CSE 421/521 - Operating Systems
Fall 2014

Lecture - XVII

Virtual Memory - II

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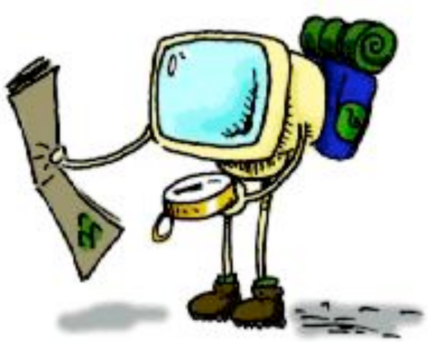
Roadmap

- Virtual Memory
  - Performance of Demand Paging
  - Page Replacement Algorithms
    - Least Recently Used (LRU)
    - LRU Approximations
    - Counting Algorithms
  - Allocation Policies
  - Thrashing
  - Working Set Model



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)

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

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

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

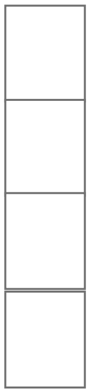
Optimal (Belady's) Algorithm

- 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)

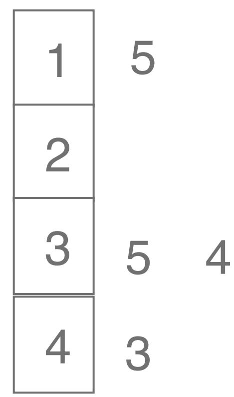
- Replace the page that has not been used for the longest amount of time in the past

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



Least Recently Used (LRU)

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



8 page faults

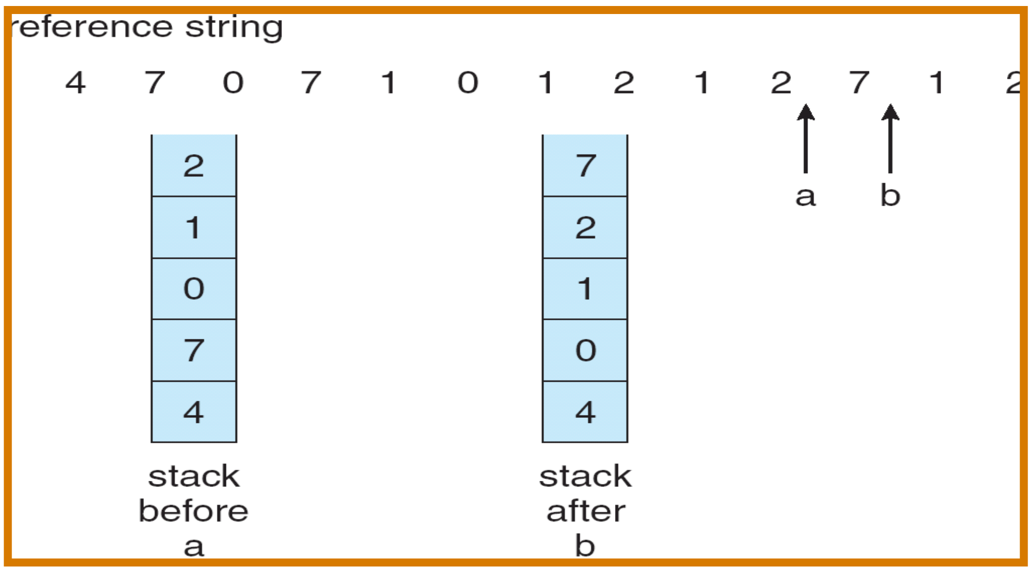
Least Recently Used (LRU)

