Virtual Memory

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Synchronization

- P2 hand-in
  - Web page will appear
  - Same basic idea as last time
  - Will try to make it simpler
  - Extra office hours (see bboard)
- Upcoming
  - P3 out: Friday (***checkpoint*** upcoming)
  - HW1; exam

Outline

- Previously
  - Hardware used for paged memory
- What virtual memory can do for me
- What's under the hood

Virtual Memory: Motivations

- Previously
  - Avoid fragmentation issues of contiguous segments
  - Avoid "final relocation"
- Enable "partial swapping"
- Share memory regions, files efficiently
- Big speed hack for fork()

Partial Memory Residence

- Error-handling code not used in every run
- Tables may be allocated larger than used
- Can run ***very*** large programs
  - Much larger than physical memory
  - As long as “active” footprint fits in RAM
  - Swapping can't do this
- Programs can launch faster
  - Needn't load whole thing

Demand Paging

- RAM frames form a cache for the set of all pages
- Page tables indicate which pages are resident
  - "valid" bit in page table entry (PTE)
  - otherwise, page fault

Page fault - Why?

- Address is invalid/illegal
  - Raise exception
- Process is growing stack
- "Cache misses"
  - Page never used
    - Fetch from executable file
  - Page "swapped" to disk
    - Bring it back in!

Page fault story - 1

- Process issues memory reference
  - TLB: miss
  - PT: invalid
- ***Trap*** to OS kernel!
  - Save registers
  - Load new registers
  - Switch to kernel's page table
  - Run trap handler

Page fault story – 2

- Classify fault address: legal/illegal
- Code/data region of executable?
  - simulate read() into a blank frame
- Heap/modified-data/stack?
  - "somewhere on the paging partition"
  - schedule disk read into blank frame
- Growing stack?
  - Allocate a zero frame, insert into PT

Page fault story – 3

- Put process to sleep (probably)
  - Switch to running another
- Complete I/O, schedule process
- Handle I/O-complete interrupt
  - mark process runnable
- Restore registers, switch page table
  - Faulting instruction re-started transparently
  - ***Single instruction may fault more than once!***

Demand Paging Performance

- Effective access time of memory word
  - $(1 - p_{miss}) * T_{memory} + p_{miss} * T_{disk}$
- Textbook example
  - T_{memory} 100 ns
  - T_{disk} 25 ms
  - $p_{miss} = 1/1{,}000$ slows down by factor of 250
  - slowdown of 10% needs $p_{miss} < 1/2{,}500{,}000$

