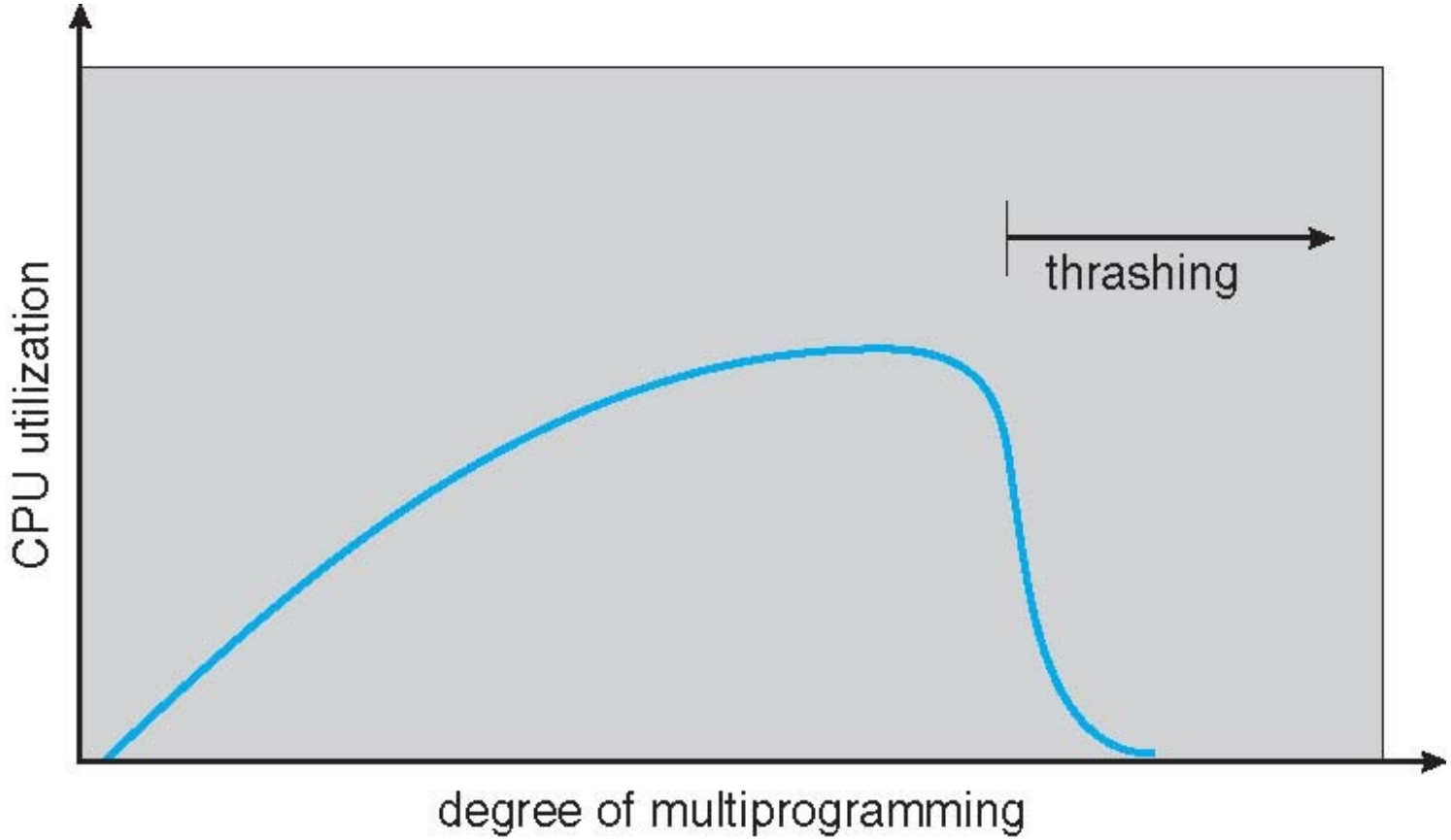
Page Fault Frequency (PFF)

- PFF is 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
    - Should fault more
    - But not always
- Hard to use PFF to distinguish between changes in locality and changes in size of working set

Thrashing ≡ a process is busy swapping pages in and out

- If a process does not have “enough” pages, the page-fault rate is very high
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
  - This leads to:
    - Low CPU utilization (No time spent doing useful work)
    - Operating system thinking that it needs to increase the degree of multiprogramming -> Another process added to the system (In this situation, the system is overcommitted)
  - Possible solutions
    - Swapping – write out all pages of a process
    - Buy more memory

Thrashing (Cont.)



