Chapter 8

Virtual Memory
Contents

- Hardware and control structures
- Operating system software
- Unix and Solaris memory management
- Linux memory management
- Windows 2000 memory management
Characteristics of Simple Paging and Segmentation

- Memory references are dynamically translated into physical addresses at run time
  - A process may be swapped in and out of main memory such that it occupies different regions
- A process may be broken up into pieces that do not need to be located contiguously in main memory
- Is it necessary that all the pages of a process be in main memory during execution?
Execution of a Program

- Operating system brings into main memory a few pieces of the program
  - Resident set - portion of process that is in main memory
- An interrupt is generated when an address is needed that is not in main memory
  - OS places the process in a blocked state
Execution of a Program

- Piece of process that contains the logical address is brought into main memory
  - OS issues a disk I/O Read request
  - Another process is dispatched to run while the disk I/O takes place
  - An interrupt is issued when disk I/O complete which causes OS to place the affected process in the Ready state
Advantages of This Maneuver

- More processes may be maintained in main memory
  - Only load in some of the pieces of each process
  - With so many processes in main memory, it is very likely a process will be in the Ready state at any particular time

- It is possible for a process to be larger than all the main memory
  - Programmer is dealing with memory size of the hard disk
Advantages of This Maneuver

- It would be wasteful to load in many pieces of the process when only a few pieces will be used.
- Time can be saved because unused pieces are not swapped in and out of memory.
Types of Memory

- Real memory
  - Main memory

- Virtual memory
  - Memory on disk
  - Allows for effective multiprogramming and relieves the user of tight constraints of main memory
Thrashing

- Swapping out a piece of a process just before that piece is needed
- Processor spends most of its time swapping pieces rather than executing user instructions
Principle of Locality

- Program and data references within a process tend to cluster
  - Only a few pieces of a process will be needed over a short period of time
- Possible to make intelligent guesses about which pieces will be needed in the future
- This suggests that virtual memory may work efficiently
Support Needed for Virtual Memory

- Hardware must support paging and segmentation
- OS must be able to manage the movement of pages and/or segments between secondary memory and main memory
VM Paging

- Each process has its own page table
- Each page table entry contains the frame number of the corresponding page in main memory
- A bit is needed to indicate whether the page is in main memory or not
Modify Bit in Page Table

- A bit is needed to indicate if the page has been altered since it was last loaded into main memory
  - If no change has been made, the page does not have to be written to the disk when it needs to be swapped out
Page Table Entries

Virtual Address

<table>
<thead>
<tr>
<th>Page Number</th>
<th>Offset</th>
</tr>
</thead>
</table>

Page Table Entry

| P | M | Other Control Bits | Frame Number |

(a) Paging only
Figure 8.3  Address translation in a paging system
Page Table Structure

- The entire page table may take up too much main memory
  - In VAX, each process can have up to 2 GB of memory
  - If page size is 512 byte, we need $2^{22}$ page table entries

- Page tables can also be stored in virtual memory
  - When a process is running, part of its page table is in main memory
Page Table Structure

- Two-level scheme
  - Assume 32-bit address, 4 KB pages and 4 GB address space
    - $2^{20}$ pages, requiring 4 MB
  - Root page table with $2^{10}$ PTEs occupying a page (4 KB)
    - Always remains in main memory
  - User page table is kept in virtual memory
    - They are mapped by a root page table
Two-Level Scheme for 32-bit Address

Figure 8.4 A Two-Level Hierarchical Page Table [JACO98a]
Figure 8.5  Address translation in a two-level paging system
Page Table Structure

● Inverted page table structure
  • Used on Power PC and on IBM’s AS/400
  • Page number portion of a virtual address is mapped into a hash table
  • Hash table contains a pointer to the inverted page table
    – There is one entry in the hash table and inverted page table for each real memory page
    – Fixed proportion of real memory is required for the tables
  • Faster access to the page is possible
Figure 8.6  Inverted page table structure
Translation Lookaside Buffer (TLB)

