Virtual Memory (Part I)

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Motivation and Background

Motivation

- A program needs to be in memory to execute.
- But, entire program rarely used.
  - Error code, unusual routines, large data structures
- Entire program code not needed at same time.

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- Program no longer constrained by limits of physical memory.
- Each program takes less memory while running: more programs run at the same time.
  - Increased CPU utilization and throughput with no increase in response time or turnaround time.
- Less I/O needed to load or swap programs into memory: each user program runs faster.

Virtual Memory

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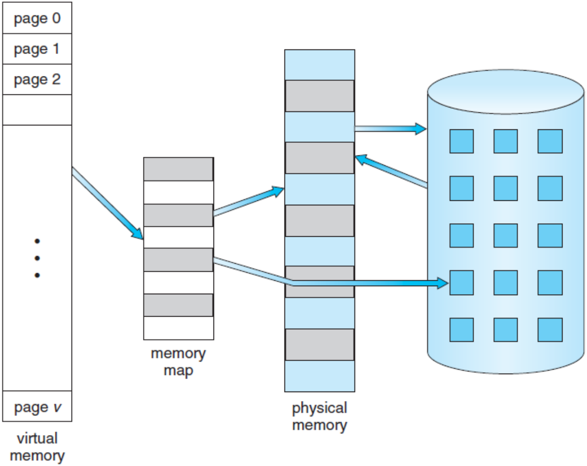
- More programs running concurrently.

Virtual Memory (2/2)



Virtual Address Space (1/3)

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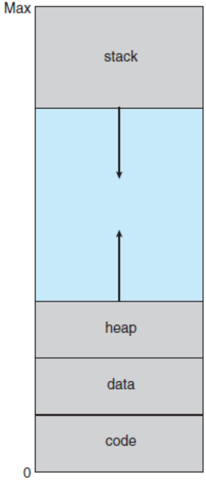
- Meanwhile, physical memory organized in page frames.
- MMU must map logical to physical.

Virtual Address Space (2/3)



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- The hole between the heap and the stack is part of the virtual address space, but will require actual physical pages only if the heap or stack grows.
- Virtual address spaces that include holes are known as sparse address spaces.

Heap vs. Stack

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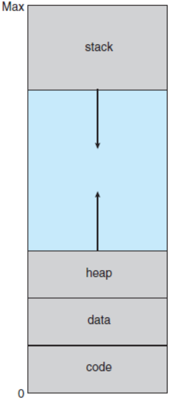
  - Stores local variables created by functions.
  - New variables are pushed onto the stack.
  - When a function exits, all of the its pushed varial are freed.



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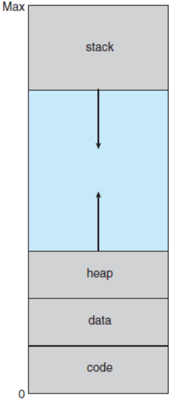
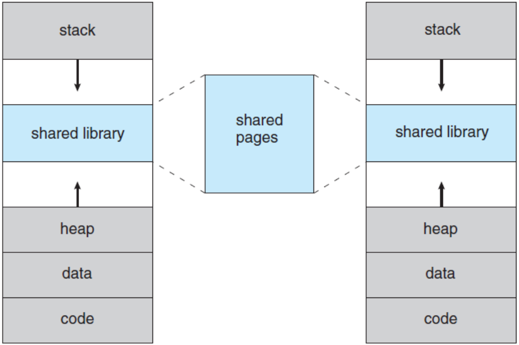
- Heap
  - Used for dynamic allocation.
  - Use `malloc()` or `calloc()` to allocate memory on the heap.
  - Use `free()` to deallocate the memory.



Virtual Memory Benefits

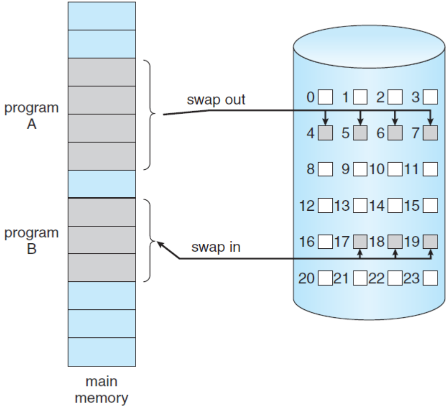
- Separating logical memory from physical memory.
- Page sharing.