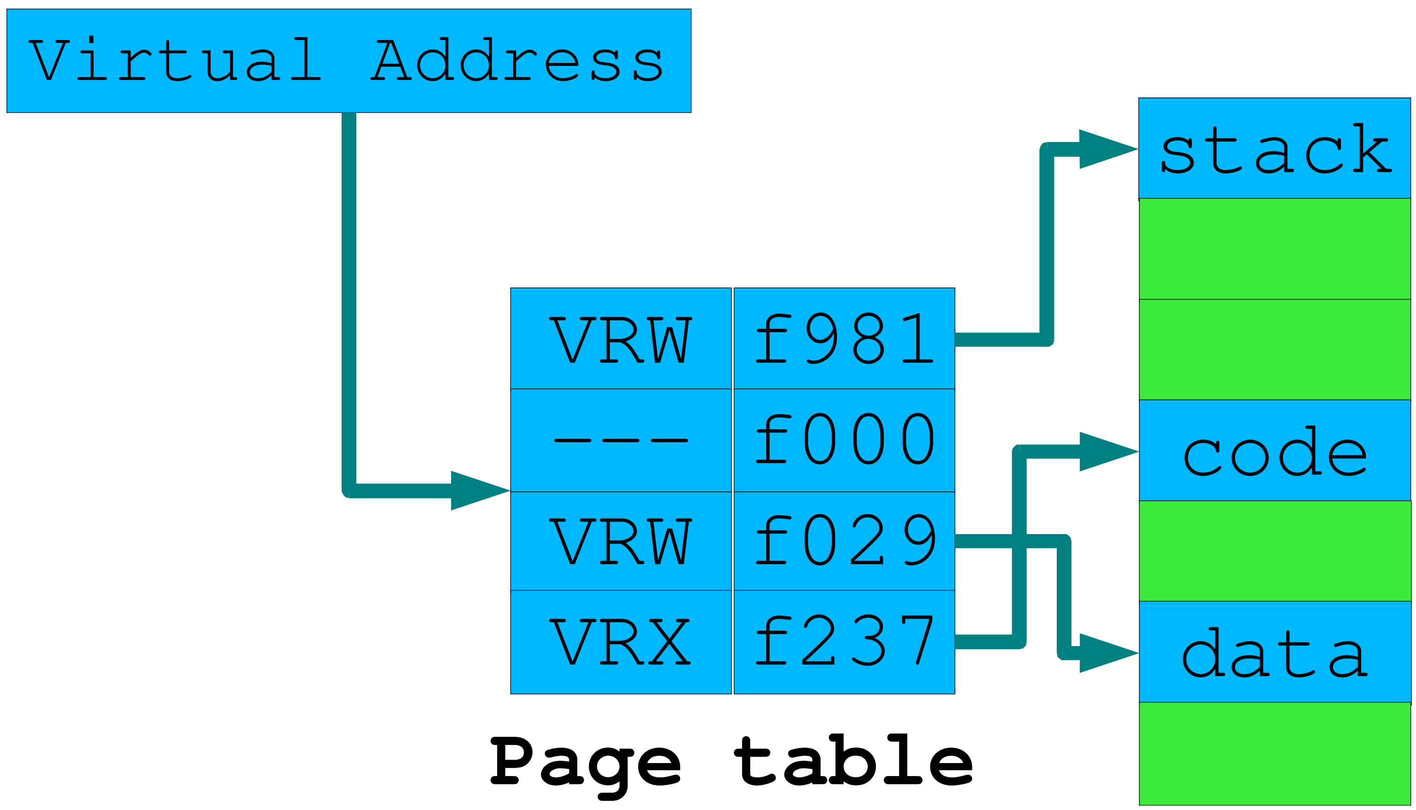
Copy-on-Write

- 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*** instead of copy?
  - Easy: code pages – read-only
  - Dangerous: stack pages!

