Virtual Memory

Chapter 9

Objectives

- To describe the benefits of a virtual memory system
- To explain the concepts of:
  - demand paging
  - page-replacement algorithms
  - allocation of page frames
- To discuss the principle of the working-set model

Chapter Outline

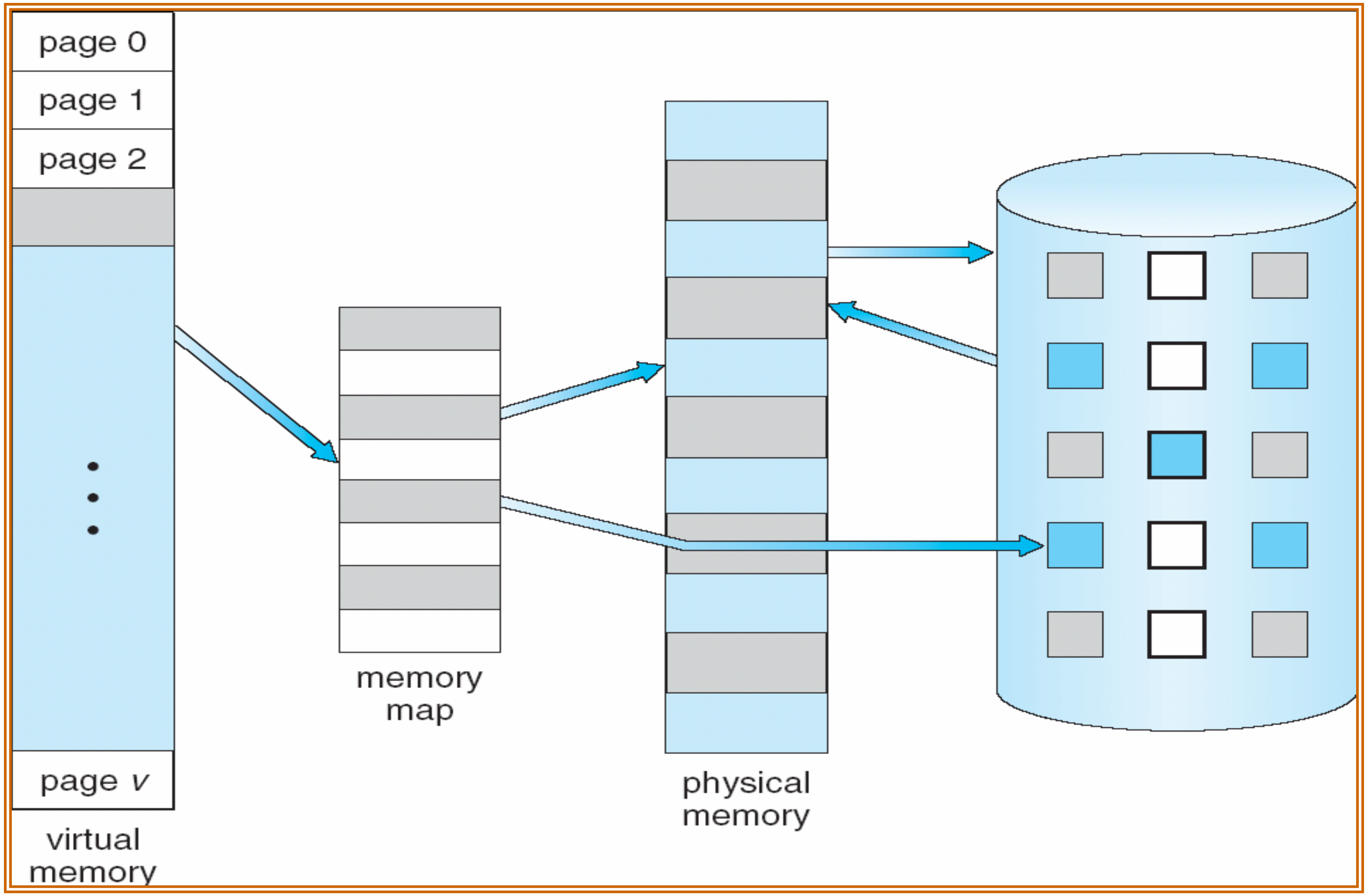
- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Allocation of Frames
- Thrashing

- Background

- **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

- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation (Skip)

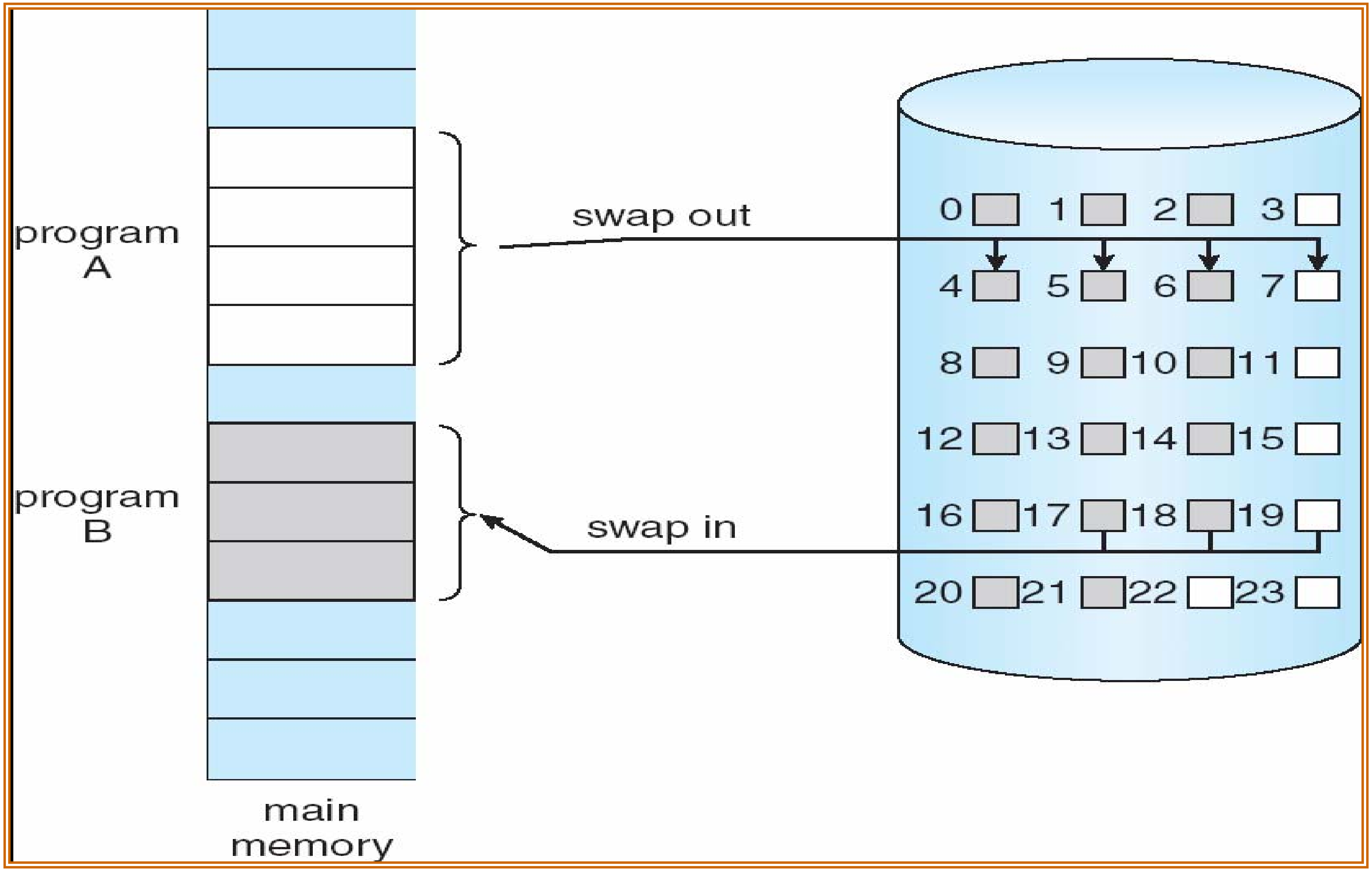
--Virtual Memory That is Larger Than Physical Memory



