Virtual Memory

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

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

Valid-Invalid Bit

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

Frame #	valid-invalid bit
	1
	1
	1
	1
	0
⋮	
	0
	0

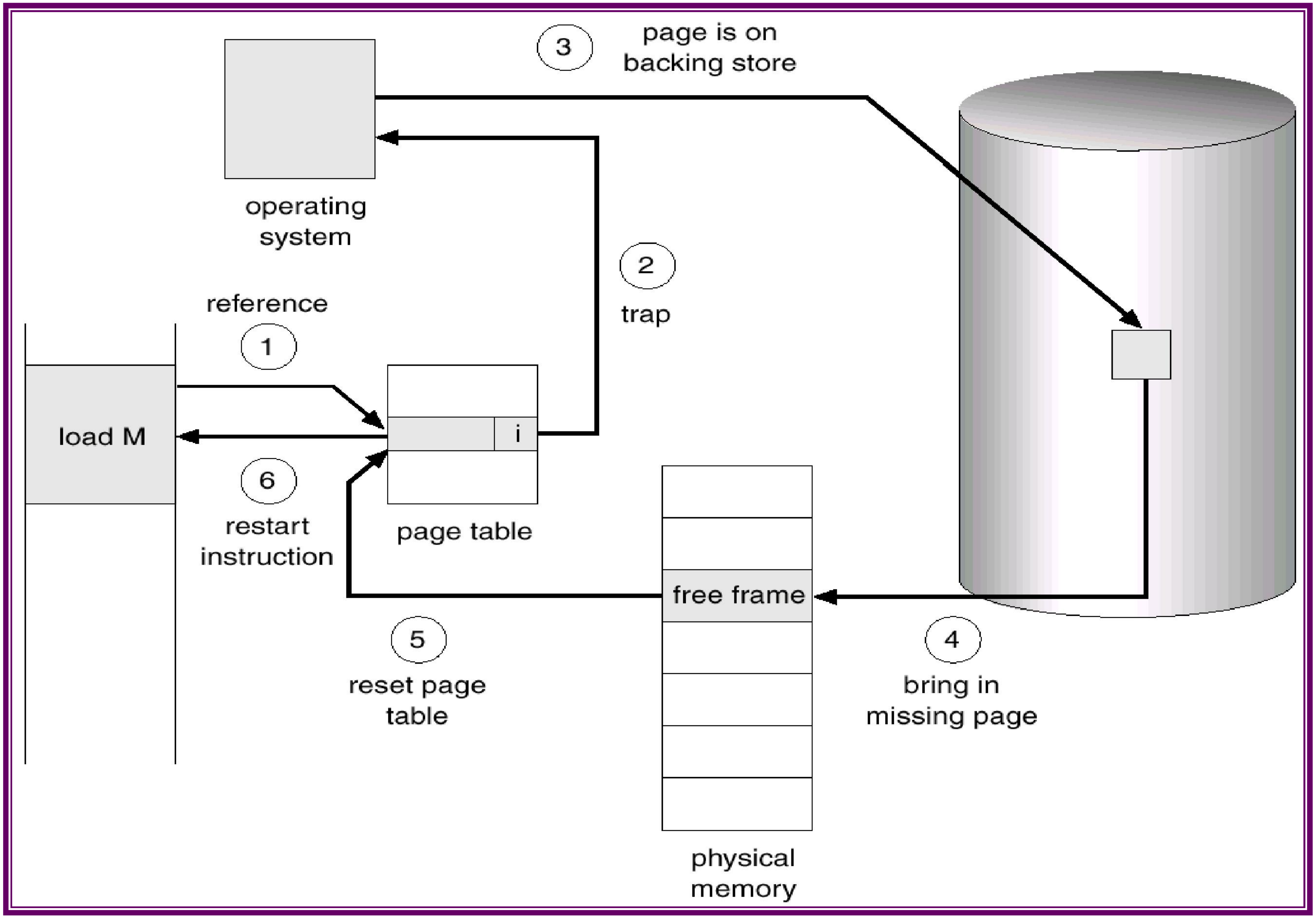
page table

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

Page Fault

- If there is ever a reference to a page, first reference will trap to OS $\Rightarrow$ page fault
- OS looks at another table to decide:
  - ➔Invalid reference $\Rightarrow$ abort.
  - ➔Just not in memory.
- Get empty frame.
- Swap page into frame.
- Reset tables, validation bit = 1.
- Restart instruction

Steps in Handling a Page Fault



What happens if there is no free frame?

- Page replacement – find some page in memory, but not really in use, swap it out.
  - ➔algorithm
  - ➔performance – want an algorithm which will result in minimum number of page faults.
- Same page may be brought into memory several times.

