



Operating Systems

Virtual Memory (Chapter 10)

Memory Management Outline

- Processes (done)
- Memory Management
 - Basic (done)
 - Paging (done)
 - Virtual memory ←

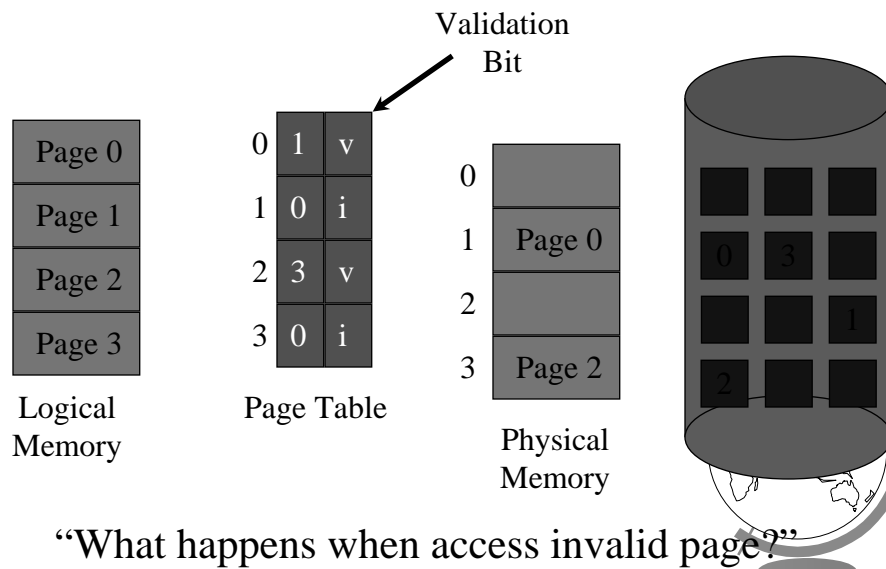


Motivation

- 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



Accessing Invalid Pages

- Page not in memory
 - interrupt OS => *page fault*
- OS looks in table:
 - invalid reference? => *abort*
 - not in memory? => *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
- $EAT = (1-p) * 100 + p * (25 \text{ msec})$
 $= (1-p) * 100 + p * 25,000,000$
 $= 100 + 24,999,900 * p$
 $= 100 + 24,999,900 * 1/1000 = 25 \text{ microseconds!}$
- Want less than 10% degradation
 $110 > 100 + 24,999,900 * p$
 $10 > 24,999,900 * p$
 $p < .0000004$ or 1 fault in 2,500,000 accesses!

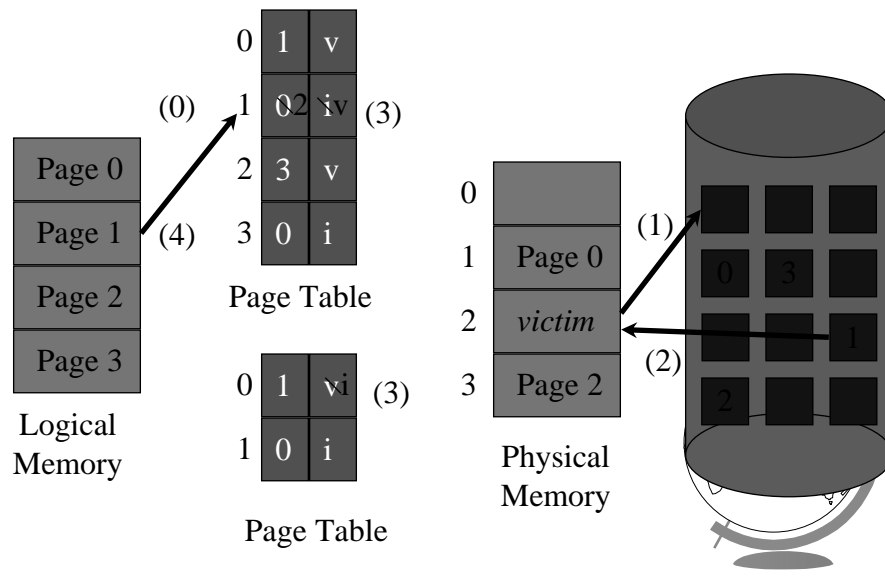


No Free Frames

- Page fault => What if no free frames?
 - terminate process (out of memory)
 - swap out process (reduces degree of multiprog)
 - 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



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

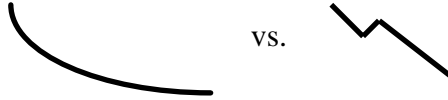
1	4	5
2	1	3
3	2	4

9 Page Faults

How could we reduce the number of page faults?



Optimal



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

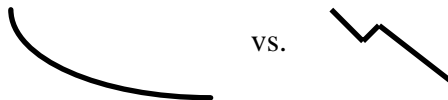
4 Frames / Process



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

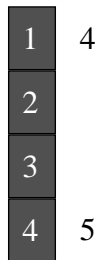


Optimal



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

4 Frames / Process



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

6 Page Faults

How do we know this?
Use as *benchmark*



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

1
2
3
4



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

1	5
2	
3	5 4
4	3

8 Page Faults



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?)



