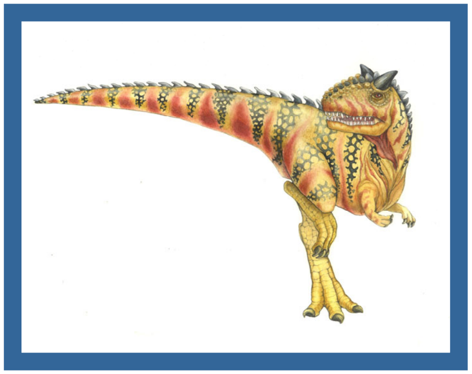
Operating System Concepts

Tenth Edition

Silberschatz, Galvin and Gagne

Chapter 10

Virtual Memory



Chapter 10: Virtual Memory

- Background
- Demand Paging
- Page Replacement
- Allocation of Frames
- Thrashing
- Operating-System Examples

Chapter 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

Chapter 10: Background [1]

- 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

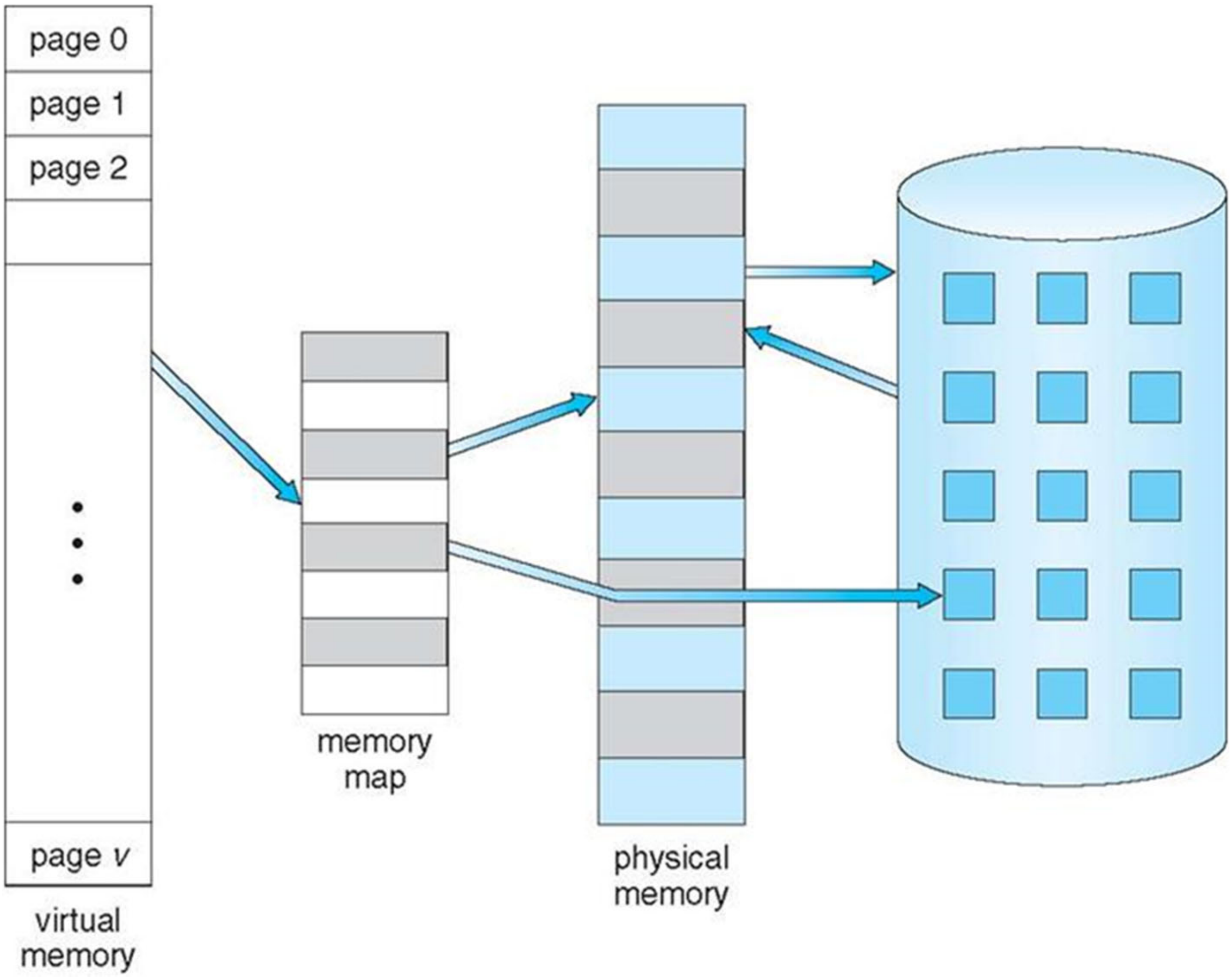
Chapter 10: Background [2]

- **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

Chapter 10: Background [3]

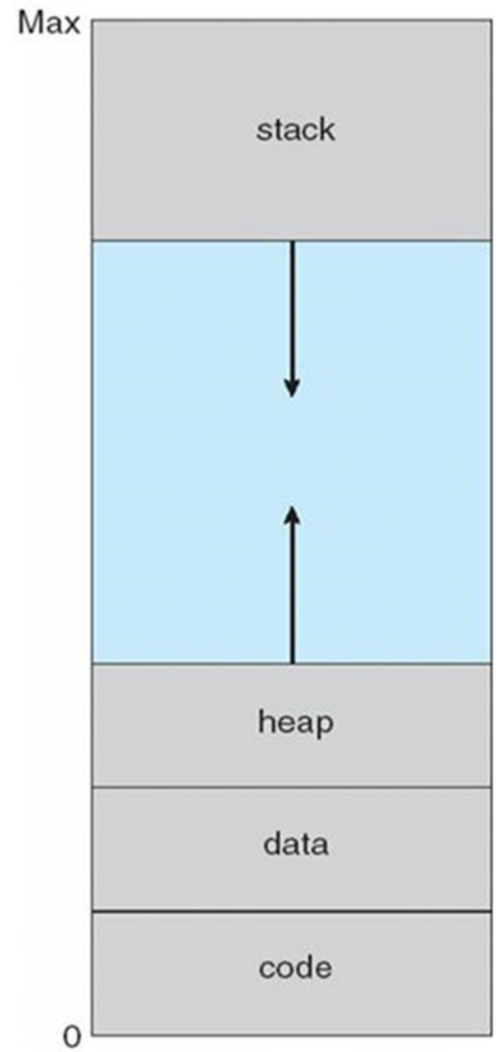
- **Virtual address space** – logical view of how process is stored in memory
  - Usually start at address 0, contiguous addresses until end of space
  - Meanwhile, physical memory organized in page frames
  - MMU must map logical to physical
- Virtual memory can be implemented via:
  - Demand paging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

