Module 9: Virtual Memory

- Background
- Demand Paging
- Performance of Demand Paging
- Page Replacement
- Page-Replacement Algorithms
- Allocation of Frames
- Thrashing
- Other Considerations
- Demand Segmentation

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.
  - Need to allow pages to be swapped in and out.
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation
**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

**Valid–Invalid Bit**

- With each page table entry a valid–invalid bit is associated (1 \(\Rightarrow\) in-memory, 0 \(\Rightarrow\) not-in-memory)
- Initially valid–invalid bit is set to 0 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>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

- During address translation, if valid–invalid bit in page table entry is 0 \(\Rightarrow\) page fault.
Page Fault

- If there is ever a reference to a page, first reference will trap to OS ⇒ page fault.
- OS looks at another table to decide:
  - Invalid reference ⇒ abort.
  - Just not in memory.
- Get empty frame.
- Swap page into frame.
- Reset tables, validation bit = 1.
- Restart instruction: Least Recently Used
  - block move
  - auto increment/decrement location

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.
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)

$$EAT = (1 - p) \times \text{memory access} + p (\text{page fault overhead} + \text{swap page out} + \text{swap page in} + \text{restart overhead})$$

Demand Paging Example

- Memory access time = 1 microsecond
- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out.
- Swap Page Time = 10 msec = 10,000 msec

$$EAT = (1 - p) \times 1 + p (15000) = 1 + 15000p \text{ (in msec)}$$
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.

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.
**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>Frame</th>
<th>Page 1</th>
<th>Page 2</th>
<th>Page 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

9 page faults

- 4 frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>Page 1</th>
<th>Page 2</th>
<th>Page 3</th>
<th>Page 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td></td>
<td>10 page faults</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- FIFO Replacement – Belady’s Anomaly
  - more frames $\not\Rightarrow$ less page faults

**Optimal Algorithm**

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

<table>
<thead>
<tr>
<th>Frame</th>
<th>Page 1</th>
<th>Page 2</th>
<th>Page 3</th>
<th>Page 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>6 page faults</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- How do you know this?
- Used for measuring how well your algorithm performs.
Least Recently Used (LRU) Algorithm

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

```
1  5
2
3  5  4
4  3
```

- 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 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
**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.

**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 – e.g., If 100 frames and 5 processes, give each 20 pages.
- Proportional allocation – Allocate according to the size of process.
  - \( s_i \) = size of process \( p_i \)
  - \( S = \sum s_i \)
  - \( m \) = total number of frames
  - \( a_i \) = allocation for \( p_i \) = \( \frac{s_i}{S} \times m \)

\[
\begin{align*}
m &= 64 \\
s_1 &= 10 \\
s_2 &= 127 \\
a_1 &= \frac{10}{137} \times 64 \approx 5 \\
a_2 &= \frac{127}{137} \times 64 \approx 59
\end{align*}
\]
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.
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.

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Why does paging work?

Locality model

- Process migrates from one locality to another.
- Localities may overlap.

Why does thrashing occur?

Σ size of locality > total memory size
**Working-Set Model**

- $\Delta \equiv$ working-set window $\equiv$ 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.
- $D = \sum WSS_i \equiv$ total demand frames
- If $D > m$ $\Rightarrow$ thrashing.
- Policy if $D > m$, then suspend one of the processes.

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

Other Considerations

- Prepaging
- Page size selection
  - fragmentation
  - table size
  - I/O overhead
  - locality
Other Considerations (Cont.)

- Program structure
  - Array $A[1024,1024]$ of integer
  - Each row is stored in one page
  - One frame
  - Program 1
    
    ```
    for j := 1 to 1024 do
      for i := 1 to 1024 do
        A[i, j] := 0;
    ```
    
    $1024 \times 1024$ page faults
  - Program 2
    
    ```
    for i := 1 to 1024 do
      for j := 1 to 1024 do
        A[i, j] := 0;
    ```
    
    1024 page faults

- I/O interlock and addressing

Demand Segmentation

- Used when insufficient hardware to implement demand paging.
- OS/2 allocates memory in segments, which it keeps track of through **segment descriptors**.
- Segment descriptor contains a valid bit to indicate whether the segment is currently in memory.
  - If segment is in main memory, access continues,
  - If not in memory, segment fault.