Demand Paging

- We’ve hinted that pages can be moved between memory and disk
  - this process is called demand paging
  - is different than swapping (entire process moved, not page)
  - OS uses main memory as a (page) cache of all of the data allocated by processes in the system
- initially, pages are allocated from physical memory frames
- when physical memory fills up, allocating a page in requires some other page to be evicted from its physical memory frame
- evicted pages go to disk (only need to write if they are dirty)
  - to a swap file
  - movement of pages between memory / disk is done by the OS
  - is transparent to the application
    - except for performance…

Page Faults

- What happens to a process that references a VA in a page that has been evicted?
  - when the page was evicted, the OS sets the PTE as invalid and stores (in PTE) the location of the page in the swap file
  - when a process accesses the page, the invalid PTE will cause an exception (page fault) to be thrown
  - the OS will run the page fault handler in response
    - handler uses invalid PTE to locate page in swap file
    - handler reads page into a physical frame, updates PTE to point to it and to be valid
    - handler restarts the faulted process
- But: where does the page that’s read in go?
  - have to evict something else (page replacement algorithm)
  - OS typically tries to keep a pool of free pages around so that allocations don’t inevitably cause evictions

Why does this work?

- Locality!
  - temporal locality
    - locations referenced recently tend to be referenced again soon
  - spatial locality
    - locations near recently referenced locations are likely to be referenced soon (think about why)
- Locality means paging can be infrequent
  - once you’ve paged something in, it will be used many times
  - on average, you use things that are paged in
  - but, this depends on many things:
    - degree of locality in application
    - page replacement policy and application reference pattern
    - amount of physical memory and application footprint
Why is this “demand” paging?

- Think about when a process first starts up:
  - It has a brand new page table, with all PTE valid bits 'false'
  - No pages are yet mapped to physical memory
- When process starts executing:
  - Instructions immediately fault on both code and data pages
  - Faults stop when all necessary code/data pages are in memory
  - Only the code/data that is needed (demanded!) by process needs to be loaded
  - What is needed changes over time, of course...

Evicting the best page

- The goal of the page replacement algorithm:
  - Reduce fault rate by selecting best victim page to remove
  - The best page to evict is one that will never be touched again
    - As process will never again fault on it
  - "Never" is a long time
    - Belady’s proof: Evicting the page that won’t be used for the longest period of time minimizes page fault rate
- Rest of this lecture:
  - Survey a bunch of replacement algorithms

#1: Belady’s Algorithm

- Provably optimal lowest fault rate (remember SJF?)
  - Pick the page that won’t be used for longest time in future
  - Problem: Impossible to predict future
- Why is Belady’s algorithm useful?
  - As a yardstick to compare other algorithms to optimal
  - If Belady’s isn’t much better than yours, yours is pretty good
- Is there a lower bound?
  - Unfortunately, lower bound depends on workload
    - But, random replacement is pretty bad

#2: FIFO

- FIFO is obvious, and simple to implement
  - When you page in something, put in on tail of list
  - On eviction, throw away page on head of list
- Why might this be good?
  - Maybe the one brought in longest ago is not being used
- Why might this be bad?
  - Then again, maybe it is being used
  - Have absolutely no information either way
- FIFO suffers from Belady’s Anomaly
  - Fault rate might increase when algorithm is given more physical memory
    - A very bad property
#3: Least Recently Used (LRU)

- LRU uses reference information to make a more informed replacement decision
  - Idea: past experience gives us a guess of future behavior
  - On replacement, evict the page that hasn’t been used for the longest amount of time
  - LRU looks at the past, Belady’s wants to look at future
- When does LRU do well?
  - When does it suck?

