CS420: Operating Systems

Virtual Memory

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Background

- **Code needs to be in memory to execute, but entire program rarely used**
  - Error code, unusual routines, large data structures

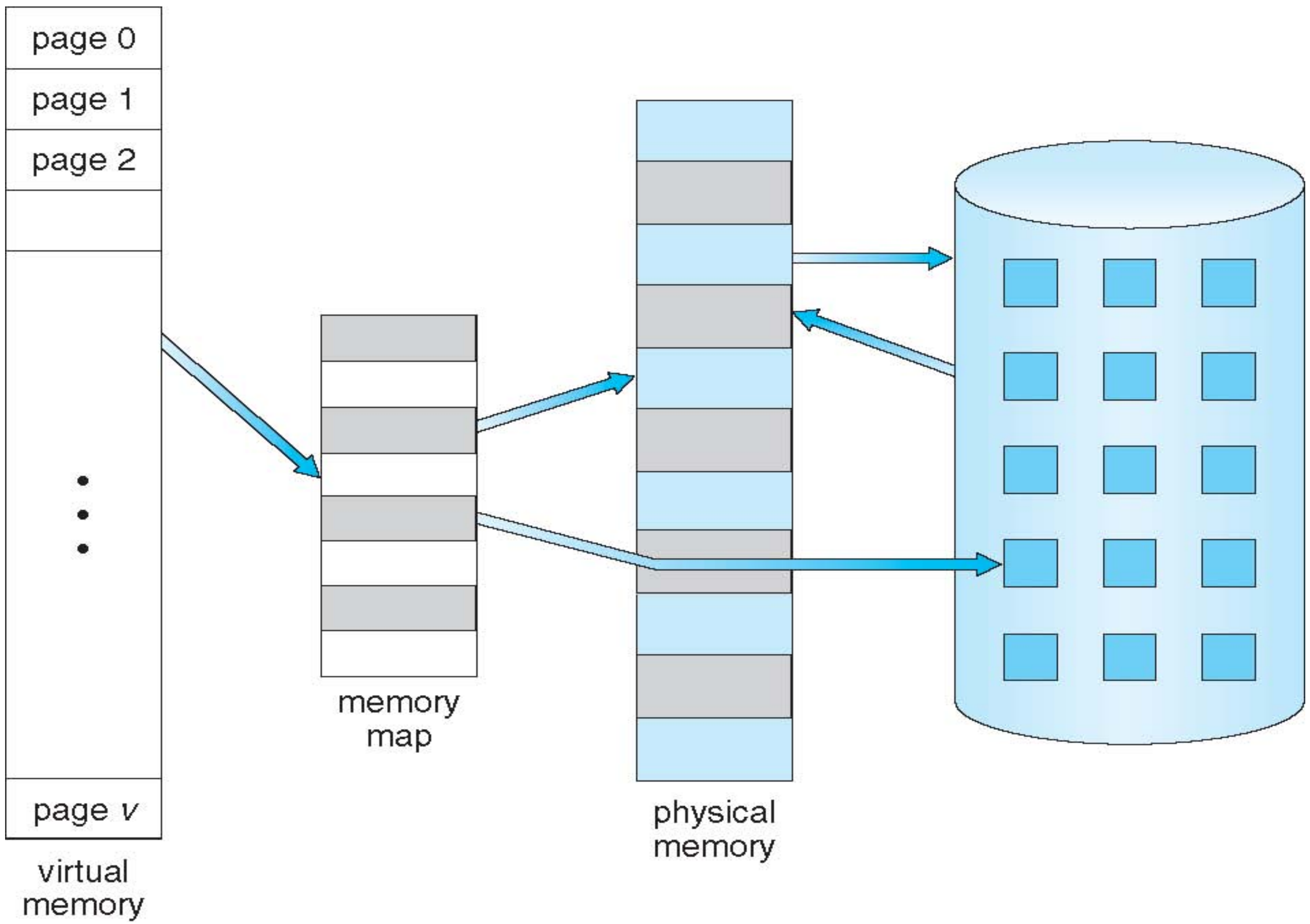
- **Want the ability to execute partially-loaded program**
  - Programs no longer constrained by limits of physical memory
  - Program data no longer constrained by limits of physical memory

Background - Virtual Memory

- **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
  - Allows physical address spaces to be shared by several processes
  - Allows for more efficient process creation
  - More programs running concurrently
  - Less I/O needed to load or swap processes

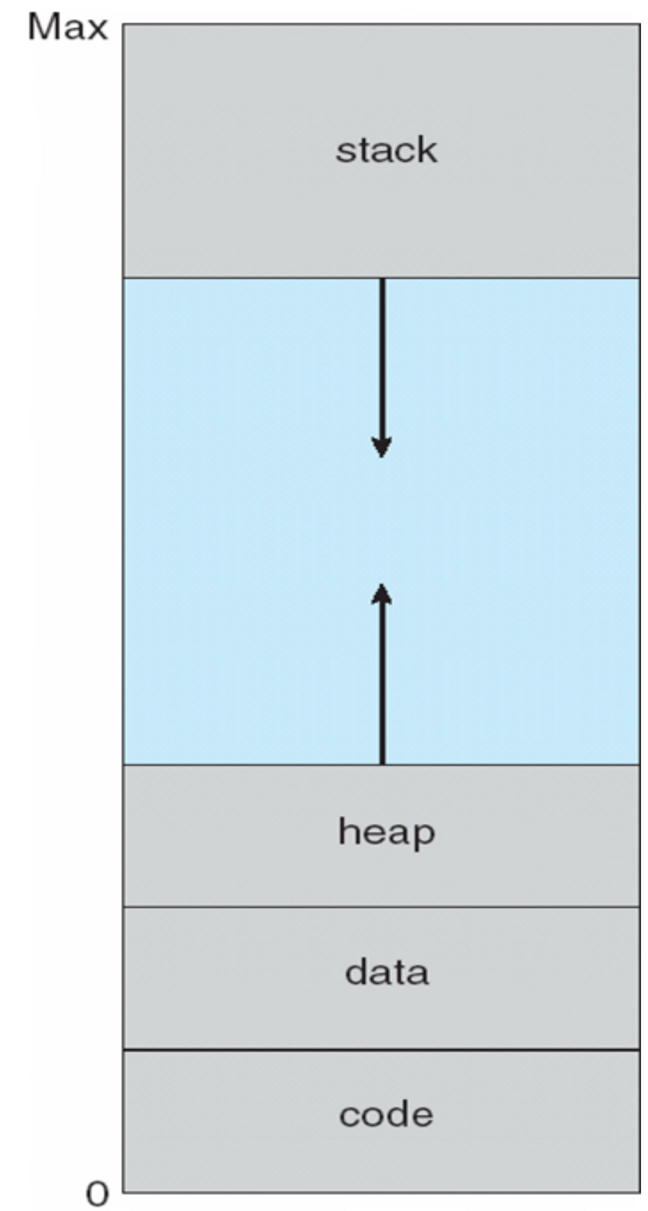
- **In contrast to dynamic loading, virtual memory does not require programmer to do anything extra**

