Chapter 9: Virtual Memory

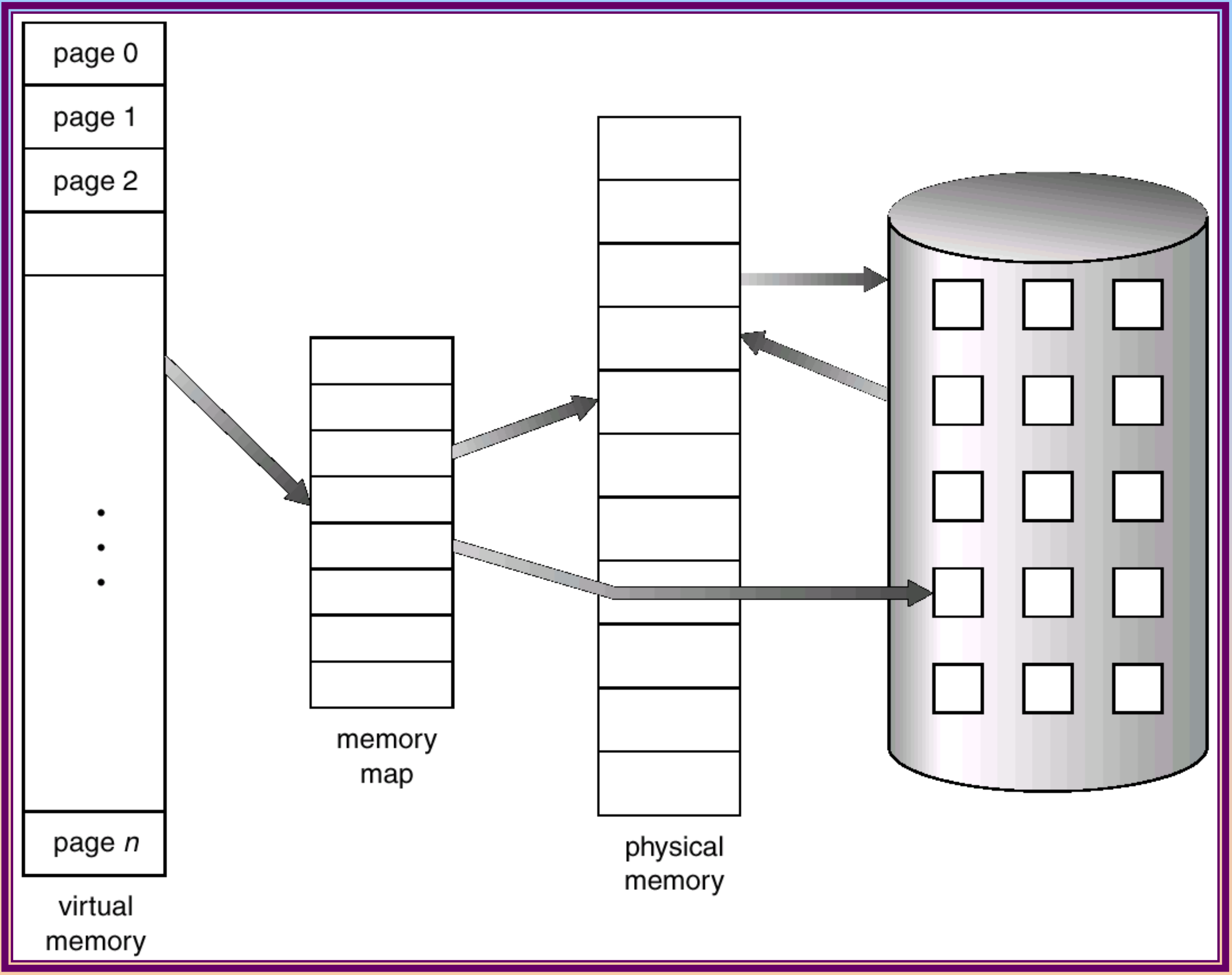
- Background
- Demand Paging
- Process Creation
- Page Replacement
- Allocation of Frames
- Thrashing
- Operating System Examples

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

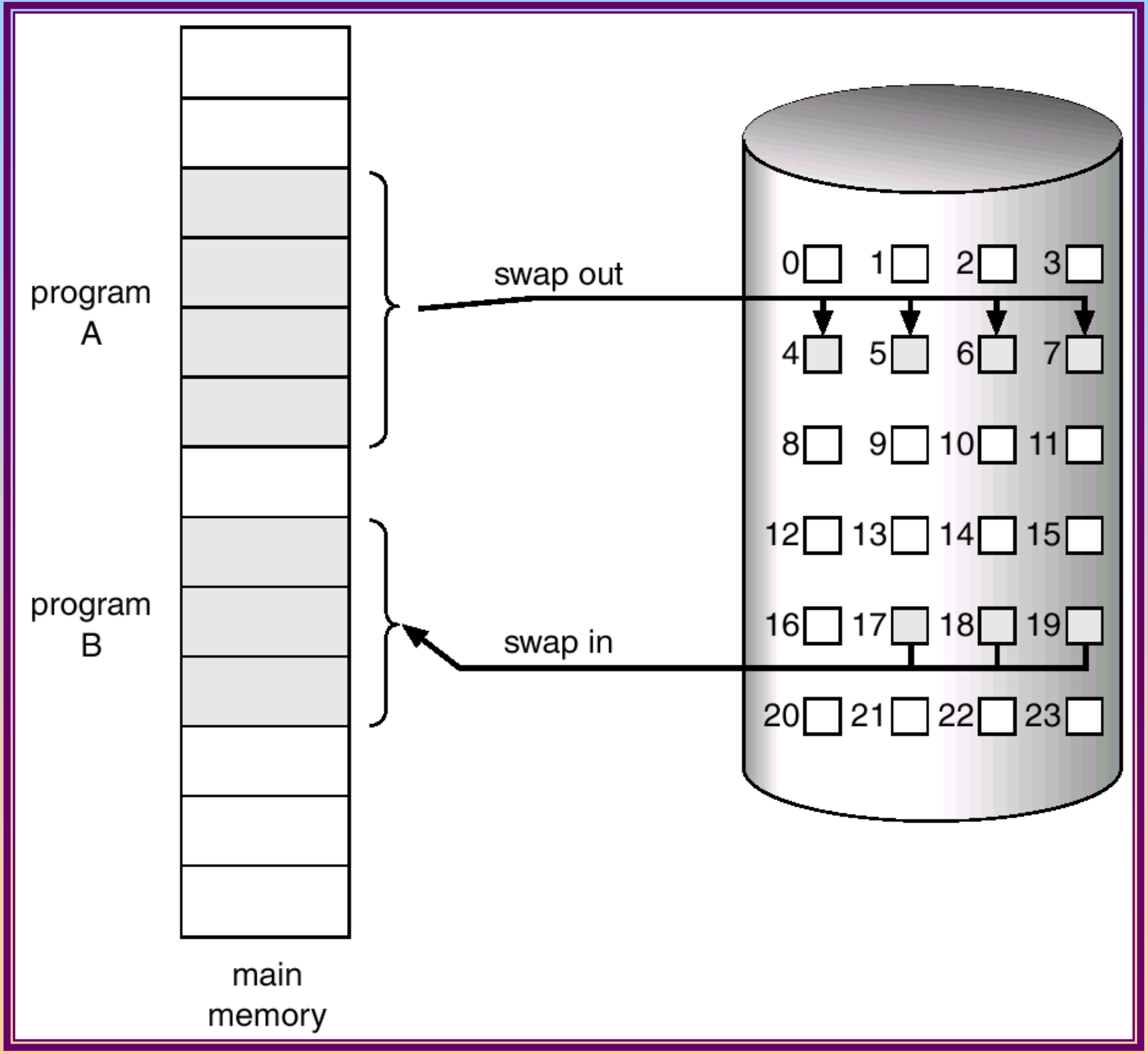
Virtual Memory That is Larger Than Physical Memory