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)

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

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

Demand Paging Example

- Memory access time = 1 microsecond
- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out.
- Swap Page Time = 10 msec = 10,000 microsec

$$EAT = (1 - p) \times 1 + p\,(10000)$$

$$1 + 10000p$$

Page Replacement

- Page-fault service routine includes 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.

Replacement Policy

- Which page is replaced?
- Page removed should be the page least likely to be referenced in the near future
- Most policies predict the future behavior on the basis of past behavior

Replacement Policy

- Frame Locking
  - ➔ If frame is locked, it may not be replaced
  - ➔ Kernel of the operating system
  - ➔ Key control structures
  - ➔ I/O buffers
  - ➔ Associate a lock bit with each frame

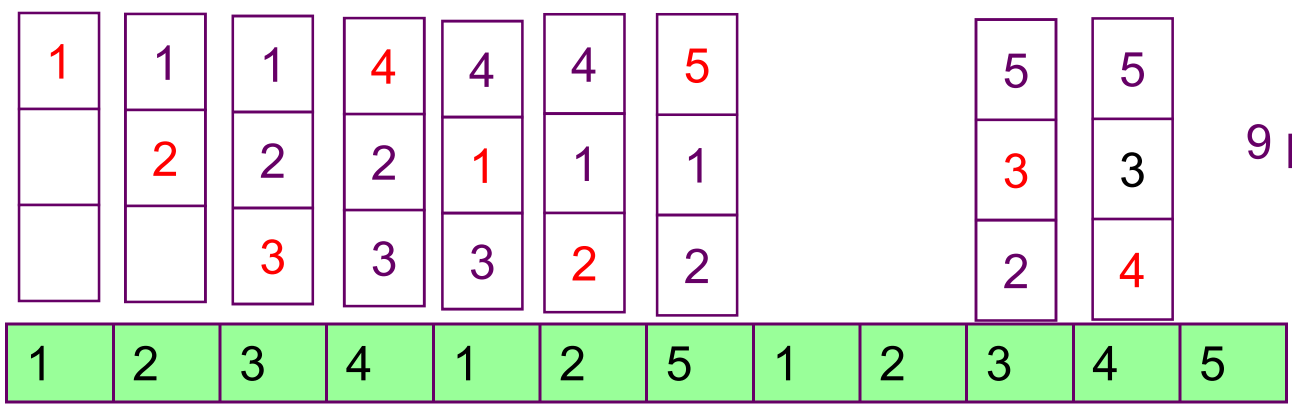
Page Replacement Algorithms

- 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.

First-In-First-Out (FIFO) Algorithm

- 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)

