Virtual Memory

CSCI 315 Operating Systems Design

Department of Computer Science

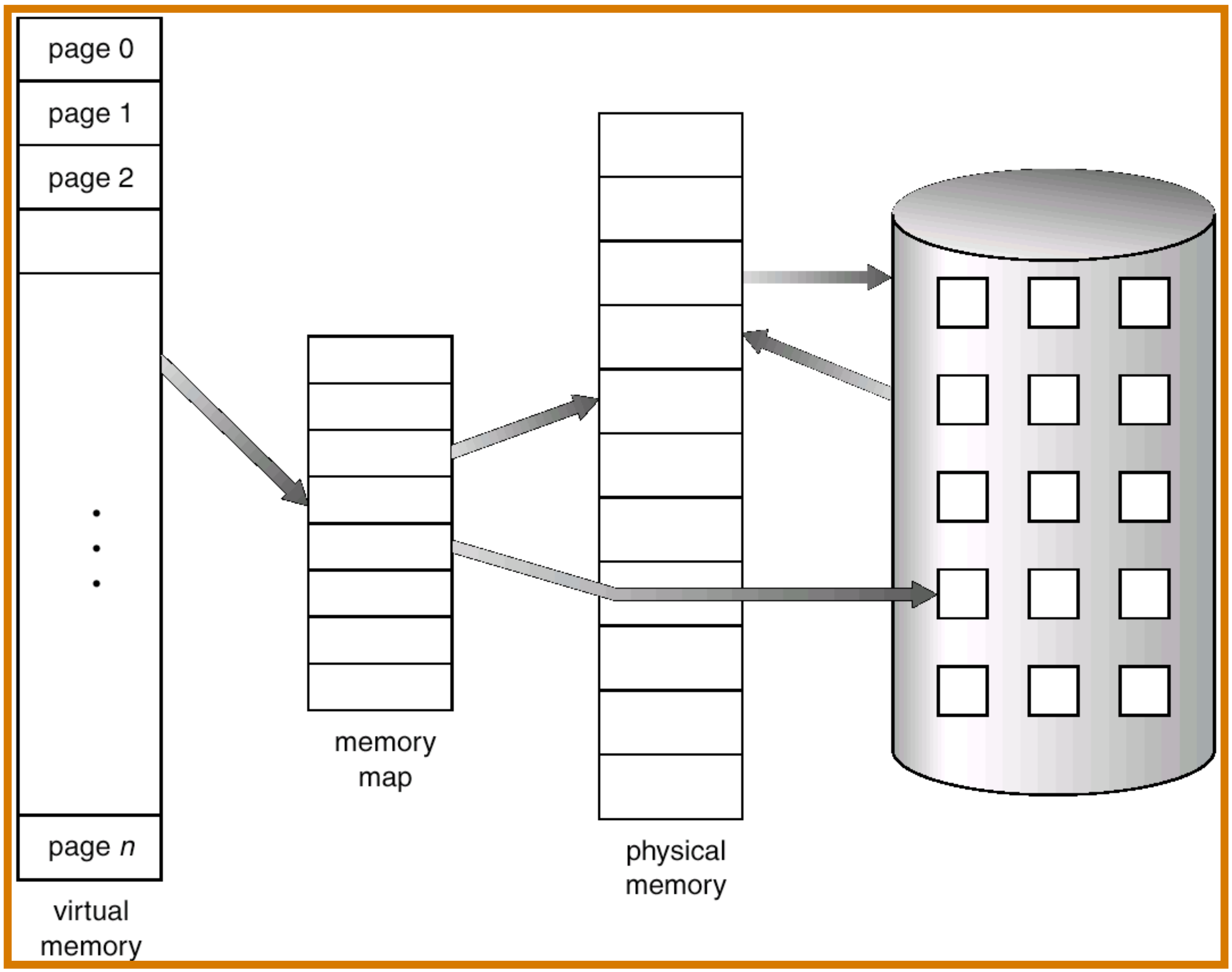
Notice: The slides for this lecture were based on those *Operating Systems Concepts, 9th ed.*, by Silberschatz, Galvin, and Gagne. Many, if not all, the illustrations contained in this presentation come from this source.

Virtual Memory

- **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

Virtual Memory Larger than Physical Memory



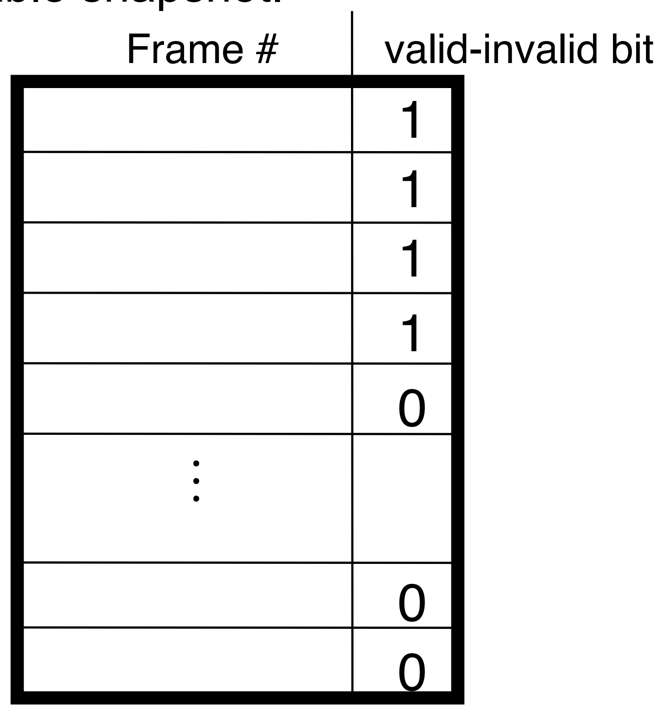
Demand Paging

- **Bring a page into memory *only* when it is needed.**
  - Less I/O needed.
  - Less memory needed.
  - Faster response.
  - More users.

- **<u>When</u>** a page is referenced:
  - if invalid reference $\Rightarrow$ **abort with error message**.
  - if not-in-memory $\Rightarrow$ **bring to memory**.
  - if already in memory $\Rightarrow$ access the location

Valid-Invalid Bit

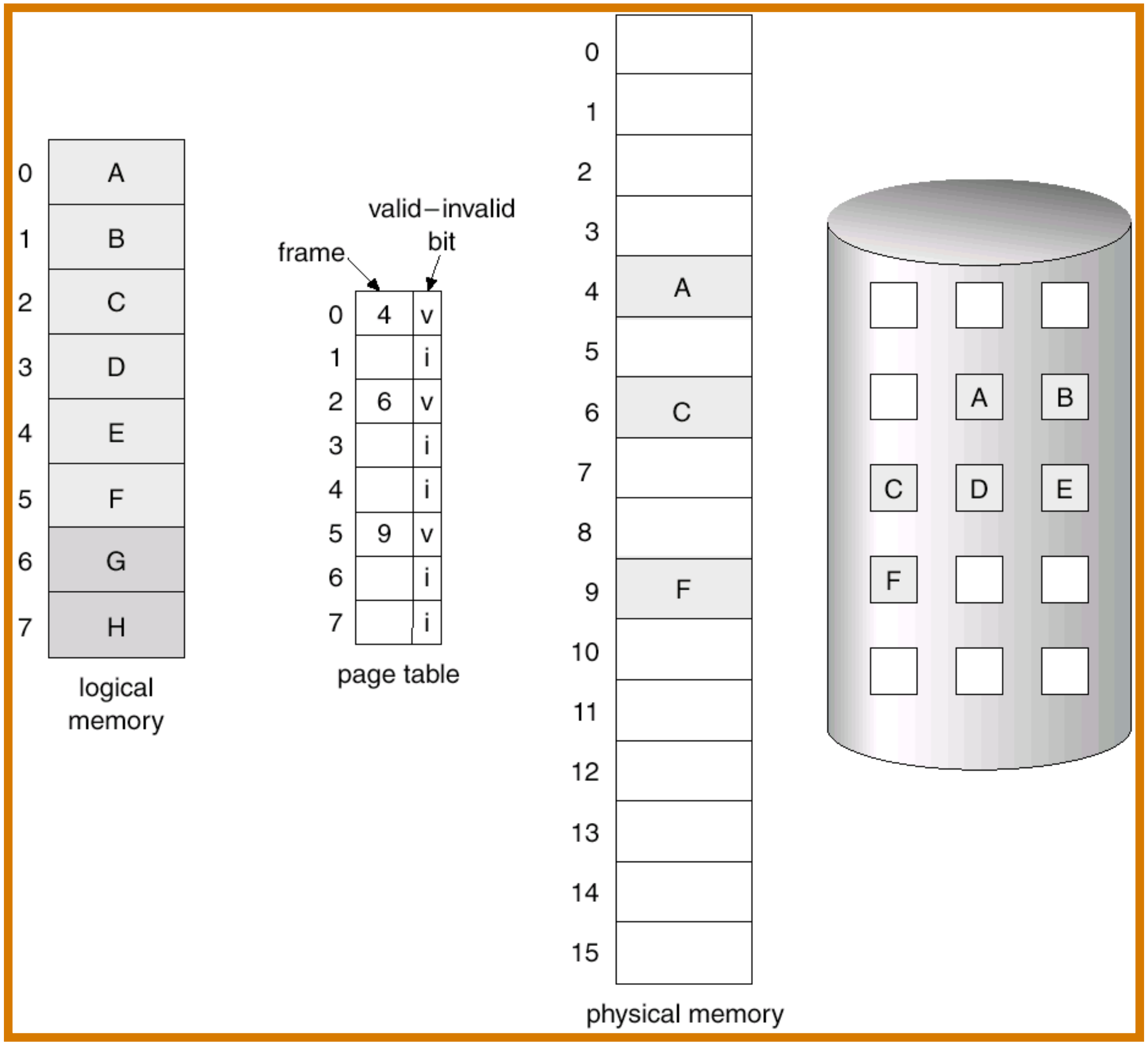
- With each page table entry a valid–invalid bit is associated ($1 \Rightarrow$ in-memory, $0 \Rightarrow$ not-in-memory)
- Initially valid–invalid but is set to 0 on all entries.
- Example of a page table snapshot.



page table

- During address translation, if valid–invalid bit in page table entry is $0 \Rightarrow$ page fault.

