Operating Systems

Virtual Memory

Motivation

- Logical address space larger than physical memory
  - $2^{32}$ about 4 GB in size
  - "Virtual Memory"
  - on special disk
- Abstraction for programmer
- Performance ok? Examples:
  - Unused libraries
  - Error handling not used
  - Maximum arrays

Paging Implementation

```
<table>
<thead>
<tr>
<th>Logical Memory</th>
<th>Page Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page 0</td>
<td>0 1 0</td>
</tr>
<tr>
<td>Page 1</td>
<td>1 0 1</td>
</tr>
<tr>
<td>Page 2</td>
<td>2 3 0</td>
</tr>
<tr>
<td>Page 3</td>
<td>3 0 1</td>
</tr>
</tbody>
</table>
```

“What happens when access invalid page?”

Accessing Invalid Pages

- Page not in memory
  - Interrupt OS $\rightarrow$ page fault
- OS looks in table:
  - invalid reference? $\rightarrow$ abort
  - not in memory? $\rightarrow$ bring it in
- Get empty frame (from list)
- Write page from disk into frame
- Reset tables (set valid bit = 1)
- Restart instruction

Performance of Demand Paging

- Page Fault Rate ($p$)
  $0 \leq p < 1.0$ (no page faults to every ref is a fault)
- Page Fault Overhead
  - write page in + update + restart
  - Dominated by time to write page in
- Effective Access Time
  - $(1-p)$ (memory access) + $p$ (page fault overhead)
Performance Example
- Memory access time ~ 100 nanoseconds
- Page fault overhead ~ 25 msec
- Page fault rate ~ 1/1000
- EAT = (1-p) * 100 + p * (25 msec)
  ≈ (1-p) * 100 + p * 25,000,000
  ≈ 100 + 24,999,900 * p
  ≈ 100 + 24,999,900 * 1/1000 ~ 25 microseconds!
- Want less than 10% degradation
  110 > 100 + 24,999,900 * p
  10 > 24,999,900 * p
  p < 0.000004 or 1 fault in 2,500,000 accesses!

Page Replacement

No Free Frames
- Page fault => What if no free frames?
  - terminate process (out of memory)
  - swap out process (reduces degree of multiprogramming)
  - replace another page with needed page
  - Page replacement
  - Page fault with page replacement:
    - if free frame, use it
    - else use algorithm to select victim frame
  - write page to disk
  - read in new page
  - change page tables
  - restart process

Page Replacement Algorithms
- Every system has its own
- Want lowest page fault rate
- Evaluate by running it on a particular string of memory references (reference string) and computing number of page faults
- Example: 1,2,3,4,1,2,5,1,2,3,4,5

First-In-First-Out (FIFO)
1,2,3,4,1,2,5,1,2,3,4,5

3 Frames/Process
1
2
3

First-In-First-Out (FIFO)
1,2,3,4,1,2,5,1,2,3,4,5

3 Frames/Process
1 4 5
2 1 3
3 2 4

9 Page Faults
How could we reduce the number of page faults?
**Optimal vs.**

- Replace the page that will not be used for the longest period of time

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

4 Frames / Process

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**Least Recently Used**

- Replace the page that has not been used for the longest period of time

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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**LRU Implementation**

- Counter implementation
  - every page has a counter; every time page is referenced, copy clock to counter
  - when a page needs to be changed, compare the counters to determine which to change
- Stack implementation
  - keep a stack of page numbers
  - page referenced: move to top
  - no search needed for replacement
- (Can we do this in software?)

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**LRU Approximations**

- LRU good, but hardware support expensive
- Some hardware support by reference bit
  - with each page, initially 0
  - when page is referenced, set 1
  - replace the one which is 0 (no order)
- Enhance by having 8 bits and shifting
  - approximate LRU
Second-Chance

- FIFO replacement, but ...
  - Get first in FIFO
  - Look at reference bit
    - bit = 0 then replace
    - bit = 1 then set bit = 0, get next in FIFO
- If page referenced enough, never replaced
- Implement with circular queue

Enhanced Second-Chance

- 2-bits, reference bit and modify bit
- (0,0) neither recently used nor modified
  - best page to replace
- (0,1) not recently used but modified
  - needs write-out ("dirty" page)
- (1,0) recently used but "clean"
  - probably used again soon
- (1,1) recently used and modified
  - used soon, needs write-out
- Circular queue in each class -- (Macintosh)

Page Buffering

- Pool of frames
  - start new process immediately, before writing old
  - write out when system idle
- list of modified pages
  - write out when system idle
- pool of free frames, remember content
  - page fault => check pool

