CSE 421/521 - Operating Systems
Fall 2018

LECTURE - XVI

VIRTUAL MEMORY - I

Tevfik Koşar

University at Buffalo

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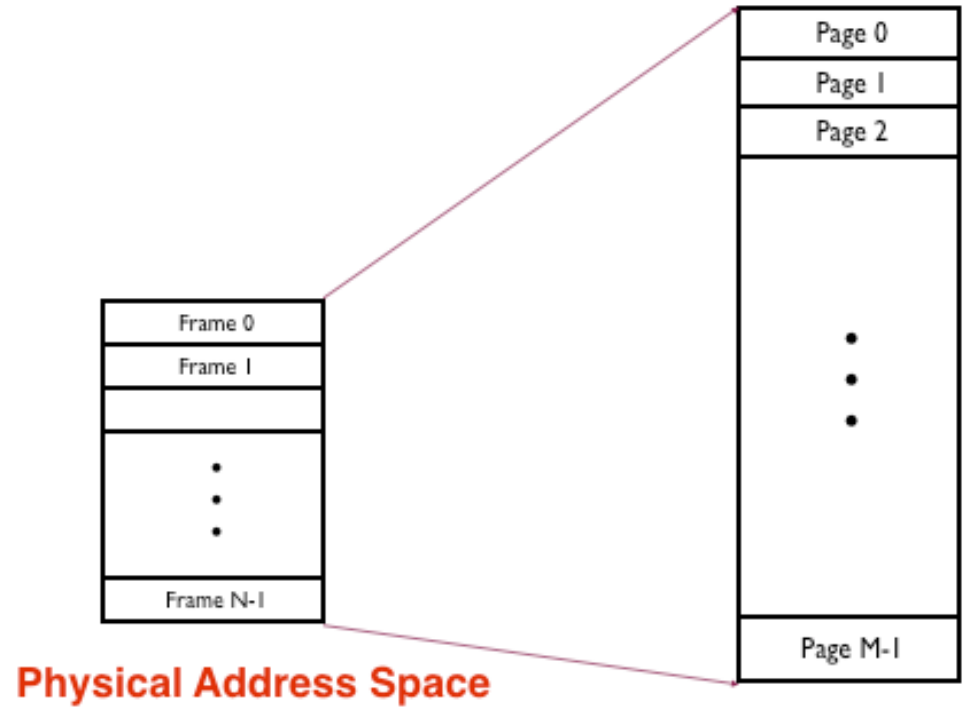
Roadmap

- Virtual Memory
  - Demand Paging
  - Page Faults
  - Page Replacement
  - Page Replacement Algorithms
    - FIFO
    - Optimal Algorithm
    - LRU & LRU Approximations
    - Counting 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.



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.

