Last Class: Demand Paged Virtual Memory

Benefits of demand paging:

- Virtual address space can be larger than physical address space.
- Processes can run without being fully loaded into memory.
  - Processes start faster because they only need to load a few pages (for code and data) to start running.
  - Processes can share memory more effectively, reducing the costs when a context switch occurs.
- A good page replacement algorithm can reduce the number of page faults and improve performance
- FIFO, MIN, LRU

Today: LRU Approximations, Multiprogramming

- LRU approximations:
  - Second Chance
  - Enhanced Second Chance
- Hardware support for page replacement algorithms
- Replacement policies for multiprogramming

Implementing LRU:

- **Perfect LRU:**
  - Keep a time stamp for each page with the time of the last access. Throw out the LRU page. **Problems?**
    - OS must record time stamp for each memory access, and to throw out a page the OS has to look at all pages. Expensive!
  - Keep a list of pages, where the front of the list is the most recently used page, and the end is the least recently used.
    - On a page access, move the page to the front of the list. Doubly link the list. **Problems?**
      - Still too expensive, since the OS must modify multiple pointers on each memory access

Approximations of LRU

- **Hardware Requirements:** Maintain reference bits with each page.
  - On each access to the page, the hardware sets the reference bit to '1'.
  - Set to 0 at varying times depending on the page replacement algorithm.
- **Additional-Reference-Bits:** Maintain more than 1 bit, say 8 bits.
  - On reference, set high bit to 1
  - At regular intervals or on each memory access, shift the byte right, placing a 0 in the high order bit.
  - On a page fault, the lowest numbered page is kicked out.

=> Approximate, since it does not guarantee a total order on the pages.

=> Faster, since setting a single bit on each memory access.

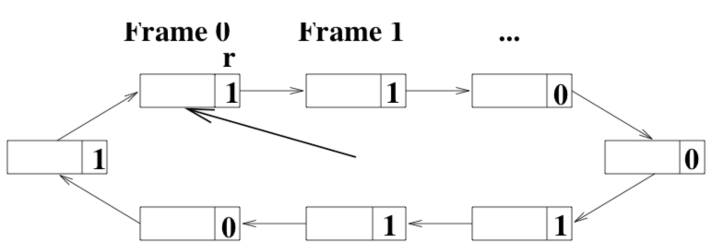
- Page fault still requires a search through all the pages.

Second Chance Algorithm: (a.k.a. Clock)

Use a single reference bit per page.

1. OS keeps frames in a circular list.
2. On reference, set page reference bit to 1
3. On a page fault, the OS
   a) Checks the reference bit of the next frame.
   b) If the reference bit is ‘0’, replace the page, and set its bit to ‘1’.
   c) If the reference bit is ‘1’, set bit to ‘0’, and advance the pointer to the next frame

Second Chance / Clock Example



=> One way to view the clock algorithm is as a crude partitioning into two categories: young and old pages.

- Expense of memory reference, page fault?

Second Chance Algorithm

- Less accurate than additional-reference-bits, since the reference bit only indicates if the page was used at all since the last time it was checked by the algorithm.
- Fast, since setting a single bit on each memory access, and no need for a shift.
- Page fault is faster, since we only search the pages until we find one with a '0' reference bit.
- Simple hardware requirements.

  Will it always find a page?

  What if all bits are '1'?

Enhanced Second Chance

- It is cheaper to replace a page that has not been written
  - OS need not be write the page back to disk

  => OS can give preference to paging out un-modified pages
  - Proactively write out modified pages

- Hardware keeps a *modify* bit (in addition to the reference bit)

  '1': page is modified (different from the copy on disk)