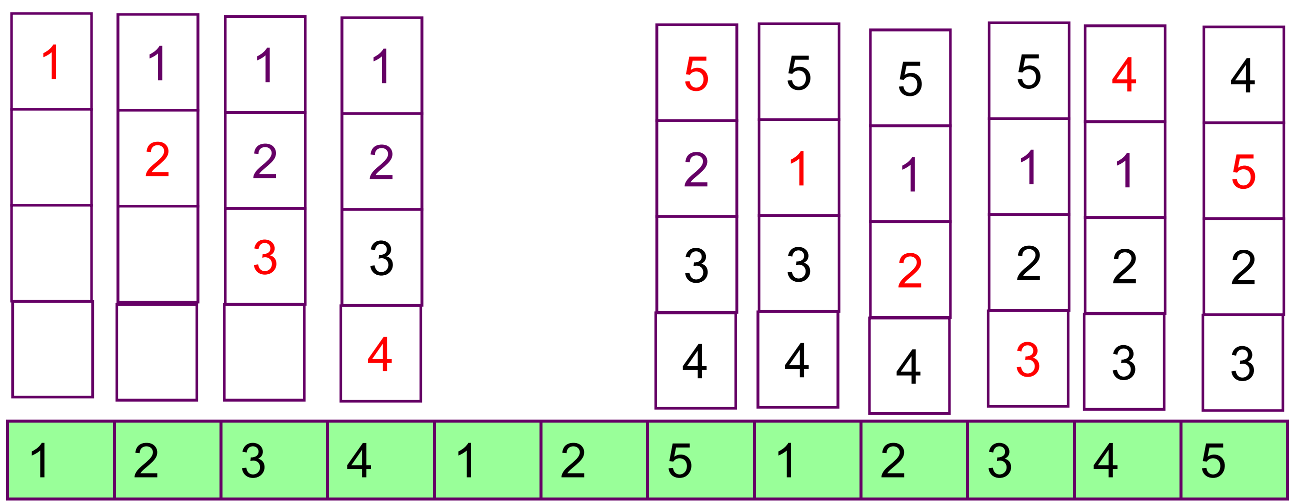


9 page faults

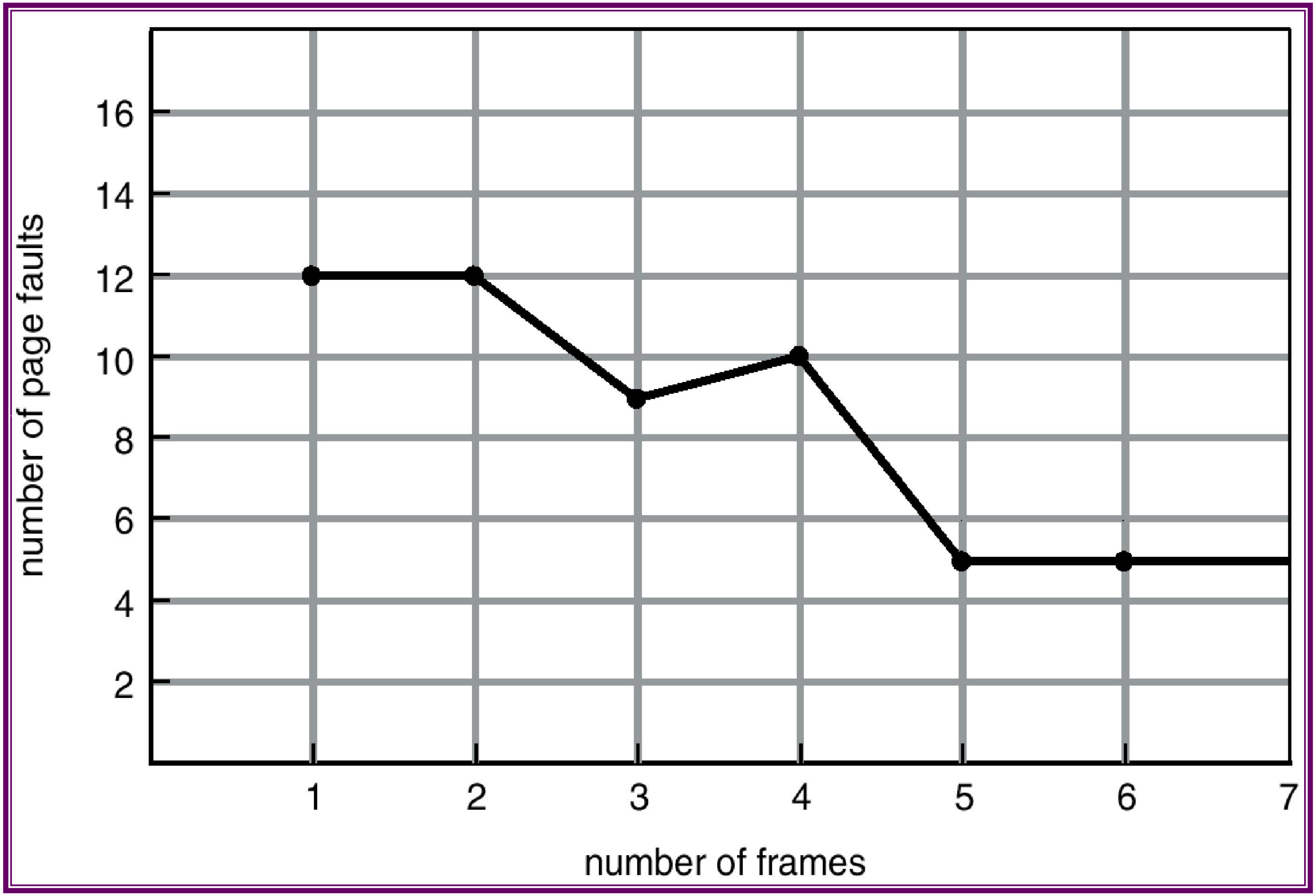
First-In-First-Out (FIFO) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 4 frames (4 pages can be in memory at a time)
- In general more frames $\Rightarrow$ less page faults
- FIFO Replacement – Belady’s Anomaly