Implementation

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

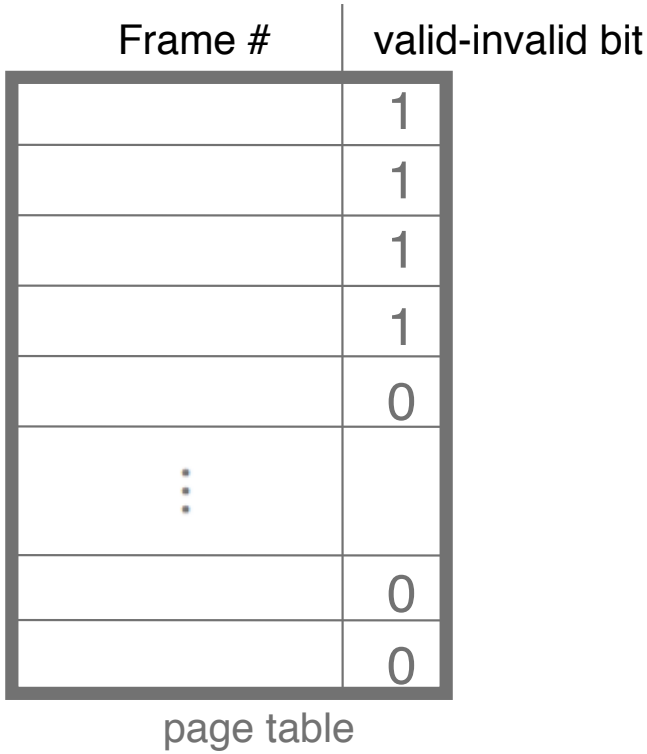
Demand Paging

- 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

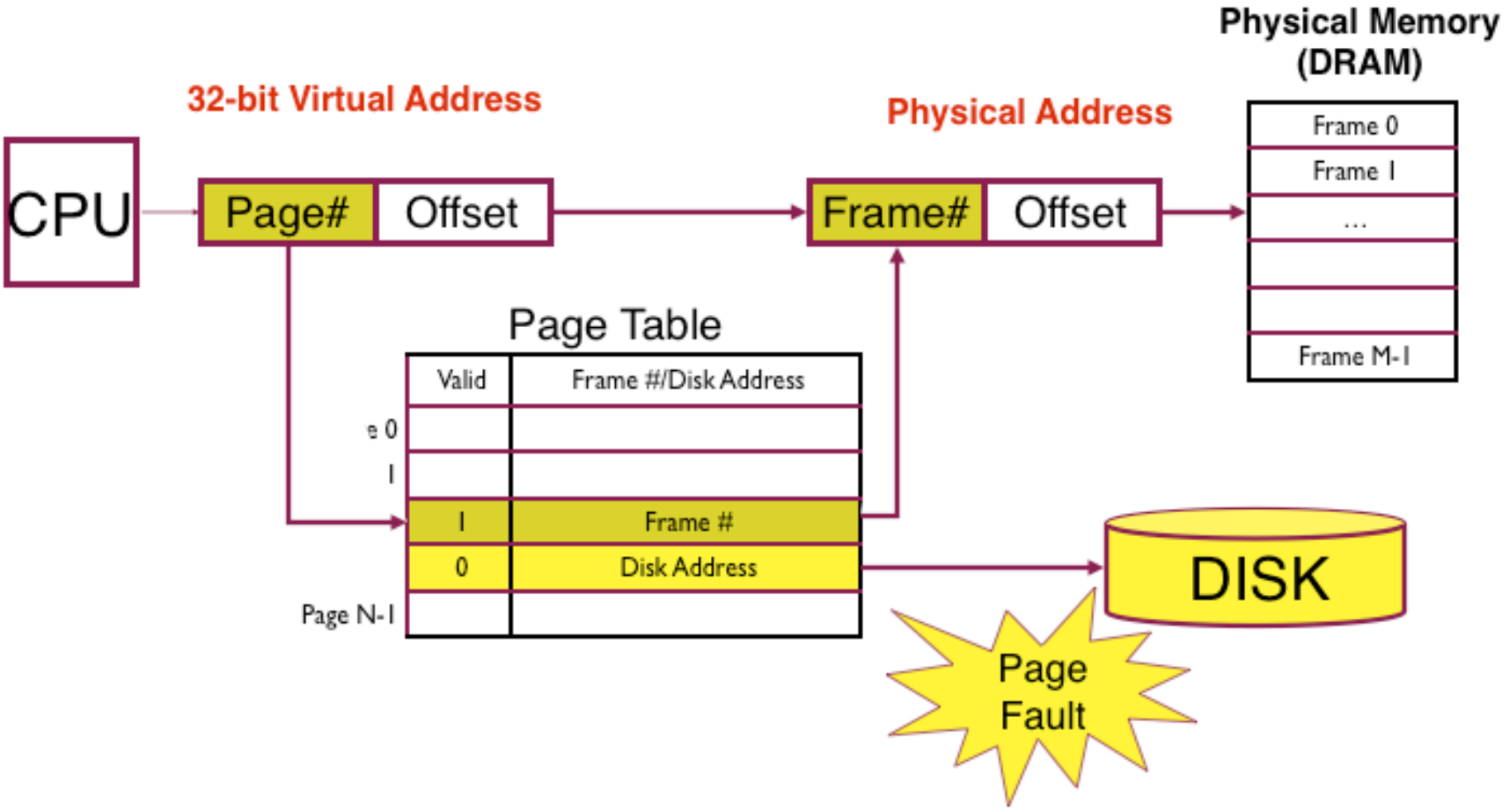
Valid-Invalid Bit

- 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:

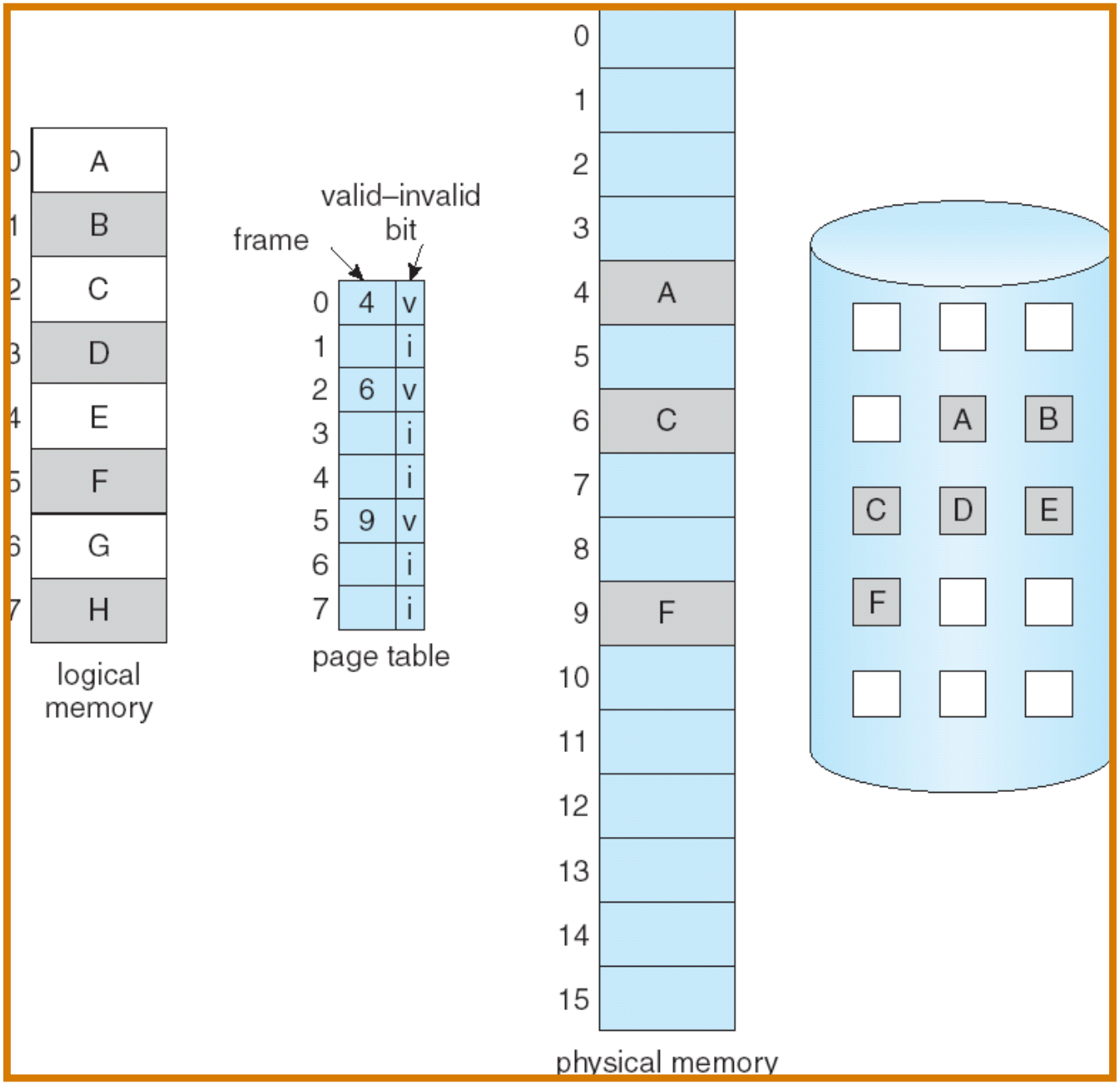


- During address translation, if valid–invalid bit in page table entry is 0 ⇒ page fault