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

Transfer of a Paged Memory to Contiguous Disk Space



Valid-Invalid Bit

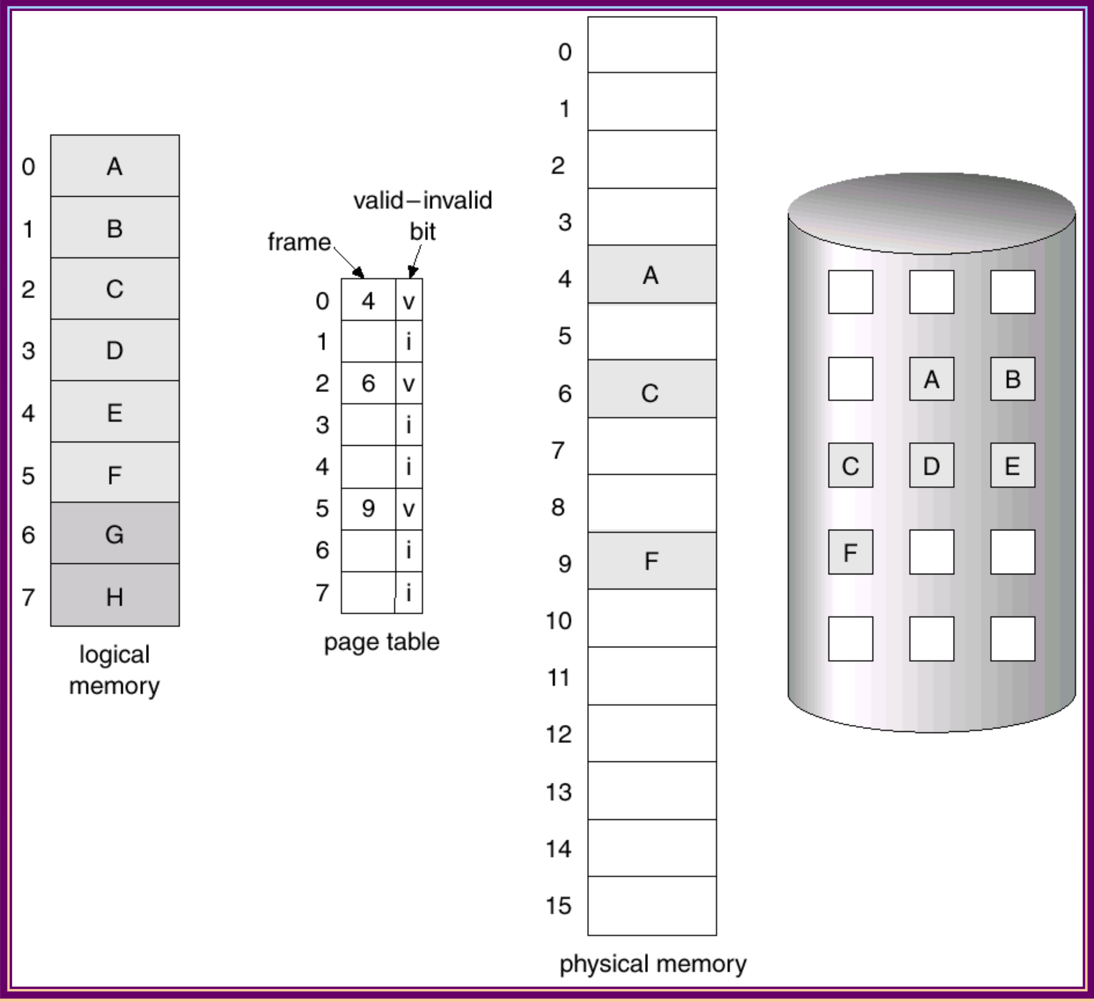
- With each page table entry a valid–invalid bit is associated
  (1 ⇒ in-memory, 0 ⇒ not-in-memory)
- Initially valid–invalid but is set to 0 on all entries.
- Example of a page table snapshot.

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

page table

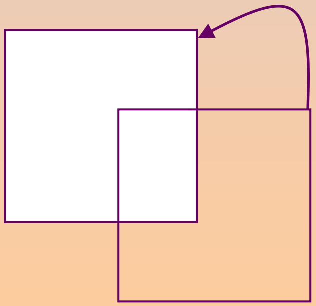
- During address translation, if valid–invalid bit in page table entry is 0 ⇒ page fault.

Page Table When Some Pages Are Not in Main Memory



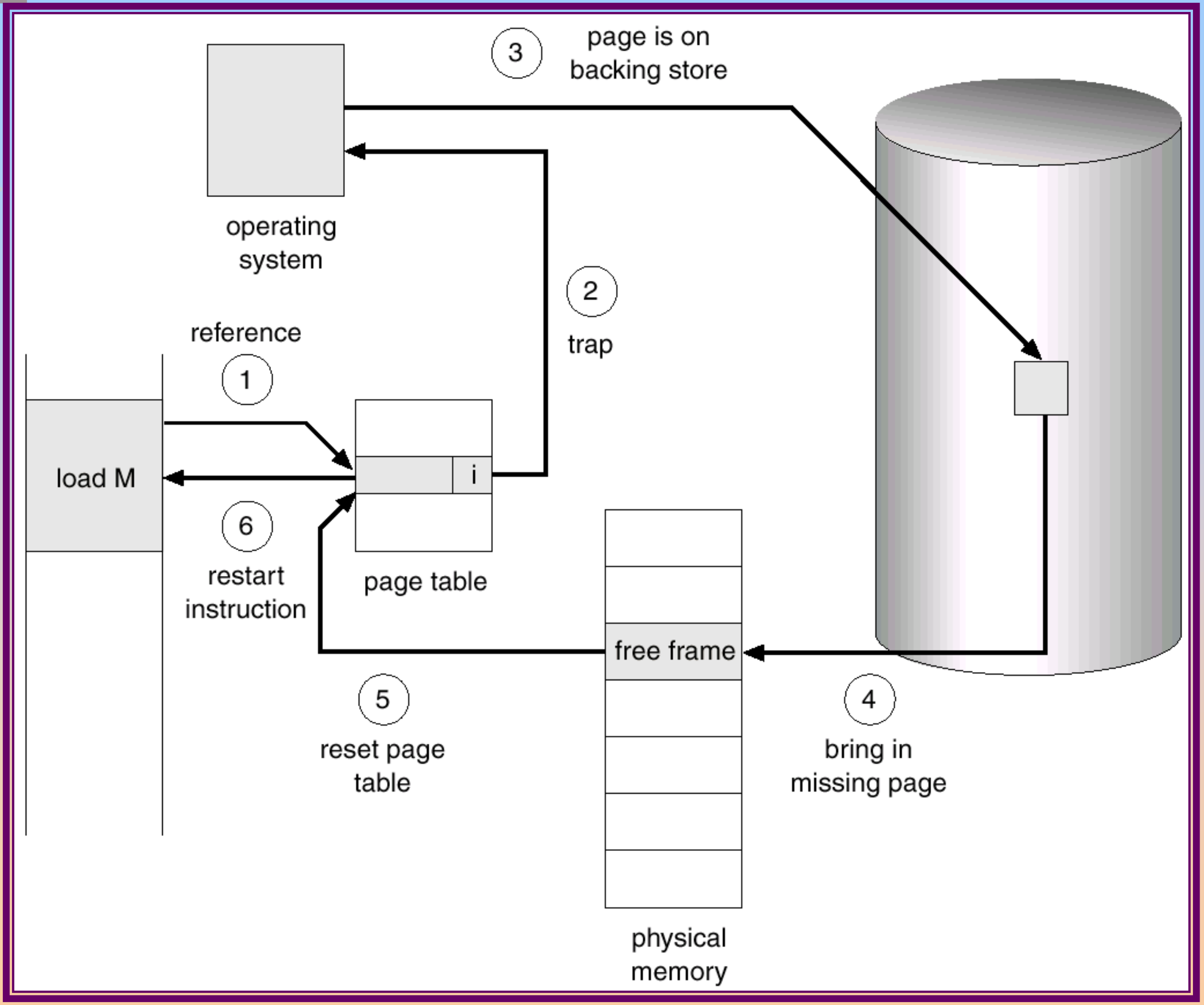
Page Fault

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



  - auto increment/decrement location

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)

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

Demand Paging Example

- Memory access time = 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 msec

  EAT = (1 – p) x 1 + p (15000)

  1 + 15000P   (in msec)

Process Creation

- Virtual memory allows other benefits during process creation:

  - Copy-on-Write

  - Memory-Mapped Files

Copy-on-Write

- 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.

