Demand Paging

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- Code pages are stored in a memory-mapped file on the backing store
  - some are currently in memory–most are not
- Data and stack pages are also stored in a memory-mapped file
- OS determines what portion of VAS is mapped in memory
  - physical memory serves as cash for memory-mapped file on backing store

Demand Paging:
Touching Valid but not Present Address

1. TLB Miss (HW managed)
2. Page Table walk
3. Page fault (Present bit P not set in Page Table)
4. Exception to kernel to run page-fault handler
5. Convert VA to file offset
6. Allocate page frame (evict page if needed)
7. Initiate disk block read into page frame
8. Disk interrupt when transfer completes
9. Set P to 1 and update PFN for page's PTE
10. Resume process at faulting instruction
11. TLB miss
12. Page Table walk – success!
13. TLB updated
14. Execute instruction

Allocating a Page Frame

- When free frames fall below Low Watermark, do until they climb above High Watermark:
  - Select "victim" page VP to evict (a policy question)
  - Find all PTEs referring to frame VP maps to
    - if page frame was shared
  - Set P bit in each such PTE to 0
  - Remove any TLB entries that included VP's victim frame
    - the PTE they are caching is now invalid!
  - Write changes to page back to disk
- Transferring pages in bulk allows to reduce transfer time

Page Replacement

- Local vs Global replacement
  - Local: victim chosen from frames of process experiencing page fault
    - fixed allocation per process
  - Global: victim chosen from frames allocated to any process
    - variable allocation per process
- Many replacement policies
  - Random, FIFO, LRU, Clock, Working set, etc.
- Goal: minimizing number of page faults

How do we pick a victim?

- We want:
  - low fault-rate for pages
  - page faults as inexpensive as possible
- We need:
  - a way to compare the relative performance of different page replacement algorithms
  - some absolute notion of what a "good" page replacement algorithm should accomplish

Comparing Page Replacement Algorithms

- Record a trace of the pages accessed by a process
  - E.g. 3,1,4,2,5,2,1,2,3,4 (or c,a,d,b,e,b,a,b,c,b)
- Simulate behavior of page replacement algorithm on trace
- Record number of page faults generated

Optimal Page Replacement

- Replace page needed furthest in future

Time		0	1	2	3	4	5	6	7	8	9	10	
Requests			c	a	d	b	e	b	a	b	c	d	b d c b e
Page Frames	0	a	a	a	a	a	a	a	a	a	a	d	
	1	b	b	b	b	b	b	b	b	b	b	b	
	2	c	c	c	c	c	c	c	c	c	c	c	
	3	d	d	d	d	d	e	e	e	e	e	e	
Faults							X					X	
Time page needed next						a = 7 b = 6 c = 9 d = 10					a = ∞ b = 11 c = 13 e = 15		

FIFO Replacement

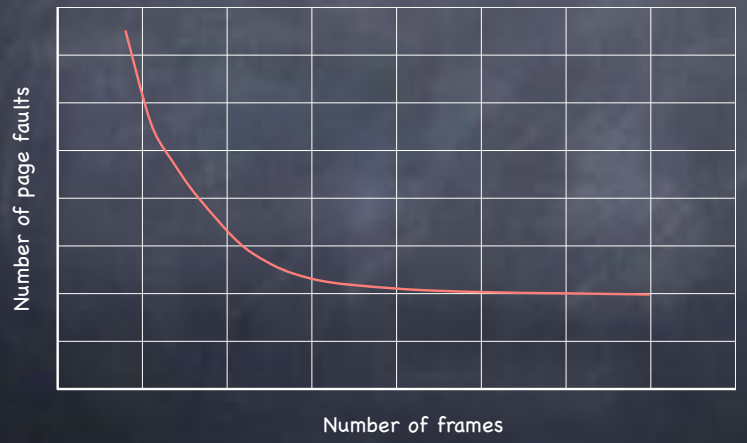
- Replace pages in the order they come into memory

Assume:

a @ -3
b @ -2
c @ -1
d @ 0

Time		0	1	2	3	4	5	6	7	8	9	10
Requests			c	a	d	b	e	b	a	b	c	d
Page Frames	0	a	a	a	a	a	e	e	e	e	e	d
	1	b	b	b	b	b	b	b	a	a	a	a
	2	c	c	c	c	c	c	c	c	b	b	b
	3	d	d	d	d	d	d	d	d	d	c	c
Faults							X		X	X	X	X

+ Frames
- Page Faults



For example...

FIFO

Time	0	1	2	3	4	5	6	7	8	9	10	11	12
Request		a	b	c	d	a	b	e	a	b	c	d	e
Page Frames 0		a	a	a	d	d	d	e	e	e	e	e	e
Page Frames 1			b	b	b	a	a	a	a	a	c	c	c
Page Frames 2				c	c	c	b	b	b	b	b	d	d
Faults		X	X	X	X	X	X	X			X	X	

- 3 frames - 9 page faults!

