TCSS 422: OPERATING SYSTEMS

Beyond Physical Memory

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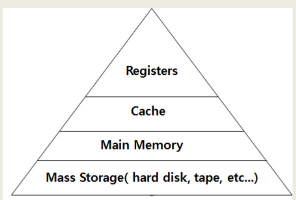
OBJECTIVES

- Chapter 21
  - Virtual "Swap" Memory
- Chapter 22
  - Page replacement algorithms
  - Replacement algorithm effectiveness

MEMORY HIERARCHY

- Disks (HDD, SSD) provide another level of storage in the memory hierarchy



Memory Hierarchy in modern system

MOTIVATION FOR EXPANDING THE ADDRESS SPACE

- Can provide illusion of an address space larger than physical RAM
- For a single process
  - Convenience
  - Ease of use
- For multiple processes
  - Large virtual memory space for many concurrent processes

LATENCY TIMES

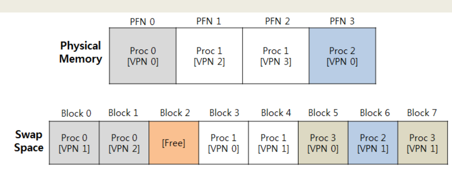
- Design considerations
  - SSDs 4x the time of DRAM
  - HDDs 80x the time of DRAM

Action	Latency (ns)	(µs)	
L1 cache reference	0.5ns		
L2 cache reference	7 ns		14x L1 cache
Mutex lock/unlock	25 ns		
Main memory reference	100 ns		20x L2 cache, 200x L1
Read 4K randomly from SSD*	150,000 ns	150 µs	~1GB/sec SSD
Read 1 MB sequentially from memory	250,000 ns	250 µs	
Read 1 MB sequentially from SSD*	1,000,000 ns	1,000 µs	1 ms ~1GB/sec SSD, 4X memory
Read 1 MB sequentially from disk	20,000,000 ns	20,000 µs	20 ms 80x memory, 20X SSD

- Latency numbers every programmer should know
- From: https://gist.github.com/jboner/2841832#file-latency-txt

SWAP SPACE

- Disk space for storing memory pages
- "Swap" them in and out of memory to disk as needed



Physical Memory and Swap Space

PAGE LOCATION

- Page table pages are:
  - Stored in memory
  - Swapped to disk
- Present bit
  - In the page table entry (PTE) indicates if page is present
- Page fault
  - Memory page is accessed, but has been swapped to disk

PAGE FAULT

- OS steps in to handle the page fault
- Loading page from disk requires a free memory page
- Page-Fault Algorithm

```
PFN = FindFreePhysicalPage()
if (PFN == -1)                    // no free page found
        PFN = EvictPage()         // run replacement algorithm
DiskRead(PTE.DiskAddr, pfn)       // sleep (waiting for I/O)
PTE.present = True                // set PTE bit to present
PTE.PFN = PFN                     // reference new loaded page
RetryInstruction()                // retry instruction
```


PAGE REPLACEMENTS

- Page daemon
  - Background threads which monitors swapped pages
- Low watermark (LW)
  - Threshold for when to swap pages to disk
  - Daemon checks: free pages < LW
  - Begin swapping to disk until reaching the highwater mark
- High watermark (HW)
  - Target threshold of free memory pages
  - Daemon free until: free pages >= HW

REPLACEMENT POLICIES

CACHE MANAGEMENT

- Replacement policies apply to "any" cache
- Goal is to minimize the number of misses
- Average memory access time can be estimated:

$$AMAT = (P_{Hit} * T_M) + (P_{Miss} * T_D)$$

Argument	Meaning
T_M	The cost of accessing memory (time)
T_D	The cost of accessing disk (time)
P_{Hit}	The probability of finding the data item in the cache(a hit)
P_{Miss}	The probability of not finding the data in the cache(a miss)

- Consider T_M = 100 ns, T_D = 10ms
- Consider P_{hit} = .9 (90%), P_{miss} = .1
- Consider P_{hit} = .999 (99.9%), P_{miss} = .001

OPTIMAL REPLACEMENT POLICY

- What if:
  - We could predict the future (… with a magical oracle)
  - All future page accesses are known
  - Always replace the page in the cache used farthest in the future
- Used for a comparison
- Provides a "best case" replacement policy
- Consider a 3-element empty cache with the following page accesses:

0 1 2 0 1 3 0 3 1 2 1

What is the hit/miss ratio?