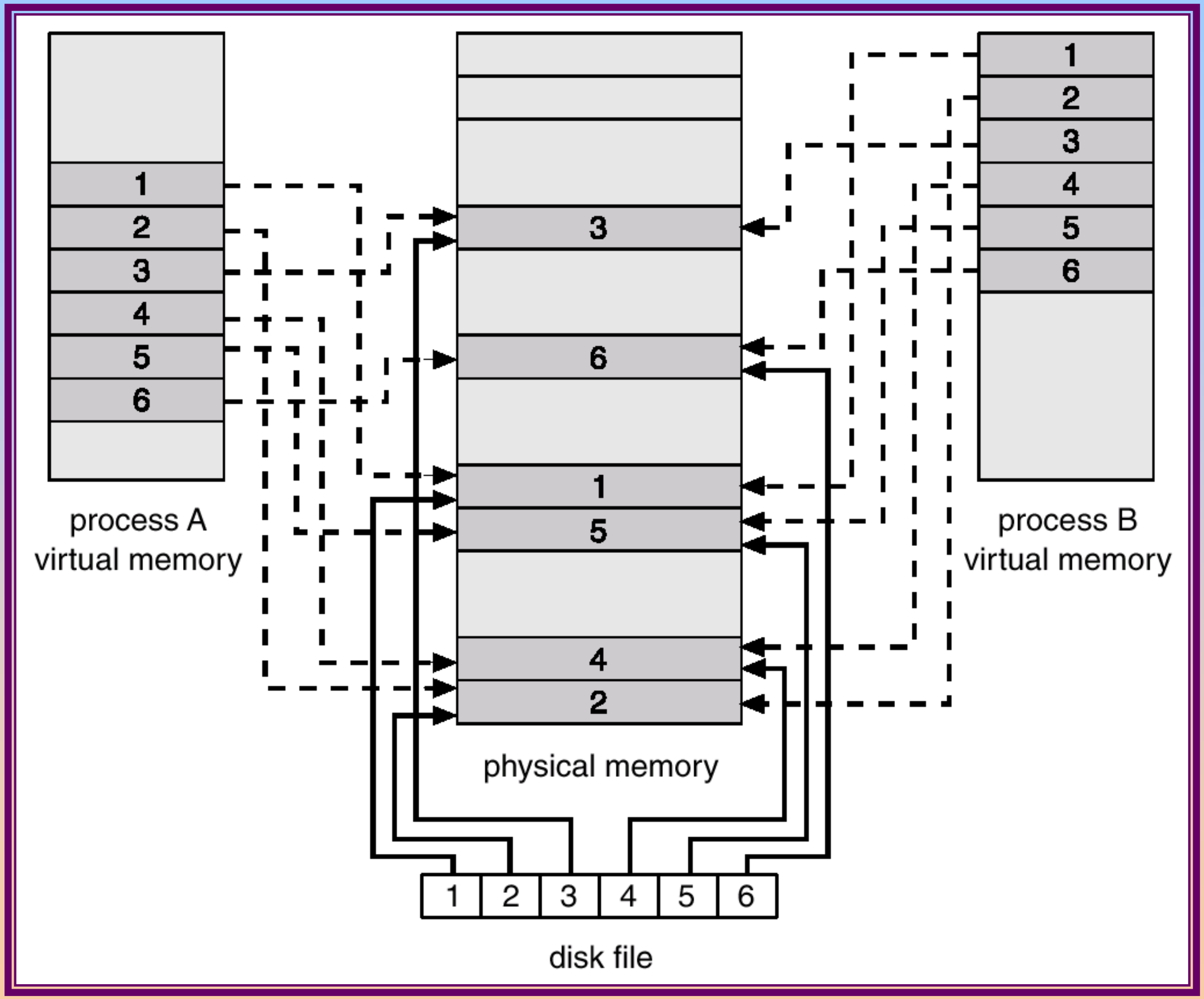
- COW allows more efficient process creation as only modified pages are copied.

- Free pages are allocated from a *pool* of zeroed-out pages.

Memory-Mapped Files

- Memory-mapped file I/O allows file I/O to be treated as routine memory access by *mapping* a disk block to a page in memory.
- A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical page. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.
- Simplifies file access by treating file I/O through memory rather than **read() write()** system calls.
- Also allows several processes to map the same file allowing the pages in memory to be shared.