- 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

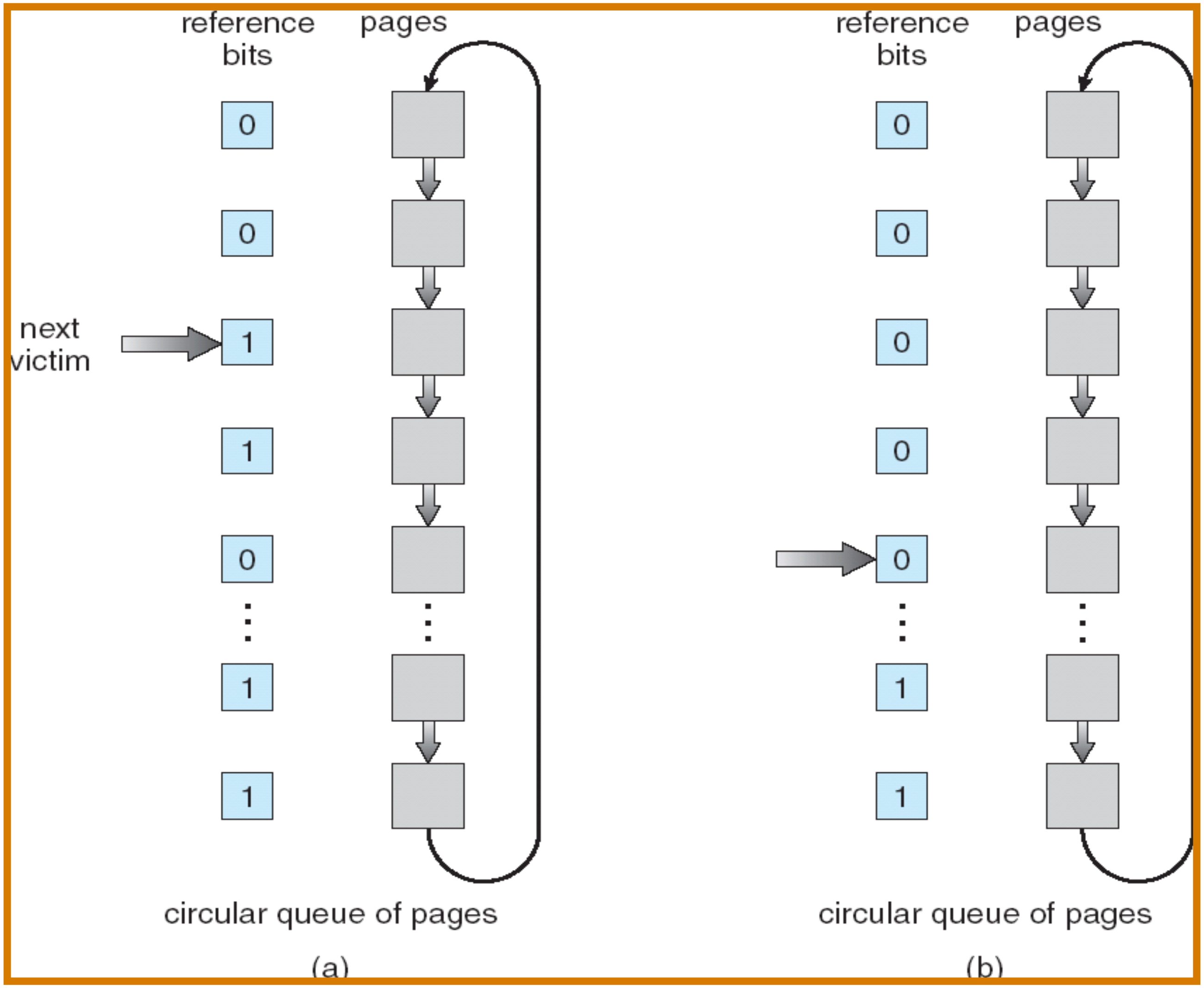
- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace the one which is 0 (if one exists). We do not know the order, however.

- 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:

