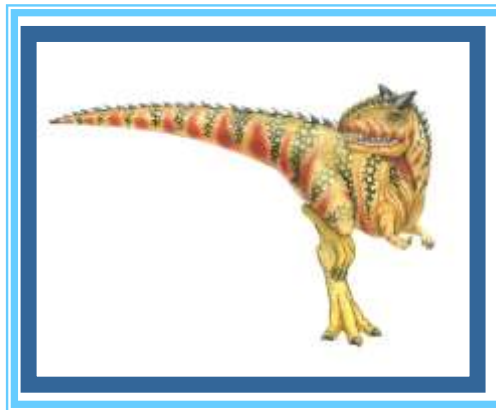


Chapter 9: Virtual Memory





Chapter 9: Virtual Memory

- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Allocation of Frames
- Thrashing
- Memory-Mapped Files
- Allocating Kernel Memory
- Other Considerations
- Operating-System Examples





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





Background

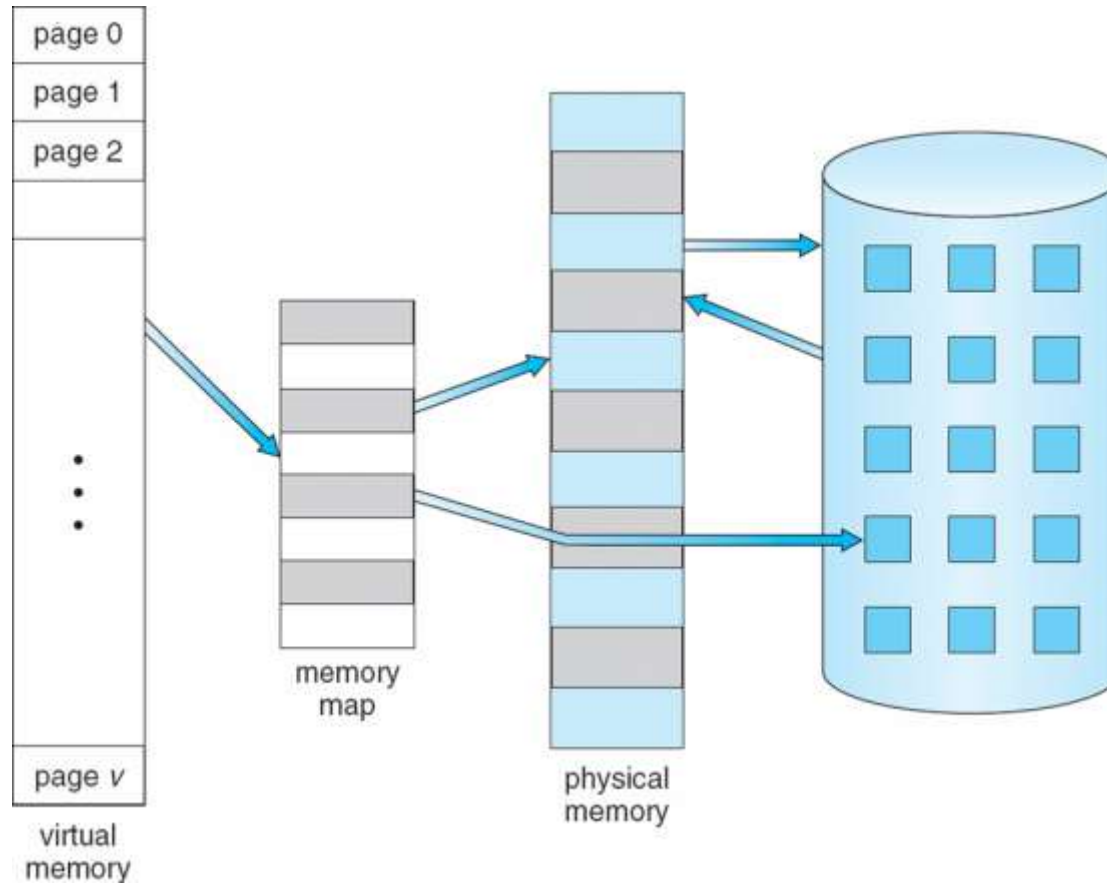
- **Virtual memory** – separation of user logical memory from physical memory.
 - Only part of the program needs to be in memory for execution
 - Logical address space can therefore be much larger than physical address space
 - Allows address spaces to be shared by several processes
 - Allows for more efficient process creation

- Virtual memory can be implemented via:
 - Demand paging –bring page only when called
 - Demand segmentation – bring pages that are referenced together into MM.