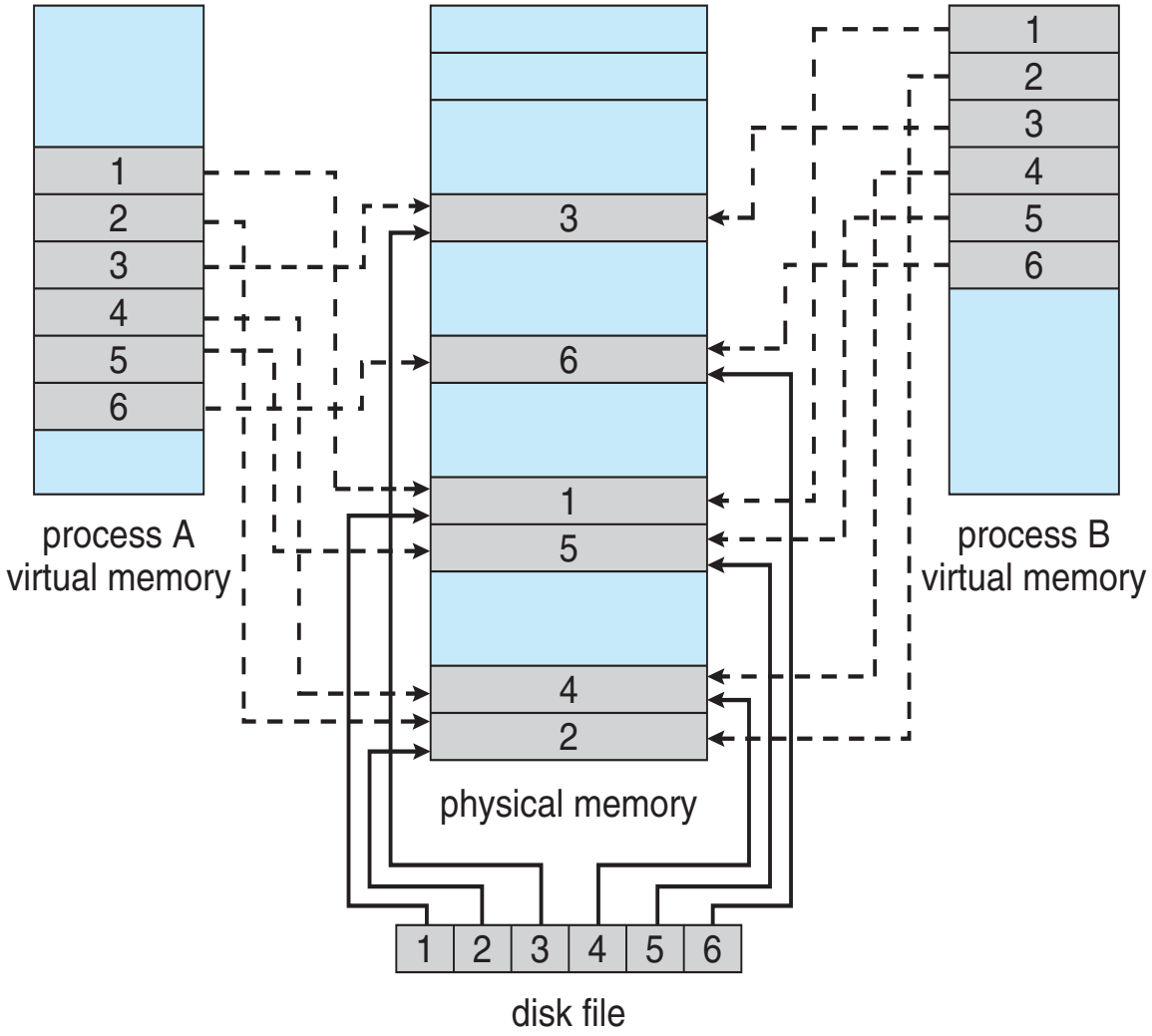
Summary

- 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

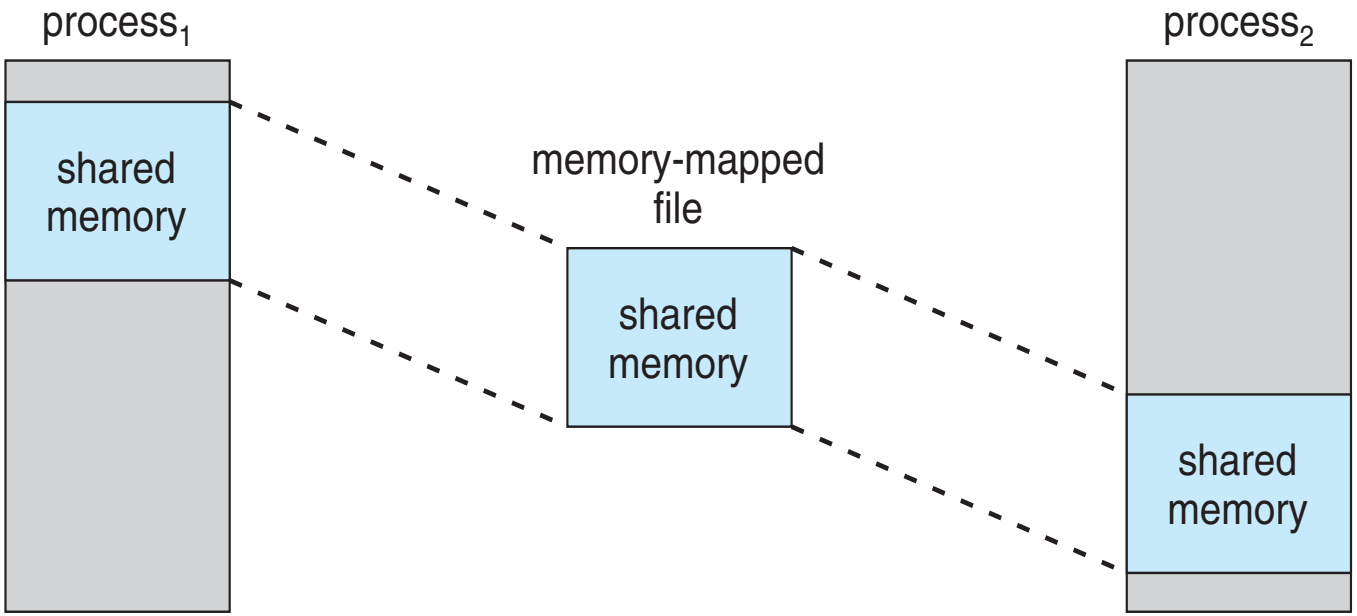
Memory-Mapped Files

- 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
- Also allows several processes to map the same file allowing the pages in memory to be shared
- 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
  - But when does written data make it to disk?
    - Periodically and / or at file `close()` time
    - For example, when the pager scans for dirty pages

Memory Mapped Files



Shared Memory via Memory-Mapped I/O



Other Issues – Page Size

- Sometimes OS designers have a choice
  - Especially if running on custom-built CPU
- Page size selection must take into consideration:
  - Fragmentation
  - Page table size
  - Resolution
  - I/O overhead
  - Number of page faults
  - Locality
  - TLB size and effectiveness
- Always power of 2, usually in the range 2^{12} (4,096 bytes) to 2^{22} (4,194,304 bytes)
- On average, growing over time