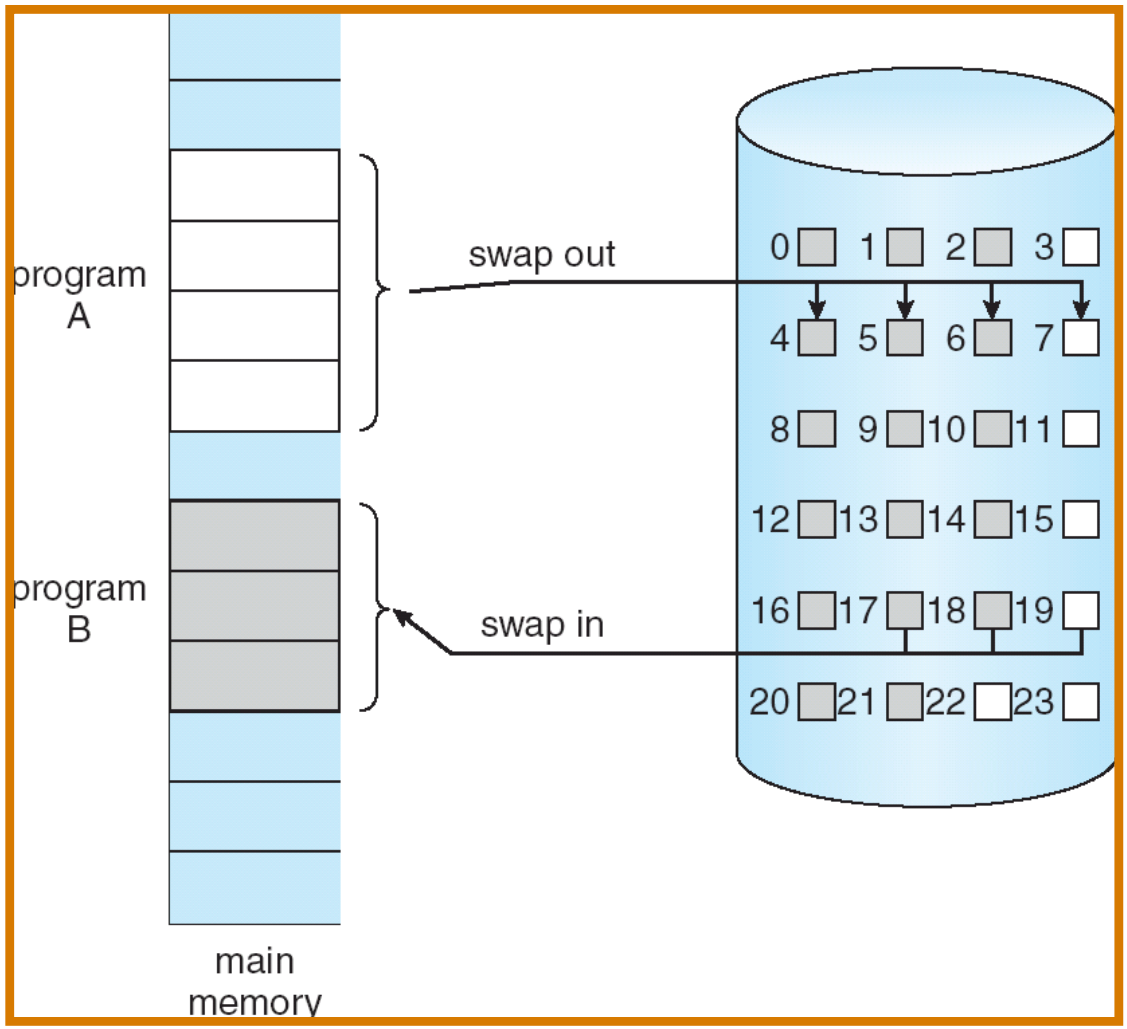
How it works?


Physical Memory
(DRAM)
32-bit Virtual Address
Physical Address
CPU
Page#
Offset
Frame#
Offset
Frame 0
Frame 1
...
Frame M-1
Page Table
Valid
Frame #/Disk Address
e 0
1
1
Frame #
0
Disk Address
Page N-1
DISK
Page
Fault