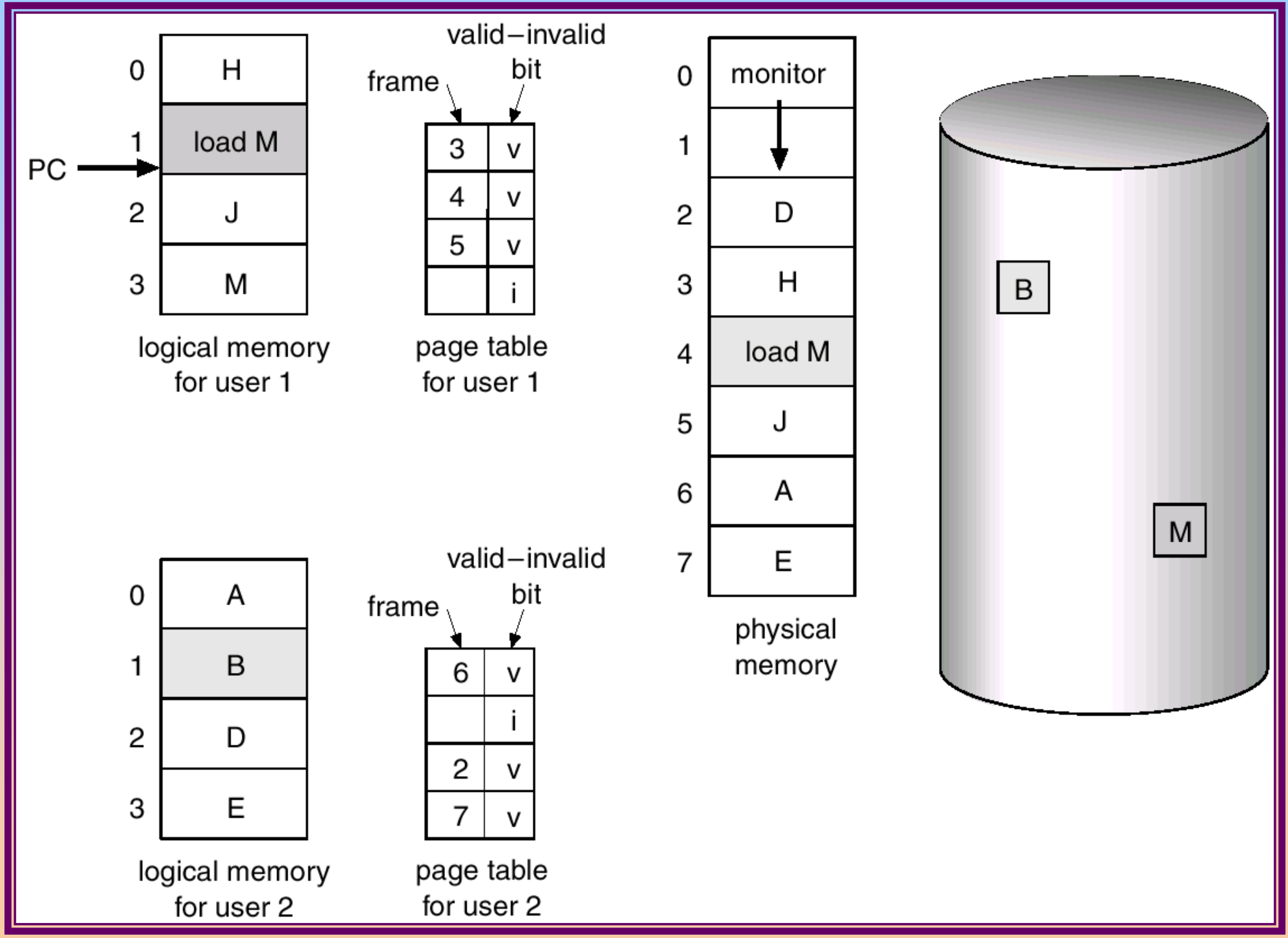
Memory Mapped Files



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

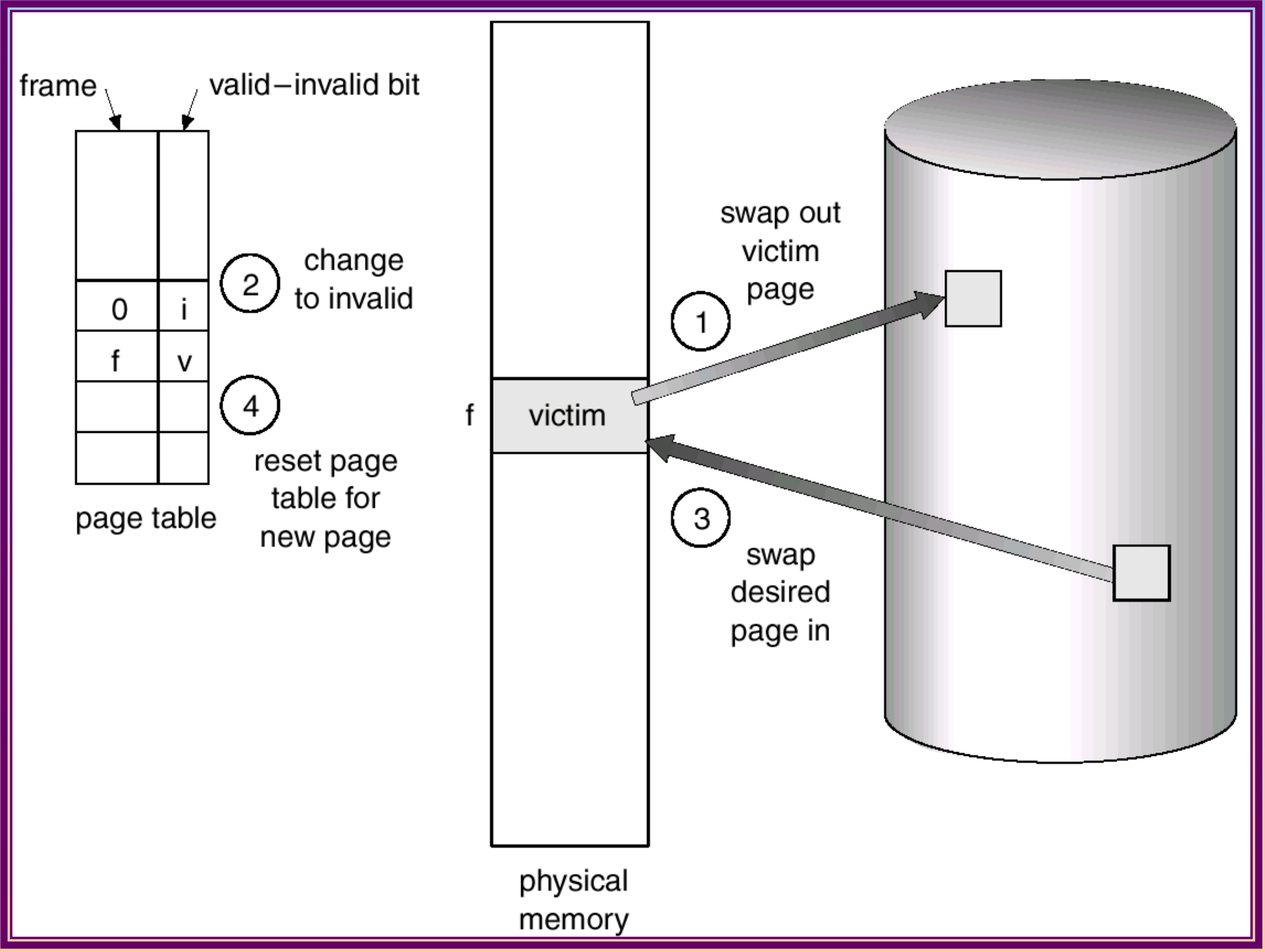
1. Find the location of the desired page on disk.

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.

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

4. Restart the process.

Page Replacement

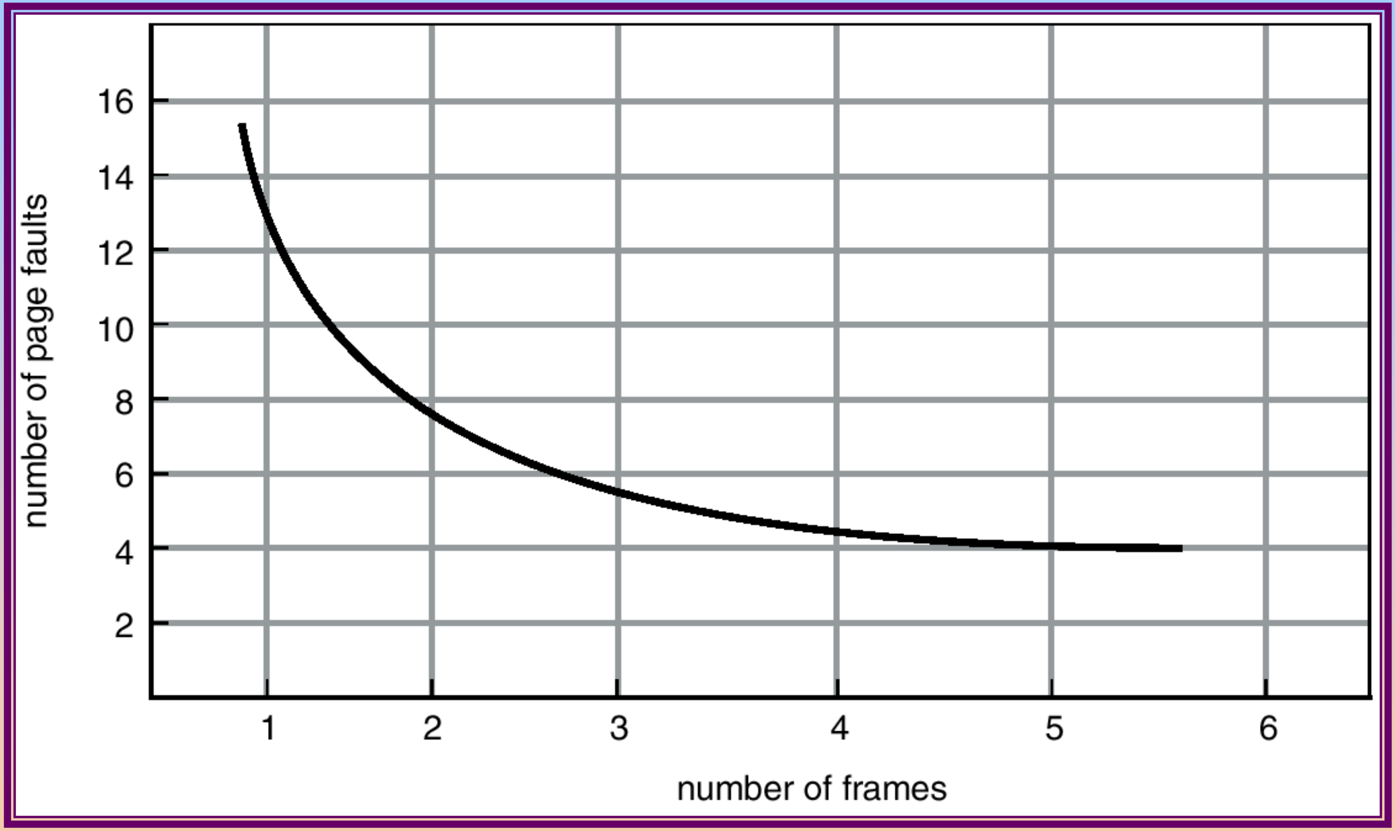


Page Replacement Algorithms

- 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

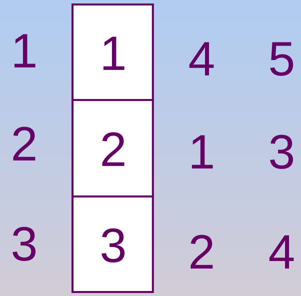
  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.