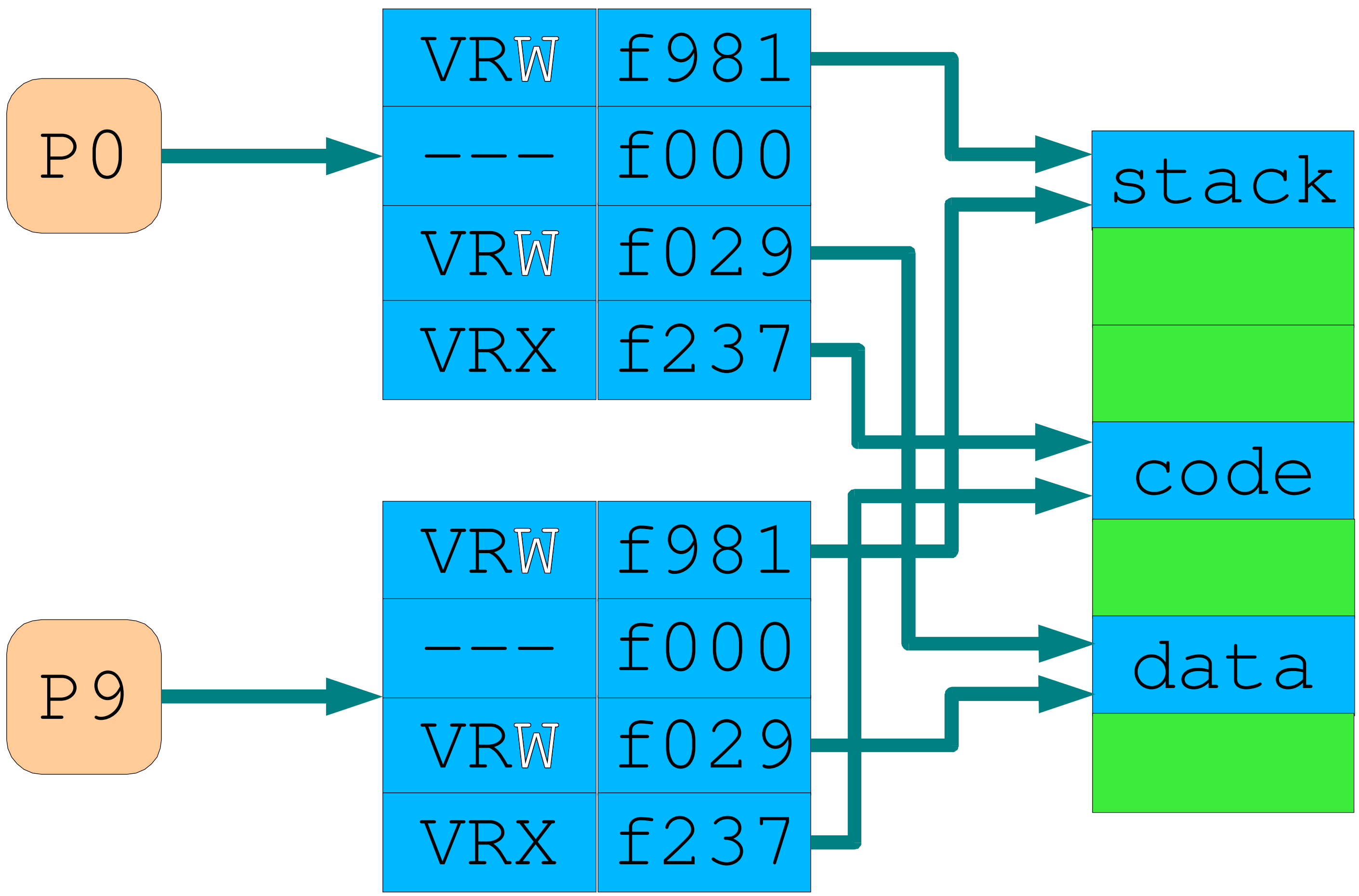
Copy-on-Write

- ***Simulated*** copy
  - Copy page table entries to new process
  - Mark PTEs read-only in old & new
  - Done! (saving factor: 1024)
- Making it real
  - Process writes to page (***oops!***)
  - Page fault handler responsible
    - Copy page into empty frame
    - Mark read-write in both PTEs

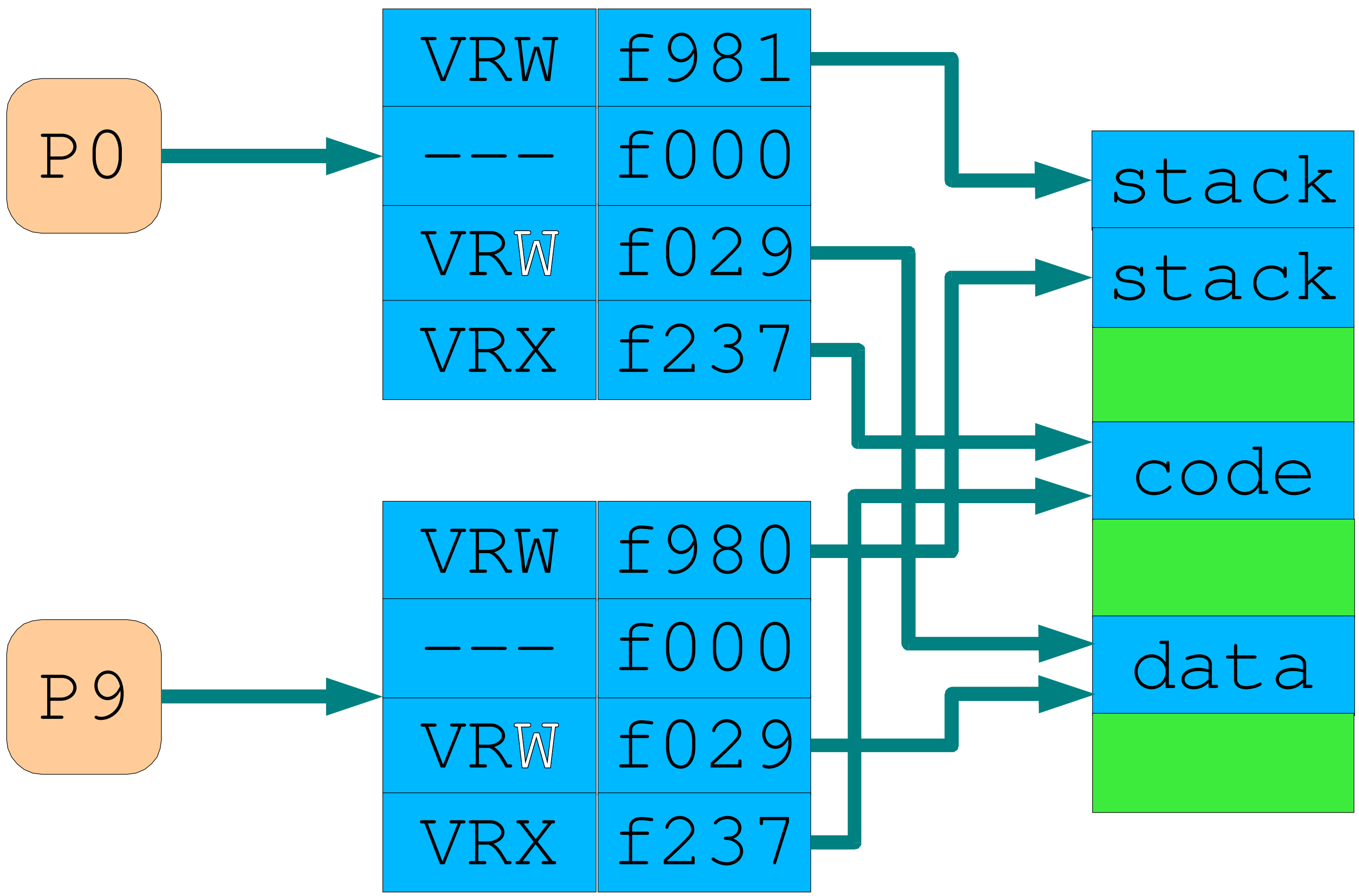
Example Page Table



Copy-on-Write of Address Space



Forking a Stack Page



Zero pages

- Very special case of copy-on-write
- Many process pages are “blank”
  - All of bss
  - New heap pages
  - New stack pages
- Have one ***system-wide*** all-zero page
  - Everybody points to it
  - Cloned as needed