6 hits

FIFO REPLACEMENT

- Queue based
- Always replace the oldest element
- Simple to implement
- Doesn't consider importance… just arrival ordering
- Consider a 3-element empty cache with the following page accesses:

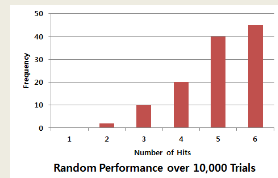
0 1 2 0 1 3 0 3 1 2 1

- What is the hit/miss ratio? **4 hits**
- How is FIFO different than LRU? **LRU incorporates history**

RANDOM REPLACEMENT

- Pick a page at random to replace
- Simple and fast implementation
- Performance depends on luck of random choices

0 1 2 0 1 3 0 3 1 2 1



HISTORY-BASED POLICIES

- LRU: Least recently used
- Always replace page with oldest access time
- Consider when a page was last accessed

0 1 2 0 1 3 0 3 1 2 1

What is the hit/miss ratio?

6 hits

- LFU: Least frequently used
- Always replace page with fewest accesses
- Consider frequency of page accesses

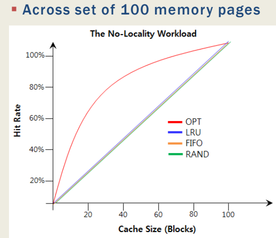
0 1 2 0 1 3 0 3 1 2 1

Hit/miss ratio is=

6 hits

WORKLOAD EXAMPLES: NO-LOCALITY

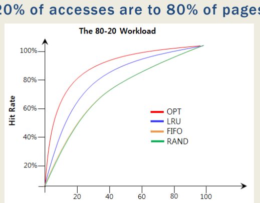
- No-Locality (Random Access) Workload
  - Perform 10,000 random page accesses
  - Across set of 100 memory pages



When the cache is large enough to fit the entire workload, it doesn't matter which policy you use.

WORKLOAD EXAMPLES: 80/20

- 80/20 Workload
  - Perform 10,000 page accesses, against set of 100 pages
  - 80% of accesses are to 20% of pages (hot pages)
  - 20% of accesses are to 80% of pages (cold pages)

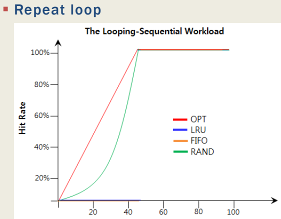


LRU is more likely to hold onto hot pages

(recalls history)

WORKLOAD EXAMPLES: SEQUENTIAL

- Looping sequential workload
  - Refer to 50 pages in sequence: 0, 1, …, 49
  - Repeat loop



Random performs better than FIFO and LRU for cache sizes < 50

Algorithms should provide "scan resistance"

IMPLEMENTING LRU

- Implementing last recently used (LRU) requires tracking access time for all system memory pages
- Times can be tracked with a list
- For cache eviction, we must scan an entire list
- Consider: 4GB memory system (2^{32}), with 4KB pages (2^{12})
- This requires 2^{20} comparisons !!!
- Simplification is needed
  - Consider how to approximate the oldest page access

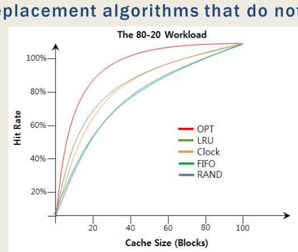
IMPLEMENTING LRU - 2

- Harness the Page Table Entry (PTE) Use Bit
- HW sets to 1 when page is used
- OS sets to 0

- Clock algorithm (*approximate LRU*)
  - Refer to pages in a circular list
  - Clock hand points to current page
  - Loops around
    - IF USE_BIT=1 set to USE_BIT = 0
    - IF USE_BIT=0 replace page

CLOCK ALGORITHM

- Not as efficient as LRU, but better than other replacement algorithms that do not consider history



CLOCK ALGORITHM - 2

- Consider dirty pages in cache
- If DIRTY (modified) bit is FALSE
  - No cost to evict page from cache
- If DIRTY (modified) bit is TRUE
  - Cache eviction requires updating memory
  - Contents have changed
- Clock algorithm should favor no cost eviction

WHEN TO LOAD PAGES

- On demand → demand paging
- Prefetching
  - Preload pages based on anticipated demand
  - Prediction based on locality
  - Access page P, suggest page P+1 may be used
- What other techniques might help anticipate required memory pages?
  - Prediction models, historical analysis
  - In general: accuracy vs. effort tradeoff
  - High analysis techniques struggle to respond in real time

OTHER SWAPPING POLICIES

- Page swaps / writes
  - Group/cluster pages together
  - Collect pending writes, perform as batch
  - Grouping disk writes helps amortize latency costs
- Thrashing
  - Occurs when system runs many memory intensive processes and is low in memory
  - Everything is constantly swapped to-and-from disk

OTHER SWAPPING POLICIES - 2

- Working sets
  - Groups of related processes
  - When thrashing: prevent one or more working set(s) from running
  - Temporarily reduces memory burden
  - Allows some processes to run, reduces thrashing

QUESTIONS