CSE 421/521 - Operating Systems
Fall 2013

Lecture - XVI

Virtual Memory - I

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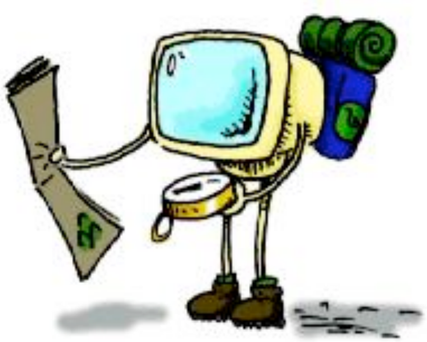
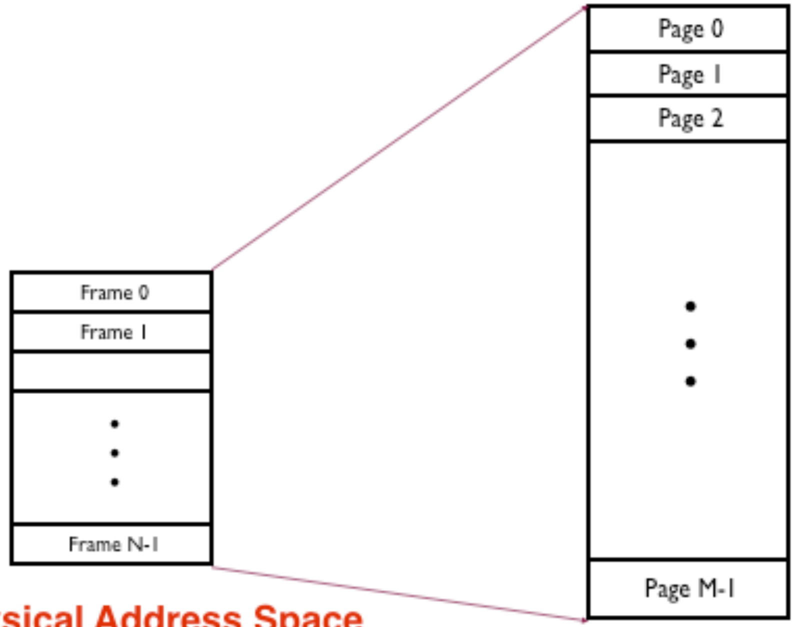
Roadmap

- Virtual Memory
  - Demand Paging
  - Page Faults
  - Page Replacement
  - Page Replacement Algorithms



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.



Physical Address Space
(installed RAM)
SMALL:(a few Gigabytes)
MESSY & FRAGMENTED

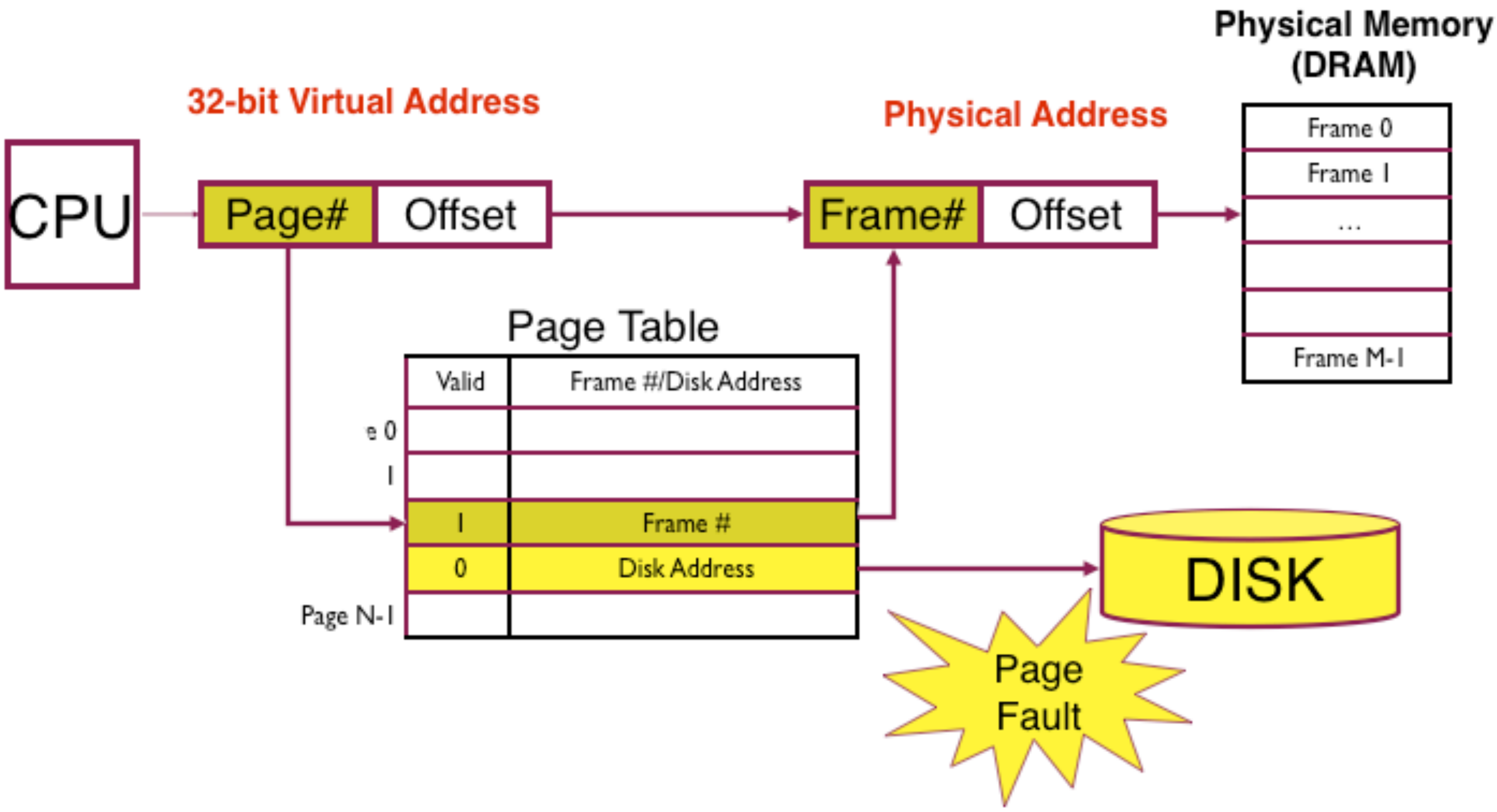
Virtual Address Space
BIG:(100s GB → TB)
CLEAN