10 page faults



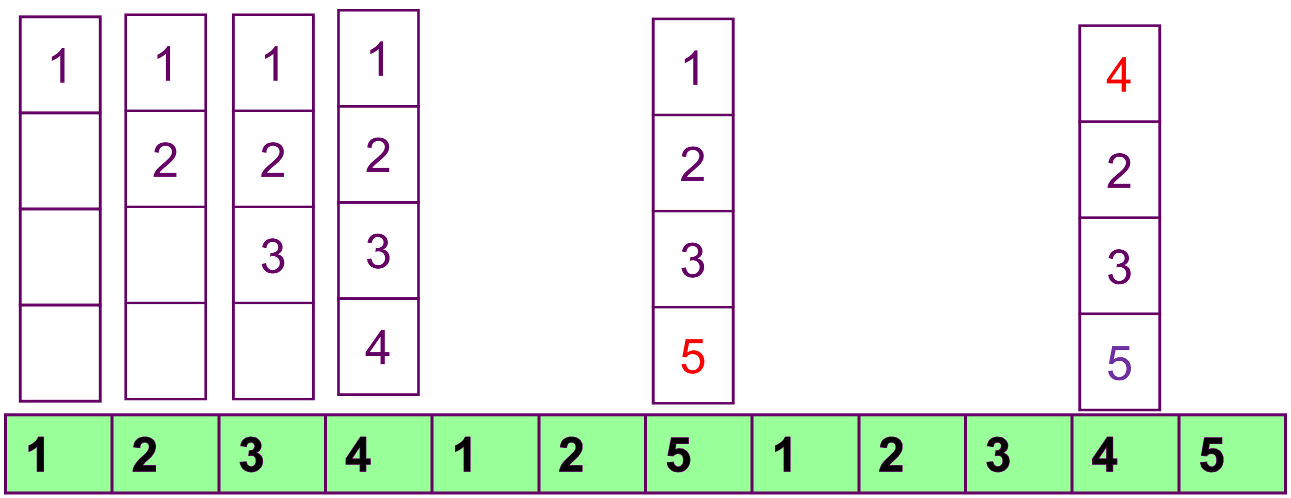
FIFO Illustrating Belady's Anomaly



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

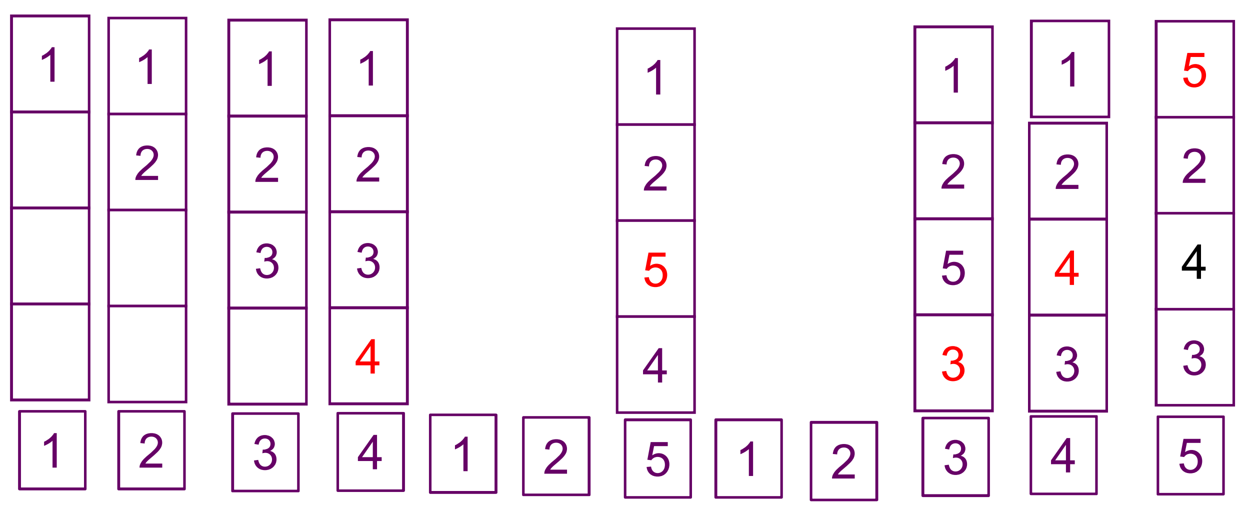


6 page faults

- Used for measuring how well algorithm performs.

Least Recently Used (LRU) Algorithm

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



LRU Implementation

- 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 Algorithm (Cont.)

- Stack implementation – keep a stack of page numbers in a double link form:
  - ➔Page referenced:
    - ➔move it to the top
  - ➔No search for replacement

