15-410
“...The cow and Zaphod...”

Virtual Memory #3
Oct. 2, 2019

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Synchronization

First Project 3 checkpoint

- October 14 during class time
- Meet in Wean 5207
  - If your group number ends with
    - 0-2 try to arrive 5 minutes early
    - 3-5 arrive at 10:42:30
    - 6-9 arrive at 10:59:27

Preparation

- Your kernel should be in mygroup/p3ck1
- It should load one program, enter user space, gettid()
  - Ideally lprintf() the result of gettid()
- We will ask you to load & run a test program we will name
- Explain which parts are “real”, which are “demo quality”
Synchronization

**Exam date**
- Tuesday is not likely (under 10%)
- Thursday seems most likely
- If you get mail from me (hopefully today), please act on it
Synchronization

**P2 scoreboard**

- One group isn't on the scoreboard *at all*!
- “Arguably not enough” groups have passed cyclone and agility_drill
- Maybe come to office hours?
Outline

Last time
- The mysterious TLB
- Partial memory residence (demand paging) in action
- The task of the page fault handler

Today
- Fun big speed hacks
- Sharing memory regions & files
- Page replacement policies
Demand Paging Performance

Effective access time of memory word

\[(1 - p_{\text{miss}}) \times T_{\text{memory}} + p_{\text{miss}} \times T_{\text{disk}}\]

Textbook example (a little dated)

- \(T_{\text{memory}} = 100\) ns
- \(T_{\text{disk}} = 25\) ms
- \(p_{\text{miss}} = 1/1,000\) slows down by factor of 250
- slowdown of 10% needs \(p_{\text{miss}} < 1/2,500,000!!!\)
Speed Hacks

COW
ZFOD (Zaphod?)
Memory-mapped files
  - What msync() is \textit{supposed} to be used for...
Copy-on-Write

fork() produces two very-similar processes
- Same code, data, stack

Expensive to copy pages
- Many will never be modified by new process
  - Especially in fork(), exec() case

Share physical frames instead of copying?
- Easy: code pages – read-only
- Dangerous: stack pages!
Copy-on-Write

*Simulated copy*
- Copy page table entries to new process
- Mark PTEs read-only in old & new
- Done! (saving factor: 1024)
  - Simulation is excellent as long as process doesn't write...
Copy-on-Write

**Simulated copy**
- Copy page table entries to new process
- Mark PTEs read-only in old & new
- Done! (saving factor: 1024)
  - Simulation is excellent as long as process doesn't write...

**Making it real**
- Process writes to page (*Oops! We lied...*)
- Page fault handler responsible
  - Kernel makes a copy of the shared frame
  - Page tables adjusted
    - ...each process points page to private frame
    - ...page marked read-write in both PTEs
Example Page Table

<table>
<thead>
<tr>
<th>Virtual Address</th>
<th>Page table</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRW f981</td>
<td>stack</td>
</tr>
<tr>
<td>---</td>
<td>code</td>
</tr>
<tr>
<td>VRW f029</td>
<td>data</td>
</tr>
<tr>
<td>VRX f237</td>
<td></td>
</tr>
</tbody>
</table>
Copy-on-Write of Address Space

```
P0

<table>
<thead>
<tr>
<th>VRW</th>
<th>f981</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>VRW</td>
<td>f029</td>
</tr>
<tr>
<td>VRX</td>
<td>f237</td>
</tr>
</tbody>
</table>

P9

<table>
<thead>
<tr>
<th>VRW</th>
<th>f981</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>VRW</td>
<td>f029</td>
</tr>
<tr>
<td>VRX</td>
<td>f237</td>
</tr>
</tbody>
</table>
```
Memory Write ⇒ Permission Fault

<table>
<thead>
<tr>
<th>VRW</th>
<th>f981</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>VRW</td>
<td>f029</td>
</tr>
<tr>
<td>VRX</td>
<td>f237</td>
</tr>
</tbody>
</table>