Graph of Page Faults Versus The Number of Frames



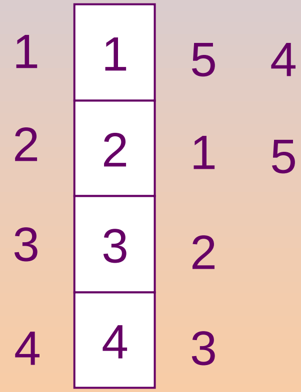
First-In-First-Out (FIFO) Algorithm

- 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

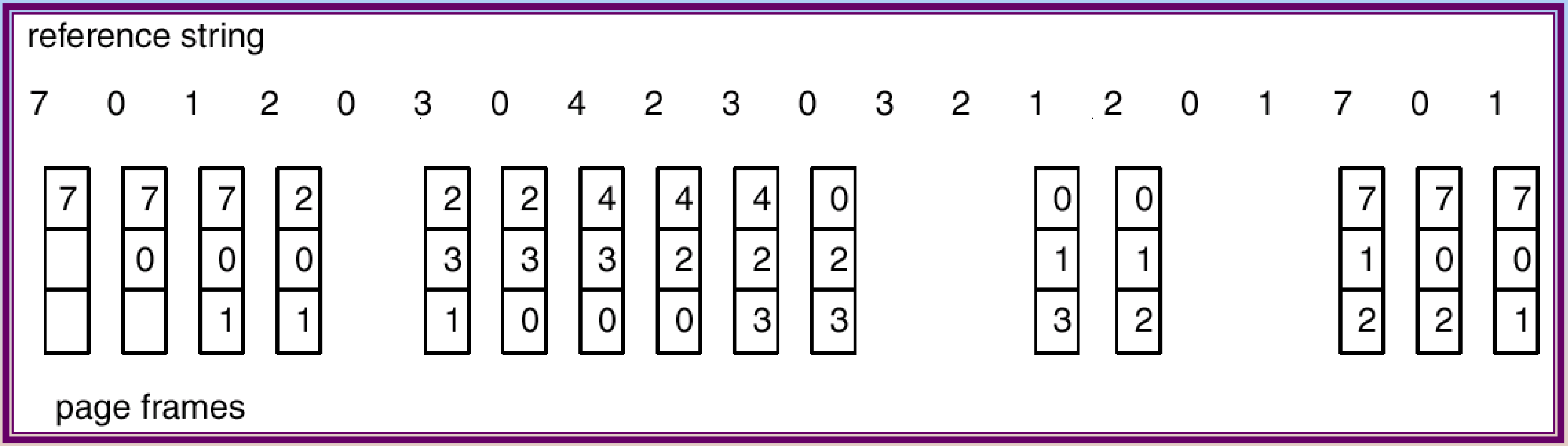
- 4 frames



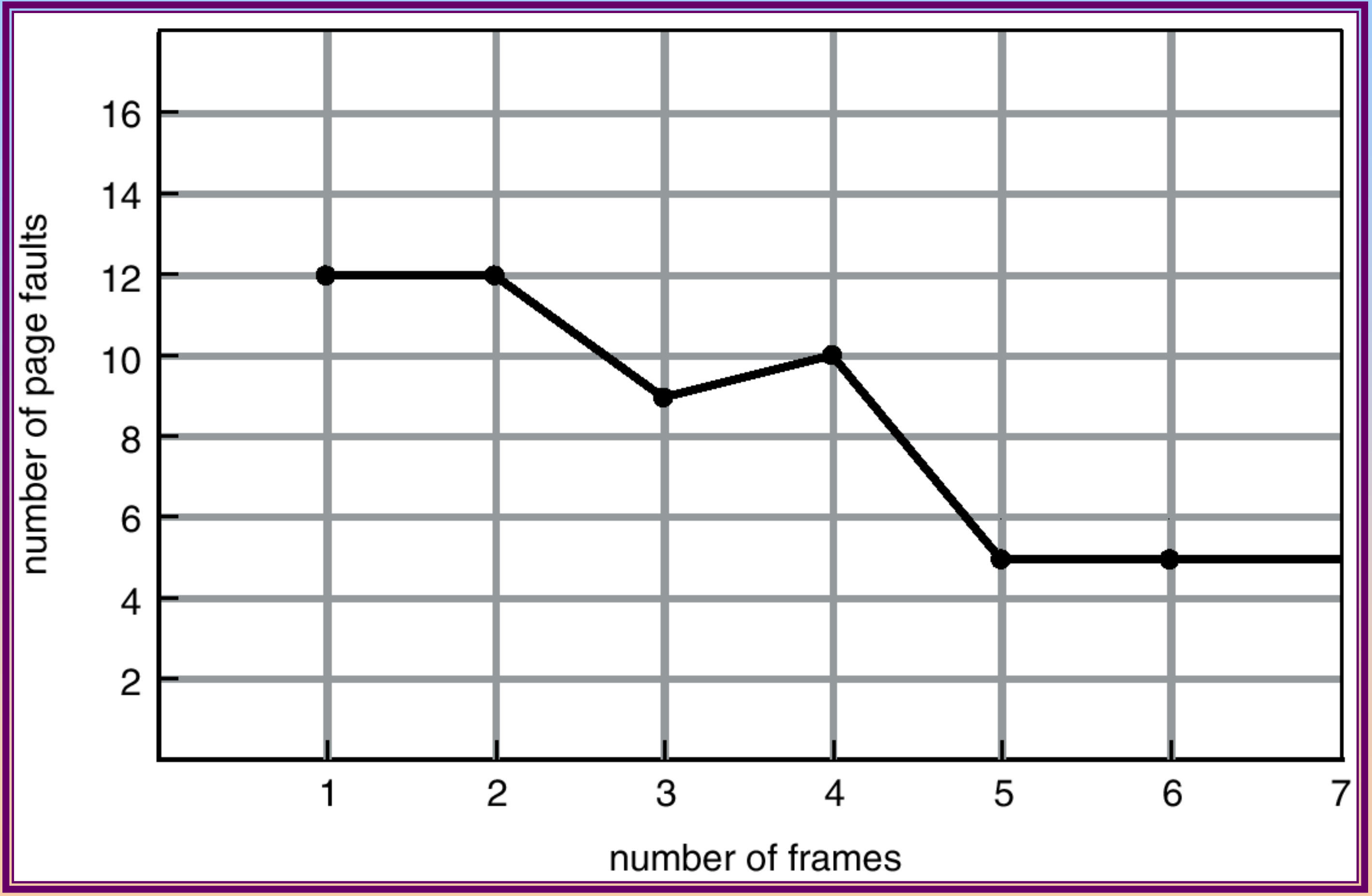
10 page faults

- FIFO Replacement – Belady’s Anomaly
  - more frames $\Rightarrow$ less page faults

FIFO Page Replacement



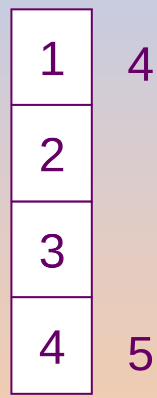
FIFO Illustrating Belady's Anamoly



Optimal Algorithm

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

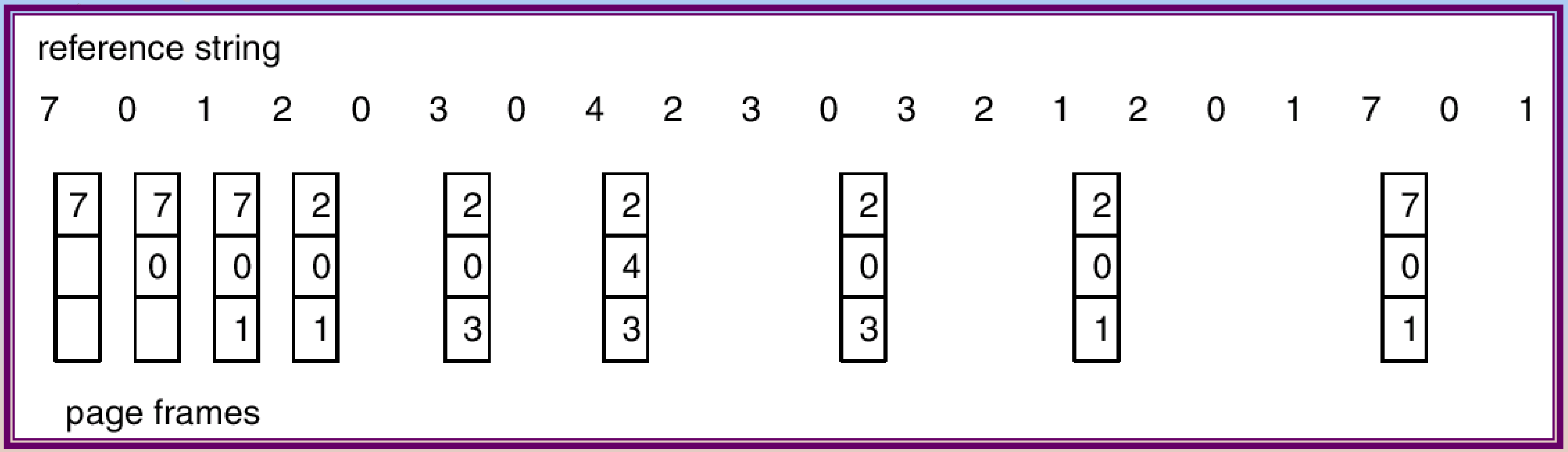
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