Demand Paging

Demand Paging (1/2)

- Could bring entire process into memory at load time, or bring a page into memory only when it is needed.



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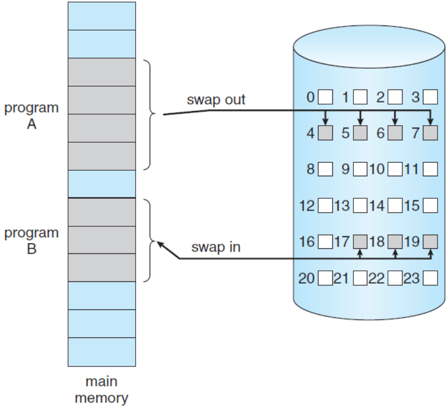
- Could bring entire process into memory at load time, or bring a page into memory only when it is needed.
- A demand-paging system is similar to a paging system with swapping.



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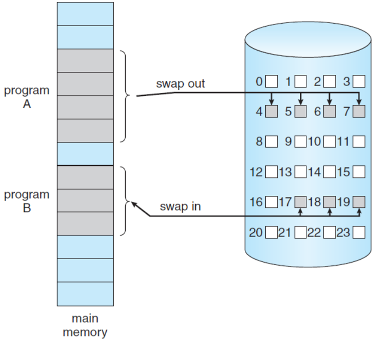
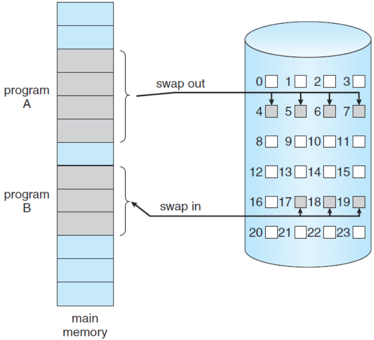
- Rather than swapping the entire process into memory, we use a lazy swapper.
- A lazy swapper never swaps a page into memory unless that page will be needed.



Demand Paging (2/2)

- Rather than swapping the entire process into memory, we use a lazy swapper.
- A lazy swapper never swaps a page into memory unless that page will be needed.
- A swapper that deals with pages is a pager.



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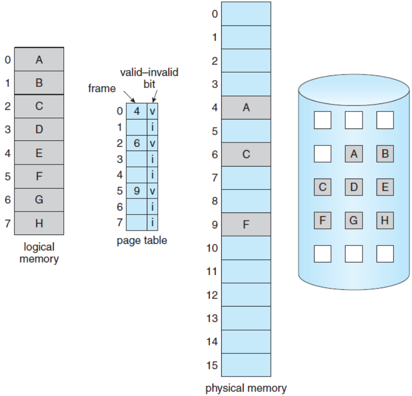
- The pager brings only the needed pages into memory.
- Uses valid-invalid bit to distinguish between the pages that are in memory and the pages that are on the disk?
  v: memory resident
  i: not in memory

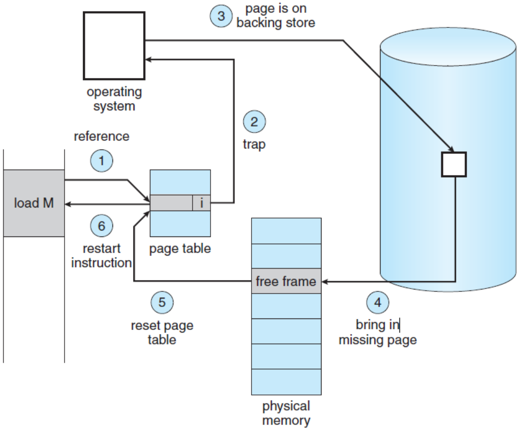


Page Fault

- Access to a page marked invalid causes a page fault.
- Causing a trap to the OS: brings the desired page into memory.

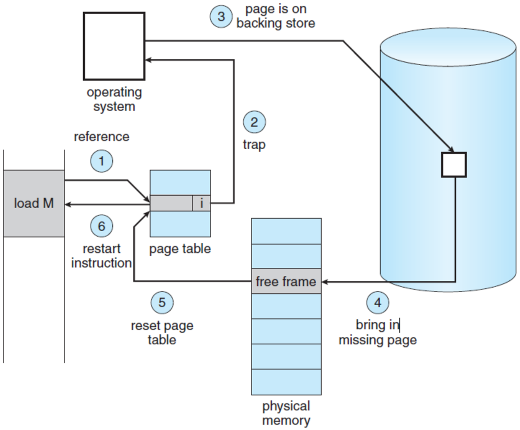
Handling Page Fault (1/6)

- Check an internal table for the process to determine whether the reference was a valid or an invalid memory access.