Page Table when some pages are not in Main Memory



Page Fault

- If there is ever a reference to a page, first reference will **trap** to OS $\Rightarrow$ page fault.

- OS looks at page table to decide:
  - **If it was an invalid reference $\Rightarrow$ abort with error message.**
  - **If it was a reference to a page that is not in memory, continue.**

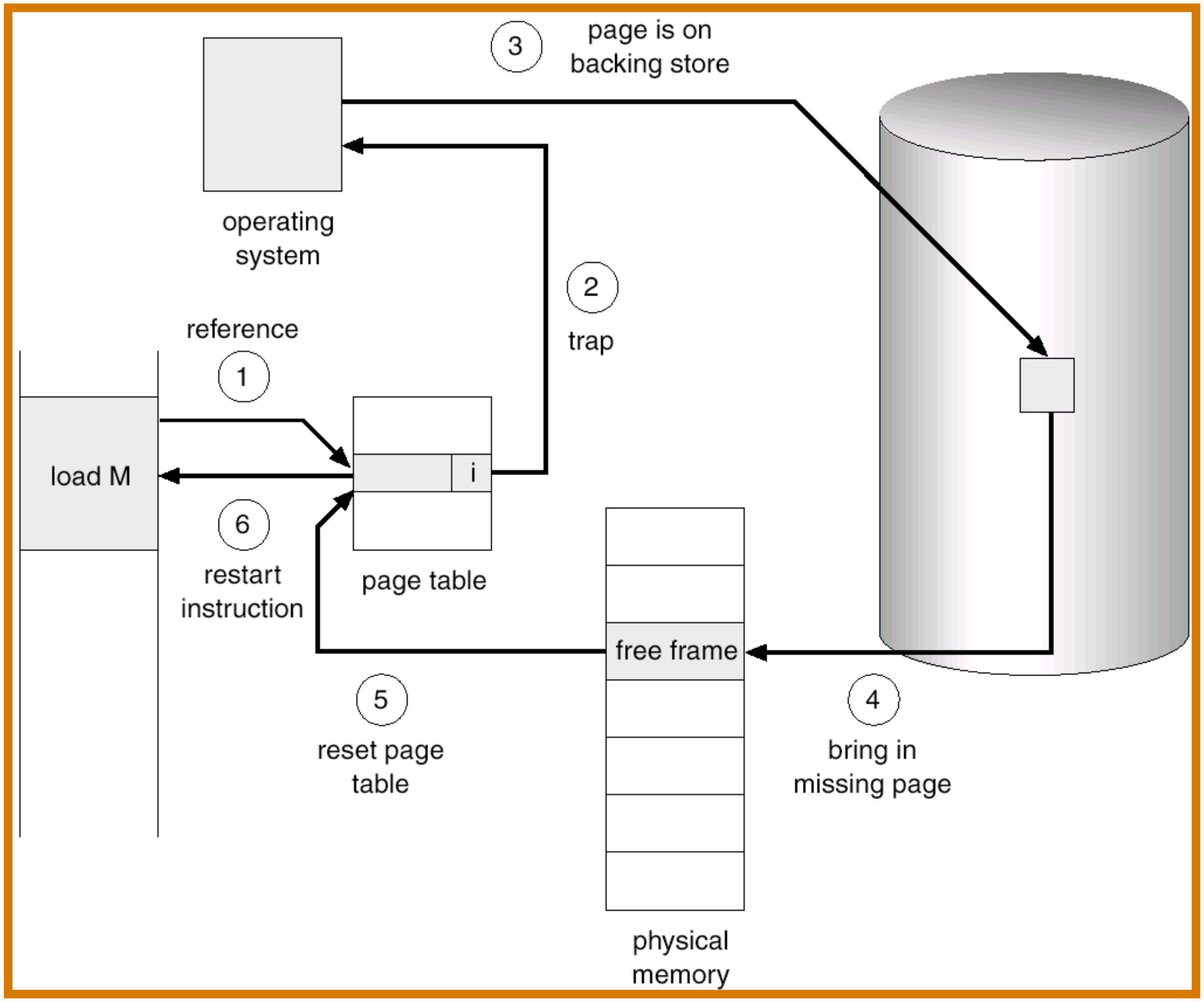
- Locate an empty frame.

- Swap page into frame.

- Correct the page table and set validation bit = 1.

- Restart the instruction that caused the page fault.

Steps in Handling a Page Fault



No free frame: now what?

- **Page replacement:** Are all those pages in memory being referenced? Choose one to *swap out* to disk and make room to load a new page.
  - **Swap out:** Do you *really* have to save it to disk?
  - **Algorithm:** How do you choose a victim?
  - **Performance:** What algorithm will result in the *lowest possible number* of page faults?
- **Life with VM:** The same page may be brought in and out of memory several times.

Performance of Demand Paging

- **Page Fault Rate:** $0 \le p \le 1.0$
  - if $p = 0$ no page faults.
  - if $p = 1$, every reference is a fault.

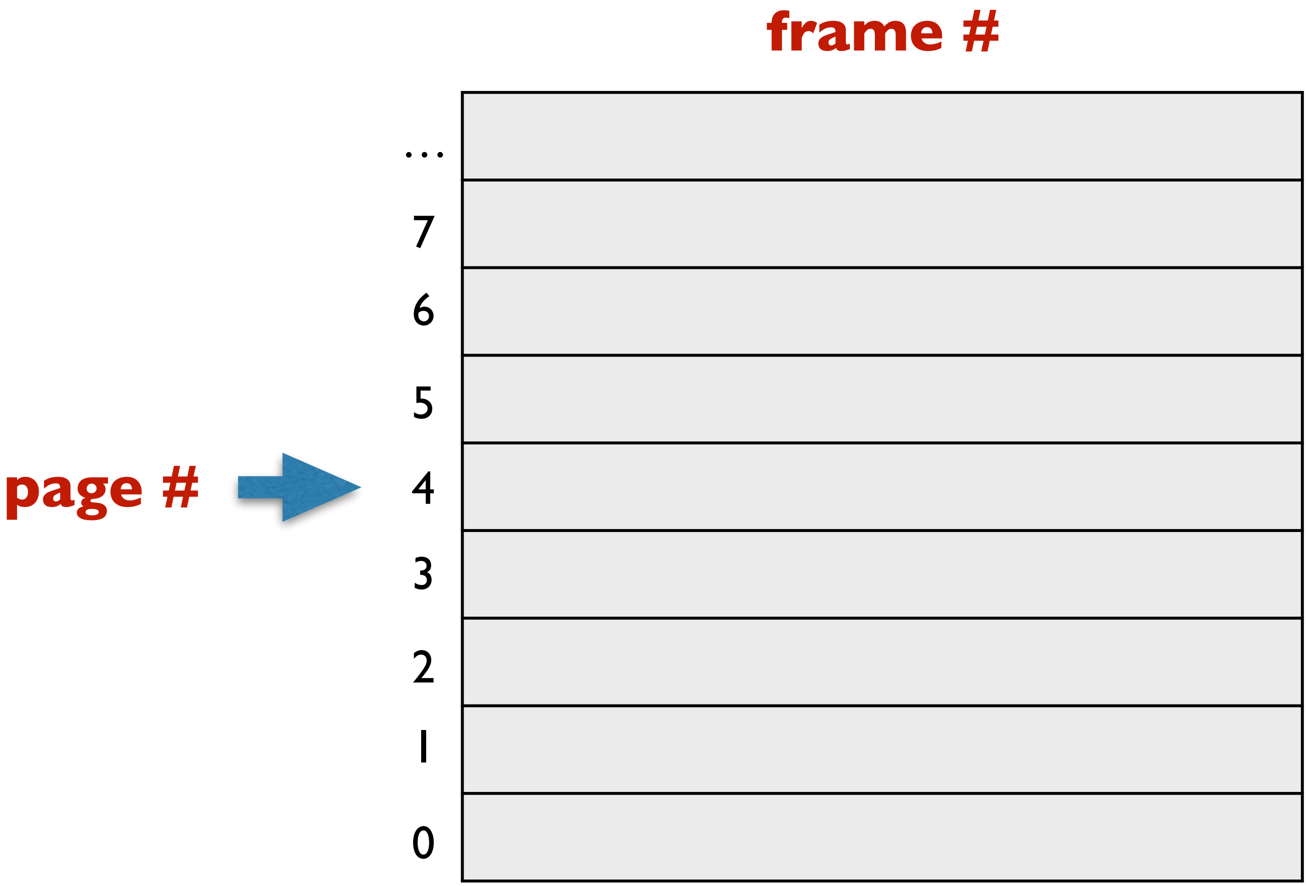
- **Effective Access Time (EAT):**

  EAT = [(1 – *p*) (memory access)] + [*p* (page fault overhead)]

where:

page fault overhead = [swap page out] + [swap page in]
+ [restart overhead]

