CSC 4103 - Operating Systems
Spring 2007

LECTURE - XIII
VIRTUAL MEMORY

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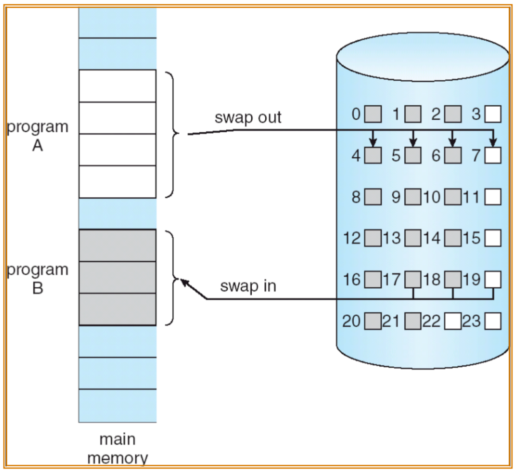
Background

- **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
  - 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

Transfer of a Paged Memory to Contiguous Disk Space



Valid-Invalid Bit

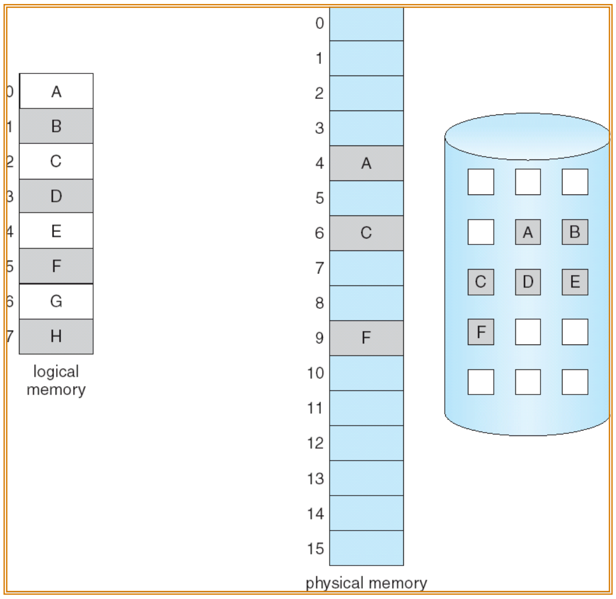
- With each page table entry a valid–invalid bit is associated (1 ⇒ in-memory and legal, 0 ⇒ not-in-memory or invalid)
- Initially valid–invalid bit is set to 0 on all entries
- Example of a page table snapshot:

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

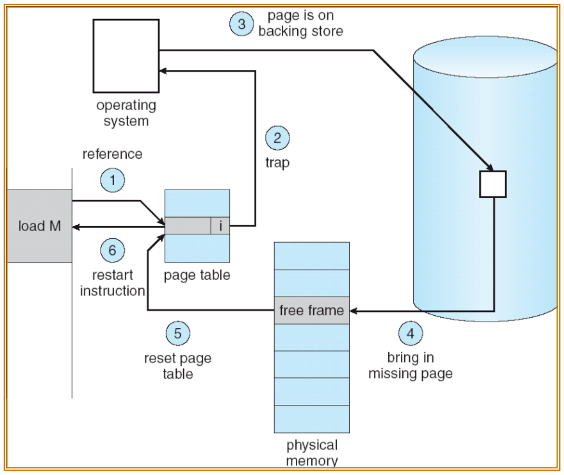
Page Table When Some Pages Are Not in Main Memory



Page Fault

- If there is ever a reference to a page, first reference will trap to
  OS ⇒ page fault
- OS looks at another table to decide:
  - Invalid reference ⇒ abort.
  - Just not in memory.
- Get empty frame.
- Swap page into frame.
- Reset tables, validation bit = 1.
- Restart instruction: Least Recently Used
  - block move
  - auto increment/decrement location

Steps in Handling a Page Fault



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

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)

EAT = (1 – *p*) x memory access
+ *p* x (page fault overhead
+ [swap page out]
+ swap page in
+ restart overhead)

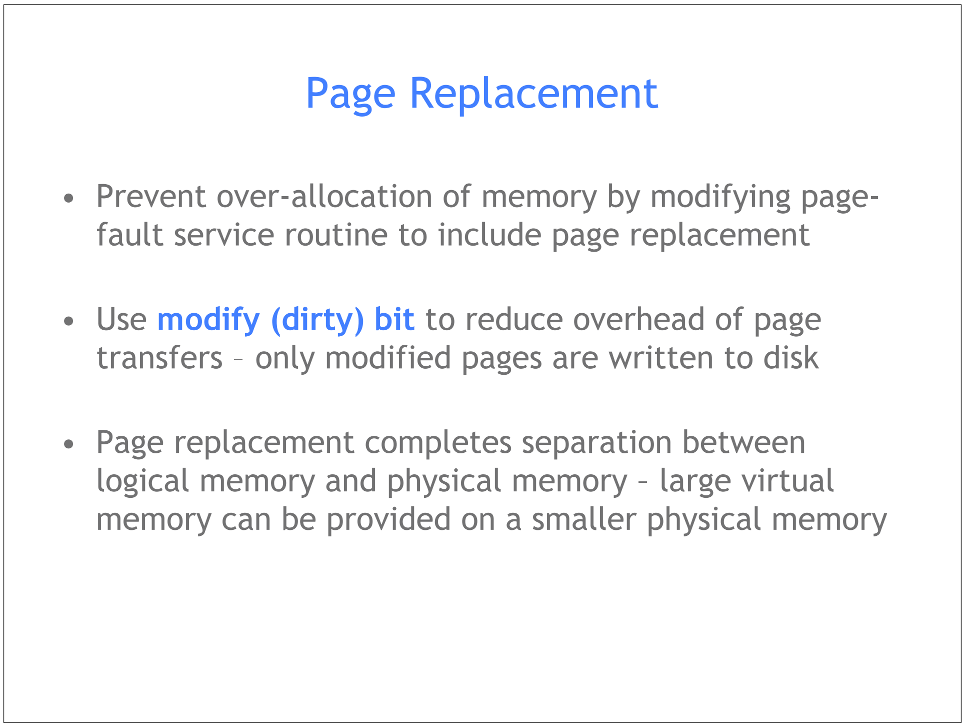
Demand Paging Example

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

Copy-on-Write

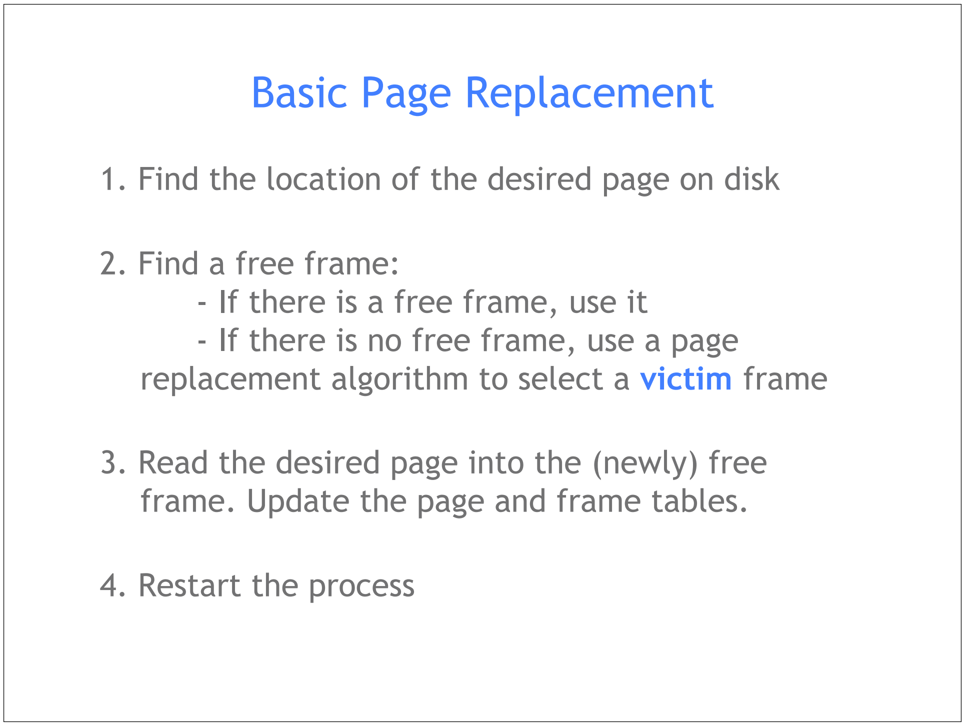
- Copy-on-Write (COW) allows both parent and child processes to initially *share* the same pages in memory

  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 (zero-fill-on-demand pages)