Stack

Code

Data
Copy Into Blank Frame

```
    VRW  f981
    ---  ---
    VRW  f029
    VRX  f237

    stack
    stack
          
    VRW  f981
    ---  ---
    VRW  f029
    VRX  f237

    code
    data
```
Adjust PTE frame pointer, access
Zero Pages

Very special case of copy-on-write
  - ZFOD = “Zero-fill on demand”

Many process pages are “blank”
  - All of bss
  - New heap pages
  - New stack pages

Have one system-wide all-zero frame
  - Everybody points to it
  - Logically read-write, physically read-only
  - Reads of zeros are free
  - Writes cause page faults & cloning
Memory-Mapped Files

Alternative interface to read(), write()
- `mmap(addr, len, prot, flags, fd, offset)`
- new memory region presents file contents
- write-back policy typically unspecified
  - unless you `msync()`...

Benefits
- Avoid serializing pointer-based data structures
- Reads and writes may be much cheaper
  - Look, Ma, no syscalls!
Memory-Mapped Files

**Implementation**
- Memory region remembers `mmap()` parameters
- Page faults trigger `read()` calls
- Pages stored back via `write()` to file

**Shared memory**
- Two processes `mmap()` “the same way”
- Point to same memory region
Page Replacement/Page Eviction

Processes always want *more* memory frames
- Explicit deallocation is rare
- Page faults are implicit allocations

System inevitably runs out of frames

Solution outline
- Pick a frame, store contents to disk
- Transfer ownership to new process
- Service fault using this frame
Pick a Frame

**Two-level approach**
- Determine # frames each process “deserves”
- “Process” chooses which frame is least-valuable
  - Most OS's: kernel actually does the choosing

**System-wide approach**
- Determine globally-least-useful frame
Store Contents to Disk

Where does it belong?
- Allocate backing store for each page
  - What if we run out?

Must we really store it?
- Read-only code/data: no!
  - Can re-fetch from executable
  - Saves paging space & disk-write delay
  - But file-system read() may be slower than paging-disk read
- Not modified since last page-in: no!
  - Hardware typically provides “page-dirty” bit in PTE
  - Cheap to “store” a page with dirty==0
Page Eviction Policies

Don't try these at home
- FIFO
- Optimal
- LRU

Practical
- LRU approximation

Current Research
- ARC (Adaptive Replacement Cache)
- CAR (Clock with Adaptive Replacement)
- CART (CAR with Temporal Filtering)
Page Eviction Policies

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Practical
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- CAR (Clock with Adaptive Replacement)
- CART (CAR with Temporal Filtering)
- CARTHAGE (CART with Hilarious AppendaGE)
FIFO Page Replacement

**Concept**
- Queue of all pages – named as (task id, virtual address)
- Page added to tail of queue when first given a frame
- Always evict oldest page (head of queue)

**Evaluation**
- Fast to “pick a page”
- Stupid
  - Will indeed evict old unused startup-code page
  - But *guaranteed* to eventually evict process's favorite page too!
Optimal Page Replacement

Concept
- Evict whichever page will be referenced \textit{latest}
  - “Buy the most time” until next page fault

Evaluation
- Requires perfect prediction of program execution
- Impossible to implement

So?
- Used as upper bound in simulation studies
LRU Page Replacement

Concept
- Evict Least-Recently-Used page
- “Past performance *may* not predict future results”
  - ...but it's an important hint!

Evaluation
- Would probably be reasonably accurate
- LRU is computable without a fortune teller
- Bookkeeping *very* expensive
  - (right?)
LRU Page Replacement

Concept
- Evict *Least-Recently-Used* page
- “Past performance *may* not predict future results”
  - ...but it's an important hint!

