Chapter 9: Virtual Memory
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- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Allocation of Frames
- Thrashing
- Memory-Mapped Files
- Allocating Kernel Memory
- Other Considerations
- Operating-System Examples
Objectives

- To describe the benefits of a virtual memory system
- To explain the concepts of demand paging, page-replacement algorithms, and allocation of page frames
- To discuss the principle of the working-set model
Background

- **Virtual memory** – separation of user logical memory from physical memory.
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation

- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation
Virtual Memory That is Larger Than Physical Memory
Virtual-address Space
Shared Library Using Virtual Memory

- Stack
- Shared Library
- Heap
- Data
- Code
- Shared Pages
- Stack
- Shared Library
- Heap
- Data
- Code
Demand Paging

- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users

- Page is needed \(\Rightarrow\) reference to it
  - invalid reference \(\Rightarrow\) abort
  - not-in-memory \(\Rightarrow\) bring to memory

- **Lazy swapper** – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a pager
Transfer of a Paged Memory to Contiguous Disk Space
Valid-Invalid Bit

- With each page table entry a valid–invalid bit is associated (v ⇒ in-memory, i ⇒ not-in-memory)
- Initially valid–invalid bit is set to i on all entries
- Example of a page table snapshot:

<table>
<thead>
<tr>
<th>Frame #</th>
<th>valid-invalid bit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>i</td>
</tr>
<tr>
<td></td>
<td>i</td>
</tr>
<tr>
<td></td>
<td>i</td>
</tr>
</tbody>
</table>

- During address translation, if valid–invalid bit in page table entry is i ⇒ page fault
Page Table When Some Pages Are Not in Main Memory
Page Fault

- If there is a reference to a page, first reference to that page will trap to operating system:
  
  **page fault**

1. Operating system looks at another table to decide:
   - Invalid reference ➞ abort
   - Just not in memory
2. Get empty frame
3. Swap page into frame
4. Reset tables
5. Set validation bit = v
6. Restart the instruction that caused the page fault
Page Fault (Cont.)

- Restart instruction
  - block move

- auto increment/decrement location
Steps in Handling a Page Fault

1. Reference
2. Trap
3. Page is on backing store
4. Bring in missing page
5. Reset page table
6. Restart instruction

Diagram:
- Operating system
- Page table
- Free frame
- Physical memory
- Load M
- 1. Reference
- 2. Trap
- 3. Page is on backing store
- 4. Bring in missing page
- 5. Reset page table
- 6. Restart instruction
Performance of Demand Paging

- Page Fault Rate $0 \leq p \leq 1.0$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault

- Effective Access Time (EAT)
  
  $EAT = (1 - p) \times \text{memory access} + p \times (\text{page fault overhead} + \text{swap page out} + \text{swap page in} + \text{restart overhead})$
Demand Paging Example

- Memory access time = 200 nanoseconds

- Average page-fault service time = 8 milliseconds

- EAT = \((1 - p) \times 200 + p \times 8,000,000\)  
  \(= 200 + p \times 7,999,800\)

- If one access out of 1,000 causes a page fault, then  
  EAT = 8.2 microseconds.  
  This is a slowdown by a factor of 40!!
Virtual memory allows other benefits during process creation:

- Copy-on-Write

- Memory-Mapped Files (later)
Copy-on-Write

- Copy-on-Write (COW) allows both parent and child processes to initially share the same pages in memory.
  
  If either process modifies a shared page, only then is the page copied.

- COW allows more efficient process creation as only modified pages are copied.

- Free pages are allocated from a pool of zeroed-out pages.
Before Process 1 Modifies Page C
After Process 1 Modifies Page C

process\textsubscript{1}

physical memory

page A

page B

page C

Copy of page C

process\textsubscript{2}
What happens if there is no free frame?

- Page replacement – find some page in memory, but not really in use, swap it out
  - algorithm
  - performance – want an algorithm which will result in minimum number of page faults
- Same page may be brought into memory several times
Page Replacement

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement.

- Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk.

- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory.
Need For Page Replacement

- Logical memory for user 1:
  - Frame 0: H (load M)
  - Frame 1: J
  - Frame 2: M

- Logical memory for user 2:
  - Frame 0: A
  - Frame 1: B
  - Frame 2: D
  - Frame 3: E

- Page table for user 1:
  - Page 3: v
  - Page 4: v
  - Page 5: v
  - Page 1: i

- Page table for user 2:
  - Page 6: v
  - Page 7: v

- Valid-invalid bit:
  - Monitor: 0
  - Frame 1: 3
  - Frame 2: 4
  - Frame 3: 5
  - Frame 4: i
  - Frame 5: 6
  - Frame 6: 2
  - Frame 7: 7

- Physical memory:
  - B
  - M
Basic Page Replacement

1. Find the location of the desired page on disk

2. Find a free frame:
   - If there is a free frame, use it
   - If there is no free frame, use a page replacement algorithm to select a victim frame

3. Bring the desired page into the (newly) free frame; update the page and frame tables

4. Restart the process
Page Replacement

1. Swap out victim page
2. Change to invalid
3. Swap desired page in
4. Reset page table for new page
Page Replacement Algorithms

- Want lowest page-fault rate

- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string

- In all our examples, the reference string is

  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
Graph of Page Faults Versus The Number of Frames

![Graph showing the relationship between the number of page faults and the number of frames. The graph indicates a decreasing trend in page faults as the number of frames increases.](image-url)
First-In-First-Out (FIFO) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames (3 pages can be in memory at a time per process)

<table>
<thead>
<tr>
<th>1</th>
<th>1</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

9 page faults

- 4 frames

<table>
<thead>
<tr>
<th>1</th>
<th>1</th>
<th>5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

10 page faults

- Belady’s Anomaly: more frames ⇒ more page faults
FIFO Page Replacement

<table>
<thead>
<tr>
<th>reference string</th>
<th>page frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 0 1 2 0 3 0 4 2 3 0 3 2 1 2 0 1 7 0 1</td>
<td>7 7 7 7 7 7 0 0 0 3 3 3 2 2 2 1 1 1 0 0</td>
</tr>
</tbody>
</table>
FIFO Illustrating Belady’s Anomaly

The graph illustrates the number of page faults as a function of the number of frames. As the number of frames increases, the number of page faults decreases, which is an example of Belady’s Anomaly.
Optimal Algorithm

- Replace page that will not be used for longest period of time
- 4 frames example

\[ 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 \]

\[
\begin{array}{c|c}
1 & 4 \\
2 & \\
3 & \\
4 & 5 \\
\end{array}
\]

- How do you know this?
- Used for measuring how well your algorithm performs
## Optimal Page Replacement

**Reference String**

| 7  | 0  | 1  | 2  | 0  | 3  | 0  | 4  | 2  | 3  | 0  | 3  | 2  | 1  | 2  | 0  | 1  | 7  | 0  | 1  |

**Page Frames**

```
7 7 7 2 2 2 2 2 2 2 2 7
0 0 0 0 4 0 0 0 0 0 0 0
1 1 3 3 3 3 3 3 1 1 1 1
```
Least Recently Used (LRU) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

- Counter implementation
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter
  - When a page needs to be changed, look at the counters to determine which are to change
### LRU Page Replacement

**Reference String**

| 0 | 1 | 2 | 0 | 3 | 0 | 4 | 2 | 3 | 0 | 3 | 2 | 1 | 2 | 0 | 1 | 7 | 0 | 1 |
| 7 | 7 | 7 | 2 | 2 | 4 | 4 | 4 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

**Page Frames**

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

---
LRU Algorithm (Cont.)