Page Table



Page Table

page# → 4

	frame #	valid
…		
7		
6		
5		
4		
3		
2		
1		
0		

Page Table

	frame #	valid	dirty
...			
7			
6			
5			
4			
3			
2			
1			
0			

page # → 4

Handling the Writes to VM

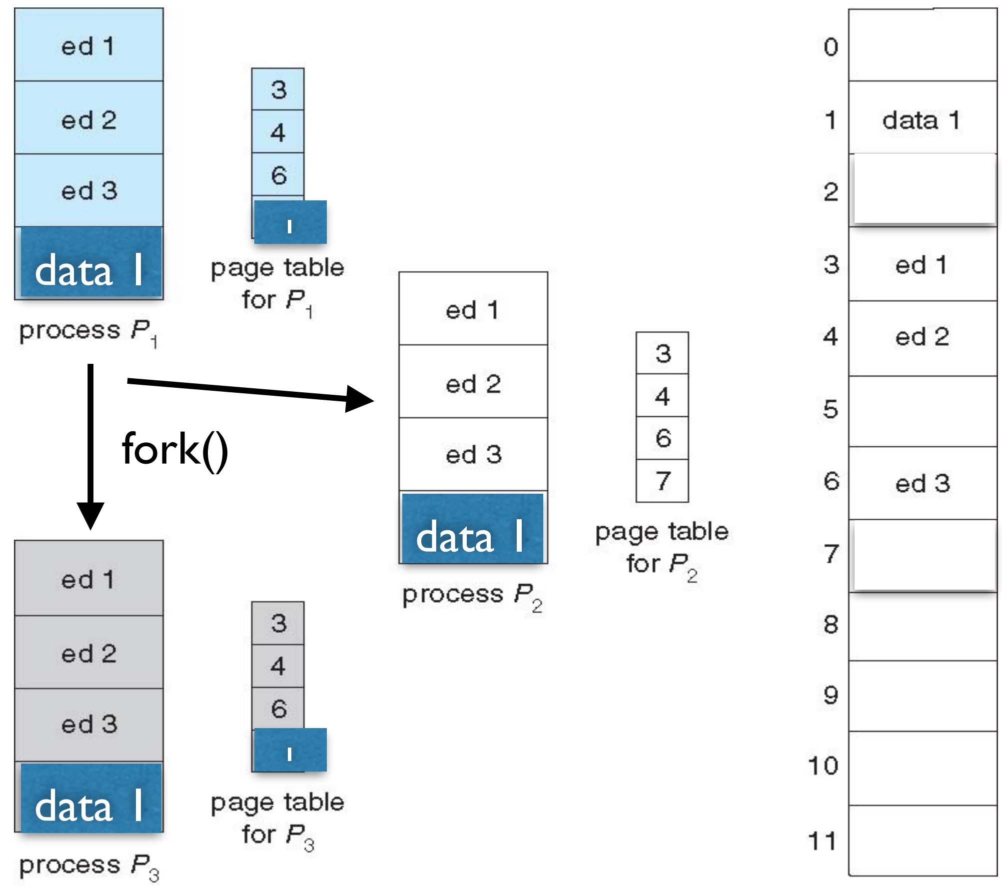
Remember the two policies used in cache memory for dealing with writes?

- **Write through**
- **Write back**

Discuss whether they are both applicable to handling writes to pages of virtual memory.

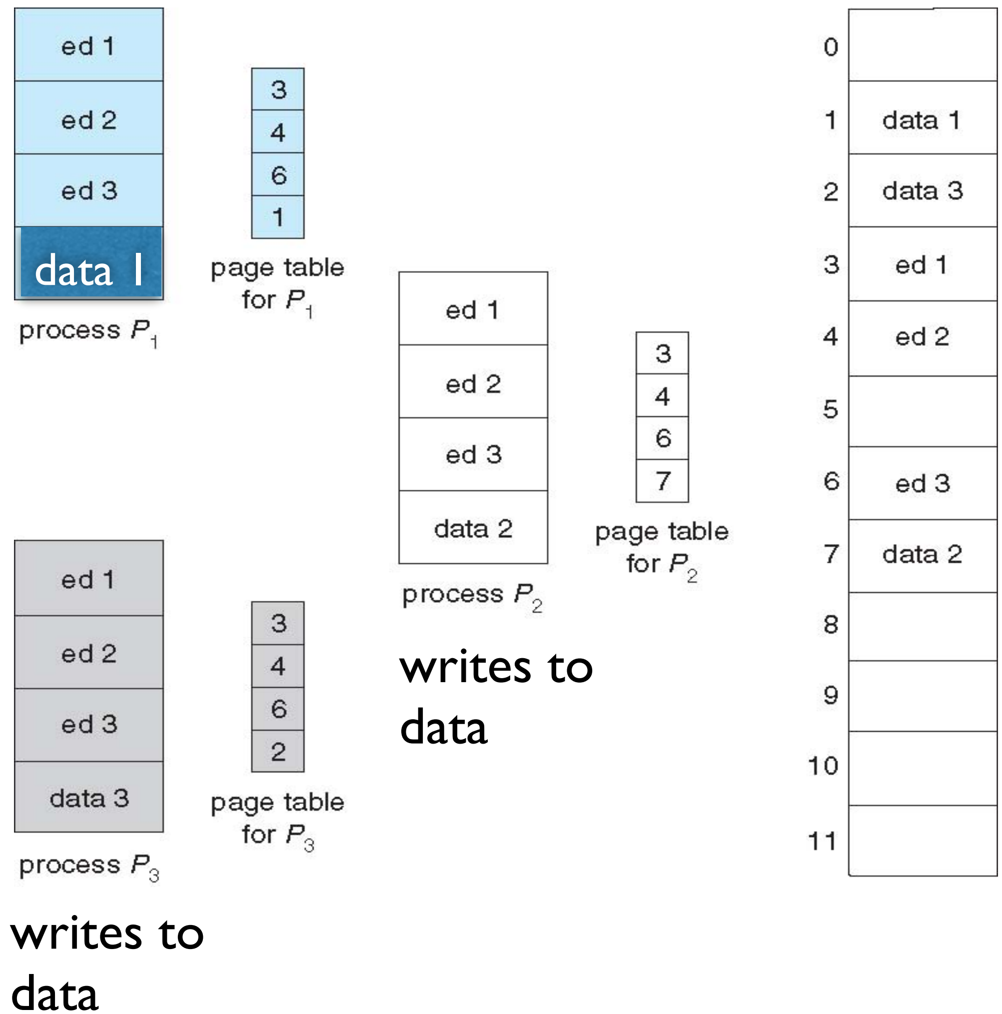
Copy-On-Write

When two processes are related by birth, there' an interesting **optimization** that comes very naturally with VM…



Copy-On-Write

When two processes are related by birth, there' an interesting **optimization** that comes very naturally with VM…