Virtual Memory that is Larger than Physical Memory



Virtual Address Space

- **Enables sparse address spaces with holes left for growth, dynamically linked libraries, etc.**
  - e.g. don't waste physical memory with empty space that is intended for the growth of the stack/heap

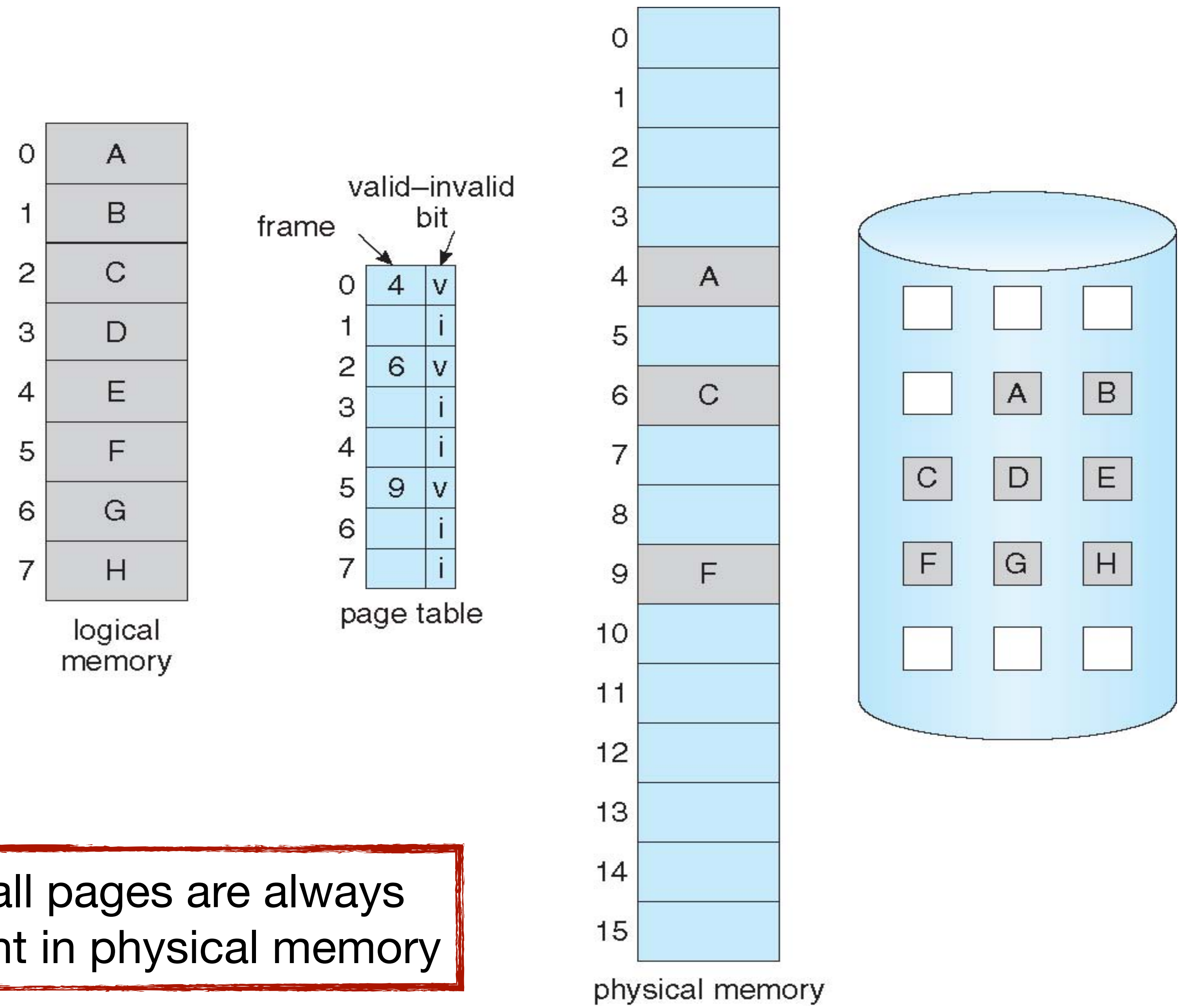


- **System libraries can be shared by mapping them into virtual address space**
- **Can create shared memory by mapping pages into virtual address space**
- **Virtual memory allows pages to be shared during fork(), speeding up process creation**

Demand Paging

- **Could bring entire process into memory at load time**
- **Or load a page into memory only when it is needed, called demand paging**
  - Pages that are never used are never loaded
    - Less I/O needed, no unnecessary I/O
    - Less memory needed
    - Faster response
  - Similar to page table system with swapping, but demand paging doesn't swap entire process into memory, instead uses a lazy swapper
- **Lazy swapper – never swaps a page into memory unless it will be needed**
  - A swapper that deals with pages is called a pager