Other Issues – TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
- TLB Reach = (TLB Size) X (Page Size)
- Ideally, the working set of each process is stored in the TLB
  - Otherwise there is a high degree of page faults
- Increase the Page Size
  - This may lead to an increase in fragmentation as not all applications require a large page size
- Provide Multiple Page Sizes
  - This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation

Other Issues – Program Structure

- Program structure
  - `int[128,128] data;`
  - Each row is stored in one page
  - Program 1

```
for (j = 0; j <128; j++)
    for (i = 0; i < 128; i++)
        data[i,j] = 0;
```

128 x 128 = 16,384 page faults

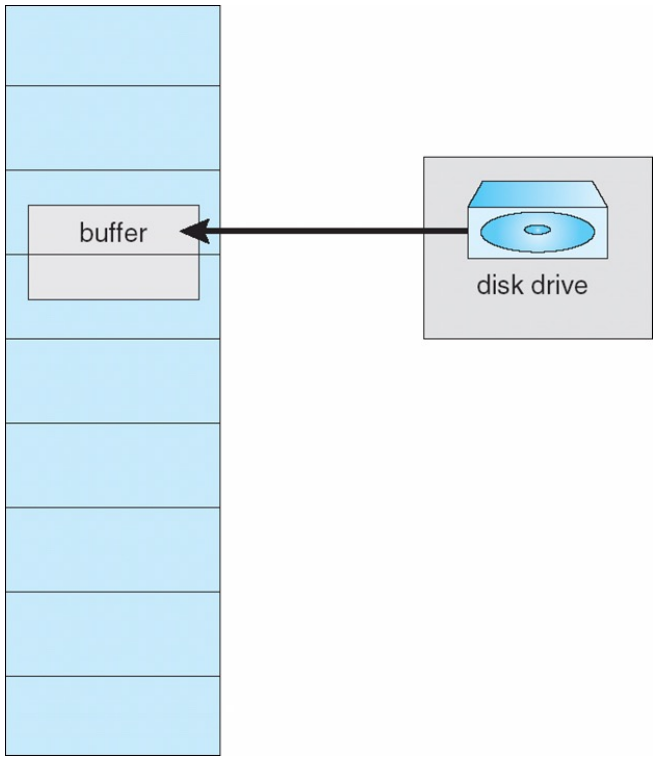
  - Program 2

```
for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i,j] = 0;
```

128 page faults

Other Issues – I/O interlock

- **I/O Interlock** – Pages must sometimes be locked into memory
- Consider I/O - Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm
- **Pinning** of pages to lock into memory



End of Chapter 10