6 page faults

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

Optimal Page Replacement



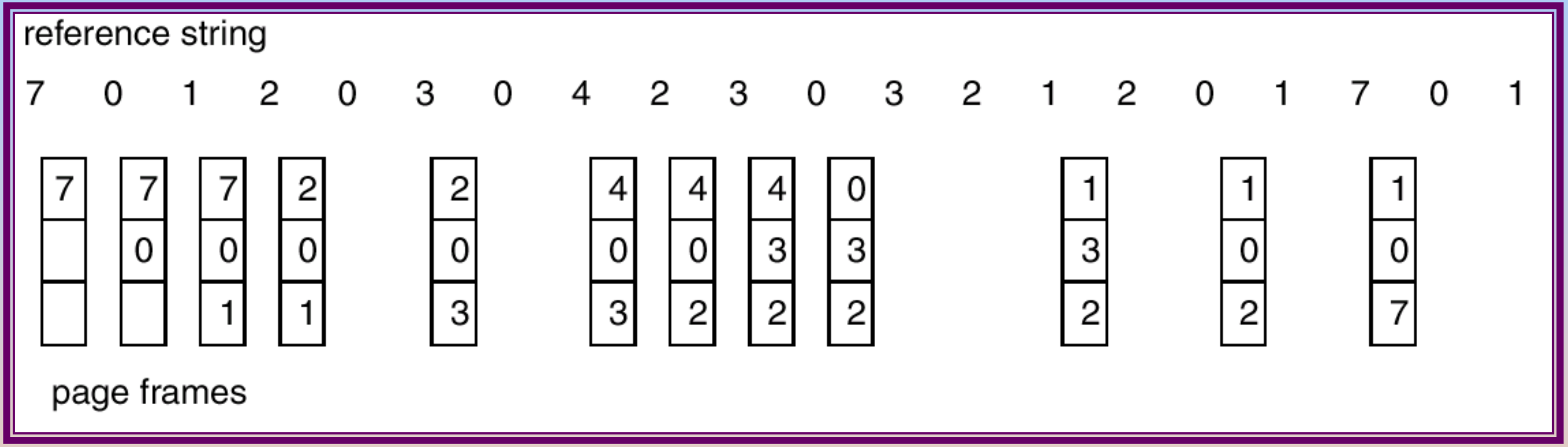
Least Recently Used (LRU) Algorithm

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

1	5	
2		
3	5	4
4	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.

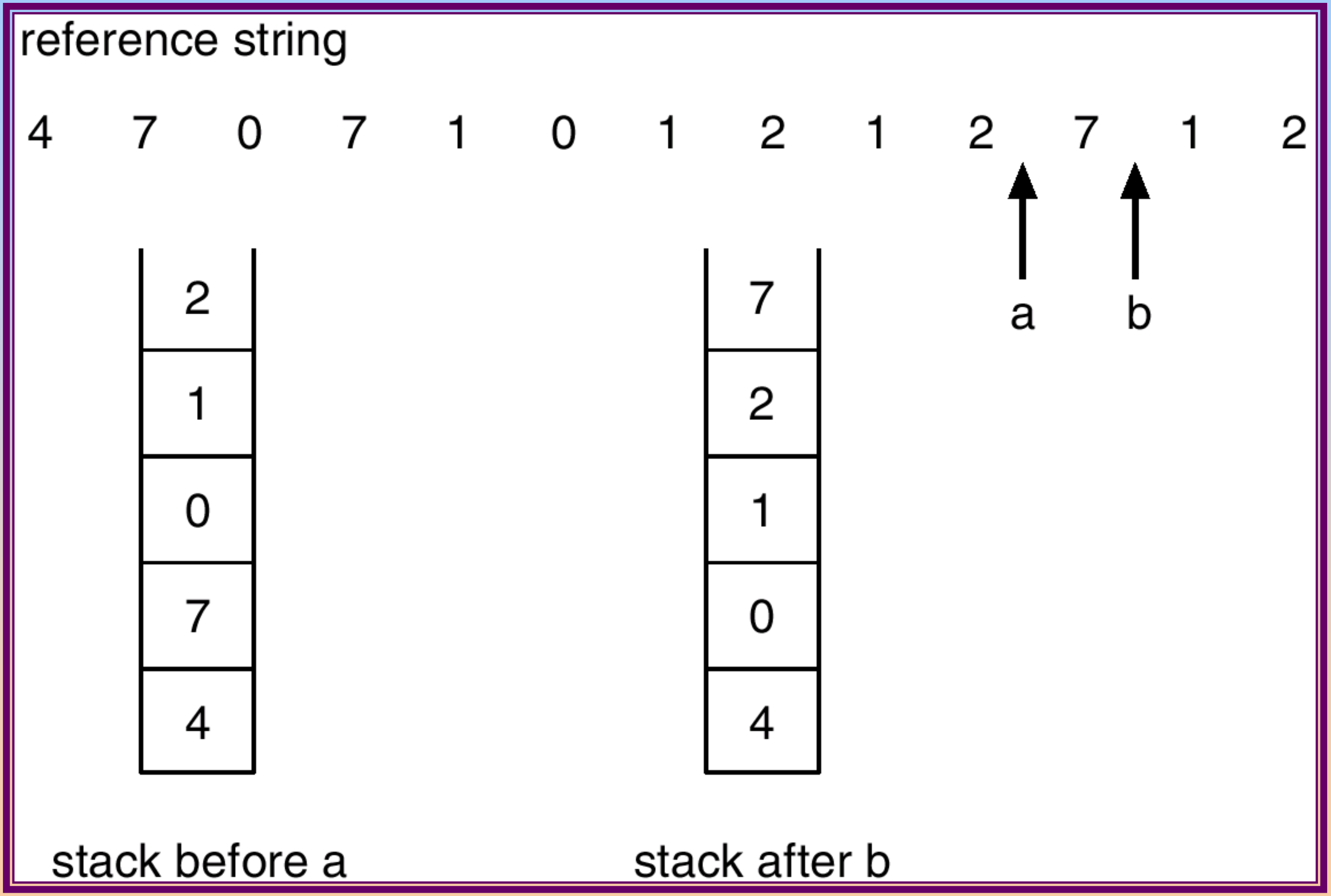
LRU Page Replacement



LRU Algorithm (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

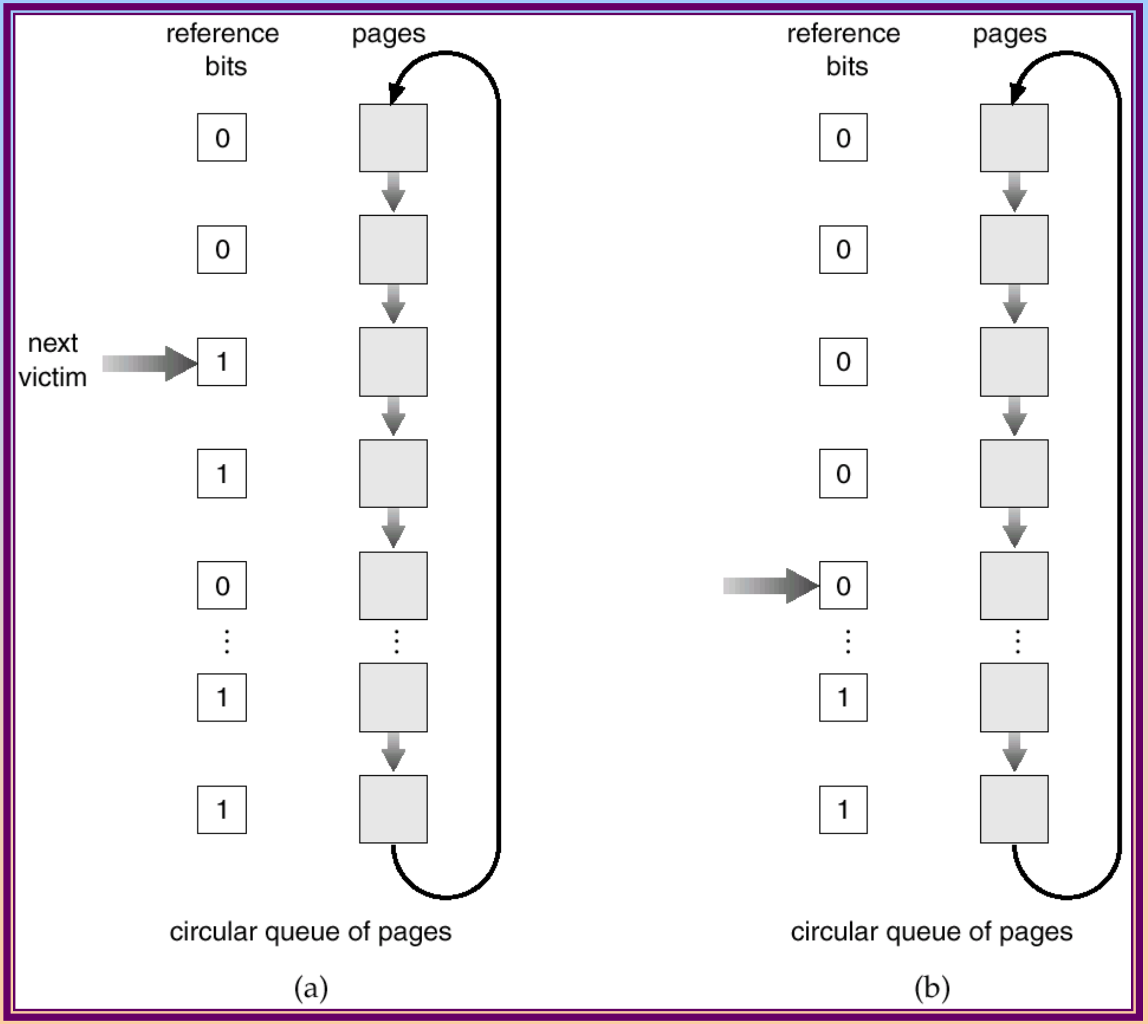
Use Of A Stack to Record The Most Recent Page References