- Stack implementation – keep a stack of page numbers in a double link form:
  - Page referenced:
    - move it to the top
    - requires 6 pointers to be changed
  - No search for replacement
Use Of A Stack to Record The Most Recent Page References

reference string

4  7  0  7  1  0  1  2  1  2  7  1  2

stack before a

<table>
<thead>
<tr>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

stack after b

<table>
<thead>
<tr>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

a  b
LRU Approximation Algorithms

- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace the one which is 0 (if one exists)
    - We do not know the order, however

- Second chance
  - Need reference bit
  - Clock replacement
  - If page to be replaced (in clock order) has reference bit = 1 then:
    - set reference bit 0
    - leave page in memory
    - replace next page (in clock order), subject to same rules
Second-Chance (clock) Page-Replacement Algorithm
Counting Algorithms

- Keep a counter of the number of references that have been made to each page

- **LFU Algorithm**: replaces page with smallest count

- **MFU Algorithm**: based on the argument that the page with the smallest count was probably just brought in and has yet to be used
Allocation of Frames

- Each process needs *minimum* number of pages
- Example: IBM 370 – 6 pages to handle SS MOVE instruction:
  - instruction is 6 bytes, might span 2 pages
  - 2 pages to handle *from*
  - 2 pages to handle *to*
- Two major allocation schemes
  - fixed allocation
  - priority allocation
Fixed Allocation

- **Equal allocation** – For example, if there are 100 frames and 5 processes, give each process 20 frames.

- **Proportional allocation** – Allocate according to the size of process
  
  - \( s_i = \text{size of process } p_i \)
  
  - \( S = \sum s_i \)
  
  - \( m = \text{total number of frames} \)
  
  - \( a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m \)

  \[
  \begin{align*}
  m &= 64 \\
  s_i &= 10 \\
  s_2 &= 127 \\
  a_1 &= \frac{10}{137} \times 64 \approx 5 \\
  a_2 &= \frac{127}{137} \times 64 \approx 59
  \end{align*}
  \]
Priority Allocation

- Use a proportional allocation scheme using priorities rather than size.

- If process $P_i$ generates a page fault,
  - select for replacement one of its frames
  - select for replacement a frame from a process with lower priority number
Global vs. Local Allocation

- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
- **Local replacement** – each process selects from only its own set of allocated frames
Thrashing

- If a process does not have "enough" pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process added to the system

- **Thrashing** ≡ a process is busy swapping pages in and out
Thrashing (Cont.)

![Graph showing the relationship between CPU utilization and degree of multiprogramming, indicating thrashing at certain point.](image-url)
Demand Paging and Thrashing

- Why does demand paging work?
  Locality model
  - Process migrates from one locality to another
  - Localities may overlap

- Why does thrashing occur?
  $\Sigma$ size of locality > total memory size
Locality In A Memory-Reference Pattern
Working-Set Model

- $\Delta$ ≡ working-set window ≡ a fixed number of page references
  Example: 10,000 instruction

- $WSS_i$ (working set of Process $P_i$) =
  total number of pages referenced in the most recent $\Delta$ (varies in time)
  - if $\Delta$ too small will not encompass entire locality
  - if $\Delta$ too large will encompass several localities
  - if $\Delta = \infty \Rightarrow$ will encompass entire program

- $D = \sum WSS_i$ ≡ total demand frames

- if $D > m \Rightarrow$ Thrashing

- Policy if $D > m$, then suspend one of the processes
Working-set model

\[ WS(t_1) = \{1, 2, 5, 6, 7\} \]
\[ WS(t_2) = \{3, 4\} \]

page reference table

\[ \ldots 2 6 1 5 7 7 7 5 1 6 2 3 4 1 2 3 4 4 3 4 4 4 1 3 2 3 4 4 3 4 4 4 \ldots \]
Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: \( \Delta = 10,000 \)
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page
  - Whenever a timer interrupts copy and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 \( \Rightarrow \) page in working set
- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units
Page-Fault Frequency Scheme

- Establish “acceptable” page-fault rate
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame
Working Sets and Page Fault Rates

![Diagram showing working sets and page fault rates over time. The x-axis represents time, the y-axis represents page fault rate, and the graph illustrates how the working set changes over time with peaks in page fault rate.]

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Memory-Mapped Files

- Memory-mapped file I/O allows file I/O to be treated as routine memory access by mapping a disk block to a page in memory.

- A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical page. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.

- Simplifies file access by treating file I/O through memory rather than read() write() system calls.

