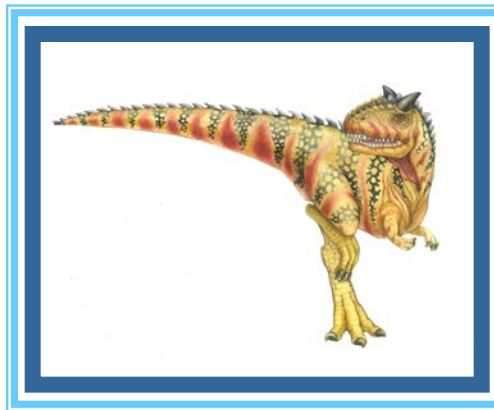


# Chapter 9: Virtual Memory

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# Background

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- Code needs to be in memory to execute, but entire program rarely used
  - Error code, unusual routines, large data structures
- Entire program code not needed at same time
- Consider ability to execute partially-loaded program
  - Program no longer constrained by limits of physical memory
  - Each program takes less memory while running -> more programs run at the same time
    - ▶ Increased CPU utilization and throughput with no increase in response time or turnaround time
  - Less I/O needed to load or swap programs into memory -> each user program runs faster





# Background (Cont.)

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- **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
  - More programs running concurrently
  - Less I/O needed to load or swap processes





# Background (Cont.)

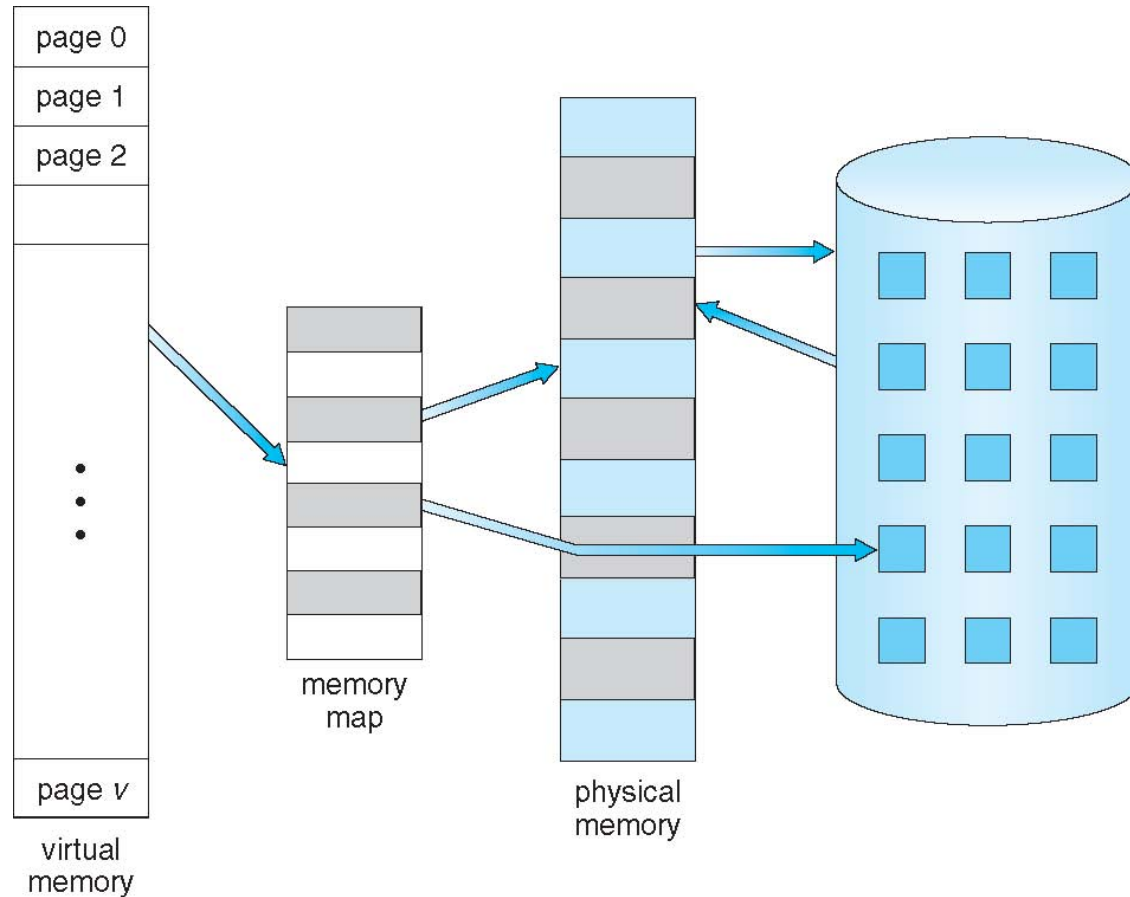
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- **Virtual address space** – logical view of how process is stored in memory
  - Usually start at address 0, contiguous addresses until end of space
  - Meanwhile, physical memory organized in page frames
  - MMU must map logical to physical
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation





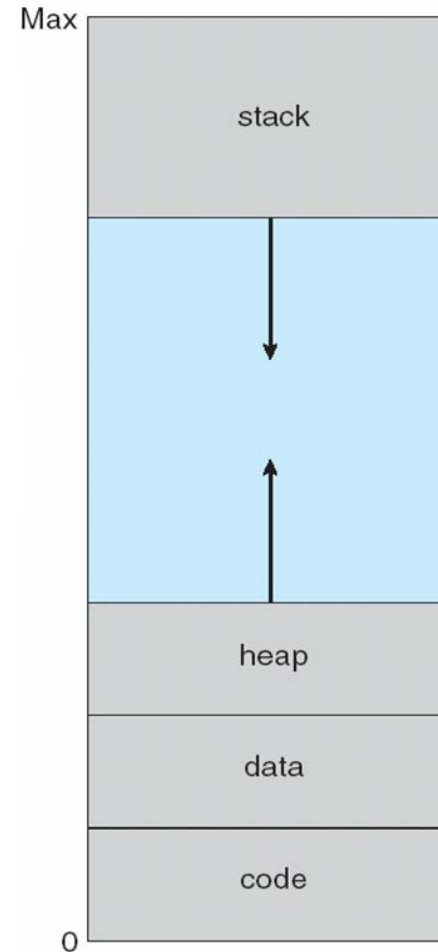
# Virtual Memory That is Larger Than Physical Memory





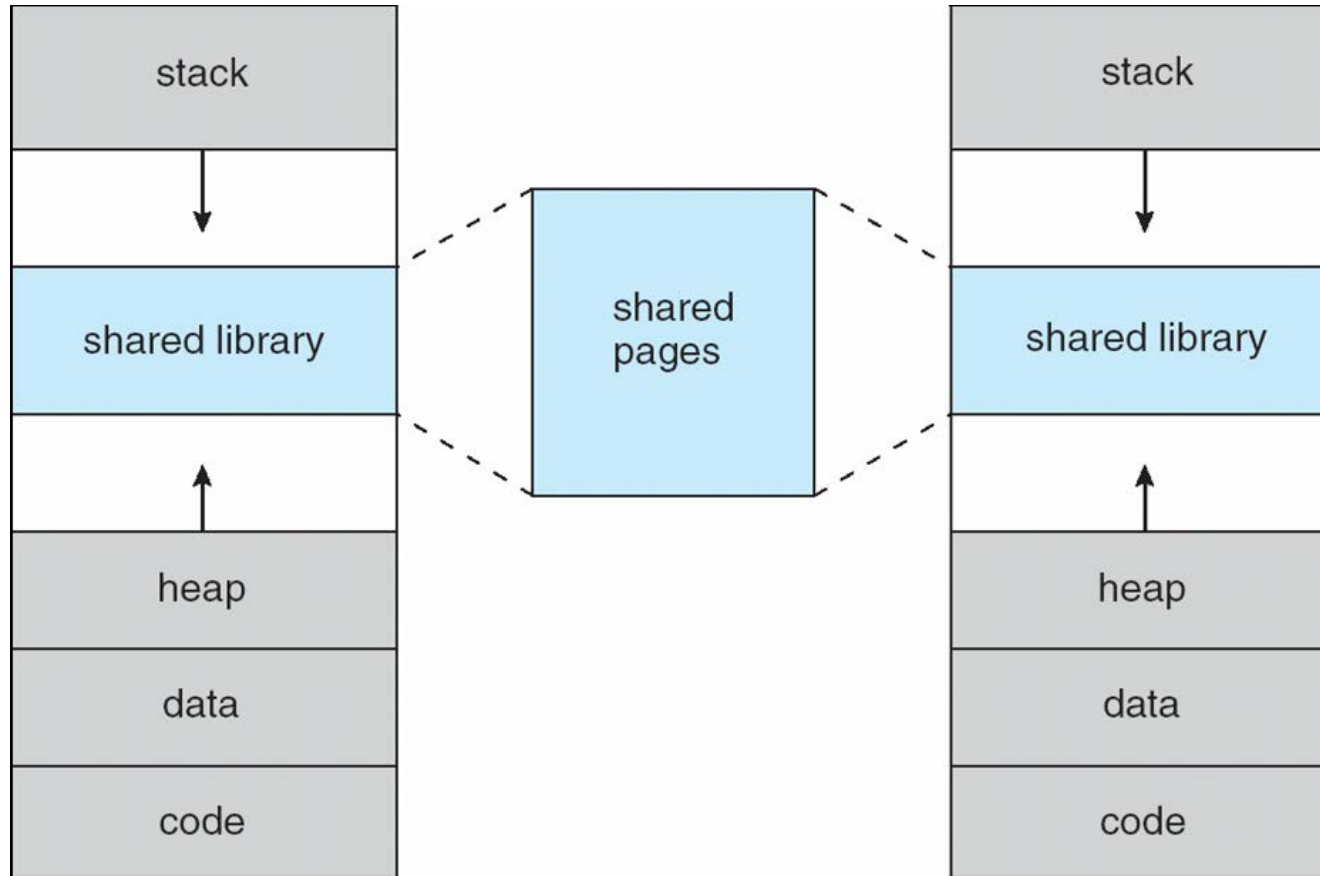
# Virtual-address Space

- Usually design logical address space for stack to start at Max logical address and grow “down” while heap grows “up”
  - Maximizes address space use
  - Unused address space between the two is hole
    - ▶ No physical memory needed until heap or stack grows to a given new page
- Enables **sparse** address spaces with holes left for growth, dynamically linked libraries, etc
- System libraries shared via mapping into virtual address space
- Shared memory by mapping pages read-write into virtual address space
- Pages can be shared during `fork()`, speeding process creation





