CS 452 Operating Systems

Paging

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Page Replacement

- Basic Page Replacement
- FIFO Page Replacement
- Optimal Page Replacement
- LRU Page Replacement
- Page Buffering Algorithms

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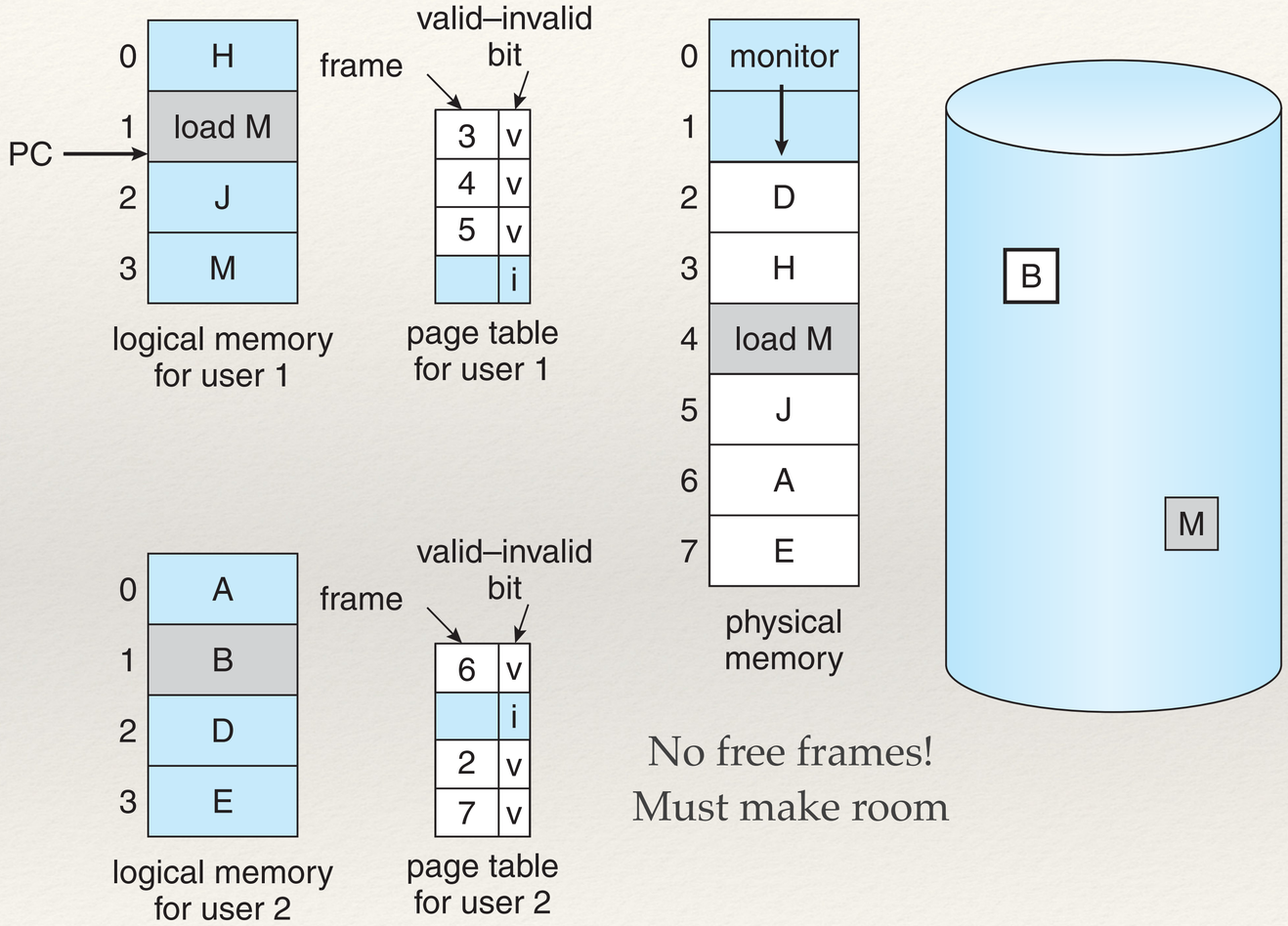
Page Replacement Motivation

- Only part of the program is loaded into memory
  - Saves I/O
  - Saves memory space
  - Can over-allocate available memory
- What to do when a program page faults and there are no available free frames?
  - Terminate another program to free up memory
  - Replace pages of other programs

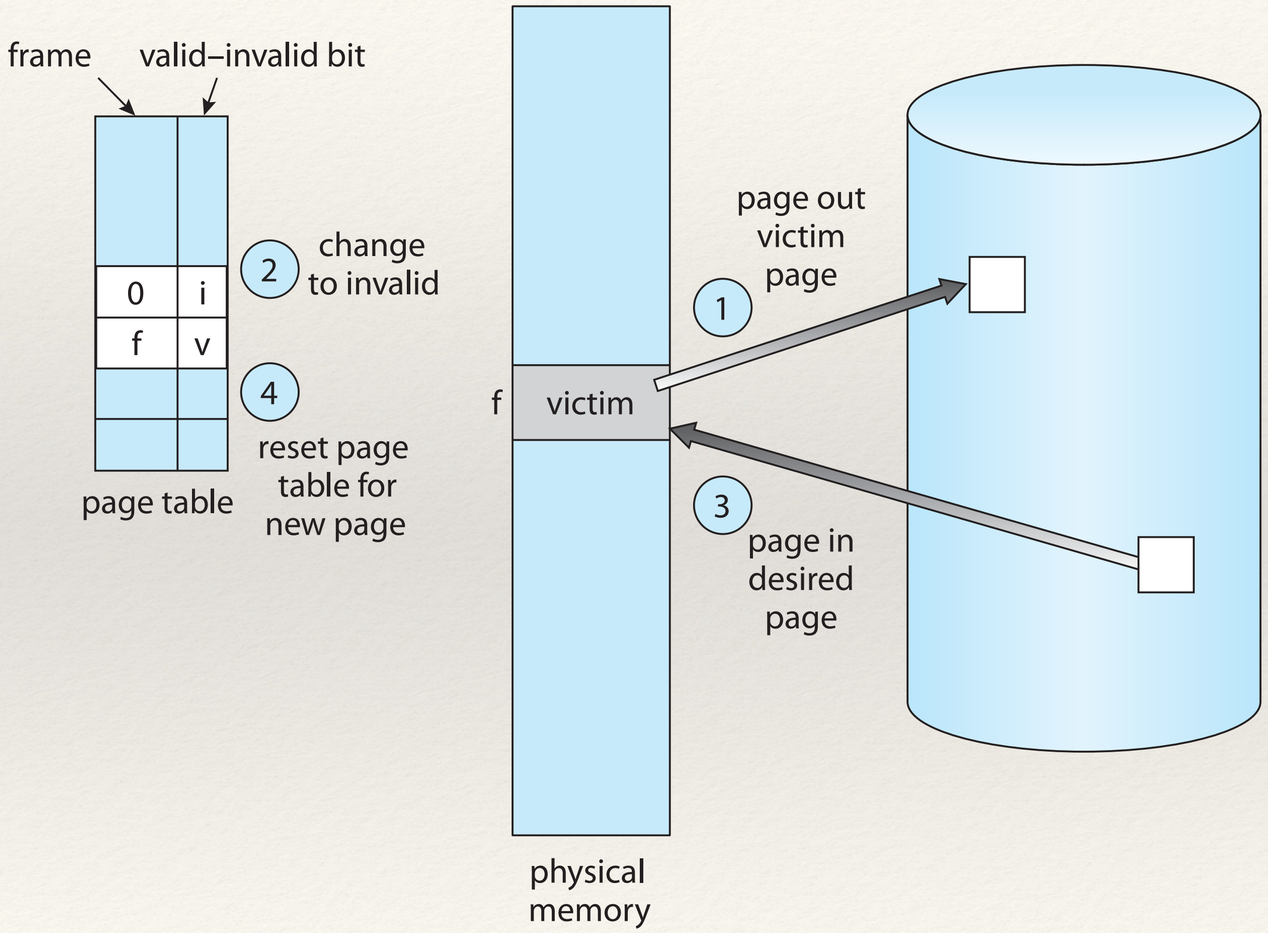
Basic Page Replacement

- If no frame is free, find one that isn't being used and replace it
- The frame being replaced is known as a **victim frame**
  - Write the victim frame to disk (Page out)
  - Load the desired page into memory (Page in)

Paging Overview



Page Replacement Algorithms



Paging Overhead

- Page out victim page
- Page in desired page

Paging Overhead

- If the victim page wasn't modified, does it need to be written back to the data store?
- Track if it was modified by using a 'modify or dirty bit'
  - If the bit isn't set, no need to write/save it to the data store