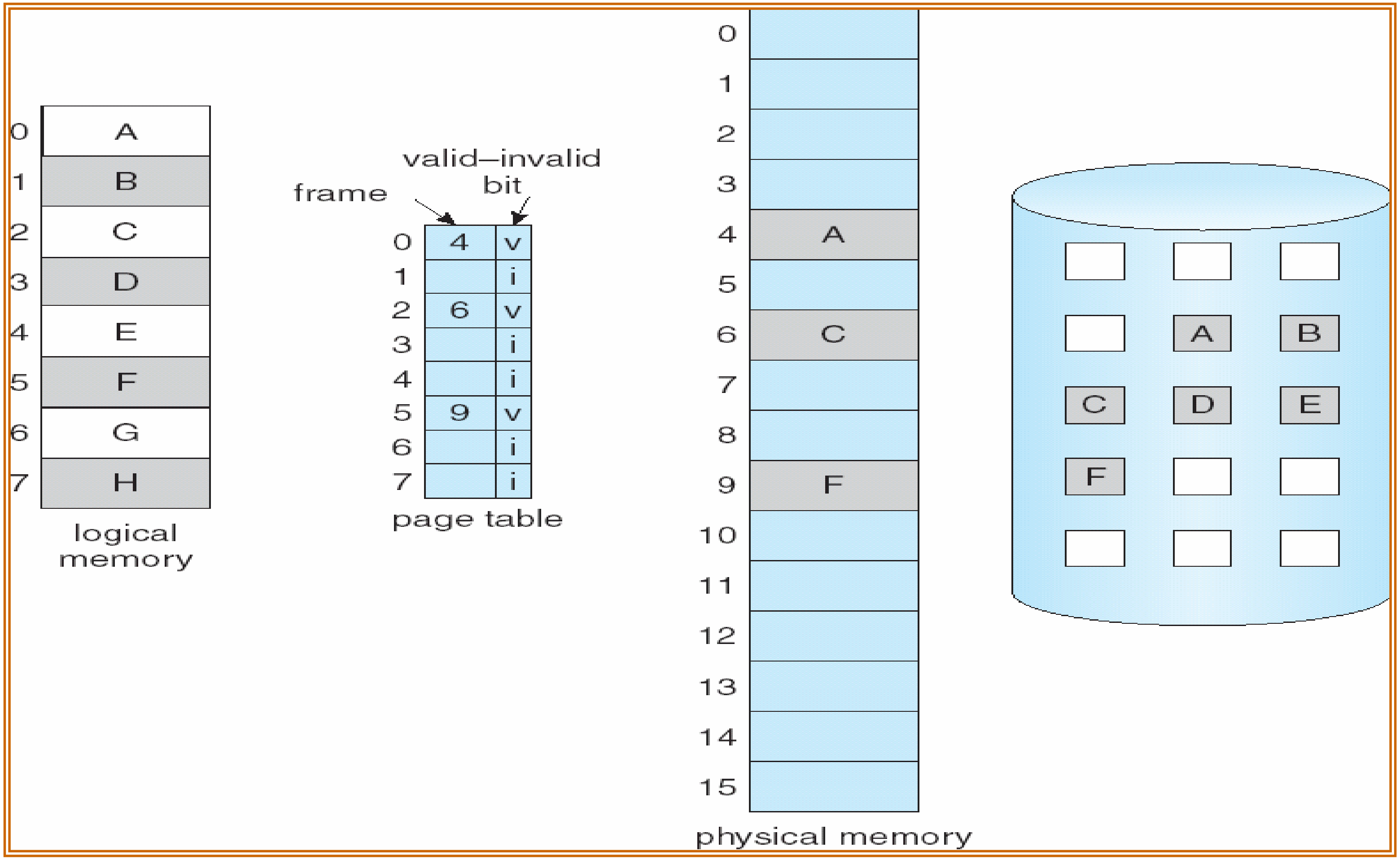
- Demand Paging

- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed $\Rightarrow$ reference to it
  - invalid reference $\Rightarrow$ abort
  - not-in-memory $\Rightarrow$ bring to memory
- **Lazy swapper** – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a **pager**

