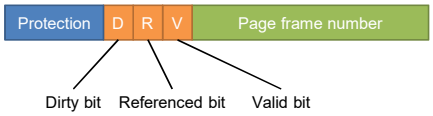
Page Fault

Exception raised by the MMU indicating a requested virtual address is not in memory

Page Table Entry



Handling a Page Fault

1. Determine faulting virtual address
2. If requested page is "bad":
   - SEGFAULT on error
3. If the page is "good":
   A. Find empty frame:
   - If physical memory is full, choose a frame to evict
   - If evicted frame is dirty, write frame to disk

   B. Load page from disk (code/data segments) or grow stack/heap into empty frame

Page Replacement Algorithms

How do we choose a frame to swap out?

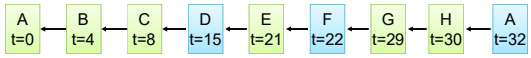
Page Replacement Algorithms

- Optimal
  - Evict the page that won't be needed until furthest in the future
- Not Recently Used (NRU)
  - Evict the page that is the oldest, preferring pages that are not dirty:

Preference	Referenced	Dirty
First Choice	0	0
	0	1
	1	0
Last Choice	1	1

- FIFO
  - First in, First out

Second Chance Page Replacement

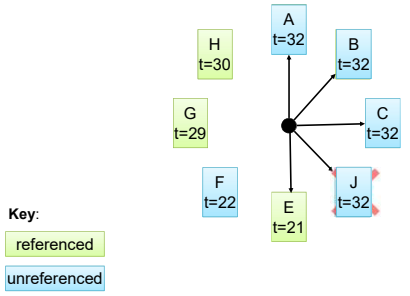


Key:

referenced

unreferenced

Clock Algorithm



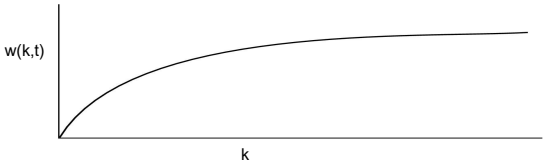
Least Recently Used (LRU)

Look to the past to predict the future

Aging Scheme

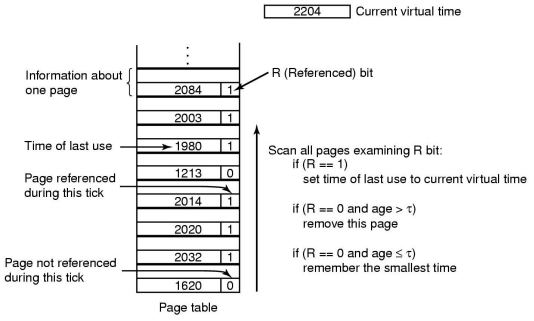
Referenced this tick	Tick 0	Tick 1	Tick 2	Tick 3	Tick 4
Page 0	10000000	11000000	11100000	01110000	10111000
Page 1	00000000	10000000	01000000	00100000	00010000
Page 2	10000000	01000000	00100000	10010000	01001000
Page 3	00000000	00000000	00000000	10000000	01000000
Page 4	10000000	01000000	10100000	11010000	01101000
Page 5	10000000	11000000	01100000	10110000	11011000

Working Set



- Working set is the set of pages used by the k most recent memory references
- w(k,t) is the size of the working set at time t

Working Set Page Replacement



Summary

Algorithm	Comment
OPT (Optimal)	Not implementable, but useful as a benchmark
NRU (Not Recently Used)	Crude
FIFO (First-In, First Out)	Might throw out useful pages
Second chance	Big improvement over FIFO
Clock	Better implementation of second chance
LRU (Least Recently Used)	Excellent, but hard to implement exactly
NFU (Not Frequently Used)	Poor approximation to LRU
Aging	Good approximation to LRU, efficient to implement
Working Set	Somewhat expensive to implement
WSClock	Implementable version of Working Set

Modeling Page Replacement

Page:	0	1	2	3	0	1	4	0	1	2	3	4
Youngest page	0	1	2	3	0	1	4	4	4	2	3	3
		0	1	2	3	0	1	1	1	4	2	2
Oldest page			0	1	2	3	0	0	0	1	4	4

- FIFO replacement on reference string

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

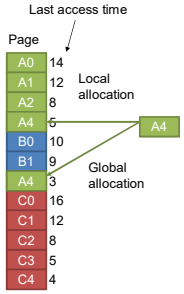
- Page replacements highlighted in orange

Belady's Anomaly

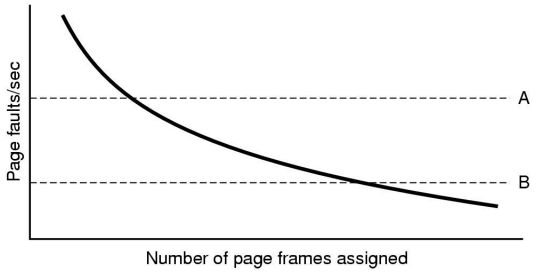
Page:	0	1	2	3	0	1	4	0	1	2	3	4
Youngest page	0	1	2	3	3	3	4	0	1	2	3	4
		0	1	2	2	2	3	4	0	1	2	3
			0	1	1	1	2	3	4	0	1	2
Oldest page				0	0	0	1	2	3	4	0	1

- Try to reduce the number of page faults by supplying more memory
  - Use previous reference string and FIFO algorithm
  - Add another page to physical memory (total 4 pages)

Local vs. Global Allocation



Page Fault Frequency



Page Size

- For larger pages
  - Smaller page tables
  - Less frames in memory (smaller degree of multiprogramming?)
  - Internal fragmentation
- For smaller pages
  - Bigger page table
  - More levels of page tables
  - Less wasted space

Page Sharing

Map multiple pages to a single frame

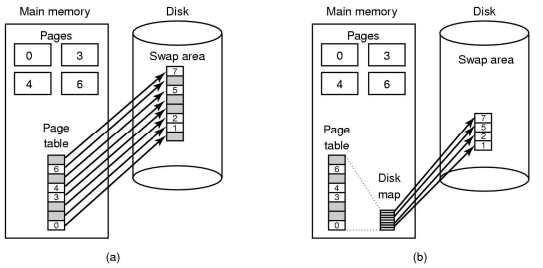
When to Write to Disk

Now or later?

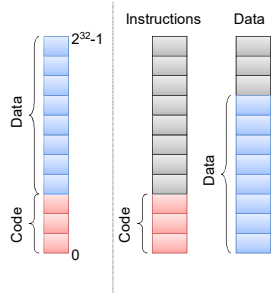
Implementation

- Process creation
- During process execution
- Page fault time
- Process termination time

Backing Store



I- and D-Spaces



Segmentation