No Belady's anomaly➔ Stack Algorithms

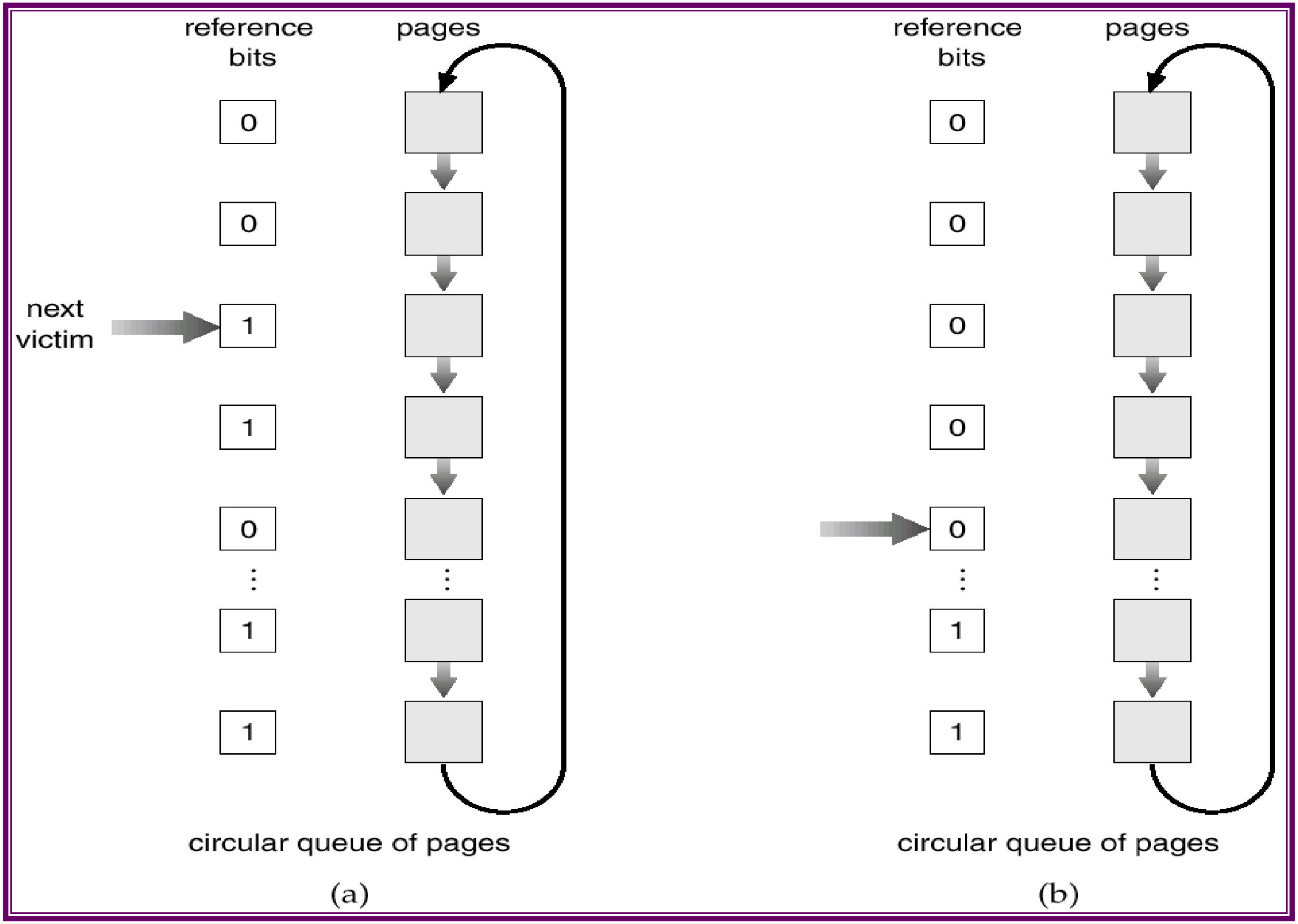
LRU Approximation Algorithms

- 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.
  - ➔If page to be replaced (in clock wise order) has reference bit = 1. then:
    - ➔set reference bit 0.
    - ➔leave page in memory.
    - ➔replace next page (in clock wise order), subject to same rules.

The Clock Policy

- A method to give ‘a chance’ to recently used pages
  - ➔a *new* page is not replaced unless there is no other choice
- The set of frames candidate for replacement is considered as a circular buffer
- When a page is replaced, a pointer is set to point to the next frame in buffer
- A use bit for each frame is set to 1 whenever
  - ➔a page is first loaded into the frame
  - ➔the corresponding page is referenced
- When it is time to replace a page, the first frame encountered with the use bit = 0 is replaced.
  - ➔During the search for replacement, each use bit set to 1 is changed to 0

Second-Chance (clock) Page-Replacement Algorithm



Enhanced Clock Policy

- In addition to reference bit use modify bit also
  - (0 ,0) not referenced not modified
  - (0, 1) Not recently used but modified
  - (1,0) recently used but not modified
  - (1,1) recently used and modified