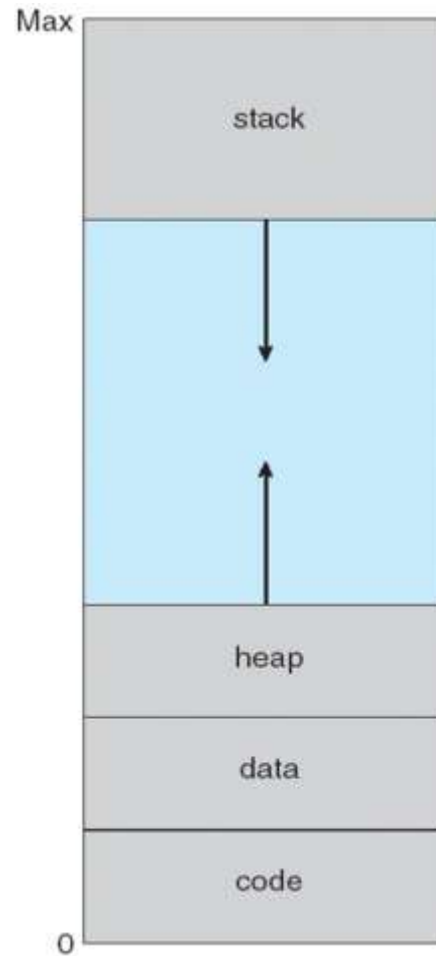


Virtual Memory That is Larger Than Physical Memory



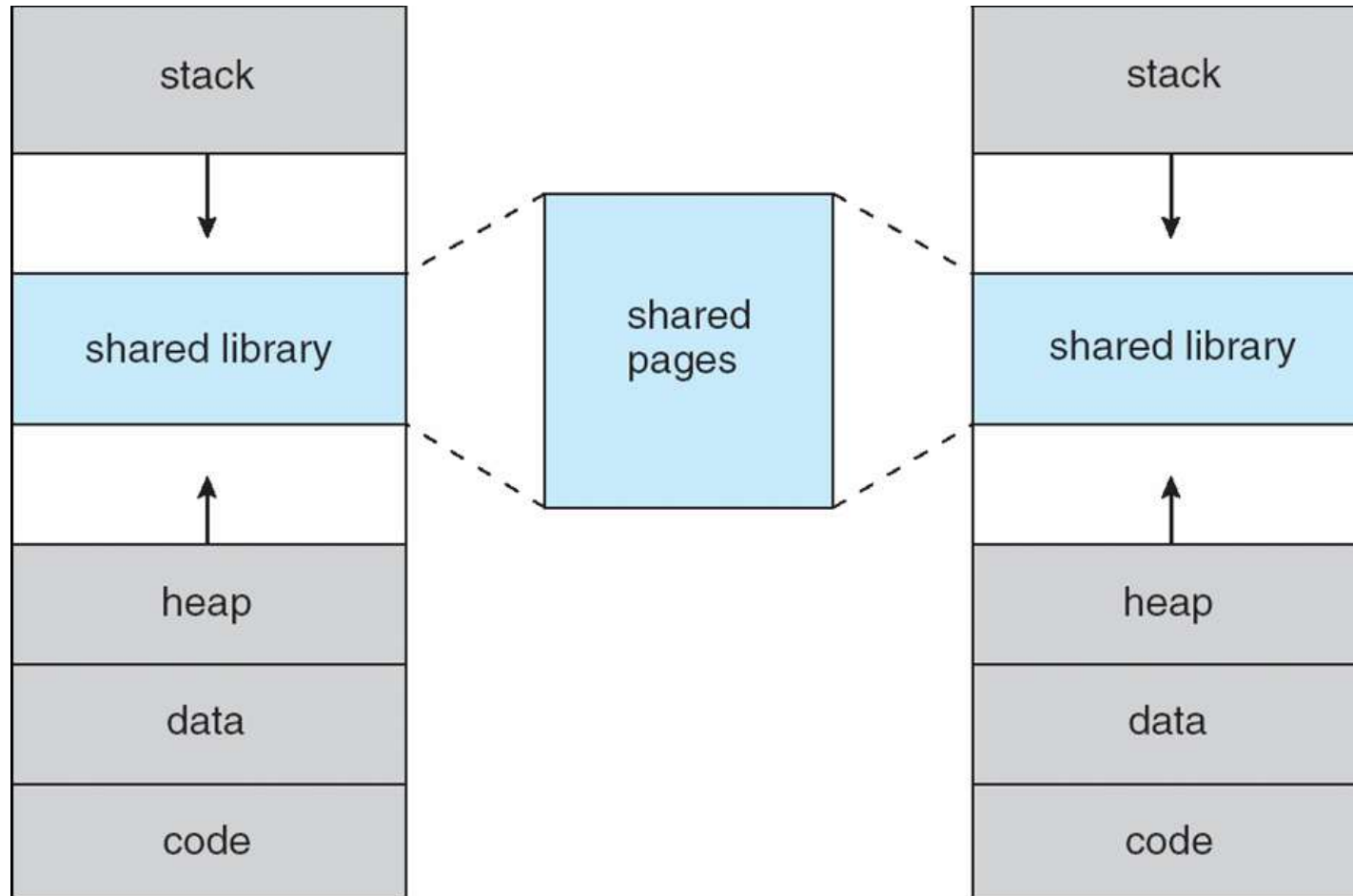


Virtual-address Space





Shared Library Using Virtual 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**





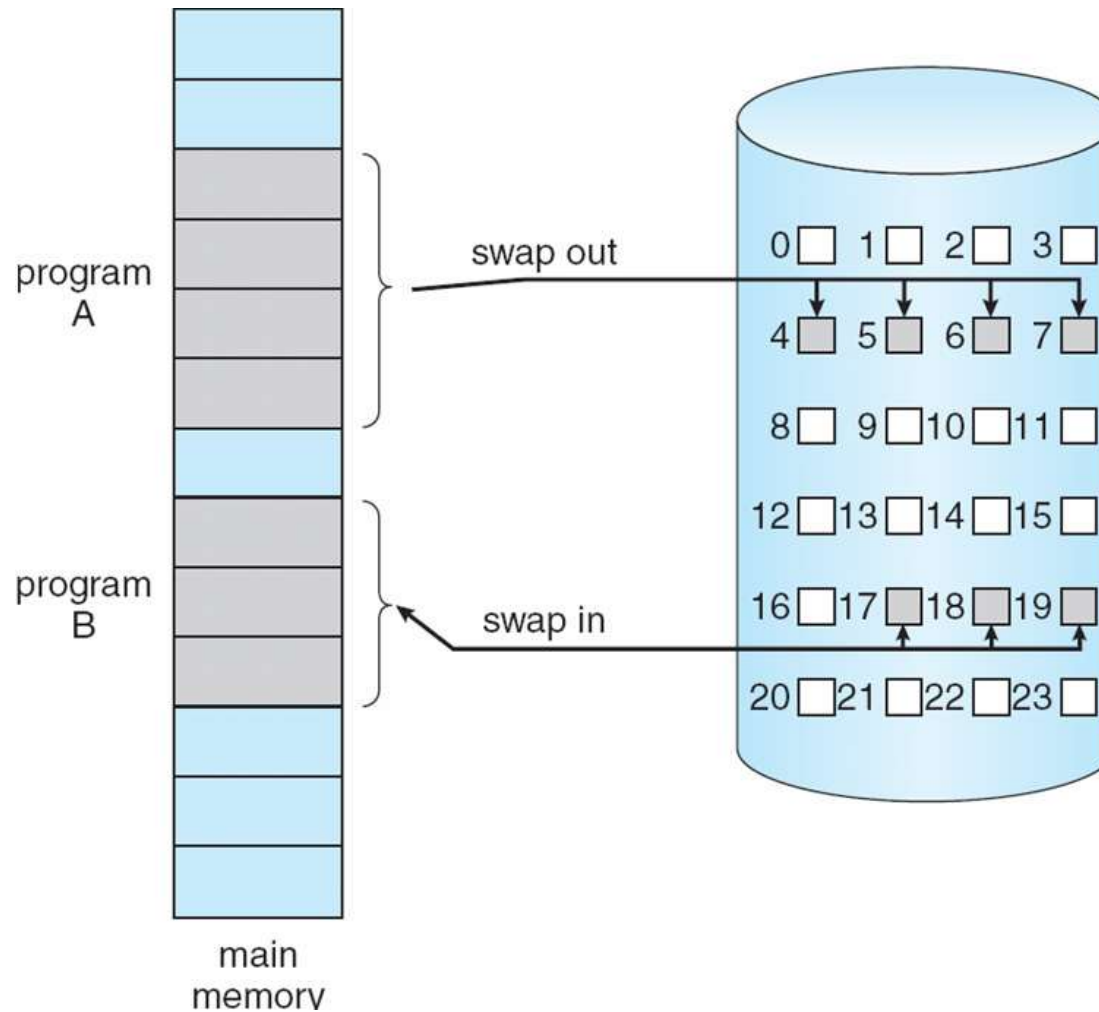
Demand Segmentation

- The segment table has a valid bit to specify if the segment is already in physical memory or not. If a segment is not in physical memory then segment fault results, which traps to the operating system and brings the needed segment into physical memory, much like a page fault.
- Demand segmentation allows for pages that are often referenced with each other to be brought into memory together, this decreases the number of page faults.





