Lecture#17: Replacement, Cache state

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Review -- 1 min

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Virtual memory – paging to disk
- Provide illusion of infinite
- Use essentially same mechanisms as already had
- Page table
- Core map
- Pageout daemon

Danger: thrashing

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Outline - 1 min

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Thrashing -- solutions
Replacement
State bits

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Preview - 1 min

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Finish virtual memory
I/O – file systems

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Lecture - 35 min

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1. Thrashing

Thrashing – memory overcomitted – pages tossed out while still needed

Example – one program touches 50 pages (each equally likely); only have 40 physical page frames
If have enough pages – 200ns/ref
If have too few pages – assume every 5th reference → page fault
4refs x 200ns
1 page fault x 10ms for disk I/O
→ 5 refs per 10ms + 800ns = 2ms/ref = **20000x slowdown!!!**

QUESTION: what hit rate do you need to get less than a 1% slowdown from paging to disk?

1.1 Problem: system doesn't know what it is getting in to

Log more and more users into system – eventually:
total number of pages needed > number of pges available

Picture: jobs/sec v. total system throughput

So, what do you do about this?
1) One process alone too big?
Change program so it needs less memory or has better locality
For example, split matrix multiply into smaller sub-matrices that each fit in memory

2) Several jobs?
- figure out needs/process (working set)
- run only groups that fit (balance sets) – kick other processes out of memory
  e.g., suppose you are paging and running at a 10,000x slowdown, if kicking half of the jobs out would get you to stop paging and run at full speed, you trade a 1.5x slowdown for a 10,000x slowdown

Remember -- issue here is not total size of process, but rather total number of pages being used at the moment.

How do we figure needs/process out?

1.1.1 Working set (denning, MIT mid 60's)

Informally – collection of pages a process is using right now

Formally – set of pages job has referenced in last T seconds

How do we pick T?

1 page fault = 10ms
10ms = 2M instructions
→ T needs to be a lot biger than 1 million instructions

How do you figure out what working set is?

- replacement policy keeps track of time to last access – use information from it (later in lcture/next lecture)

a) modify clock algorithm so that it seeps at fixed intervals (keep idle time/page; how many seconds since last reference)
b) with second chance list – how many seconds since got put on 2nd chance list

Now you know how many pages each program needs. What do you do?

Balance set

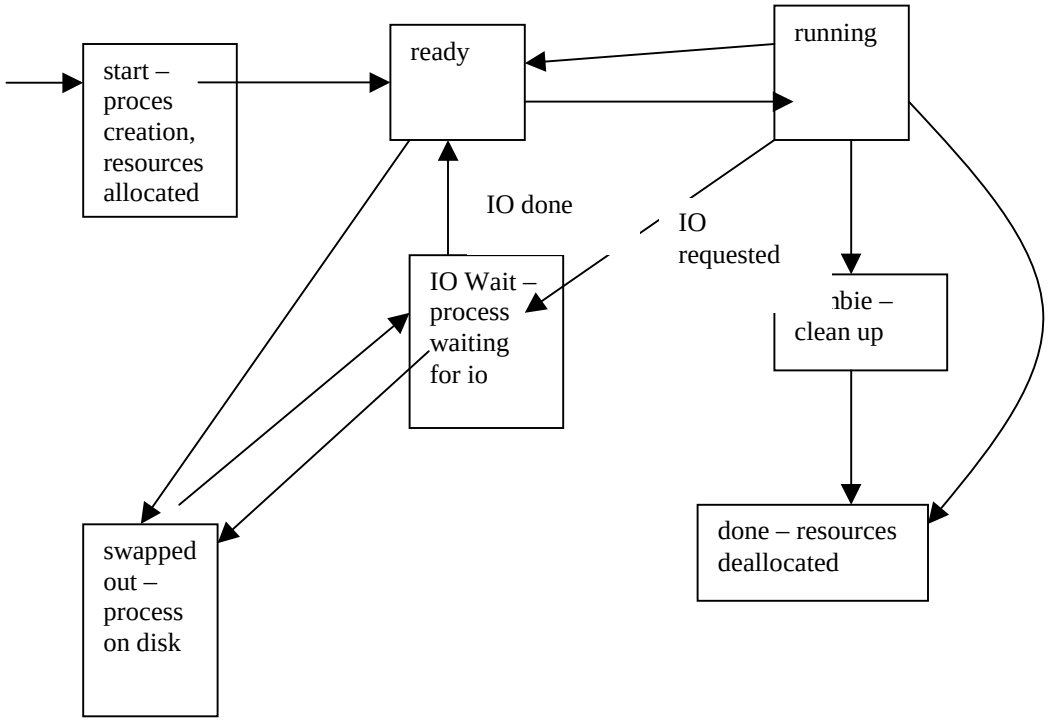
1) if all fits? Done
2) if not? Throw out fat cats; bring them back eventually