Goals

- Make programmers job easier
  - Can write code without knowing how much DRAM is there
  - Only need to know general memory architecture
    - (e.g., 32-bit address space)

- Enable Multiprogramming
- Keep several programs running concurrently
  - Together, these programs may need more DRAM than we have.
  - Keep just the actively used pages in DRAM.
- Share when possible
  - When one program does I/O switch CPU to another.

How it works?



	Valid	Frame #/Disk Address
e 0		
I		
	I	Frame #
	0	Disk Address
Page N-I		

Implementation

- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

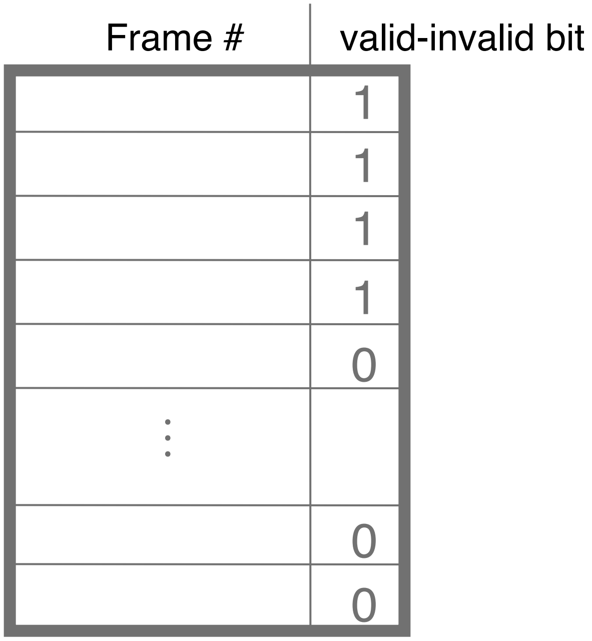
Demand Paging

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

- Page is needed ⇒ reference to it
  - invalid reference ⇒ abort
  - not-in-memory ⇒ bring to memory