-- Transfer of a Paged Memory to Contiguous Disk Space



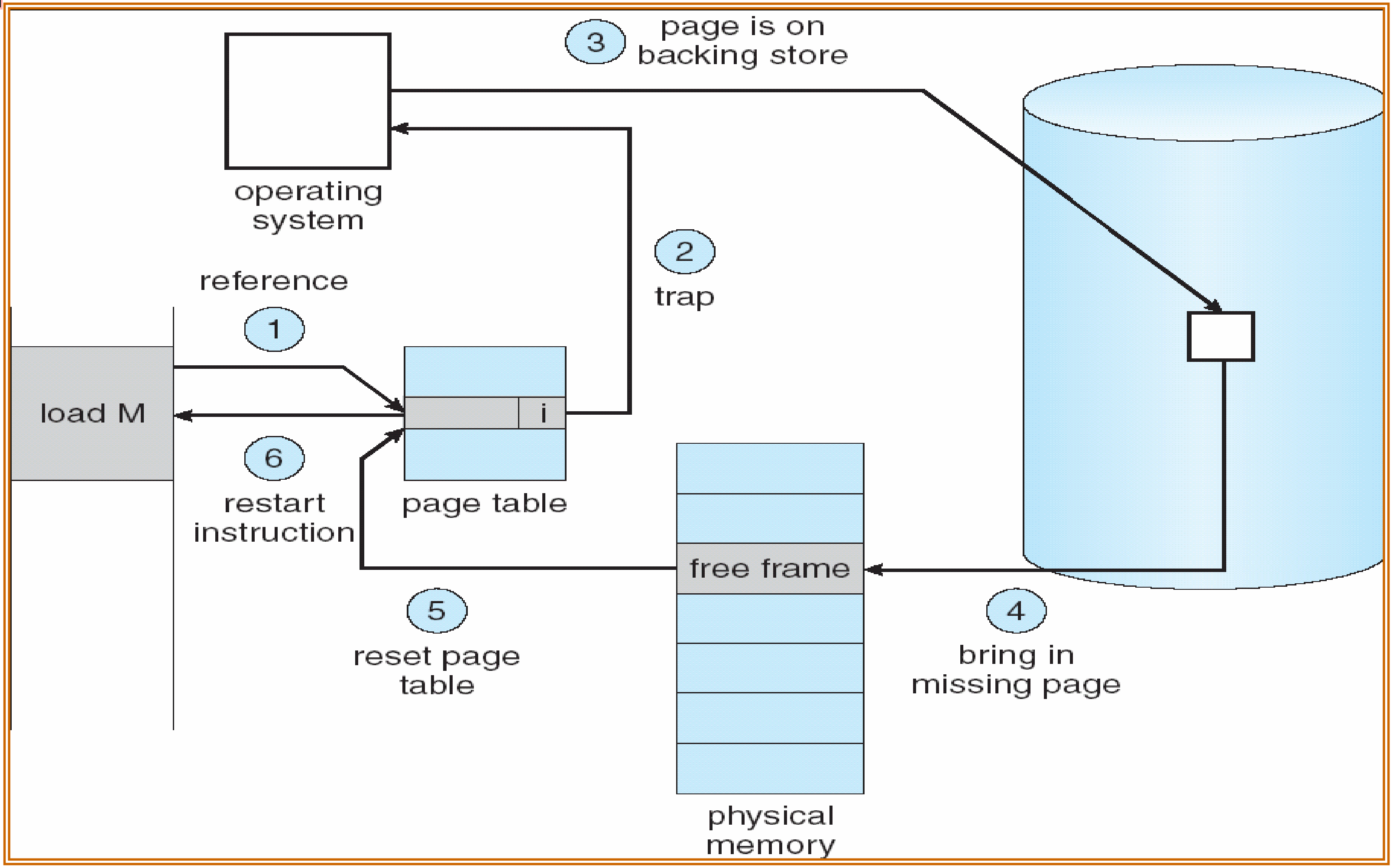
-- Page Table When Some Pages Are Not in Main Memory



-- Page Fault

1. Operating system looks at another table to decide:
   - Invalid reference ⇒ abort
   - Just not in memory
2. Get empty frame
3. Swap page into frame
4. Reset tables
5. Set validation bit = **v**
6. Restart the instruction that caused the page fault

-- Steps in Handling a Page Fault



-- Performance of Demand Paging

- Page Fault Rate $0 \leq p \leq 1.0$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault
- Effective Access Time (EAT)

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

-- 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 + 7,999,800 X p
- 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!!

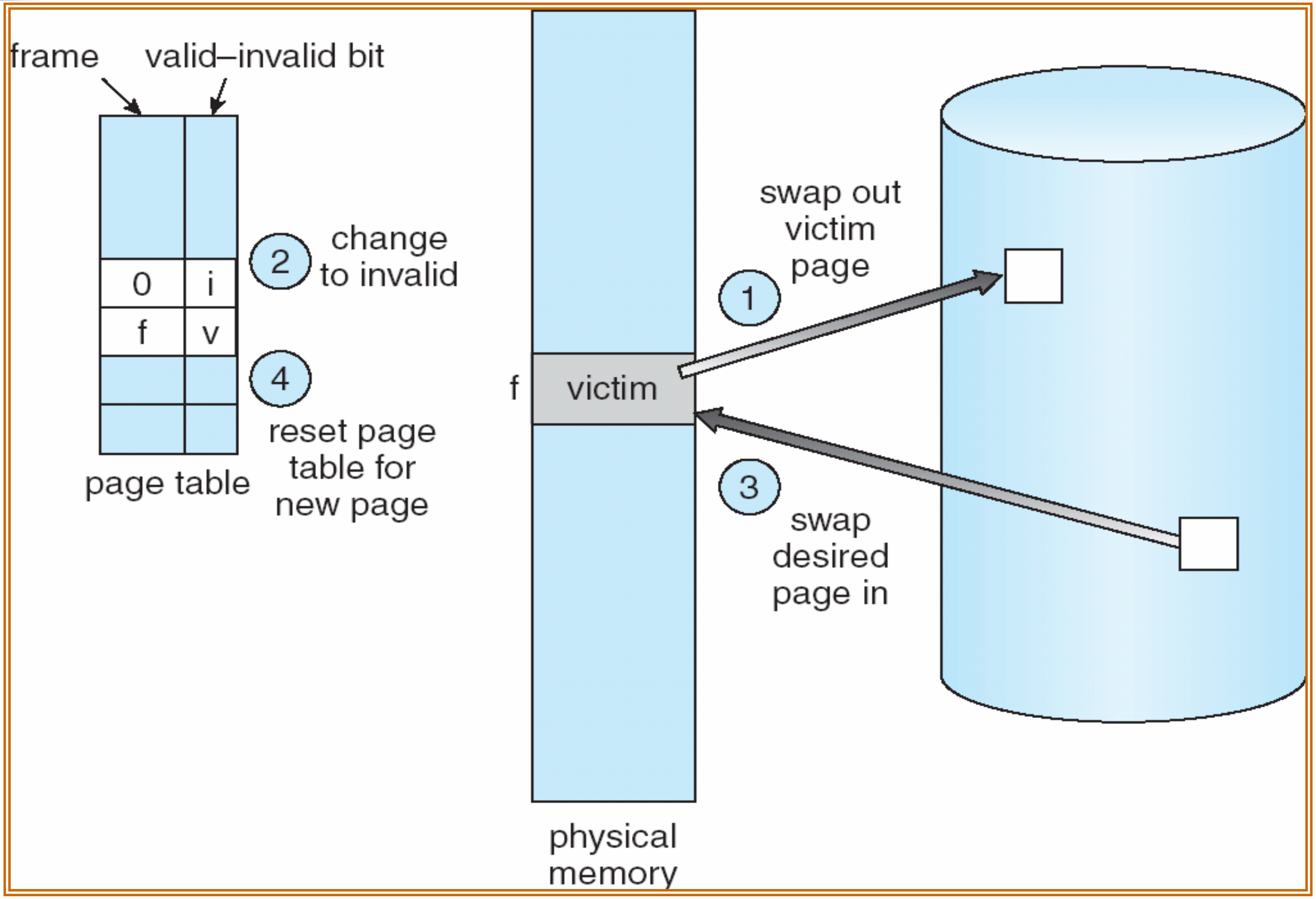
- What happens if there is no free frame?