Transfer of a Paged Memory to Contiguous Disk Space





Valid-Invalid Bit

- With each page table entry a valid–invalid bit is associated (**v** \Rightarrow in-memory, **i** \Rightarrow not-in-memory)
- Initially valid–invalid bit is set to **i** on all entries
- Example of a page table snapshot:

Frame #	valid-invalid bit
	v
	v
	v
	v
	i
....	
	i
	i

page table

- During address translation, if valid–invalid bit in page table entry is **i** \Rightarrow page fault





Page Table When Some Pages Are Not in Main Memory

0	A
1	B
2	C
3	D
4	E
5	F
6	G
7	H

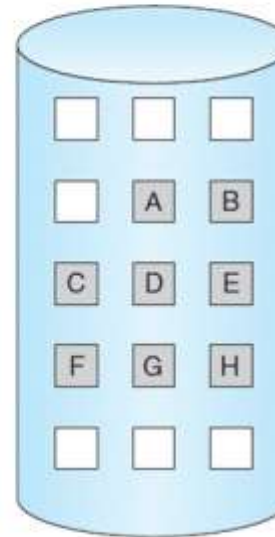
logical
memory

valid-invalid bit		
frame		
0	4	v
1		i
2	6	v
3		i
4		i
5	9	v
6		i
7		i

page table

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

physical memory





Page Fault

- If there is a reference to a page, first reference to that page will trap to operating system:

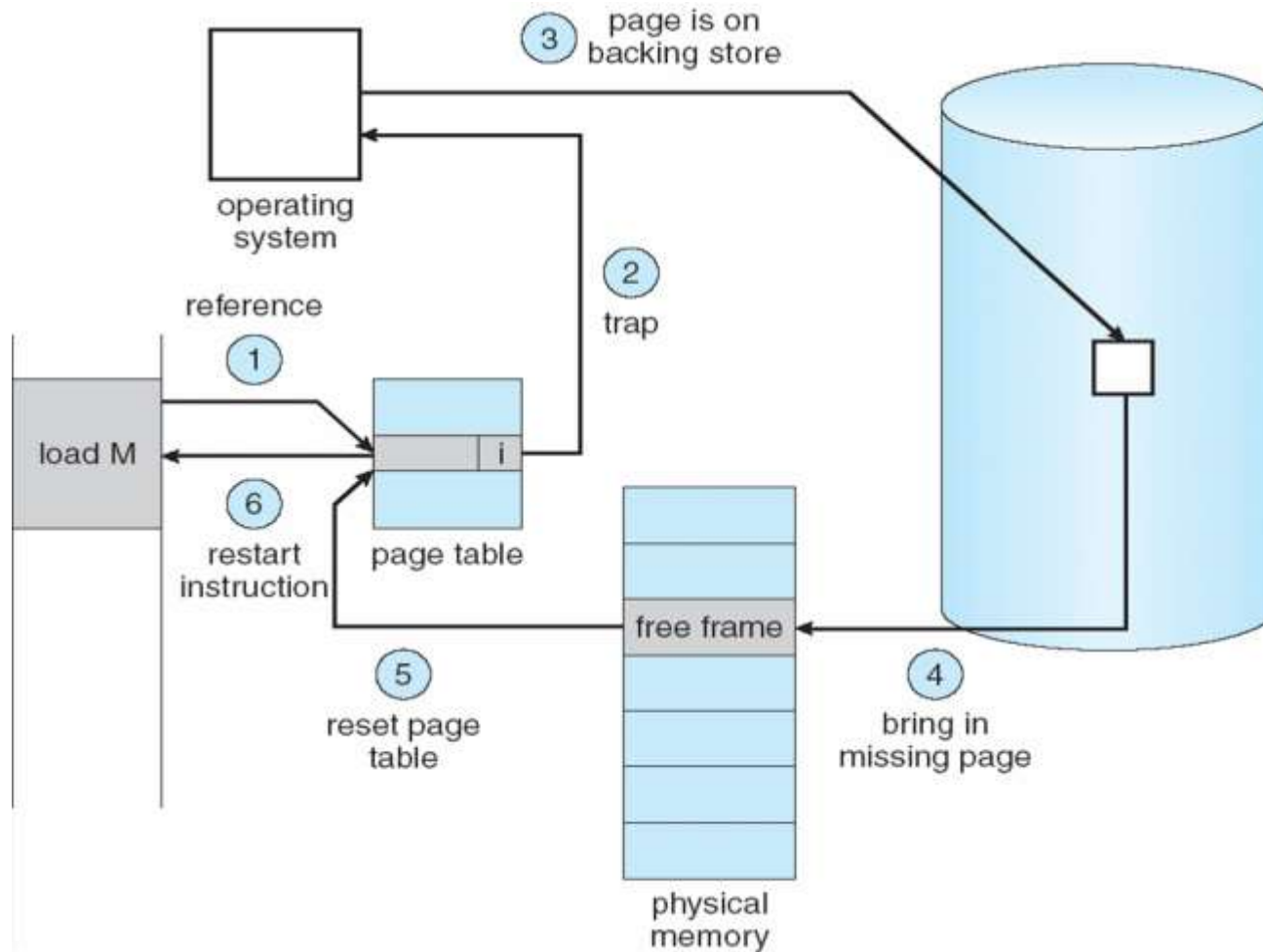
page fault

1. Operating system looks at another table to decide:
 - Invalid reference \Rightarrow abort
 - Just not in memory
2. 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)

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





Demand Paging Example

- 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 8200 (page fault access time) / 200ns (memory access) = approx 40!!





Process Creation

- Virtual memory allows other benefits during process creation:
 - Copy-on-Write
 - Memory-Mapped Files (later)





Copy-on-Write

- Copy-on-Write (COW) allows both parent and child processes to initially *share* the same pages in memory

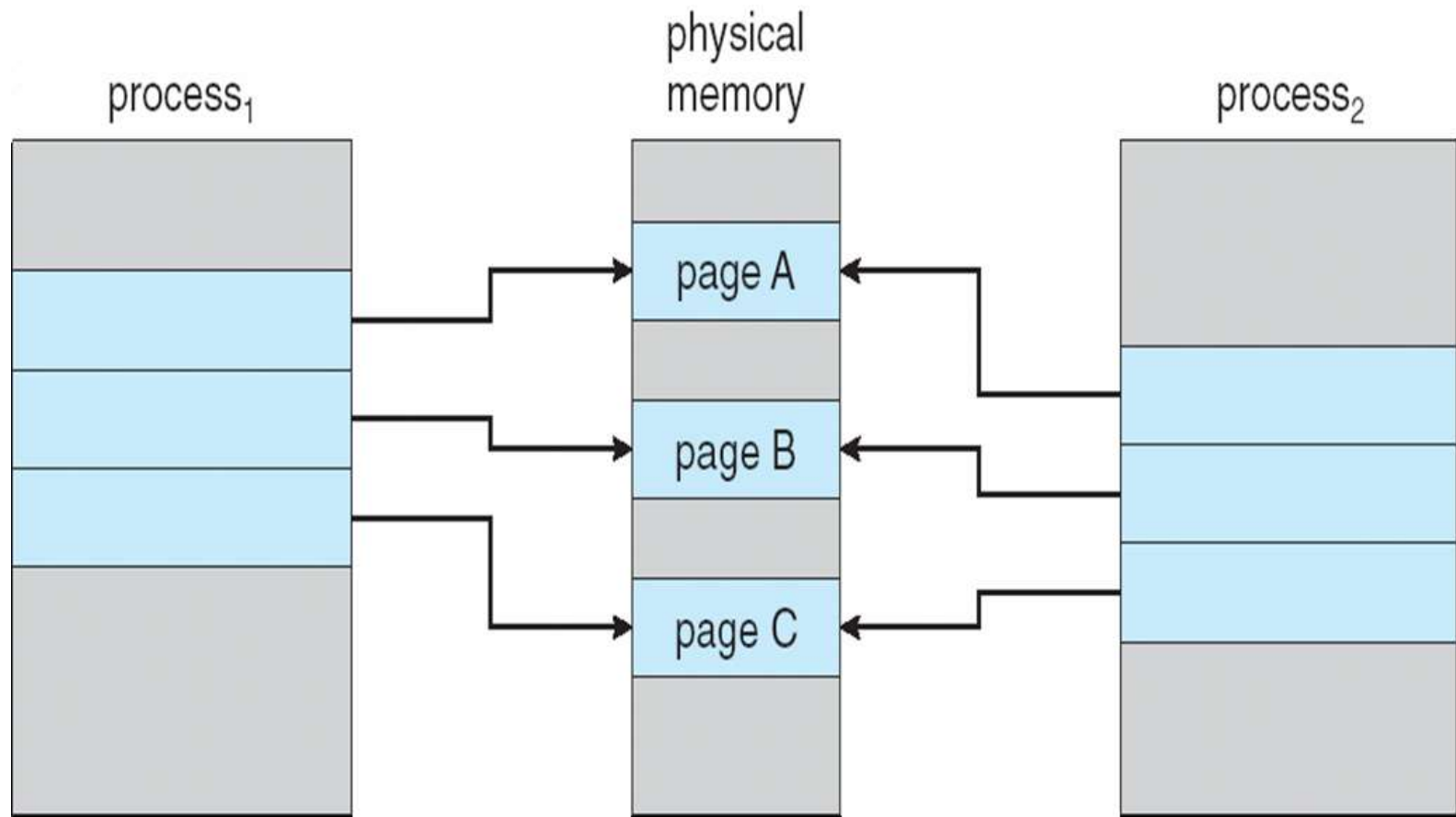
If either process modifies a shared page, only then is the page copied