- Each virtual memory reference can cause two physical memory accesses
  - One to fetch the page table entry
  - One to fetch the data

- To overcome this problem, a special cache is set up for page table entries
  - Called a TLB - Translation Lookaside Buffer
    - Contains page table entries that have been most recently used
    - Works similar to a memory cache
TLB

Operations

- Given a virtual address, processor examines the TLB
- If page table entry is present (a hit), the frame number is retrieved and the real address is formed
- If page table entry is not found in the TLB (a miss), the page number is used to index the process page table
- Check if page is already in main memory
  - If not in main memory a page fault is issued
- TLB is updated to include the new page entry
Figure 8.7  Use of a Translation Lookaside Buffer
Figure 8.8  Operation of Paging and Translation Lookaside Buffer (TLB) [FURH87]
Figure 8.10  TLB and cache operation
Page Size

- Smaller page size, less amount of internal fragmentation
- Smaller page size, more pages required per process
  - More pages per process means larger page tables
  - Larger page tables means large portion of page tables in virtual memory
- Secondary memory devices favor a larger page size for more efficient block transfer of data
Page Size and Page Fault Rate

- Small page size
  - Large number of pages will be found in main memory
- As time goes on during execution, the pages in memory will all contain portions of the process near recent references
  - Page faults low
- Increased page size causes pages to contain locations further from any recent reference
  - Effect of the principle of locality is weakened and page fault rate rise
  - Page fault rate will begin to fall as the size of a page approaches the size of the entire process
Figure 8.11 Typical Paging Behavior of a Program

- $P =$ size of entire process
- $W =$ working set size
- $N =$ total number of pages in process
Page Size and TLB Performance

- Multiple page sizes provide the flexibility needed to effectively use a TLB
  - Large pages can be used for program instructions
  - Small pages can be used for thread stacks
- But most OS support only one page size
Table 8.2  Example Page Sizes

<table>
<thead>
<tr>
<th>Computer</th>
<th>Page Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas</td>
<td>512 48-bit words</td>
</tr>
<tr>
<td>Honeywell-Multics</td>
<td>1024 36-bit word</td>
</tr>
<tr>
<td>IBM 370/XA and 370/ESA</td>
<td>4 Kbytes</td>
</tr>
<tr>
<td>VAX family</td>
<td>512 bytes</td>
</tr>
<tr>
<td>IBM AS/400</td>
<td>512 bytes</td>
</tr>
<tr>
<td>DEC Alpha</td>
<td>8 Kbytes</td>
</tr>
<tr>
<td>MIPS</td>
<td>4 kbytes to 16 Mbytes</td>
</tr>
<tr>
<td>UltraSPARC</td>
<td>8 Kbytes to 4 Mbytes</td>
</tr>
<tr>
<td>Pentium</td>
<td>4 Kbytes or 4 Mbytes</td>
</tr>
<tr>
<td>PowerPc</td>
<td>4 Kbytes</td>
</tr>
</tbody>
</table>
VM Segmentation

- May be unequal, dynamic size

- Advantages
  - Simplifies handling of growing data structures
    - OS will expand or shrink the segment as needed
  - Allows parts of a program to be altered and recompiled independently
  - Used for sharing data among processes
  - Lends itself to protection
    - A segment can be constructed to contain a well-defined set of programs or data
Segment Tables

- Address: (segment number, offset)
- Each entry contains the starting address of the corresponding segment in main memory
- Each entry contains the length of the segment
- A bit is needed to determine if segment is already in main memory
- A bit is needed to determine if the segment has been modified since it was loaded in main memory
Segment Table Entries

Virtual Address

<table>
<thead>
<tr>
<th>Segment Number</th>
<th>Offset</th>
</tr>
</thead>
</table>