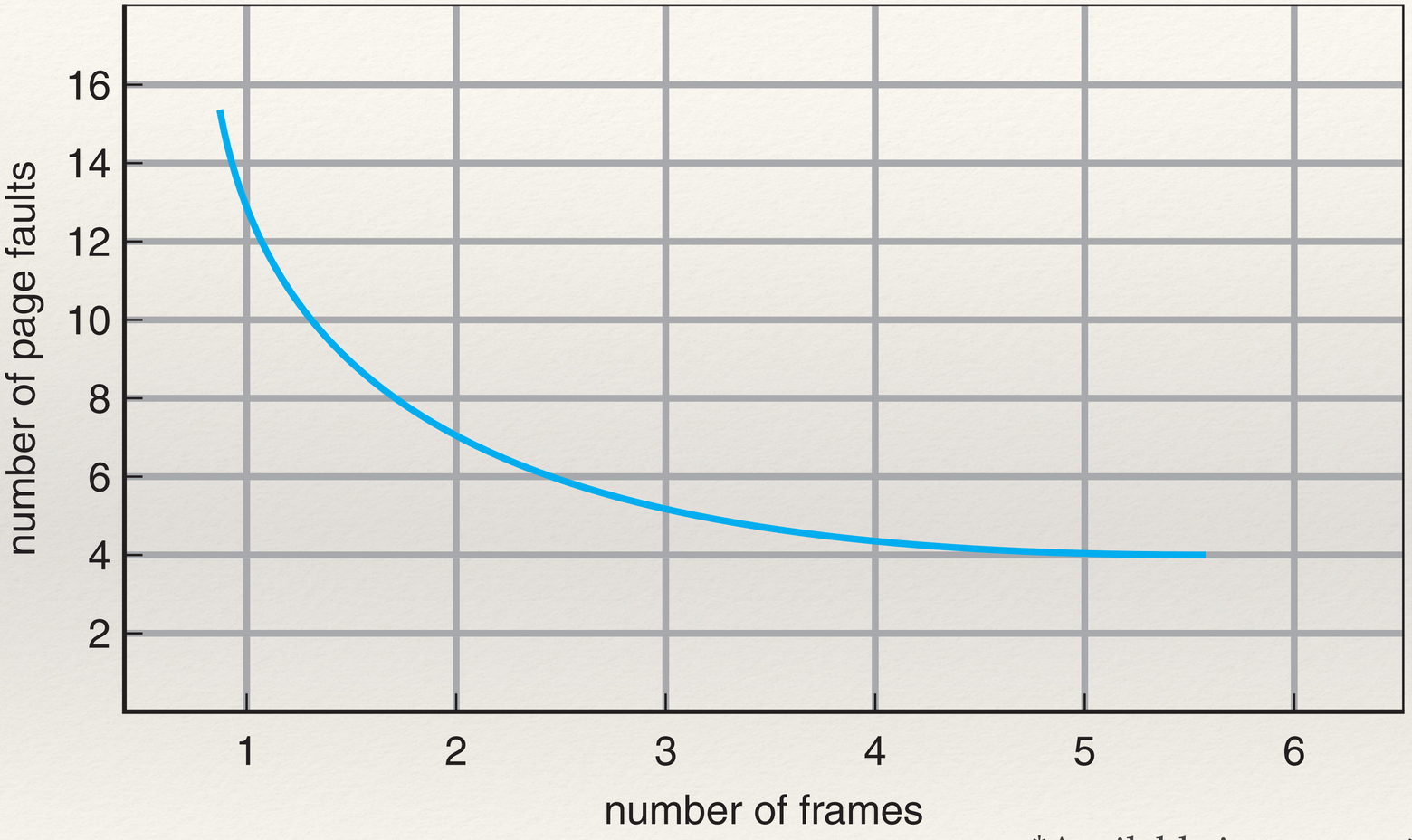
Demand Paging

- Requires
  - Frame allocation algorithm
    - How many frames does each process get in memory?
  - Page-replacement algorithm
    - Which frames/pages will be replaced.

Page Replacement Algorithms

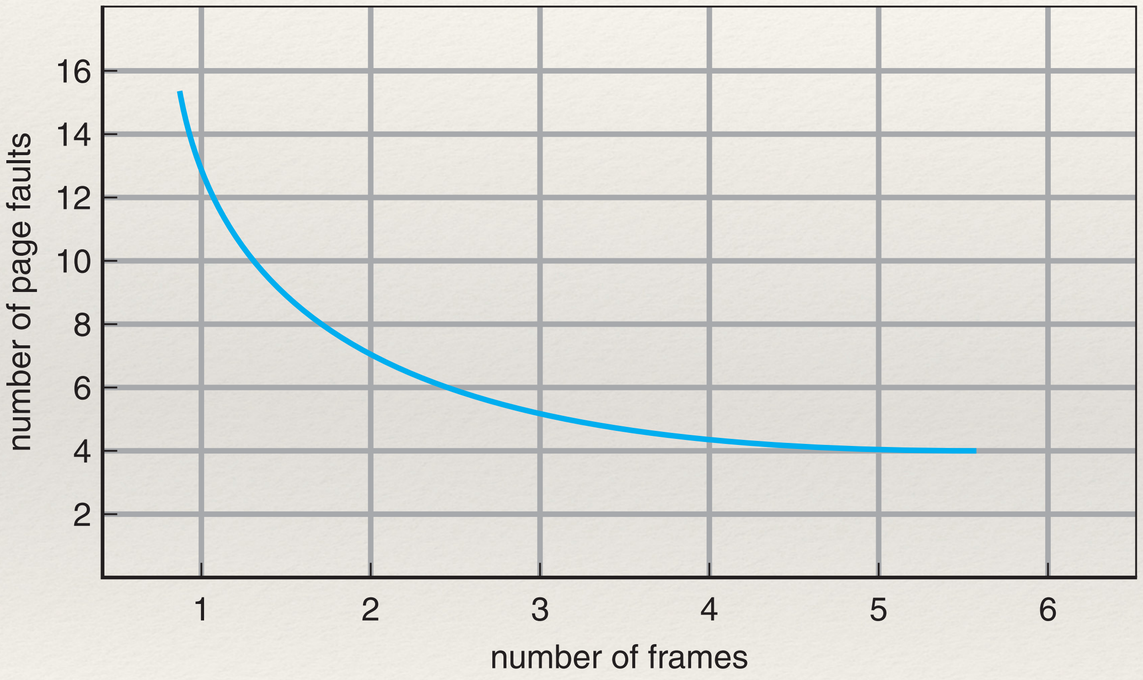
- What makes a good one?
  - Lowest page-fault rate
- Evaluate an algorithm by running it against a string of memory references
  - The string of memory references is called a **reference string**
  - Can be generated artificially

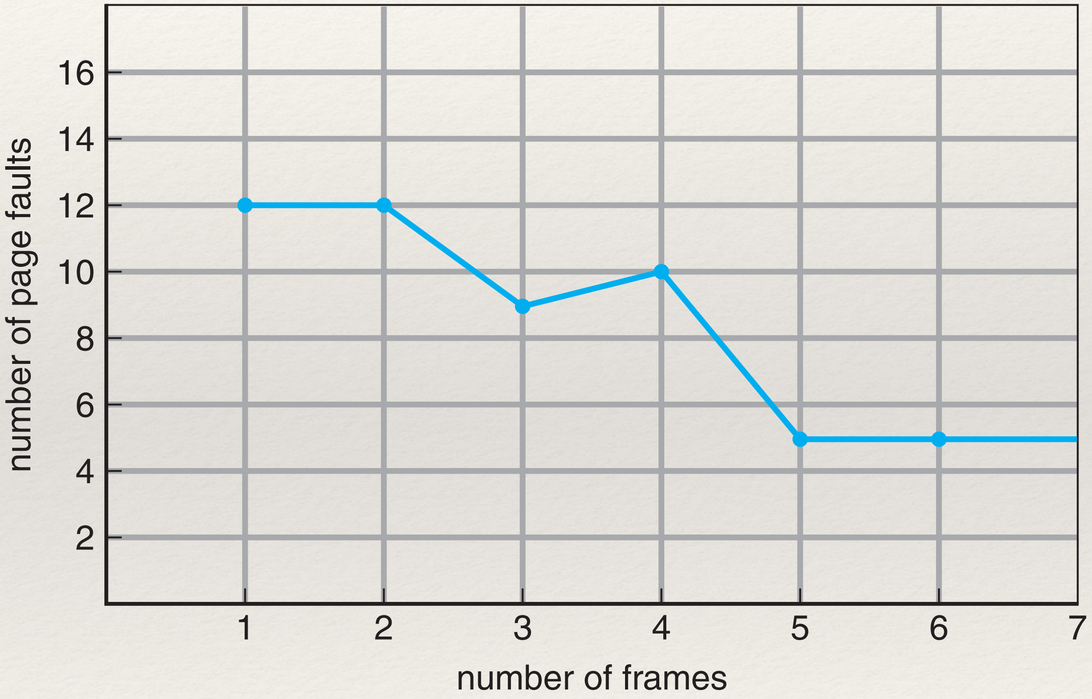
Page Replacement Algorithms



Available in memory

Belady's Anomaly





Paging Performance

- Belady's anomaly: for some page replacement algorithms, the page-fault rate may increase as the number of allocated frames increases.
  - Note: You would normally expect this to decrease

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FIFO Page Replacement

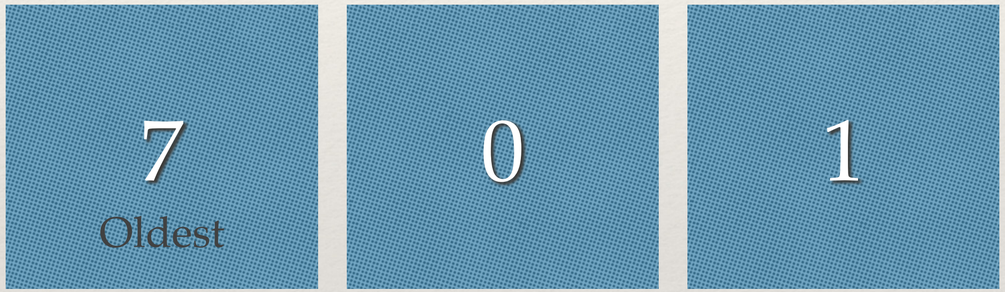
- Associate a time with each page, implement First-in, First-out algorithm for replacement
- Keep track of pages using a queue

FIFO Page Replacement

- Given the following reference string, let's illustrate the FIFO behavior
  - 7, 0, 1, 2, 0, 3, 0, 4, 2, 3
  - Three frames initially empty are filled with 7, 0, 1