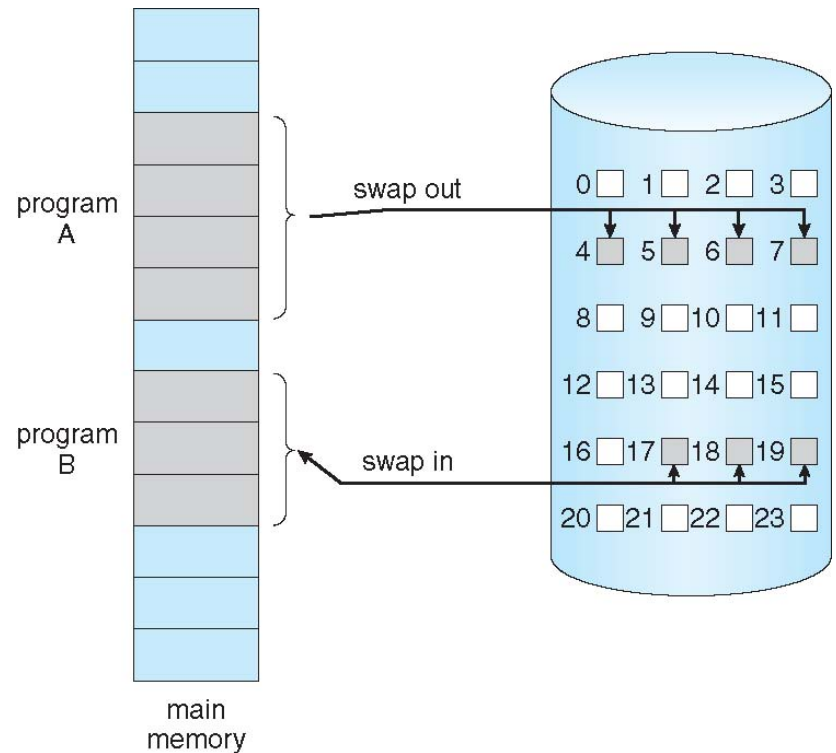
# Shared Library Using Virtual Memory





# Demand Paging

- Could bring entire process into memory at load time
- Or bring a page into memory only when it is needed
  - Less I/O needed, no unnecessary I/O
  - Less memory needed
  - Faster response
  - More users
- Similar to paging system with swapping (diagram on right)
- 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**







# Basic Concepts

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- With swapping, pager guesses which pages will be used before swapping out again
- Instead, pager brings in only those pages into memory
- How to determine that set of pages?
  - Need new MMU functionality to implement demand paging
- If pages needed are already **memory resident**
  - No difference from non demand-paging
- If page needed and not memory resident
  - Need to detect and load the page into memory from storage
    - ▶ Without changing program behavior
    - ▶ Without programmer needing to change code





# Valid-Invalid Bit

- With each page table entry a valid–invalid bit is associated (**v**  $\Rightarrow$  in-memory – **memory resident**, **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
	<b>v</b>
	<b>v</b>
	<b>v</b>
	<b>i</b>
...	
	<b>i</b>
	<b>i</b>

page table

- During MMU 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

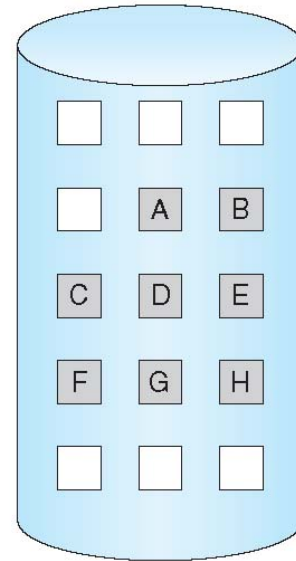
logical  
memory

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

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

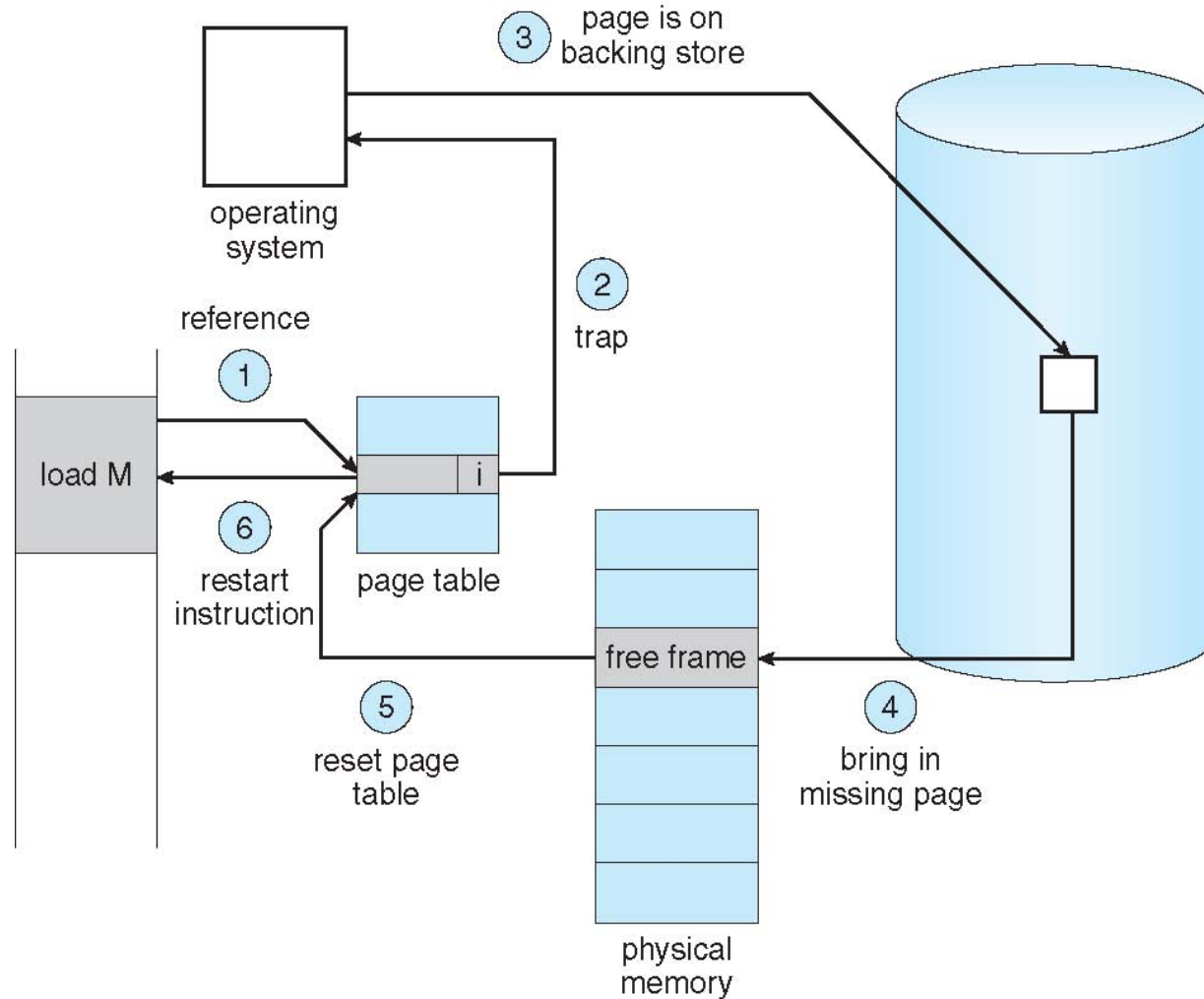
## page fault

1. Operating system looks at another table to decide:
  - Invalid reference  $\Rightarrow$  abort
  - Just not in memory
2. Find free frame
3. Swap page into frame via scheduled disk operation
4. Reset tables to indicate page now in memory  
Set validation bit = **V**
5. Restart the instruction that caused the page fault





# Steps in Handling a Page Fault





# Aspects of Demand Paging

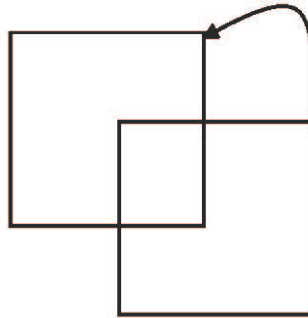
- Extreme case – start process with *no* pages in memory
  - OS sets instruction pointer to first instruction of process, non-memory-resident -> page fault
  - And for every other process pages on first access
  - **Pure demand paging**
- Actually, a given instruction could access multiple pages -> multiple page faults
  - Consider fetch and decode of instruction which adds 2 numbers from memory and stores result back to memory
  - Pain decreased because of **locality of reference**
- Hardware support needed for demand paging
  - Page table with valid / invalid bit
  - Secondary memory (swap device with **swap space**)
  - Instruction restart





# Instruction Restart

- Consider an instruction that could access several different locations
  - block move



- auto increment/decrement location
- Restart the whole operation?
  - ▶ What if source and destination overlap?





# Performance of Demand Paging

## ■ Stages in Demand Paging (worse case)

1. Trap to the operating system
2. Save the user registers and process state
3. Determine that the interrupt was a page fault
4. Check that the page reference was legal and determine the location of the page on the disk
5. Issue a read from the disk to a free frame:
  1. Wait in a queue for this device until the read request is serviced
  2. Wait for the device seek and/or latency time
  3. Begin the transfer of the page to a free frame
6. While waiting, allocate the CPU to some other user
7. Receive an interrupt from the disk I/O subsystem (I/O completed)
8. Save the registers and process state for the other user
9. Determine that the interrupt was from the disk
10. Correct the page table and other tables to show page is now in memory
11. Wait for the CPU to be allocated to this process again
12. Restore the user registers, process state, and new page table, and then resume the interrupted instruction







# Performance of Demand Paging (Cont.)

- Three major activities
  - Service the interrupt – careful coding means just several hundred instructions needed
  - Read the page – lots of time
  - Restart the process – again just a small amount of time
- Page Fault Rate  $0 \leq p \leq 1$ 
  - if  $p = 0$  no page faults
  - if  $p = 1$ , every reference is a fault
- Effective Access Time (EAT)

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





# Demand Paging Example

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- $EAT = (1 - p) \times 200 + p (8 \text{ milliseconds})$   
 $= (1 - p) \times 200 + p \times 8,000,000$   
 $= 200 + p \times 7,999,800$
- 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!!
- If want performance degradation < 10 percent
  - $220 > 200 + 7,999,800 \times p$   
 $20 > 7,999,800 \times p$
  - $p < .0000025$
  - < one page fault in every 400,000 memory accesses