Comparison

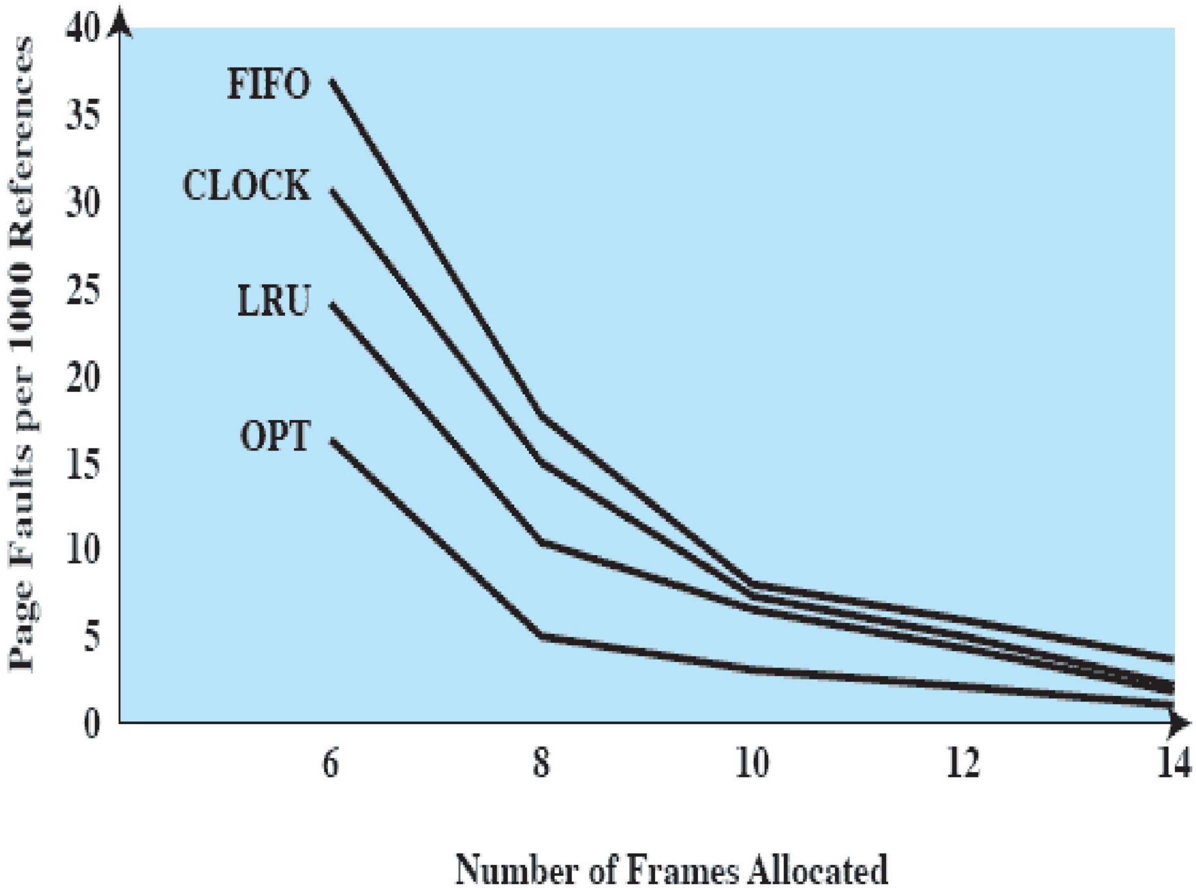


Figure 8.17 Comparison of Fixed-Allocation, Local Page Replacement Algorithms

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 **minimum** number of pages.
- Example:
- MOV source, destination
  - ➔instruction is 4 bytes, might span 2 pages.
  - ➔2 pages to handle **from**.
  - ➔2 pages to handle **to**.

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

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

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.

  ➔ Process cannot control its own Page fault rate

- **Local** replacement – each process selects from only its own set of allocated frames.