- Find a page in memory, but not really in use, and swap it out
- For better performance:
  - Find an algorithm which will result in minimum number of page faults
  - Prevent over-allocation of memory.
  - Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk

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

-- Page Replacement



-- Page Replacement Algorithms

- Want lowest page-fault rate
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
- In all our examples, the reference string is

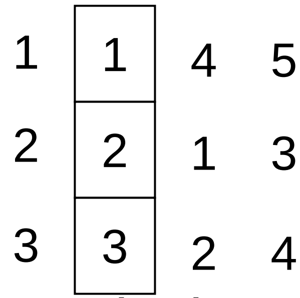
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

... -- Page replacement Algorithms

- First-In-First-Out (FIFO)
- Optimal
- Least Recently Used (LRU)

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

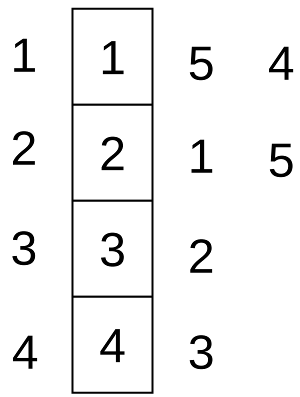
- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



9 page faults

- 3 frames (3 pages can be in memory at a time per process)

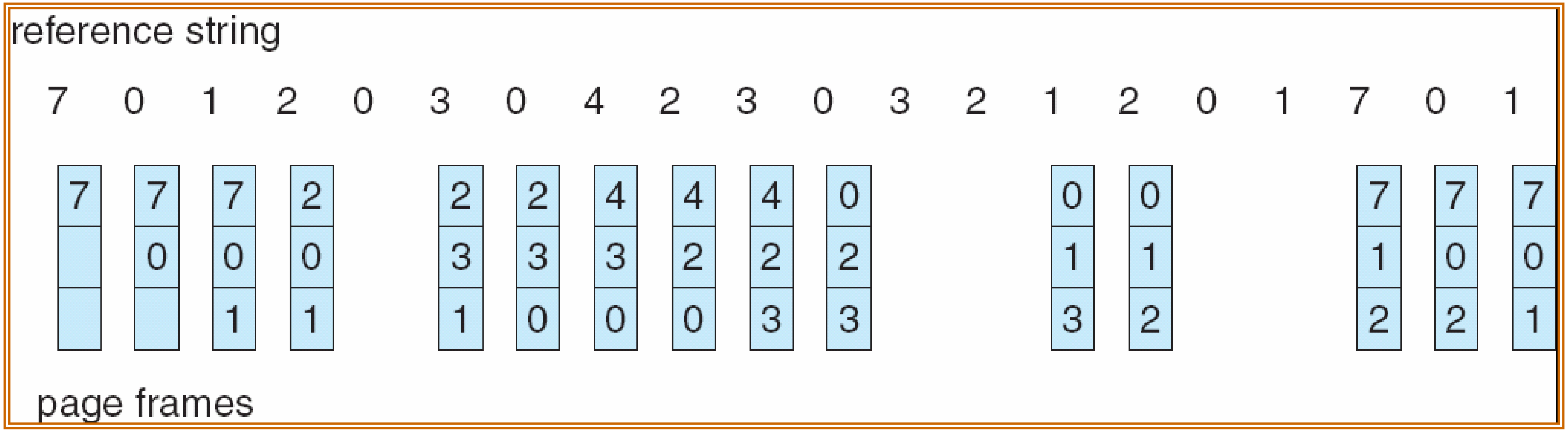
- 4 frames



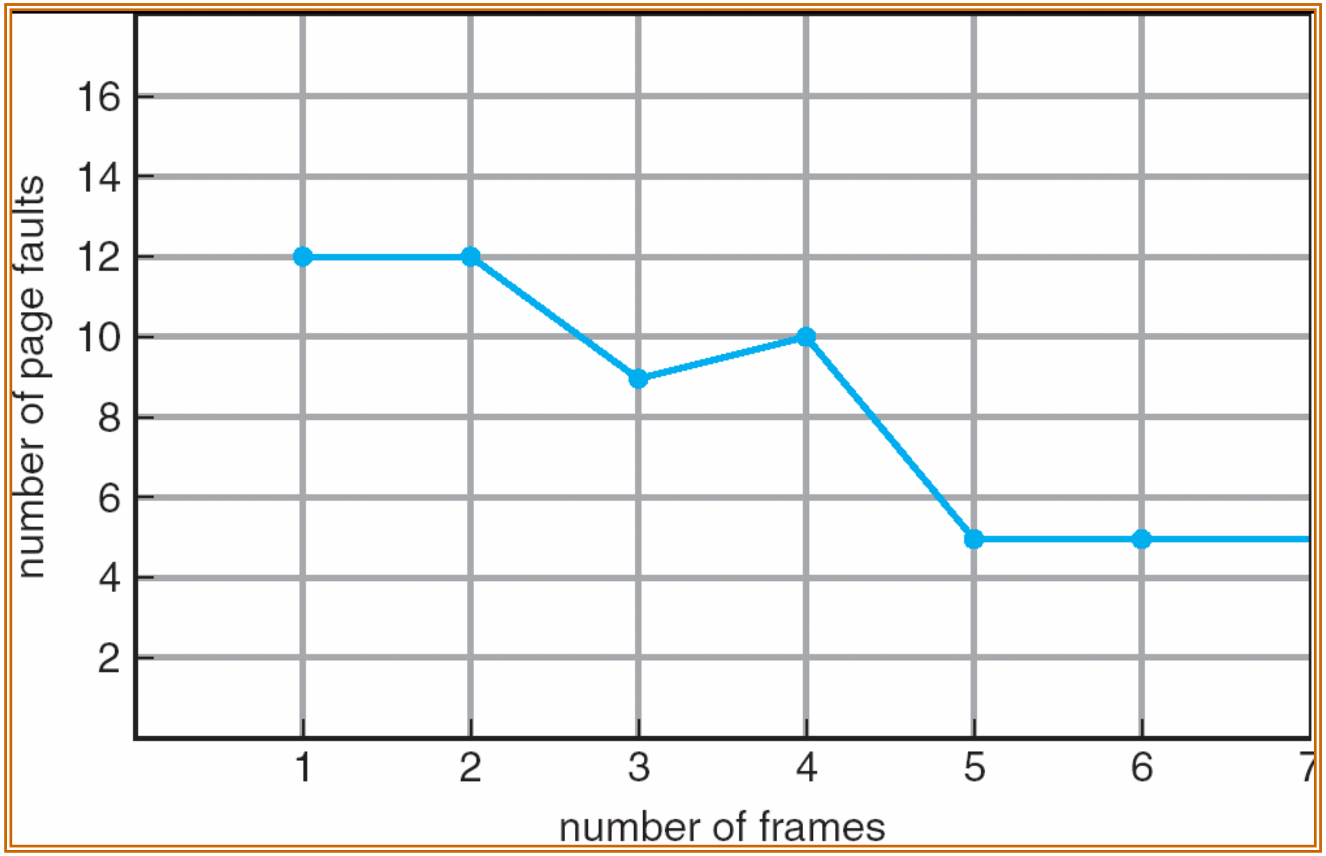
10 page faults

- Belady's Anomaly: more frames $\Rightarrow$ more page faults

--- FIFO Page Replacement



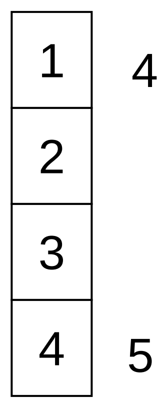
--- FIFO Illustrating Belady's Anomaly



-- Optimal Algorithm

- Replace page that will not be used for longest period of time
- 4 frames example

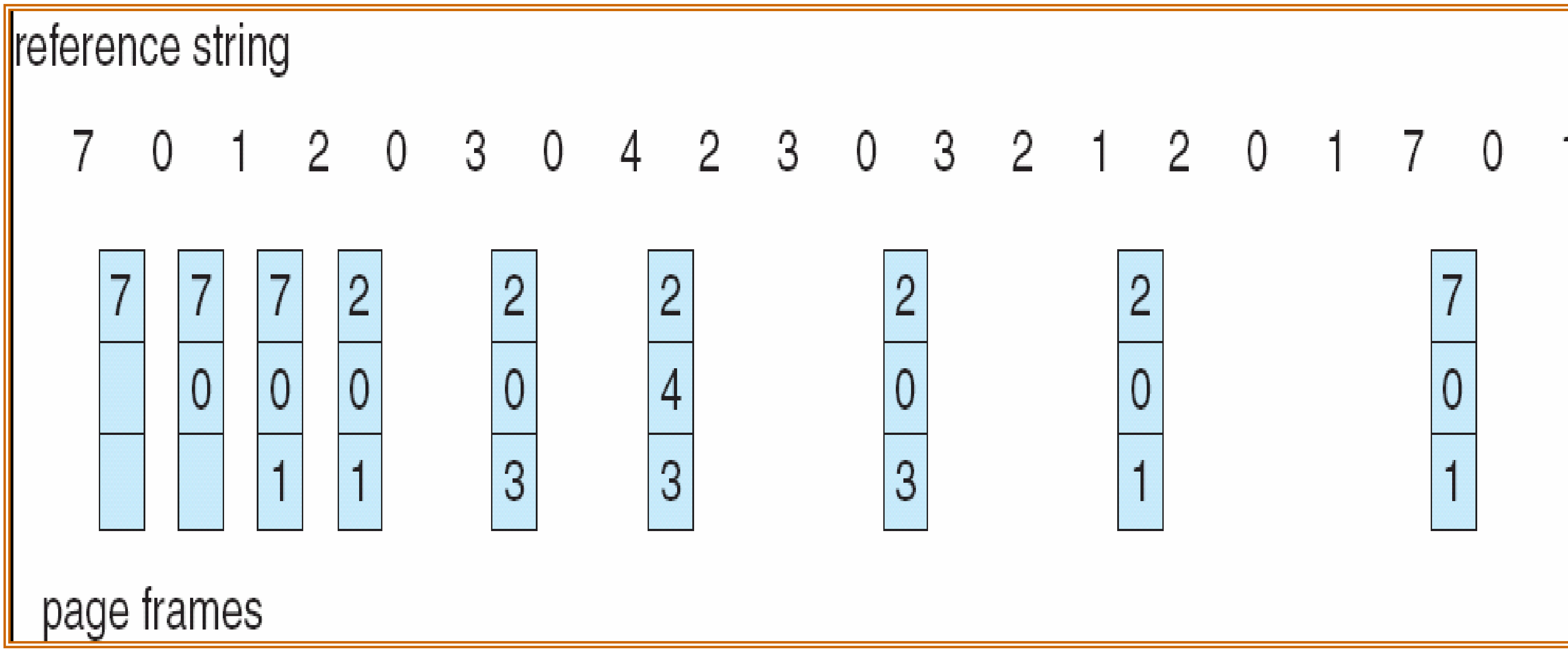
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