- COW allows more efficient process creation as only modified pages are copied
- Free pages are allocated from a **pool** of zeroed-out pages



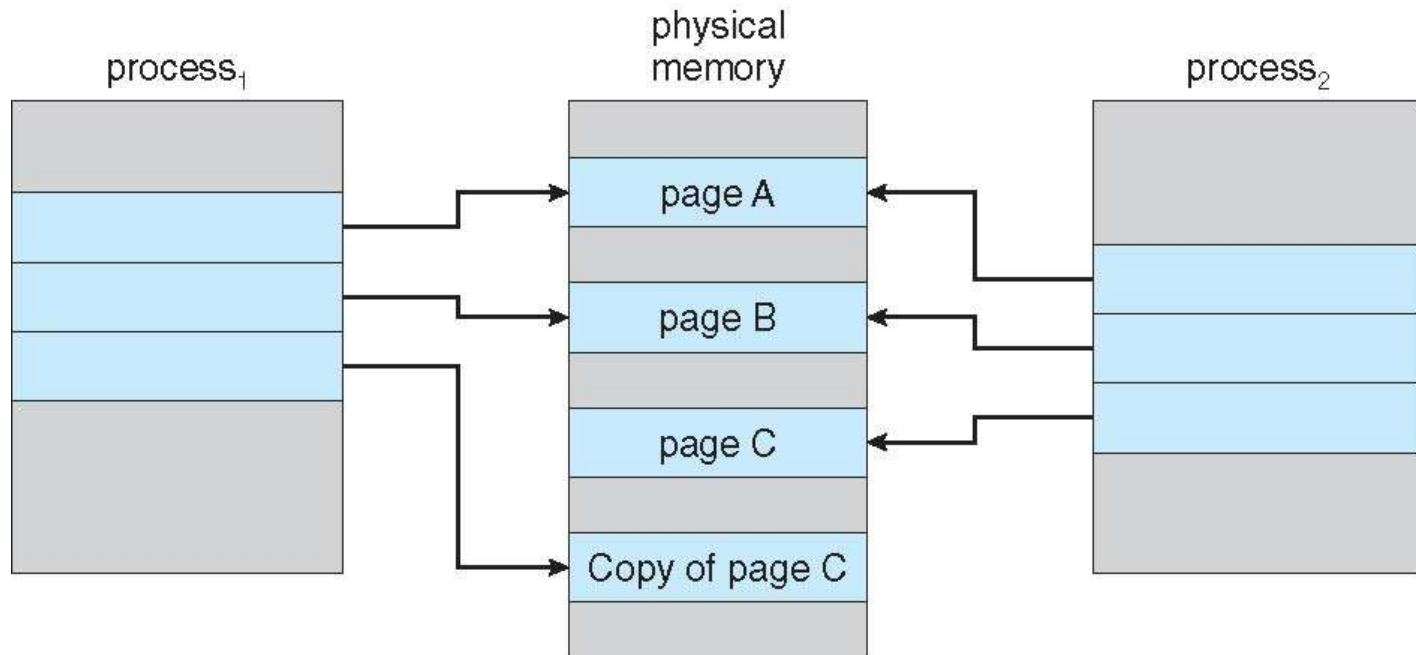


Before Process 1 Modifies Page C





After Process 1 Modifies Page C





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





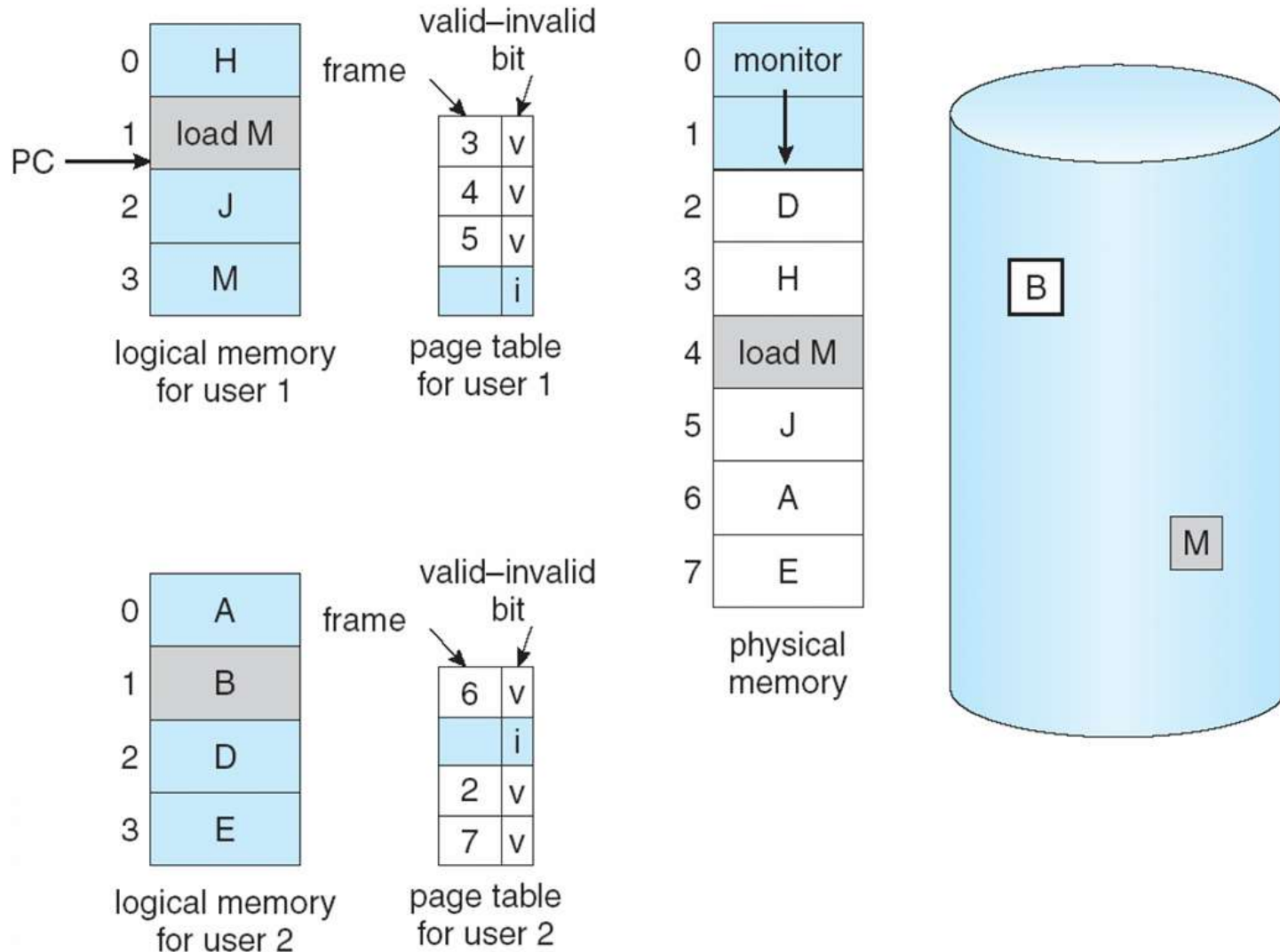
Page Replacement