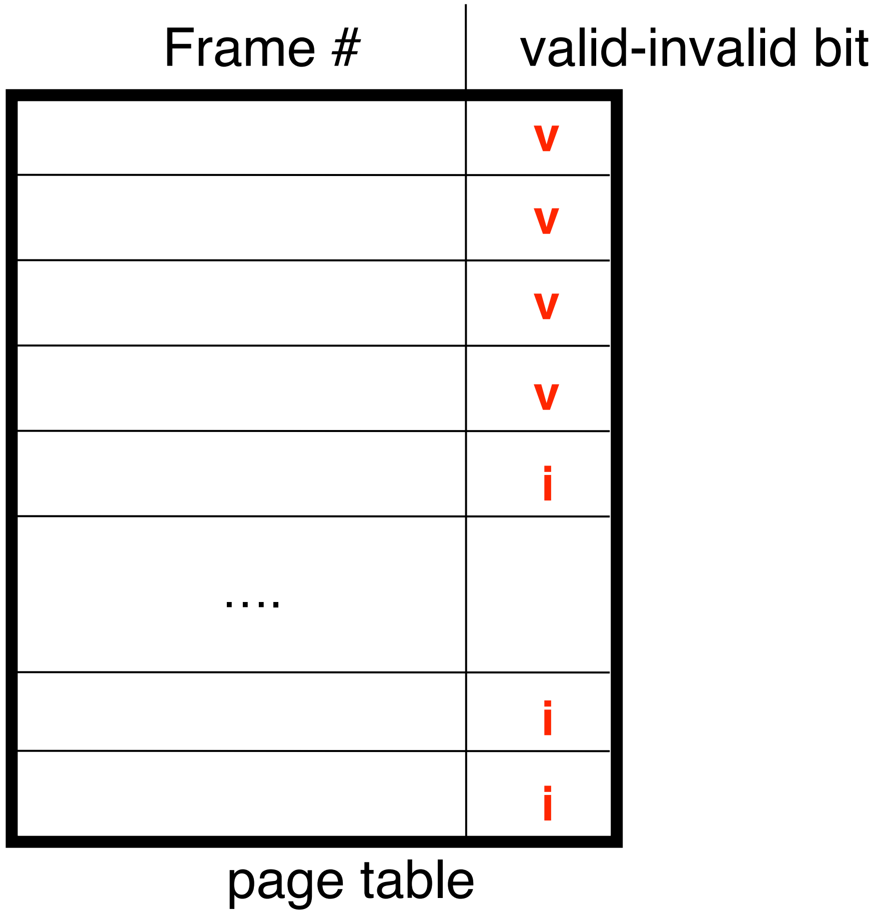
Page Table Example



Not all pages are always resident in physical memory

Valid-Invalid Bit

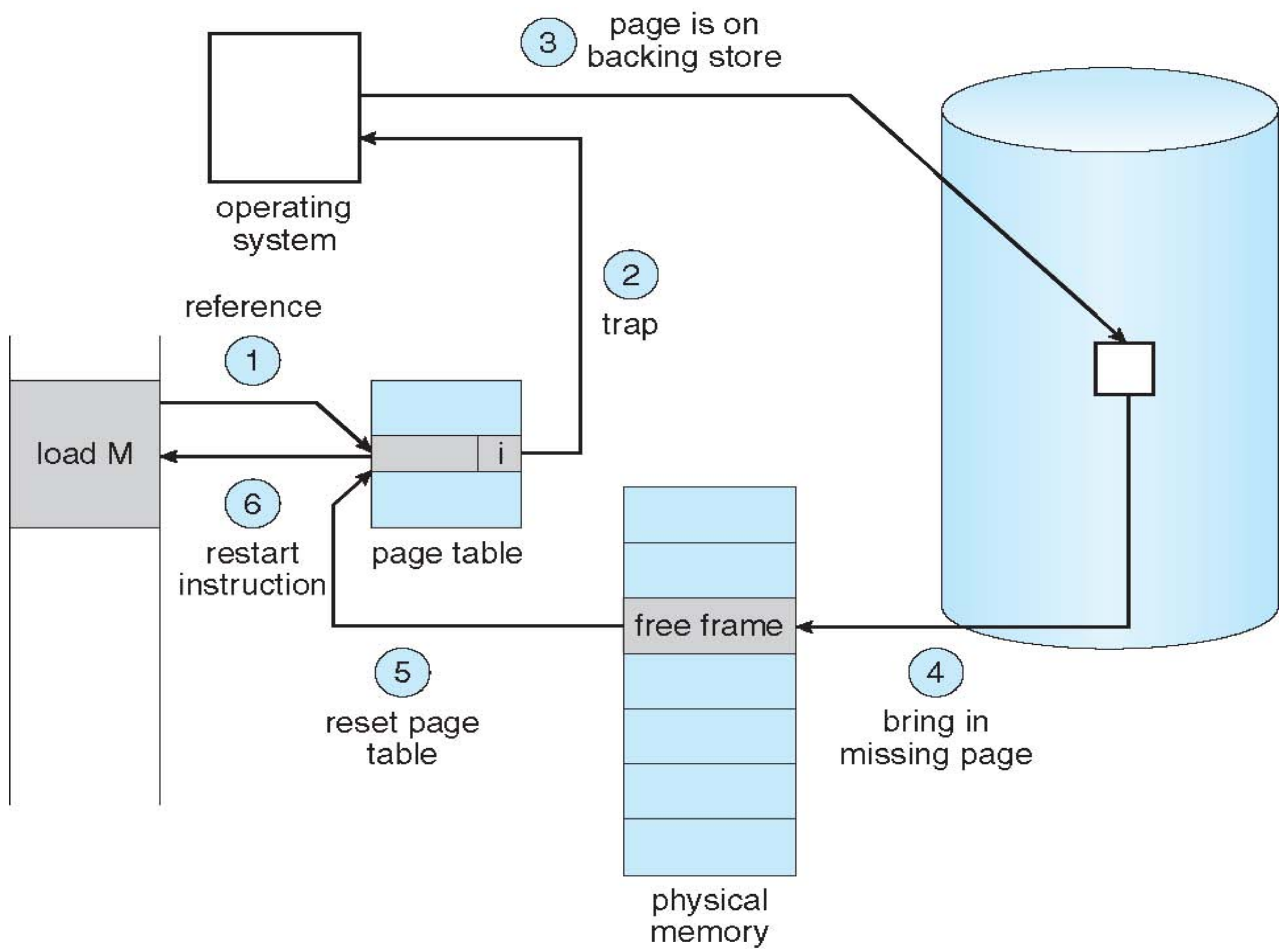
- **Each page table entry includes a valid–invalid bit**
  - If valid, then process is allowed to access that page, AND it is in physical memory
  - If invalid, process may not be allowed to access the requested page, or the page may not yet be in physical memory
- **Initially valid–invalid bit is set to i on all entries**



Page Fault

- **If requested page is memory resident, then process can operate normally**
- **If requested page not in physical memory (i.e. page is invalid in page table), then a page fault occurs**
- **If page fault occurs, first check to see if the requested page was an illegal request or if it just isn't in physical memory**
    - If an illegal reference, the process terminates (seg fault, bus error, ...)
    - If simply not in memory:
        - Get a free frame of physical memory from the free-list
        - Swap page from disk into the frame via a scheduled disk operation
        - Update tables to indicate that the page is now in physical memory (i.e. set valid-invalid bit to 'v')
        - Restart the instruction that caused the page fault