Virtual Memory That is Larger Than Physical Memory



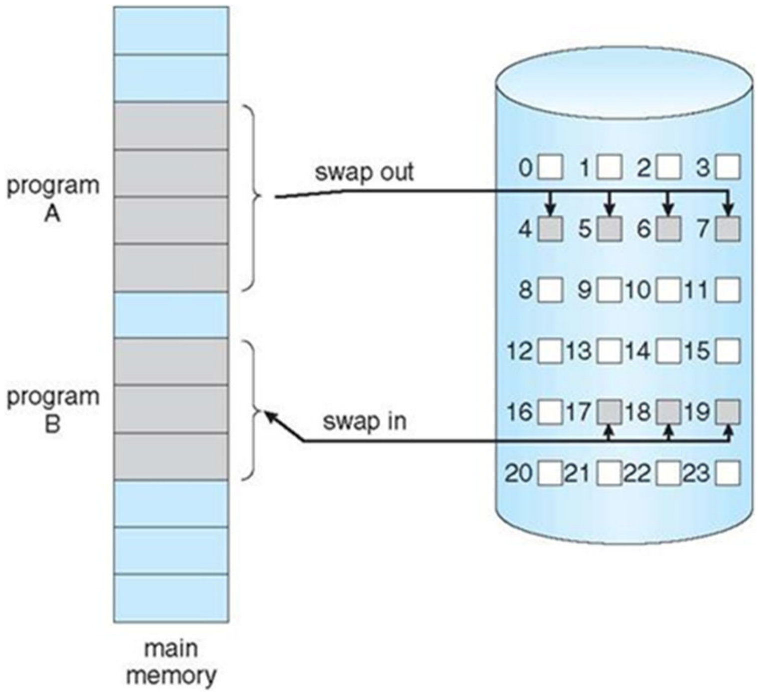
Virtual-address Space

- 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



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
- **Lazy swapper** – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a **pager**

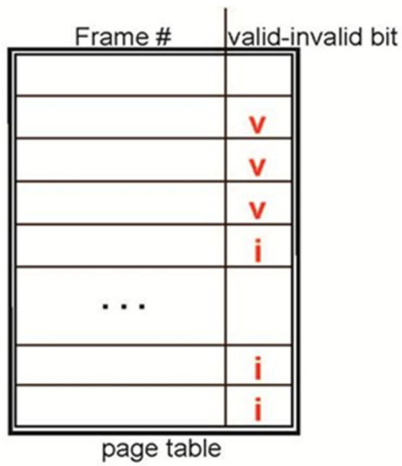


Basic Concepts

- With swapping, pager guesses which pages will be used before swapping out again
- Instead, pager brings in only those pages into memory
- How to determine that set of pages?
  - Need new MMU functionality to implement demand paging
- If pages needed are already **memory resident**
  - No difference from non demand-paging
- If page needed and not memory resident
  - Need to detect and load the page into memory from storage
    - Without changing program behavior
    - Without programmer needing to change code

