Operating Systems

Virtual Memory

Memory Management Outline

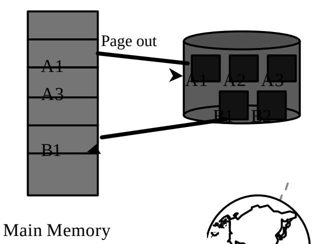
- Processes ✓
- Memory Management
  - Basic ✓
  - Paging ✓
  - Virtual memory ¬

Motivation

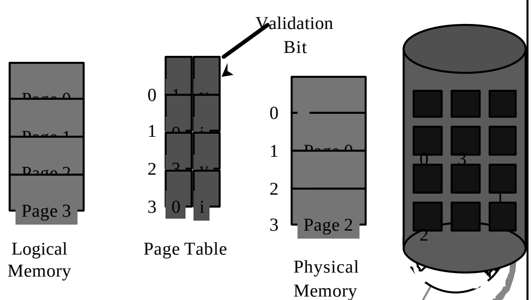
- Logical address space larger than physical memory
  - "Virtual Memory"
  - on special disk
- Abstraction for programmer
- Performance ok?
  - Error handling not used
  - Maximum arrays

Demand Paging

- Less I/O needed
- Less memory needed
- Faster response
- More users
- No pages in memory initially
  - *Pure demand paging*



Paging Implementation



Page Fault

- 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)
- Swap page into frame
- Reset tables (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)

Effective Access Time

= (1-p) (memory access) + p (page fault overhead)

- Page Fault Overhead
  - = (swap page out) + swap page in + restart

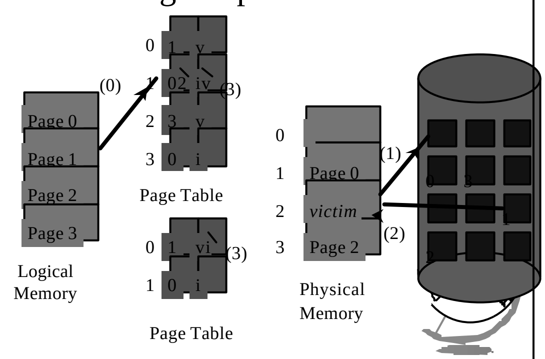
Performance Example

- 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 > 24,999,9000 * p
  - p < .0000004 or 1 fault in 2,500,000 accesses!

Page Replacement

- Page fault => What if no free frames?
  - terminate user process (ugh!)
  - swap out process (reduces degree of multiprog)
  - replace other page with needed page
- 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

Review

- True or False:
  - The logical address space cannot be bigger than the physical address space
  - Processes have big address spaces because they need them
- What is demand paging?
- What is a page fault?
- What does an OS do during a page fault?
- What is "Belady's Anomaly"?

First-In-First-Out (FIFO)

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

3 Frames / Process

Frame		
1	4	5
2	1	3
3	2	4

9 Page Faults

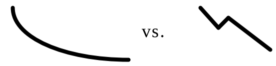
4 Frames / Process

Frame		
1	5	4
2	1	5
3	2	
4	3	

10 Page Faults!

Belady's Anomaly

Optimal



- 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

Frame	
1	4
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

Frame		
1		5
2		
3	5	4
4	3	

8 Page Faults

No Belady's Anomoly
- "Stack" Algorithm
- *N* frames subset of *N*+1

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?)

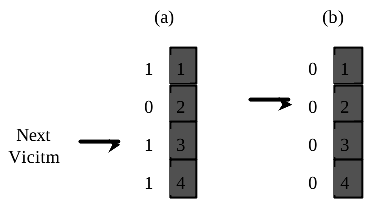
LRU Approximations

- 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)

Counting Algorithms

- Keep a counter of number of references
  - LFU - replace page with smallest count
    - if does all in beginning, won't be replaced
    - decay values by shift
  - MFU - replace page with largest count
    - smallest count just brought in and will probably be used
    - lock in place for some time, maybe
- Not too common (expensive) and not too good

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

Allocation of Frames

- How many fixed frames per process?
- Two allocation schemes:
  - fixed allocation
  - priority allocation

Fixed Allocation

- Equal allocation
  - ex: 93 frames, 5 procs = 18 per proc (3 in pool)
- Proportional Allocation
  - number of frames proportional to size
  - ex: 64 frames, s1 = 10, s2 = 127
    - f1 = 10 / 137 x 64 = 5
    - f2 = 127 / 137 x 64 = 59
- Treat processes equal

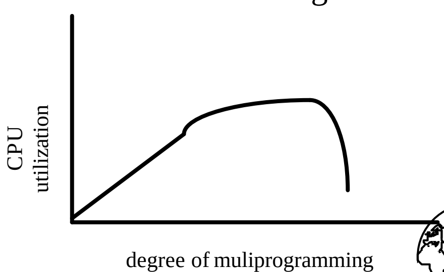
Priority Allocation

- Use a proportional scheme based on priority
- If process generates a page fault
  - select replacement a process with lower priority
- "Global" versus "Local" replacement
  - local consistent (not influenced by others)
  - global more efficient (used more often)

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 procces 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

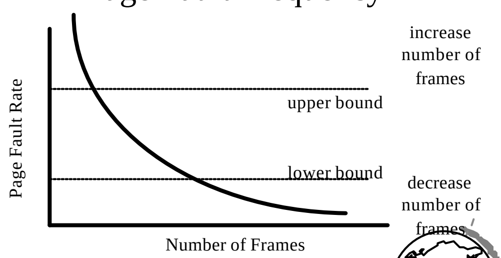
- Working set window *W* = a fixed number of page references
  - total number of pages references in time *T*
- *D* = sum of size of *W*'s

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* => infinity, will encompass entire program
- if *D* > *m* => 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

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

- 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

- 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)
- New Virtual Memory
  - 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
  - block devices (disk cache)
  - reserved 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

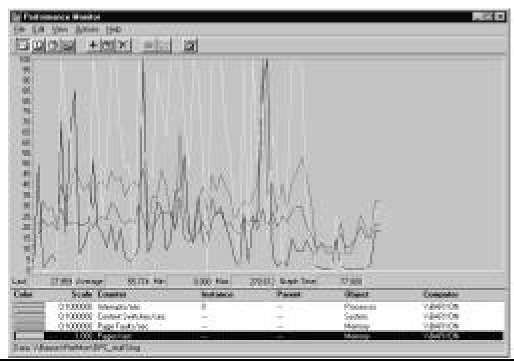
Experiment Design

- **System**
  - Pentium 133 MHz
  - NT Server 4.0
  - 64 MB RAM
  - IDE NTFS
- `clearmem`
- Experiments
  - Page Faults
  - Caching
- Analysis
  - `perfmon`

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