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

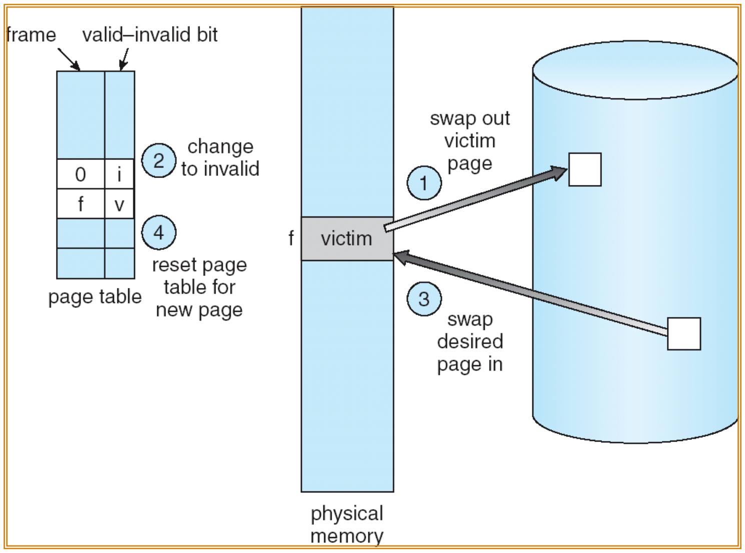
1. Find the location of the desired page on disk

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

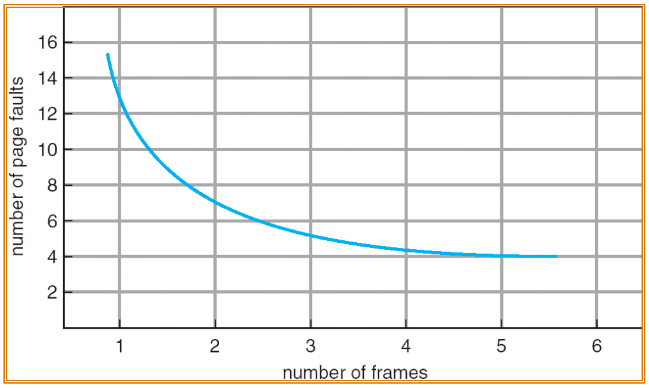


Page Replacement Algorithms

- 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)

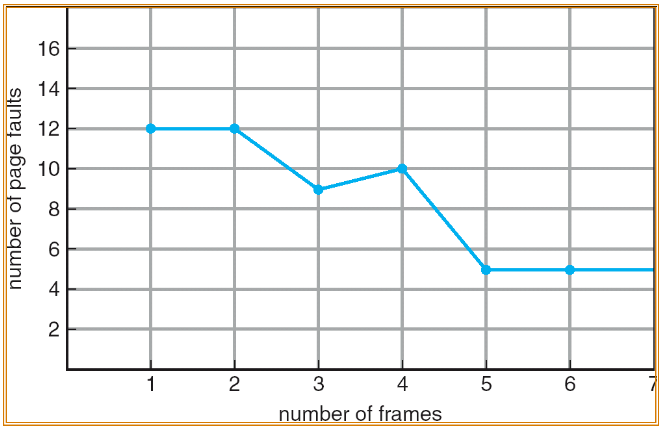
1	1	4	5	
2	2	1	3	9 page faults
3	3	2	4	

- 4 frames

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

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

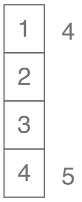
FIFO Illustrating Belady’s Anomaly



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



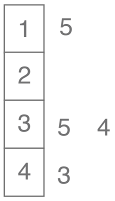
1	4
2	
3	
4	5

6 page faults

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

Least Recently Used (LRU) Algorithm

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

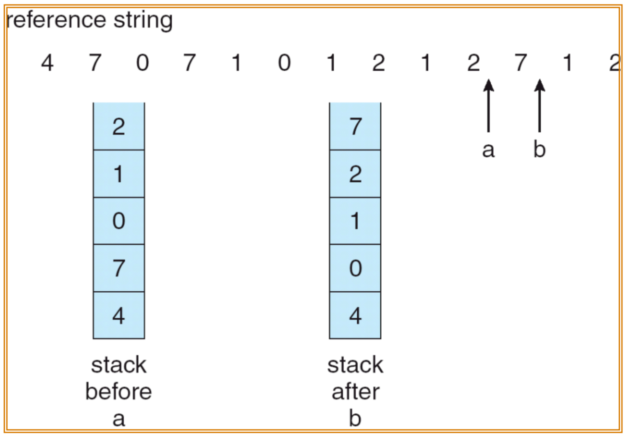


- Needs hardware assistance
- Counter implementation
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter
  - When a page needs to be changed, look at the counters to determine which are to change