Segment Table Entry

<table>
<thead>
<tr>
<th>P</th>
<th>M</th>
<th>Other Control Bits</th>
<th>Length</th>
<th>Segment Base</th>
</tr>
</thead>
</table>

(b) Segmentation only
Figure 8.12 Address translation in a segmentation system
Combined Paging and Segmentation

- Paging is transparent to the programmer
- Paging eliminates external fragmentation
- Segmentation is visible to the programmer
- Segmentation allows for growing data structures, modularity, and support for sharing and protection
- Each segment is broken into fixed-size pages
### Combined Segmentation and Paging

#### Virtual Address

<table>
<thead>
<tr>
<th>Segment Number</th>
<th>Page Number</th>
<th>Offset</th>
</tr>
</thead>
</table>

#### Segment Table Entry

<table>
<thead>
<tr>
<th>Other Control Bits</th>
<th>Length</th>
<th>Segment Base</th>
</tr>
</thead>
</table>

#### Page Table Entry

<table>
<thead>
<tr>
<th>Other Control Bits</th>
<th>Frame Number</th>
</tr>
</thead>
</table>

- **P** = present bit
- **M** = Modified bit

(c) Combined segmentation and paging
Figure 8.12  Address translation in a segmentation/paging system
OS Software

- Design of memory-management depends on the following areas of choice
  - Whether or not to use virtual memory
  - Use of paging or segmentation or both
  - Algorithms employed for various aspects of memory management
    - See next slide
Table 8.3 Operating System Policies for Virtual Memory

<table>
<thead>
<tr>
<th>Fetch Policy</th>
<th>Resident Set Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>Resident set size</td>
</tr>
<tr>
<td>Prepaging</td>
<td>Fixed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Placement Policy</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement Policy</td>
<td>Replacement Scope</td>
</tr>
<tr>
<td>Basic Algorithms</td>
<td>Global</td>
</tr>
<tr>
<td>Optimal</td>
<td>Local</td>
</tr>
<tr>
<td>Least recently used (LRU)</td>
<td></td>
</tr>
<tr>
<td>First-in-first-out (FIFO)</td>
<td></td>
</tr>
<tr>
<td>Clock</td>
<td></td>
</tr>
<tr>
<td>Page buffering</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cleaning Policy</th>
<th>Load Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>Degree of multiprogramming</td>
</tr>
<tr>
<td>Precleaning</td>
<td></td>
</tr>
</tbody>
</table>


Fetch Policy

• Determines when a page should be brought into memory
  ✷ Demand paging only brings pages into main memory when a reference is made to a location on the page
    – Many page faults when process first started
  ✷ Prepaging brings in more pages than needed
    – More efficient to bring in pages that reside contiguously on the disk
Placement Policy

- Determines where in real memory a process piece is to reside
- Case of the segmentation system
  - Best-fit, first-fit, next-fit...
- Case of the paging system
  - Nothing to consider
Replacement Policy

- Deals with the selection of a page in memory to be replaced when a new page is brought in
- Frame locking used for frames that may not be replaced
  - Kernel and key control structures of OS
  - I/O buffers
Replacement Policy

• Basic algorithms
  ♦ Optimal
  ♦ Least recently used (LRU)
  ♦ First-in-first-out (FIFO)
  ♦ Clock
Replacement Policy

- Optimal algorithm
  - Selects for replacement that page for which the time to the next reference is the longest
    - Results in the fewest number of page faults
  - Impossible to have perfect knowledge of future events
    - Impossible to implement
  - Used to judge other algorithms
Replacement Policy

- Least Recently Used (LRU)
  - Replaces the page that has not been referenced for the longest time
  - By the principle of locality, this should be the page least likely to be referenced in the near future
  - Each page needs to be tagged with the time of last reference
    - Require a great deal of overhead.
Replacement Policy

- First-In, First-Out (FIFO)
  - Simplest replacement policy to implement
  - Treats page frames allocated to a process as a circular buffer
  - Page that has been in memory the longest is replaced
    - These pages may be needed again very soon
Replacement Policy