Valid-Invalid Bit

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

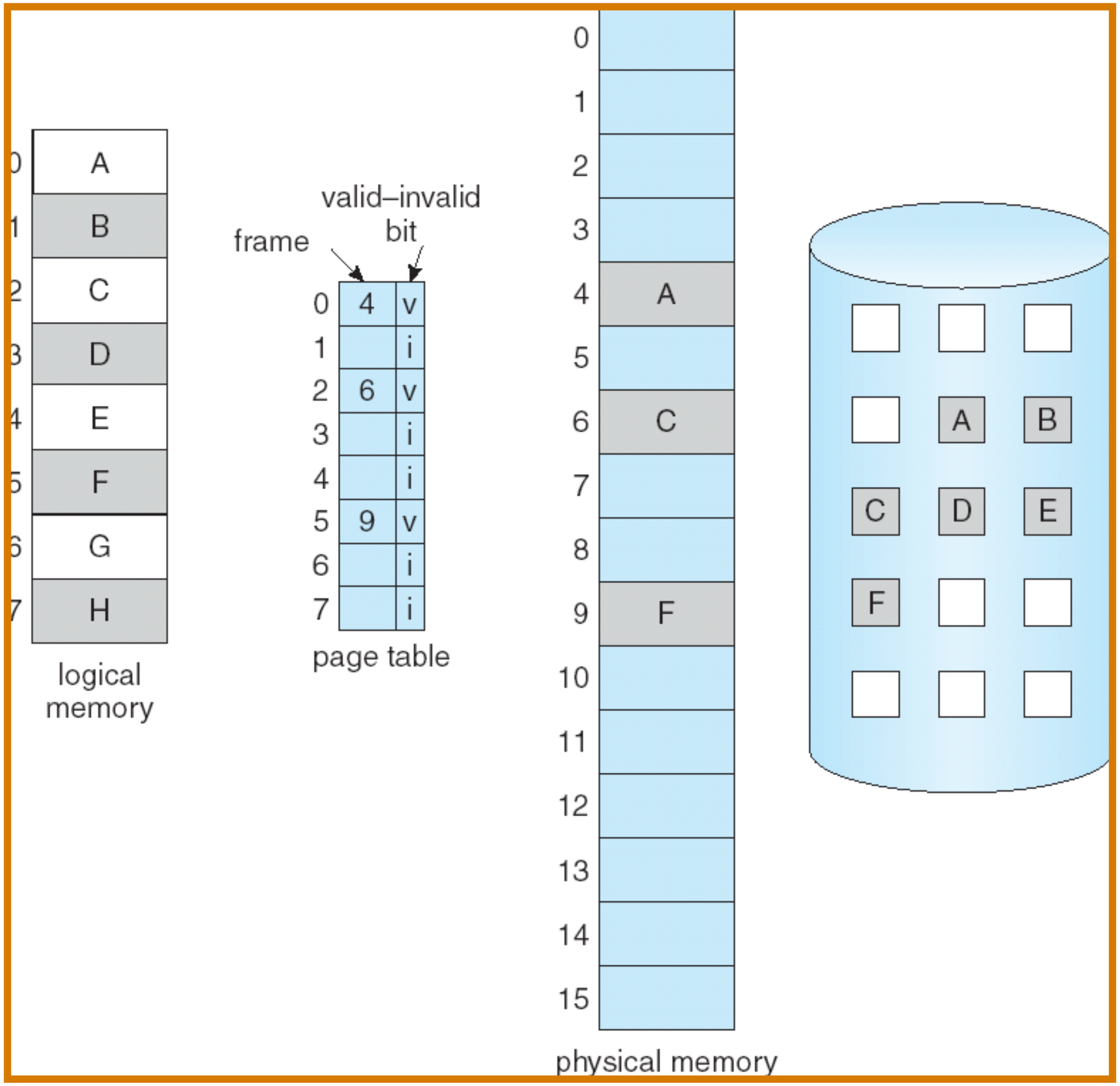


Frame #	valid-invalid bit
	1
	1
	1
	1
	0
⋮	
	0
	0

