• Start working on Lab 2 if you haven’t
• This Thursday is project hacking day, no lecture
• **Goals of memory management**
  - To provide a convenient abstraction for programming
  - To allocate scarce memory resources among competing processes to maximize performance with minimal overhead

• **Mechanisms**
  - Physical and virtual addressing (1)
  - Techniques: Partitioning, paging, segmentation (1)
  - Page table management, TLBs, VM tricks (2)

• **Policies**
  - Page replacement algorithms (3)
Lecture Overview

• Review paging and page replacement
• Survey page replacement algorithms
• Discuss local vs. global replacement
• Discuss thrashing
Review: Paging

• Recall paging from the OS perspective:
  - Pages are evicted to disk when memory is full
  - Pages loaded from disk when referenced again
  - References to evicted pages cause a TLB miss
    • PTE was invalid, causes fault
  - OS allocates a page frame, reads page from disk
  - When I/O completes, the OS fills in PTE, marks it valid, and restarts faulting process

• Dirty vs. clean pages
  - Actually, only dirty pages (modified) need to be written to disk
  - Clean pages do not – but you need to know where on disk to read them from again
• Use disk to simulate larger virtual than physical mem
Paging Challenges

• How to resume a process after a fault?
  - Need to save state and resume
  - Process might have been in the middle of an instruction!

• What to fetch from disk?
  - Just needed page or more?

• What to eject?
  - How to allocate physical pages amongst processes?
  - Which of a particular process’s pages to keep in memory?
  - A poor choice can lead to horrible performance
Locality

• All paging schemes depend on locality
  - Processes 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

• Although the cost of paging is high, if it is infrequent enough it is acceptable
  - Processes usually exhibit both kinds of locality during their execution, making paging practical
• **Disk much, much slower than memory**
  - Goal: run at memory speed, not disk speed

• **80/20 rule: 20% of memory gets 80% of memory accesses**
  - Keep the hot 20% in memory
  - Keep the cold 80% on disk
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Page Replacement

• When a page fault occurs, the OS loads the faulted page from disk into a page frame of physical memory

• At some point, the process used all of the page frames it is allowed to use
  - This is likely (much) less than all of available memory

• When this happens, the OS must replace a page for each page faulted in
  - It must evict a page to free up a page frame

• The page replacement algorithm determines how this is done
  - Greatly affect performance of paging (virtual memory)
  - Also called page eviction policies
First-In First-Out (FIFO)

- Evict oldest fetched page in system
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 physical pages: 9 page faults
First-In First-Out (FIFO)

- Evict oldest fetched page in system
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 physical pages: 9 page faults
- 4 physical pages: 10 page faults

```
 1 1 5 4
 2 2 1 5
 3 3 2
 4 4 3
```

10 page faults
Belady’s Anomaly

• More physical memory doesn’t always mean fewer faults
Optimal Page Replacement

• What is optimal (if you knew the future)?
Optimal Page Replacement

- What is optimal (if you knew the future)?
  - Replace page that will not be used for longest period of time

- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

- With 4 physical pages:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

  6 page faults
Belady’s Algorithm

- **Known as the optimal page replacement algorithm**
  - Rationale: the best page to evict is the one never touched again
  - Never is a long time, so picking the page closest to “never” is the next best thing
  - Proved by Belady

- **Problem: Have to predict the future**

- **Why is Belady’s useful then? Use it as a yardstick**
  - Compare implementations of page replacement algorithms with the optimal to gauge room for improvement
  - If optimal is not much better, then algorithm is pretty good
  - If optimal is much better, then algorithm could use some work
    - Random replacement is often the lower bound
Least Recently Used (LRU)

- **Approximate optimal with least recently used**
  - Because past often predicts the future
  - On replacement, evict the page that has not been used for the longest time in the past (Belady’s: future)

- **Example**—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

- **With 4 physical pages:** 8 page faults

```
1 1 5
2 2
3 3 5 4
4 4 3
```
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• **Example**—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

• With 4 physical pages: 8 page faults

• **Problem 1:** Can be pessimal – example?
  - Looping over memory (then want MRU eviction)

• **Problem 2:** How to implement?
Straw Man LRU Implementations

• **Stamp PTEs with timer value**
  - E.g., CPU has cycle counter
  - Automatically writes value to PTE on each page access
  - Scan page table to find oldest counter value = LRU page
  - Problem: Would double memory traffic!