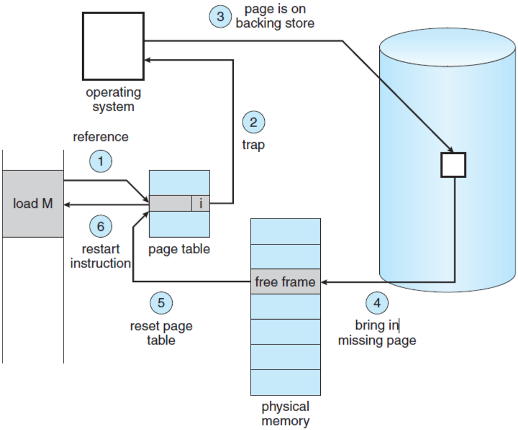
Handling Page Fault (2/6)

- If the reference was invalid, we terminate the process.
- If it was valid but we have not yet brought in that page, we now page it in.



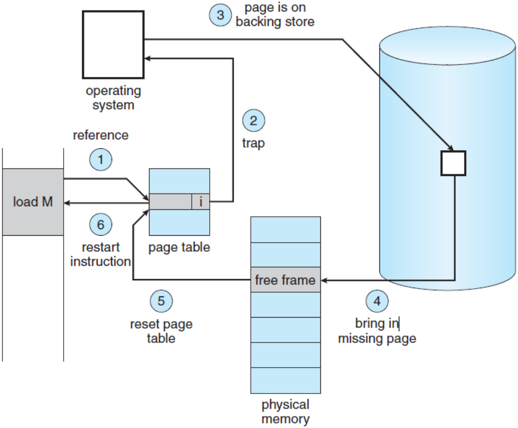
Handling Page Fault (3/6)

- We find a free frame.



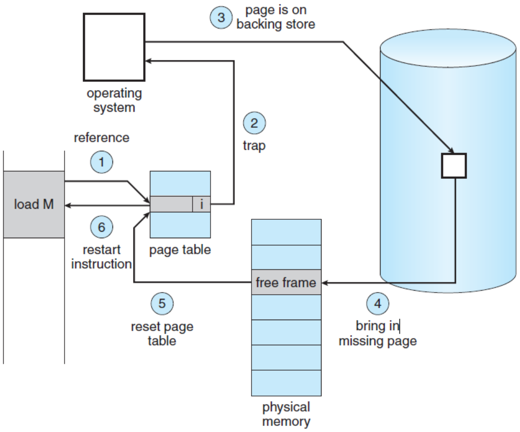
Handling Page Fault (4/6)

- We schedule a disk operation to read the desired page into the newly allocated frame.



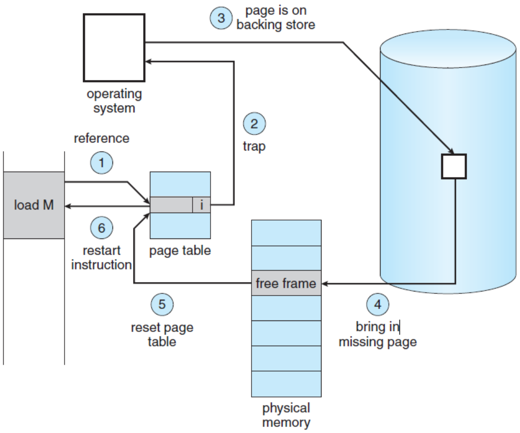
Handling Page Fault (5/6)

- When the disk read is complete, we modify the internal table kept with the process and the page table to indicate that the page is now in memory.



Handling Page Fault (6/6)

- We restart the instruction that was interrupted by the trap.



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- Pure demand paging

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- Locality of reference results in reasonable performance from demand paging.

Demand Paging Hardware

- The hardware to support demand paging is the same as the hardware for paging and swapping:
  - Page table with valid-invalid bit
  - Secondary memory with swap space

- The ability to restart any instruction after a page fault.

Stages in Demand Paging (1/3)

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- 2. Save the user registers and process state.
- 3. Determine that the interrupt was a page fault.
- 4. Check that the page reference was legal and determine the location of the page on the disk.