LRU 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

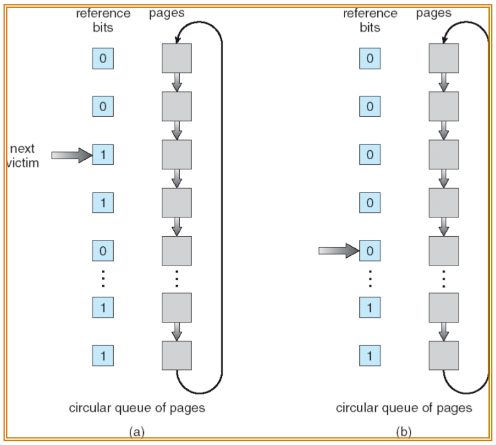
Use Of A Stack to Record The Most Recent Page References



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
- 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

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

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

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

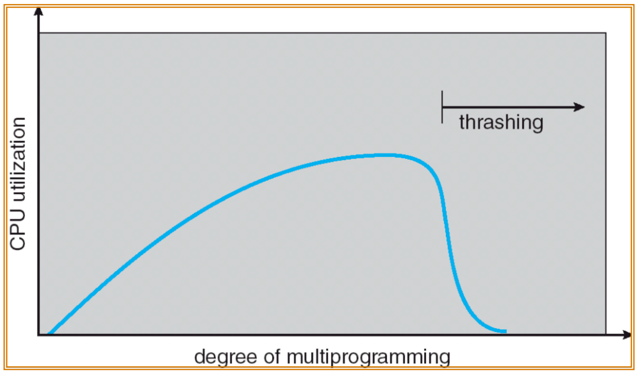
Global vs. Local Allocation

- **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

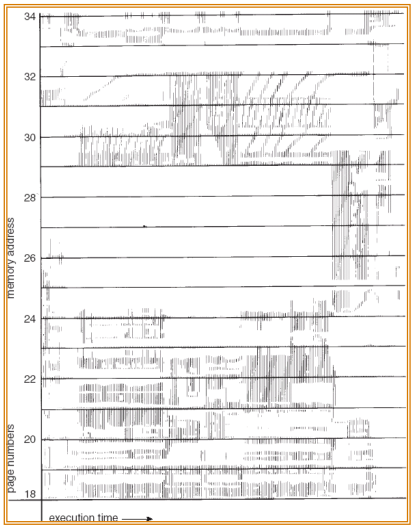
Thrashing

- 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.)



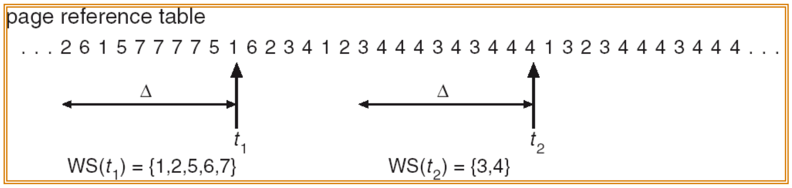
Locality In A Memory-Reference Pattern



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



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 1 3 2 3 4 4 4 3 4 4 4 . . .

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

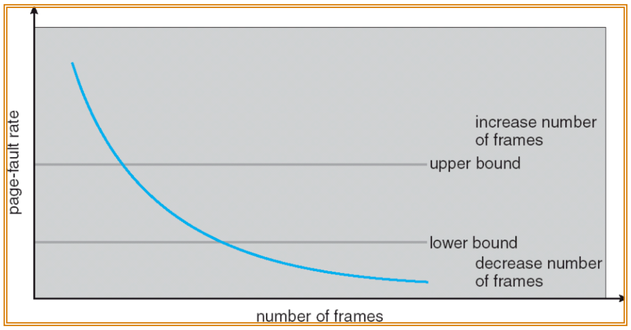
$WS(t_2) = \{3,4\}$

Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: Δ = 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



Any Questions?

Reading Assignment

- Read chapter 9 from Silberschatz.

Acknowledgements

- “Operating Systems Concepts” book and supplementary material by Silberschatz, Galvin and Gagne.