Page Table When Some Pages Are Not in Main Memory

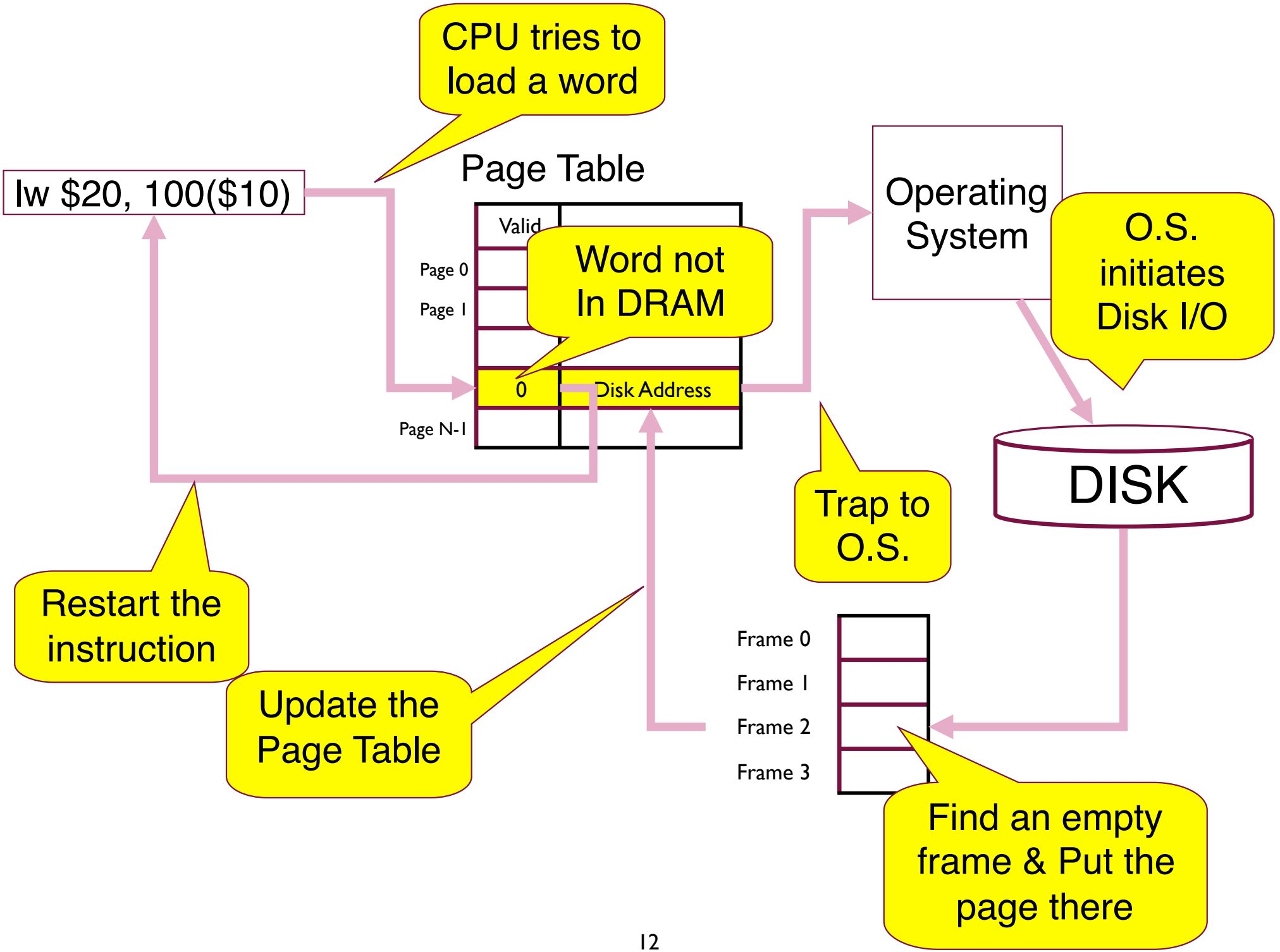


Transfer of a Paged Memory to Contiguous Disk Space



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


CPU tries to load a word
lw $20, 100($10)
Page Table
Valid
Page 0
Page 1
0
Disk Address
Page N-1
Word not In DRAM
Operating System
O.S. initiates Disk I/O
DISK
Trap to O.S.
Restart the instruction
Update the Page Table
Frame 0
Frame 1
Frame 2
Frame 3
Find an empty frame & Put the page there

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

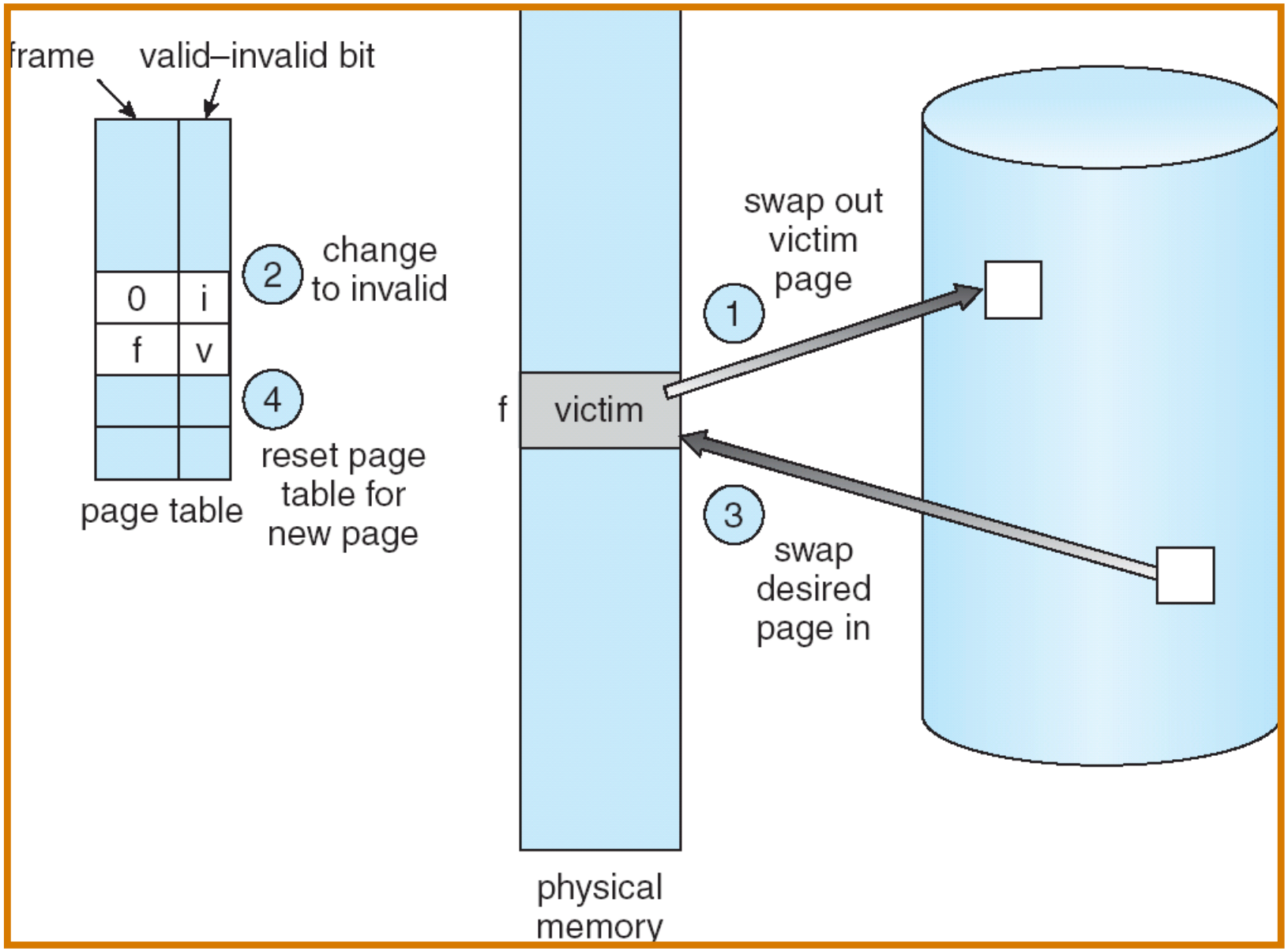
1. Find the location of the desired page on disk