Steps in Handling a Page Fault



Aspects of Demand Paging

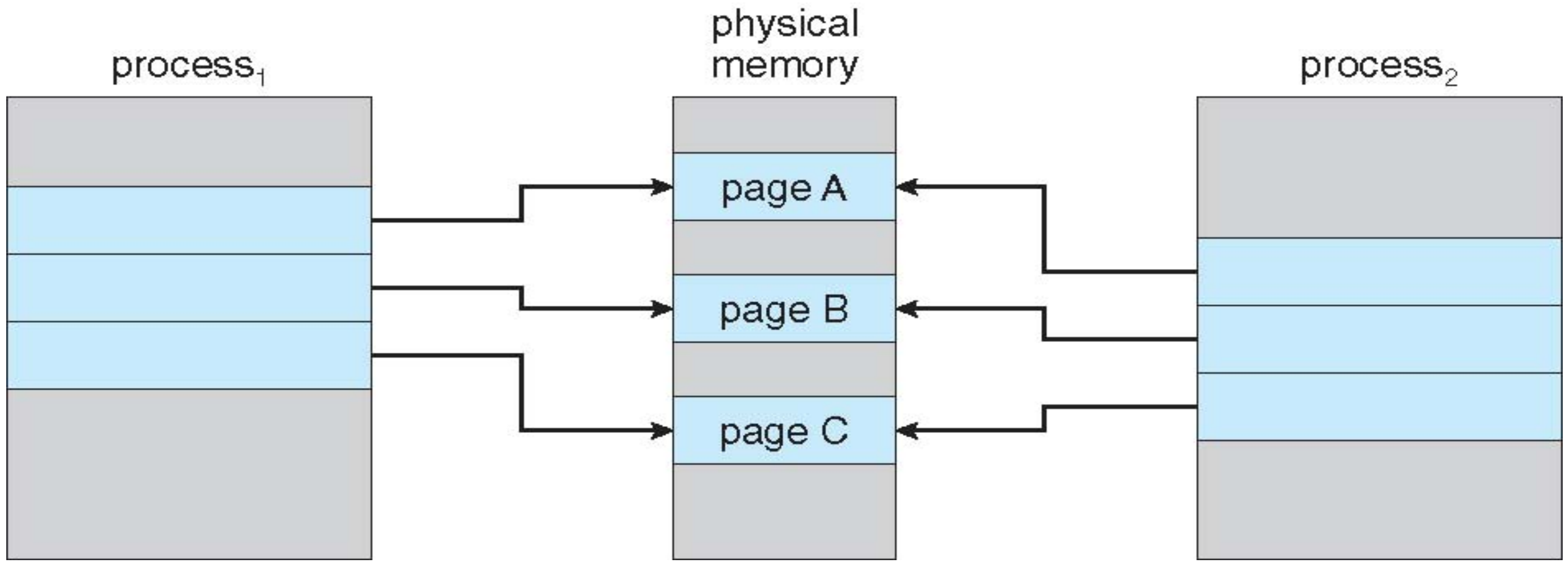
- **Extreme case of demand paging – start a process with no pages in memory**
  - Never bring a page into physical memory until it is needed
  - A page fault will occur each time a new page is requested, including on the very first page
  - The scheme is called pure demand paging
- **Demand paging (and pure demand paging) require hardware support**
  - Page table with valid / invalid bit
  - Secondary memory (swap device with swap space)
  - Ability to restart an instruction
- **Performance of system can be severely impacted if too much page swapping is required**

Page Sharing - Copy-on-Write

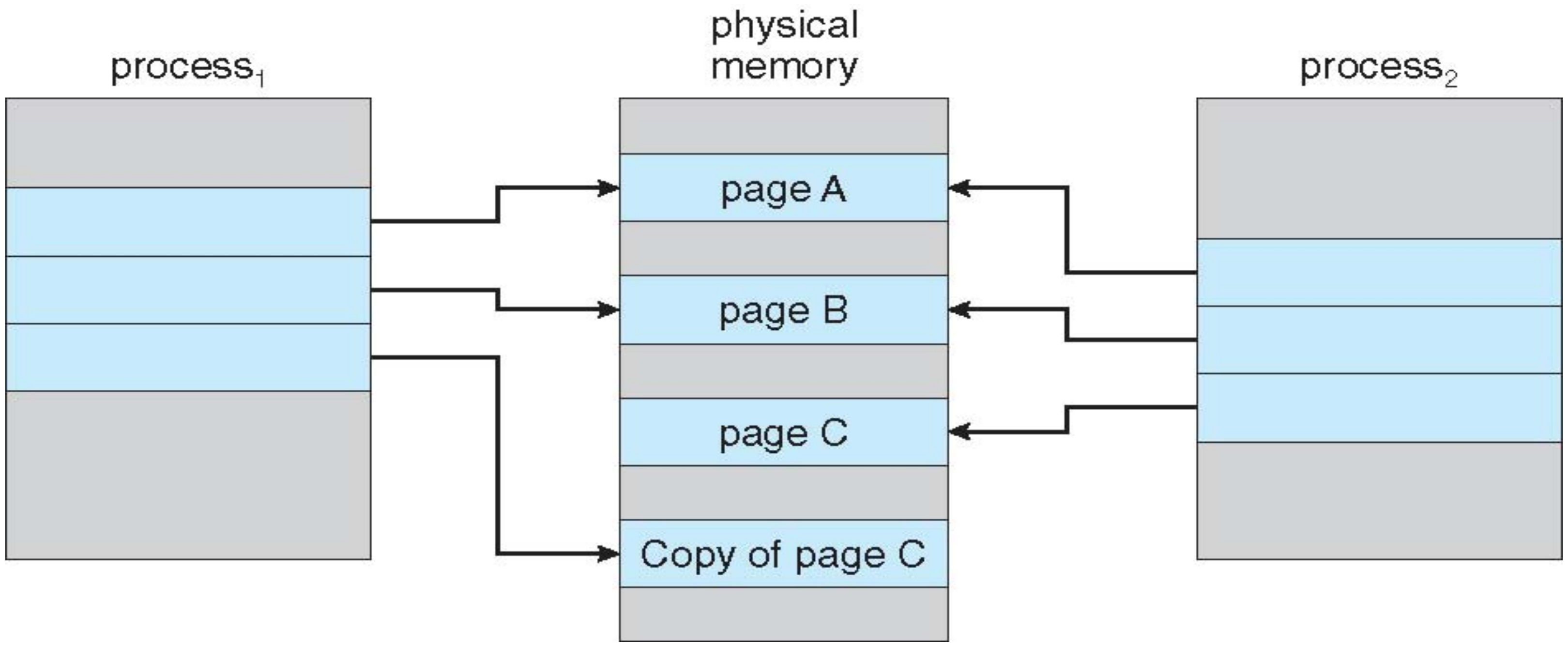
- **During process creation Copy-On-Write (COW) allows both parent and child processes to initially share the same pages in memory**
  - If either process modifies a shared page, only then is the page copied
- **COW allows more efficient process creation as only modified pages are copied**
- **Free pages are typically allocated from a pool of zero-fill-on-demand pages**
- **A variation of `fork()` exists called `vfork()` (virtual memory fork)**
  - Parent suspends so child can use its memory address space
  - If child modifies parent's address space, those changes will be visible to parent (i.e. it does NOT use copy-on-write)
  - Designed to be used when child calls `exec()` immediately after `fork()`
  - Very efficient since no pages are copied during creation of child

Example of Copy-on-Write

Memory before either process tries to write to shared pages



Memory after process$_1$ writes to page C



What Happens if There is no Free Frame?