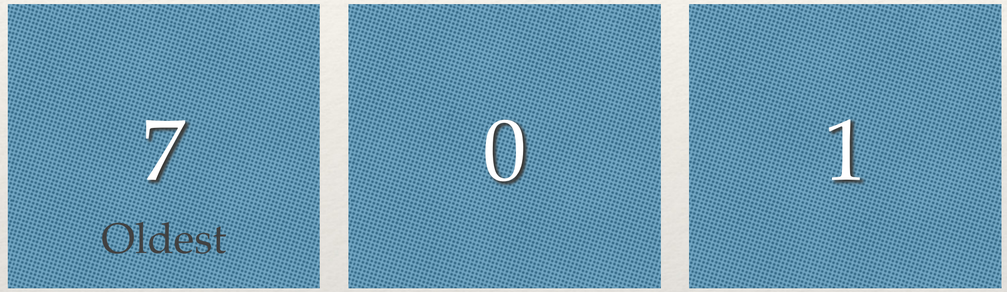
FIFO Page Replacement

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3



FIFO Page Replacement

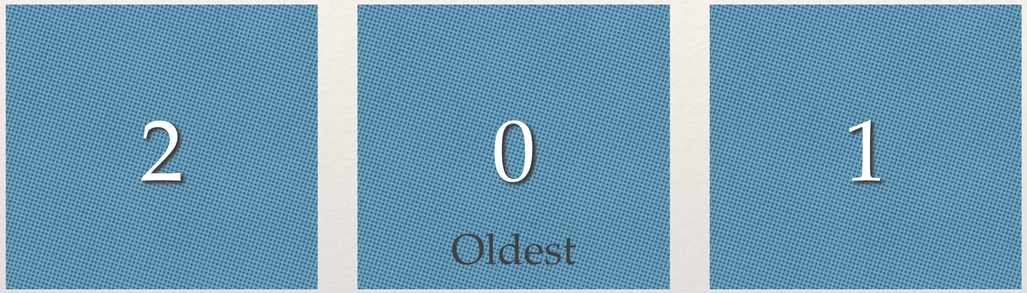
- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3



2 replaces the 7

FIFO Page Replacement

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3

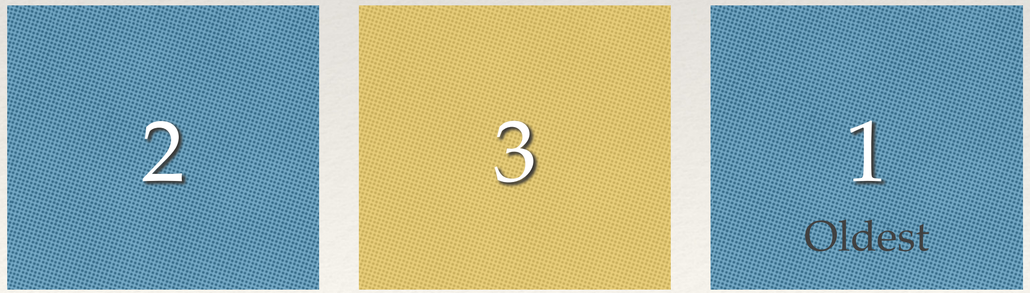


0 already in memory, no change

FIFO Page Replacement

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3

3 replaces 0



FIFO Page Replacement

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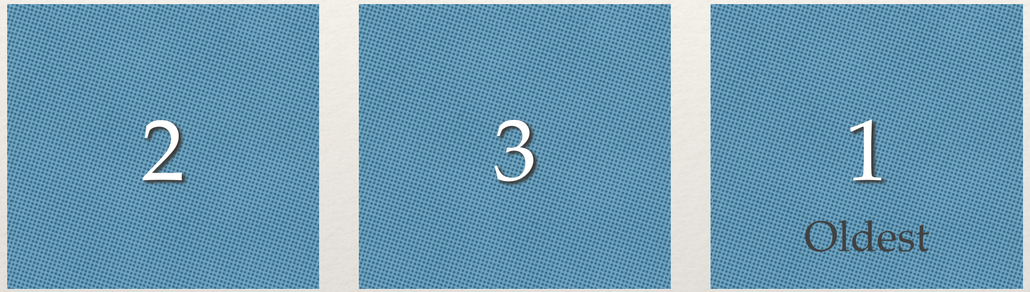
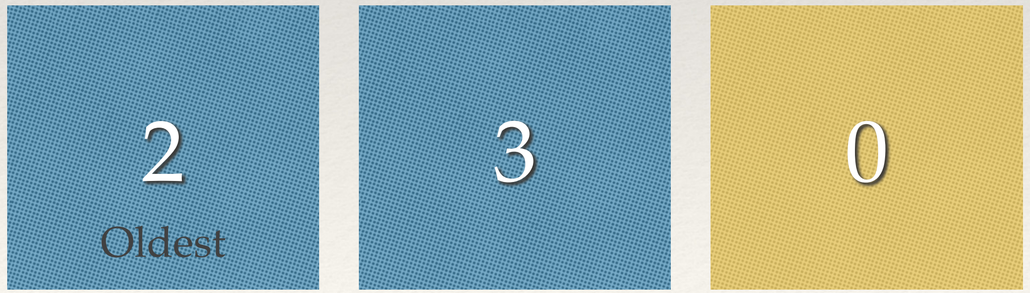
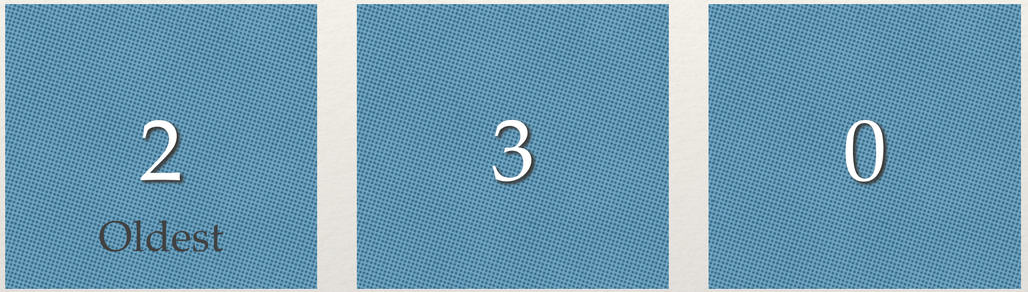


0 replaces 1



FIFO Page Replacement

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3

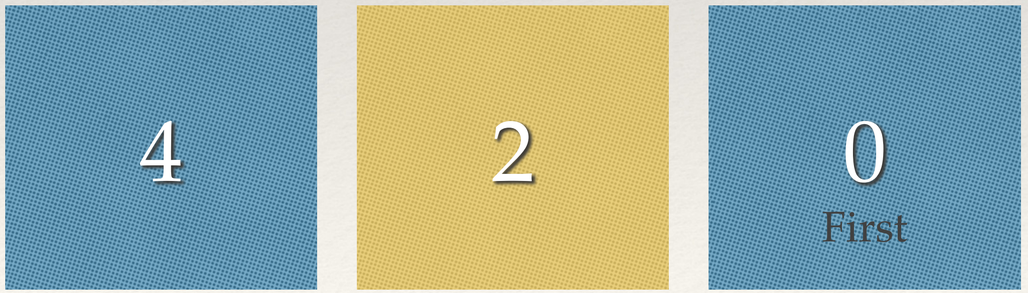


4 replaces 2

FIFO Page Replacement

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3

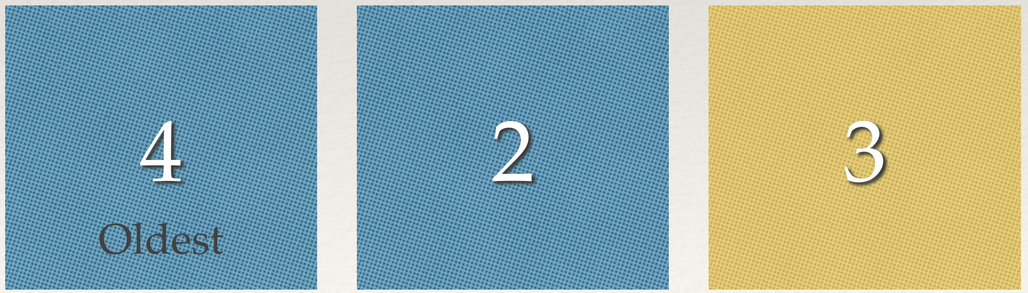
2 replaces 3



FIFO Page Replacement

- Reference String: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3

3 replaces 0



Reference Strings

- Different reference strings will return different results
- Certain strings may generate situations where a page that was just swapped out will need to be swapped back in again.