6 page faults

- How do you know this?
- Used for measuring how well your algorithm performs

- Optimal Page Replacement



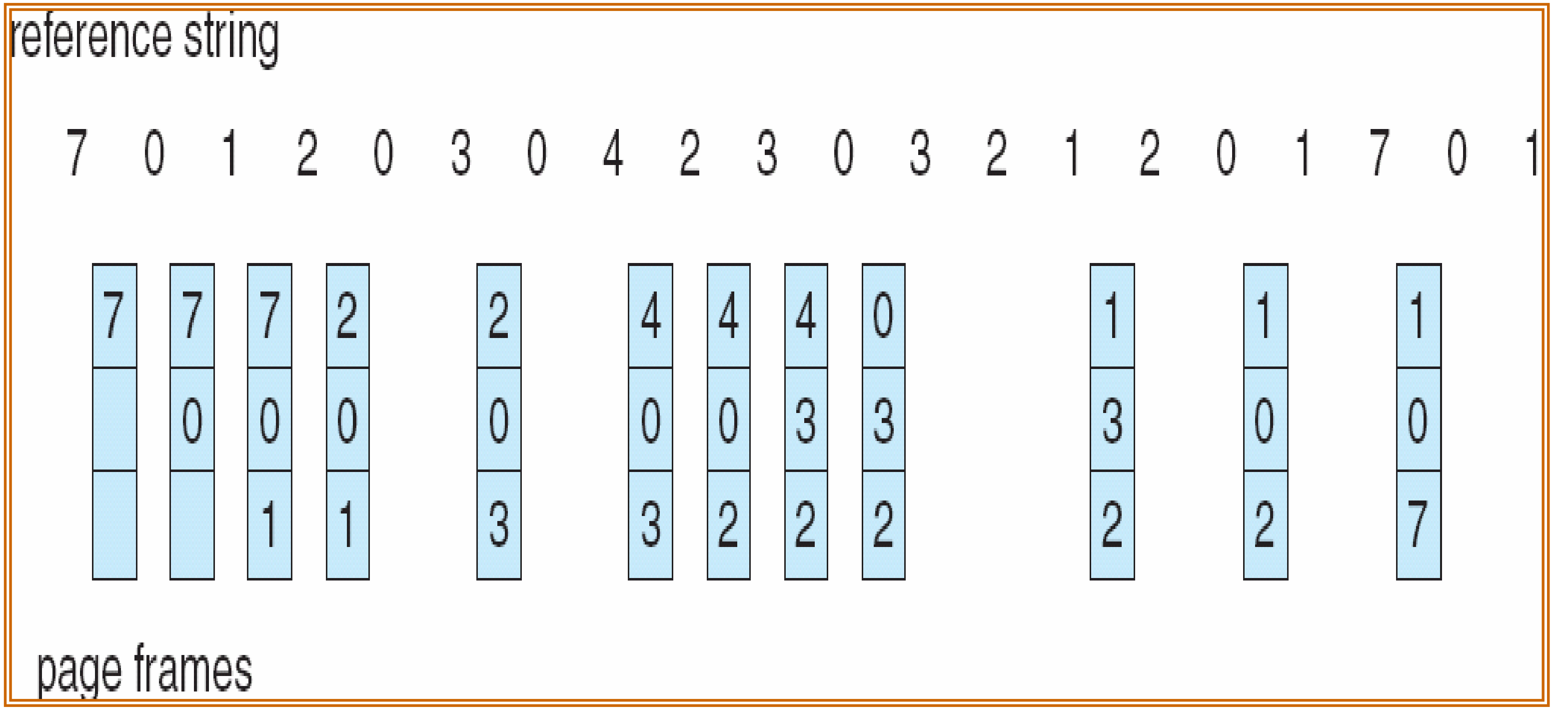
-- Least Recently Used (LRU) Algorithm ...

- Reference string: 1, 2, 3, 4, 1, 2, **5**, 1, 2, **3**, **4**, **5**

1	1	1	1	**5**
2	2	2	2	2
3	**5**	5	**4**	4
4	4	**3**	3	3

- 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 determine which are to change

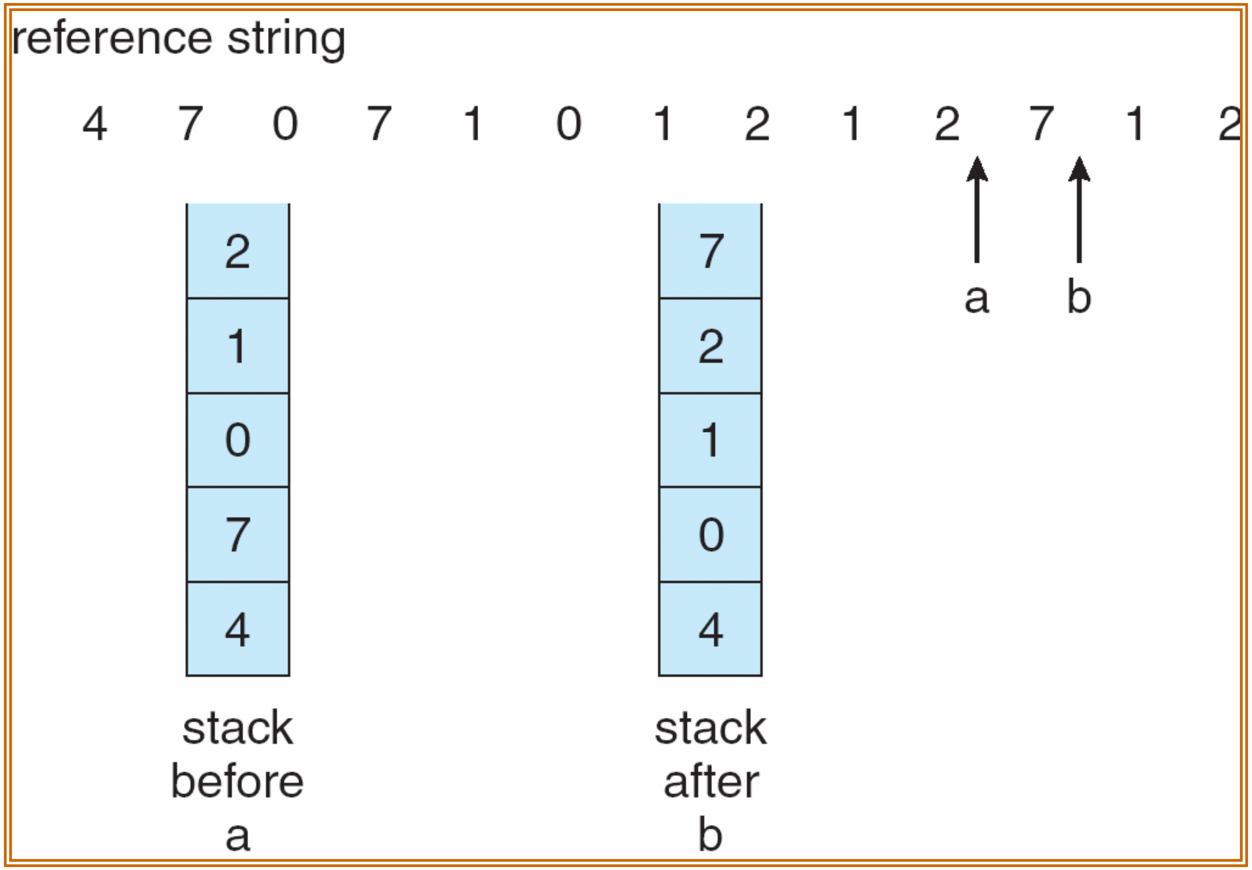
--- LRU Page Replacement



-- LRU Algorithm Implementation

- 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
  - No search for replacement

--- Use Of A Stack to Record The Most Recent Page References



- Allocation of Frames

- Each process needs *minimum* number of pages
  - 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*
- Two major allocation schemes
  - fixed allocation
    - Equal allocation
    - Proportional allocation
  - priority allocation

-- Fixed Allocation

- Equal allocation – For example, if there are 100 frames and 5 processes, give each process 20 frames.