- **All frames used up by process pages and I/O buffers**
  - How much memory should be allocated to I/O and how much to processes?

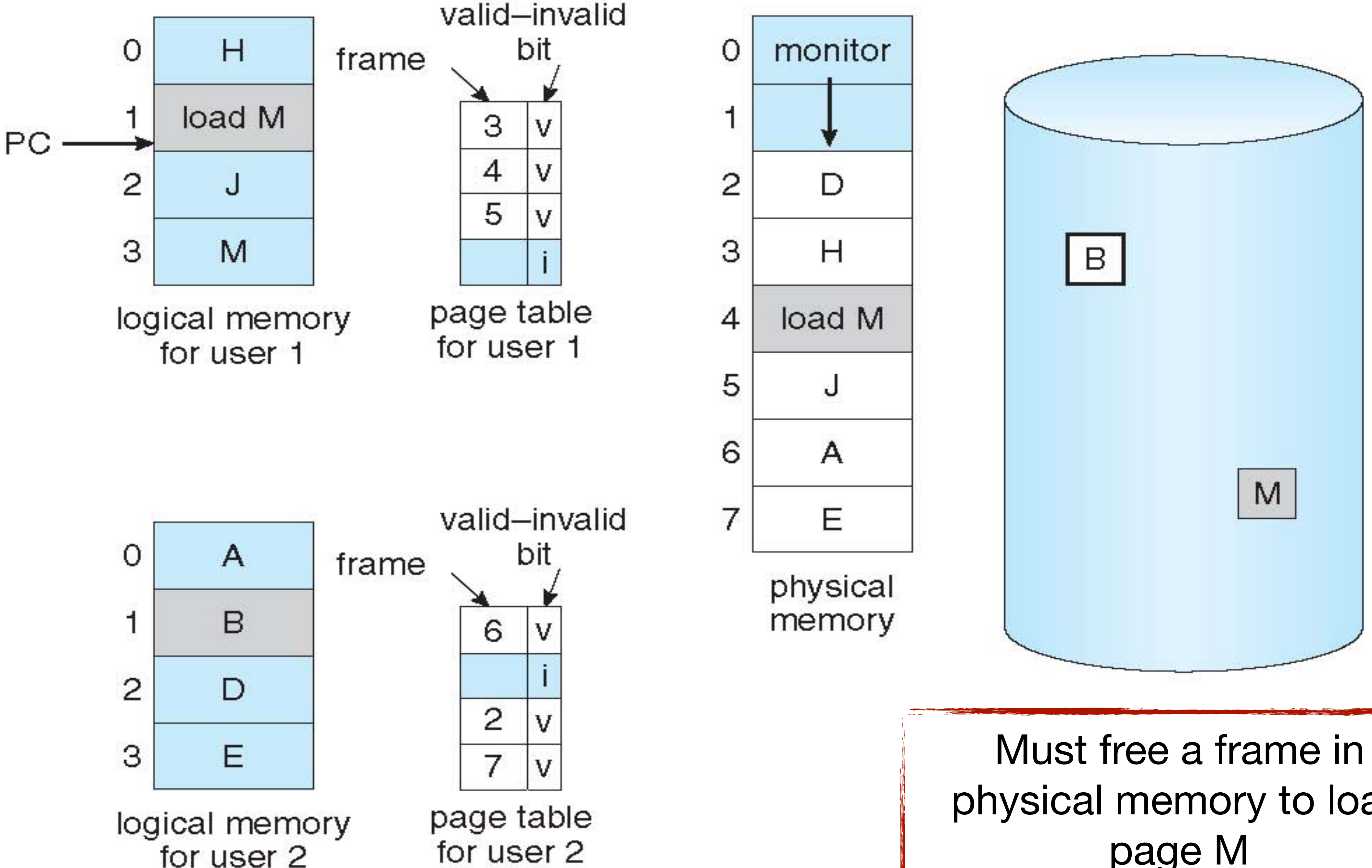
- **Page replacement – find some page in physical memory, but not really in use, page it out to swap space**
  - Once a page is in physical memory, that doesn't mean it will always be in physical memory
  - Same page may be brought into physical memory several times
  - For performance reasons, want a page replacement algorithm which will result in minimum number of page faults

Page Replacement

- **Must prevent over-allocation of physical memory by modifying page-fault service routine to include page replacement**
  - If no free frame exists, must select a victim frame and write the page that it contains off to swap space
  - After writing page to swap space, must update pages tables accordingly
  - Required page can then be read into newly freed frame
  - Continue process by restarting instruction that caused the page-fault

- **Use modify (dirty) bit to reduce overhead of page transfers**
  - Only modified pages are written back to disk from physical memory
  - Without modify bit, unmodified pages may be unnecessarily written back to swap space

Need For Page Replacement



Must free a frame in physical memory to load page M

Page and Frame Replacement Algorithms

- **Frame-allocation algorithm determines**
  - How many frames to give each process
- **Page-replacement algorithm determines**
  - Which frames to replace
  - Want lowest page-fault rate on both first access and re-access
- **Evaluate algorithms by running them on a particular sequence of memory references (reference string) and computing the number of page faults on that sequence**
  - Reference string is just page numbers, not full addresses
    - Example reference string: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 0, 3, 2, 1, 2, 0, 1, 7, 0, 1
  - Repeated access to the same page does not cause a page fault
  - The more physical memory a system has, the more frames it has ... resulting in fewer page-faults