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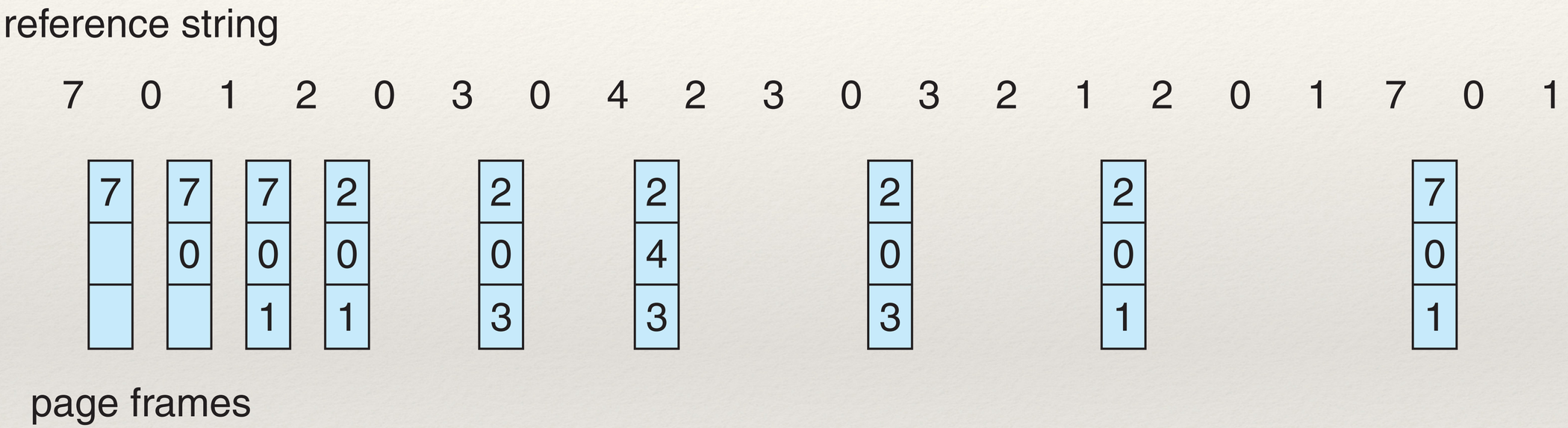
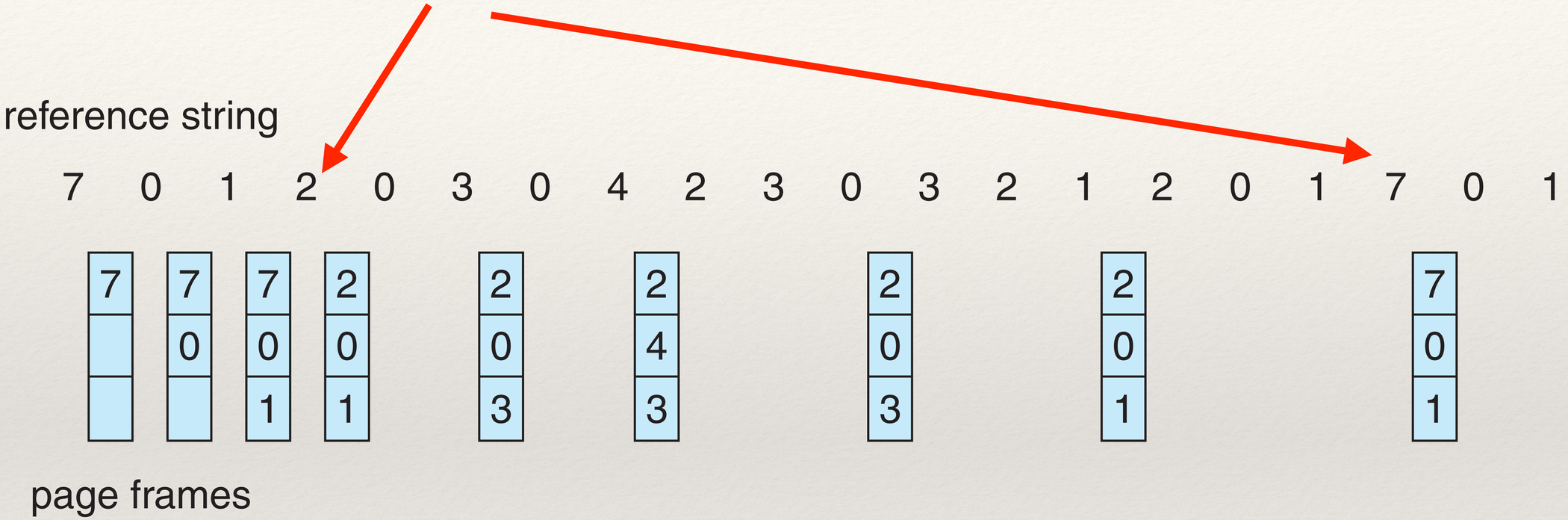
Optimal Page Replacement

- Guaranteed lowest possible page-fault rate
- Replace the page that will not be used for the longest period of time
- Difficult to actually implement as you need to know the future.
- Mainly used for comparison studies
- Similar situation to SJF CPU scheduling