  '0': page is the same as the copy on disk

Enhanced Second Chance

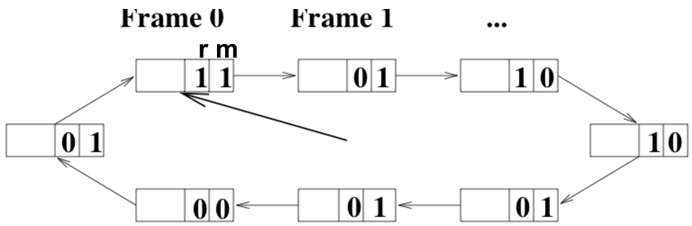
- The reference bit and modify bit form a pair (r,m) where
  1. (0,0) neither recently used nor modified - replace this page!
  2. (0,1) not recently used but modified - not as good to replace, since the OS must write out this page, but it might not be needed anymore.
  3. (1,0) recently used and unmodified - probably will be used again soon, but OS need not write it out before replacing it
  4. (1,1) recently used and modified - probably will be used again soon and the OS must write it out before replacing it

- On a page fault, the OS searches for the first page in the lowest nonempty class.

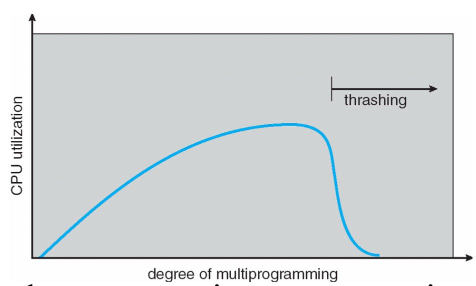
Page Replacement in Enhanced Second Chance

- The OS goes around at most three times searching for the (r = 0, m = 0) class.
  1. Page with (0,0) => replace the page.
  2. Page with (0,1) => initiate an I/O to write out the page, locks the page in memory until the I/O completes, clears the modified bit, and continue the search
  3. For pages with the reference bit set, the reference bit is cleared.
  4. If the hand goes completely around once, there was no (0,0) page.
     - On the second pass, a page that was originally (0,1) or (1,0) might have been changed to (0,0) => replace this page
     - If the page is being written out, waits for the I/O to complete and then remove the page.
     - A (0,1) page is treated as on the first pass.
     - By the third pass, all the pages will be at (0,0).

Clock Example



Multiprogramming and Thrashing



- **Thrashing:** the memory is over-committed and pages are continuously tossed out while they are still in use
  - memory access times approach disk access times since many memory references cause page faults
  - Results in a serious and very noticeable loss of performance.
- What can we do in a multiprogrammed environment to limit thrashing?

Replacement Policies for Multiprogramming

- Give each process enough memory to avoid thrashing
  - OS must decide this via the replacement policy
- **Global replacement:** put all pages from all processes in one pool so that the physical memory associated with a process can grow
  - Use a single LRU queue for all pages
  - **Advantages:** Flexible, adjusts to divergent process needs
  - **Disadvantages:** Thrashing might become more likely (Why?)

Replacement Policies for Multiprogramming

- **Per-process replacement:** Each process has its own pool of frames.
  - Run only groups of processes that fit in memory.
  - **Advantages:** Isolation, protects processes
  - **Disadvantages:** May not give a process enough memory and harm performance
- How do we figure out how many page frames a process needs?
  - Split evenly?
- **Proportional allocation:** allocate more page frames to large processes.
  - alloc = procSize / allProcSize * memSize

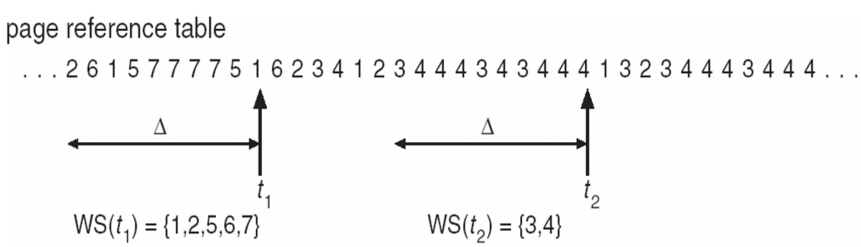
Match Working Set

- **Objective:** Give each process enough frames for its working set size
  – Informally, the working set is the set of pages the process is using right now
  – More formally, it is the set of all pages that a process referenced in the past **T** seconds

- How does the OS pick **T**?
  – 1 page fault = 10msec
  – 10msec = 2 million instructions

  => T needs to be a whole lot bigger than 2 million instructions.
  – What happens if T is too small? too big?