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

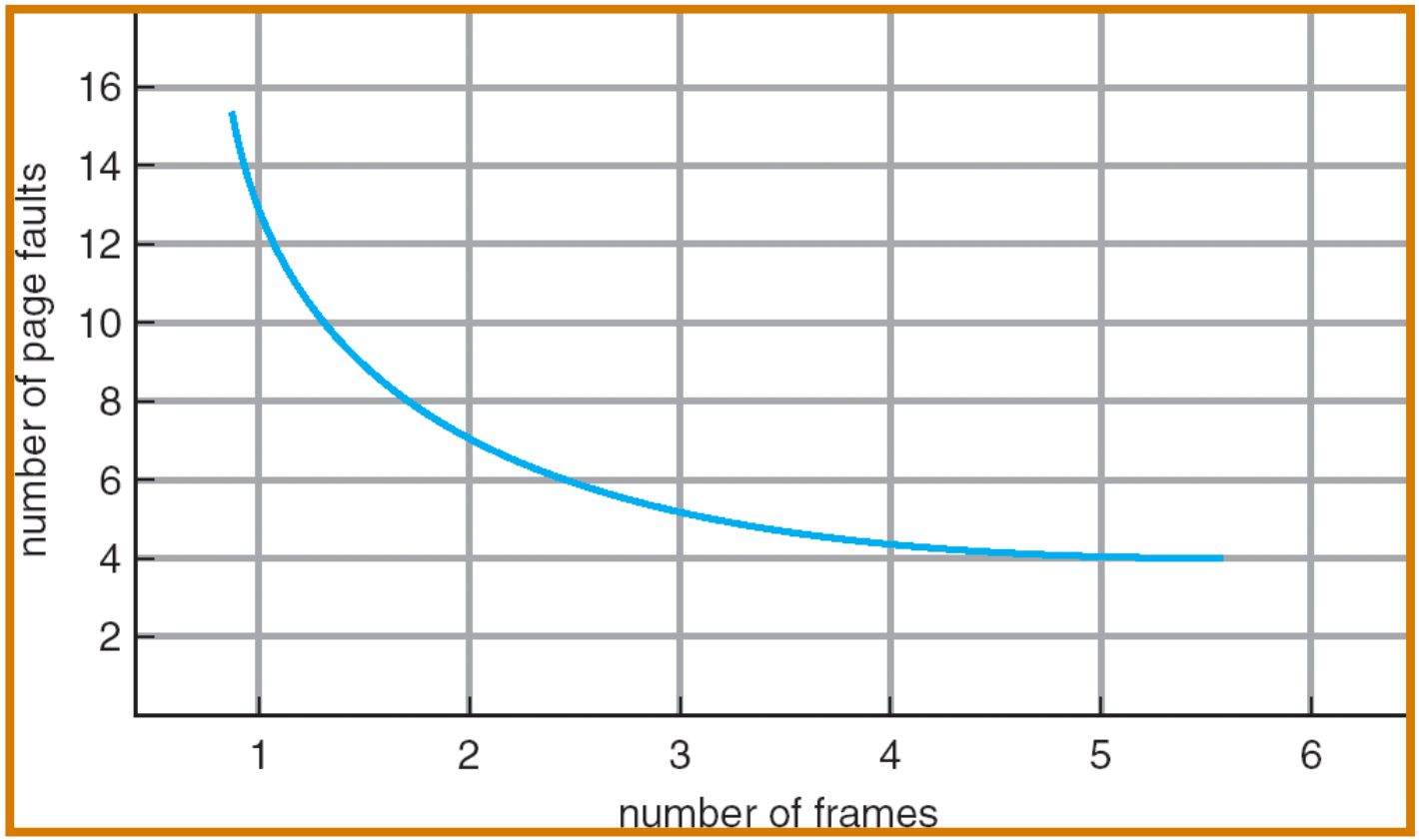


Page Replacement Algorithms

- 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

Expected Graph of Page Faults vs 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	

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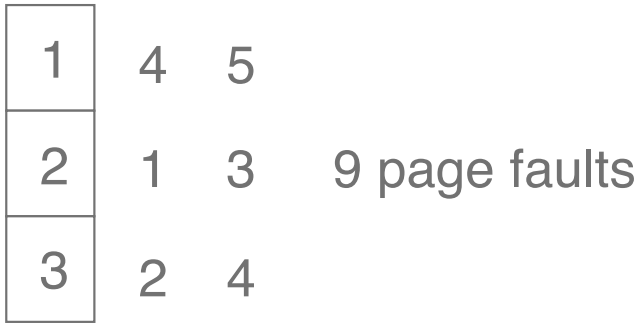
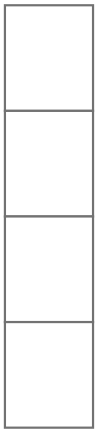