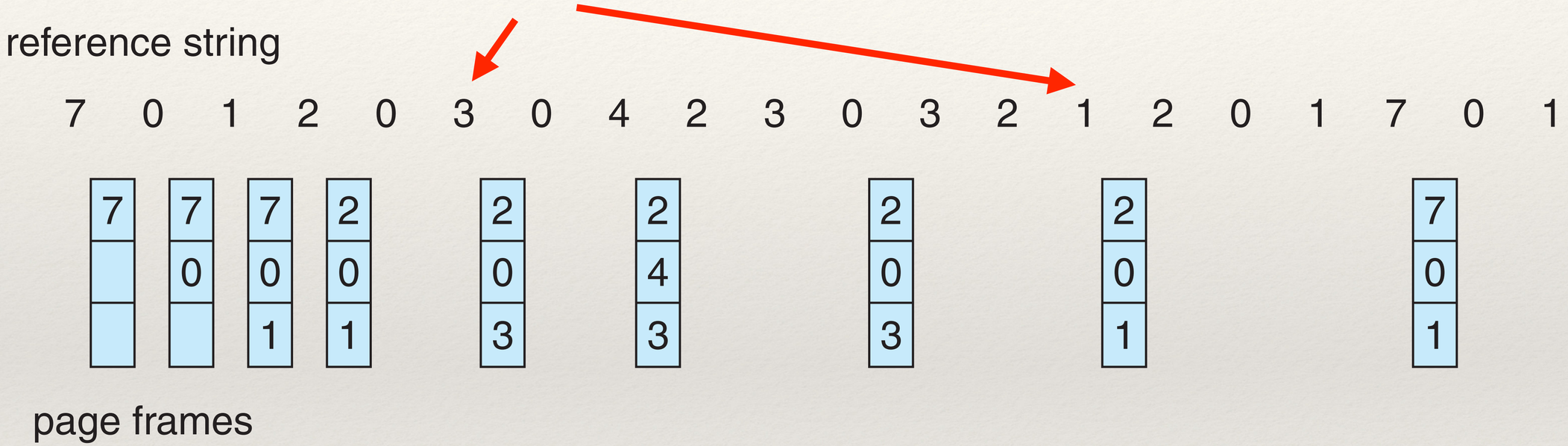
Optimal Page Replacement



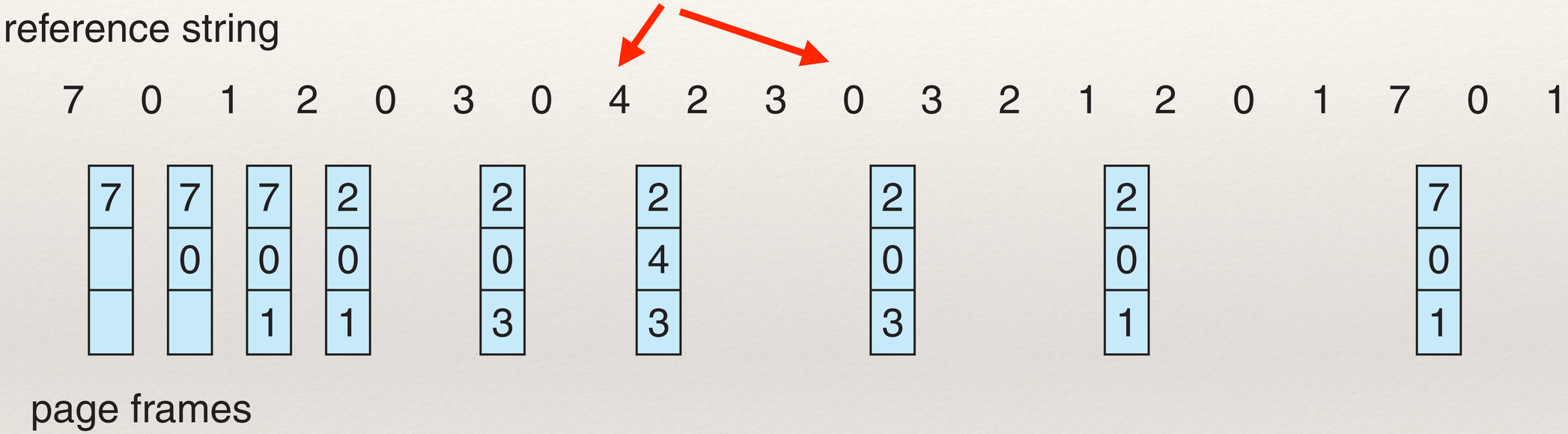
Optimal Page Replacement



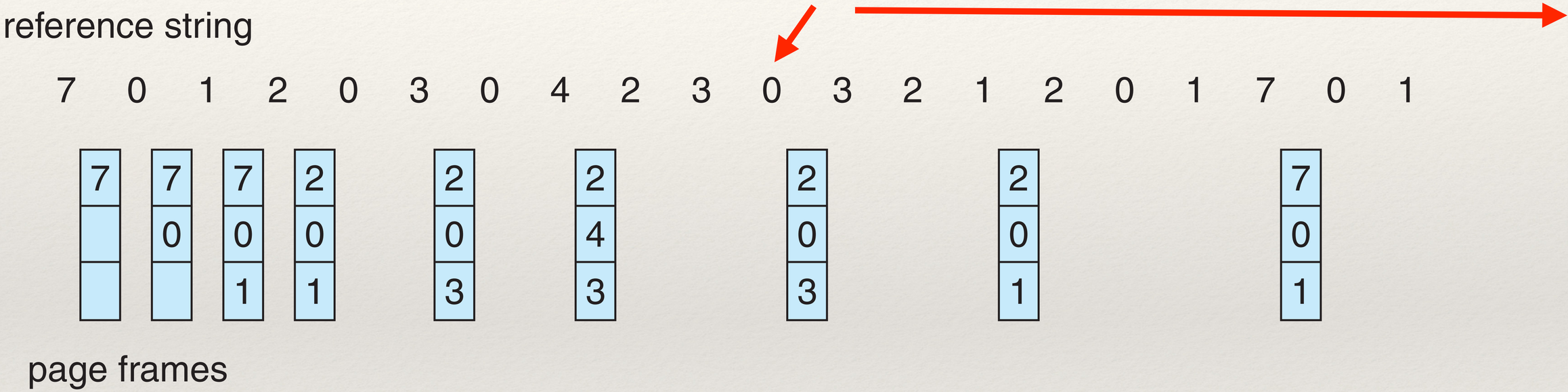
Optimal Page Replacement



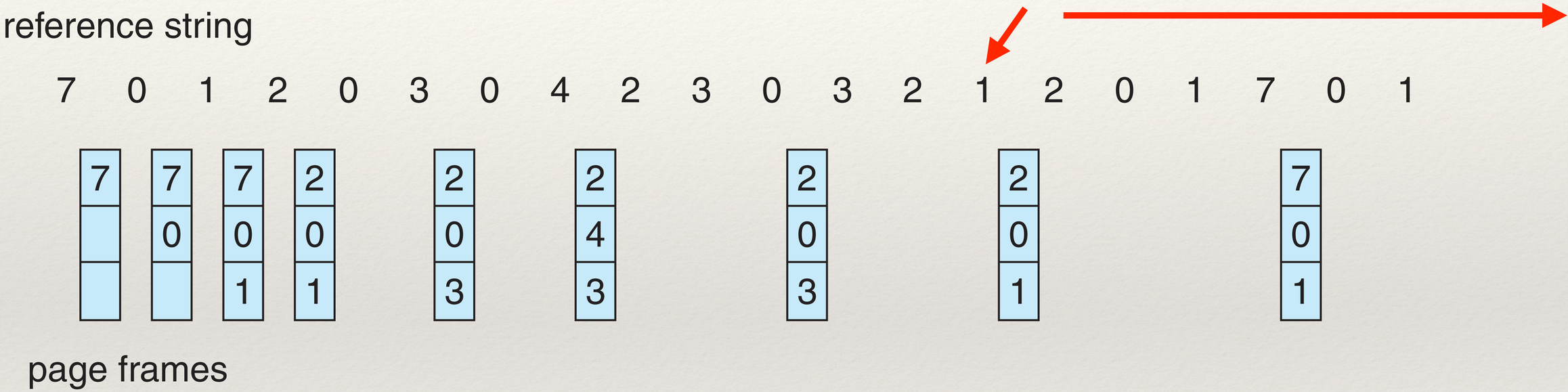
Optimal Page Replacement



Optimal Page Replacement



Optimal Page Replacement



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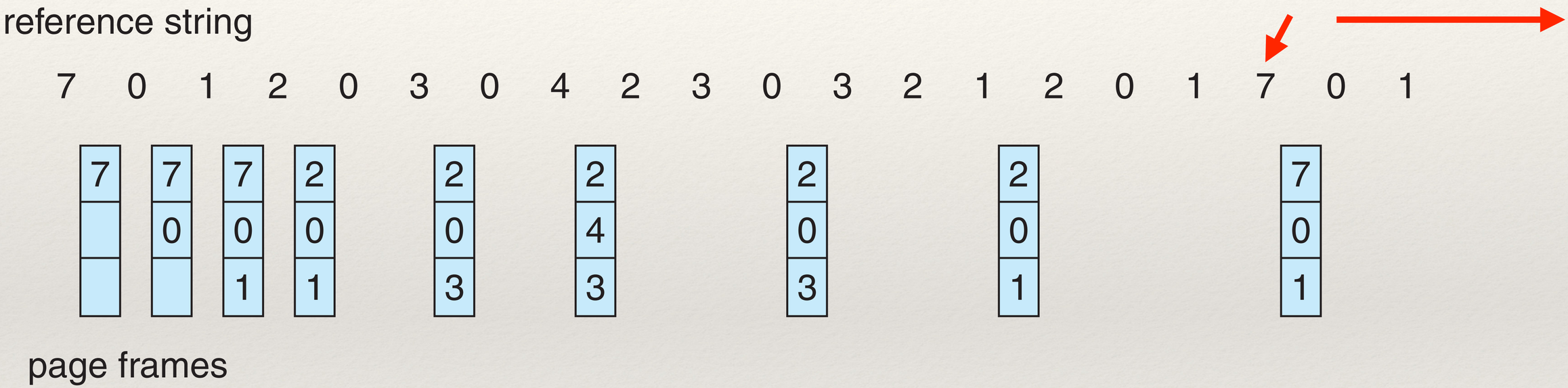

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- Page Buffering Algorithms

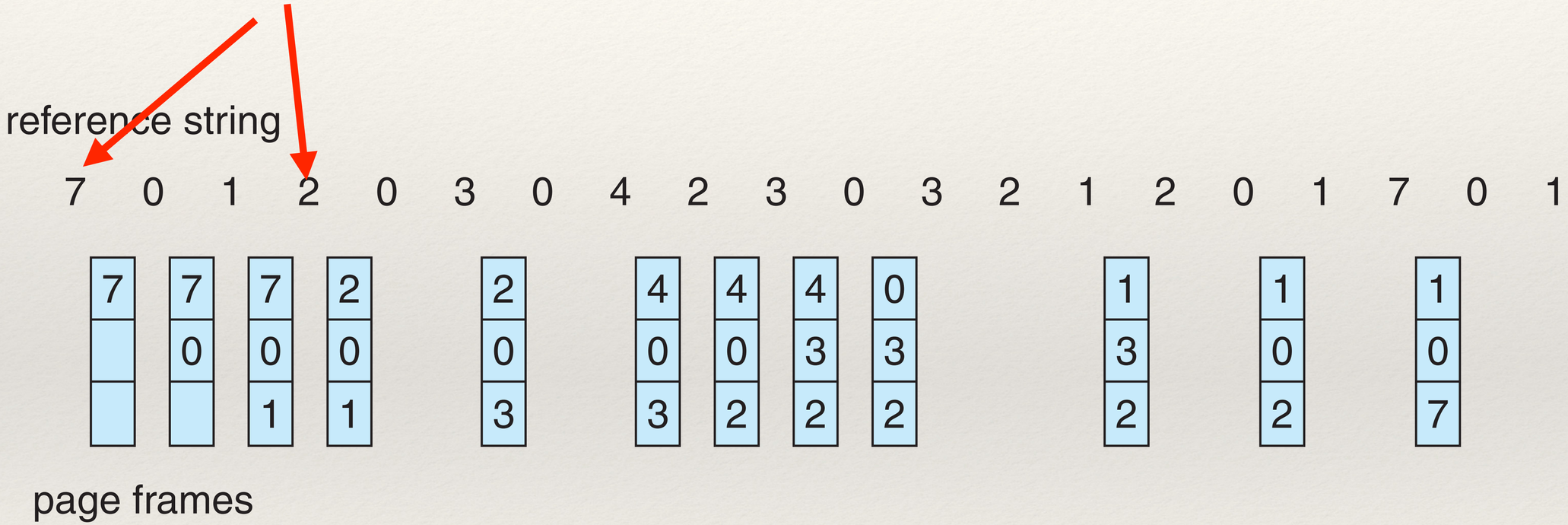
LRU Page Replacement

- Replace the page that has not been used for the longest
  - Looking backwards instead of forward (Optimum)
  - Don’t need to foresee the future, just the past

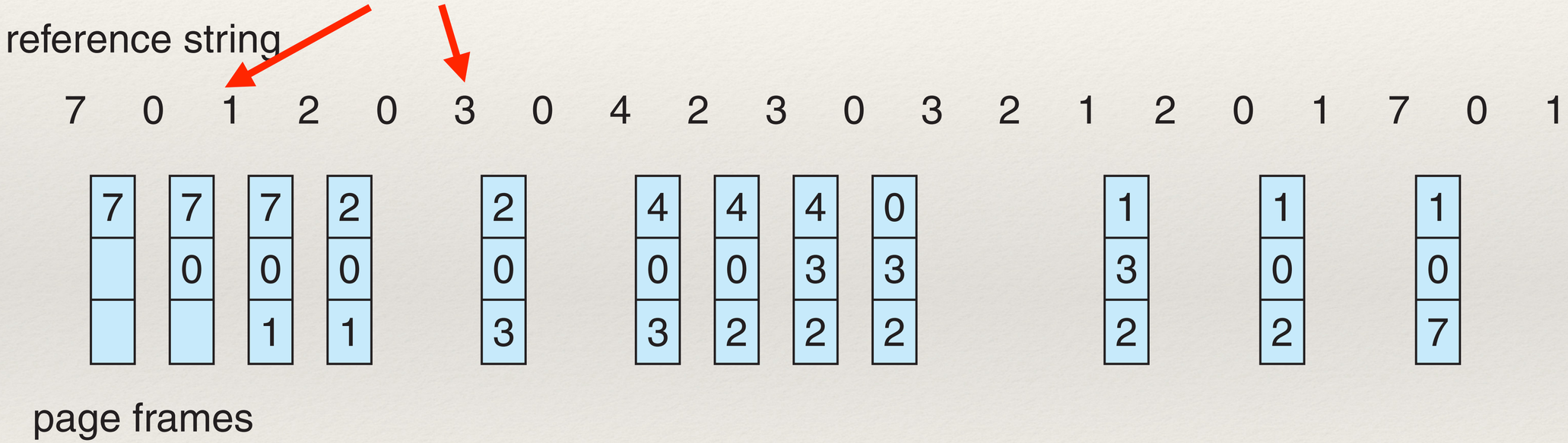
LRU Page Replacement

- Need to track when the page was last used
- Swap out the least recently used page

LRU Page Replacement



LRU Page Replacement



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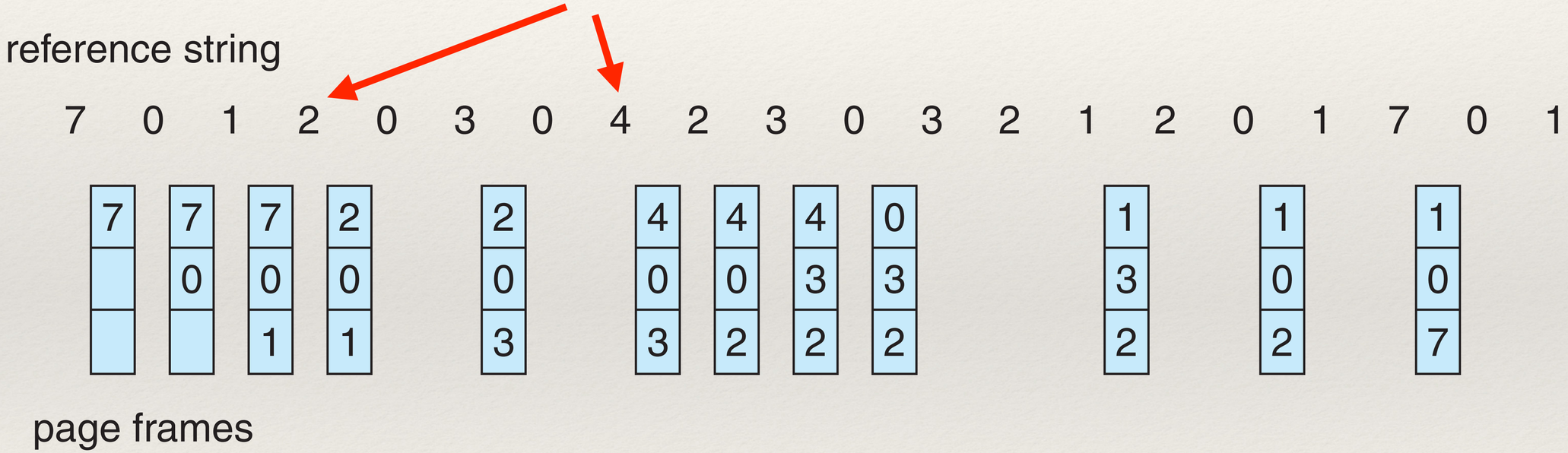