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*

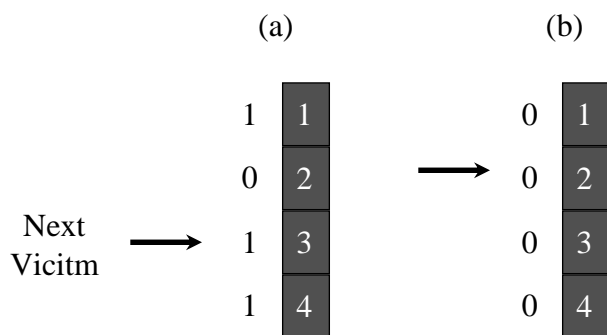


Second-Chance

- 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



Second-Chance



If all 1, degenerates to FIFO



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

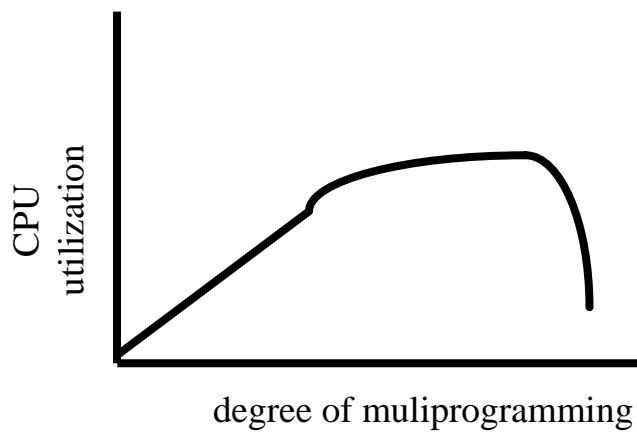


Thrashing

- 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



Thrashing



Cause of Thrashing

- Why does paging work?
 - Locality model
 - + process migrates from one locality to another
 - + localities 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

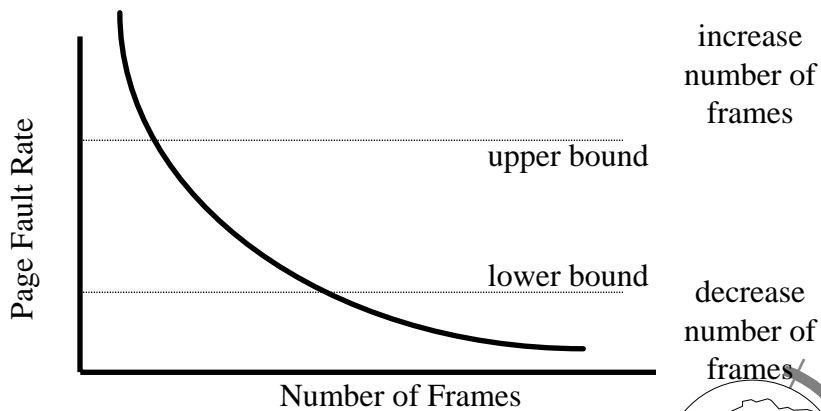


Working Set Example

- $T = 5$
- 1 2 3 2 3 1 2 4 3 4 7 4 3 3 4 1 1 2 2 2 1
 ↙ ↑ ↙ ↑ ↙ ↑
 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 $T \Rightarrow$ infinity, 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 finer resolution, but more faults
 - ex: 200K process (1/2 used), 1 fault / 200k, 100K faults/1 byte
- Historical trend towards larger page sizes
 - CPU, mem faster proportionally than disks



Program Structure

- consider:

```
int A[1024][1024];
for (j=0; j<1024; j++)
    for (i=0; i<1024; i++)
        A[i][j] = 0;
```
- suppose:
 - process has 1 frame
 - 1 row per page
 - => 1024x1024 page faults!



Program Structure

```
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 awhile, 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, factor 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

Mikhail Mikhailov

Ganga Kannan

Mark Claypool

David Finkel

WPI

Saqib Syed

Divya Prakash

Sujit Kumar

BMC Software, Inc.

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
- **Experiments**
 - Page Faults
 - Caching
- **Analysis**
 - perfmon
- clearmem

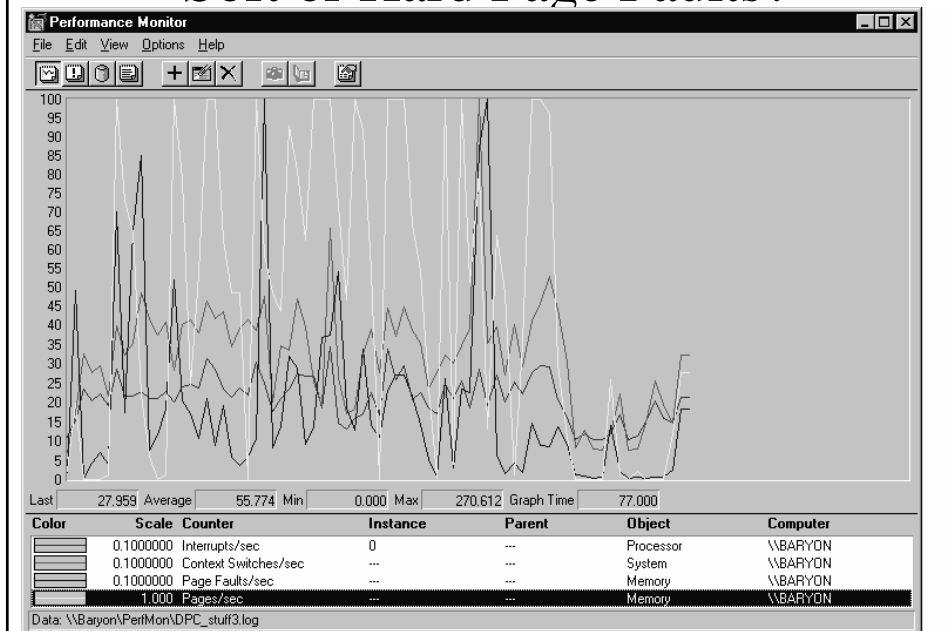


Page Fault Method

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



Soft or Hard Page Faults?



Caching and Prefetching

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



Page Metrics with Caching On