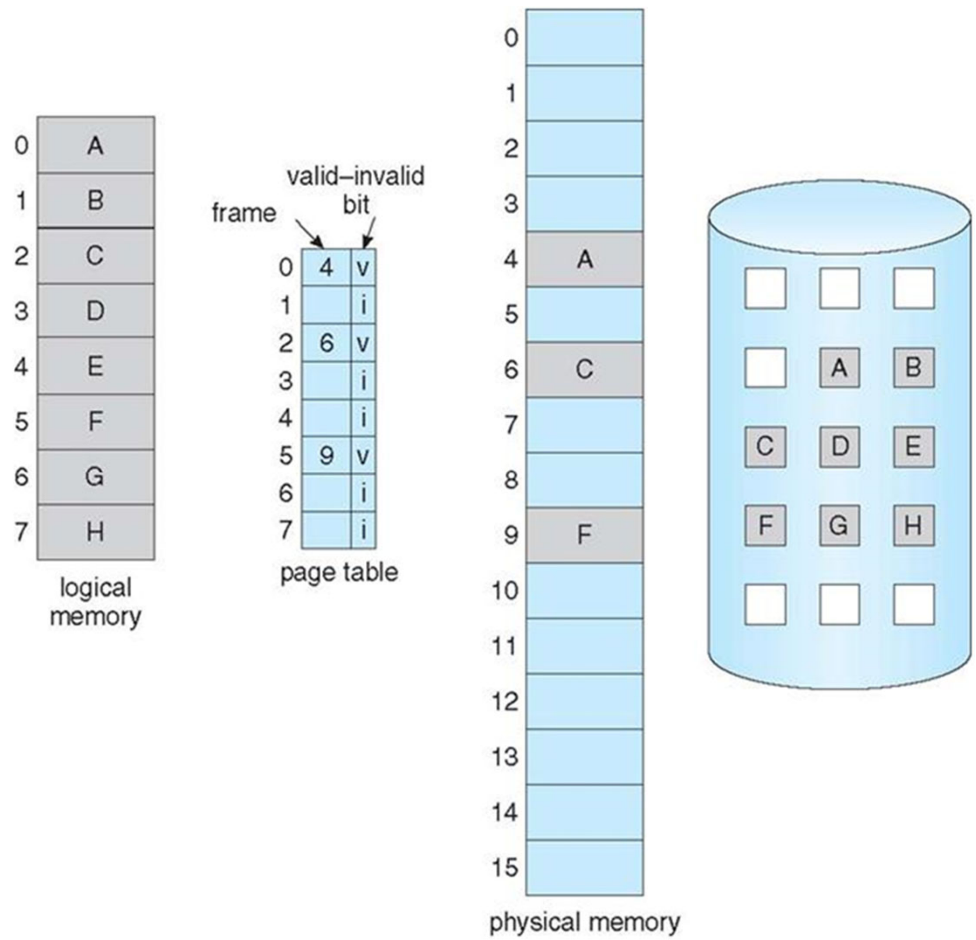
Valid-Invalid Bit

- 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



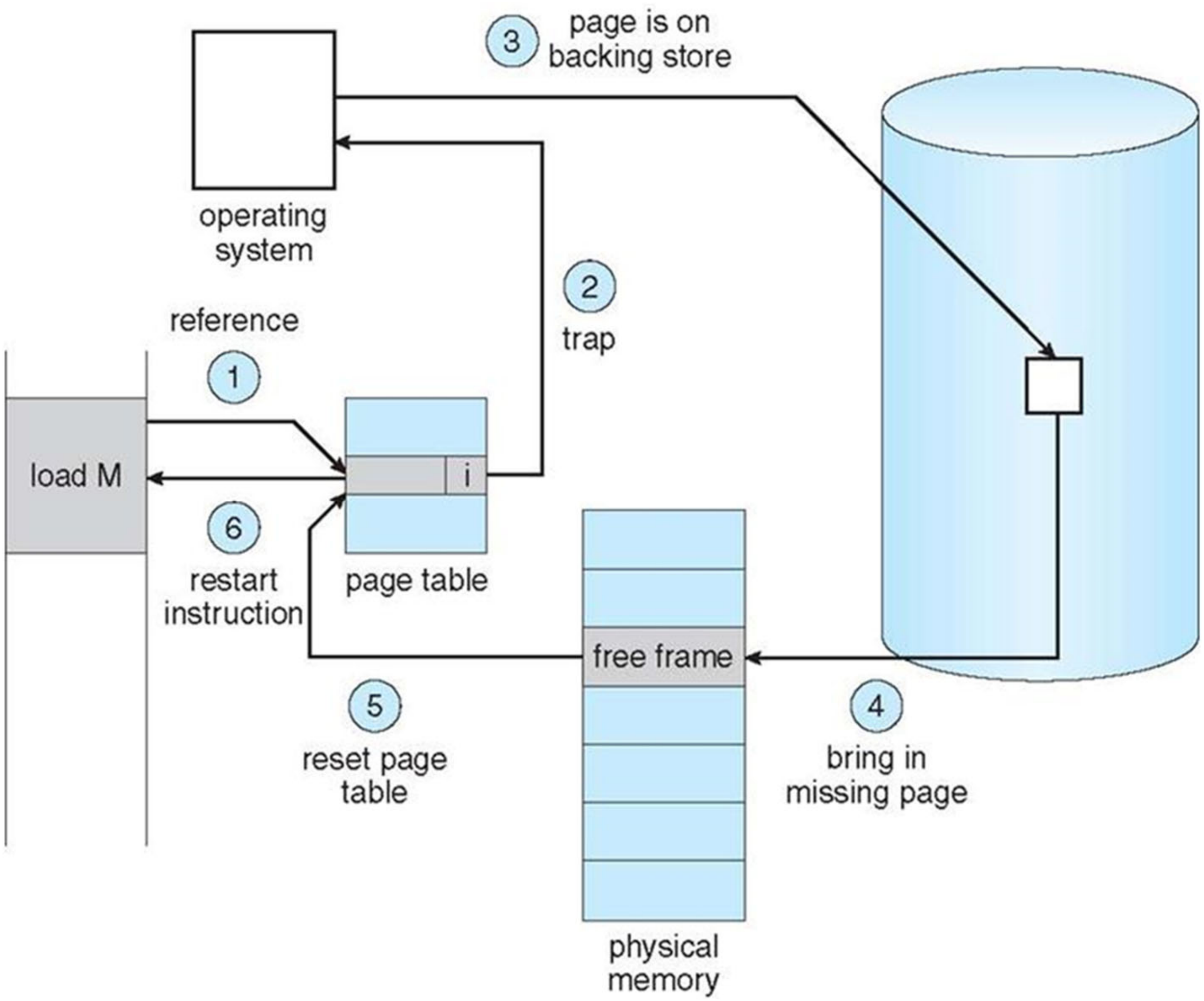
Page Fault

- 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 $\Rightarrow$ 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

Steps in Handling a Page Fault



Aspects of Demand Paging 1

- 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**

Aspects of Demand Paging 2

- Hardware support needed for demand paging
  - Page table with valid / invalid bit
  - Secondary memory (swap device with **swap space**)
  - Instruction restart

Performance of Demand Paging [1]

- 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

Performance of Demand Paging [2]

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 [3]

- 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

Performance of Demand Paging 4

- <u>Effective Access Time (EAT)</u>

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

Demand Paging Example 1

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- $$\begin{aligned} \text{EAT} &= (1-p) \times 200 + p(8 \text{ milliseconds}) \\ &= (1-p) \times 200 + p \times 8{,}000{,}000 \\ &= 200 + p \times 7{,}999{,}800 \end{aligned}$$
- 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!!

Demand Paging Example 2

- If want performance degradation < 10 percent
  - $220 > 200 + 7{,}999{,}800 \times p$

    $20 > 7{,}999{,}800 \times p$
  - $p < .0000025$
  - < one page fault in every 400,000 memory accesses

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

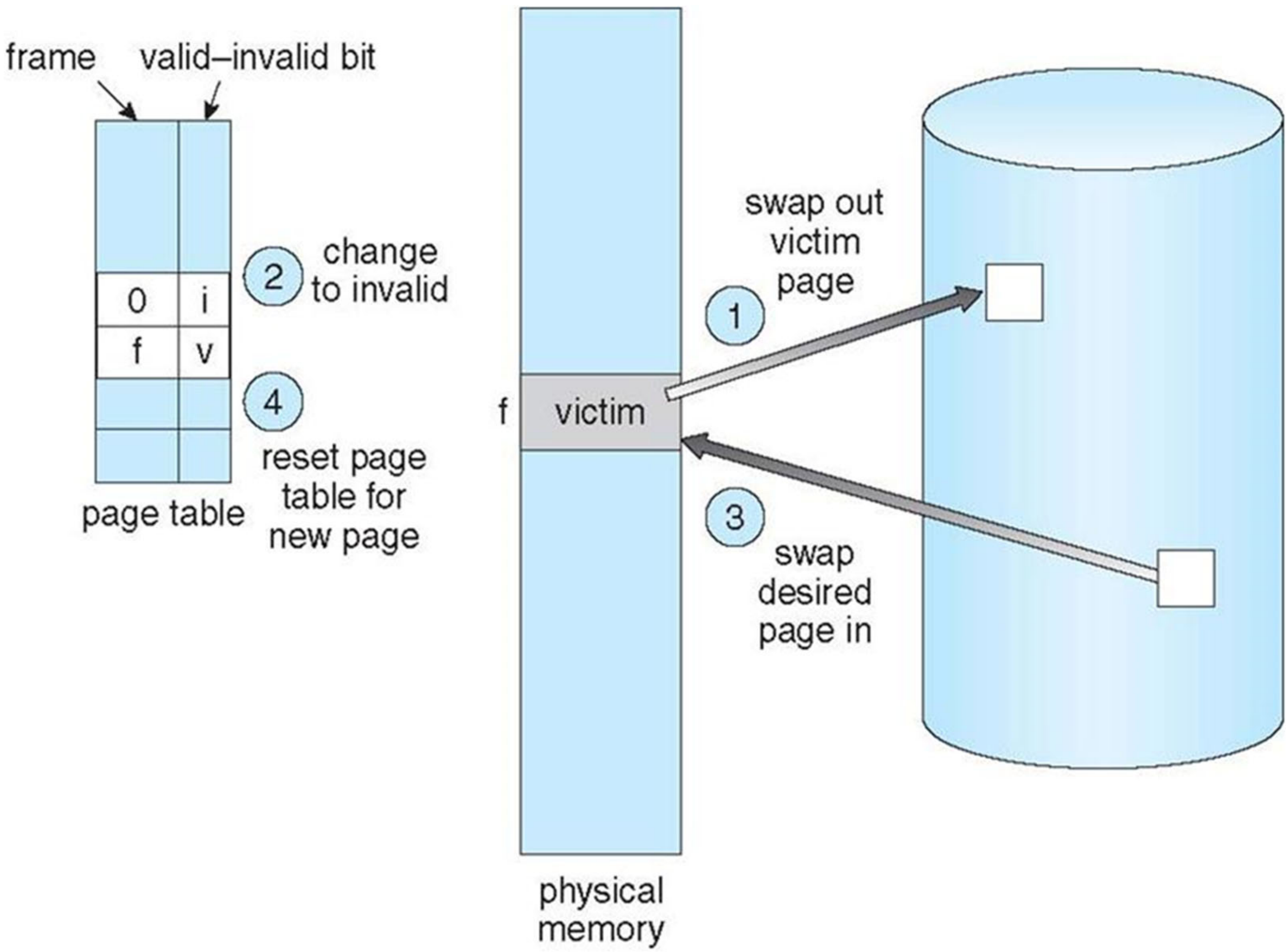
- Prevent **over-allocation** of memory by modifying page-fault service routine to include page replacement
- Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk
- Page replacement completes separation between logical memory and physical memory –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

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 2



Page and Frame Replacement Algorithms [1]