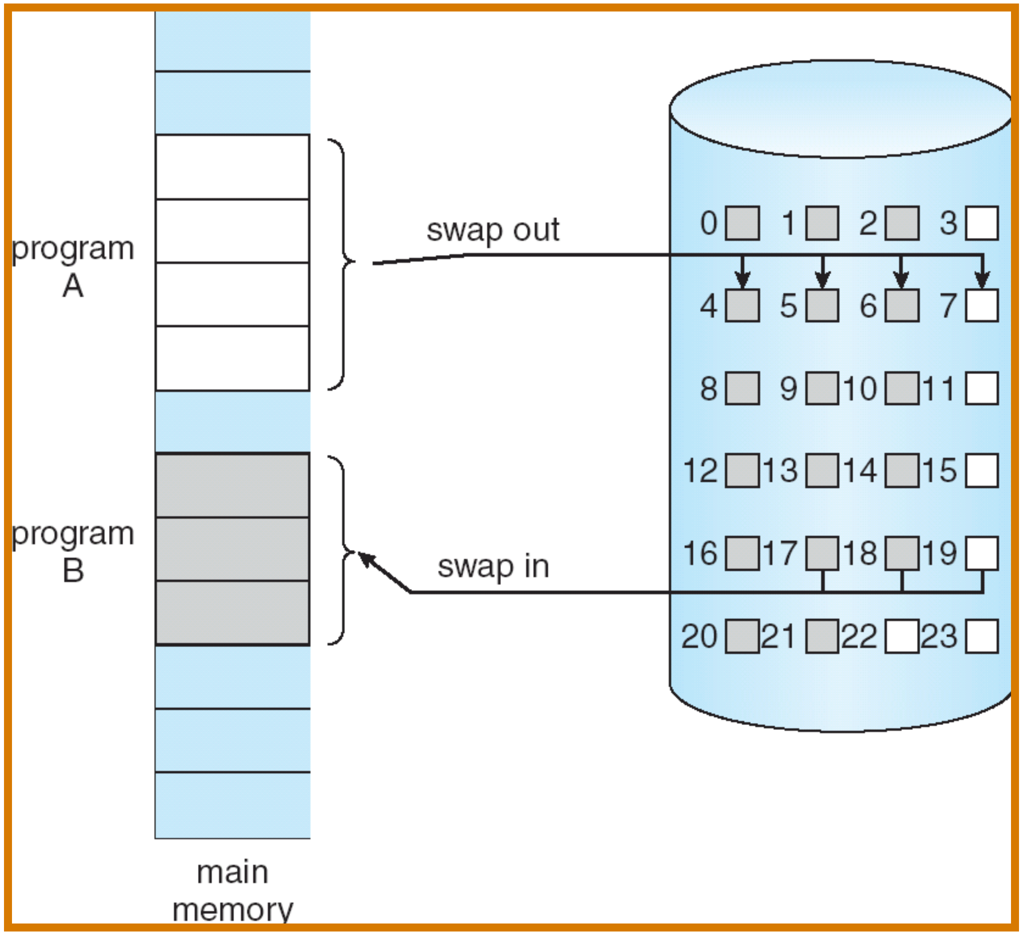
page table

- 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



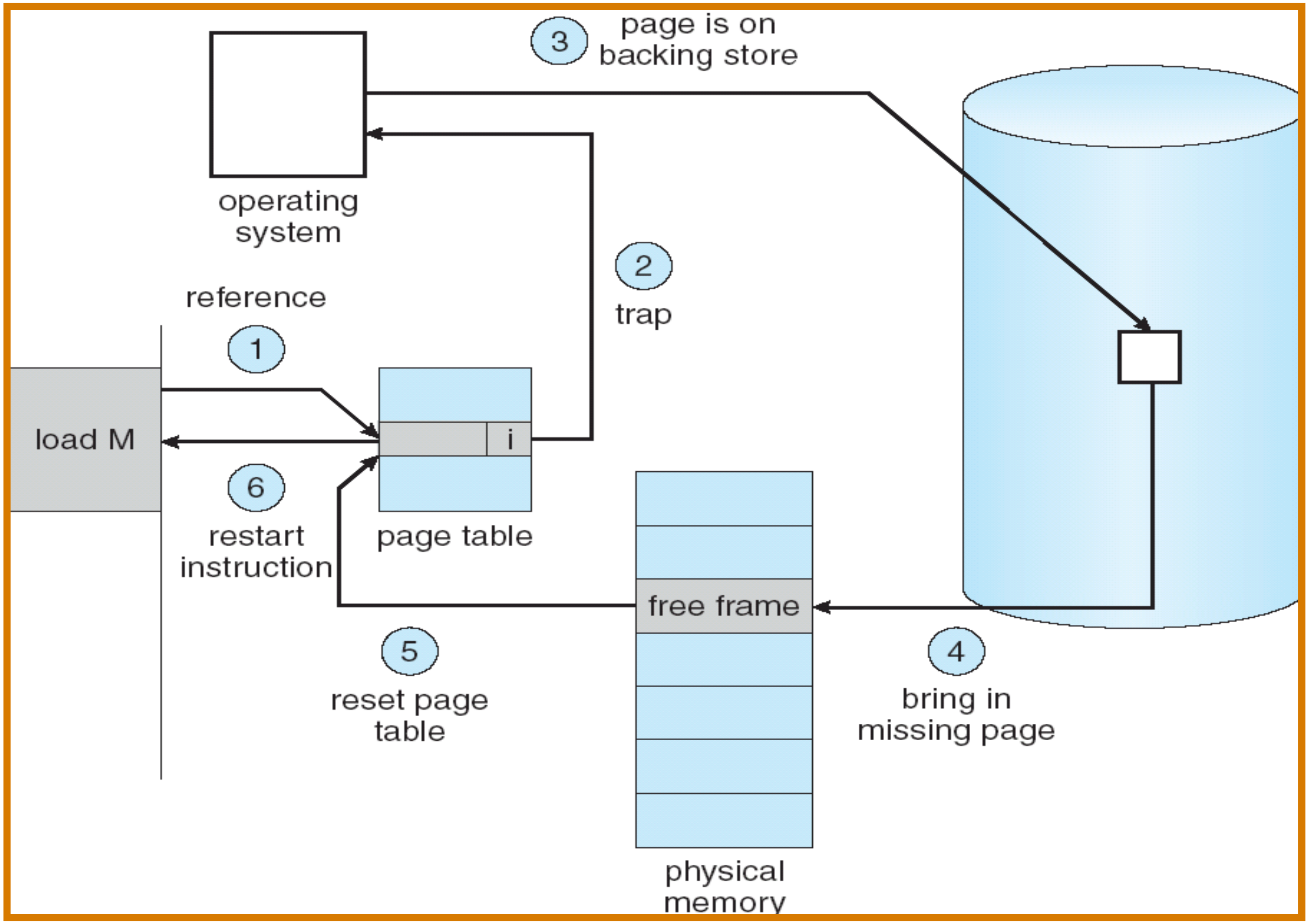
Transfer of a Paged Memory to Contiguous Disk Space