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

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

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

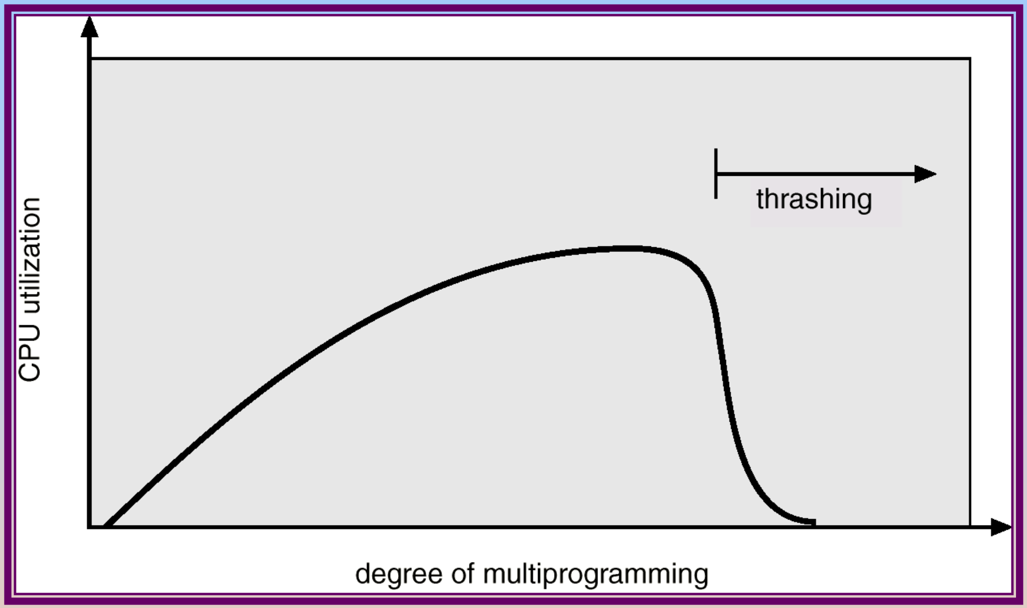
- **Global** replacement – process selects a replacement frame from the set of all frames; one process can take a frame from another.
- **Local** replacement – each process selects from only its own set of allocated frames.

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.

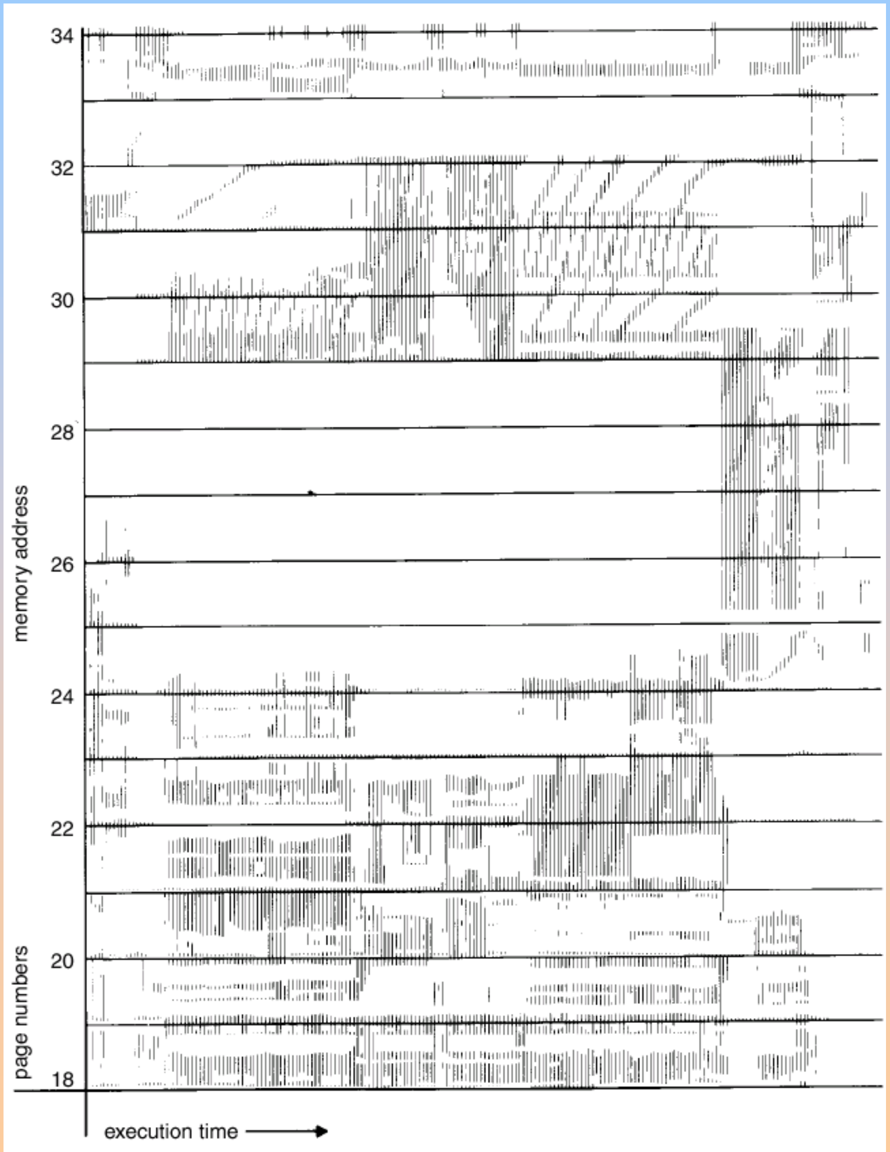
- **Thrashing** ≡ a process is busy swapping pages in and out.