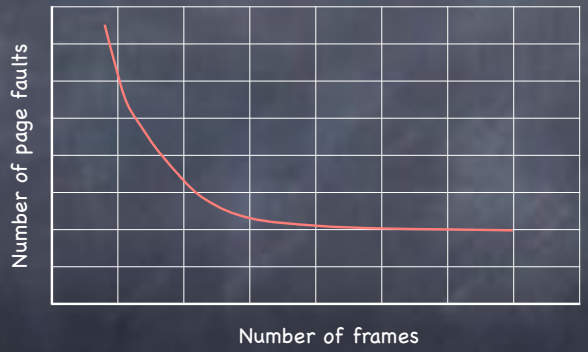
Belady's Anomaly

FIFO

Time	0	1	2	3	4	5	6	7	8	9	10	11	12
Request		a	b	c	d	a	b	e	a	b	c	d	e
Page Frames 0		a	a	a	a	a	a	e	e	e	e	d	d
Page Frames 1			b	b	b	b	b	a	a	a	a	a	e
Page Frames 2				c	c	c	c	c	b	b	b	b	b
Page Frames 3					d	d	d	d	d	d	c	c	c
Faults		X	X	X	X			X	X	X	X	X	X

- 4 frames - 10 page faults!

+ Frames
- Page Faults?



- Yes, but only for stack page replacement policies
  - set of pages in memory with n frames is a subset of set of pages in memory with n+1 frames

Locality of Reference

- If a process access a memory location, then it is likely that
  - the same memory location is going to be accessed again in the near future (temporal locality)
  - nearby memory locations are going to be accessed in the future (spatial locality)
- 90% of the execution of a program is sequential
- Most iterative constructs consist of a relatively small number of instructions

LRU: Least Recently Used

- Replace page not referenced for the longest time

Time		0	1	2	3	4	5	6	7	8	9	10
Requests			c	a	d	b	e	b	a	b	c	d
Page Frames	0	a	a	a	a	a	a	a	a	a	a	a
	1	b	b	b	b	b	b	b	b	b	b	b
	2	c	c	c	c	c	e	e	e	e	e	d
	3	d	d	d	d	d	d	d	d	d	c	c
Faults							X				X	X
Time page last used						a = 2 b = 4 c = 1 d = 3				a = 7 b = 8 e = 5 d = 3	a = 7 b = 8 e = 5 c = 9	

Implementing LRU

- Maintain a "stack" of recently used pages

Time	0	1	2	3	4	5	6	7	8	9	10
Requests		c	a	d	b	e	b	a	b	c	d
Page Frames 0	a	a	a	a	a	a	a	a	a	a	a
1	b	b	b	b	b	b	b	b	b	b	b
2	c	c	c	c	c	e	e	e	e	e	d
3	d	d	d	d	d	d	d	d	d	c	c
Faults						X				X	X

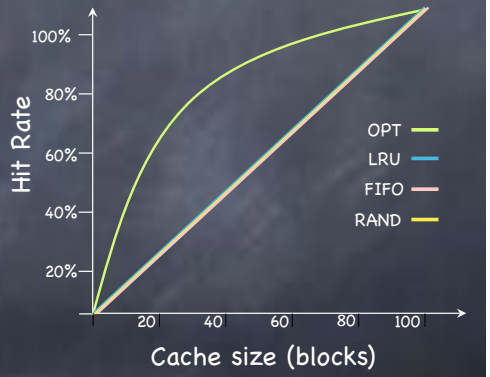
LRU Page Stack

c	a	d	b	e	b	a	b	c	d	
	c	a	d	b	e	b	a	b	c	d
		c	a	d	b	e	b	a	b	c
			c	a	d	d	e	d	a	b
				c	a	a	d	e	e	a

Page to replace: c, d, e

No-Locality Workload

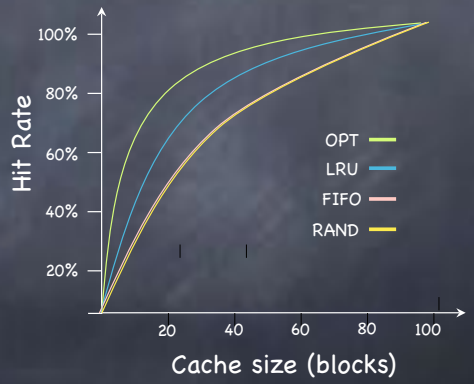
- Workload references 100 unique pages over time
- 10,000 references
- Next page chosen at random



What do you notice?