# Page Replacement

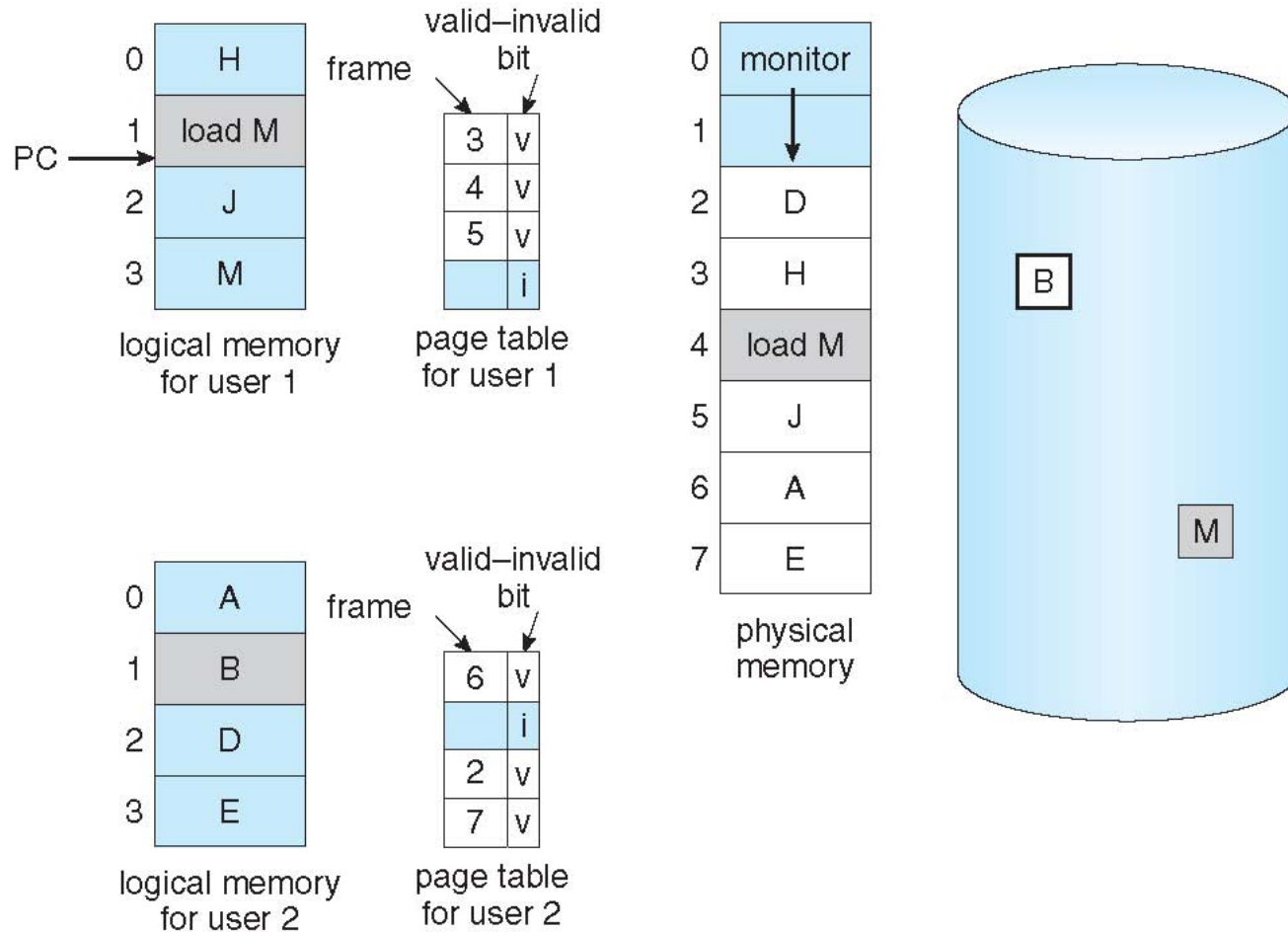
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- Prevent **over-allocation** of memory by modifying page-fault service routine to include page replacement
- Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory





# Need For Page Replacement





# Basic Page Replacement

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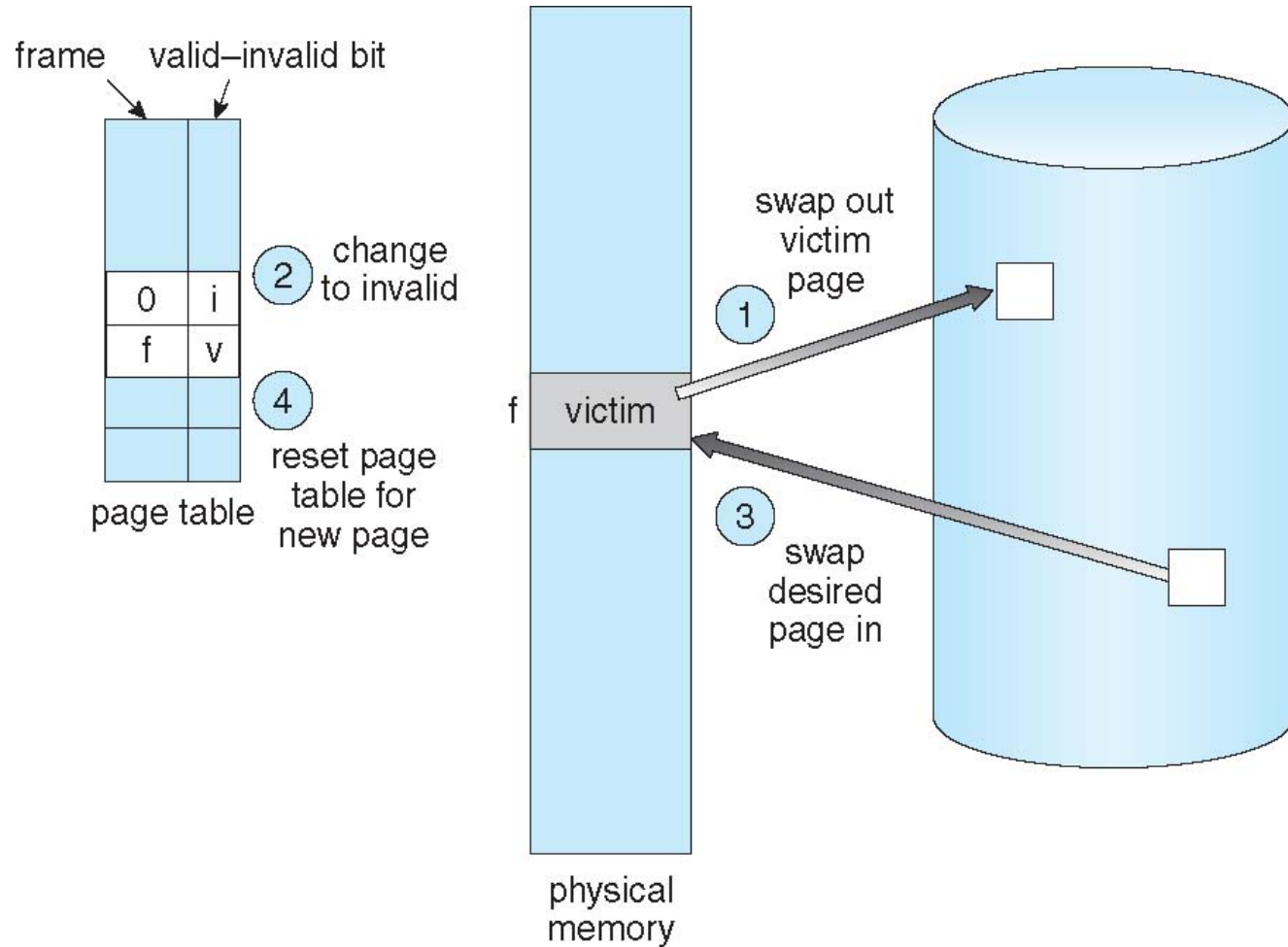
1. Find the location of the desired page on disk
2. Find a free frame:
  - If there is a free frame, use it
  - If there is no free frame, use a page replacement algorithm to select a **victim frame**
    - Write victim frame to disk if dirty
3. Bring the desired page into the (newly) free frame; update the page and frame tables
4. Continue the process by restarting the instruction that caused the trap

Note now potentially 2 page transfers for page fault – increasing EAT





# Page Replacement





# Page and Frame Replacement Algorithms

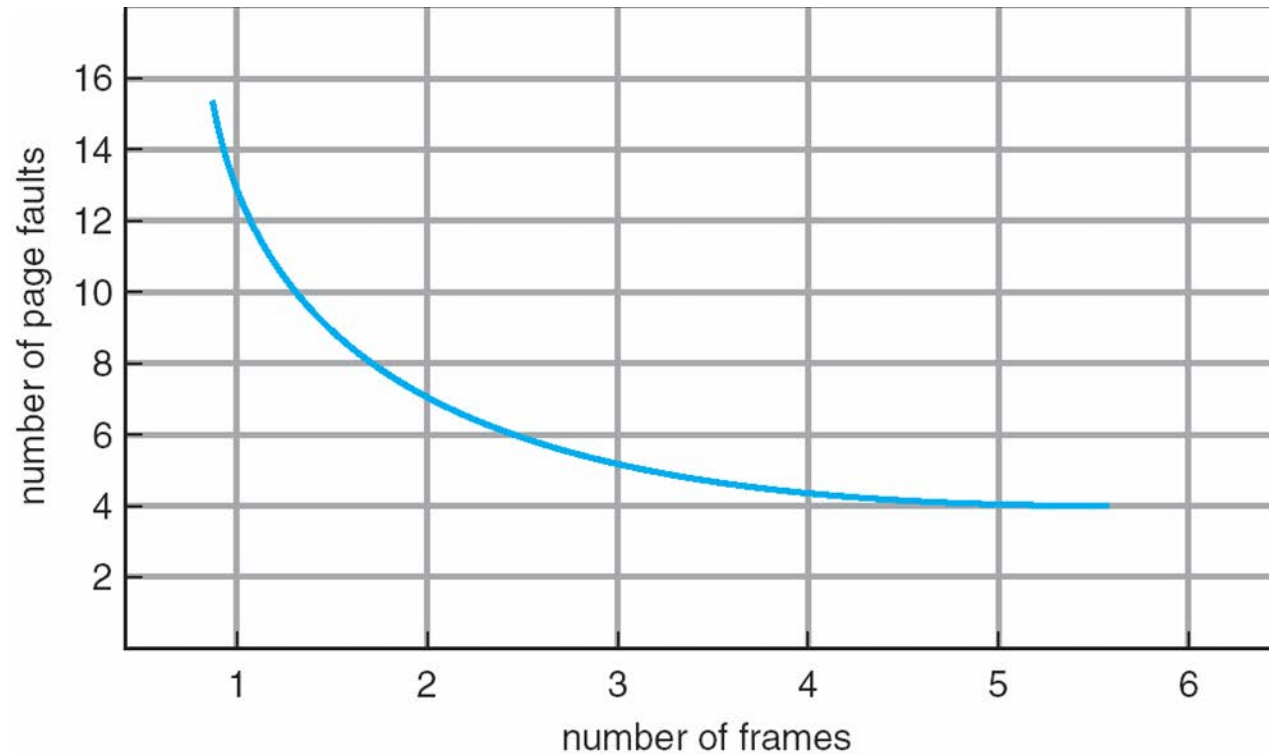
- **Frame-allocation algorithm** determines
  - How many frames to give each process
  - Which frames to replace
- **Page-replacement algorithm**
  - Want lowest page-fault rate on both first access and re-access
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
  - String is just page numbers, not full addresses
  - Repeated access to the same page does not cause a page fault
  - Results depend on number of frames available
- In all our examples, the **reference string** of referenced page numbers is