Page Replacement Algorithms

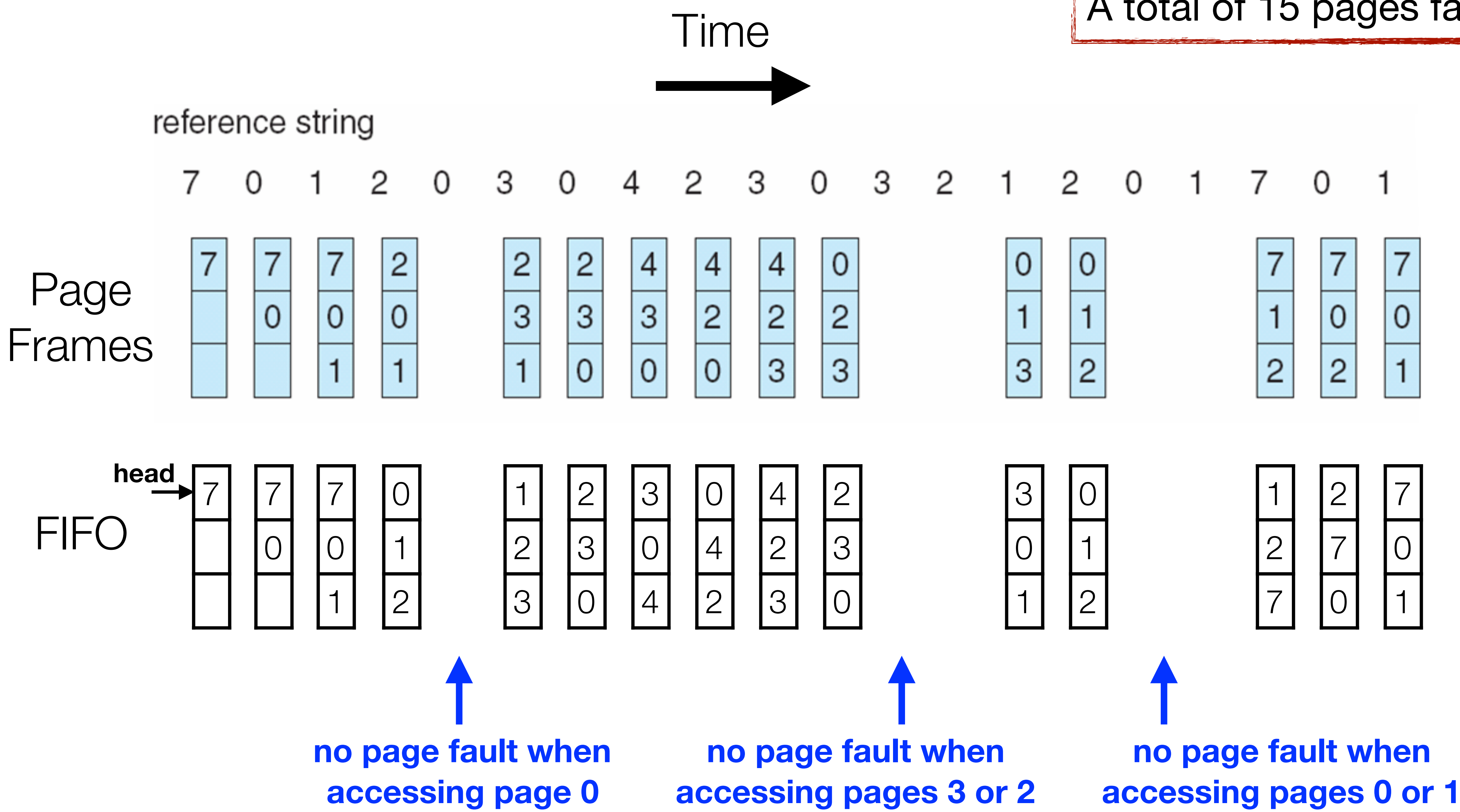
- **Many different page replacement algorithms exist**
  - FIFO Page Replacement
  - Optimal Page Replacement (theoretical best case)
  - Least-Recently Used (LRU) Page Replacement
  - Counting-Based Page Replacement

FIFO Page Replacement

- **A very simple page replacement algorithm**
  - When a page is brought into physical memory, insert a reference to that page into a FIFO
  - When a page must be replaced, replace the oldest page first (i.e. the page at the head of the FIFO)
- **Pros:**
  - Very easy to understand and program
- **Cons:**
  - Performance may not be very good
  - May result in a high number of page faults

FIFO Page Replacement Example

A total of 15 pages faults



Optimal Page Replacement

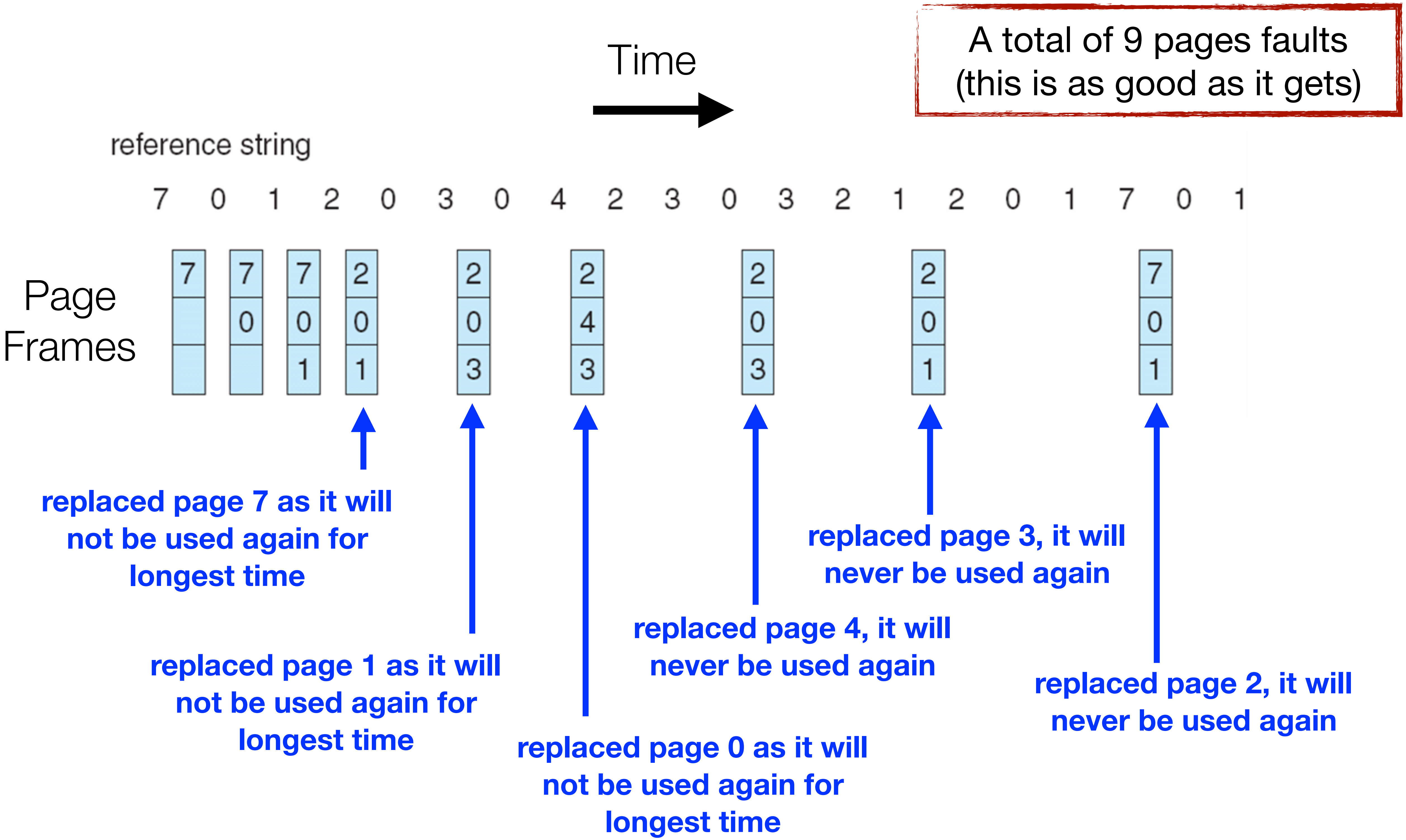
- **An optimal page replacement algorithm can be described very simply:**
  - *Replace the page that will not be used for longest period of time*

- **Guarantees the lowest possible page-fault rate for a fixed number of frames**

- **Sadly, it is not possible to know which page won't be used for the longest period of time (can't see the future)**

- **Optimal algorithm is still very useful**
  - Used for measuring how well other algorithm performs
  - How close are other algorithms to optimal?