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
- 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 evicted via write() to file
- Shared memory
  - Two processes mmap() “the same way”
  - Point to same memory region

Memory Regions vs. Page Tables

- What's a poor page fault handler to do?
  - Kill process?
  - Copy page, mark read-write?
  - Fetch page from file? Which? Where?
- Page Table not a good data structure
  - Format defined by hardware
  - Per-page nature is repetitive
  - Not enough bits to encode OS metadata

Dual-view Memory Model

- Logical
  - Process memory is a list of regions
  - "Holes" between regions are ***illegal addresses***
  - Per-region methods
    - fault(), evict(), unmap()
- Physical
  - Process memory is a list of pages
  - Many "invalid" pages can be made valid
  - Faults delegated to per-region methods

Page-fault story (for real)

- Examine fault address
- Look up: address ⇒ region
- `region->fault(addr, access_mode)`
  - ***Quickly*** fix up problem
  - Or put process to sleep, run scheduler

Page Replacement – When

- Process always want ***more*** memory frames
  - Explicit deallocation is rare
  - Page faults are implicit allocations
- System inevitably runs out
- Solution
  - 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
- 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 space, may be slower
  - Not modified since last page-in: no!
    - Hardware may provide "page-dirty" bit

FIFO Page Replacement

- Concept
  - Page queue
  - Page added to queue when created/faulted in
  - Always evict oldest page
- Evaluation
  - Cheap
  - Stupid
    - May evict old unused startup-code page
    - But ***guaranteed*** to 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
  - 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"
- Evaluation
  - Would work well
  - LRU is computable without fortune teller
  - Bookkeeping ***very*** expensive
    - Hardware must sequence-number every page reference!

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
  - OS periodically scans for active pages
- Second-chance algorithm
  - FIFO chooses victim page
    - Skip victims with reference == 1

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

- Maintain a pool of blank pages
  - Page fault handler can be fast
  - Disk write can happen in background
- "page-out daemon"
  - Scan system for dirty pages
    - Write to disk
    - Clear dirty bit
    - Page can be instantly evicted later

“Reclaim” fault

- DEC VAX-11/780 had no reference bit
  - What to page out?
- Approach
  - Remove pages from PT's according to FIFO
    - Dirty pages queued to disk, then marked clean
  - Add clean pages to FIFO free-page list
  - Page fault can “re-claim” page from free-page list
    - “Yes, I ***was*** using that page”

Frame Allocation

- How many frames should a process have?
- Minimum
  - Examine worst-case instruction
    - Can multi-byte instruction cross page boundary?
    - Can memory parameter cross page boundary?
    - How many memory parameters?
    - Indirect pointers?

Frame Allocation

- Equal
  - Every process gets same # frames
    - “Fair”
    - Probably wasteful
- Proportional
  - Larger processes get more frames
    - Probably the right approach
    - Encourages greediness

Thrashing

- Problem
  - Process ***needs*** N pages
  - OS provides N-1, N/2, etc.
- Result
  - Every page OS evicts generates “immediate” fault
  - More time spent paging than executing
  - Denial of “paging service” to other processes

Working-Set Model

- Approach
  - Determine necessary # pages
  - If unavailable, start swapping
- How to measure?
  - Periodically scan process reference bits
  - Combine multiple scans (see text)
- Evaluation
  - Expensive

Page-Fault Frequency

- Approach
  - Thrashing == “excessive” paging
  - Adjust each frame quotas to balance fault rates
    - Fault rate “too low”: reduce quota
    - Fault rate “too high”: increase quota
- What if quota increase doesn't help?
  - Start swapping

Program optimizations

- Locality depends on data structures
  - Arrays encourage sequential accesss
  - Random pointer data structures scatter references
- Compiler & linker can help
  - Don't split a routine across two pages
  - Place helper functions on same page as main routine
- Effects can be ***dramatic***

Summary

- Process address space
  - Logical: list of regions
  - Hardware: list of pages
- Fault handler is ***complicated***
  - Page-in, copy-on-write, zero-fill, ...
- Understand definition & use of
  - Dirty bit
  - Reference bit