80%-20% Workload

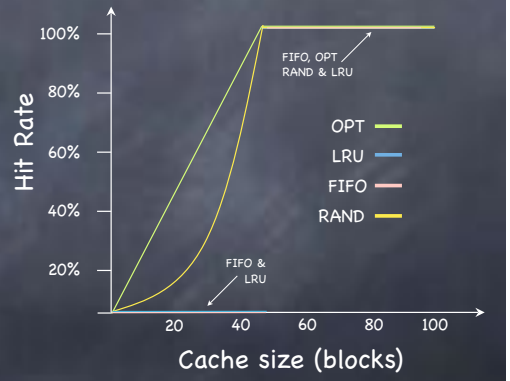
- 10,000 references, but with some locality
  - 80% of references to 20% of the pages
  - 20% of references to the remaining 80% of pages.



What do you notice?

Sequential-in-a-loop Workload

- 10,000 references
- We access 50 pages in sequence, then repeat, in a loop.



What do you notice?

Implementing LRU

- Add a (64-bit) timestamp to each page table entry
  - HW counter incremented on each instruction
  - Page table entry timestamped with counter when referenced
  - Replace page with lowest timestamp

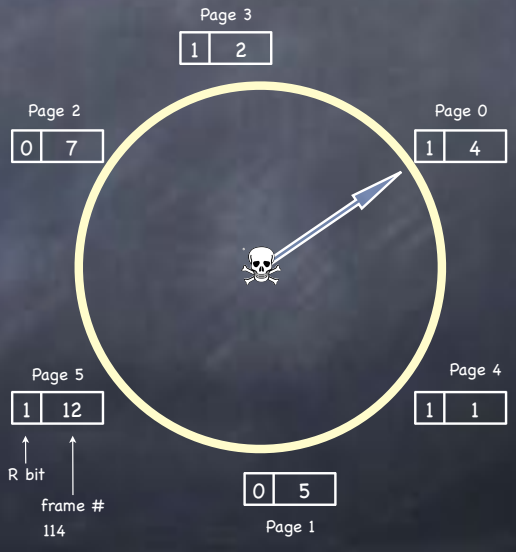
Implementing LRU

- Add a (64-bit) timestamp to each page table entry
  - HW counter incremented on each instruction
  - Page table entry timestamped with counter when referenced
  - Replace page with lowest timestamp
- Approximate LRU through aging
  - keep a k-bit tag in each table entry
  - at every "tick": i) Shift tag right one bit
    ii) Copy Referenced (R) bit in tag
    iii) Reset Refereced bits to 0
  - If needed, evict page with lowest tag

	R bits at Tick 0	R bits at Tick 1	R bits at Tick 2	R bits at Tick 4	R bits at Tick 5
	10101	11001	11010	10001	01100
Page 0	10000000	11000000	11100000	11110000	01111000
Page 1	00000000	10000000	11000000	01100000	10110000
Page 2	10000000	01000000	00100000	00100000	10001000
Page 3	00000000	00000000	10000000	01000000	00100000
Page 4	10000000	11000000	01100000	10110000	01011000
Page 5	10000000	01000000	10100000	01010000	00101000

The Clock Algorithm

- Organize pages in memory as a circular list
- When page is referenced, set its reference bit R to 1
- On page fault, look at page the hand points:
  - if R = 0:
    - evict the page
    - set R bit of newly loaded page to 1
  - else (R = 1): clear R
  - advance hand

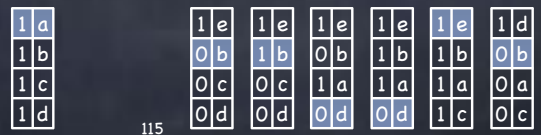


Clock Page Replacement

Time	0	1	2	3	4	5	6	7	8	9	10
Requests		c	a	d	b	e	b	a	b	c	d
Page Frames 0	a	a	a	a	a	e	e	e	e	e	d
Page Frames 1	b	b	b	b	b	b	b	b	b	b	b
Page Frames 2	c	c	c	c	c	c	c	a	c	a	a
Page Frames 3	d	d	d	d	d	d	d	d	d	c	c
Faults						X		X		X	X

Page table entries for resident pages

Hand clock:



The Second Chance Algorithm

- Dirty pages get "second chance" before eviction
  - synchronously replacing dirty pages is expensive!

If clock's hand points at P and this is P's state...

dirty	R
0	0
0	1
1	0
1	1

...this is what happens

dirty	R
replace page	
0	0
0	0
1	0

[Start asynchronous transfer of dirty page to disk]

Second Chance Page Replacement

Time	0	1	2	3	4	5	6	7	8	9	10
Requests		c	a^w	d	b^w	e	b	a^w	b	c	d
Page Frames 0	a	a	a	a	a	a	a	a	a	a	a
Page Frames 1	b	b	b	b	b	b	b	b	b	b	d
Page Frames 2	c	c	c	c	c	e	e	e	e	e	e
Page Frames 3	d	d	d	d	d	d	d	d	d	c	c
Faults						X				X	X

Page table entries for resident pages

Hand clock:

Async copy: