15-410

"...The cow and Zaphod..."

Virtual Memory #3
Feb. 16, 2011

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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

- $(1 - p_{miss}) * T_{memory} + p_{miss} * T_{disk}$

Textbook example (a little dated)

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

Speed Hacks

COW

ZFOD (Zaphod?)

Memory-mapped files

- **What msync() is *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

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- Done! (saving factor: 1024)
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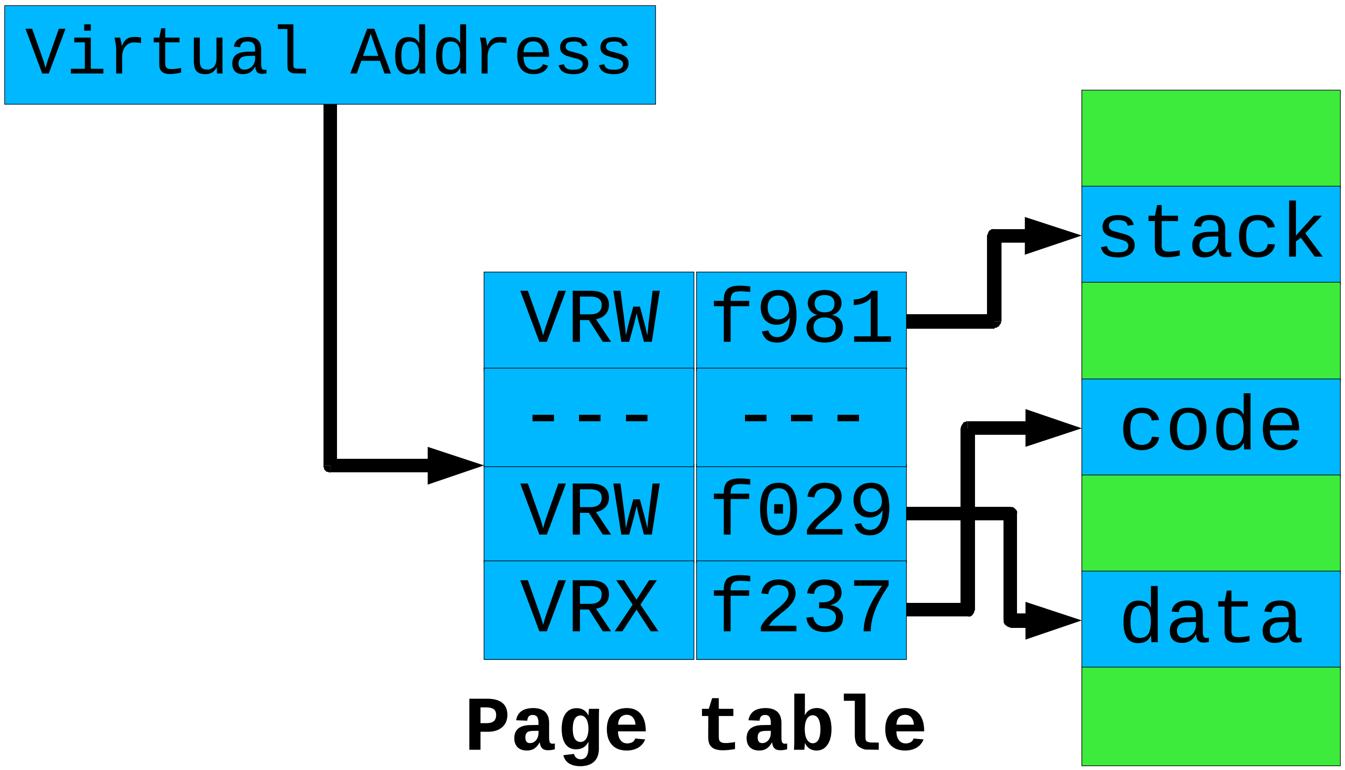
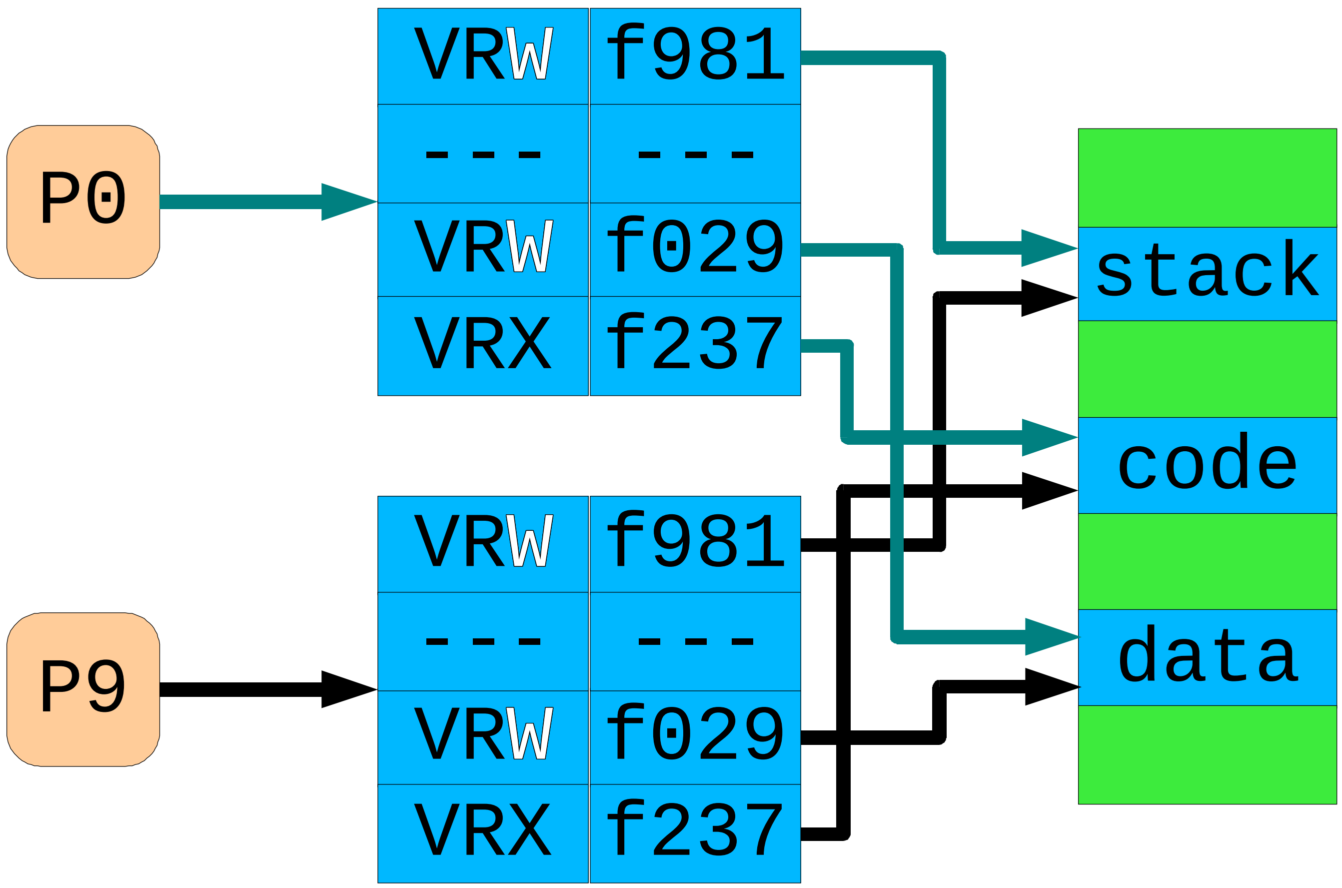
Making it real