Optimal Page Replacement Example



Least Recently Used (LRU) Algorithm

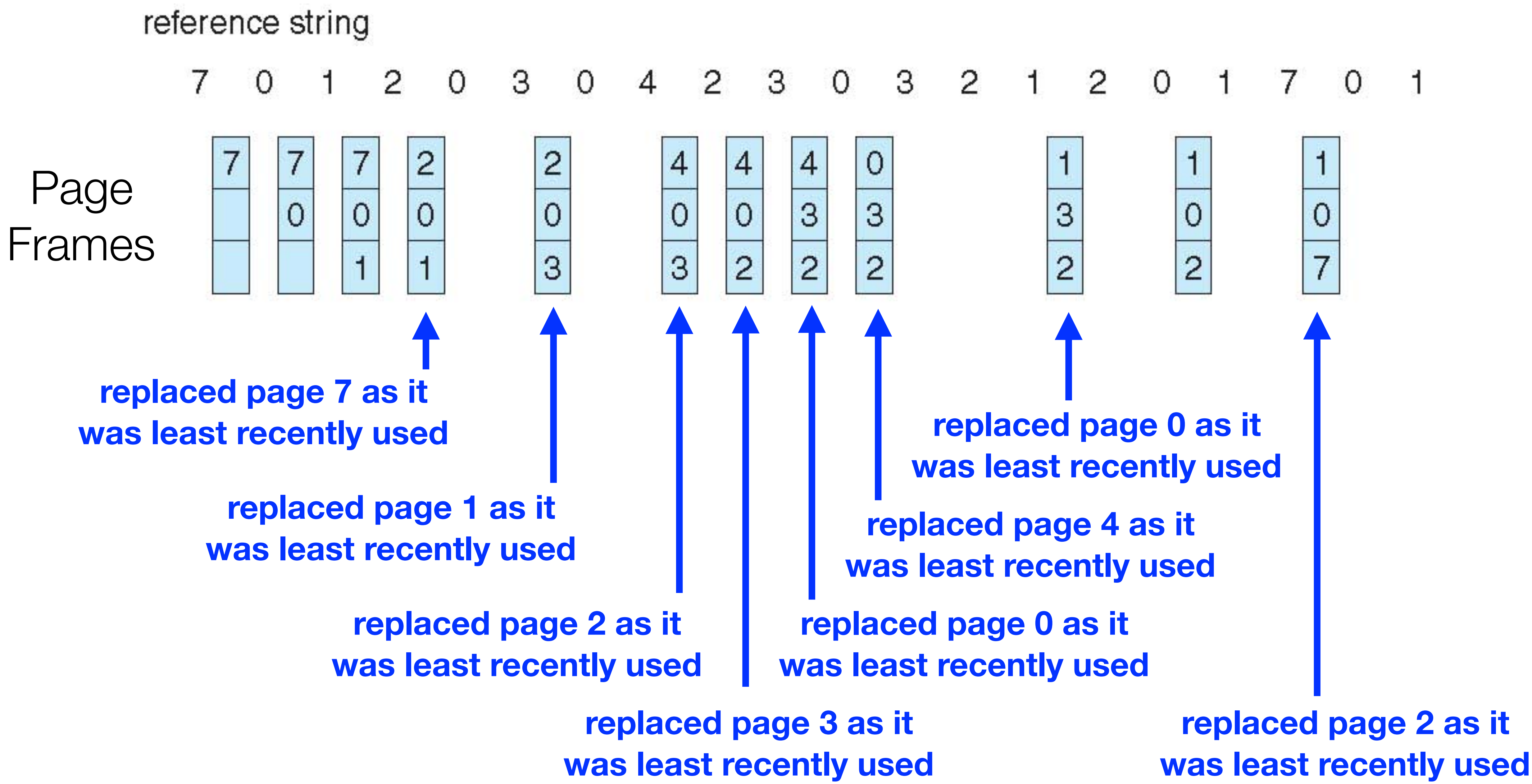
- **Interestingly, the same number of page-faults occur if a reference string is read either forwards or backwards and used to access pages**
  - Because of this property, it is possible to use past knowledge of page use rather than future knowledge

- **Least Recently Used (LRU) Replacement Algorithm:**
  - Replace page that has not been used in the most amount of time (i.e. replace the page that is the least recently used page)
    - Associate time of last use with each page