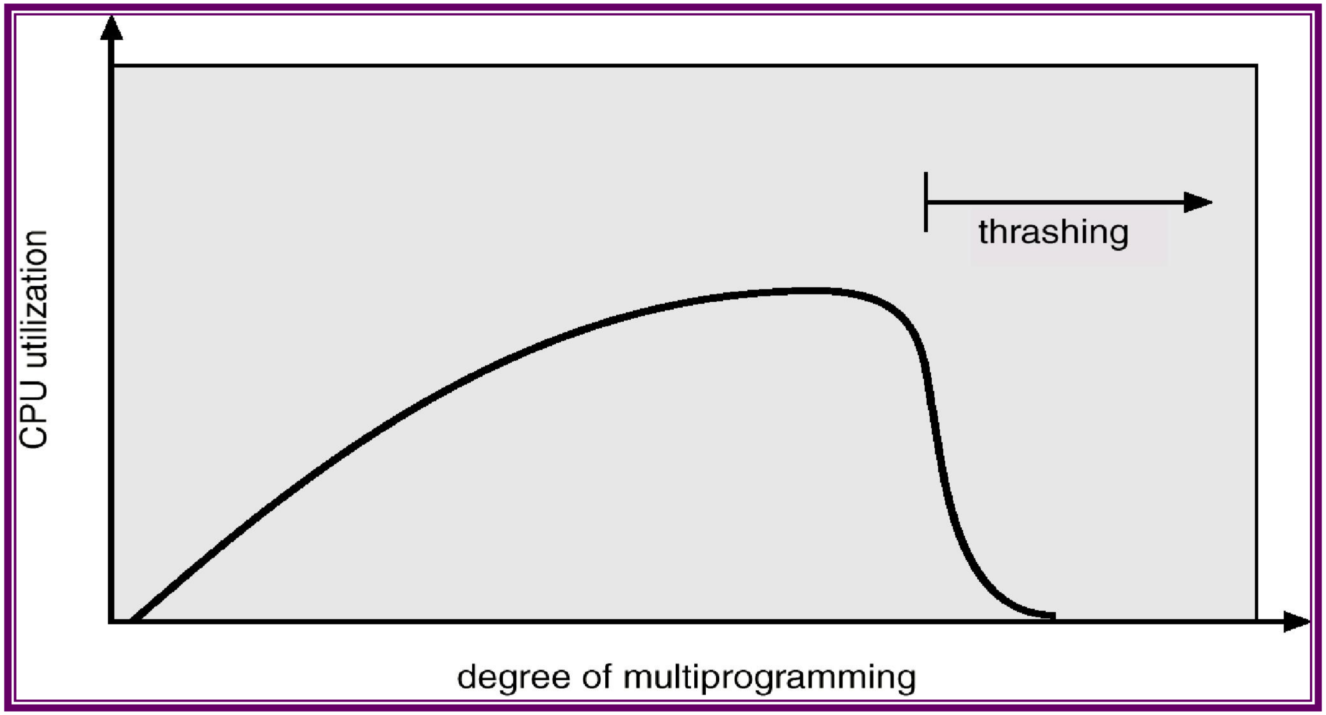
  ➔Number of frames allocated to a process do not change

  ➔Does not make use of less used pages belonging to other processes

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.
  - ➔ More pronounced for Global page replacement policy

Thrashing

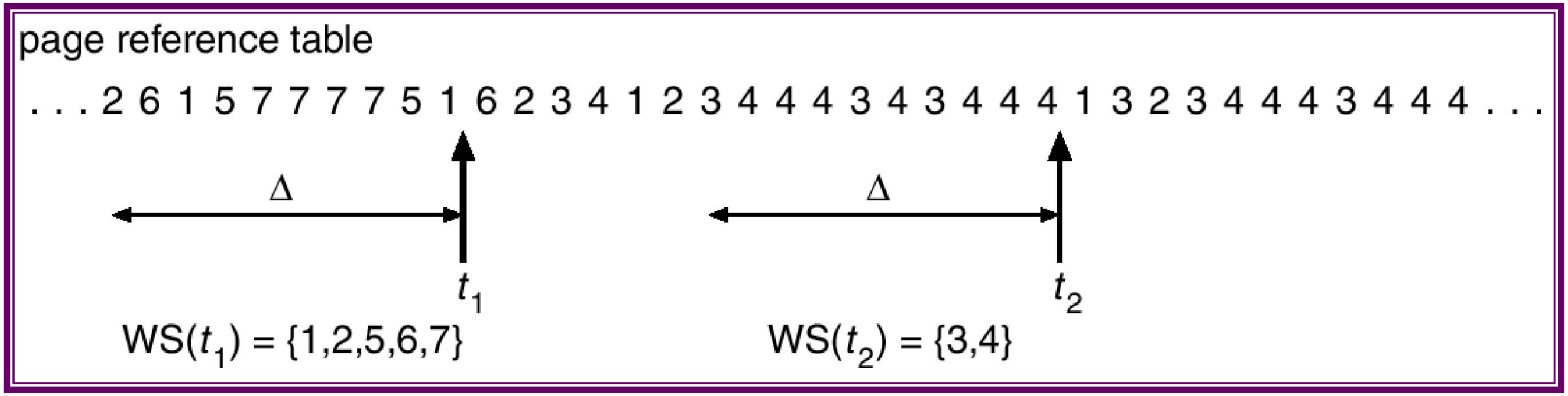


- Why does paging work?
  Locality model
  - ➔Process migrates from one locality to another.
  - ➔Localities may overlap.
- Why does thrashing occur?
  Σ size of locality > total memory size