- **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

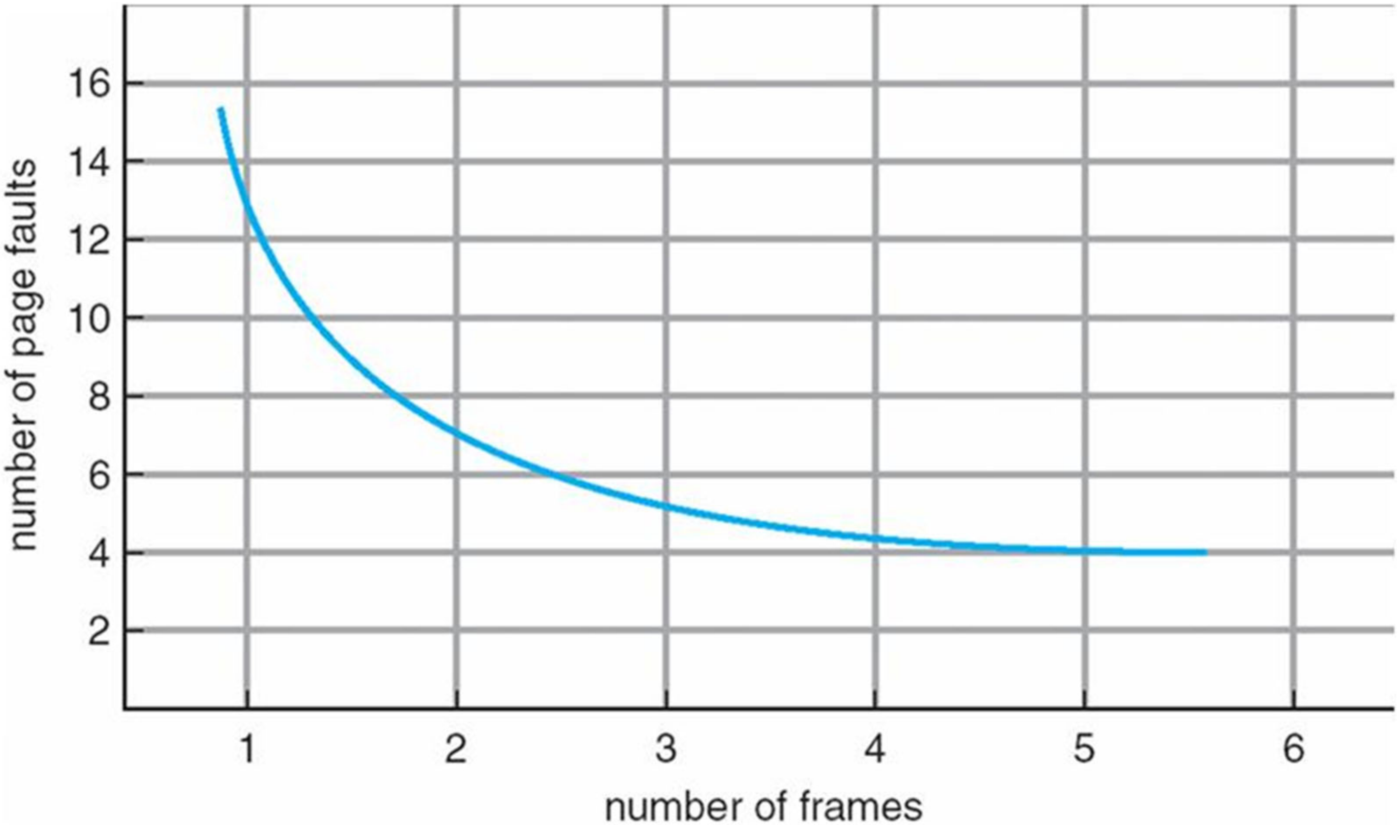
Page and Frame Replacement Algorithms 2

- 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

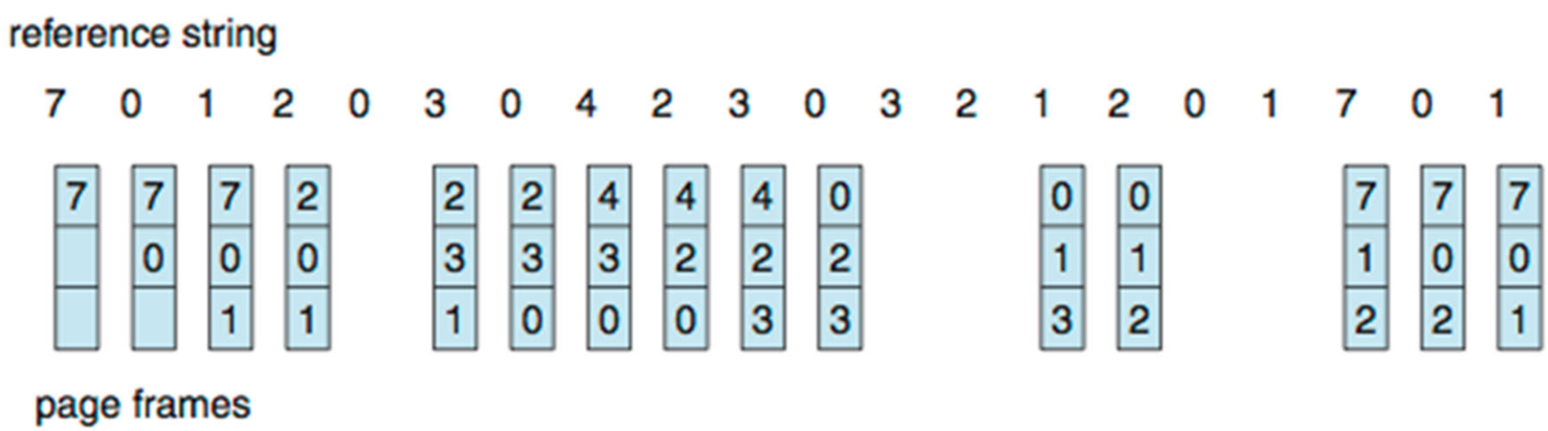
7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1

Graph of Page Faults Versus The Number of Frames



First-In-First-Out (FIFO) Algorithm 1

- 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)