**7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1**





# Graph of Page Faults Versus The Number of Frames







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

- Reference string: **7,0,1,2,0,3,0,4,2,3,0,3,2,1,2,0,1,7,0,1**
- 3 frames (3 pages can be in memory at a time per process)

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

page frames

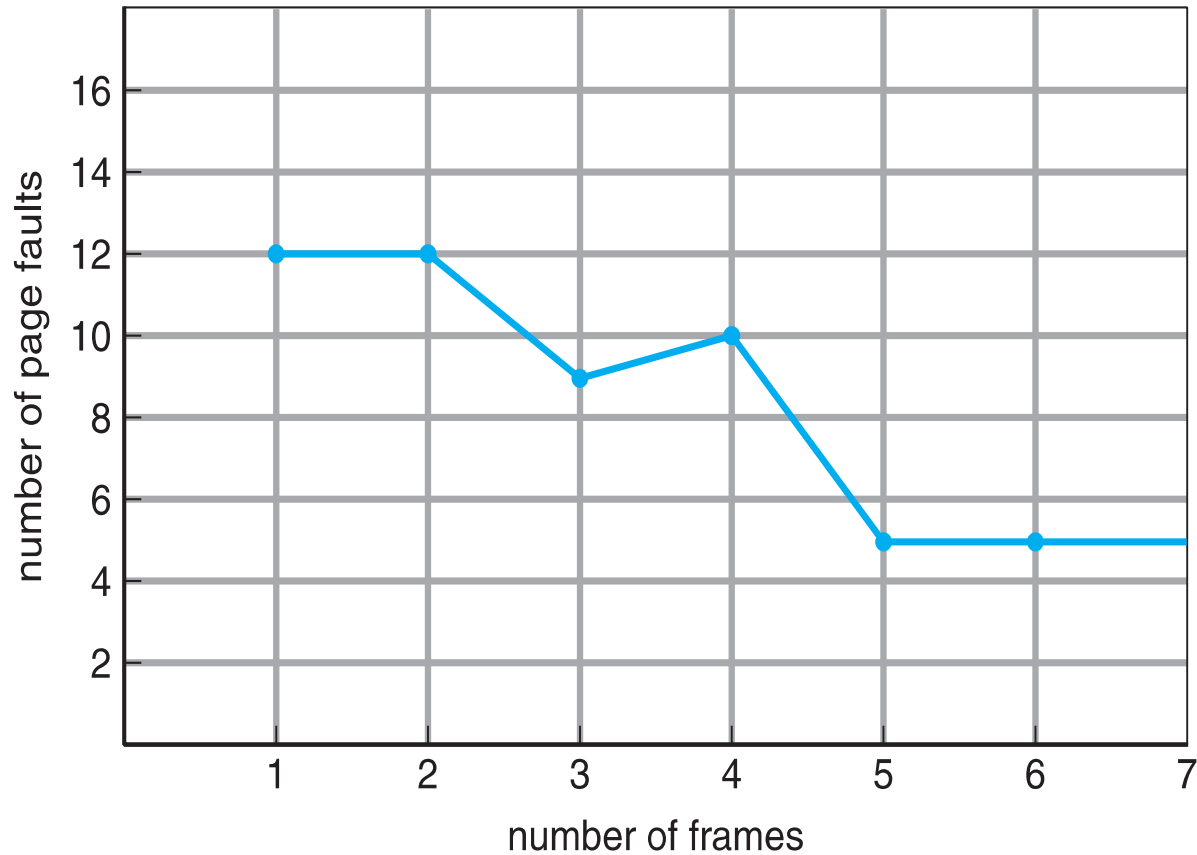
15 page faults

- Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5
  - Adding more frames can cause more page faults!
    - ▶ **Belady's Anomaly**
- How to track ages of pages?
  - Just use a FIFO queue





# FIFO Illustrating Belady's Anomaly





# Optimal Algorithm

- Replace page that will not be used for longest period of time
  - 9 is optimal for the example
- How do you know this?
  - Can't read the future
- Used for measuring how well your algorithm performs

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

page frames





# Least Recently Used (LRU) Algorithm

- Use past knowledge rather than future
- Replace page that has not been used in the most amount of time
- Associate time of last use with each page

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

- 12 faults – better than FIFO but worse than OPT
- Generally good algorithm and frequently used
- But how to implement?