- 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





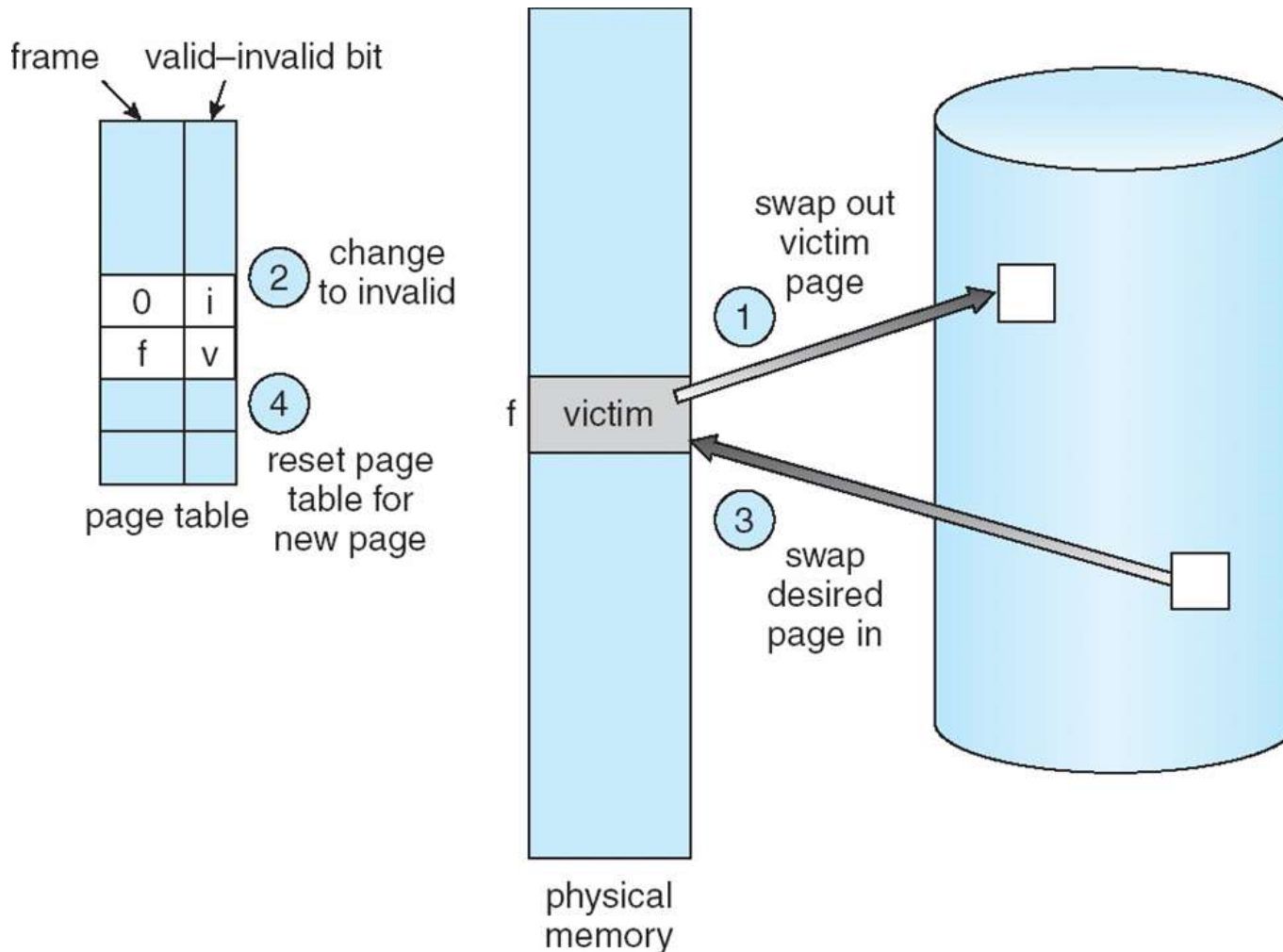
Basic Page Replacement

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





Page Replacement





Page Replacement Algorithms

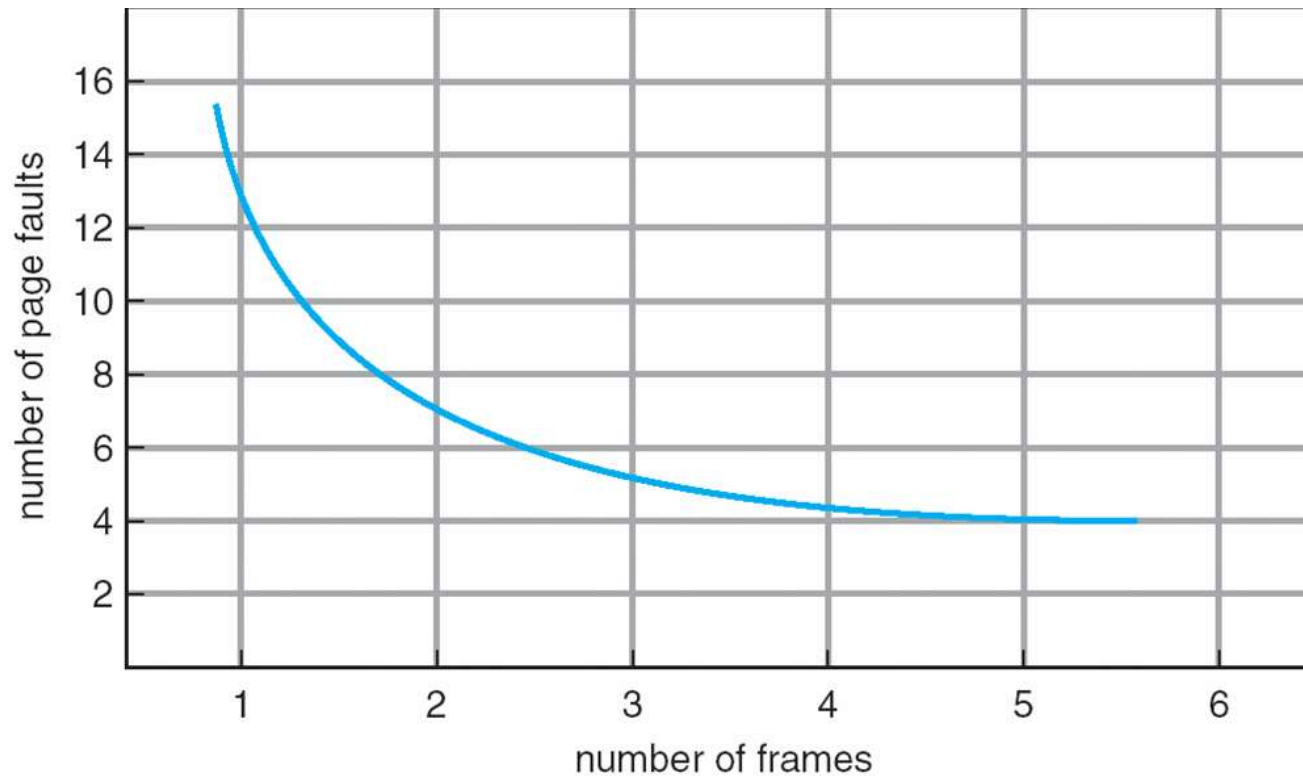
- Want lowest page-fault rate
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
- In all our examples, the reference string is

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





Expected Graph of Page Faults Vs 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)

1	1	4	5	9 page faults
2	2	1	3	
3	3	2	4	

- 4 frames

1	1	5	4	10 page faults
2	2	1	5	
3	3	2		
4	4	3		

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





FIFO Page Replacement

reference string

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

7	7	7	2
	0	0	0
		1	1

2	2	4	4	4	0
3	3	3	2	2	2
1	0	0	0	3	3

0	0
1	1
3	2

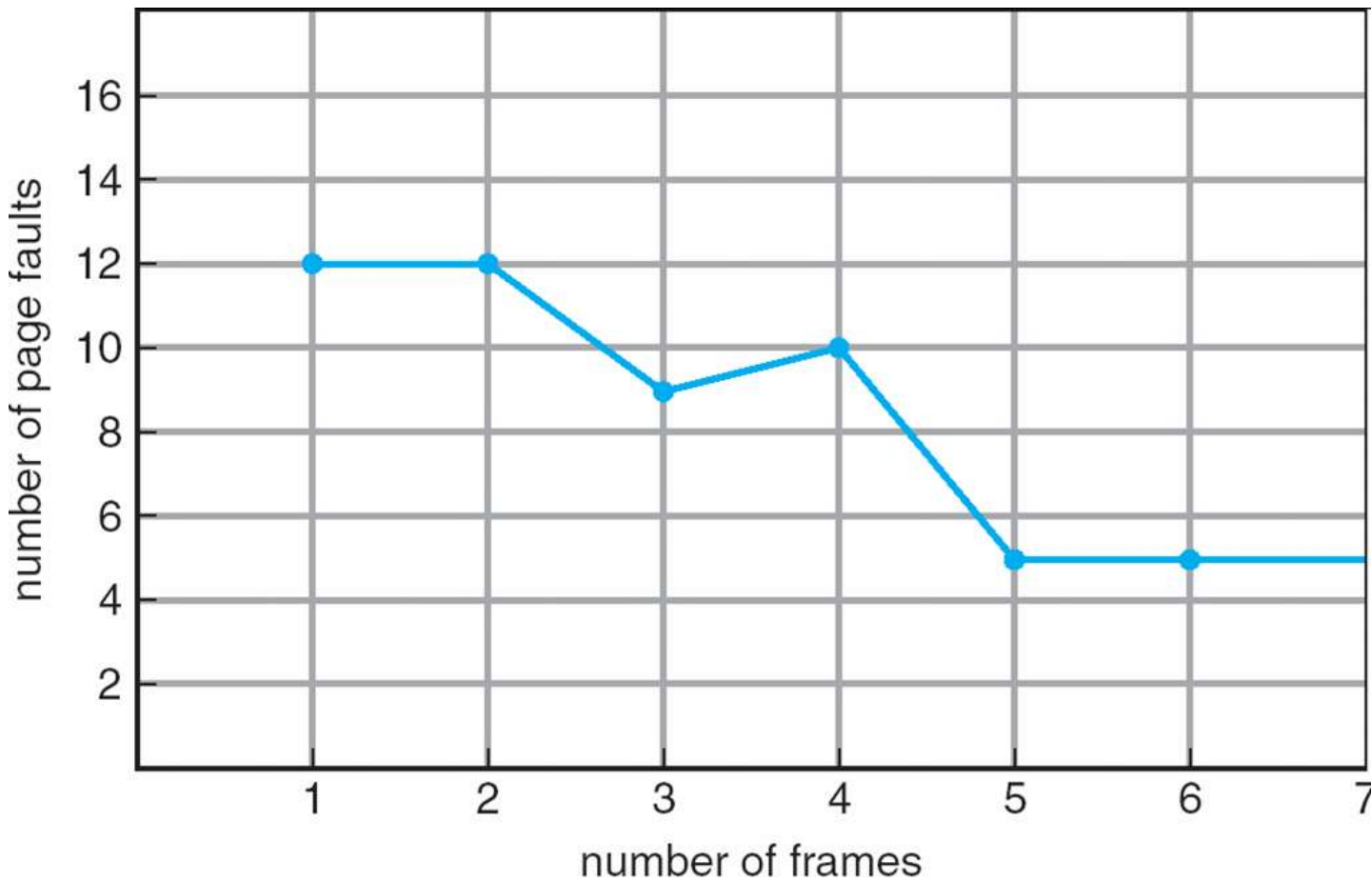
7	7	7
1	0	0
2	2	1

page frames





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

1
2
3
4

4

6 page faults

5

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





Optimal Page Replacement

reference string

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

7	7	7	2		2		2		2								7		
	0	0	0		0		0		0								0		
		1	1		3		3		3								1		

page frames





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

reference string

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

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

page frames





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

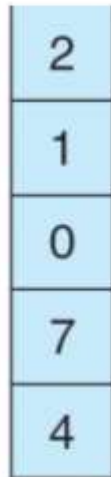




Use Of A Stack to Record The Most Recent Page References

reference string

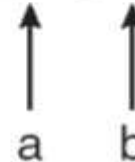
4 7 0 7 1 0 1 2 1 2 7 1 2



stack
before
a



stack
after
b





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

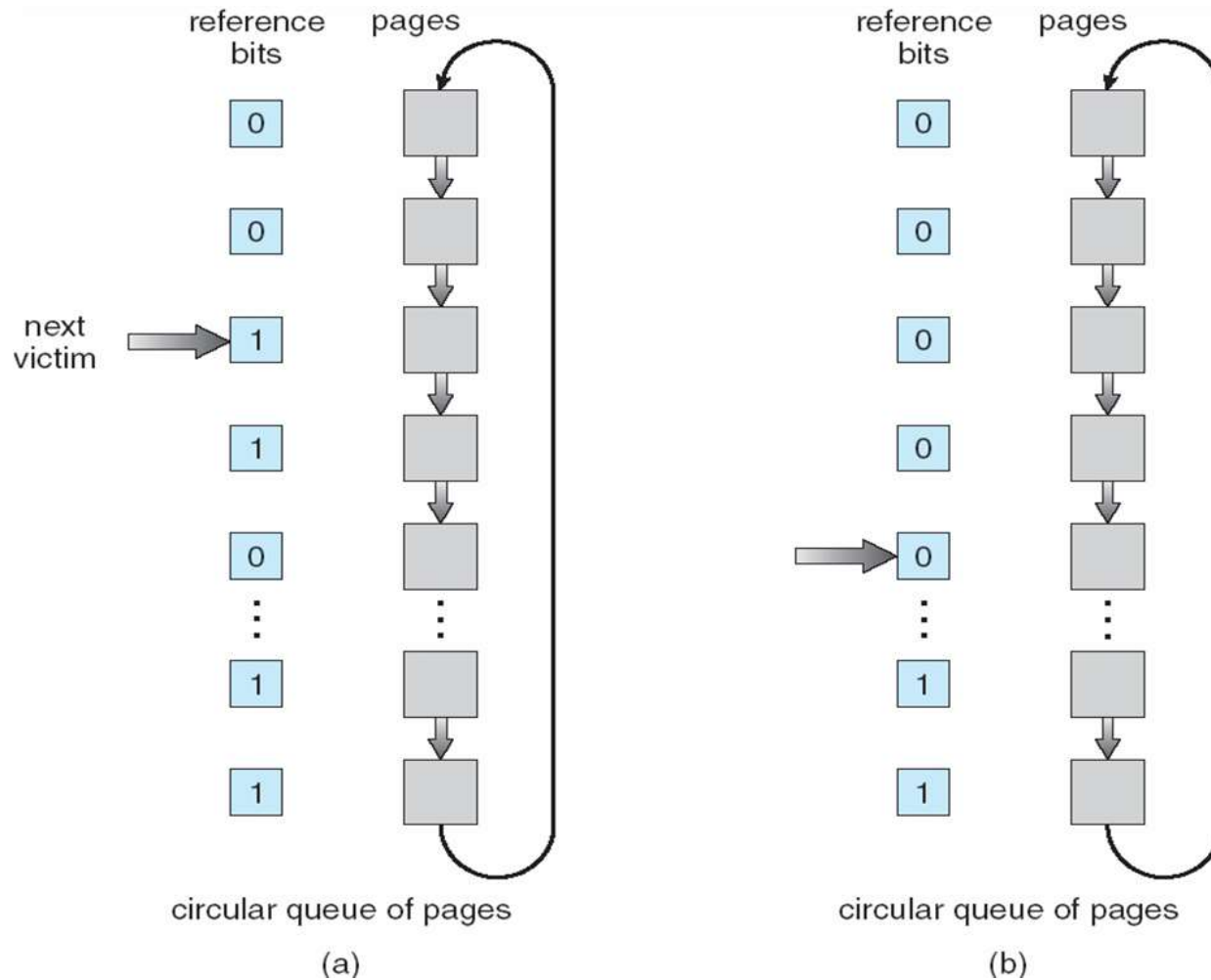
■ Second chance

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