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

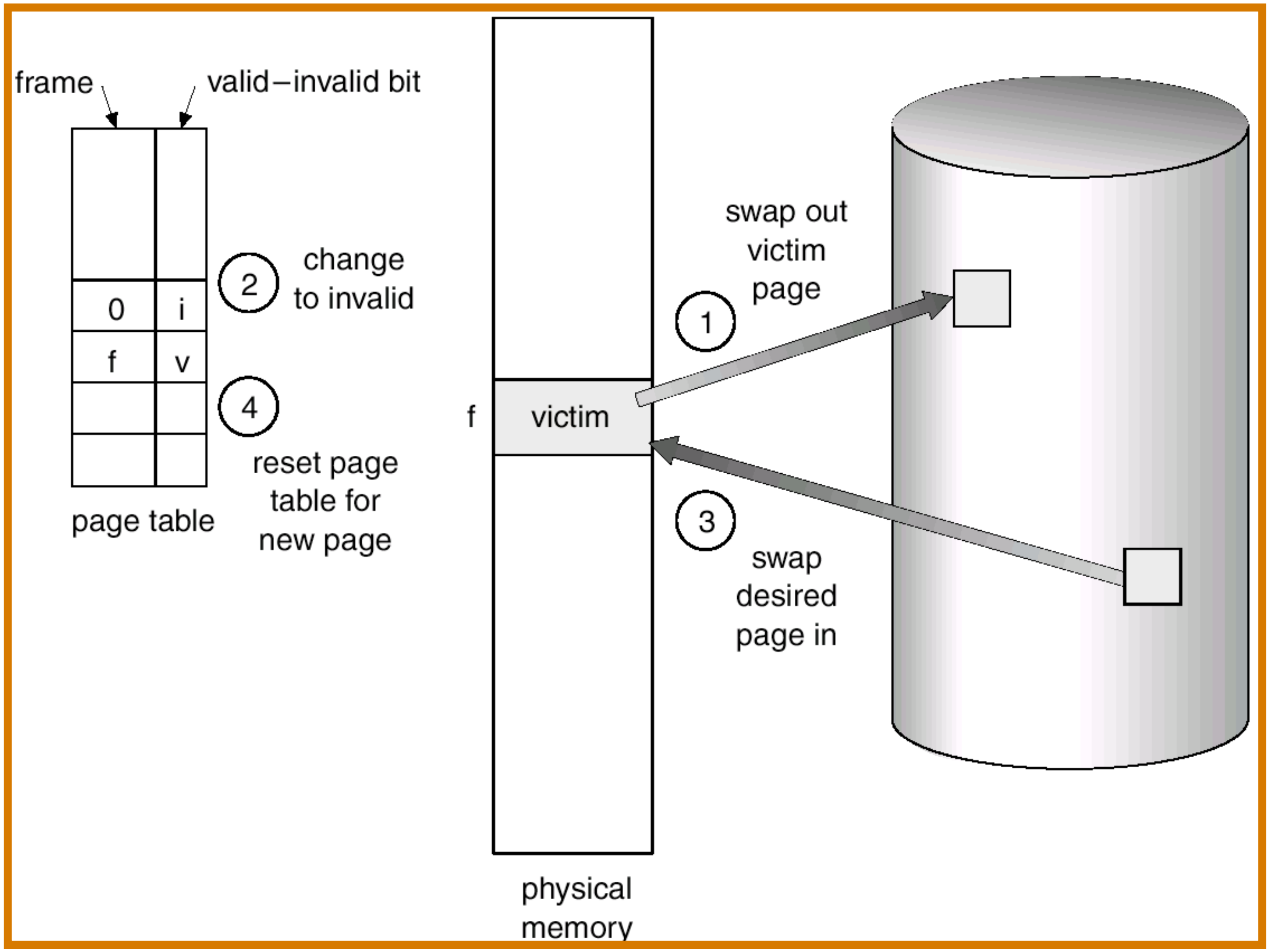
1. Find the location of the desired page on disk.

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.

3. Read the desired page into the (newly) free frame. Update the page and frame tables.

4. Restart the instruction.

Page Replacement

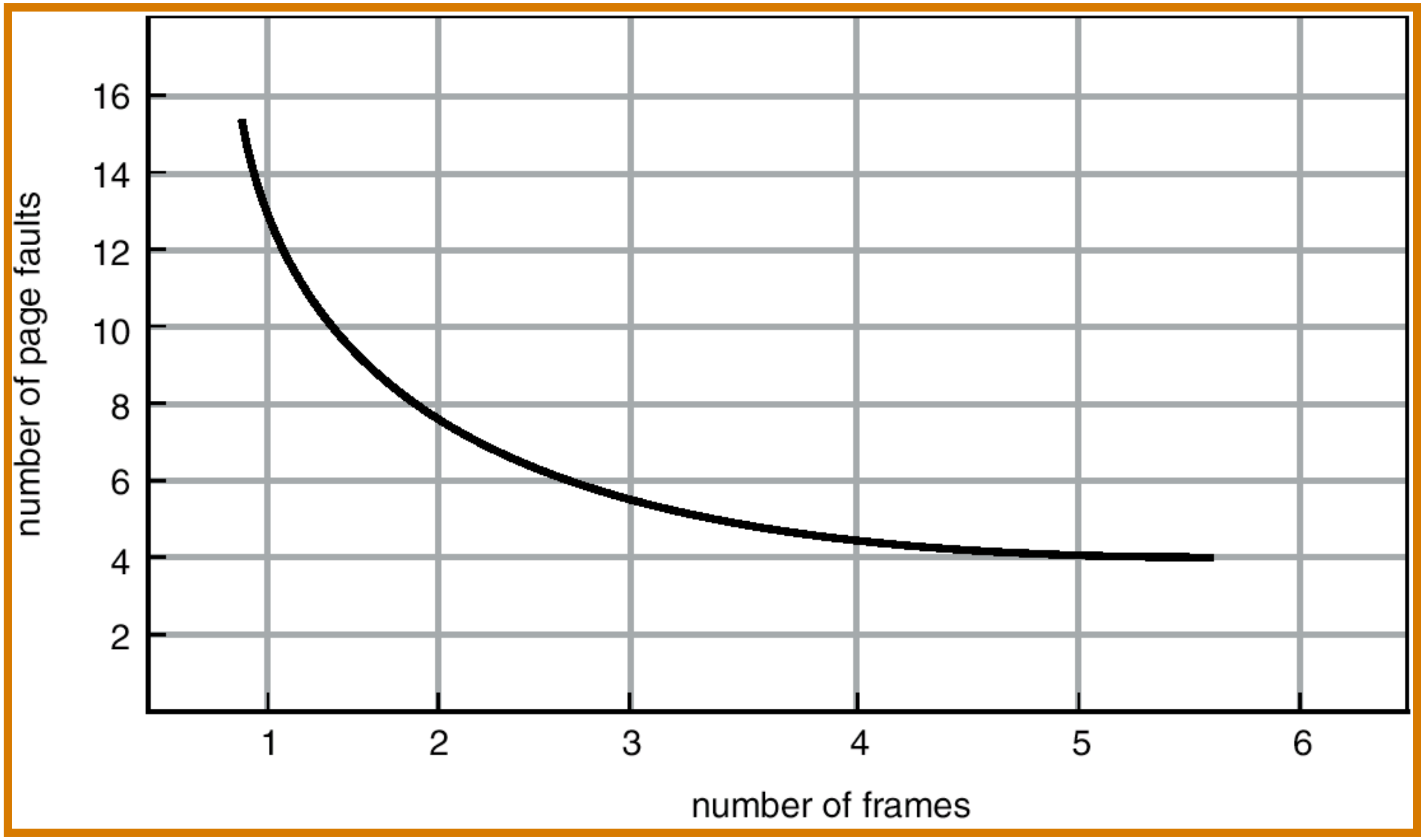


Page Replacement Algorithms

- **Goal:** Produce a low 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.
- The reference string is produced by tracing a real program or by some stochastic model. We look at every address produced and strip off the page offset, leaving only the page number. For instance:

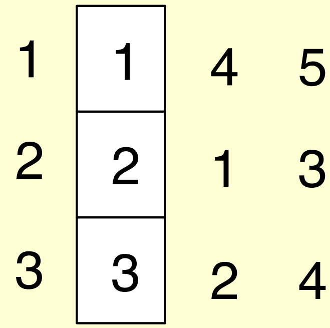
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

Graph of Page Faults Versus The Number of Frames



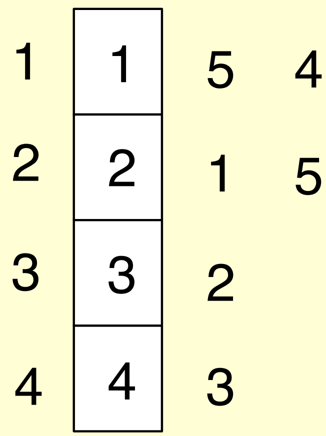
FIFO Page Replacement

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.
- 3 frames (3 pages can be in memory at a time per process)