What if T too big?
→ waste memory – too few programs fit in memory
What if T too small?
→ thrashing

2. Swapping v. paging

If system low on memory, may be better off moving an entire process to disk and stopping it from running for a whil

System stop thrashing -> system runs more efficiently → average (and perhaps all) jobs run faster



2.1.1 Need two levels of scheduling

Upper level decides on swapping

- when
- who
- for how long

Lower levels decide who on ready queue actually runs on CPU

Upper level invoked when there are processes swapped out and whenever we need to load more programs than can fit in main memory

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Admin - 3 min

Project 3

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Lecture - 35 min

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3. Cache replacement policies

TLB – fully associative – can replace any entry on a miss
hardware → random
Virtual memory cache – replace any page
software → more flexibility

Replacement policy is an issue for any caching system

3.1 Random

Typical solution for TLBs. Easy to implement in HW

3.2 FIFO

Throw out oldest page. Be fair – let every page live in memory for the same amount of time, then toss it.

Bad because throws out heavily used pages instead of those that are not frequently used

3.3 MIN

Replace page that won't be used for the longest time into the future

3.4 LRU

Replace page that hasn't been used for the longest time

If induction works, LRU is a good approximation to MIN. Actually, people don't use even LRU, they approximate it.

3.5 Example

Suppose we have 3 page frames and 4 virtual pages with the reference string ABCABDADBCB (virtual page references)

3.5.1 FIFO

reference phys slot	A	B	C	A	B	D	A	D	B	C	B
1	A					D				C	
2		B					A				
3			C						B		

3.5.2 MIN

reference phys slot	A	B	C	A	B	D	A	D	B	C	B
1	A									C	
2		B									
3			C			D					

3.5.3 LRU

Same as MIN for this pattern
Won't always be this way

QUESTION: When will LRU perform badly?
When next reference is to the least recently used page

Reference string ABCDABCDABCD
LRU

reference phys slot	A	B	C	D	A	B	C	D	A	B	C	D
1	A			D			C			B		
2		B			A			D			C	
3			C			B			A			D

Same behavior with FIFO! What about MIN?

MIN

reference	A	B	C	D	A	B	C	D	A	B	C	D
phys slot												
1	A									B		
2		B					C					
3			C	D								

3.5.4 Does adding memory always reduce the number of page faults?

Yes for LRU, MIN

No for FIFO (Belady's anomoly)

reference	A	B	C	D	A	B	E	A	B	C	D	E
phys slot												
1	A			D			E					
2		B			A					C		
3			C			B					D	
reference	A	B	C	D	A	B	E	A	B	C	D	E
phys slot												
1	A						E				D	
2		B						A				E
3			C						B			
4				D						C		

With FIFO, contents of memory can be completely different with different number of page frames

By contrast, with LRU or MIN, contents of memory with X pages is subset of contents with X+1 pages. So with LRU or MIN, having more pages never hurts.

4. Implementing LRU

4.1 Perfect

Timestamp page on each reference

Keep list of pages ordered by time of reference

On every memory reference – move page to front of LRU list
Too much work per mem reference

4.2 Clock

Approximate LRU (approx to approx of MIN)

Replace **an** old page, not **the** oldest page

Clock algorithm: arrange physical pages in a circle, with a clock hand

1. Hardware keeps a **use bit** per physical page
2. Hardware sets use bit on each reference (TLB)

If bit isn't set, means not referenced for a long time

3. On page fault
   Advance clock hand (not real time)
   check use bit
   1 → clear, go on
   2 → replace page

Will it always find a page or loop indefinitely?
Even if all use bits are set, it will eentually loop around, clearing all use bits → FIFO

What if hand is moving slowly?
Not many page faults and/or find page quickly

What if hand is moving quickly?
Lots of page faults and/or lots of reference bits set

One way to view clock: crude partitioning of pages into two groups – young and old. Why not partition into more than 2 groups?

4.3 Nth chance

Nth chance algorithm – don't throw page out until hand has swept by N times

OS keeps counter per page -- # sweeps

On page fault, OS checks use bit
1→ clear use and also clear counter, go on
0 → increment counter; if < N go on else replace page

How do we pick N?

Large N → better approximate LRU
Small N → more efficient; otherwise might have to look a long way to find a free page

Dirty pages have to be written back to disk when replaced. Takes extra overhead to replace a dirty page, so give dirty pages an extra chance before replacing.

Common approach
clean pages – use N = 1
dirty pages – use N = 2 (and write back when N = 1)

5. State per page table entry

To summarize, many machines maintain 4 bits per page table entry

use – set when page referenced; cleared by clock algorithm
modified – set when page is modified; cleared when page written to disk
valid – OK for pogram to reference this page
read-only OK for program to read page, but not to modify it (e.g. don't allow modifcation of code page)

5.1 Do we really need a "modified" bit?

No. Can emulate it (e.g. BSD UNIX). Keep two sets of books:
(i) pages user program can access w/o taking fault
(ii) pages in memory

Set I is a subset of set ii. Initially, masrk all pages as read-only. On write, trap to OS. OS sets (SW) modified bit and marks page as read-write

When page comes back in from disk, mark as read-only

5.2 Do we really need a "use" bit?

No. Can emulate it, exactly the same as above

(i) Mark all pages as invalid, even if in memory
(ii) On read to invalid page, trap to OS
(iii) OS sets use bit, and marks page read-only
(iv) on write, set use and modified bit, and mark page read-write
(v) when clock hand passes by, reset use bit and mark page as invalid

But remember, clock is just approximation of LRU
Can we do better approximation, given that we have to take page fault on some reads and writes to collect use information. Need to identify an old page, not the oldest page!

VAX/VMS didnt have a use or modify bit, so had to come up with some solution.
Idea was to split memory into two parts – mapped and unmapped

i) directly accessible to program (marked as read-write) (managed FIFO)
ii) second-chance list (marked as invalid, but in memory) (managed pure LRU)

On page reference
    if mapped, access at full speed
    otherwise page fault:
    if on second chance list, mark read-write
        move first page on FIFO list onto end of second chance list (and mark invalid)
    if not on second chance list, bring into memory
    move first page on FIFO list onto end of second chance
    replace first page on second chance list

How many pages for second chance list?
If 0, FIFO
if all, LRU, but page fault on every page reference

Pick intermediate value
Result:
+ few disk accesses (page only goes to disk if it is unused for along time)
- increase overhead trapping to OS (sw/hw tradeoff)

5.3 Does sw-loaded TLB need a use bit?

Two options:
1) hardware sets use bit in TLB; when TLB entry is replaced, sofware copies use bit back to page table
2) Sofware manages TLB entries as FIFO list; everything not in TLB is second chance list, managed as strict LRU

5.4 Core map

page tables map virtual page # → physical page #

Do we need the reverse? Physical page # → virtual page #?

Yes. Clock algorithm runs through page frames. What if it ran through page tables
(i) many more entries
(ii) what if there is sharing? (e.g., what do you do if a shared page becomes "dirty"?

6. Fairness

On a page fault, do you consider all pages in one pool or only those of the process that caused the page fault

Global replacement (UNIX) – all pages in one pool

More flexible – if my process needs a lot, and you need a little, I can grab pages from you. Problem – one turkey can ruin whole system (want to favor jobs that need only a few pages!)

Per-process (VMS) – give each a separate pool; for example, a separate clock for each process. Less flexible

Example:

intermittent interactive job (emacs)
batch job (compilation)

When compilation is over, emacs page have to be brought back in, and no history information.