

CS330: Operating Systems

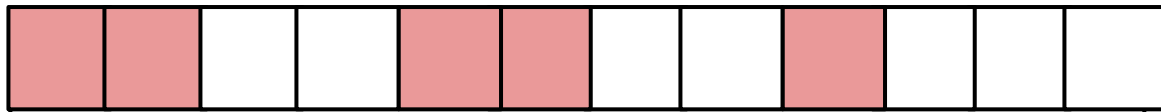
Virtual memory: Page fault and Swapping

Recap: Address translation (TLB + PTW)

- How TLB is shared across multiple processes?
- Full TLB flush during context switch, using ASID
- Why page fault is necessary?
- Page fault is required to support memory over-commitment through lazy allocation and swapping
- How OS handles the page fault?
- The hardware invokes the page fault handler by placing the error code and virtual address. The OS handles the page fault either fixing it or raising a SEGFAULT.

Swapping (swap-out)

DRAM



Swap (Hard disk)

Number of free PFNs are very few in the system. I can not break my promise made to the applications. Let me swap-out some memory. But which one to swap-out?

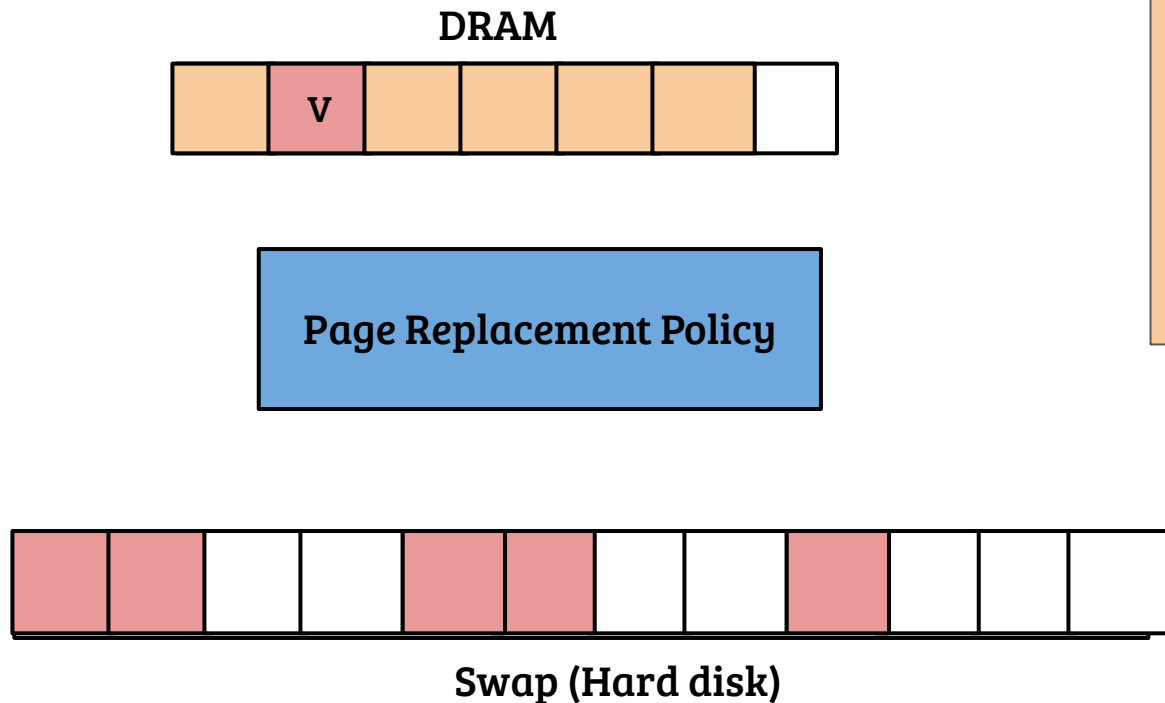


OS

AllocatePFN()



Swapping (swap-out)



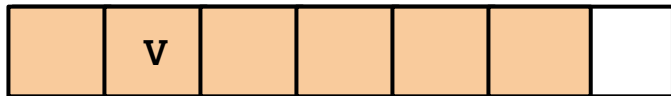
My page replacement policy will help me deciding the victims (V). Can I just swap-out? What if the swapped-out pages are accessed? I should be prepared for that too!



AllocatePFN()

Swapping (swap-out)

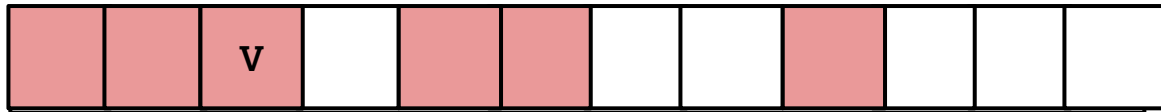
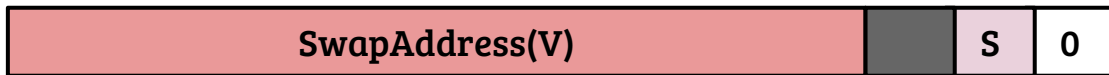
DRAM



PTE mapping the victim PFN (before swap)



PTE mapping the victim PFN (after swap)



Swap (Hard disk)

Update the present-bit to 0 in the PTE such that any access to the page through the virtual address will result in a page fault. Also maintain the swap address in the PTE.