9 page faults

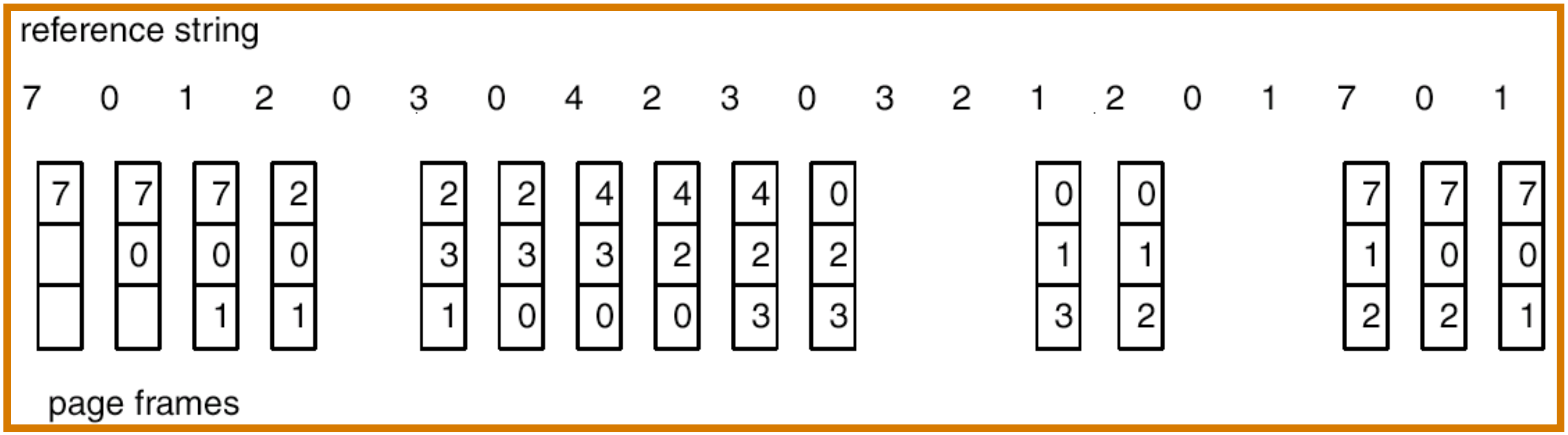
- 4 frames



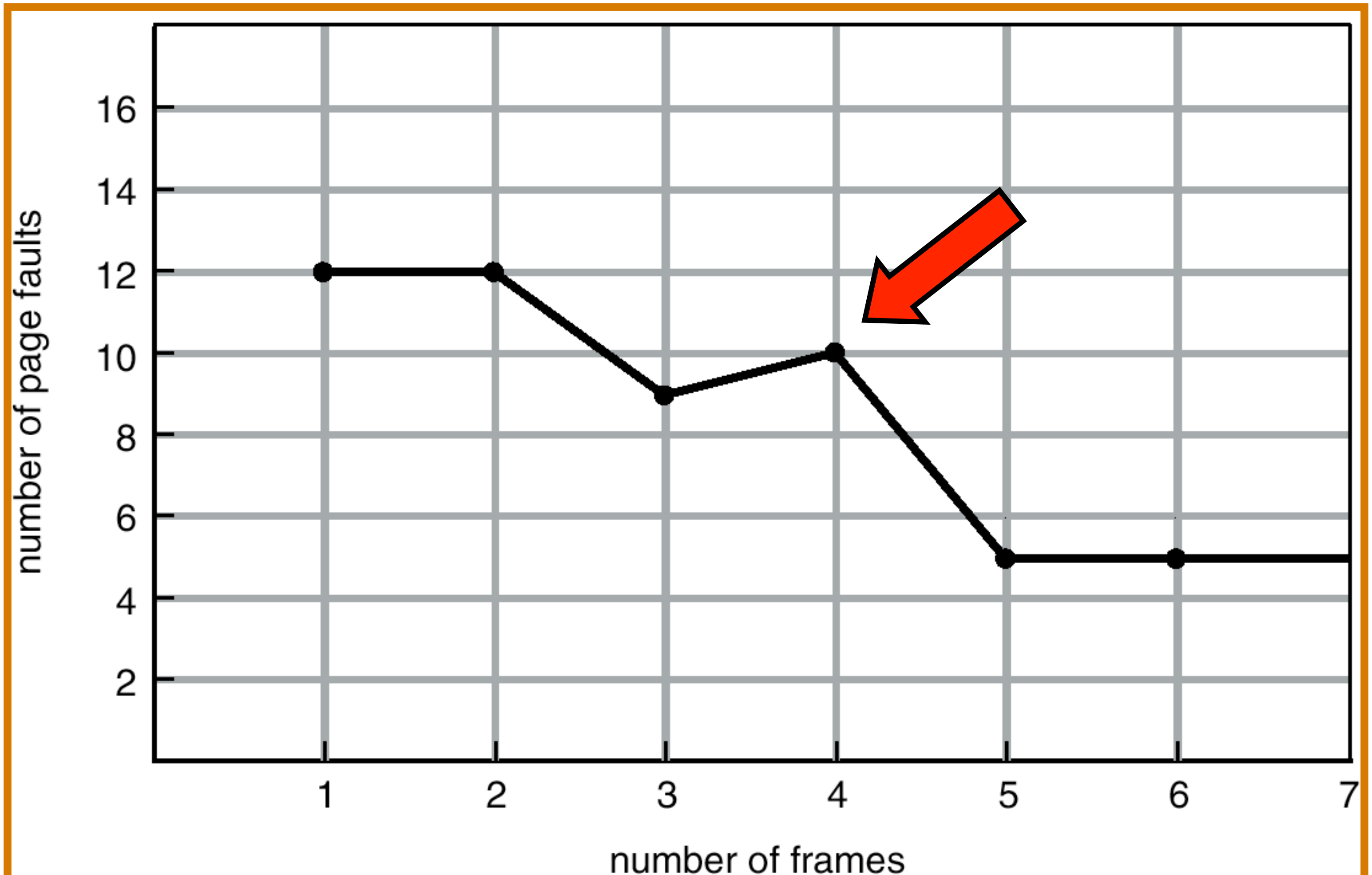
10 page faults

- FIFO Replacement ⇒ **Belady's Anomaly:** more frames, *more* page faults.

FIFO Page Replacement

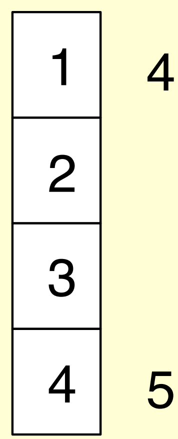


FIFO (Belady's Anomaly)



Optimal Algorithm

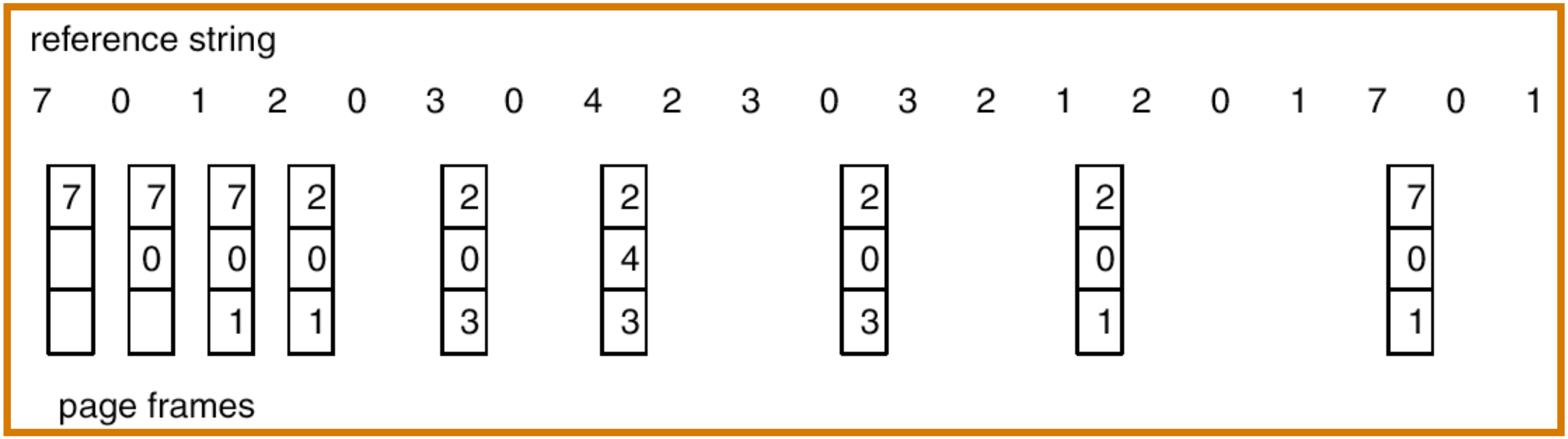
- Replace the page that will not be used for longest period of time. (How can you know what the future references will be?)
- 4 frames example: **1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**



6 page faults

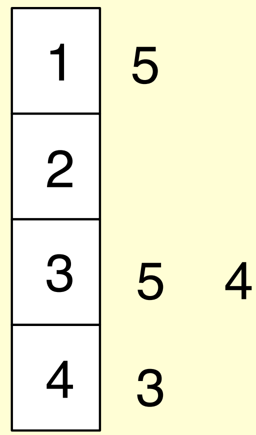
- Used for measuring how well your algorithm performs.