# Counting Algorithms

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- Keep a counter of the number of references that have been made to each page
  - Not common
- **Least Frequently Used (LFU) Algorithm:** replaces page with smallest count
- **Most Frequently Used (MFU) Algorithm:** based on the argument that the page with the smallest count was probably just brought in and has yet to be used





# Global vs. Local Allocation

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- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
  - But then process execution time can vary greatly
  - But greater throughput so more common
  
- **Local replacement** – each process selects from only its own set of allocated frames
  - More consistent per-process performance
  - But possibly underutilized memory





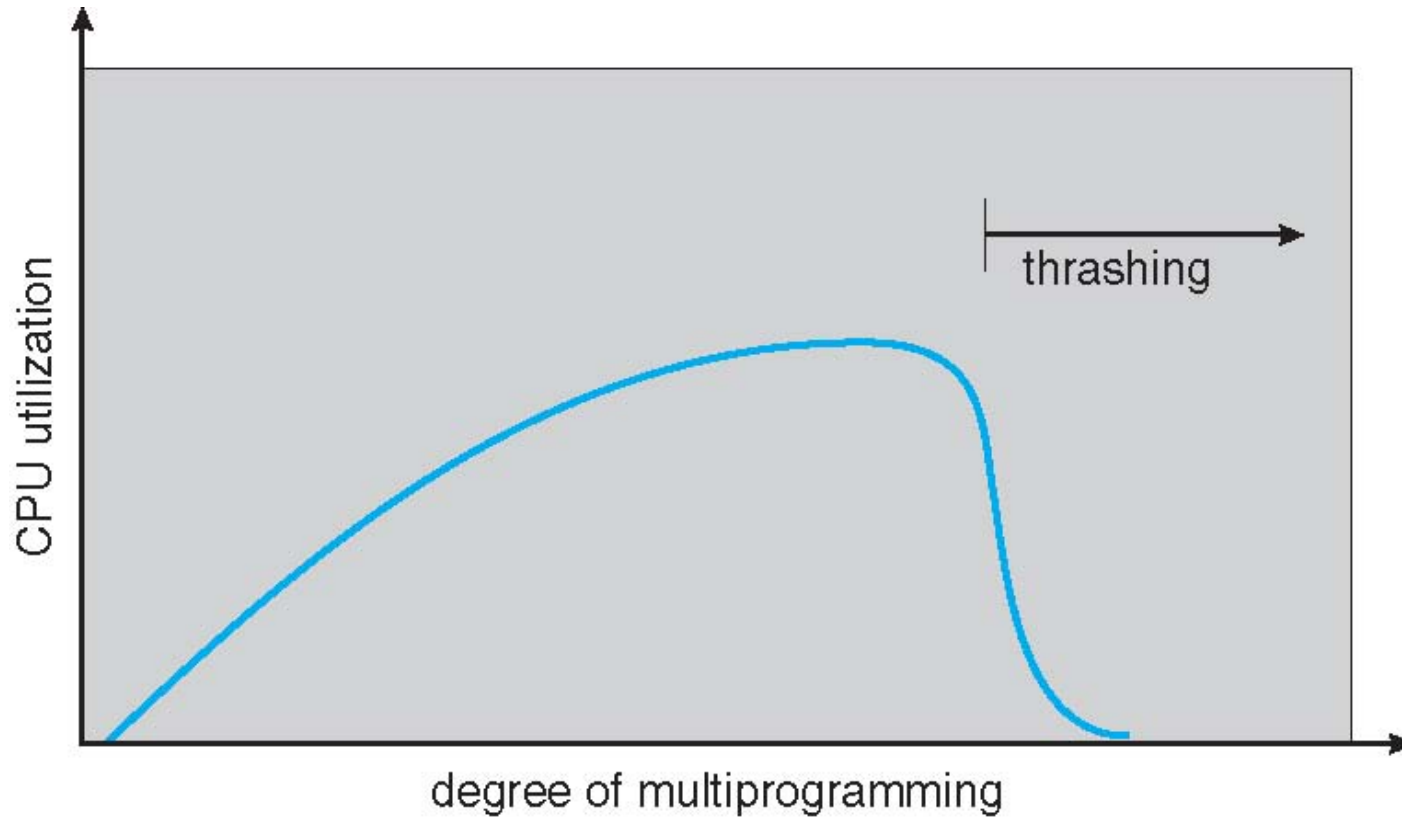
# Thrashing

- If a process does not have “enough” pages, the page-fault rate is very high
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
  - This leads to:
    - ▶ Low CPU utilization
    - ▶ Operating system thinking 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





# Thrashing (Cont.)







# Demand Paging and Thrashing

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- Why does demand paging work?

## Locality model

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

- Why does thrashing occur?

$\Sigma$  size of locality > total memory size

- Limit effects by using local or priority page replacement



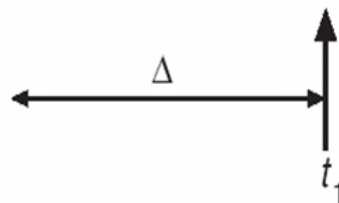


# Working-Set Model

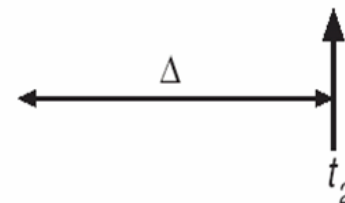
- $\Delta \equiv$  working-set window  $\equiv$  a fixed number of page references  
Example: 10,000 instructions
- $WSS_i$  (working set of Process  $P_i$ ) =  
total number of pages referenced in the most recent  $\Delta$  (varies in time)
  - if  $\Delta$  too small will not encompass entire locality
  - if  $\Delta$  too large will encompass several localities
  - if  $\Delta = \infty \Rightarrow$  will encompass entire program
- $D = \sum WSS_i \equiv$  total demand frames
  - Approximation of locality
- if  $D > m \Rightarrow$  Thrashing
- Policy if  $D > m$ , then suspend or swap out one of the processes

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 ...



$$WS(t_1) = \{1, 2, 5, 6, 7\}$$



$$WS(t_2) = \{3, 4\}$$