Thrashing



- 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

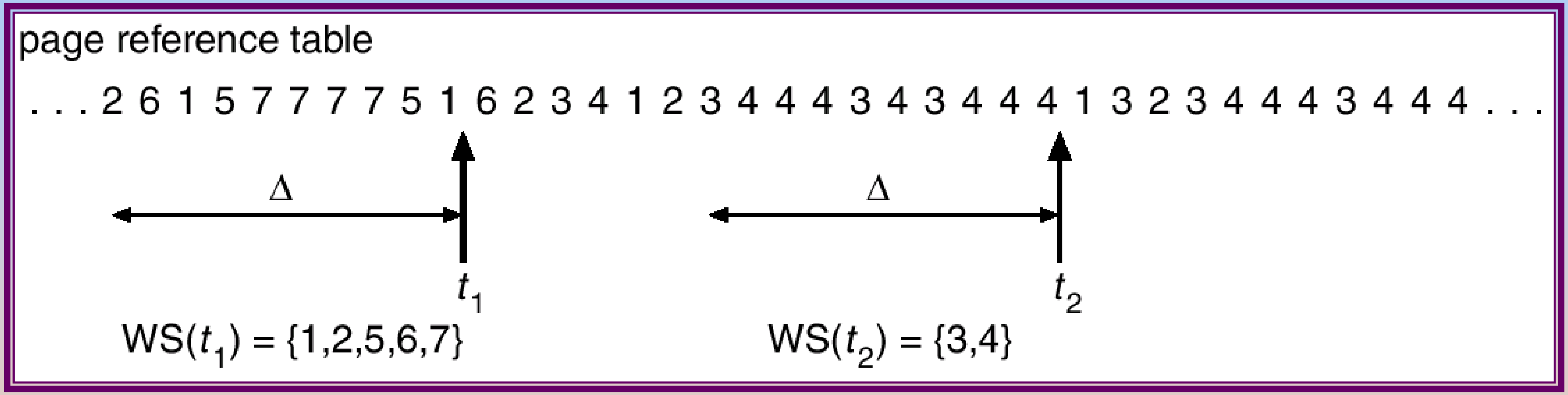
Locality In A Memory-Reference Pattern



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 $D > m \Rightarrow$ Thrashing
- Policy if D > m, then suspend one of the processes.

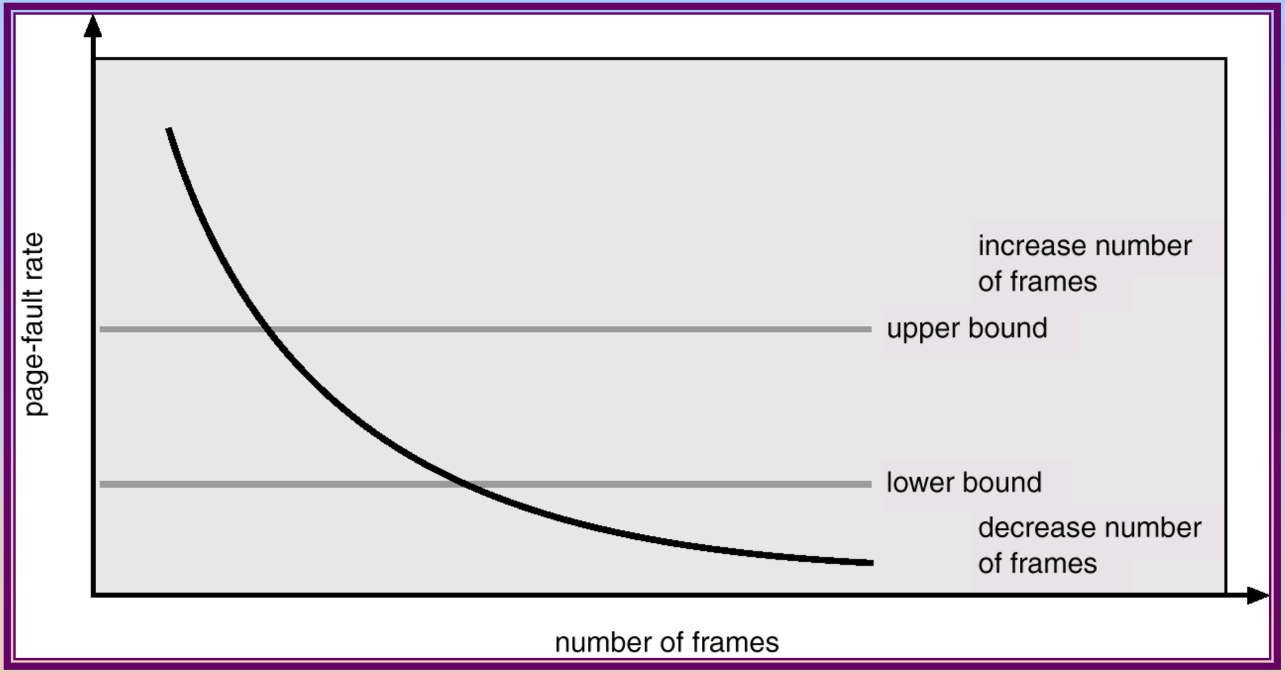
Working-set model



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.

Other Considerations

- Prepaging
- Page size selection
  - fragmentation
  - table size
  - I/O overhead
  - locality

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.

Increasing the Size of the TLB

- **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 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;
```

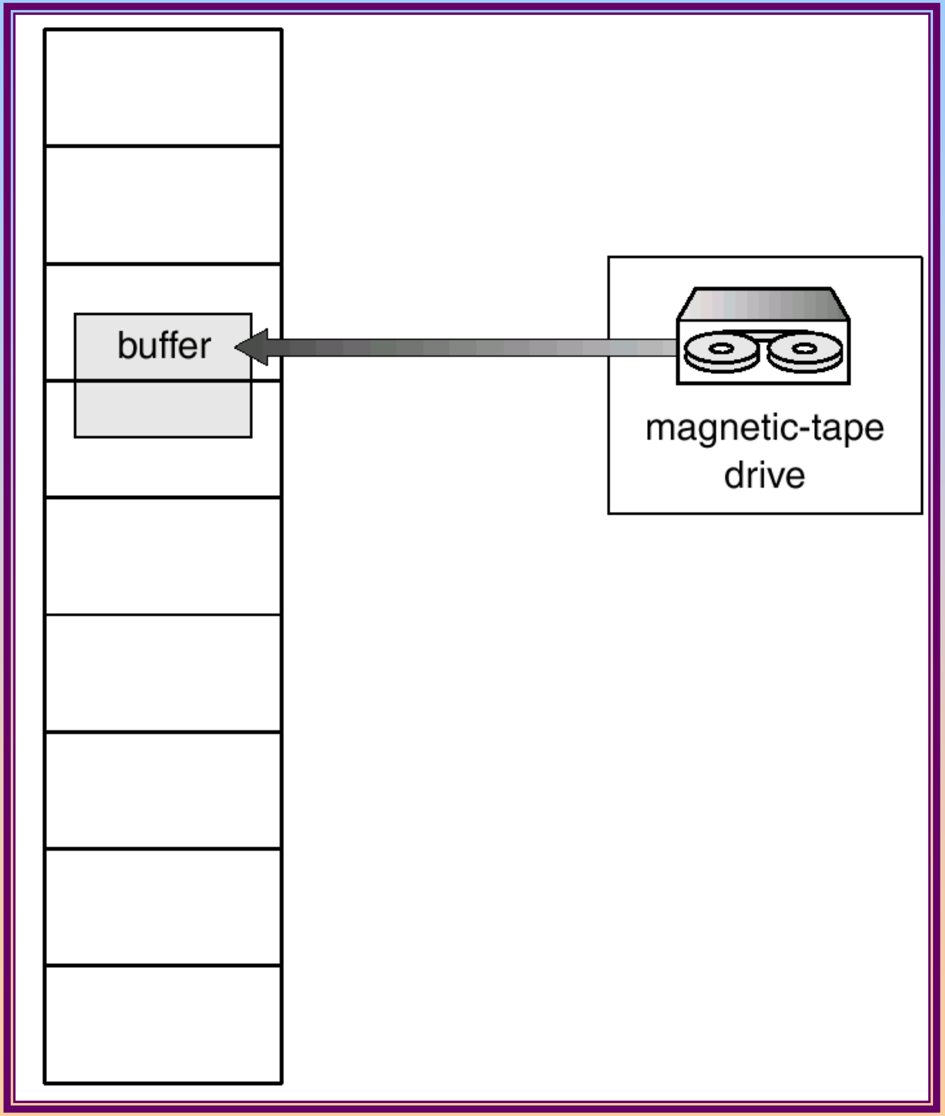
    1024 page faults

Other Considerations (Cont.)

- **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.

Reason Why Frames Used For I/O Must Be In Memory



Operating System Examples

- Windows NT
- Solaris 2

Windows NT

- 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.

Solaris 2

- Maintains a list of free pages to assign faulting processes.
- **Lotsfree** – threshold parameter to begin paging.
- Paging is peformed by *pageout* process.
- Pageout scans pages using modified clock algorithm.
- **Scanrate** is the rate at which pages are scanned. This ranged from **slowscan** to **fastscan**.
- Pageout is called more frequently depending upon the amount of free memory available.

Solar Page Scanner