- 4 frames



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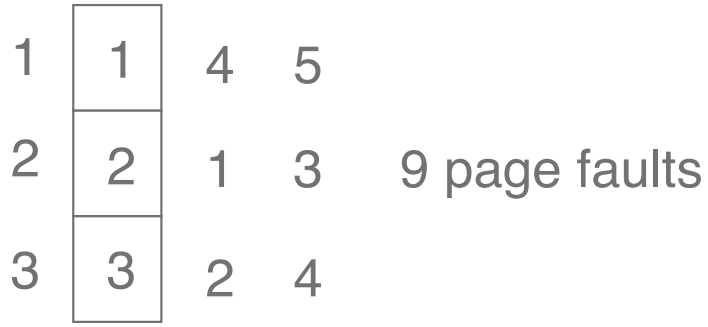
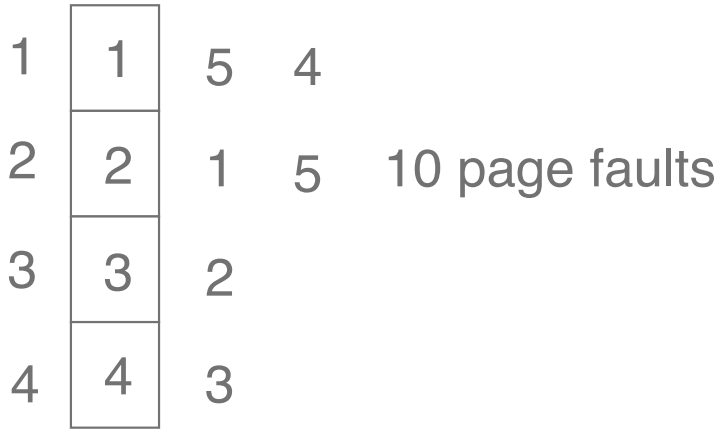
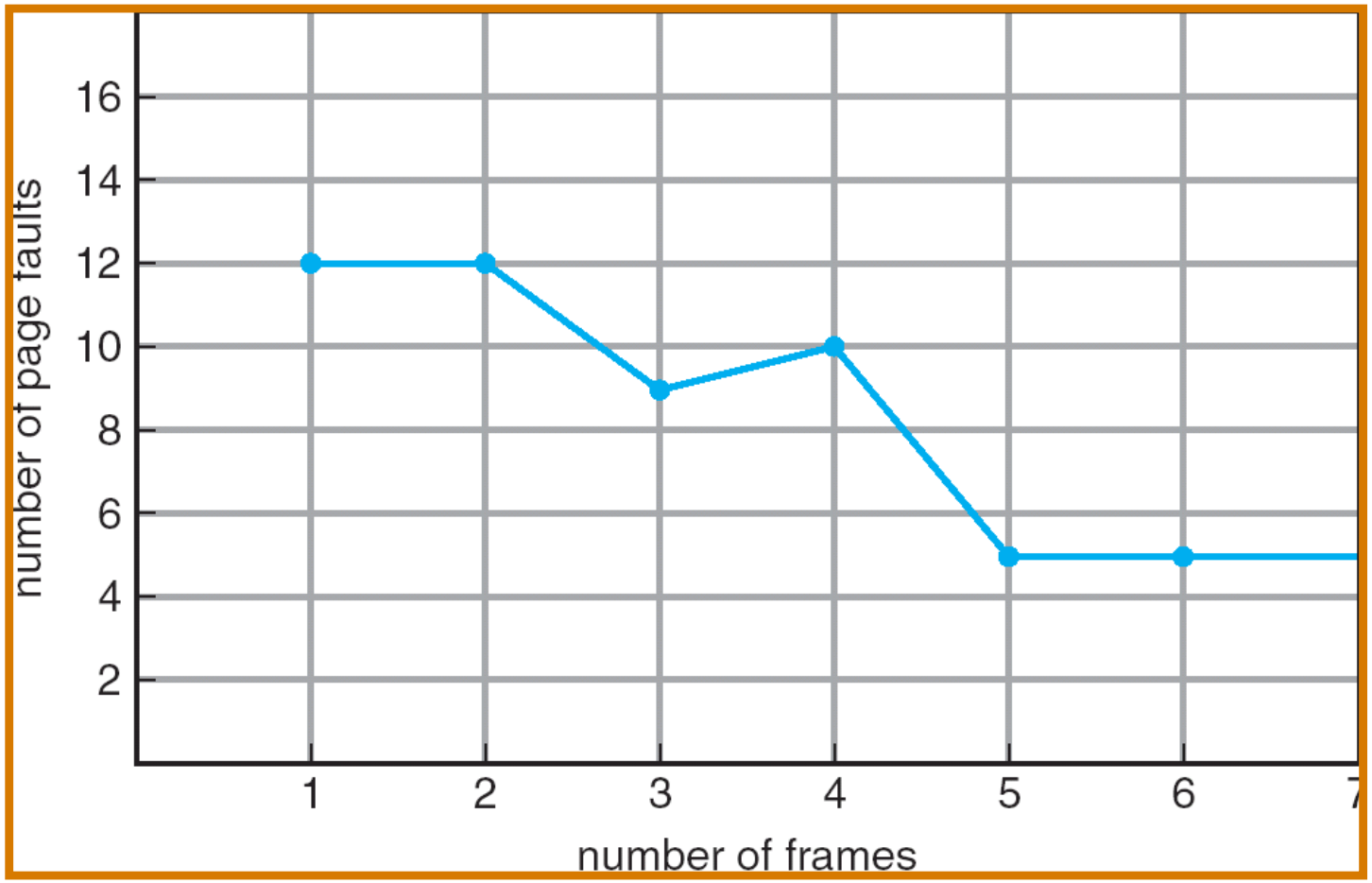


- 4 frames



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

FIFO Illustrating Belady's Anomaly



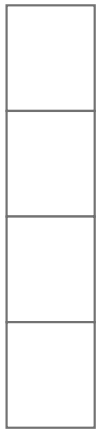
FIFO

- FIFO is obvious, and simple to implement
  - when you page in something, put it on the tail of a list
  - evict page at the head of the list
- Why might this be good?
  - maybe the one brought in longest ago is not being used
- Why might this be bad?
  - then again, maybe it *is* being used
  - have absolutely no information either way
- In fact, FIFO's performance is typically lousy
- In addition, FIFO suffers from Belady's Anomaly
  - there are reference strings for which the fault rate *increases* when the process is given more physical memory

Optimal Algorithm

- Replace page that will not be used for the longest time in future
- 4 frames example

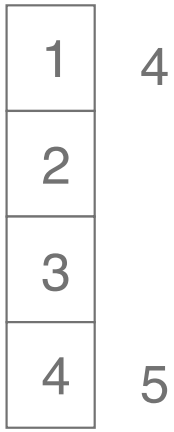
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



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 would you know this in advance?

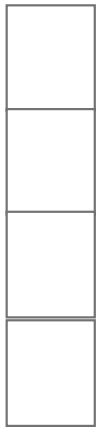
Optimal (Belady's) Algorithm

- Provably optimal: lowest fault rate (remember SJF?)
  - evict the page that won't be used for the longest time in future
  - problem: impossible to predict the future
- Why is Belady's Optimal algorithm useful?
  - as a yardstick to compare other algorithms to optimal
    - if Belady's isn't much better than yours, yours is pretty good
      - how could you do this comparison?
- Is there a best practical algorithm?
  - no; depends on workload
- Is there a worst algorithm?
  - no, but random replacement does pretty badly
    - there are some other situations where OS's use near-random algorithms quite effectively!