Stages in Demand Paging (2/3)

- 5. Issue a read from the disk to a free frame:
  - Wait in a queue for this device until the read request is serviced.
  - Wait for the device seek and/or latency time.
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- 7. Receive an interrupt from the disk I/O subsystem (I/O completed).

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- 12. Restore the user registers, process state, and new page table, and then resume the interrupted instruction.

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- Effective Access Time (EAT)
- $EAT = (1 - p) \times memory\_access + p \times page\_fault\_time$

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- If want performance degradation < 10 percent:
  - $220 > 200 + p \times 7,999,800$
  - $20 > p \times 7,999,800$
  - $p < .0000025$: less than one page fault in every 400,000 memory accesses

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- Copy entire process image to swap space at process load time.
  - Then page in and out of swap space.
- Demand page in from program binary on disk, but discard rather than paging out when freeing frame.
  - Pages not associated with a file, i.e., heap and stack (anonymous memory) till need to write to swap space.

Copy-on-Write

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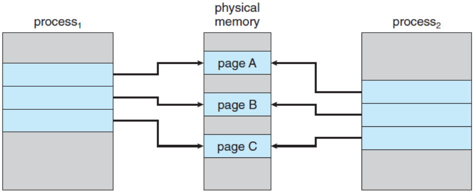
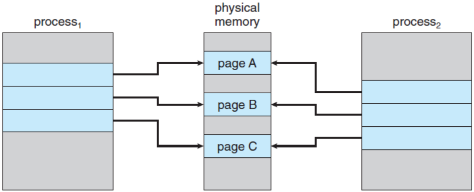
- Copy-on-Write allows both parent and child processes to initially share the same pages in memory.
- If either process modifies a shared page, only then is the page copied.

Copy-on-Write Example



Before modification

Copy-on-Write Example



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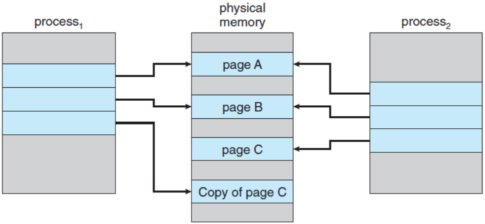

After modification

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  - Pool should always have free frames for fast demand page execution.
  - Zero-fill-on-demand pages have been zeroed-out before being allocated, thus erasing the previous contents.
- `vfork()` variation on `fork()` does not use Copy-on-Write: with `vfork()`, the parent process is suspended, and the child process uses the address space of the parent.

Page Replacement

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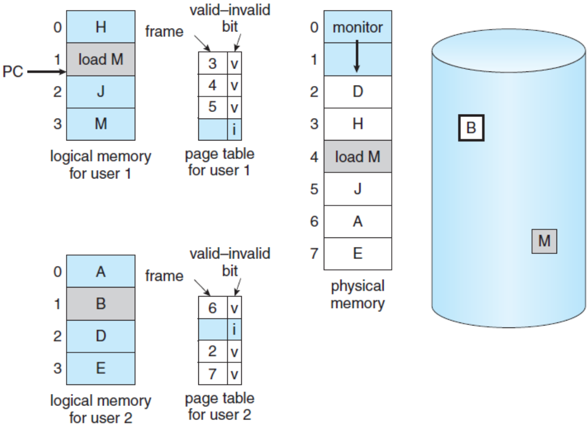
- Increasing the degree of multiprogramming: over-allocating memory

Over-Allocation of Memory

- While a user process is executing, a page fault occurs.
- The OS determines where the desired page is residing on the disk.
- But, it finds that there are no free frames on the free-frame list.
- Need for page replacement