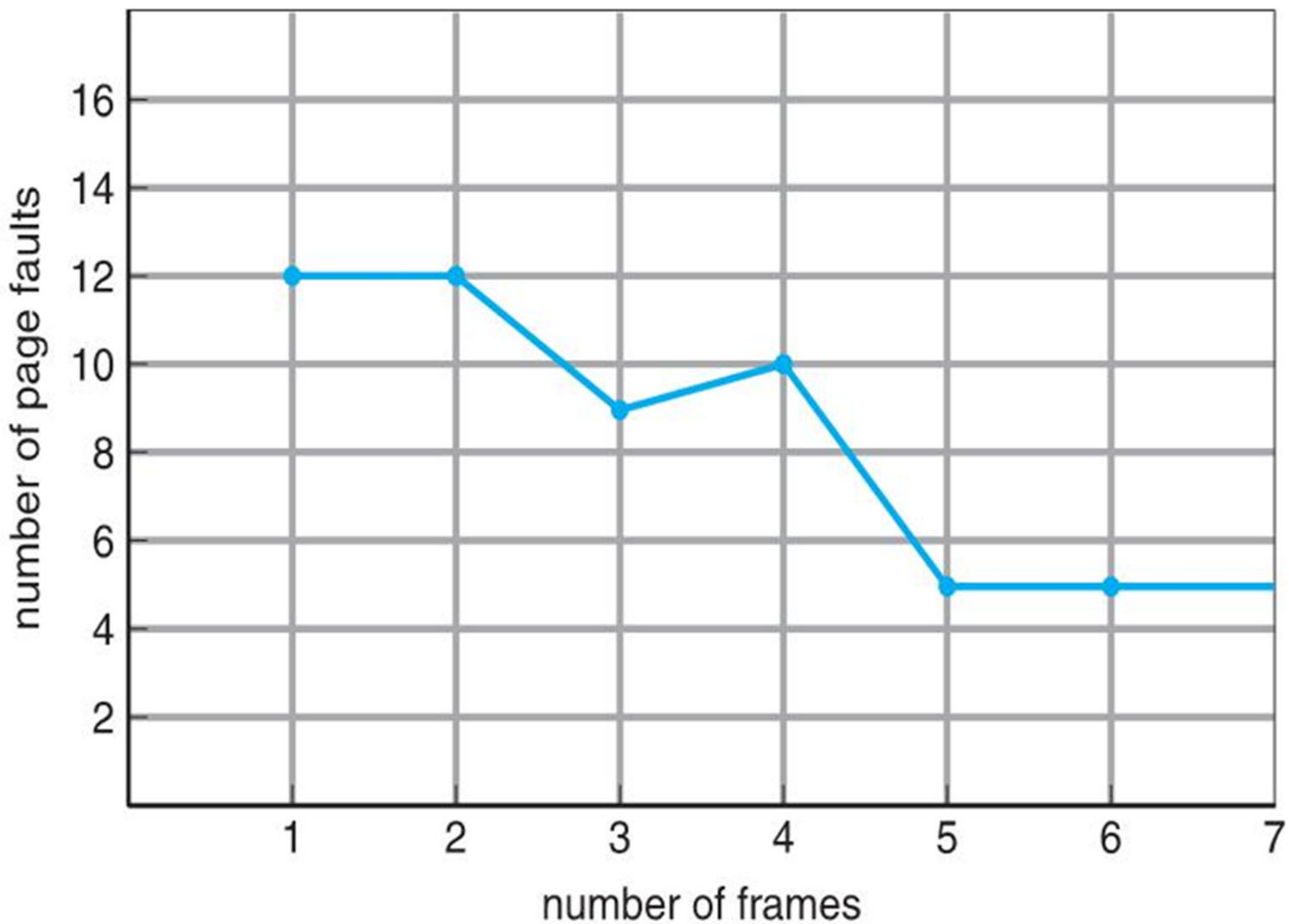


First-In-First-Out (FIFO) Algorithm [2]

15 page faults

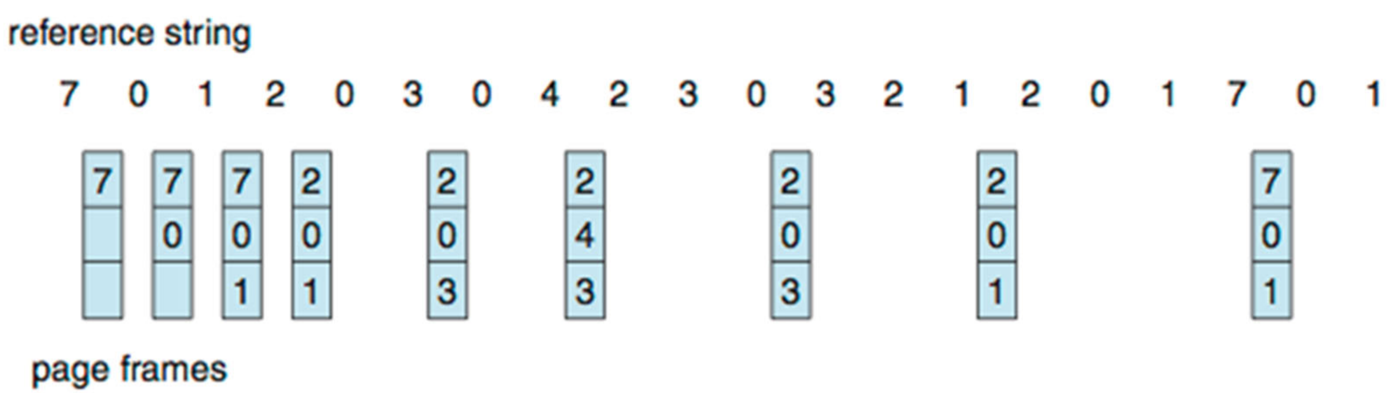
- Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5
  - Adding more frames can cause more page faults!
    - **Belady's Anomaly**
- How to track ages of pages?
  - Just use a FIFO queue

FIFO Illustrating Belady's Anomaly



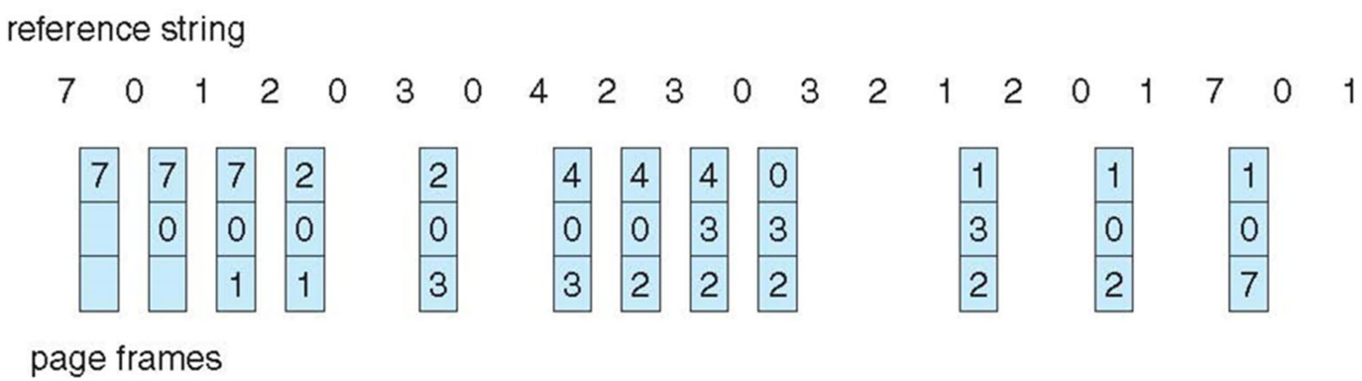
Optimal Algorithm

- 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



Least Recently Used (LRU) Algorithm [1]

- Use past knowledge rather than future
- <u>Replace page that has not been used in the most amount of time</u>
- 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?