$$m = 64$$

$$s_i = 10$$

$$s_2 = 127$$

$$a_1 = \frac{10}{137} \times 64 \approx 5$$

$$a_2 = \frac{127}{137} \times 64 \approx 59$$





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

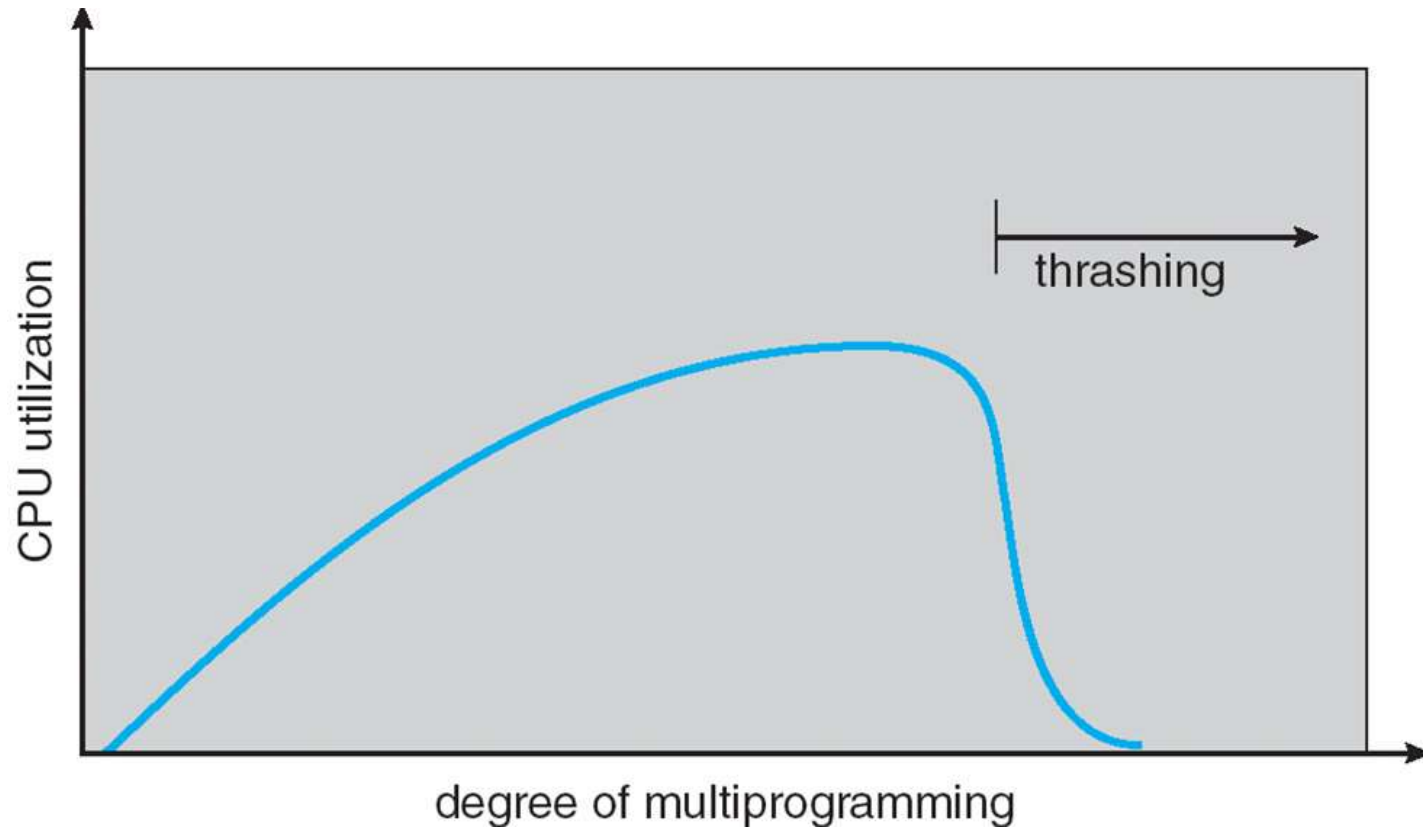
- If a process does not have “enough” pages, the page-fault rate is very high. This leads to:
 - low CPU utilization
 - operating system thinks that it needs to increase the degree of multiprogramming
 - another process added to the system

- **Thrashing** \equiv a process is busy swapping pages in and out
 - A global page replacement algorithm takes frames from other processes which start faulting.
 - Processes queue up for the paging device, and slowly the ready queue empties.
 - CPU utilisation decreases.





Thrashing (Cont.)





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

To prevent thrashing provide process as many frames as it needs. How many? –working set strategy





Preventing Thrashing

- Working Set Model
- Page Fault Frequency Scheme





Locality model

- As a process executes, it moves from locality to locality.
- A locality is a set of pages that are actively used together.
- A program is generally composed of several different localities which may overlap





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
- $D = \sum WSS_i \equiv$ total demand frames
- if $D > m(\text{available frames}) \Rightarrow$ Thrashing
- Policy if $D > m$, then suspend one of the processes

Avoids thrashing while keeping degree of multiprogramming at max possible.