- Second Chance algorithm
  - FIFO with use-bit (or reference bit R)
  - Avoid the problem of throwing out heavily used pages
  - If the R bit is 0, the page is both old and unused, so it is replaced immediately
  - If the R bit is 1, the bit is cleared, the page is put onto the end of the list of pages, and its load time is updated as though it had just arrived in memory
  - Inefficient because it is constantly moving pages around on its list
Replacement Policy

● Clock algorithm
  ✷ Additional bit called a use bit
  ✷ When a page is first loaded in memory, use bit is set to 1
  ✷ When the page is referenced, use bit is set to 1
  ✷ When it is time to replace a page, the first frame encountered with the use bit set to 0 is replaced.
  ✷ During the search for replacement, each use bit with 1 is changed to 0
Example 8.16  Example of clock policy operation
Example 8.16  Example of clock policy operation
Figure 8.15  Behavior of four page replacement algorithms
Figure 8.17 Comparison of Fixed-Allocation, Local Page Replacement Algorithms
Replacement Policy

- NRU (Not Recently Used)
  - Reference bit (R) and modified bit (M)
  - Timer interrupt: periodically clear R bit
    - Class 0: not recently referenced, not modified
    - Class 1: not recently referenced, modified
    - Class 2: referenced, not modified
    - Class 3: referenced, modified
  - Removes a page at random from the lowest numbered nonempty class
Figure 8.18  The clock page replacement algorithm
Replacement Policy

- NFU (Not Frequently Used)
  - Reference bit (R) and software counter
  - Timer interrupt
    - Periodically add R bit (0 or 1) to the counter
  - Counters are an attempt to keep track of how often each page had been referenced
  - When a page fault occurs, the page with the lowest counter is chosen for replacement
Replacement Policy

● Aging (NFU with aging)
  ✦ Timer interrupt
    − Periodically add R bit (0 or 1) to the leftmost bit of the counter, rather than the rightmost bit
    − Counter is shifted right 1 bit before the R bit is added in
  ✦ When a page fault occurs, the page with the lowest counter is chosen for replacement
Resident Set Management

- Fixed-allocation
  - Gives a process a fixed number of pages within which to execute
  - When a page fault occurs, one of the pages of that process must be replaced

- Variable-allocation
  - Number of pages allocated to a process varies over the lifetime of the process
# Resident Set Management

<table>
<thead>
<tr>
<th></th>
<th>Local Replacement</th>
<th>Global Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed Allocation</strong></td>
<td>Number of frames allocated to process is fixed. Page to be replaced is chosen from among the frames allocated to that process</td>
<td>Not possible</td>
</tr>
<tr>
<td><strong>Variable Allocation</strong></td>
<td>The number of frames allocated to a process may be changed from time to time, to maintain the working set of the process. Page to be replaced is chosen from among the frames allocated to that process</td>
<td>Page to be replaced is chosen from all available frames in main memory; this causes the size of the resident set of processes to vary</td>
</tr>
</tbody>
</table>
Resident Set Management

● Variable-allocation, local scope
  • When a new process is loaded into main memory, allocate to it a certain number of page frames
  • When a page fault occurs, select the page to replace from among the resident set of the faulting process
  • From time to time, reevaluate the allocation provided to the process, and increase or decrease

● Key elements of this strategy are the resident set size and the timing of changes
Working Set Strategy