- Also allows several processes to map the same file allowing the pages in memory to be shared.
Memory Mapped Files

process A
virtual memory

physical memory

process B
virtual memory

disk file
Memory-Mapped Shared Memory in Windows

Diagram showing two processes, `process_1` and `process_2`, connected by memory-mapped file. Each process has shared memory that is mapped to the file.
Allocating Kernel Memory

- Treated differently from user memory
- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
  - Some kernel memory needs to be contiguous
Buddy System

- Allocates memory from fixed-size segment consisting of physically-contiguous pages
- Memory allocated using **power-of-2 allocator**
  - Satisfies requests in units sized as power of 2
  - Request rounded up to next highest power of 2
  - When smaller allocation needed than is available, current chunk split into two buddies of next-lower power of 2
    - Continue until appropriate sized chunk available
Buddy System Allocator

physically contiguous pages

256 KB

128 KB

A_L

128 KB

A_R

64 KB

B_L

64 KB

B_R

32 KB

C_L

32 KB

C_R
Slab Allocator

- Alternate strategy
- **Slab** is one or more physically contiguous pages
- **Cache** consists of one or more slabs
- Single cache for each unique kernel data structure
  - Each cache filled with **objects** – instantiations of the data structure
- When cache created, filled with objects marked as **free**
- When structures stored, objects marked as **used**
- If slab is full of used objects, next object allocated from empty slab
  - If no empty slabs, new slab allocated
- Benefits include no fragmentation, fast memory request satisfaction
Slab Allocation

- Kernel objects
- Caches
- Slabs

3 KB objects

7 KB objects

Physical contiguous pages
Prepaging

- To reduce the large number of page faults that occurs at process startup
- Prepage all or some of the pages a process will need, before they are referenced
- But if prepaged pages are unused, I/O and memory was wasted
- Assume $s$ pages are prepaged and $\alpha$ of the pages is used
  - Is cost of $s \times \alpha$ save pages faults $>$ or $<$ than the cost of prepaging
    $s \times (1-\alpha)$ unnecessary pages?
  - $\alpha$ near zero $\Rightarrow$ prepaging loses
Other Issues – Page Size

- Page size selection must take into consideration:
  - fragmentation
  - table size
  - I/O overhead
  - locality
Other Issues – TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
  
- TLB Reach = (TLB Size) X (Page Size)

- Ideally, the working set of each process is stored in the TLB
  
  - Otherwise there is a high degree of page faults

- Increase the Page Size
  
  - This may lead to an increase in fragmentation as not all applications require a large page size

- Provide Multiple Page Sizes
  
  - This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation
Program structure

- Int[128,128] data;
- Each row is stored in one page
- Program 1

```c
for (j = 0; j < 128; j++)
    for (i = 0; i < 128; i++)
        data[i,j] = 0;
```

128 x 128 = 16,384 page faults

- Program 2

```c
for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i,j] = 0;
```

128 page faults
Other Issues – I/O interlock

- **I/O Interlock** – Pages must sometimes be locked into memory

- Consider I/O - Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm
Reason Why Frames Used For I/O Must Be In Memory
Operating System Examples

- Windows XP
- Solaris
Windows XP

- Uses demand paging with **clustering**. Clustering brings in pages surrounding the faulting page.
- Processes are assigned **working set minimum** and **working set maximum**.
- Working set minimum is the minimum number of pages the process is guaranteed to have in memory.
- A process may be assigned as many pages up to its working set maximum.
- When the amount of free memory in the system falls below a threshold, **automatic working set trimming** is performed to restore the amount of free memory.
- Working set trimming removes pages from processes that have pages in excess of their working set minimum.
Maintains a list of free pages to assign faulting processes

- *Lotsfree* – threshold parameter (amount of free memory) to begin paging
- *Desfree* – threshold parameter to increasing paging
- *Minfree* – threshold parameter to being swapping

Paging is performed by *pageout* process

Pageout scans pages using modified clock algorithm

- *Scanrate* is the rate at which pages are scanned. This ranges from *slowscan* to *fastscan*

Pageout is called more frequently depending upon the amount of free memory available
Solaris 2 Page Scanner

![Diagram showing the relationship between scan rate and amount of free memory. The x-axis represents the amount of free memory (minfree, desfree, lotsfree), and the y-axis represents the scan rate (8192 fastscan, 100 slowscan). The line shows a decrease in scan rate as the amount of free memory increases.]
End of Chapter 9