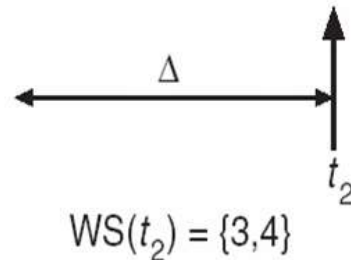
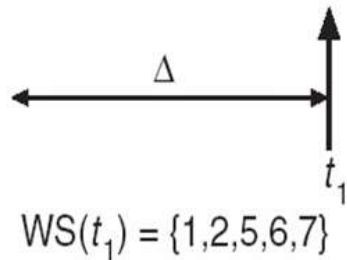




Working-set model

page reference table

... 2 6 1 5 7 7 7 7 5 1 6 2 3 4 1 2 3 4 4 4 3 4 3 4 4 4 4 1 3 2 3 4 4 4 3 4 4 4 ...





Keeping Track of the Working Set

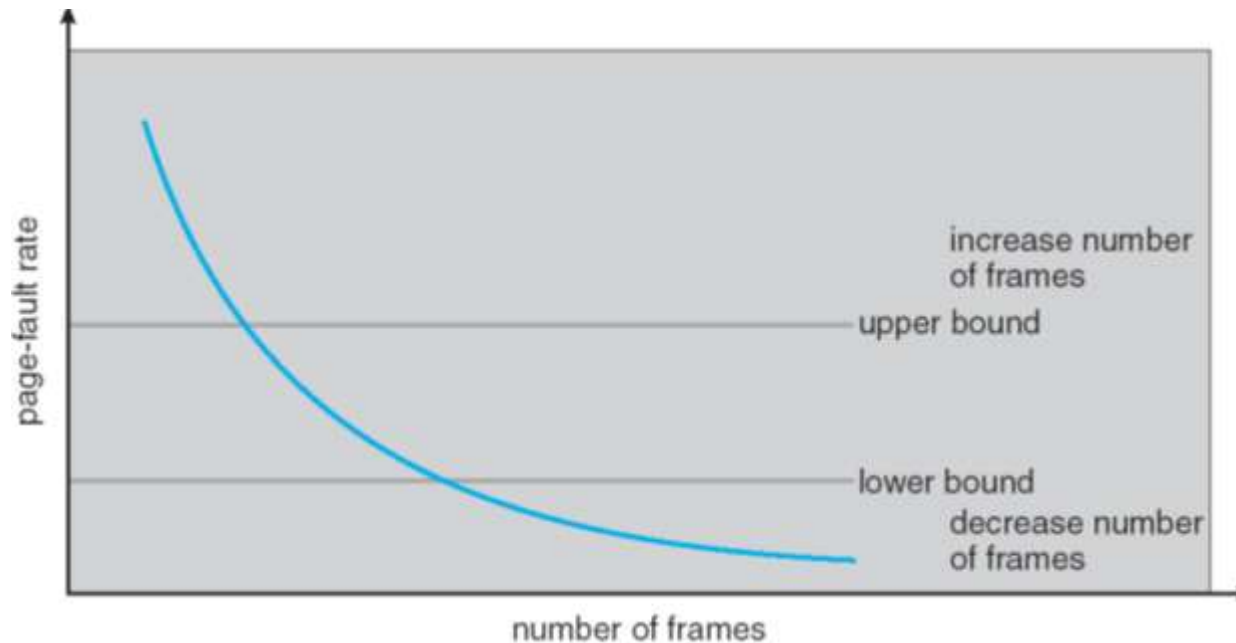
- Approximate with interval timer + a reference bit
- Example: $\Delta = 10,000$
 - Timer interrupts after every 5000 time units
 - Keep in memory 2 bits for each page
 - Whenever a timer interrupts copy and sets the values of all reference bits to 0
 - If one of the bits in memory = 1 \Rightarrow page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





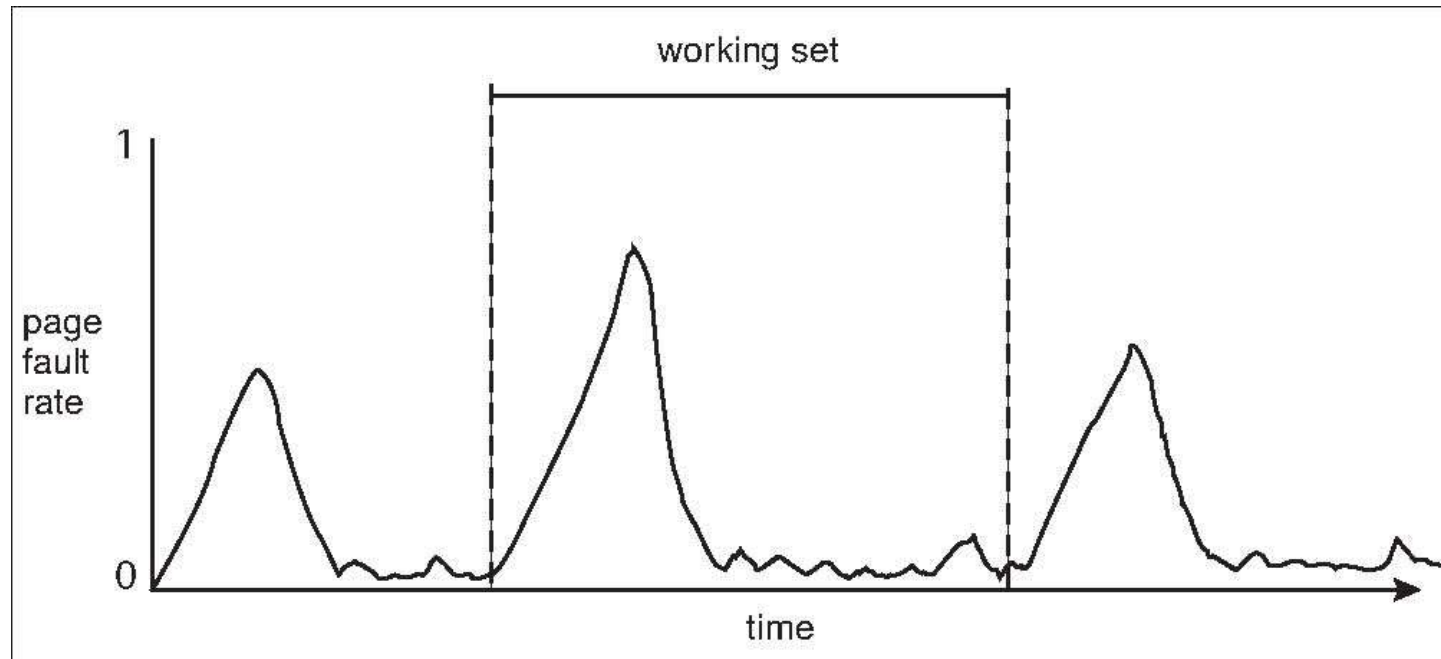
Page-Fault Frequency Scheme

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





Working Sets and Page Fault Rates





Working Set Model and PFF

- According to the working set model, we might need to suspend some process if page fault increases and free frames are not available.
- In the page fault frequency scheme, we are able to give or take away frames from process based on the page fault rate