- Working Set: $W(t, \Delta)$
  - Set of pages in the most recent $\Delta$ page references
  - $\Delta$: working set window
  - Working set size
    - Nondecreasing function of the window size
    - $W(t, \Delta + 1) \supseteq W(t, \Delta)$
    - $1 \leq |W(t, \Delta)| \leq \min(\Delta, N)$
<table>
<thead>
<tr>
<th>Sequence of Page References</th>
<th>Window Size, Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>24</td>
<td>24</td>
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<tr>
<td>15</td>
<td>24 15</td>
</tr>
<tr>
<td>18</td>
<td>24 15 18</td>
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<td>23</td>
<td>24 15 18 23</td>
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<td>24 17 15 24</td>
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<tr>
<td>18</td>
<td>24 17 15 24</td>
</tr>
<tr>
<td>17</td>
<td>24 17 15 24</td>
</tr>
</tbody>
</table>

Figure 8.19  Working set of process as defined by window size
Working Set Strategy

● Working Set Policy
  ✷ Monitor the working set of each process
  ✷ Periodically remove from the resident set of a process those pages that are not in its working set
  ✷ A process may execute only if its working set is in main memory
Problems with Working Set

● The past does not always predict the future
● A true measurement of working set is impractical (too much overhead)
● Optimal value of $\Delta$ is unknown and in any case would vary
PFF algorithm

- Page Fault Frequency algorithm
  - An attempt to approximate the working set strategy
  - Use bit is set to 1 when a page is accessed
  - A threshold $F$ is defined
  - When a page fault occurs, OS notes the time since the last page fault
    - If the amount of time since the last page fault is less than $F$, a page is added to the resident set
    - Otherwise, discard all pages with a use bit of zero
      + reset the use bit on the remaining pages to zero
Cleaning Policy

● Demand cleaning
  ✷ Page is written out only when it has been selected for replacement

● Precleaning
  ✷ Pages are written out in batches
Cleaning Policy

Better approach uses page buffering

- Replaced pages are placed in two lists
  - Modified and unmodified
- Pages in the modified list are periodically written out in batches
- Pages in the unmodified list are either reclaimed if referenced again or lost when its frame is assigned to another page
Load Control

- Determines the number of processes that will be resident in main memory
- Too few processes, many occasions when all processes will be blocked and processor will be idle
- Too many processes will lead to thrashing
Load Control

- Process suspension
  - Lowest priority process
  - Faulting process
    - This process does not have its working set in main memory so it will be blocked anyway
  - Last process activated
    - This process is least likely to have its working set resident
  - Process with smallest resident set
    - this process requires the least future effort to reload
  - Largest process
    - obtains the most free frames
  - Process with the largest remaining execution window
UNIX and Solaris Memory Management

- Paging system for user processes
  - Page table
  - Disk block descriptor
  - Page frame data table
  - Swap-use table

- Kernel memory allocator for memory allocation for the kernel
UNIX and Solaris Memory Management

- Data Structures
  - Page table - one per process
  - Disk block descriptor - describes the disk copy of the virtual page
  - Page frame data table - describes each frame of real memory
  - Swap-use table - one for each swap device
<table>
<thead>
<tr>
<th>Page frame number</th>
<th>Age</th>
<th>Copy on write</th>
<th>Modify</th>
<th>Reference</th>
<th>Valid</th>
<th>Protect</th>
</tr>
</thead>
</table>

(a) Page table entry

<table>
<thead>
<tr>
<th>Swap device number</th>
<th>Device block number</th>
<th>Type of storage</th>
</tr>
</thead>
</table>

(b) Disk block descriptor
## Page Table Entry

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page frame number</td>
<td>Refers to frame in real memory.</td>
</tr>
<tr>
<td>Age</td>
<td>Indicates how long the page has been in memory without being referenced. The length and contents of this field are processor dependent.</td>
</tr>
<tr>
<td>Copy on write</td>
<td>Set when more than one process shares a page. If one of the processes writes into the page, a separate copy of the page must first be made for all other processes that share the page. This feature allows the copy operation to be deferred until necessary and avoided in cases where it turns out not to be necessary.</td>
</tr>
<tr>
<td>Modify</td>
<td>Indicates page has been modified.</td>
</tr>
<tr>
<td>Reference</td>
<td>Indicates page has been referenced. This bit is set to zero when the page is first loaded and may be periodically reset by the page replacement algorithm.</td>
</tr>
<tr>
<td>Valid</td>
<td>Indicates page is in main memory.</td>
</tr>
<tr>
<td>Protect</td>
<td>Indicates whether write operation is allowed.</td>
</tr>
<tr>
<td>Page state</td>
<td>Reference count</td>
</tr>
<tr>
<td>------------</td>
<td>----------------</td>
</tr>
</tbody>
</table>