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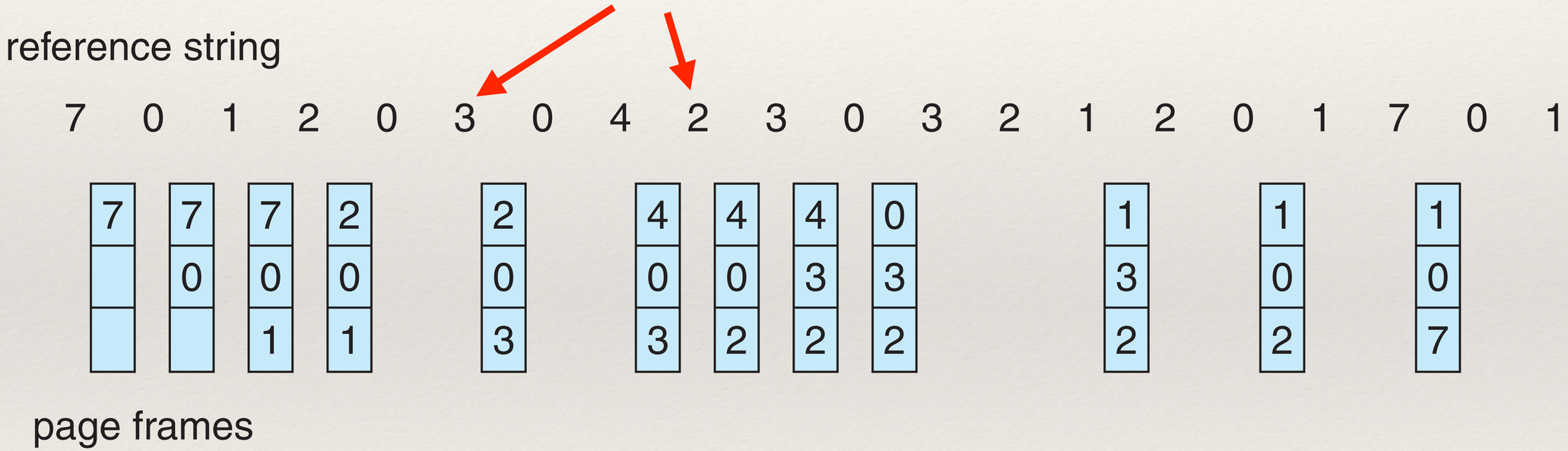

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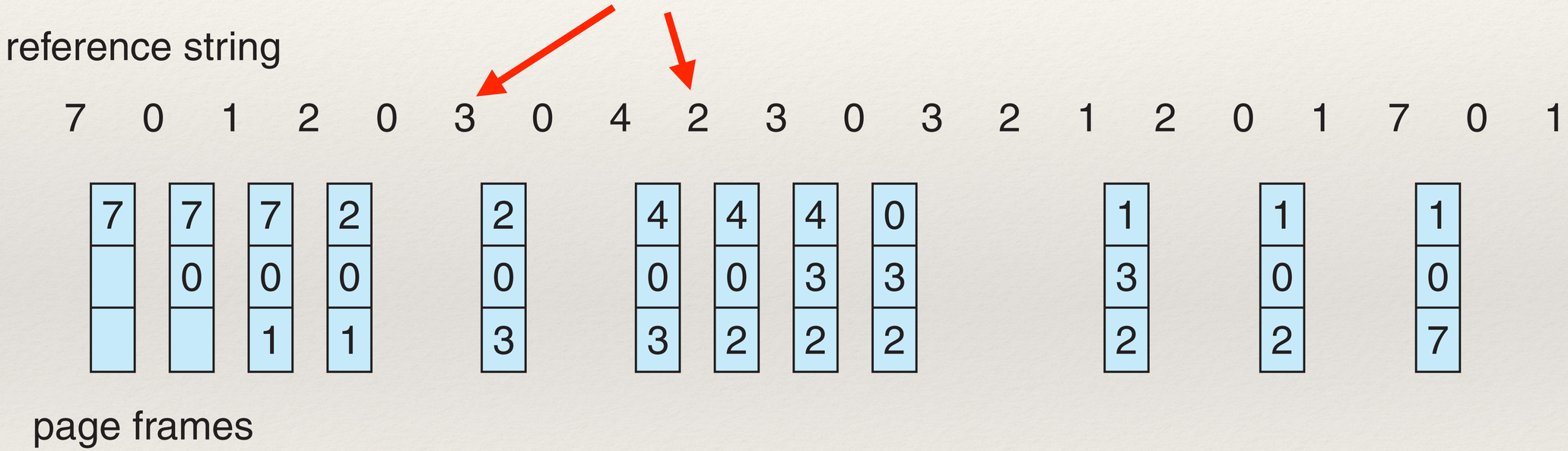

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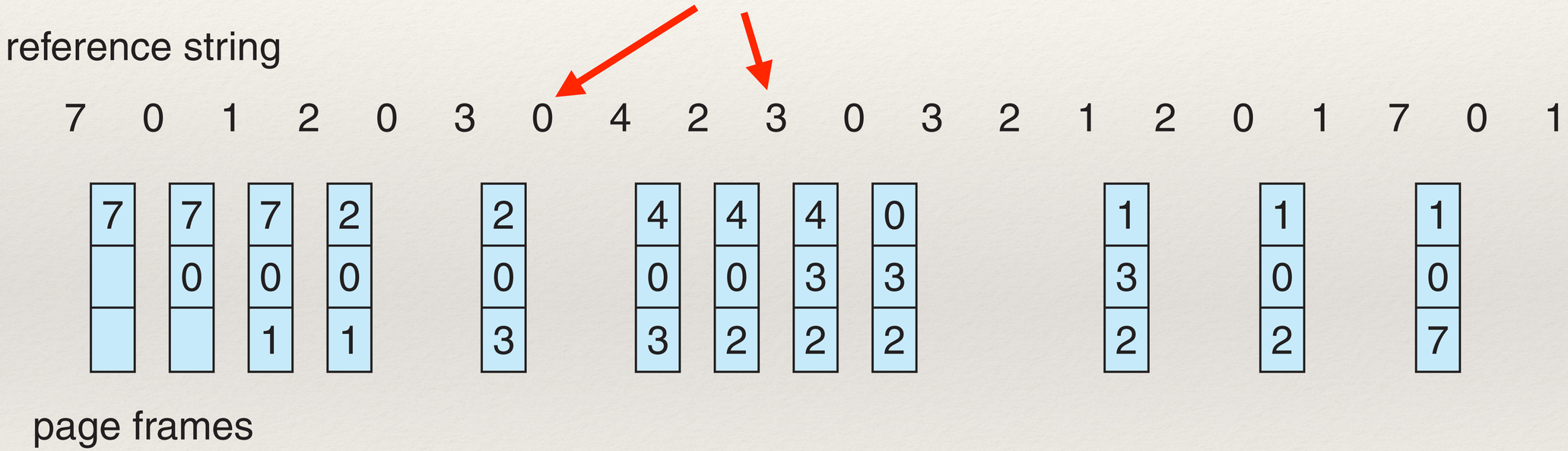

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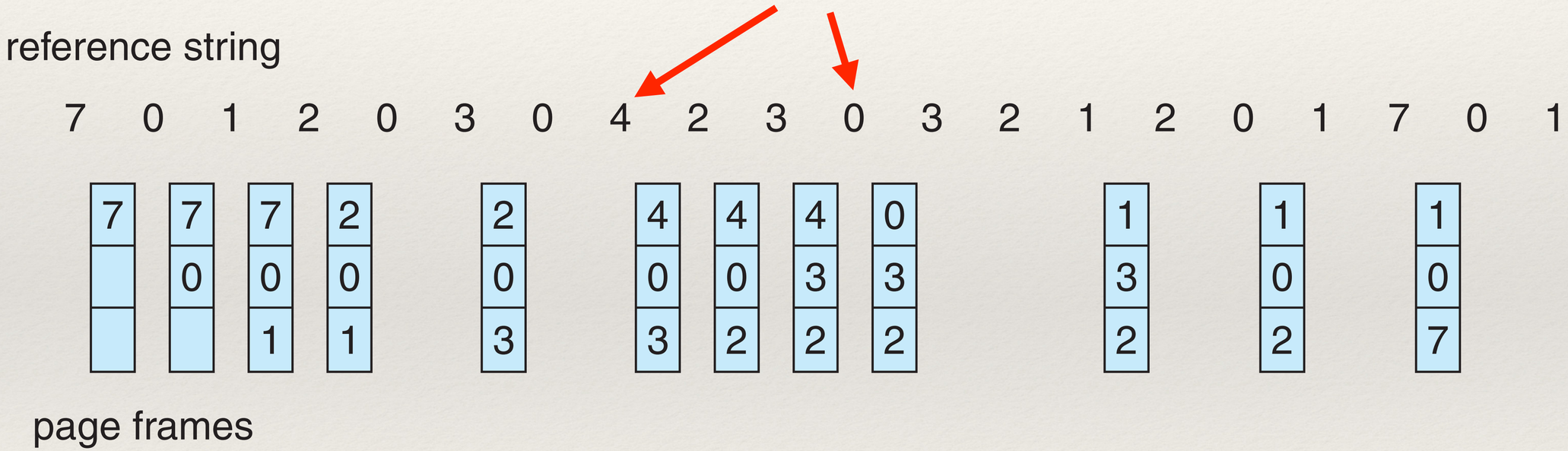