Optimal Page Replacement



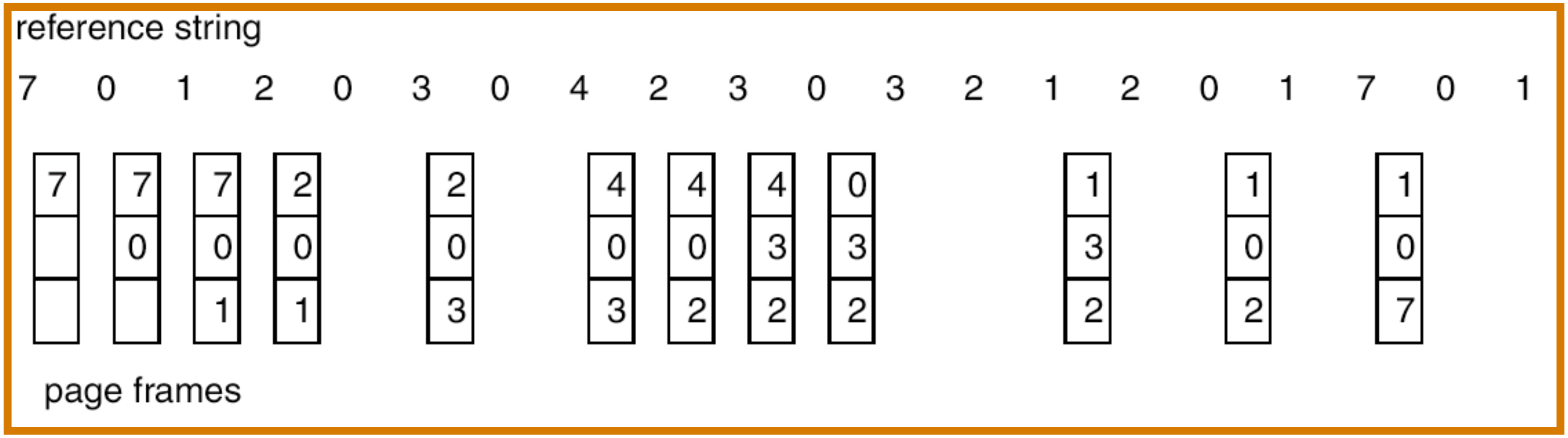
LRU Algorithm

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



- 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



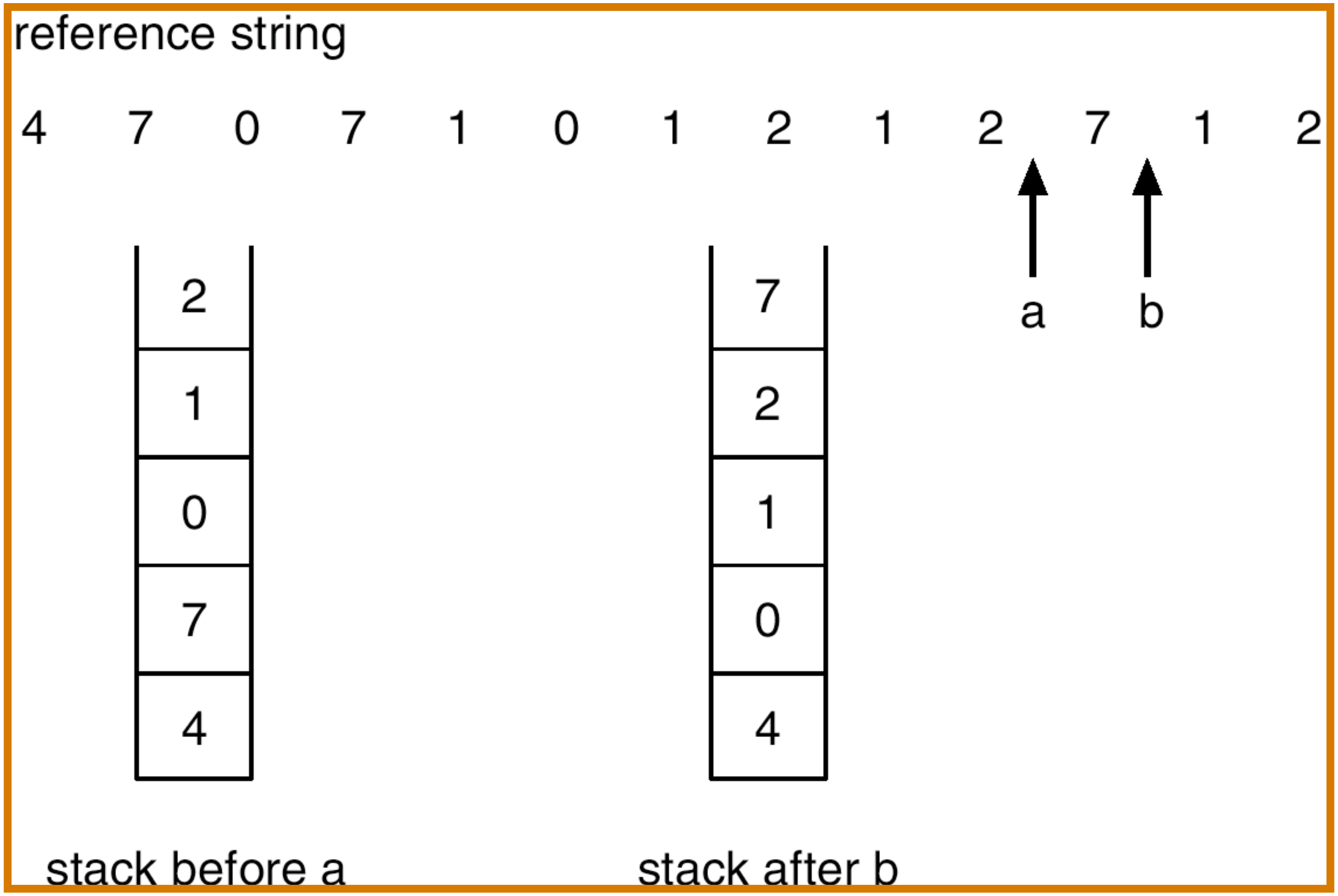
LRU Algorithm (Cont.)

- 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.

LRU and Belady's Anomaly

- LRU does not suffer from Belady's Anomaly (OPT doesn't either).
- It has been shown that algorithms in a class called **stack algorithms** can never exhibit Belady's Anomaly.
- A **stack algorithm** is one for which the set of pages in memory for n frames is a subset of the pages that would be in memory if you had $n+1$ frames.

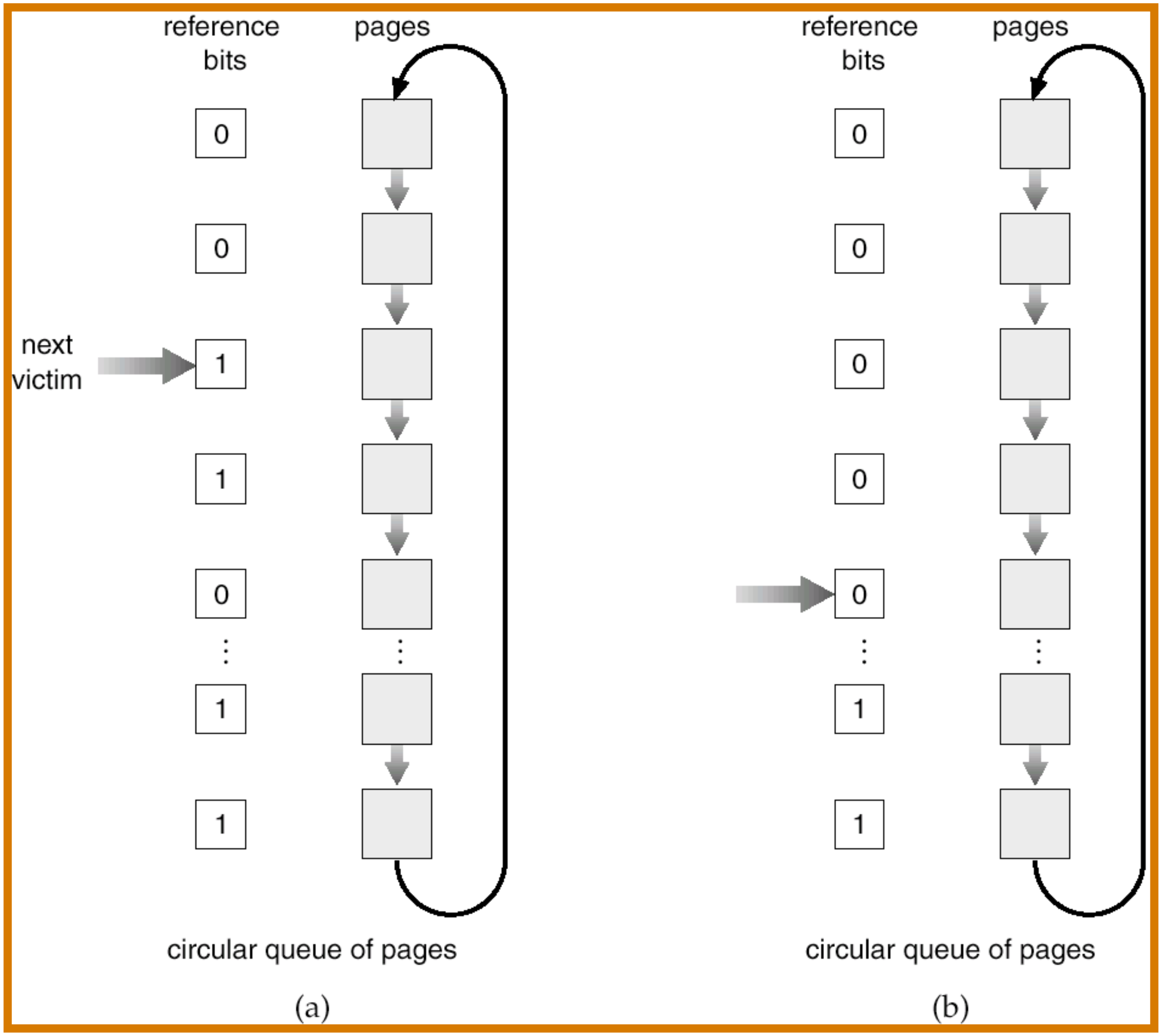
Use Of A Stack to Record The Most Recent Page References



LRU Approximation Algorithms

- **Reference bit**
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1.
  - Replace the one which is 0 (if one exists). We do not know the order, however.
- **Second chance**
  - Need reference bit.
  - Clock replacement.
  - If page to be replaced (in clock order) has reference bit = 1. then:
    - set reference bit 0.
    - leave page in memory.
    - replace next page (in clock order), subject to same rules.

Second-Chance (clock) Page-Replacement Algorithm



Counting Algorithms

- Keep a counter of the number of references that have been made to each page.

- **LFU Algorithm:** replaces page with smallest count.

- **MFU Algorithm:** based on the argument that the page with the smallest count was probably just brought in and has yet to be used.

Allocation of Frames

- Each process needs a **minimum** number of pages.

- There are two major allocation schemes:
  - **fixed allocation**
  - **priority allocation**

Fixed Allocation

- Equal allocation – e.g., if 100 frames and 5 processes, give each 20 pages.
- Proportional allocation – Allocate according to the size of process.

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

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

Priority Allocation

- The **proportional allocation** scheme can use **priorities instead of 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 Replacement

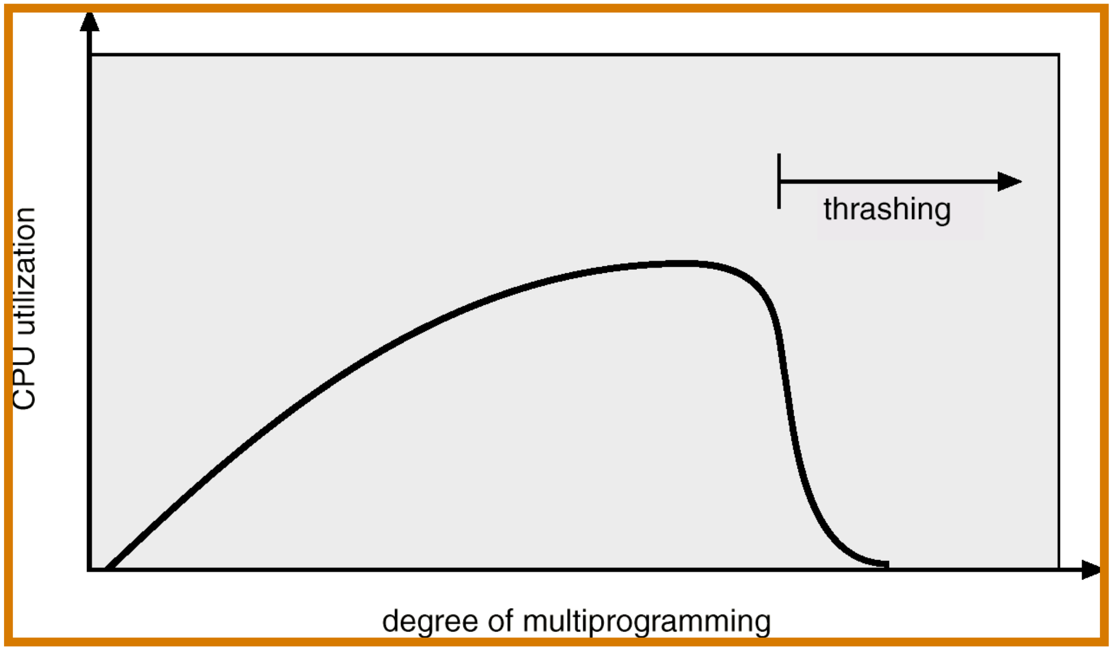
- **Global** replacement – process selects a replacement frame from the set of all frames; one process can take a frame from another.
- **Local** replacement – each process selects from only its own set of allocated frames.

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.

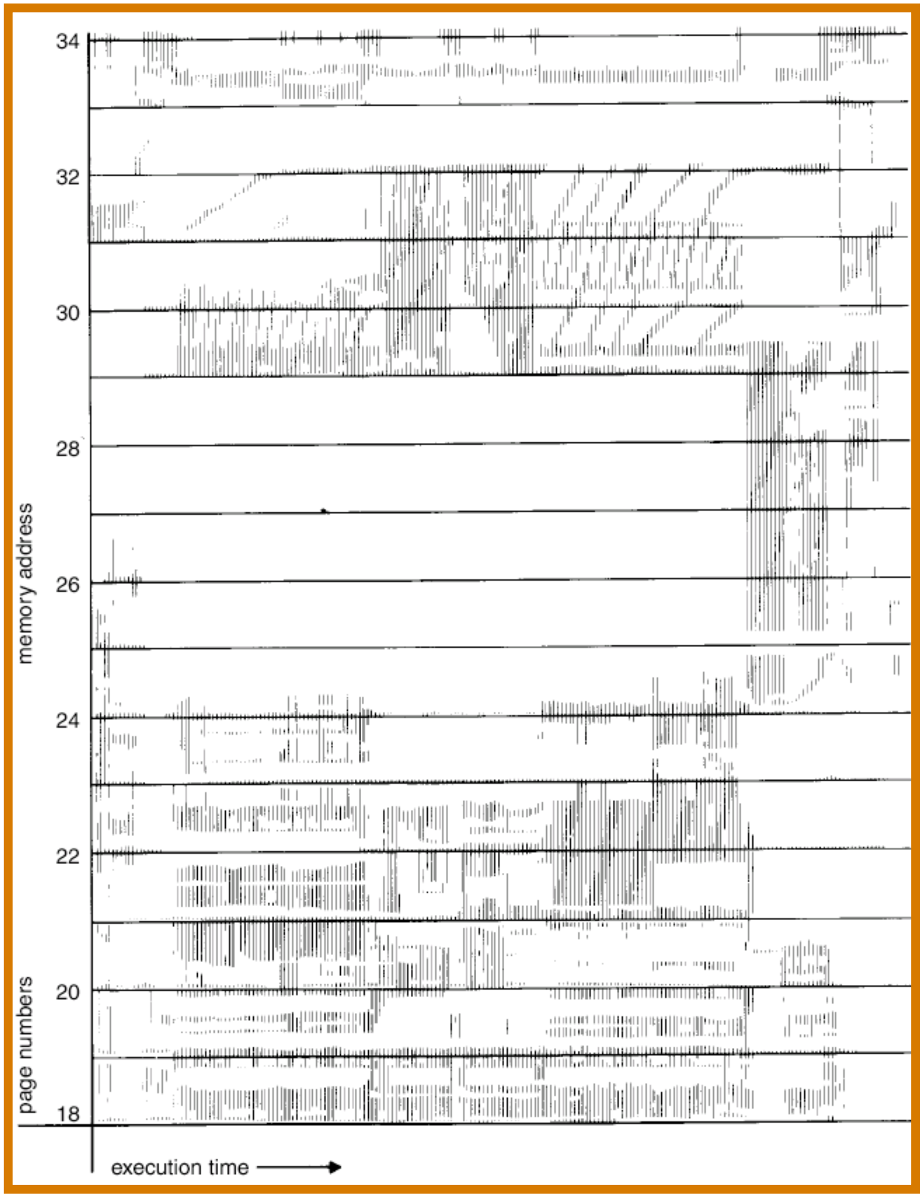
- **Thrashing** ≡ a process is busy swapping pages in and out.

Thrashing



- Why does 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 Memory-Reference Pattern

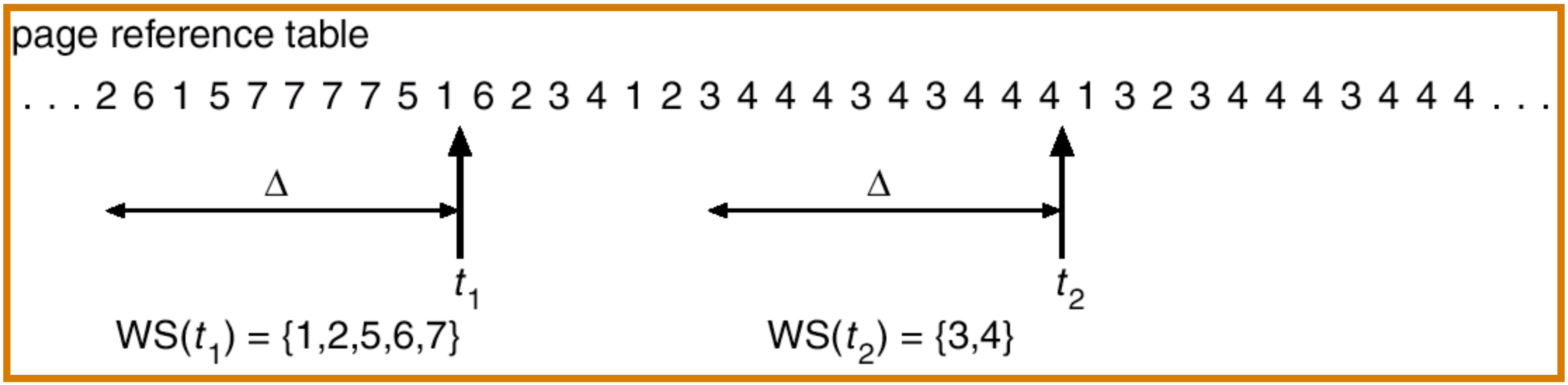


Working-Set Model

- $\Delta \equiv$ **working-set window** $\equiv$ a fixed number of page references.