Need For Page Replacement



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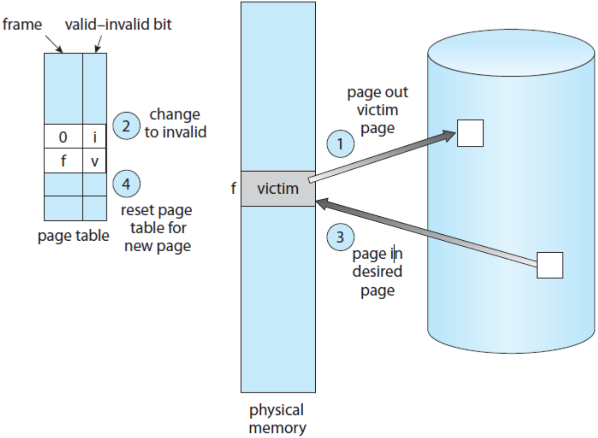
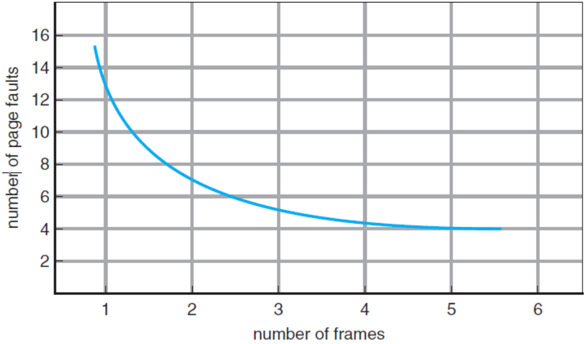
4. Continue the process by restarting the instruction that caused the trap.

Page Replacement



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

Page Faults vs. The Number of Frames



Evaluate Page Replacement Algorithms

- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string.
- String is just page numbers, not full addresses.
- For example, a reference string could be
  7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 0, 3, 2, 1, 2, 0, 1, 7, 0, 1

Page Replacement Algorithms

- First-In-First-Out (FIFO) page replacement
- Optimal page replacement
- Least Recently Used (LRU) page replacement
- LRU-Approximation page replacement
- Counting-Based page replacement

FIFO Page Replacement

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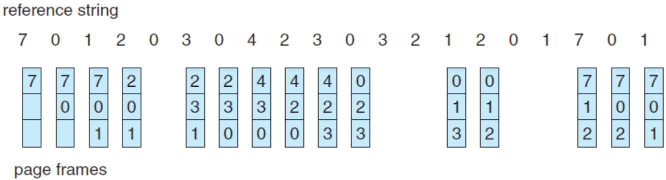
- Reference string: 7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1
- 3 frames (3 pages can be in memory at a time per process)



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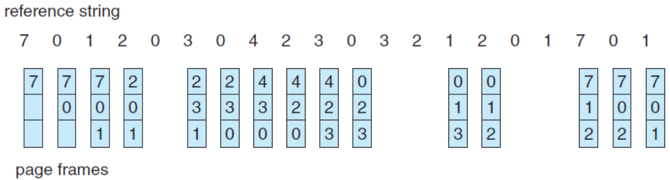
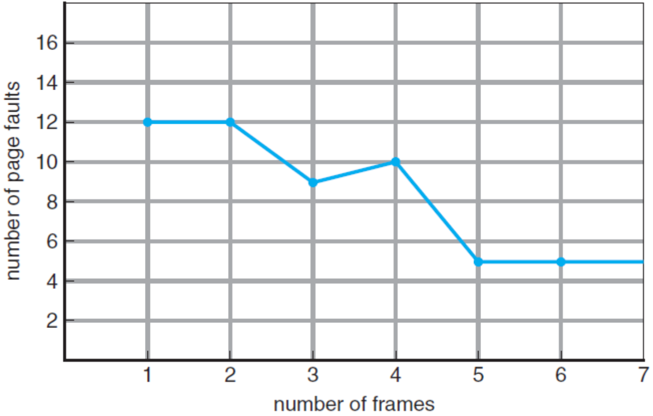


- 15 page faults

FIFO Belady's Anomaly

- Adding more frames can cause more page faults: Belady's Anomaly



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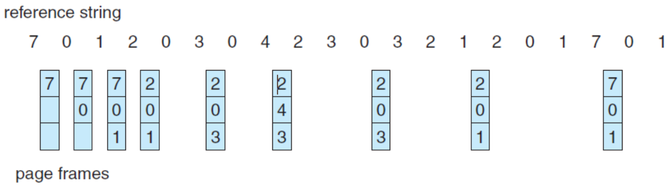
- How do you know this? Can't read the future



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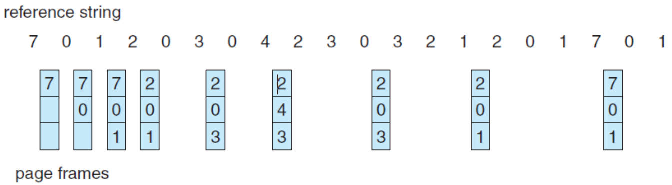

- Used for measuring how well your algorithm performs.