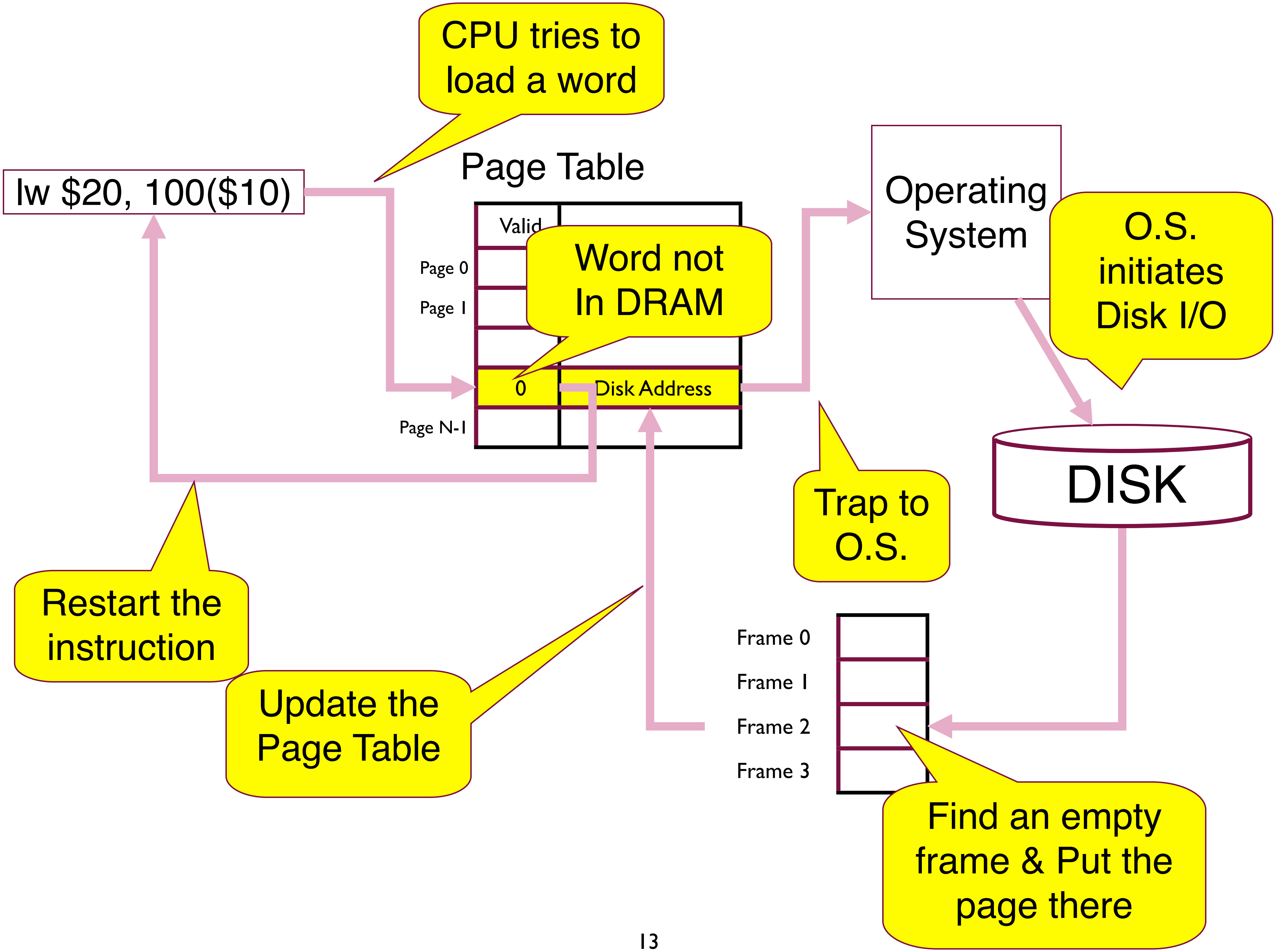


Page Fault

- If there is ever a reference to a page not in memory, first reference will trap to OS ⇒ page fault
- OS looks at another table (in PCB) to decide:
  - Invalid reference ⇒ abort.
  - Just not in memory. ==> page-in
- Get an empty frame.
- Swap (read) page into the new frame.
- Set validation bit = 1.
- Restart instruction

Steps in Handling a Page Fault





CPU tries to load a word

lw $20, 100($10)

Page Table

Word not In DRAM

Trap to O.S.

Operating System

O.S. initiates Disk I/O

Find an empty frame & Put the page there

Update the Page Table

Restart the instruction

What happens if there is no free frame?