- Proportional allocation – Allocate according to the size of process

  - $s_i = \text{size of process } p_i$
  - $S = \sum s_i$
  - $m = \text{total number of frames}$
  - $a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$

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

-- 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

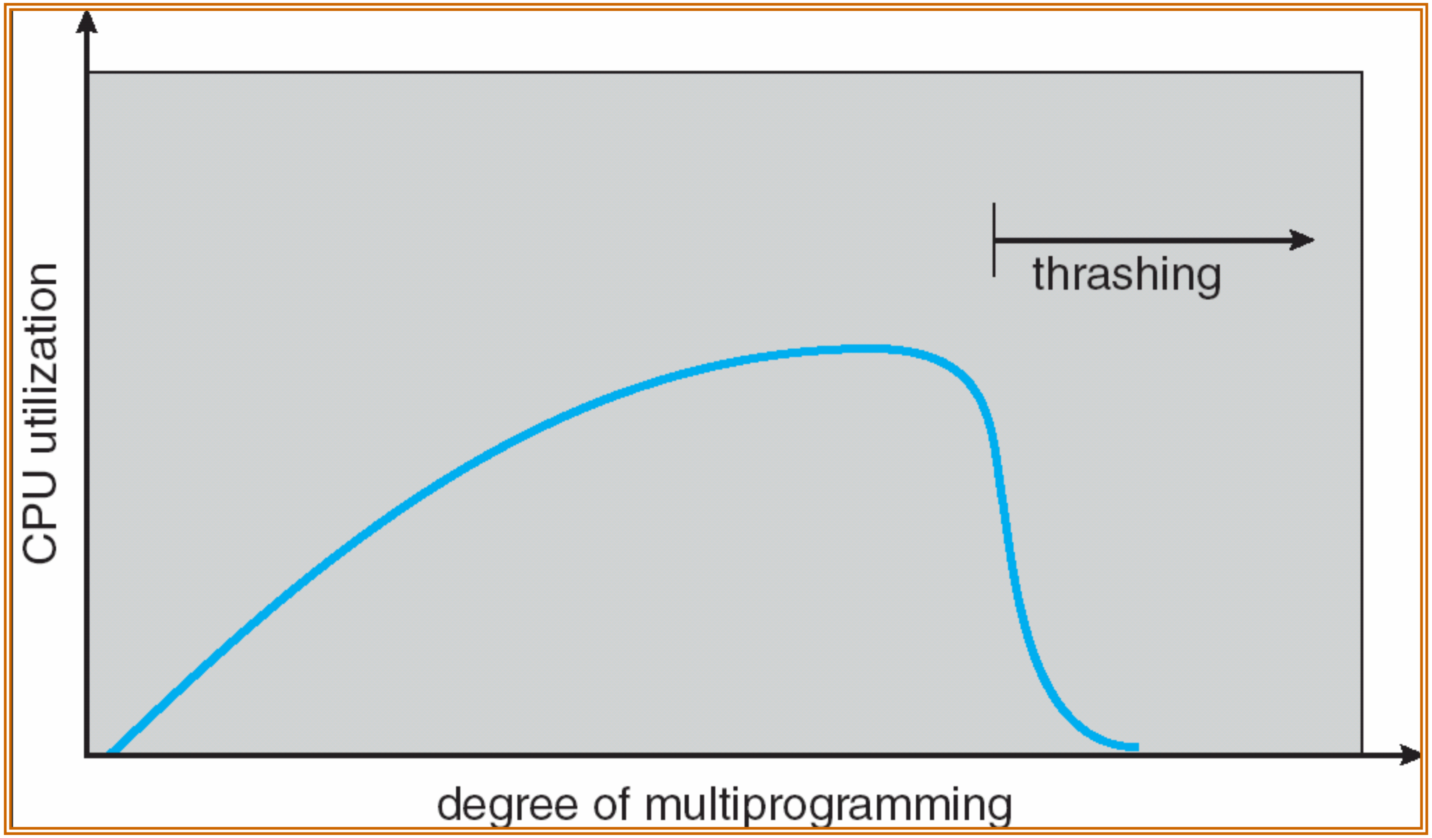
-- Global vs. Local Allocation

- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
- **Local replacement** – each process selects from only its own set of allocated frames

- Thrashing ...

- If a process does not have "enough" pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system thinks 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



-- Demand Paging and Thrashing

- Why does demand paging work?

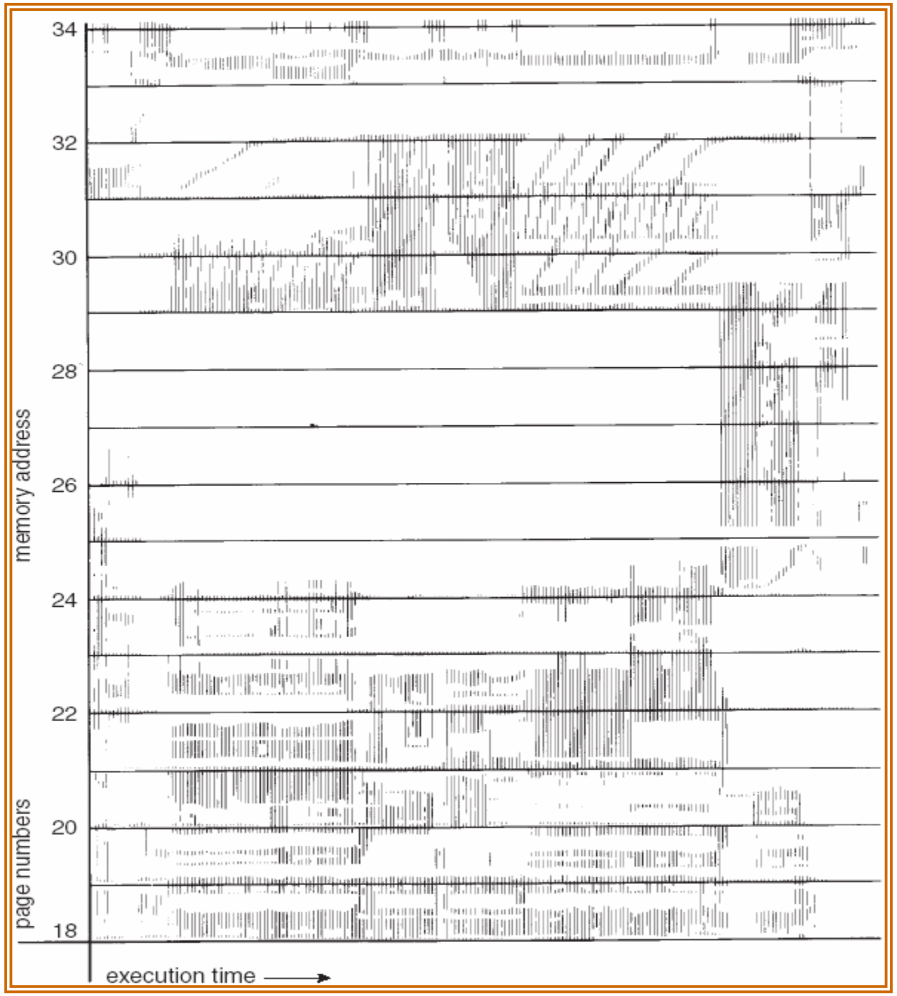
  Locality model

  - Process migrates from one locality to another
  - Localities may overlap

- Why does thrashing occur?