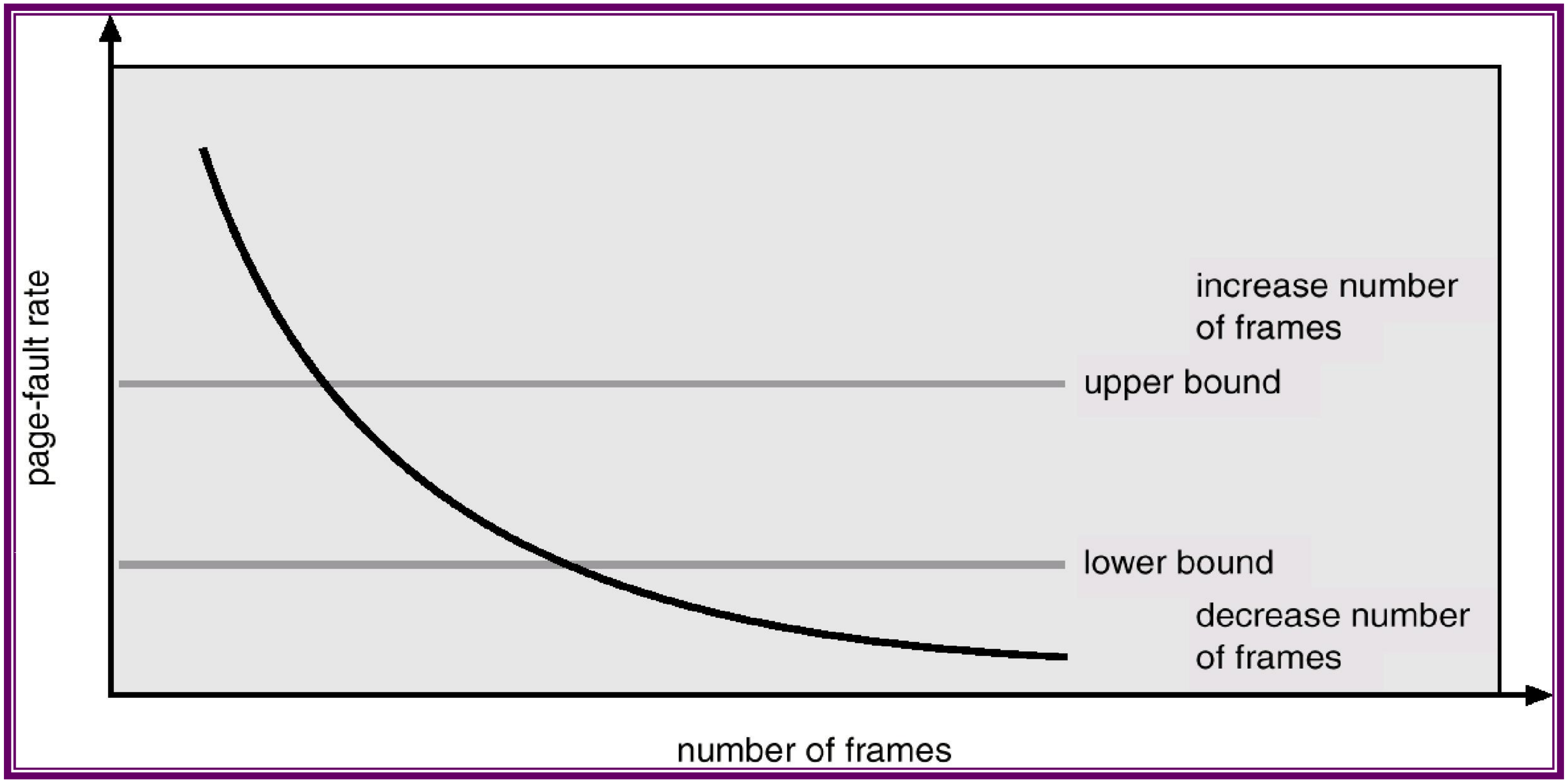
Working-Set Model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  Example: 10,000 instruction
- 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 $D > m$ *(Total number of available frames)* $\Rightarrow$ Thrashing
- Policy if $D > m$, then suspend one of the processes.

Working-set model



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.

Other Considerations

- Page Buffering:

➔Maintain a pool of free frames to quickly restart a faulting process

➔ Can be used to improve performance of some simple page replacement algorithms like FIFO

- Prepaging:
  ➔Bring in the complete working set of a swapped out process to avoid initial multiple faults

Other Considerations (Cont.)

- **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.

Other Considerations (Cont.)

- Program structure
  - ➔**int A[ ][ ] = new int[1024][1024];**
  - ➔Each row is stored in one page
  - ➔Program 1

```
for (j = 0; j < A.length; j++)
    for (i = 0; i < A.length; i++)
            A[i,j] = 0;
```

    1024 x 1024 page faults

  - ➔Program 2

```
for (i = 0; i < A.length; i++)
    for (j = 0; j < A.length; j++)
            A[i,j] = 0;
```

    1024 page faults

Thanks