- Page replacement – find some page in memory, but not really in use, swap it out
  - Algorithms (FIFO, LRU ..)
  - 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

Basic Page Replacement

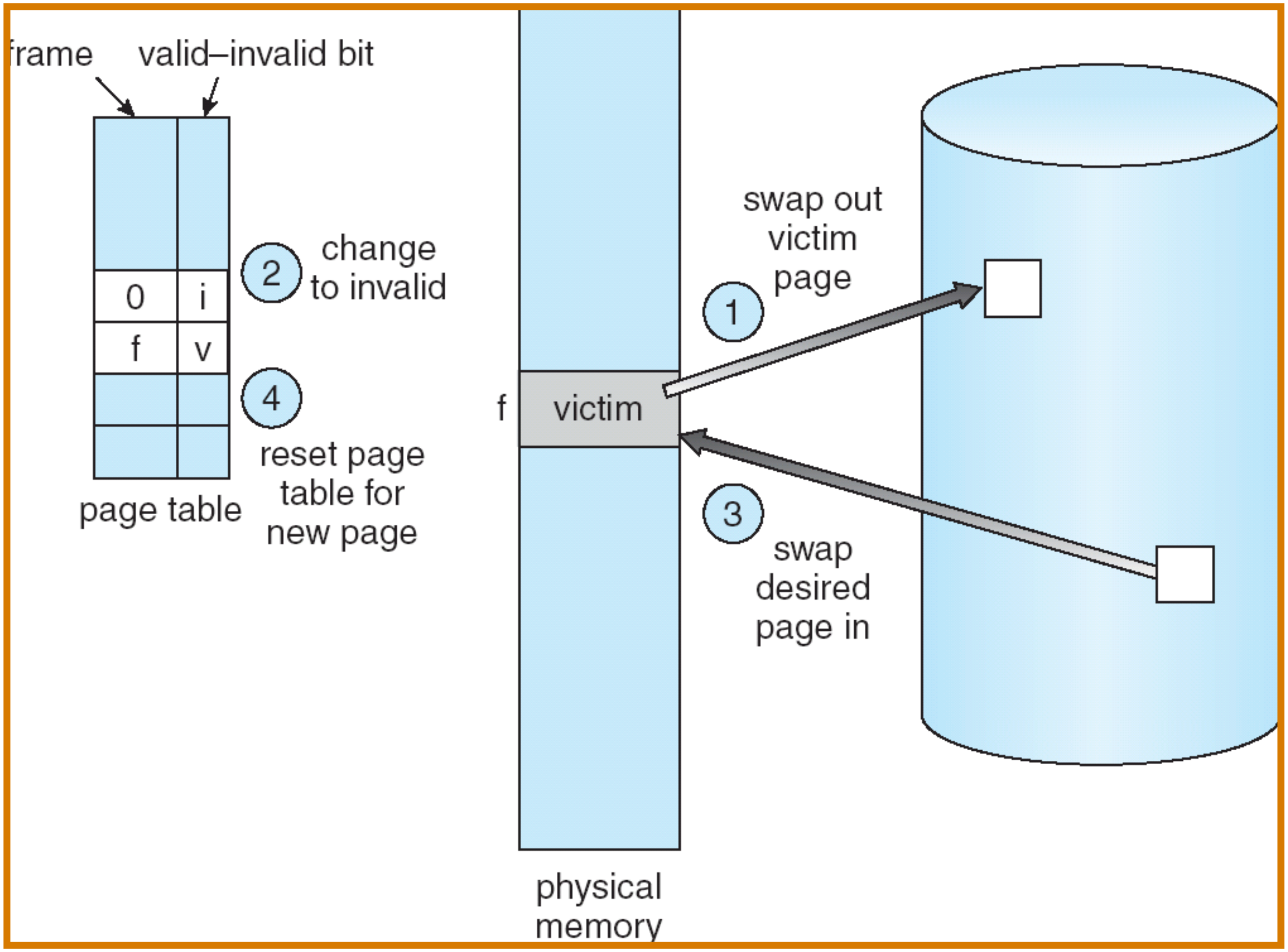
1. Find the location of the desired page on disk

