VM Page Replacement

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All Paging Schemes Depend on **Locality**

- Processes tend to reference pages in localized patterns
- Temporal locality
  - » locations referenced recently likely to be referenced again
- Spatial locality
  - » locations near recently referenced locations are likely to be referenced soon.
  - » Goal of a paging system is
    - – **stay out of the way when there is plenty of available memory**
    - – **don't bring the system to its knees when there is not.**

Demand Paging

- ***Demand Paging*** **refers to a technique where program pages are loaded from disk into memory as they are referenced.**
- **Each reference to a page not previously touched causes a page fault.**
- **The fault occurs because the reference found a page table entry with its valid bit off.**
- **As a result of the page fault, the OS allocates a new page frame and reads the faulted page from the disk.**
- **When the I/O completes, the OS fills in the PTE, sets its valid bit, and restarts the faulting process.**

Paging

- Demand paging
  - » don't load page until absolutely necessary
  - » commonly used in most systems
  - » doing things one at a time can be slower than batching them.
- Prepaging
  - » anticipate fault before it happens
  - » overlap fetch with computation
  - » hard to predict the future
  - » some simple schemes (hints from programmer or program behavior) can work.
    - – **vm_advise**
    - – **larger "virtual" page size**
    - – **sequential pre-paging from mapped files**

High Level

- Imagine that when a program starts, it has:
  - no pages in memory
  - a page table with all valid bits off
- The first instruction to be executed faults, loading the first page.
- Instructions fault until the program has enough pages to execute for a while.
- It continues until the next page fault.
- Faults are expensive, so once the program is running they should not occur frequently, assuming the program is "well behaved" (has good locality).

Page Replacement

- When a fault occurs, the OS loads the faulted page from disk into a page of memory.
- At some point, the process has used all of the page frames it is allowed to use.
- When this happens, the OS must *replace* a page for each page faulted in. That is, it must select a page to throw out of primary memory to make room.
- How it does this is determined by the *page replacement algorithm*.
- The goal of the replacement algorithm is to reduce the fault rate by selecting the best victim page to remove.

Finding the Best Page

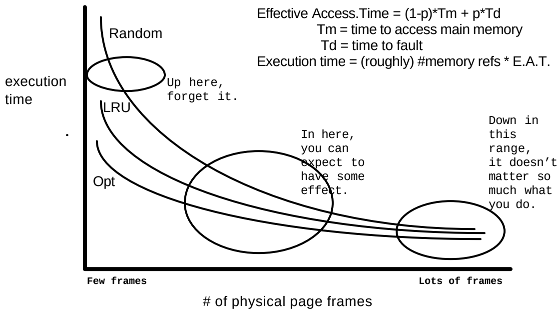
- A good property
  - » if you put more memory on the machine, then your page fault rate will go down.
  - » Increasing the size of the resource pool helps everyone.
- The best page to toss out is the one you'll never need again
  - » that way, no faults.
- Never is a long time, so picking the one closest to "never" is the next best thing.
  - » Replacing the page that won't be used for the longest period of time absolutely minimizes the number of page faults.
  - » Example:

Optimal Algorithm

- The optimal algorithm, called Belady's algorithm, has the lowest fault rate for any reference string.
- Basic idea: replace the page that will not be used for the longest time in the future.
- Basic problem: phone calls to psychics are expensive.
- Basic use: gives us an idea of how well any implementable algorithm is doing relative to the best possible algorithm.
  - » compare the fault rate of any proposed algorithm to Optimal
  - » if Optimal does not do much better, then your proposed algorithm is pretty good.
  - » If your proposed algorithm doesn't do much better than Random, go home.

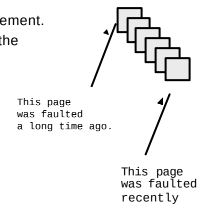
Evaluating Replacement Policies

Effective Access.Time = (1-p)*Tm + p*Td
Tm = time to access main memory
Td = time to fault
Execution time = (roughly) #memory refs * E.A.T.



FIFO

- FIFO is an obvious algorithm and simple to implement.
- Basic idea, maintain a list or queue of pages in the order in which they were paged into memory.
- On replacement, remove the one brought in the longest time ago.
- Why might it work?
  - » Maybe the one brought in the longest ago is one we're not using now.
- Why it might not work?
  - » Maybe it's not.
  - » We have no real information to tell us if it's being used or not.
- FIFO suffers from "Belady's anomaly"
  - » the fault rate might actually increase when the algorithm is given more memory -- a bad property.



An Example of Optimal and FIFO in Action

Reference stream is A B C A B D A D B C

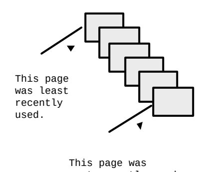
OPTIMAL
A B C A B D A D B C B
5 Faults toss C toss A or D

A
B
C
D
A
B
C

FIFO
A B C A B D A D B C B
7 Faults toss A toss ?