• **Keep doubly-linked list of pages**
  - On access remove page, place at tail of list
  - Problem: again, very expensive

• **What to do?**
  - Just approximate LRU, don’t try to do it exactly
Clock Algorithm

- Use accessed bit supported by most hardware
  - E.g., Pentium will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same

- Do FIFO but skip accessed pages

- Keep pages in circular FIFO list

- Scan:
  - page’s A bit = 1, set to 0 & skip
  - else if A = 0, evict

- A.k.a. second-chance replacement
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Clock Algorithm

- **Use accessed bit supported by most hardware**
  - E.g., Pentium will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same
- **Do FIFO but skip accessed pages**
- **Keep physical pages in circular list**
- **Scan:**
  - page’s A bit = 1, set to 0 & skip
  - else if A = 0, evict
- **A.k.a. second-chance replacement**
Clock Algorithm (continued)

- **Large memory may be a problem**
  - Most pages referenced in long interval

- **Add a second clock hand**
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
Clock Algorithm (continued)

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Other Replacement Algorithms

• **Random eviction**
  - Dirt simple to implement
  - Not overly horrible (avoids Belady & pathological cases)

• **LFU (least frequently used) eviction**
  - Instead of just A bit, count # times each page accessed
  - Least frequently accessed must not be very useful (or maybe was just brought in and is about to be used)
  - Decay usage counts over time (for pages that fall out of usage)

• **MFU (most frequently used) algorithm**
  - Because page with the smallest count was probably just brought in and has yet to be used

• **Neither LFU nor MFU used very commonly**
Fixed vs. Variable Space

• How to determine how much memory to give to each process?
  • Fixed space algorithms
    - Each process is given a limit of pages it can use
    - When it reaches the limit, it replaces from its own pages
    - Local replacement
      • Some processes may do well while others suffer
  • Variable space algorithms
    - Process’ set of pages grows and shrinks dynamically
    - Global replacement
      • One process can ruin it for the rest
Working Set Model

• A working set of a process is used to model the dynamic locality of its memory usage
  - Defined by Peter Denning in 60s, published at the first SOSP conference

• Definition
  - $WS(t, w) = \{\text{pages P such that P was referenced in the time interval (}t, \ t-\ w)\}$
  - $t$ – 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
Working Set Size

- The working set size is the # of unique pages in the working set
  - The number of pages referenced in the interval \((t, t - w)\)

- The working set size changes with program locality
  - During periods of poor locality, you reference more pages
  - Within that period of time, the working set size is larger

- Intuitively, want the working set to be the set of pages a process needs in memory to prevent heavy faulting
  - Each process has a param \(w\) that determines a working set with few faults
  - Denning: Don’t run a process unless working set is in memory
Example: gcc Working Set
Working Set Problems

• Problems
  - How do we determine \( w \)?
  - How do we know when the working set changes?

• Too hard to answer
  - So, working set is not used in practice as a page replacement algorithm

• However, it is still used as an abstraction
  - The intuition is still valid
  - When people ask, “How much memory does Firefox need?”, they are in effect asking for the size of Firefox’s working set
Page Fault Frequency (PFF)

• Page Fault Frequency (PFF) is a variable space algorithm that uses a more ad-hoc approach
  - Monitor the fault rate for each process
  - If the fault rate is above a high threshold, give it more memory
    • So that it faults less
    • But not always (FIFO, Belady’s Anomaly)
  - If the fault rate is below a low threshold, take away memory
    • Should fault more
    • But not always

• Hard to use PFF to distinguish between changes in locality and changes in size of working set
Thrashing

• **Page replacement algorithms avoid thrashing**
  - When OS spent most of the time in paging data back and forth from disk
  - Little time spent doing useful work (making progress)
  - In this situation, the system is overcommitted
    - No idea which pages should be in memory to reduce faults
    - Ex: Running Windows95 with 4 MB of memory…
Reasons for Thrashing

- Access pattern has no temporal locality (past $\neq$ future)
- Hot memory does not fit in physical memory
- Each process fits individually, but too many for system

80/20 rule has broken
Thrashing & Multiprogramming

![Graph showing relationship between CPU utilization and degree of multiprogramming with a peak indicating thrashing.](image-url)
Dealing with Thrashing

• Only run processes if memory requirements can be satisfied
  - Thrashing viewed from a caching perspective: given locality of reference, how big a cache does the process need?
  - Or: how much memory does the process need in order to make reasonable progress (its working set)

• Swapping – write out all pages of a process

• Buy more memory…
Summary

• Page replacement algorithms
  - Belady’s – optimal replacement (minimum # of faults)
  - FIFO – replace page loaded furthest in past
  - LRU – replace page referenced furthest in past
    • Approximate using PTE reference bit
  - LRU Clock – replace page that is “old enough”
  - Working Set – keep the set of pages in memory that has minimal fault rate (the “working set”)
  - Page Fault Frequency – grow/shrink page set as a function of fault rate

• Multiprogramming
  - Should a process replace its own page, or that of another?
Next time...

- Read Chapter 14, 17