Working Set Determination

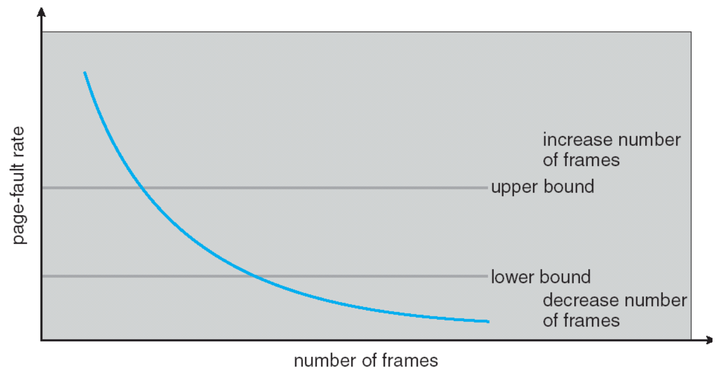


- Like LRU, exact tracking is too expensive to use

- **Sample:** pick a small number of the page references (e.g., every 1000th reference) and assume this gives the working set
  – Cheaper but just an approximation

Page Fault Frequency Scheme

- **Track faults:** Track page fault frequency of each process instead
  - If the page fault frequency > some threshold, give it more frames.
  - If the page fault frequency < a second threshold, take away some frames
- **Goal:** the system-wide mean time between page faults should be equal to the time it takes to handle a page fault.
  - May need to suspend a process until overall memory demands decrease.



Page Fault Frequency Scheme

- **Advantages:** Thrashing is less likely as process only competes with itself. More consistent performance independent of system load.
- **Disadvantages:** The OS has to figure out how many pages to give each process and if the working set size grows dynamically adjust its allocation.

Kernel Memory Allocators

- Buddy allocator
  - Allocate memory in size of 2^n
  - Can lead to internal fragmentation
- Slab allocator
  - Group objects of same size in a "slab"
  - Object cache points to one or more slabs
  - Separate cache for each kernel data structure (e.g., PCB)
  - Used in solaris, linux

Page Sizes

- Reasons for small pages?
- Reasons for large pages?
- Page sizes are growing because:
  - Physical memory is cheap. As a result, page tables could get huge with small pages. Also, internal fragmentation is less of a concern with abundant memory.
  - CPU speed is increasing faster than disk speed. As a result, page faults result in a larger slow down than they used to. Reducing the number of page faults is critical to performance.

Summary of Page Replacement Algorithms

- Unix and Linux use variants of Clock, Windows NT uses FIFO.
- Experiments show that all algorithms do poorly if processes have insufficient physical memory (less than half of their virtual address space).
- All algorithms approach optimal as the physical memory allocated to a process approaches the virtual memory size.
- The more processes running concurrently, the less physical memory each process can have.
- A critical issue the OS must decide is how many processes and the frames per process that may share memory simultaneously.

OS X Mavericks - Memory Management

Key Features of Apple's New Operating System Released Today Based on Technology from UMass Amherst and Amherst College

Researchers point to open sourcing as key to industry adoption of research ideas

October 22, 2013

Contact: Janet Lathrop 413/545-0444

AMHERST, Mass. – With the release today of Apple's new operating system, "Mavericks," computer science professors and long-time friends Emery Berger at the University of Massachusetts Amherst and Scott Kaplan of Amherst College are hoisting a beer to celebrate as "proud papas" of some key components based on their research.

Berger (left) and Kaplan

Their contributions will significantly improve performance and extend the battery life of Apple computers operating around the world with the new OS. It uses an algorithm by Berger that lets it manage internal memory resources more efficiently. Modern computers have multiple 'cores,' each a bit like an individual brain, he explains. "Like people, when they can operate independently, those brains can run at full speed, but if they have to have a meeting to discuss something, things slow down."

His "Hoard" algorithm adopted by Apple manages memory resources in a way that reduces this communication and lets the computer make decisions faster. "Not only does this make the system faster overall, it also extends battery life because it spends less power to do the same job," Berger notes.