- 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.
- $D = \Sigma\, WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ **Thrashing**
- Policy if $D > m$, then suspend one of the processes.

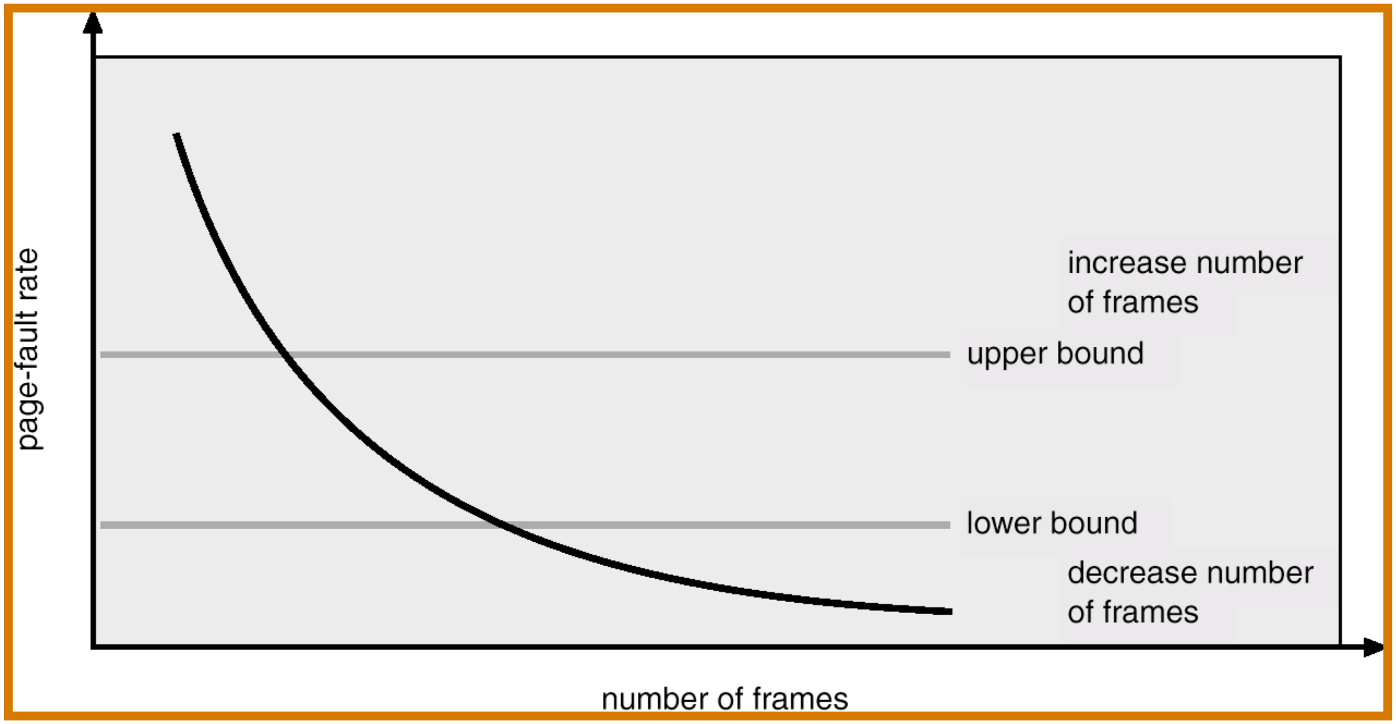
Working-set model



Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: $\Delta = 10{,}000$
  - Timer interrupts after every 5000 time units.
  - Keep in memory 2 bits for each page.
  - Whenever a timer interrupts copy and set 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.

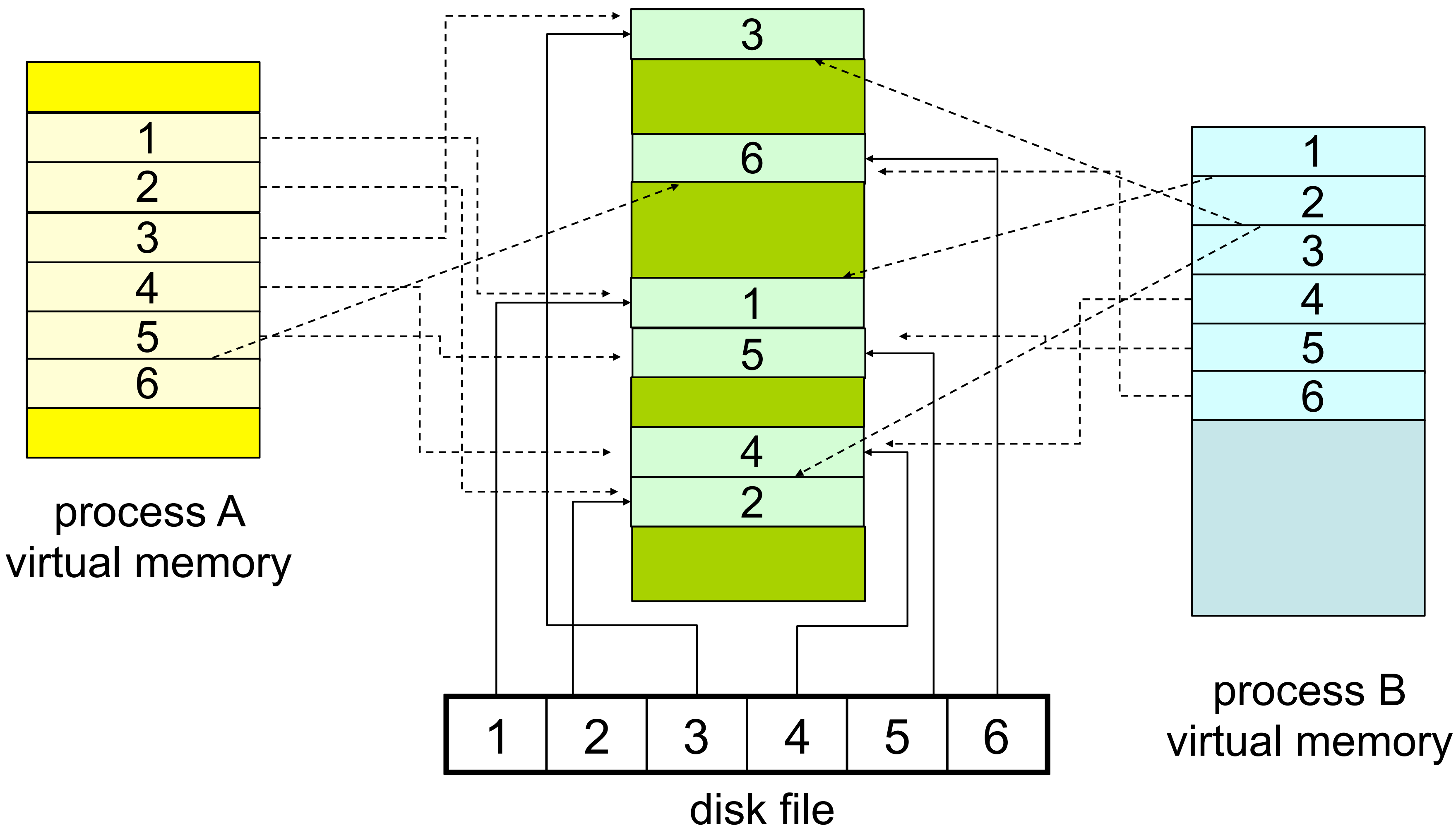
Memory-mapped Files

- Memory mapping a file can be accomplished by mapping a disk block to one or more pages in memory.

- A page-sized portion of the file is read from the file system into a physical page. Subsequent **`read()`** and **`write()`** operations are handled as memory (not disk) accesses.

- Writing to the file in memory is not necessarily synchronous to the file on disk. The file can be committed back to disk when it's closed.

Memory-mapped Files



Prepaging

- **Prepaging**: In order to avoid the initial number of page faults, the system can bring into memory all the pages that will be needed all at once.

- This can also be applied when a swapped-out process is restarted. The smart thing to do is to remember the working set of the process.

- One question that arises is whether all the pages brought in will actually be used…

- Is the cost of prepaging less than the cost of servicing each individual page fault?