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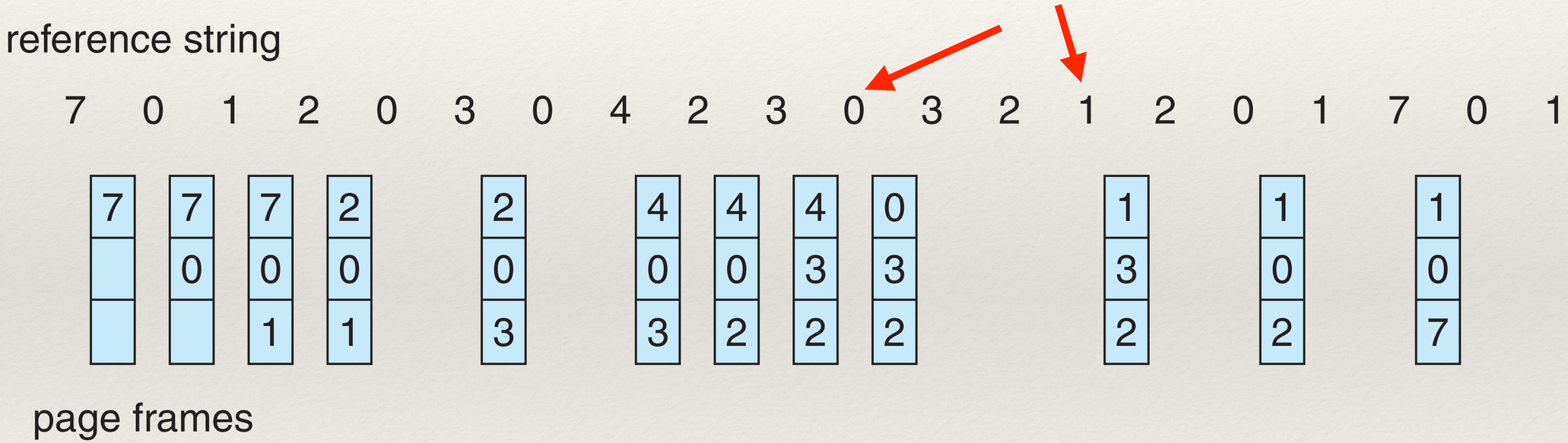

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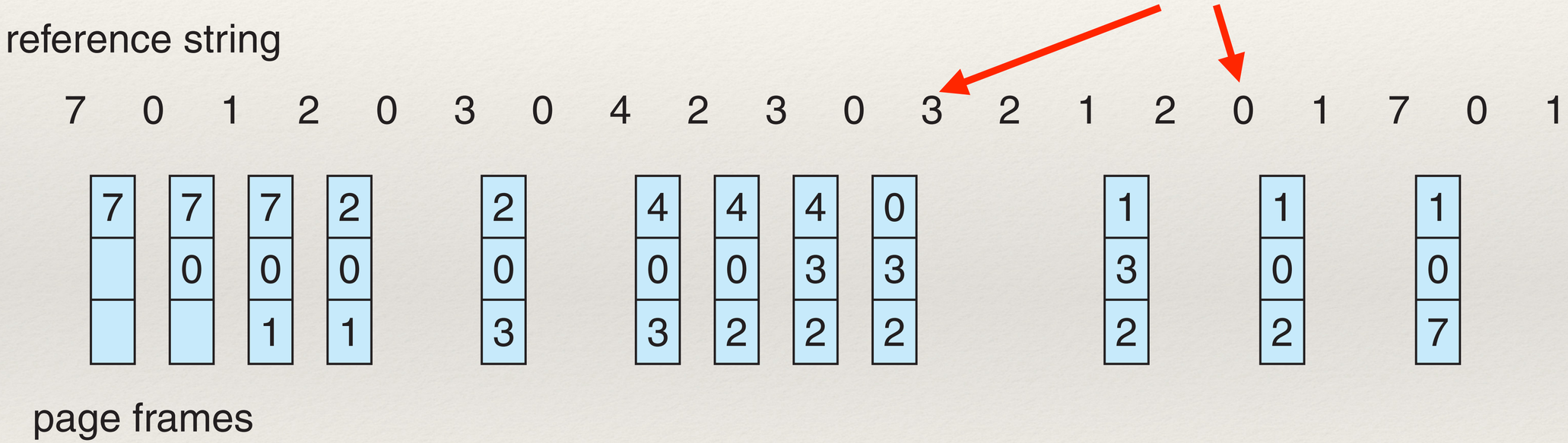

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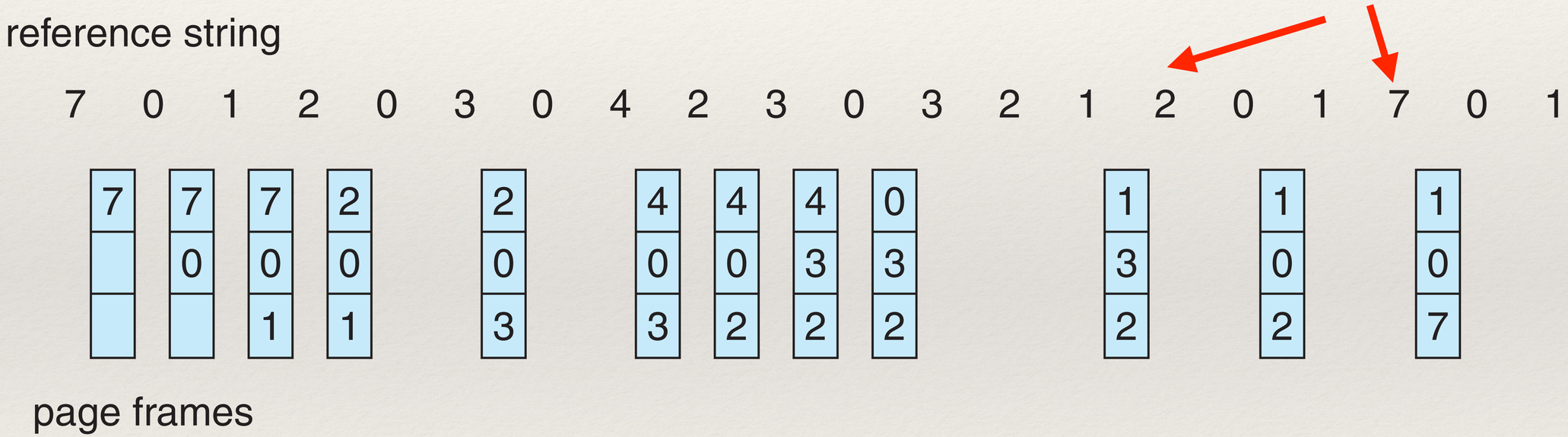

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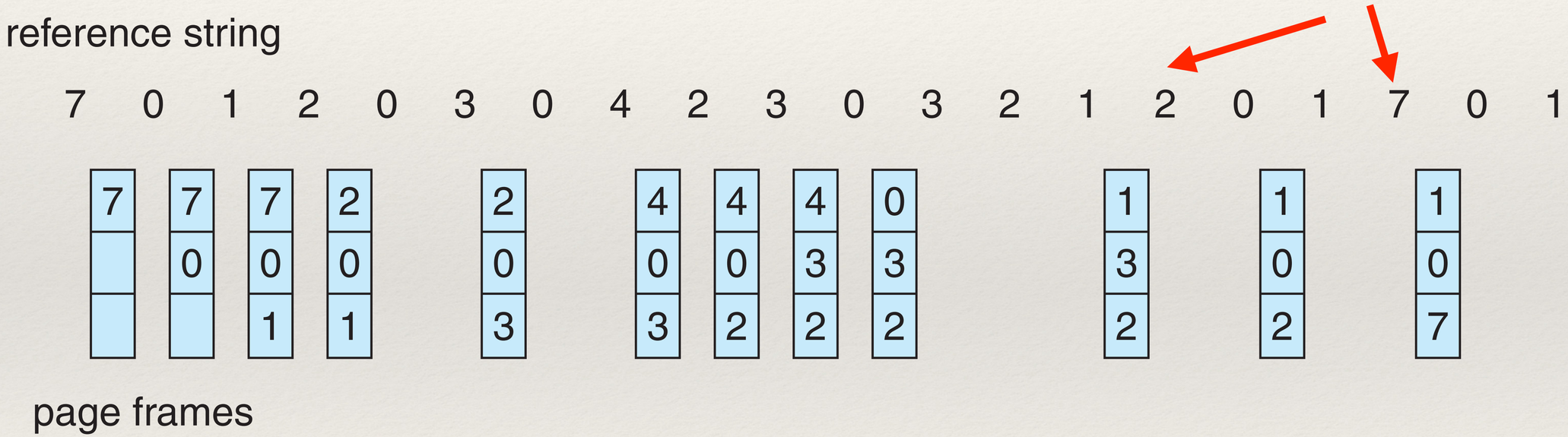


LRU Page Replacement Implementation

- Hardware assistance is needed
  - A table lookup in memory will take too long for every page fault!
  - Can use a counter
    - Clock is incremented with every reference
    - Clock register is copied to a ‘time of use’ field in the page-table entry for that page

LRU Page Replacement Implementation

- Alternative approach
  - Use a stack
    - When a page is referenced it is removed from the stack and put on the top
    - Least used page is on the bottom of the stack
    - Also requires hardware assistance