Least Recently Used (LRU)

- Basic idea: we can't look into the future, but let's look at past experience to make a good guess.
- LRU: on replacement, remove the page that has not been used for the longest time in the past.
- Implementation: to really implement this, we would need to time stamp every reference, or maintain a stack that's updated on every reference. This would be too costly.
- So, we can't implement this exactly, but we can try to approximate it.
  - » why is an approximate solution totally acceptable?



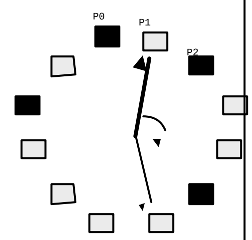
Our "bet" is that pages which you used recently are ones which you will use again (principle of locality) and, by implication, those that you didn't, you won't.

Using the Reference Bit

- Various LRU approximations use the PTE reference bit.
  - – keep a counter for each page
  - – at regular intervals, do:
  - – for every page:
    - if ref bit = 0, increment its counter
    - if ref bit = 1, zero its counter
    - zero the reference bit
  - – the counter will thus contain the number of intervals since the last reference to the page.
  - – the page with the largest counter will be least recently used one.
- If we don't have a reference bit, we can simulate it using the VALID bit and taking a few extra faults.
  - » therefore want impact when there is plenty of memory to be low.

LRU Clock (Not Recently Used)

- Basic idea is to reflect the passage of time in the actual data structures and sweeping method.
- Arrange all of physical pages in a big circle (a clock).
- A clock hand is used to select a good LRU candidate:
  - » sweep through the pages in circular order like a clock.
  - » if the ref bit is off, it's a good page.
  - » else, turn the ref bit off and try next page.
- Arm moves quickly when pages are needed.
- Low overhead when plenty of memory
- If memory is big, "accuracy" of information degrades.
  - » add in additional hands



Fixed Space Vs. Variable Space

- In a multiprogramming system, we need a way to allocate memory to the competing processes.
  - » Question is: how to determine how much memory to give to each process?
- In a fixed-space algorithm each process is given a limit of pages it can use; when it reaches its limit, it starts replacing new faults with its own pages. This is called *local* replacement.
  - » some processes may do well while others suffer.
- In variable-spaced algorithms, each process can grow or shrink dynamically, displacing other process' pages. This is *global* replacement.
  - » one process can ruin it for the rest.

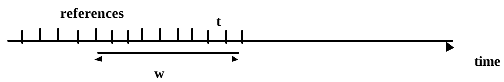
Working Set Model

- Peter Denning defined the working set of a program as a way to model the dynamic *locality* of a program in execution.
- Definition:

  WS(t,w) = {pages i s.t. i was referenced in the interval (t,t-w)}

  t is a time, w is the working set window, a backward looking interval,measured in *references*.
- So, a page is in the WS only if it was referenced in the last w references.

Working Set Size



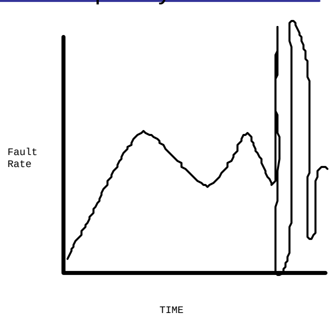
- The <u>working set size</u> is the *number* of pages in the working set; i.e., the number of pages touched in the interval (t, t-w).
- The working set size changes with program locality.
  - » during periods of poor locality, you reference more pages.
  - » so, within that period of time, you will have a larger working set size.
- For some parameter w, we could keep the working sets of each process in memory.
- Don't run process unless working set is in memory.

WS

- But, we have two problems:
  - – how do we select w?
  - – how do we know when the working set changes?
- So, working set is not used in practice.

Page Fault Frequency

- PFF is a variable space algorithm that uses a more ad hoc approach.
- Basic idea:
  - – monitor the fault rate for each process
  - – if the fault rate is above a high threshold, give it more memory
    - • **should fault less**
    - • **but it doesn't always**
  - – if the rate is below a low threshold, take away memory
    - • **should fault more**
    - • **but it doesn't always**
- Hard to tell between changes in locality and changes in size of working set.



What do you do to pages?

- If the page is dirty, you have to write it out to disk.
  - » record the disk block number for the page in the PTE.
- If the page is clean, you don't have to do anything.
  - » just overwrite the page with new data
  - » make sure you know where the old copy of the page came from
- Want to avoid THRASHING
  - » When a paging algorithm breaks down
  - » Most of the OS time spent in ferrying pages to and from disk
  - » no time spent doing useful work.
  - » the system is OVERCOMMITTED
    - – **no idea what pages should be resident in order to run effectively**
  - » Solutions include:
    - – **SWAP**
    - – **Buy more memory**