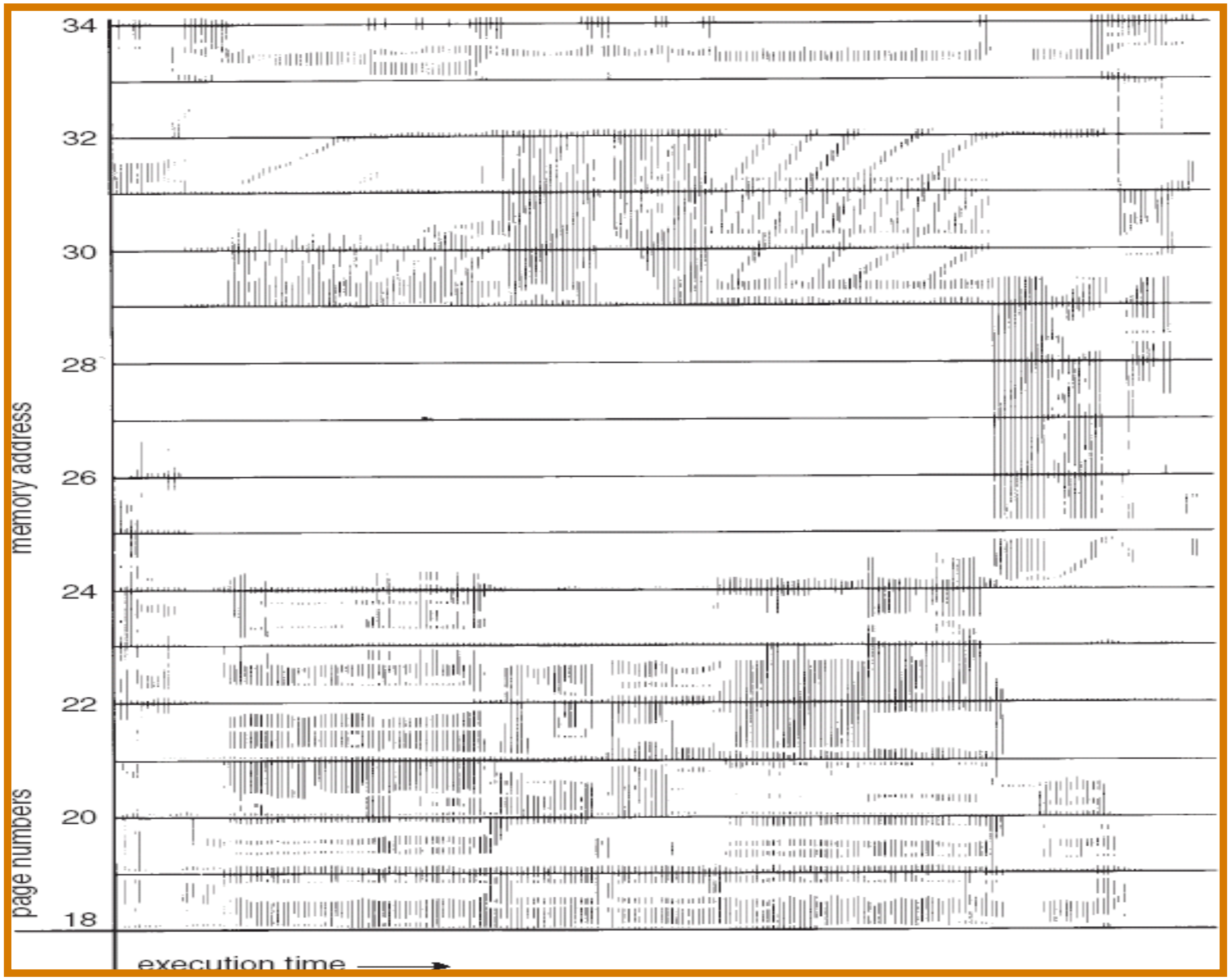
1, 2, 3, 4, 4, 3, 2, 1, 5, 6, 2, 1, 2, 3, 7, 8, 3, 2, 1, 5