- 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

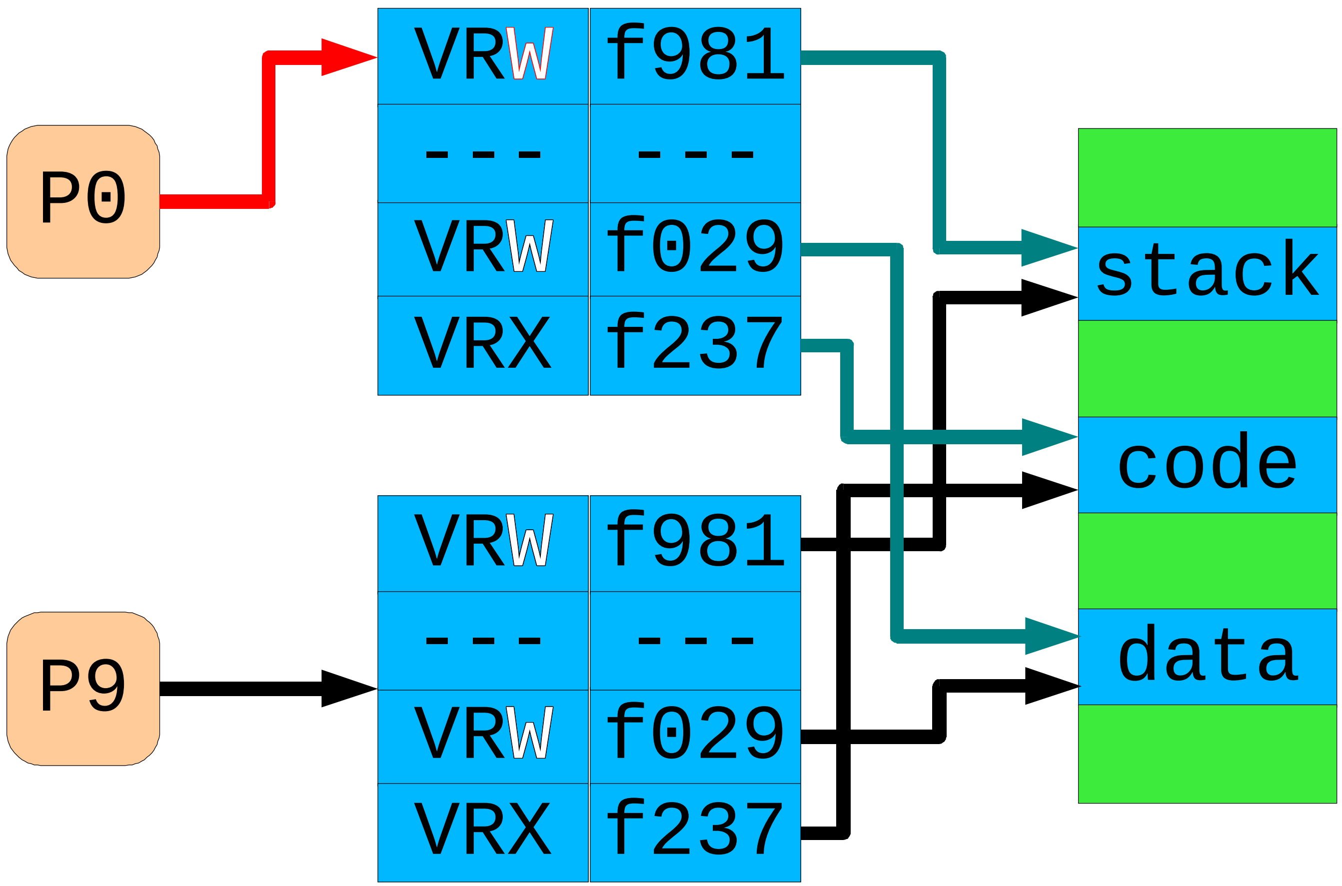
Example Page Table



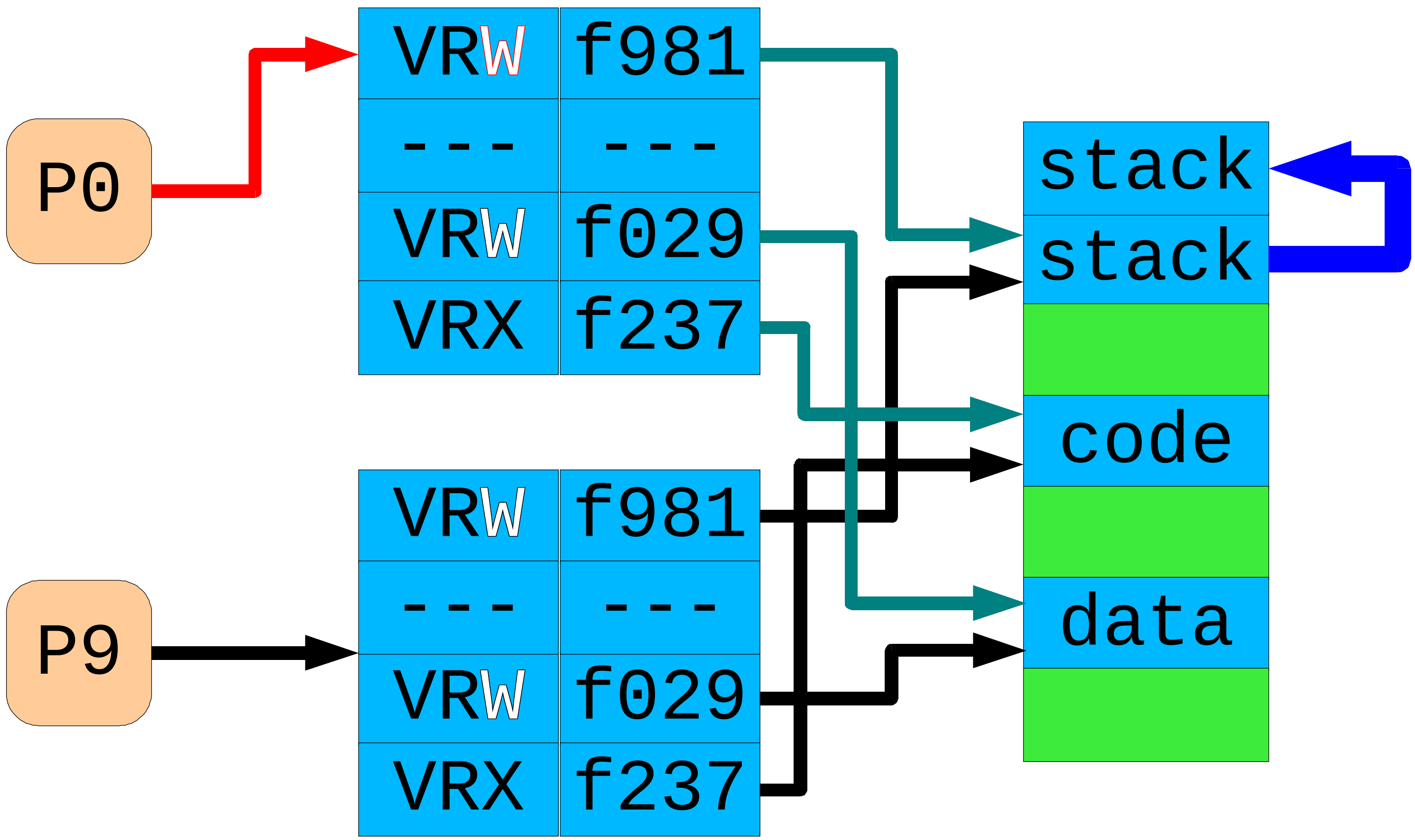
Copy-on-Write of Address Space



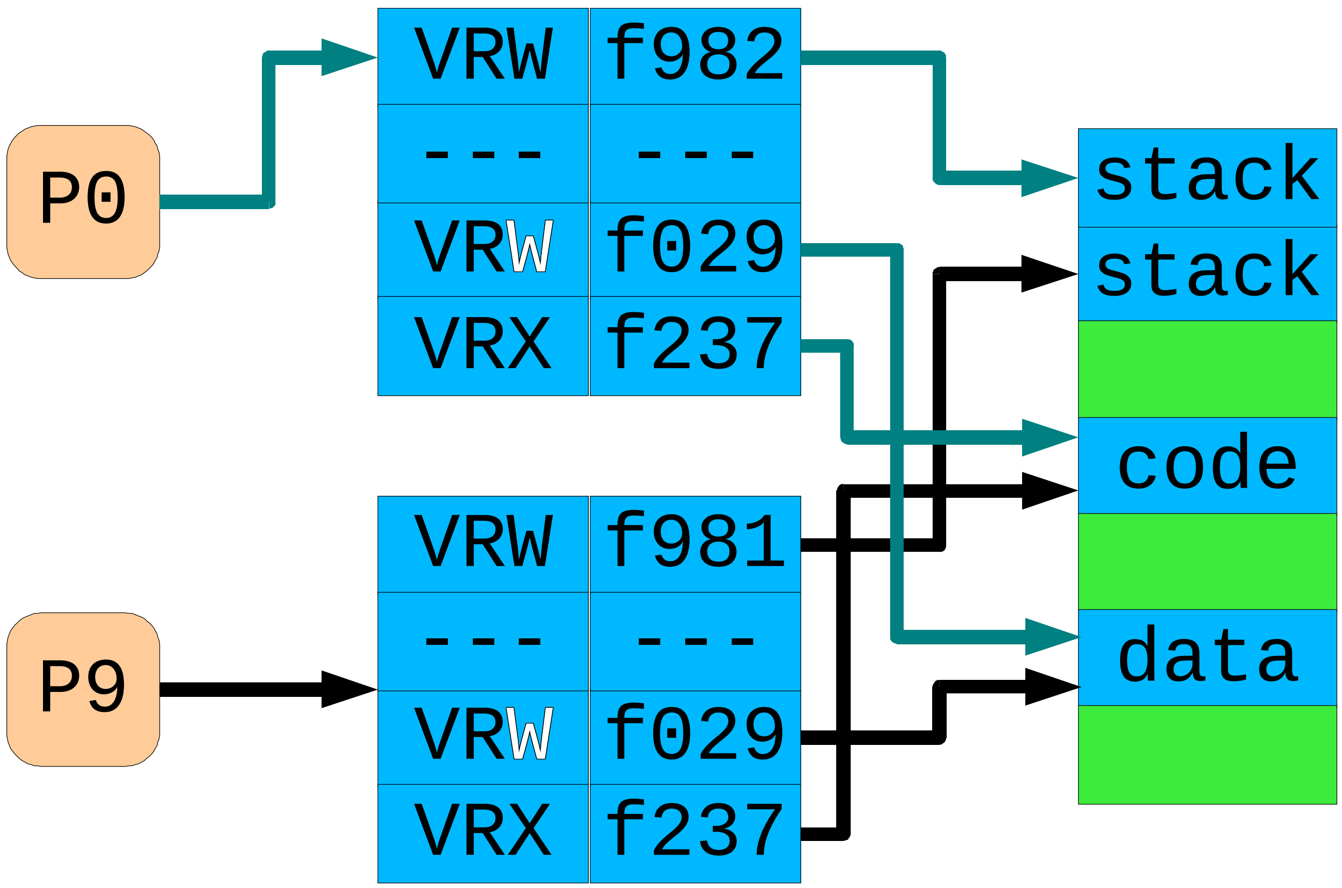
Memory Write ⇒ Permission Fault



Copy Into Blank Frame



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

Process 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)

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- 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 ***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

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- 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 *number of frames*
  - “Fair” - in a sense
  - Probably wasteful

Proportional allocation

- Every process gets same *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