Least Recently Used (LRU)

- Replace the page that has not been used for the longest amount of time in the past

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



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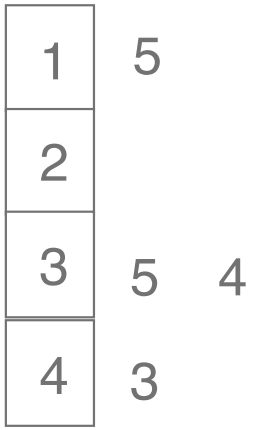
- 4 frames example:



8 page faults

Least Recently Used (LRU)

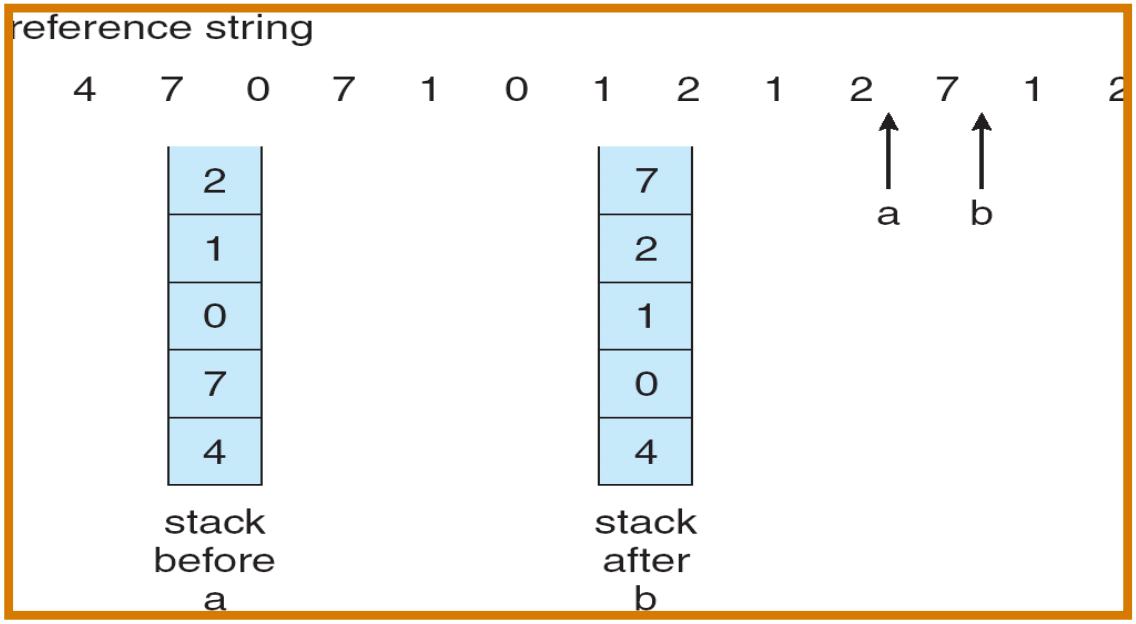
- LRU uses reference information to make a more informed replacement decision
  - idea: past experience gives us a guess of future behavior
  - on replacement, evict the page that hasn't been used for the longest amount of time
    - LRU looks at the past, Belady's wants to look at future
    - *How is LRU different from FIFO?*

- Implementation

- to be perfect, must grab a timestamp on every memory reference, then order or search based on the timestamps …
- way too costly in memory bandwidth, algorithm execution time, etc.
- so, we need a cheap approximation …

LRU Implementations

- **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



LRU Approximation Algorithms

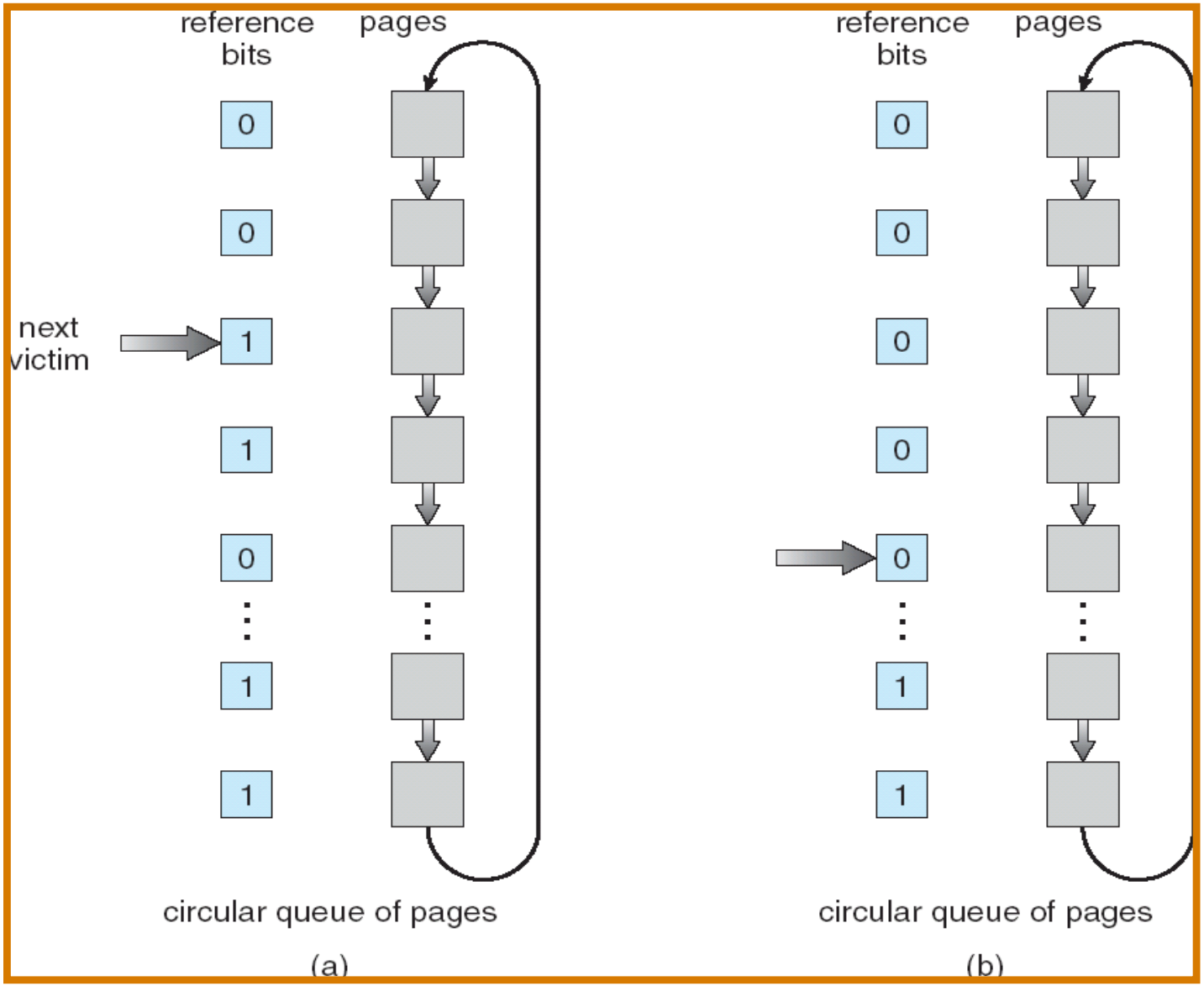
- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace the one which is 0 (if one exists). We do not know the order, however.