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

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

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

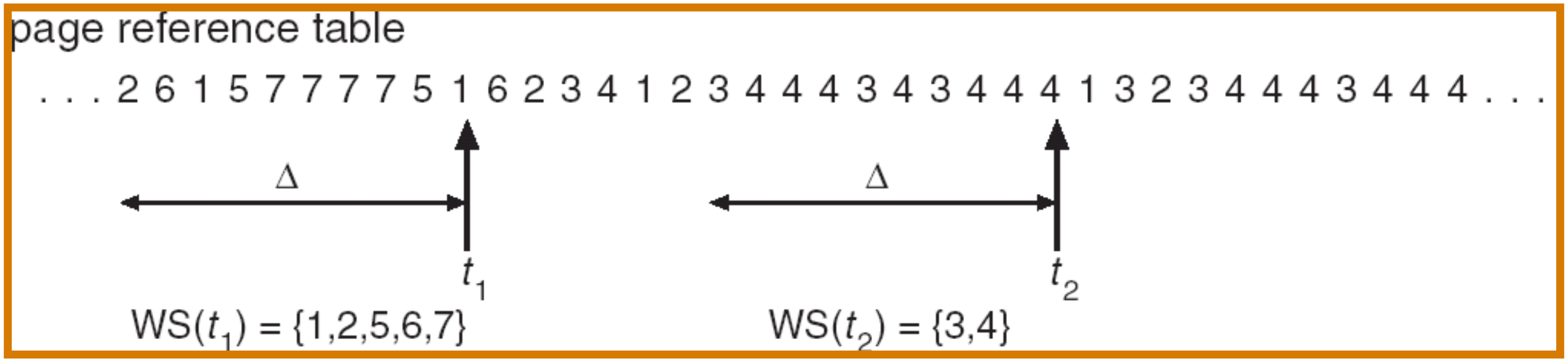
Locality in a Memory-Reference Pattern



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

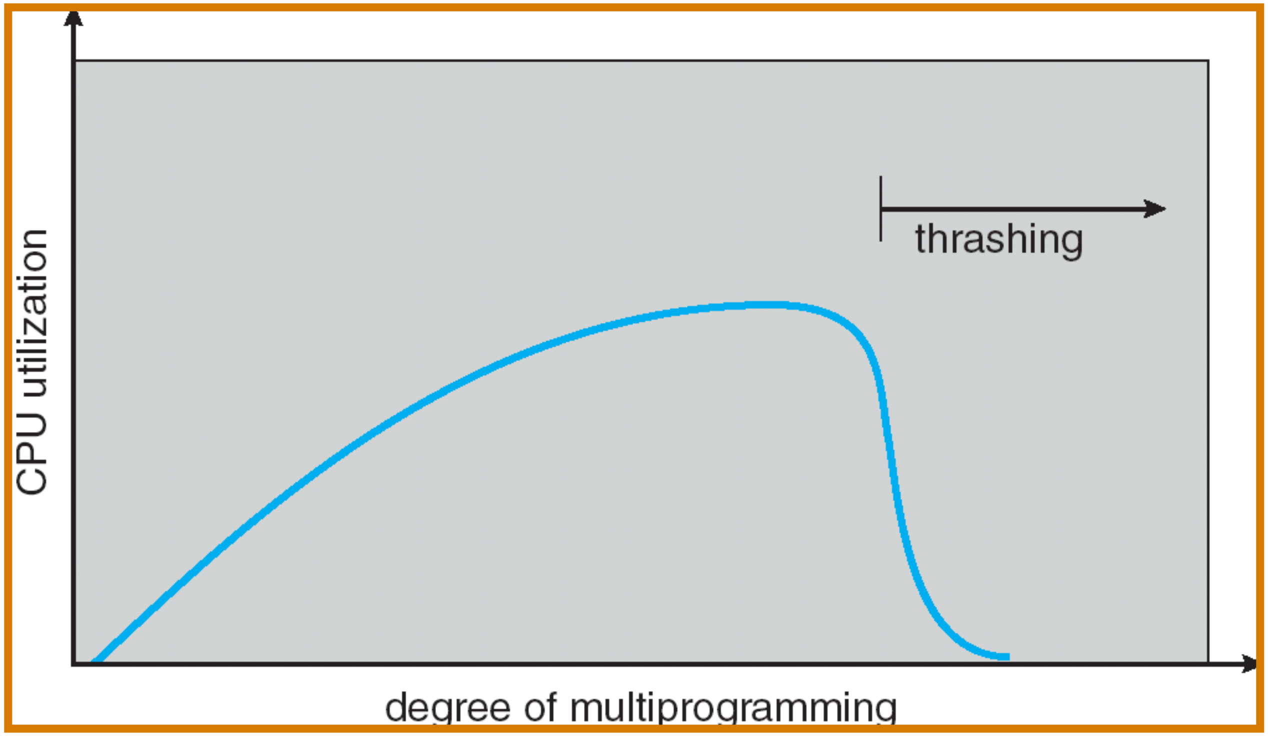


Thrashing

- If a process does not have “enough” frames, the page-fault rate is very high. This leads to:
  - Replacement of active pages which will be needed soon again

  ➔ **Thrashing** ≡ a process is busy swapping pages in and out
- Which will in turn cause:
  - low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process added to the system

Thrashing (Cont.)



Allocation of Frames

- Each process needs *minimum* number of pages
- 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

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

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

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

Summary

- Virtual Memory
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    - Least Recently Used (LRU)
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  - Allocation Policies
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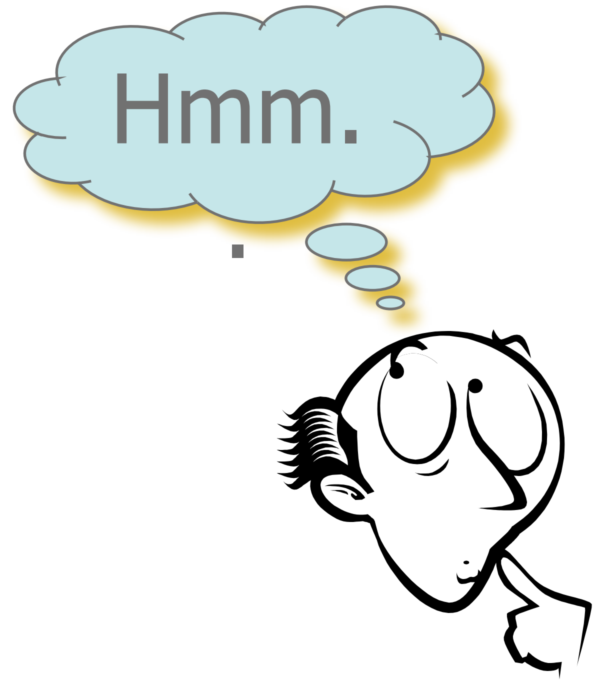
  - Working Set Model



- Next Lecture: Project 2 Discussion
- 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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