  Σ size of locality > total memory size

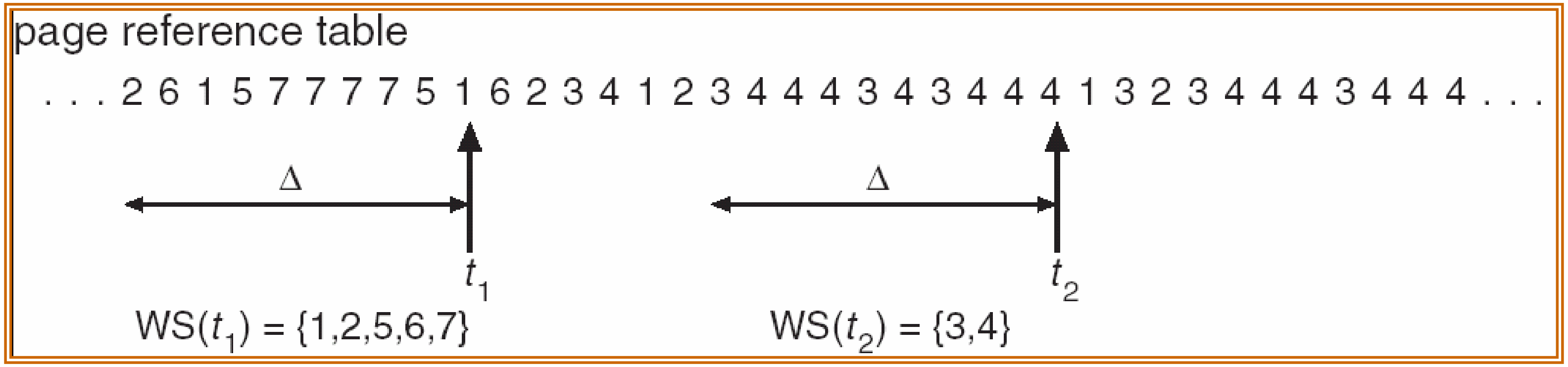
-- Locality In A Memory-Reference Pattern



-- Working-Set Model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  Example: 10,000 memory references
- WSS_i (working set of Process P_i) =
  total number of pages referenced in the most recent Δ memory references (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
- $D = \Sigma\ WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
- Policy if D > m, then suspend one of the processes

-- Working-set model

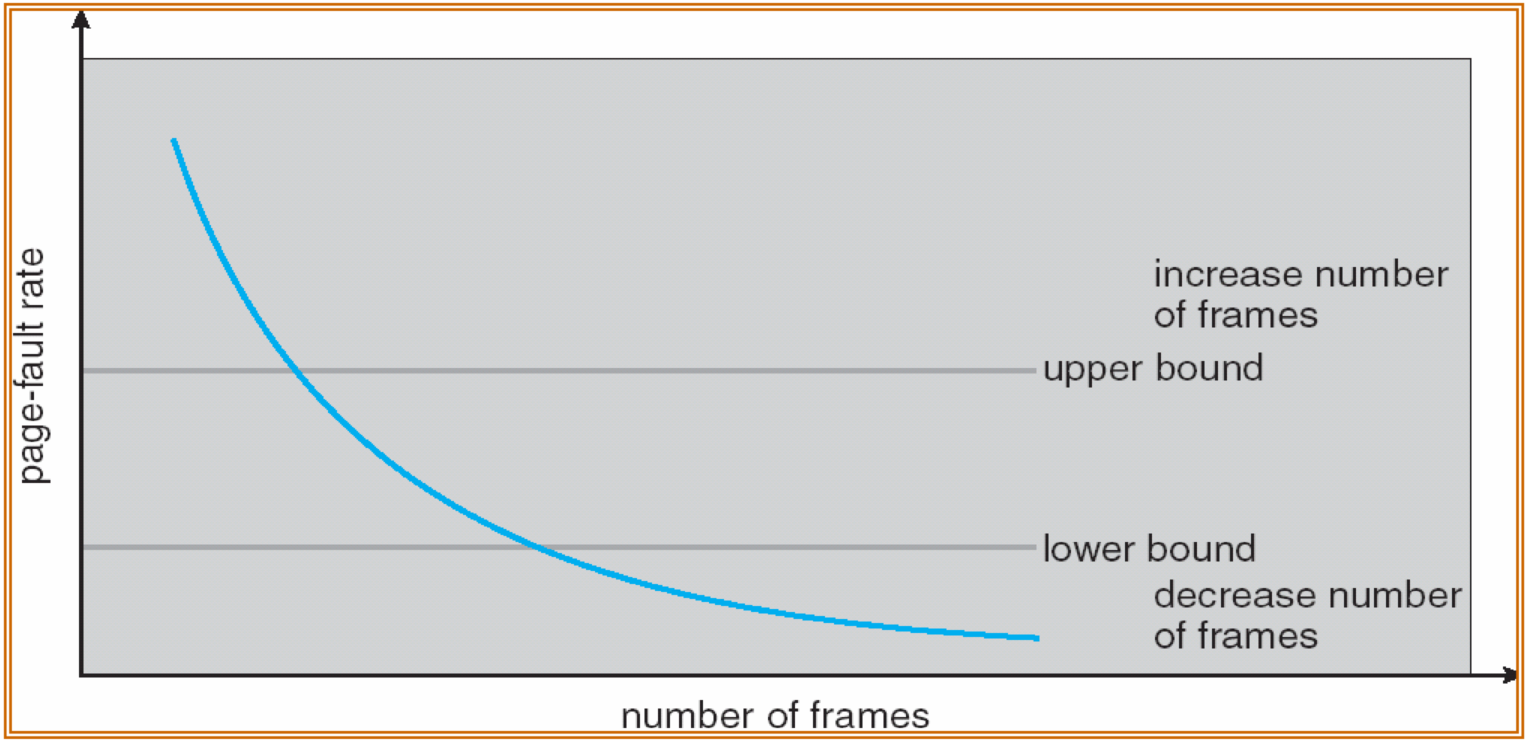


-- Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: Δ = 10,000
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page
  - Whenever a timer interrupts copy and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 $\Rightarrow$ page in working set
- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units

- Page-Fault Frequency Scheme

- Establish “acceptable” page-fault rate
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame



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