OS

AllocatePFN()

Swapping (swap-out)

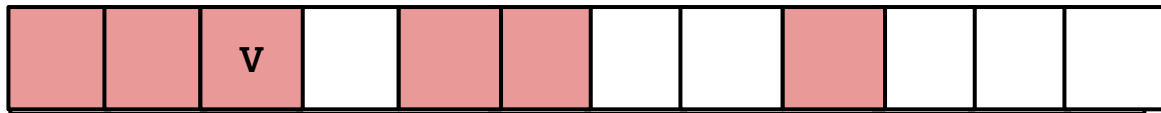
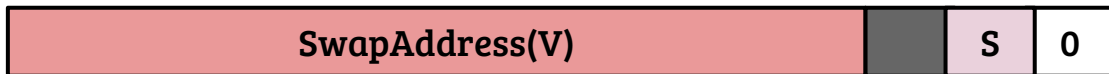
DRAM



PTE mapping the victim PFN (before swap)



PTE mapping the victim PFN (after swap)



Swap (Hard disk)

Content of the PFN is now in the swap device. In future, any translation using the PTE will result in a page fault. The page fault handler would copy it back from the swap device.



OS

AllocatePFN()

Page fault: Swap-in procedure (simplified)

```
HandlePageFault( u64 address, u64 error_code)
{
    If ( AddressExists(current → mm_state, address) &&
        AccessPermitted(current → mm_state, error_code) {
        PFN = allocate_pfn();
        If ( is_swapped_pte(address) )           // Check if the PTE is swapped out
            swapin(getPTE(address), PFN); // Copy the swap block to PFN
        install_pte(address, PFN);             // and update the PTE
        return;
    }
    RaiseSignal(SIGSEGV);
}
```

Page replacement

- Objective: minimize number of page faults (due to swapping)
- We can model this problem with three parameters
 - A given sequence of access to virtual pages
 - # of memory pages (Frames)
 - Page replacement policy
- Metrics to measure the effectiveness: # of page faults, page fault rate, average memory access time

Belady's optimal algorithm (MIN)

- Strategy: Replace the page that will be referenced after the longest time

- Example:

#of frames = 3

Reference sequence (in temporal order)

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

- #of page faults = ?

Belady's optimal algorithm (MIN)

- Strategy: Replace the page that will be referenced after the longest time
- Example:
 - #of frames = 3
 - Reference sequence (in temporal order)
1, 3, 1, 5, 4, 1, 2, 5, 2, 2, 5, 3
- #of page faults = 6 (3 cold-start misses result in page faults, no swapping)
- Belady's MIN is proven to be optimal, but impractical as it requires knowledge of future access

First In First Out (FIFO)

- Strategy: Replace the page that is in memory for the longest time

- Example:

#of frames = 3

Reference sequence (in temporal order)

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

- #of page faults = ?

First In First Out (FIFO)

- Strategy: Replace the page that is in memory for the longest time
- Example:
 - #of frames = 3
 - Reference sequence (in temporal order)
1, 3, 1, 5, 4, 1, 2, 5, 2, 2, 5, 3
- #of page faults = 8 (3 cold-start misses)
- FIFO suffers from an anomaly known as Belady's anomaly
 - With increased #of frames, #of page fault may also increase!

First In First Out (FIFO)

- Strategy: Replace the page that is in memory for the longest time
- Example:
 - #of frames = 3
 - Reference sequence (in temporal order)
1, 3, 1, 5, 4, 1, 2, 5, 2, 2, 5, 3
- #of page faults = 8 (3 cold-start misses)
- FIFO suffers from an anomaly known as Belady's anomaly
 - With increased #of frames, #of page fault may also increase!
 - Example access sequence: 0, 1, 2, 3, 0, 1, 4, 0, 1, 2, 3, 4
 - #of page faults with 3 frames < #of page faults with 4 frames

Least recently used (LRU)

- Strategy: Replace the page that is not referenced for the longest time

- Example:

#of frames = 3

Reference sequence (in temporal order)

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

- #of page faults = ?

Least recently used (LRU)

- Strategy: Replace the page that is not referenced for the longest time

- Example:

#of frames = 3

Reference sequence (in temporal order)

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

- #of page faults = 7 (3 cold-start)
- LRU shown to be useful for workloads with access locality
- Implementation of LRU using a single accessed-bit may not be practical, can be approximated using CLOCK (homework)
- Stack property or inclusion property of eviction algorithms