Least Recently Used (LRU) Algorithm 2

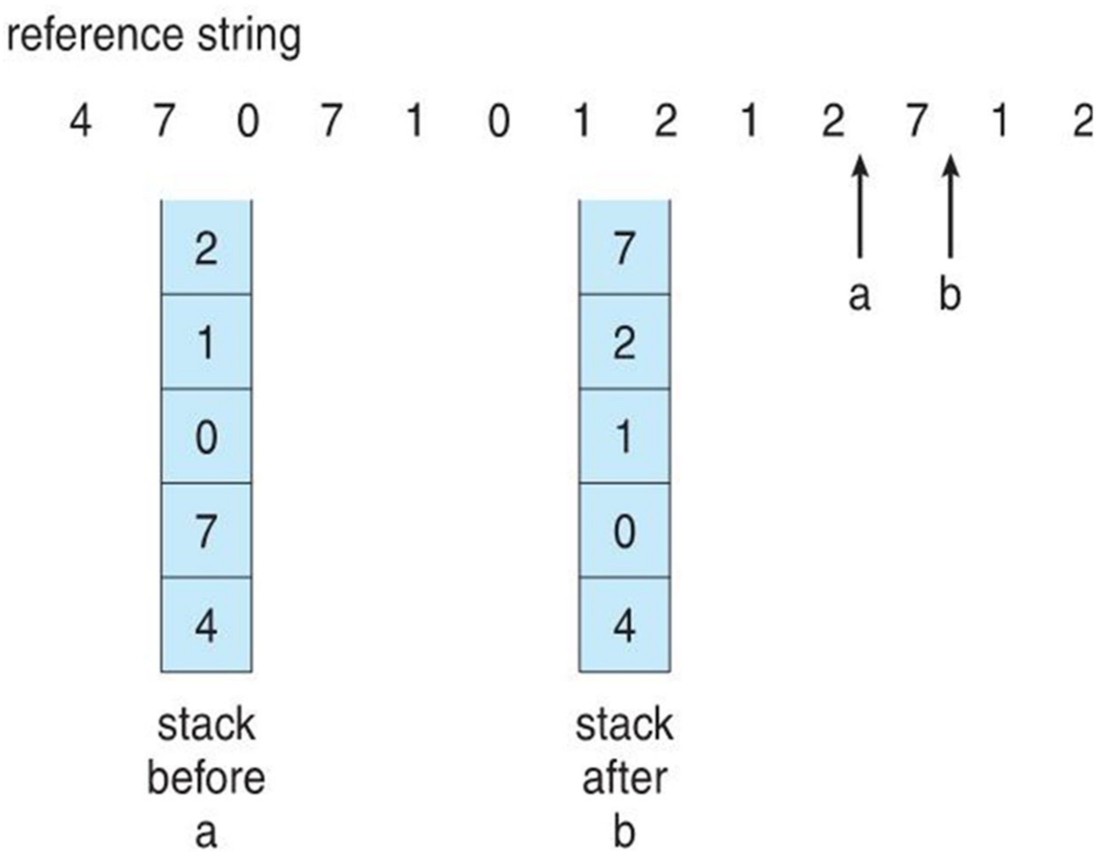
- Counter implementation
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter
  - When a page needs to be changed, look at the counters to find smallest value
    - Search through table needed
- Stack implementation
  - Keep a stack of page numbers in a double link form:
  - Page referenced:

Least Recently Used (LRU) Algorithm 3

  - 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



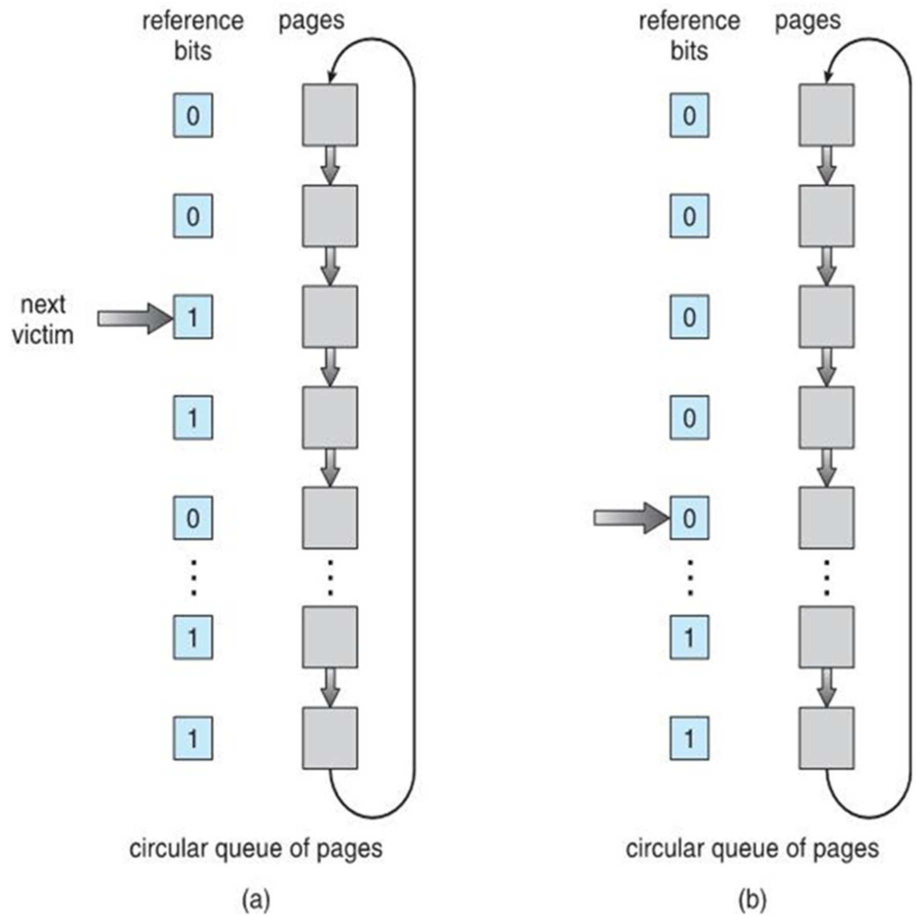
LRU Approximation Algorithms [1]

- LRU needs special hardware and still slow
- **Reference bit**
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - 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

LRU Approximation Algorithms [2]

- **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



Allocation of Frames

- Each process needs *minimum* number of frames
- Example: IBM 370 – 6 pages to handle SS MOVE instruction:
  - instruction is 6 bytes, might span 2 pages
  - 2 pages to handle *from*
  - 2 pages to handle *to*
- *Maximum* of course is total frames in the system
- Two major allocation schemes
  - fixed allocation
  - priority allocation
- Many variations

Fixed Allocation

- Equal allocation – For example, if there are 100 frames (after allocating frames for the OS) and 5 processes, give each process 20 frames
  - Keep some as free frame buffer pool
- Proportional allocation – Allocate according to the size of process
  - Dynamic as degree of multiprogramming, process sizes change

$-s_i = \text{ size of process } p_i$

$-S = \sum s_i$

$-m = \text{ total number of frames}$

$-a_i = \text{ allocation for } p_i = \frac{s_i}{S} \times m$

$$m = 64$$
$$s_1 = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 64 \approx 5$$
$$a_2 = \frac{127}{137} \times 64 \approx 59$$

Priority Allocation

- Use a proportional allocation scheme using priorities rather than size
- If process P_i generates a page fault,
  - select for replacement one of its frames
  - select for replacement a frame from a process with lower priority number