- Additional Reference bits
  - 1 byte for each page: eg. 00110011
  - Shift right at each time interval

LRU Clock Algorithm

- AKA Not Recently Used (NRU) or Second Chance
  - replace page that is “old enough”
  - logically, arrange all physical page frames in a big circle (clock)
    - just a circular linked list
  - a “clock hand” is used to select a good LRU candidate
    - sweep through the pages in circular order like a clock
    - if ref bit is off, it hasn’t been used recently, we have a victim
      - so, what is minimum “age” if ref bit is off?
    - if the ref bit is on, turn it off and go to next page
  - arm moves quickly when pages are needed
  - low overhead if have plenty of memory
  - if memory is large, “accuracy” of information degrades
    - add more hands to fix

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

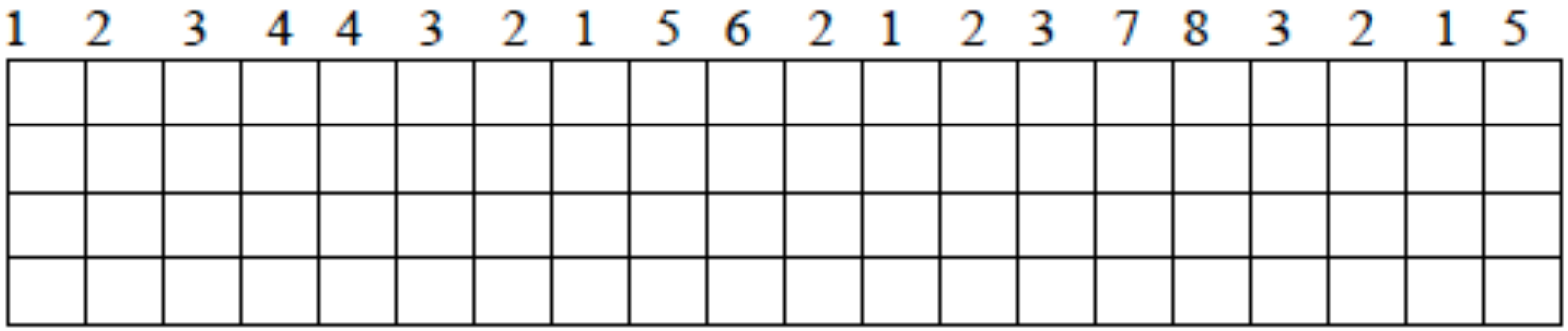
- **MFU Algorithm**: based on the argument that the page with the smallest count was probably just brought in and has yet to be used

Exercise

- Consider the following page-reference string:

1, 2, 3, 4, 4, 3, 2, 1, 5, 6, 2, 1, 2, 3, 7, 8, 3, 2, 1, 5

Assuming 4 memory frames and LRU, LFU, or Optimal page replacement algorithms, how many page faults, page hits, and page replacements would occur? Show your page assignments to frames.



# of page faults:
# of page hits:
# of page replacements:

Summary

- Virtual Memory
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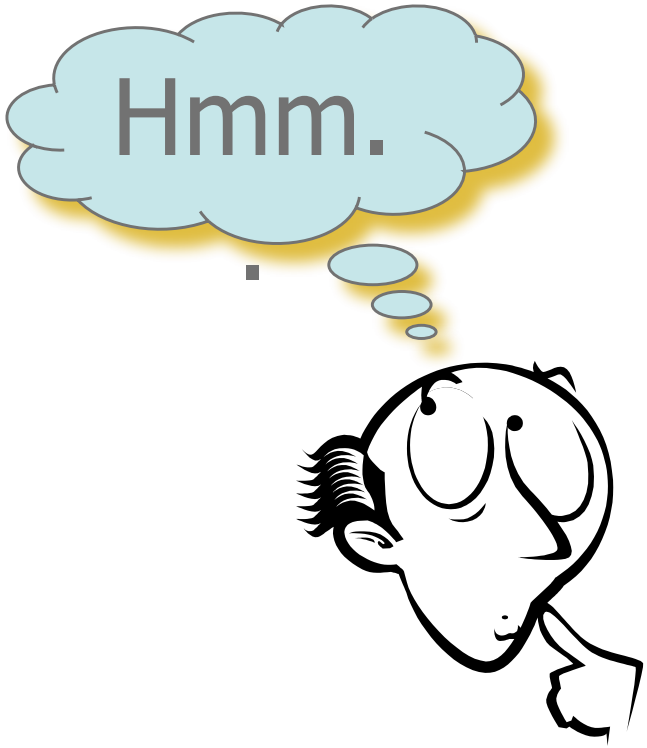

- Next Lecture: Virtual Memory - II
- Reading Assignment: Chapter 9 from Silberschatz.

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

- “Modern Operating Systems” book and supplementary material by A. Tanenbaum

- R. Doursat and M. Yuksel from UNR