CSE 306/506 Operating Systems
Virtual Memory

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Operating System Policies for VM

- Fetch policy
  - Demand paging, prefetching
- Placement policy
- Replacement policy
  - Optimal, LRU, FIFO, clock, page buffering
- Resident set management
  - Fixed/variable set size, global/local scope
- Cleaning policy
  - Demand cleaning, precleaning
- Load control (degree of multiprogramming)
Fetch Policy

- **Demand paging**
  - A page is brought into main memory only when the page is accessed

- **Prepaging**
  - Pages other than the one accessed are brought in
  - Exploits the characteristics of secondary memory (disks have latency and rotational delay)
Placement Policy

- In pure segmentation system
  - Best-fit, first-fit, ...
  - In pure paging or paging + segmentation systems, placement is usually irrelevant

- In **NonUniform Memory Access (NUMA)** system
  - Access time to a particular memory location varies with the distance between the processor and the memory
  - Need to place data close to the processors that use them
Replacement Policy

- Replacement Policy
  - Selecting a page frame to be replaced

- Frame Locking
  - When a frame is locked, the page stored in the frame will not be replaced
  - Most kernel code and key control structures are held in locked frames
Replacement Policy

- Optimal algorithm
  - Select the page that will not be referenced longest
  - Not implementable: for the comparison purpose
Replacement Policy

- **Least Recently Used (LRU) algorithm**
  - Select the page that has not been referenced longest
  - Tag each page with the time of its last reference
  - Alternatively, maintain a stack of page references

![Page address stream and LRU diagram]
Replacement Policy

- **First In First Out (FIFO) Algorithm**
  - Replace the page that has been in memory the longest
  - Simple to implement (a pointer that cycles all frames)
Replacement Policy

- Clock algorithm
  - Add a use bit to each frame: whenever a page is referenced its use bit is set
  - Like FIFO, a page pointer cycles frames to find a frame whose use bit is 0
  - While scanning frames, the use bit is set to 0
Replacement Policy (Clock)

First frame in circular buffer of frames that are candidates for replacement.

(a) State of buffer just prior to a page replacement

(b) State of buffer just after the next page replacement
Replacement Policy

- Clock algorithm with **modify bit**
  - Each frame falls into
    - Not accessed, not modified (u=0, m=0)
    - Accessed, not modified (u=1, m=0)
    - Not accessed, modified (u=0, m=1)
    - Accessed, modified (u=1, m=1)
  - Step 1: starting from the current position, try to find a frame with (u=0, m=0)
  - Step 2: from the current position try to find a frame with (u=0, m=1). During this scan set u of encountered frames to 0
  - Step 3: Repeat step 1 and step 2 if necessary
Replacement Policy (Clock with modify bit)
Replacement Policy: Comparison

The diagram illustrates the number of page faults per 1000 references for different replacement policies as a function of the number of frames allocated.

- FIFO
- CLOCK
- LRU
- OPT

As the number of frames allocated increases, the number of page faults decreases for all policies, indicating better performance.
Replacement Policy

- Page buffering
  - Similar to FIFO, but victim frames are moved to one of frame pools: free or modified frame pools
    - Their entries in the page table are removed
    - If a frame in the pools is accessed, only the page table is updated without reading the frame from disk

- When a pool is full, swap some frames out to disk
  - Modified frames can be swapped out to the disk together considering the seek time and the rotational delay
Resident Set Management

- **Resident set** of a process
  - The portion of a process that is actually in main memory at any time

- **Resident set size**
  - Smaller the size
    - → More processes can reside in main memory
    - → More page fault
  - After a certain point, adding more pages to a particular process will have no noticeable effects
Resident Set Size

- **Fixed-allocation policy**
  - Give a process a fixed number of frames
  - On a page fault, one of the frames of the process needs to be replaced

- **Variable-allocation policy**
  - # of frames allocated to a process will vary over time
  - More frames will be given to processes experiencing a high page fault rates
  - Frames will be taken from processes with exceptionally low page fault rates
Replacement Scope

- Local replacement policy
  - Find a victim frame among the frames of the process that caused the page fault

- Global replacement policy
  - Consider all unlocked pages in main memory
Fixed Allocation, Local Scope

- OS must choose one of the frames of the process for the replacement

- Decide, ahead of time, the amount of frames to give to a process
  - Too small allocation: high page fault rate
  - Too much allocation: low degree of multiprogramming
Variable Allocation, Global Scope

- Replacement algorithm
  - Typically, OS maintains a list of free frames
  - On page fault, a free frame is added to the resident set of the process causing the fault
  - When no free frame is available, select a frame from any processes
Variable Allocation, Local Scope

Strategy

- When a new process is loaded, allocate to it a certain number of frames
- **Victim page** is selected from among the resident set of the process that caused the fault
- From time to time, reevaluate the allocation and expand or shrink the allocation to improve overall performance
Variable Allocation, Local Scope

- **Working set**
  - \( W(t, \Delta) \): the set of pages referenced during \((t-\Delta, t]\)
    - \( t \): virtual time representing the memory reference count of a process
  - Working set is a non-decreasing function of the window size
    - \( W(t, \Delta) \subseteq W(t, \Delta + 1) \)
  - The bound of the working set size
    - \( 1 \leq |W(t, \Delta)| \leq \min(\Delta, N) \), where the entire process is held in \( N \) pages
Working Set Example

<table>
<thead>
<tr>
<th>Sequence of Page References</th>
<th>Window Size, Δ</th>
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<tbody>
<tr>
<td></td>
<td>2</td>
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<td>24</td>
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Working Set

- For many programs, periods of relative stable working set sizes alternate with periods of rapid changes.
Variable Allocation, Local Scope

- Working set strategy
  - Monitor the working set of each process
  - Periodically remove from the resident set of a process those pages not in the working set (like LRU)
  - A process may execute only if its working set is in main memory

- Problems
  - The past does not always predict the future
  - Computing the working set of processes is impractical
  - Optimal value of $\Delta$ is unknown
Variable Allocation, Local Scope

- **Page fault frequency (PFF) algorithm**
  - When a page fault occurs, OS records its virtual time
  - If the **elapsed time** since the last page fault is **less than a threshold F**, add a frame to the resident set of the process
  - Otherwise, discard all frames whose use bit is 0 and shrink the resident set size accordingly

- **Problems with PFF**
  - Does not perform well during **transition periods** (shift to a new locality) → resident set size grows
Variable Allocation, Local Scope

- Variable-interval sampled working set (VSWS)
  - When accessing a frame, set its use bit
  - Any faulted pages are added to the resident set
  - At each sampling time, scan the frames in the resident set and discard the frames whose use bit is not set
  - Clear the use bit of the remaining frames
Variable Allocation, Local Scope

- Variable-interval sampled working set (VSWS)
  - Parameters
    - M: the minimum duration of the sampling interval
    - L: the maximum duration of the sampling interval
    - Q: the number of page faults allowed to occur between sampling instances
    - E: the virtual time since the last sampling time

- If E reaches L, suspend the process and scan the use bit
- If Q page faults occur before L
  - If E is less than M, then wait until it reaches M
  - Otherwise, suspend the process and scan the use bit
Load Control

- Load control
  - Determines the number of processes that will reside in main memory

- Too few processes
  - All processes can be blocked
  - Processor utilization will be low

- Too many processes
  - Thrashing: page fault will occur frequently
  - Processor utilization will be low