LRU-Approximation Page Replacement

- True LRU can be expensive (in terms of hardware support and time)
- An approximation can be used by setting a reference bit

LRU-Approximation Page Replacement

- When a page is read from or written to, the reference bit is set
- Can use 1 bit, or an 8 bit byte for the reference bit, set the right most bit.
- After a period of time the OS will shift all bits by 1

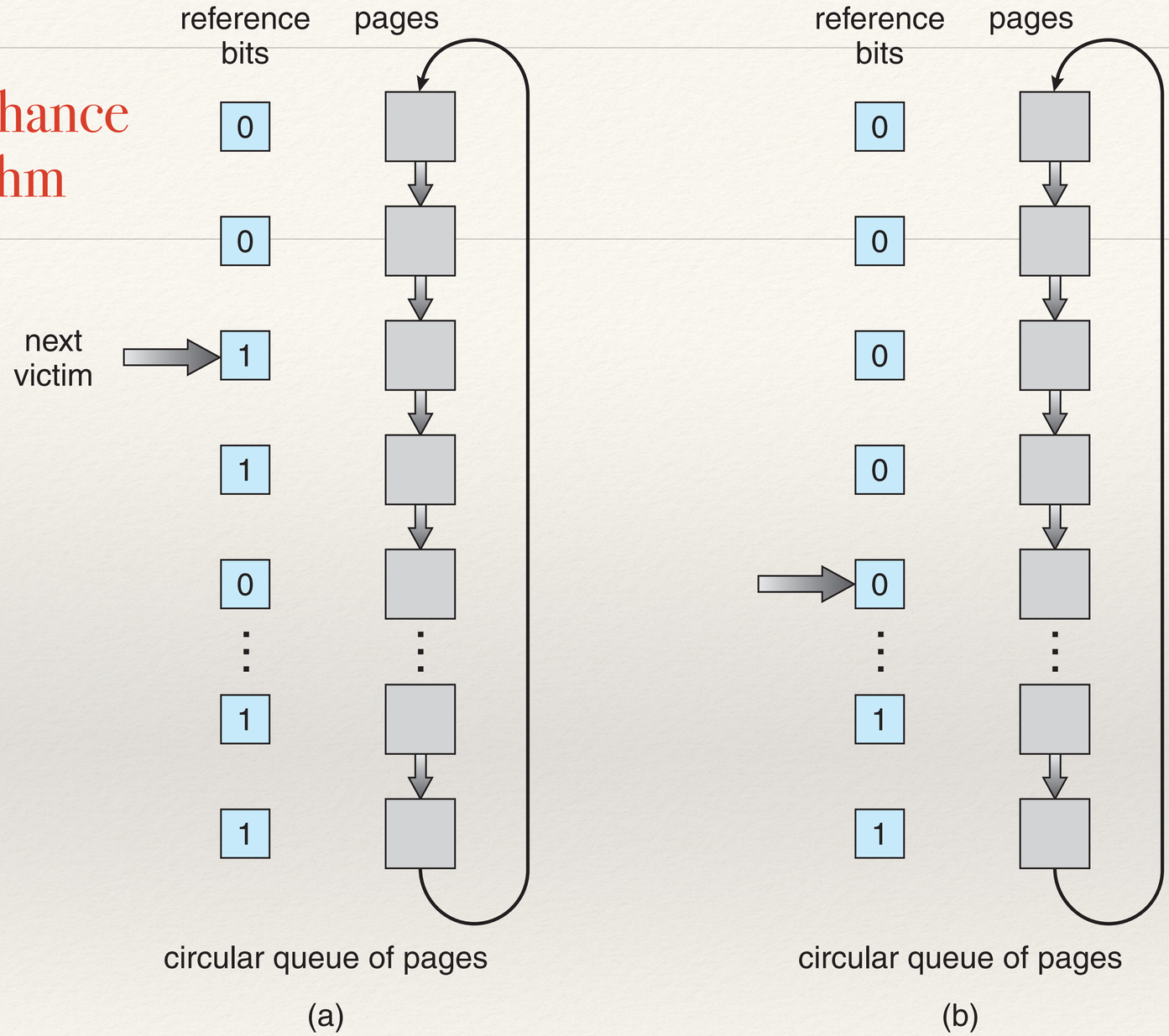
LRU-Approximation Page Replacement

- 00000000 - This page has not been utilized in the last 8 cycles
- 11111111 - This page has been utilized every time in the last 8 cycles
- 00000010 - This page was accessed 2 cycles ago, but no other times
- 10000000 - This page was accessed 8 cycles ago, but no other times
- 11110000 - This page was accessed for 4 cycles, then not accessed for 4 cycles

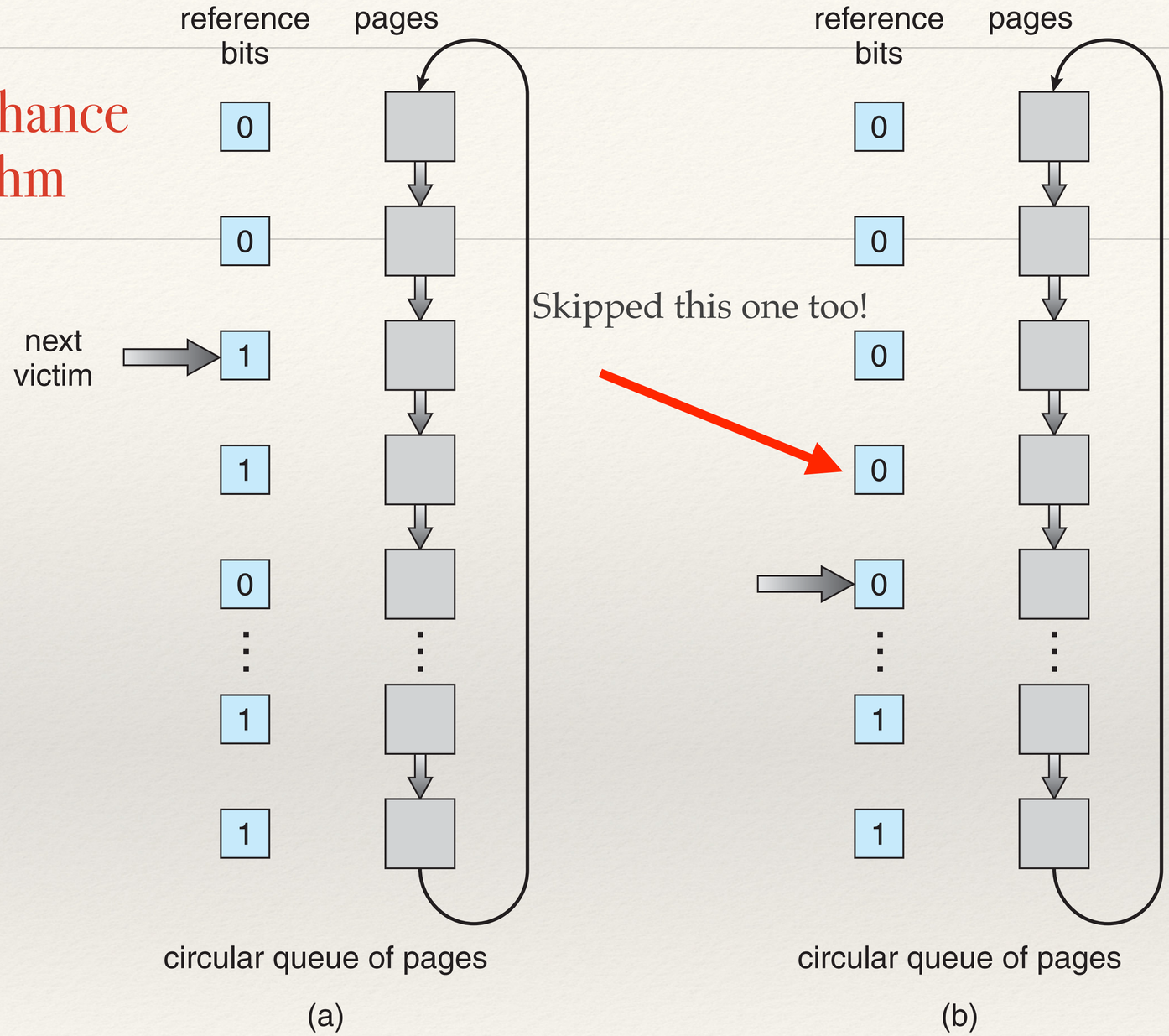
Second-Chance Algorithm

- Utilize a FIFO replacement algorithm
- A single reference bit is used
- Your turn to be replaced? Second chance if the reference bit is set

Second-Chance Algorithm



Second-Chance Algorithm



Enhanced Second Chance Algorithm

- Add a ‘modify’ bit to the reference bit
- (0, 0) not recently used nor modified (Best page to replace)
- (0, 1) not recently used but modified - page will need to be written
- (1, 0) recently used but not modified - may be used again?
- (1, 1) recently used and modified - worse choice

Counting-Based Page Replacement

- Least frequently used (LFU)
  - The page with the smallest count is replaced
  - Problem: a page could be used heavily initially and then never used again
  - Solution: shift bits at regular intervals
- Most frequently used (MFU)
  - The logic with this is that the page with the smallest count was probably just brought in and has yet to be used

Counting-Based Page Replacement

- Least frequently used (LFU)
- Most frequently used (MFU)

Both are expensive and do not approximate the optimum algorithm well

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Page-Buffering Algorithms

- Create a pool of free frames
- Victim Frame is selected
- Page brought directly to a page from the free pool
- After the victim frame is written out, added to the free pool

Page-Buffering Algorithms Modifications

- Keep track of what frames are in the “free” pool
- May get lucky and reuse it (since the frame contents are not modified when the frame is written to disk)

Applications and Page Replacement

- Certain applications may understand their need for memory management and I/O buffering better than the operating system
  - Database, Data warehouses
  - OS can give access to a large sequential array of logical blocks without filesystem data structures (raw disk) for the application to manage.