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

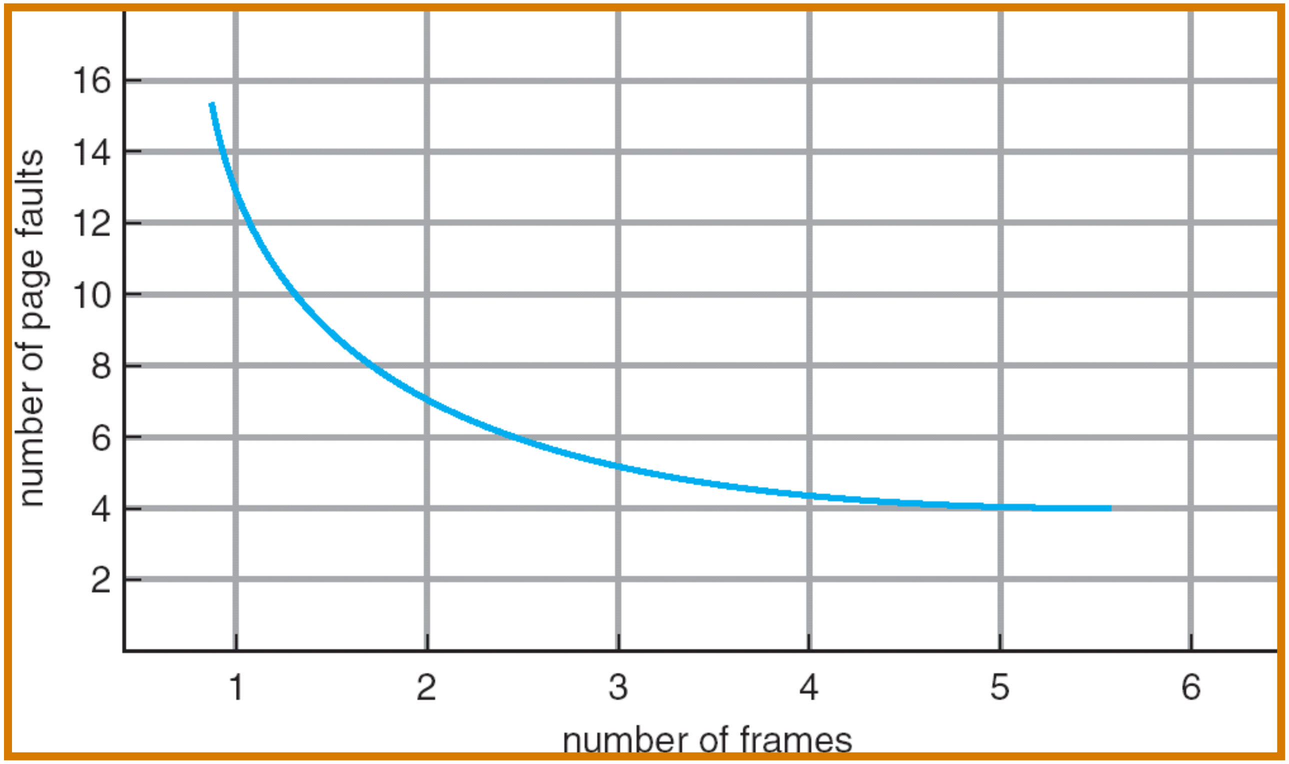


Page Replacement Algorithms

- 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

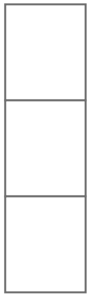
  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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)



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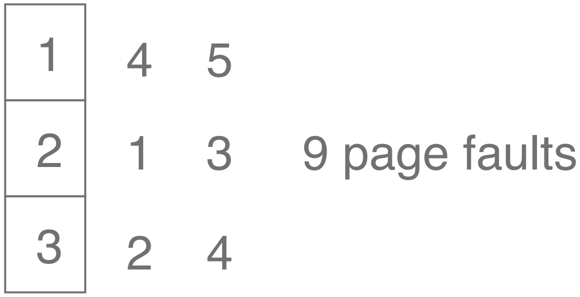

1 4 5

2 1 3 9 page faults

3 2 4

First-In-First-Out (FIFO) Algorithm

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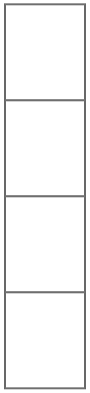
1	4	5	
2	1	3	9 page faults
3	2	4	

- 4 frames



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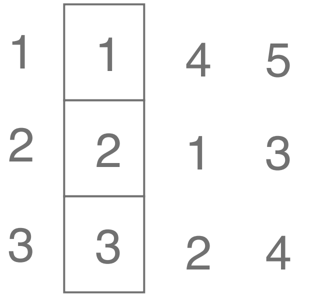
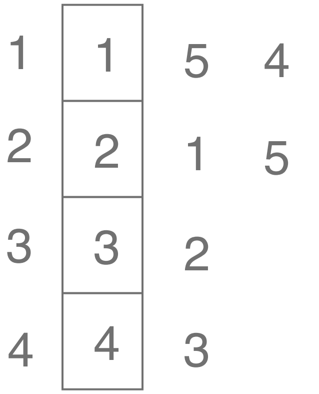