Evaluation
- Would probably be reasonably accurate
- LRU is computable without a fortune teller
- Bookkeeping *very* expensive
  - Hardware must sequence-number every page reference
    - Evictor must scan every page's sequence number
  - Or you can “just” do a doubly-linked-list operation per ref
Approximating LRU

Hybrid hardware/software approach

- 1 reference bit per page table entry
- OS sets reference = 0 for all pages
- Hardware sets reference=1 when PTE is used in lookup
- OS periodically scans
  - (reference == 1) ⇒ “recently used”

Result:
- Hardware sloppily partitions memory into “recent” vs. “old”
- Software periodically samples, makes decisions
Approximating LRU

“Second-chance” algorithm
- Use stupid FIFO queue to choose victim candidate page
- reference == 0?
  - not “recently” used, evict page, steal its frame
- reference == 1?
  - “somewhat-recently used” - don't evict page this time
  - append page to rear of queue (“second chance”)
  - set reference = 0
    » Process must use page again “soon” for it to be skipped

Approximation
- Observe that queue is randomly sorted
  - We are evicting not-recently-used, not least-recently-used
Approximating LRU

“Clock” algorithm

- Observe: “Page queue” requires linked list
  - Extra memory traffic to update pointers
- Observe: Page queue's order is essentially random
  - Doesn't add anything to accuracy
- Revision
  - Don't have a queue of pages
  - Just treat memory as a circular array
Clock Algorithm

static int nextpage = 0;
boolean reference[NPAGES];

int choose_victim() {
    while (reference[nextpage]) {
        reference[nextpage] = false;
        nextpage = (nextpage + 1) % NPAGES;
    }
    return(nextpage);
}
“Page Buffering”

**Problem**
- Don't want to evict pages only *after* a fault needs a frame
- Must wait for disk write before launching disk read (slow!)

“Assume a blank page...”
- Page fault handler can be much faster

“page-out daemon”
- Scans system for dirty pages
  - Write to disk
  - Clear dirty bit
  - Page can be instantly evicted later
- When to scan, how many to store? Indeed...
Frame Allocation

How many frames should a process have?

Minimum allocation

- Examine worst-case instruction
  - Can multi-byte instruction cross page boundary?
  - Can memory parameter cross page boundary?
  - How many memory parameters?
  - Indirect pointers?
“Fair” Frame Allocation

Equal allocation
- Every process gets same \textit{number of frames}
  - “Fair” - in a sense
  - Probably wasteful

Proportional allocation
- Every process gets same \textit{percentage of residence}
  - (Everybody 83% resident, larger processes get more frames)
  - “Fair” - in a different sense
  - Probably the right approach
    - Theoretically, encourages greediness
Thrashing

**Problem**
- Process *needs* N frames...
  - Repeatedly rendering image to video memory
  - Must be able to have all “world data” resident 20x/second
- ...but OS provides N-1, N/2, etc.

**Result**
- Every page OS evicts generates “immediate” fault
- More time spent paging than executing
- Paging disk constantly busy
  - Denial of “paging service” to other processes
- Widespread unhappiness
“Working-Set” Allocation Model

**Approach**
- Determine necessary # frames for each process
  - “Working set” - size of frame set you need to get work done
- If unavailable, swap entire process out
  - (later, swap some *other* process entirely out)

**How to measure working set?**
- Periodically scan all reference bits of process's pages
- Combine multiple scans (see text)

**Evaluation**
- Expensive
- Can we approximate it?
Page-Fault Frequency Approach

Approach

- Recall, “thrashing” == “excessive” paging
- Adjust per-process frame quotas to balance fault rates
  - System-wide “average page-fault rate” (10 faults/second)
  - Process A fault rate “too high”: increase frame quota
  - Process A fault rate “too low”: reduce frame quota

What if quota increase doesn't help?

- If giving you *some* more frames didn't help, maybe you need *a lot* more frames than you have...
  - Swap you out entirely for a while
Program Optimizations

Is paging an “OS problem”?  
- Can a programmer reduce working-set size?

Locality depends on data structures  
- Arrays encourage sequential accesses  
  - Many references to same page  
  - Predictable access to next page  
- Random pointer data structures scatter references

Compiler & linker can help too  
- Don't split a routine across two pages  
- Place helper functions on same page as main routine

Effects can be dramatic
Summary

Speed hacks

Page-replacement policies
- The eviction problem
- Sample policies
  - For real: LRU approximation with hardware support
- Page buffering
- Frame Allocation (process page quotas)

Definition & use of
- Dirty bit, reference bit

Virtual-memory usage optimizations