LRU Page Replacement

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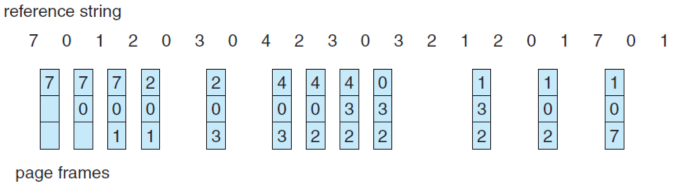

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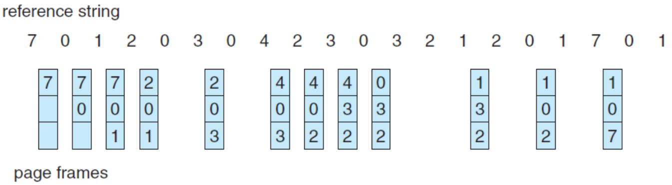

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LRU Page Replacement

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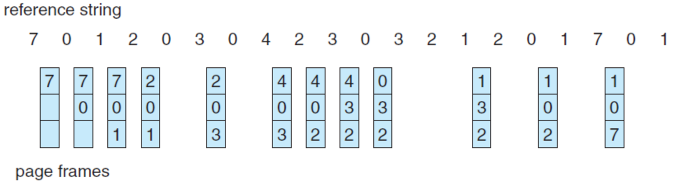

- 12 faults: better than FIFO but worse than OPT
- Generally good algorithm and frequently used

LRU Implementation (1/2)

- 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 find smallest value.
- Search through table needed.

LRU Implementation (2/2)

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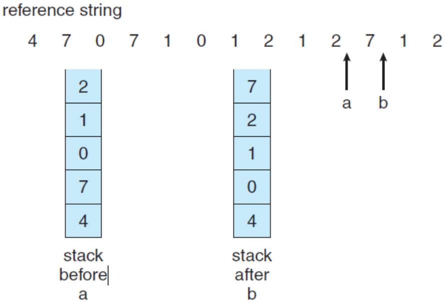
- No search for replacement.
- LRU and OPT are cases of stack algorithms with no Belady's Anomaly.

Stack Implementation

- Use of a stack to record most recent page references.



LRU-Approximation Page Replacement

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- LRU needs special hardware and still slow
- Improvements: LRU-Approximation
  - Reference bit
  - Second-chance algorithm
  - Enhanced second-chance algorithm

Reference Bit

- With each page associate a bit, initially $= 0$

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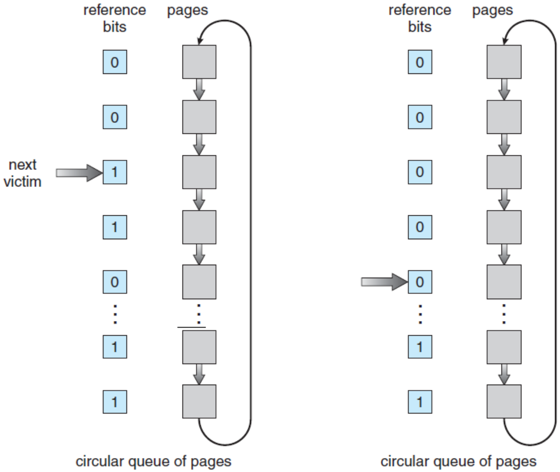
- Replace any with reference bit $= 0$ (if one exists)
- We do not know the order

Second-Chance Algorithm (1/2)

- It is also called clock algorithm.
- Generally FIFO, plus hardware-provided reference bit
- If page to be replaced has
  - Reference bit $= 0 \rightarrow$ replace it
  - Reference bit $= 1$ then, set reference bit 0, leave page in memory, and replace next page, subject to same rules.

Second-Chance Algorithm (2/2)



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  1. (0, 0) neither recently used not modified: best page to replace
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  3. (1, 0) recently used but clean: probably will be used again soon
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- Might need to search circular queue several times.

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- Lease Frequently Used (LFU) algorithm: replaces page with smallest count.
- Most Frequently Used (MFU) algorithm: based on the argument that the page with the smallest count was probably just brought in and has yet to be used.

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- Virtual memory: much larger than physical memory
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- Page fault
- Page replacement algorithms:
  - FIFO, optimal, LRU, LRU-approximate, counting-based

Questions?

Acknowledgements

Some slides were derived from Avi Silberschatz slides.