1	1	4	5
2	2	1	3
3	3	2	4

9 page faults

- 4 frames

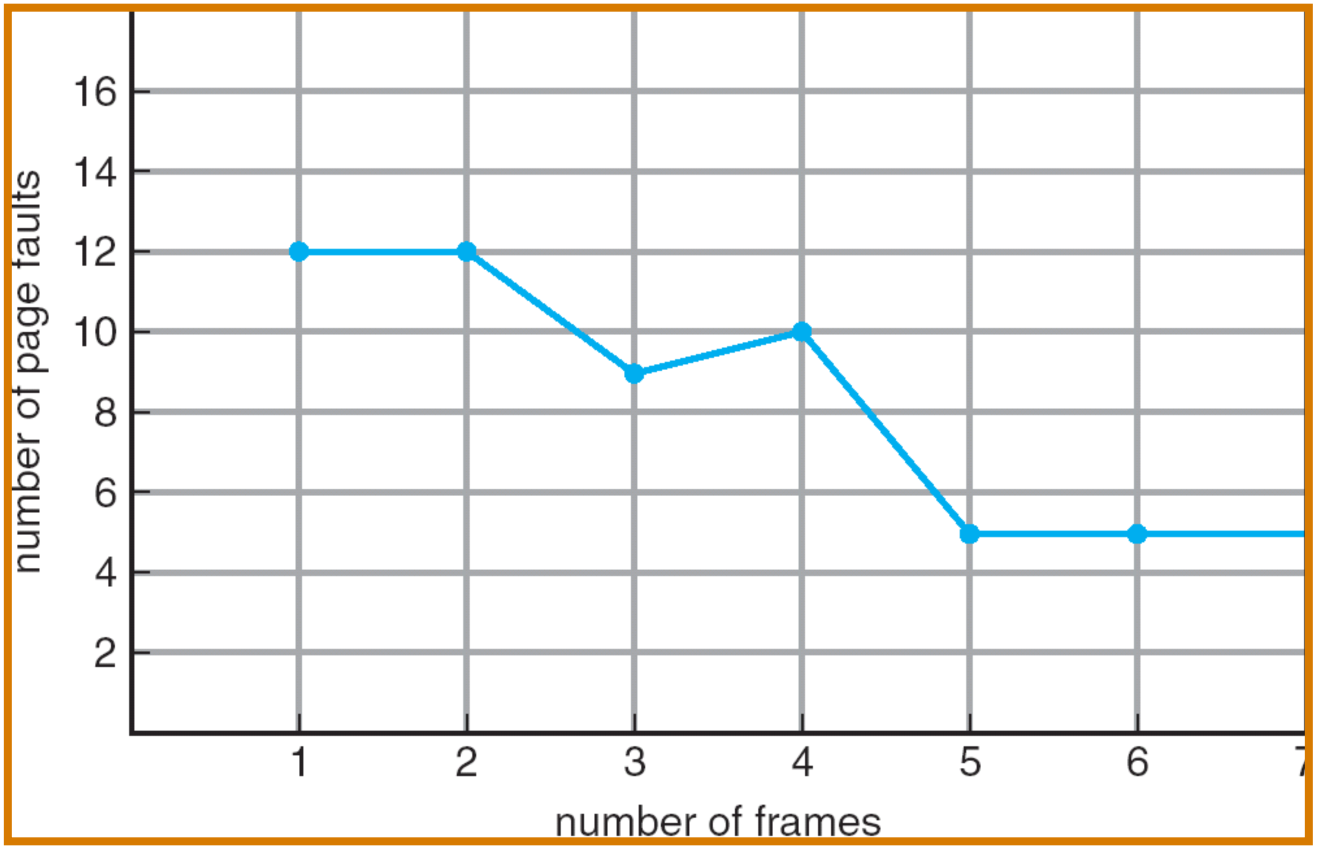


1	1	5	4
2	2	1	5
3	3	2	
4	4	3	

10 page faults

- FIFO Replacement – Belady’s Anomaly
  - more frames ⇒ more page faults

FIFO Illustrating Belady's Anomaly



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)

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

Demand Paging Example

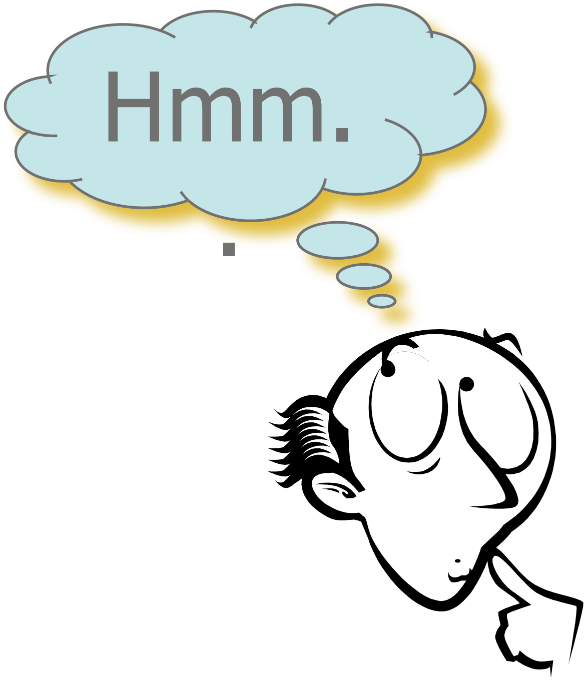
- Memory access time = 1 microsecond
- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out
- Swap Page Time = 10 msec = 10,000 microsec
- EAT = ?

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
- $\text{EAT} = (1 - p) \times 1 + p \times (10{,}000 + 1/2 \times 10{,}000)$
  $= 1 + 14{,}999 \times p$ (in microsec)
- What if 1 out of 1000 memory accesses cause a page fault?
- What if we only want 30% performance degradation?

Summary

- Virtual Memory
  - Demand Paging
  - Page Faults
  - Page Replacement
  - Page Replacement Algorithms
    - FIFO



- Next Lecture: Virtual Memory - II
- Reading Assignment: Chapter 9 from Silberschatz.

Acknowledgements

- “Operating Systems Concepts” book and supplementary material by A. Silberschatz, P. Galvin and G. Gagne
- “Operating Systems: Internals and Design Principles” book and supplementary material by W. Stallings
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