(c) Page frame data table entry

<table>
<thead>
<tr>
<th>Reference count</th>
<th>Page/storage unit number</th>
</tr>
</thead>
</table>

(d) Swap-use table entry

Figure 8.22 UNIX SVR4 Memory Management Formats
Page Frame Data Table Entry

Page State
Indicates whether this frame is available or has an associated page. In the latter case, the status of the page is specified: on swap device, in executable file, or DMA in progress.

Reference Count
Number of processes that reference the page.

Logical Device
Logical device that contains a copy of the page.

Block Number
Block location of the page copy on the logical device.

Pfddata Pointer
Pointer to other pfddata table entries on a list of free pages and on a hash queue of pages.
<table>
<thead>
<tr>
<th><strong>Disk Block Descriptor</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Swap device number</strong></td>
</tr>
<tr>
<td>Logical device number of the secondary device that holds the corresponding page. This allows more than one device to be used for swapping.</td>
</tr>
<tr>
<td><strong>Device block number</strong></td>
</tr>
<tr>
<td>Block location of page on swap device.</td>
</tr>
<tr>
<td><strong>Type of storage</strong></td>
</tr>
<tr>
<td>Storage may be swap unit or executable file. In the latter case, there is an indication as to whether the virtual memory to be allocated should be cleared first.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Swap-use Table Entry</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference count</strong></td>
</tr>
<tr>
<td>Number of page table entries that point to a page on the swap device.</td>
</tr>
<tr>
<td><strong>Page/storage unit number</strong></td>
</tr>
<tr>
<td>Page identifier on storage unit.</td>
</tr>
</tbody>
</table>
UNIX and Solaris Memory Management

- Page Replacement
  - Refinement of the clock policy known as the two-handed clock algorithm
  - Uses the reference bit
    - Set to 0 when the page is first brought in
    - Set to 1 when the page is referenced
  - Fronthand sweeps through the pages and sets the reference bit to 0
  - Sometime later, backhand sweeps through the pages and collects the pages with reference bit 0
Figure 8.23  Two-handed clock page replacement algorithm
UNIX and Solaris Memory Management

Kernel Memory Allocator

- Kernel generates and destroys small tables and buffers frequently during execution
  - They require dynamic memory allocation
- Most of these blocks are significantly smaller than the typical machine page size
  - Paging mechanism is inefficient here
- In SVR4, modification of the buddy system is used
Linux Memory Management

- Linux virtual memory
  - Virtual memory addressing (3 level scheme)
    - Page directory
    - Page middle directory
    - Page table
  - Virtual address consists of four fields
Linux Memory Management

• Page allocation
  - Buddy system is used
    - To enhance the efficiency of reading and writing, Linux defines a mechanism for dealing with contiguous blocks of pages mapped into contiguous blocks of page frames

• Page replacement algorithm
  - Modified clock algorithm is used
    - Aging is considered
Windows 2000 Memory Management

- W2K virtual address map
  - Each process has a 32-bit address space
    - 2 GB for user process
    - 2 GB for system space which is shared by all processes
Figure 8.25  Windows 2000 Default Virtual Address Space
Windows 2000 Memory Management

● W2K Paging
  - A page can be in one of 3 states
    - Available
      + pages not currently used by this process
    - Reserved
      + reserved but not counted against the process’s memory quota
    - Committed
      + pages for which the virtual memory manager has set aside space in its paging file