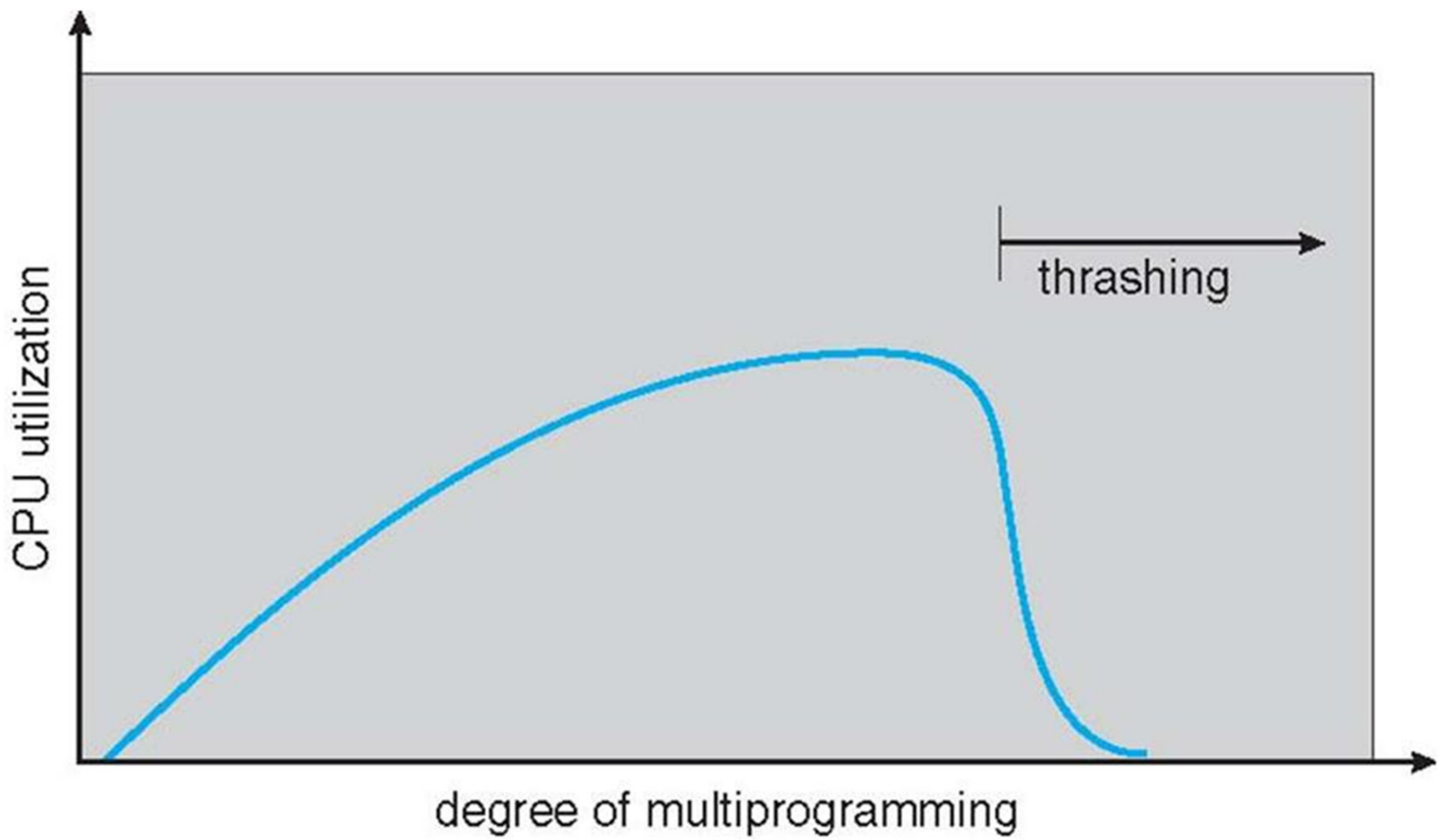
Global vs. Local Allocation

- **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 [1]

- 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
    - Operating system thinking that it needs to increase the degree of multiprogramming
    - Another process added to the system
- **Thrashing** ≡ a process is busy swapping pages in and out

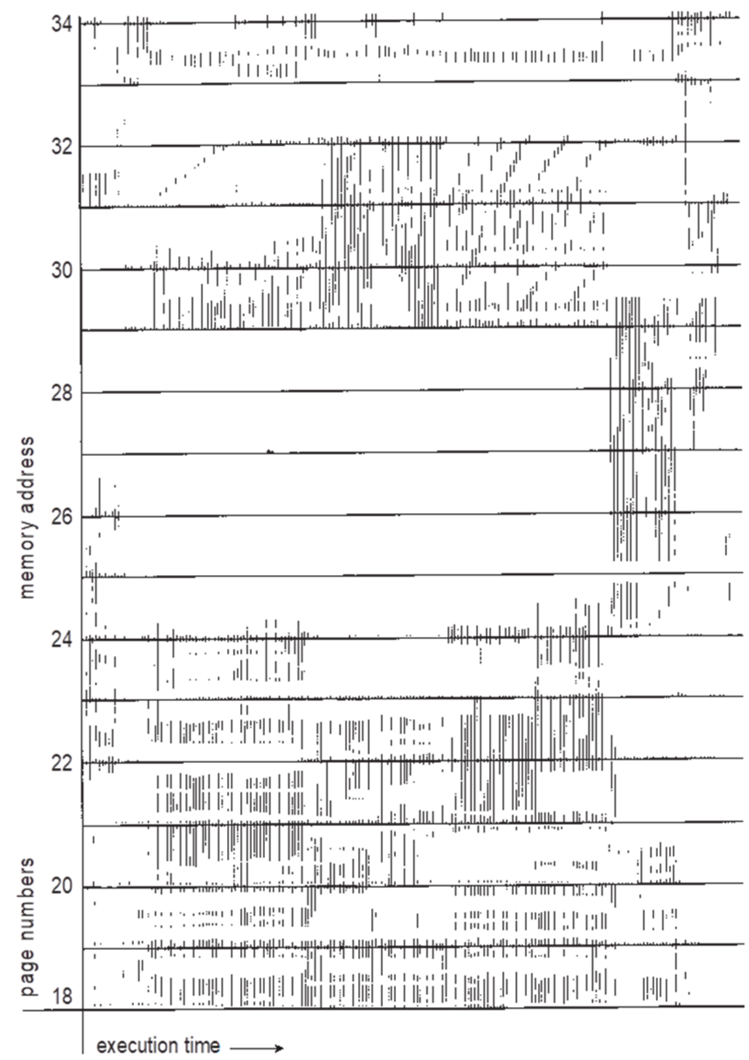
Thrashing 2



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

Locality In A Memory-Reference Pattern

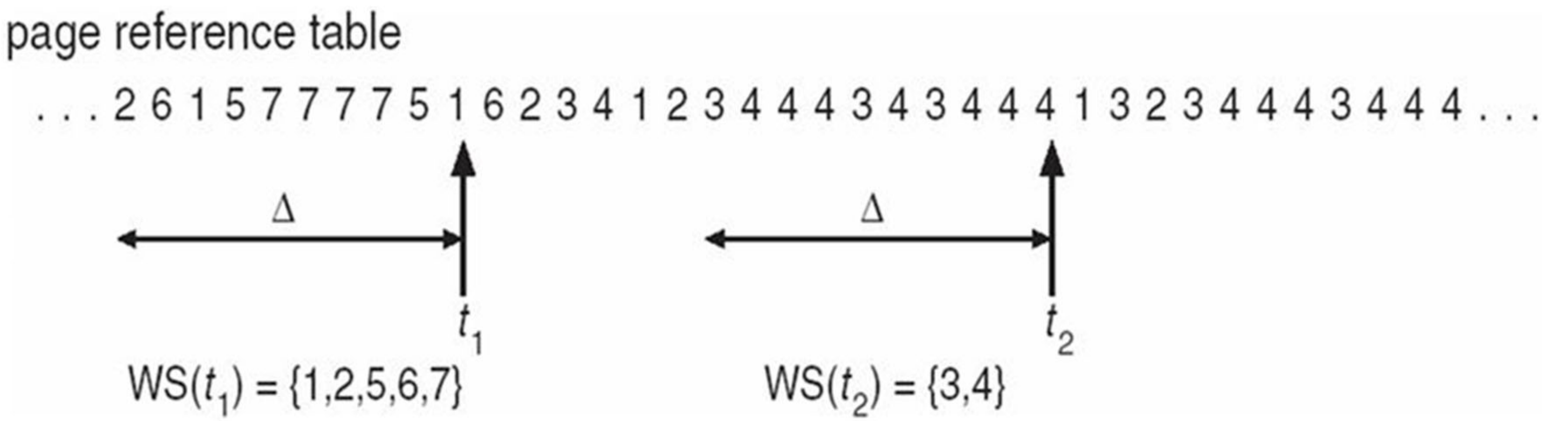


Working-Set Model 1

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  Example: 10,000 instructions
- WSS_i (working set of Process P_i) =
  total number of pages referenced in the most recent Δ (varies in time)
  - if Δ too small will not encompass entire locality
  - if Δ too large will encompass several localities
  - if $\Delta = \infty \Rightarrow$ will encompass entire program