- Implementation
  - To be perfect, must grab a timestamp on every memory reference and put it in the PTE (way too $$)
  - So, we need an approximation…

Approximating LRU

- Many approximations, all use the PTE reference bit
  - Keep a counter for each page
  - At some regular interval, for each page, do:
    - If ref bit = 0, increment the counter (hasn’t been used)
    - If ref bit = 1, zero the counter (has been used)
    - Regardless, zero ref bit
  - The counter will contain the # of intervals since the last reference to the page
  - Page with largest counter is least recently used
- Some architectures don’t have PTE reference bits
  - Can simulate reference bit using the valid bit to induce faults
  - Hack, hack, hack

#4: LRU Clock

- AKA Not Recently Used (NRU) or Second Chance
  - Replace page that is “old enough”
  - Arrange all physical page frames in a big circle (clock)
  - Just a circular linked list
  - A “clock hand” is used to select a good LRU candidate
    - Sweep through the pages in circular order like a clock
    - If ref bit is off, it hasn’t been used recently, we have a victim
    - So, what is minimum “age” if ref bit is off?
    - If the ref bit is on, turn it off and go to next page
  - Arm moves quickly when pages are needed
  - Low overhead if have plenty of memory
  - If memory is large, accuracy of information degrades
  - Add more hands to fix

Another Problem: allocation of frames

- In a multiprogramming system, we need a way to allocate physical memory to competing processes
  - What if a victim page belongs to another process?
  - Family of replacement algorithms that takes this into account
- Fixed space algorithms
  - Each process is given a limit of pages it can use
  - When it reaches its limit, it replaces from its own pages
  - Local replacement: some process may do well, others suffer
- Variable space algorithms
  - Processes’ set of pages grows and shrinks dynamically
  - Global replacement: one process can ruin it for the rest
    - Linux uses global replacement
Important concept: working set model

• A **working set** of a process is used to model the dynamic locality of its memory usage
  – i.e., working set = set of pages process currently “needs”
  – formally defined by Peter Denning in the 1960’s
• **Definition:**
  – \( WS(t,w) = \{ \text{pages } P \text{ such that } P \text{ was referenced in the time interval } (t, t-w) \} \)
  – \( t \) – time, \( w \) – working set window (measured in page refs)
  – a page is in the working set (WS) only if it was referenced in the last \( w \) references

#5: Working Set Size

• The working set size changes with program locality
  – during periods of poor locality, more pages are referenced
  – within that period of time, the working set size is larger
• Intuitively, working set must be in memory, otherwise you’ll experience heavy faulting (thrashing)
  – when people ask “How much memory does Netscape need?”, really they are asking “what is Netscape’s average (or worst case) working set size?”
• Hypothetical algorithm:
  – associate parameter “\( w \)” with each process
  – only allow a process to start if it’s “\( w \)”, when added to all other processes, still fits in memory
  – use a local replacement algorithm within each process

#6: Page Fault Frequency (PFF)

• PFF is a variable-space algorithm that uses a more ad-hoc approach
  – monitor the fault rate for each process
  – if fault rate is above a given threshold, give it more memory
  – so that it faults less
  – doesn’t always work (FIFO, Belady’s anomaly)
  – if the fault rate is below threshold, take away memory
    • should fault more
    • again, not always

Thrashing

• What the OS does if page replacement algo’s fail
  – happens if most of the time is spent by an OS paging data back and forth from disk
  – no time is spent doing useful work
  – the system is overcommitted
  – no idea which pages should be in memory to reduced faults
  – could be that there just isn’t enough physical memory for all processes
• **solutions?**
• Yields some insight into systems research(ers)
  – if system has too much memory
    • page replacement algorithm doesn’t matter (overprovisioning)
  – if system has too little memory
    • page replacement algorithm doesn’t matter (overcommitted)
  – problem is only interesting on the border between overprovisioned and overcommitted
  • many research papers live here, but not many real systems do...
Summary

- demand paging
  - start with no physical pages mapped, load them in on demand
- page replacement algorithms
  - #1: Belady’s – optimal, but unrealizable
  - #2: FIFO – replace page loaded furthest in past
  - #3: LRU – replace page referenced furthest in past
    - approximate using PTE reference bit
  - #4: LRU Clock – replace page that is “old enough”
  - #5: working set – keep set of pages in memory that induces the minimal fault rate
  - #6: page fault frequency – grow/shrink page set as a function of fault rate
- local vs. global replacement
  - should processes be allowed to evict each other’s pages?