Thrashing

- If a process does not have "enough" pages, the page-fault rate is very high
  - low CPU utilization
  - OS thinks it needs increased multiprogramming
  - adds another process to system
- Thrashing is when a process is busy swapping pages in and out
Cause of Thrashing

- Why does paging work?
  - Locality model
  - processes migrate from one locality to another
  - location may overlap
- Why does thrashing occur?
  - sum of localities > total memory size
- How do we fix thrashing?
  - Working Set Model
  - Page Fault Frequency

Working-Set Model

- Working set window $W$ - a fixed number of page references
  - total number of pages references in time $T$
- $Total$ = sum of size of $W$'s
- $m$ = number of frames

Working Set Example

- $T = 5$
- $12323124347434112221$
- $W = \{1,2,3\}$, $W = \{3,4,7\}$, $W = \{1,2\}$
  - if $T$ too small, will not encompass locality
  - if $T$ too large, will encompass several localities
  - if $T \to \infty$, will encompass entire program
- if $Total > m \Rightarrow$ thrashing, so suspend a process
- Modify LRU appx to include Working Set

Page Fault Frequency

- Establish “acceptable” page-fault rate
  - If rate too low, process loses frame
  - If rate too high, process gains frame

Outline

- Demand Paging Intro (done)
- Page Replacement Algorithms (done)
- Thrashing (done)
- Misc Paging
- WinNT
- Linux
- “Application Performance Studies”

Prepaging

- Pure demand paging has many page faults initially
  - use working set
  - does cost of prepaging unused frames outweigh cost of page-faulting?
Page Size
- Old - page size fixed, New - choose page size
- How do we pick the right page size? Tradeoffs:
  - Fragmentation
  - Table size
  - Minimize I/O
    - transfer small (1ms), latency + seek time large (10ms)
  - Locality
    - small entry resolution, but many faults
    - ex: 200K process (1/2 used), 1ms/200k, 100K faults/byte
- Historical trend towards larger page sizes
  - CPU, mem faster proportionally than disks

Program Structure
- Consider:
  ```
  int A[1024][1024];
  for (i=0; i<1024; i++)
    for (j=0; j<1024; j++)
      A[i][j] = 0;
  ```
  - 1024 page faults
  - Stack vs. Hash table
  - Compiler
    - separate code from data
    - keep routines that call each other together
  - LISP (pointers) vs. Pascal (no-pointers)

Priority Processes
- Consider
  - low priority process faults,
    - bring page in
  - low priority process in ready queue for a while,
    - waiting while high priority process runs
  - high priority process faults
    - low priority page clean, not used in a while
    - => perfect!
- Lock-bit (like for I/O) until used once

Real-Time Processes
- Real-time
  - bounds on delay
  - hard real-time: systems crash, lives lost
    - air-traffic control, feature automation
  - soft real-time: application sucks
    - audio, video
- Paging adds unexpected delays
  - don’t do it
  - lock bits for real-time processes

Virtual Memory and WinNT/2000
- Page Replacement Algorithm
  - FIFO
  - Missing page, plus adjacent pages
- Working set
  - default is 30
  - take victim frame periodically
  - if no fault, reduce set size by 1
- Reserve pool
  - hard page faults
  - soft page faults
Virtual Memory and WinNT/2000

- Shared pages
  - level of indirection for easier updates
  - same virtual entry
- Page File
  - stores only modified logical pages
  - code and memory mapped files on disk already

Virtual Memory and Linux

- Regions of virtual memory
  - paging disk (normal)
  - file (text segment, memory mapped file)
- Re-examine fork() and exec()
  - exec() creates new page table
  - fork() copies page table
  - reference to common pages
  - if written, then copied

Virtual Memory and Linux

- Page Replacement Algorithm
  - look in reserve pool for free frames
  - reserves for block devices (disk cache)
  - reserves for shared memory
  - user-space blocks
  - enhanced second chance (with more bits)
    - "dirty" pages not taken first

Application Performance Studies and Demand Paging in Windows NT

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Capacity Planning Then and Now

- Capacity Planning in the good old days
  - used to be just mainframes
  - simple CPU-load based queuing theory
  - Unix
- Capacity Planning today
  - distributed systems
  - networks of workstations
  - Windows NT
  - MS Exchange, Lotus Notes

Experiment Design

Does NT have more hard page faults or soft page faults?

- System
  - Pentium 133 MHz
  - NT Server 4.0
  - 64 MB RAM
  - IDE NTFS
  - NT v 4.0
  - clearem

- Experiments
  - Page Faults
  - Caching

- Analysis
  - perfmon
Page Fault Method

- "Work hard"
- Run lots of applications, open and close
- All local access, not over network

Caching and Prefetching

- Start process
  - wait for "Enter"
- Start perfmon
- Hit "Enter"
- Read 1 4-K page
- Exit
- Repeat