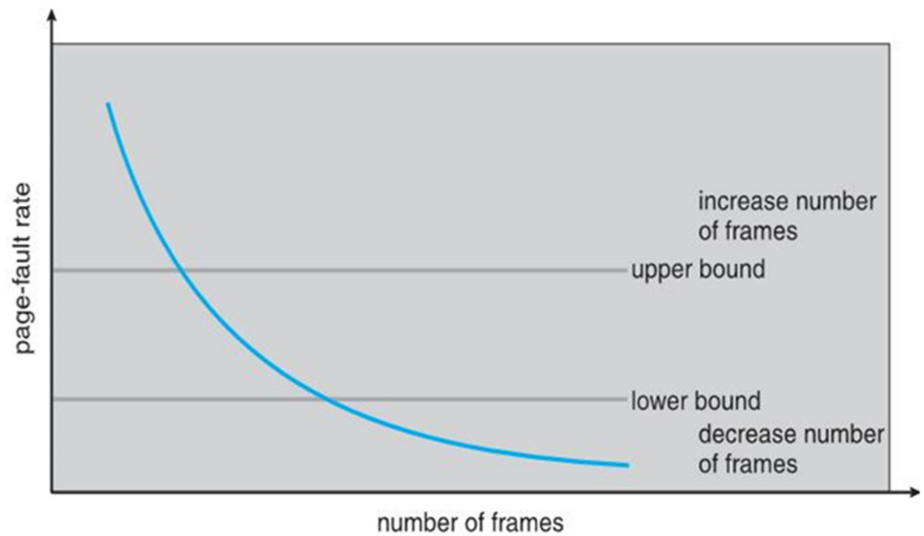
Working-Set Model (Cont.)

- $D = \Sigma\ WSS_i \equiv$ total demand frames
  - Approximation of locality
- if $D > m \Rightarrow$ Thrashing
- Policy if D > m, then suspend or swap out one of the processes



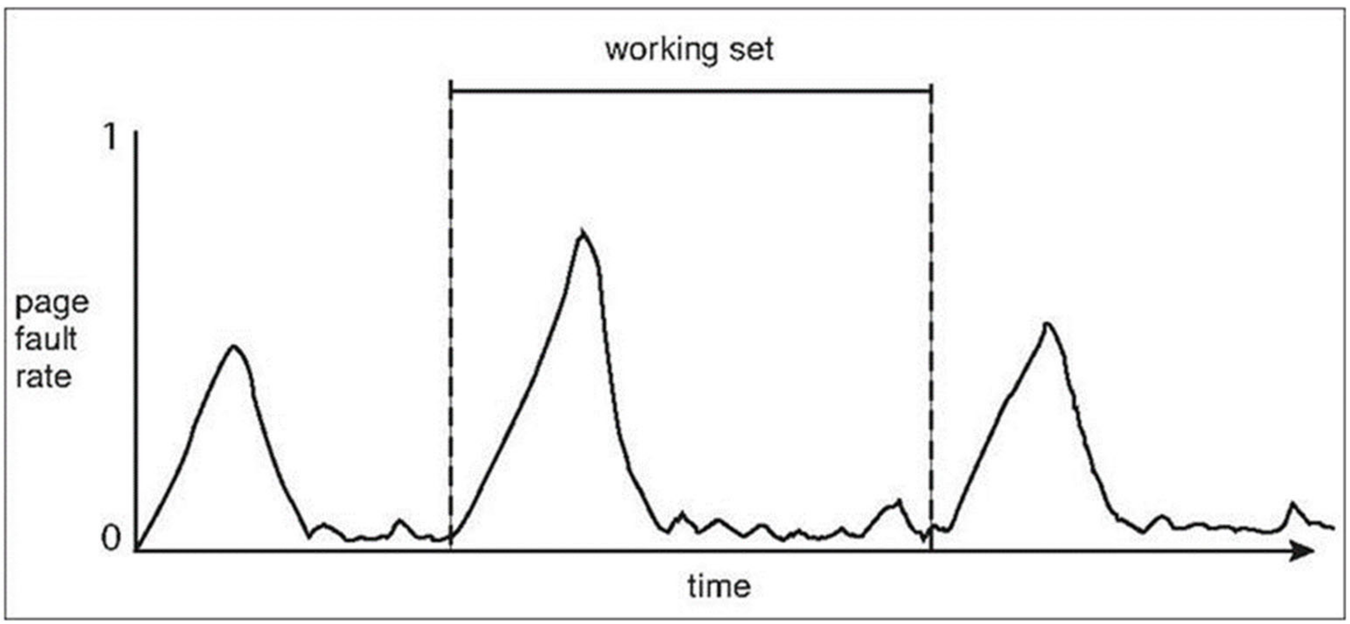
Page-Fault Frequency

- More direct approach than WSS
- Establish "acceptable" **page-fault frequency** (**PFF**) rate and use local replacement policy
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame



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



Windows

- Uses demand paging with **clustering**. Clustering brings in pages surrounding the faulting page
- Processes are assigned **working set minimum** and **working set maximum**
- Working set minimum is the minimum number of pages the process is guaranteed to have in memory
- A process may be assigned as many pages up to its working set maximum
- When the amount of free memory in the system falls below a threshold, **automatic working set trimming** is performed to restore the amount of free memory
- Working set trimming removes pages from processes that have pages in excess of their working set minimum

Multiple-Choice Question [1]

- In demand paging,

  A) a page loaded in memory may never be accessed.

  B) all pages that a program will access during execution are loaded in memory in the beginning.

  C) a page is loaded in memory only when it is needed during execution.

  D) a page is loaded in memory just before it is needed.

Multiple-Choice Question 2

- The dirty (modify) bit identifies

A) a page that has been corrupted.

B) a page that needs to be reloaded when accessed.

C) a page that is shared by multiple processes.

D) a page that has been modified since it was loaded.

Multiple-Choice Question 3

- Given the reference string of page accesses: 1 2 3 4 2 3 4 1 2 1 1 3 1 3 and a system with three page frames, what is the final configuration of the three frames after the OPT algorithm is applied?

A) 1, 3, 4

B) 1, 2, 3

C) 2, 3, 4

D) 1, 2, 1

Essay Questions

- Explain the distinction between a demand-paging system and a paging system with swapping.

- How is the effective access time computed for a demand-paged memory system?

- Why doesn't a local replacement algorithm solve the problem of thrashing entirely?