- **Generally good algorithm and used frequently**

Least Recently Used (LRU) Algorithm Example

A total of 12 pages faults;
better than FIFO, but not optimal

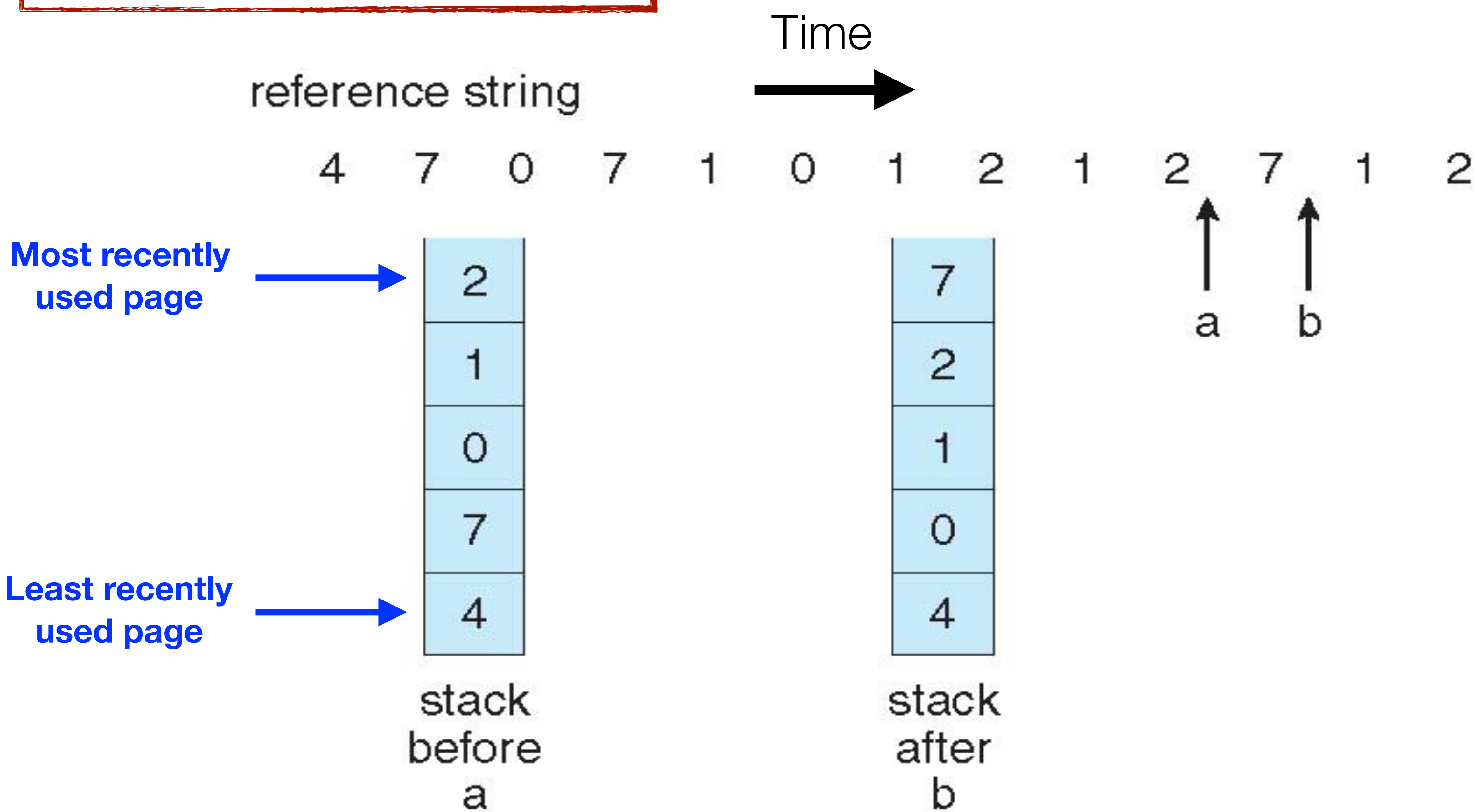


Least Recently Used (LRU) Algorithm

- **How should a least-recently-used algorithm be implemented?**
  - Option #1 - 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 replaced, look at the counters to find smallest value
      - Requires a potentially lengthy search through the page table (SLOW)
  - Option #2 - Stack implementation
    - Keep a stack of page numbers in a doubly linked list
    - If a page is referenced, move it to the top of the stack (not a pure stack implementation)
      - Most recently used page is always at the top of the stack; the least recently used page is always at the bottom of the stack
    - Finding and moving page numbers in the stack takes time (updates to the stack must be done on *every* memory reference) (SLOW)

Stack Implementation

Using a Stack to Record the
Most Recent Page References



LRU Approximation Algorithms

- **The LRU algorithm as described previous is too slow, even with specialized hardware**
- **Instead of finding exactly which page was least recently used, an approximation will do**
- **One possible approach for approximating the least recently used page is to use a reference bit**
  - Associate a reference bit with each page, initially = 0
  - When page is referenced, set bit to 1
  - When it is time to replace a page, replace any that have reference bit = 0 (if one exists)
  - Can also use multiple reference bits to maintain a longer history and thus more closely approximate a true LRU algorithm

Counting-Based Page Replacement

- **Keep a counter of the number of references that have been made to each page**
  - Not common
- **Least-frequently-used (LFU) algorithm: replaces the page with smallest count**
- **Most-frequently-used (MFU) algorithm: replaces the page with the largest count**
  - Based on the argument that the page with the smallest count was probably just brought in and has yet to be used

Speeding Up Page Replacement

- **Always maintain a pool of free frames**
  - No need to search for a free frame when the page-fault occurs
  - Load page into free frame and select victim to evict and add to free pool
  - When convenient, evict victim
    - No longer have to wait for victim frame to get paged out before new page can get paged in
- **Possibly, keep list of modified pages**
  - When backing store is otherwise idle, write pages and set to non-dirty
- **Possibly, keep free frame contents intact and note what is in them**
  - If referenced again before reused, no need to load contents again from disk
  - Generally useful to reduce penalty if wrong victim frame selected

Allocation of Frames

- **Each process needs some minimum number of frames that it cannot run without**
  - Even a single instruction may require more than a single frame of physical memory
- **Example: IBM 370 – 6 pages to handle SS MOVE instruction:**
  - Instruction is 6 bytes, and therefore might span 2 pages
  - 2 pages to handle for *from*
  - 2 pages to handle for *to*
- **Maximum number of frames that can be allocated is the total number of frames in the system**
- **Two major allocation frame schemes**
  - Fixed allocation
    - Equal allocation
    - Proportional allocation
  - Priority allocation

Types of Fixed Allocation

- **Equal allocation – every process in the system is allocated an equal share of the available frames**
  - If the number of frames is *m* and the number of processes is *n*, each process is allocated *m*/*n* frames
  - For example, if there are 100 frames (after allocating frames for the OS) and 5 processes, give each process 100/5 = 20 frames
    - Maybe keep some as free frame buffer pool for faster paging
  - Pros: Easy to implement
  - Cons:
    - Why allocate 20 frames to a process that might actually only need 5?
    - Can be very wasteful
    - A higher priority process doesn't get any more frames than a lower priority process

Types of Fixed Allocation (Cont.)

- **Proportional allocation – Allocate available frames according to the size of a process**
  - Larger processes are allocated more frames than smaller processes
  - Dynamic as degree of multiprogramming change

$$
\begin{aligned}
&- s_i = \text{size of process } p_i \\
&- S = \sum s_i \\
&- m = \text{total number of frames} \\
&- a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m
\end{aligned}
$$

$$
\begin{aligned}
m &= 64 \\
s_1 &= 10 \\
s_2 &= 127 \\
a_1 &= \frac{10}{137} \times 64 \approx 5 \\
a_2 &= \frac{127}{137} \times 64 \approx 59
\end{aligned}
$$

  - Pros: Better allocation scheme than equal allocation
  - Cons: A higher priority process doesn’t get any more frames than a lower priority process

Priority Allocation

- **Use a proportional allocation scheme using process priorities rather than process size**
- **If process P_i generates a page fault,**
  - Select for replacement one of its frames (local replacement)
  - Select for replacement a frame from a process with lower priority number (global replacement)

Global vs. Local Allocation

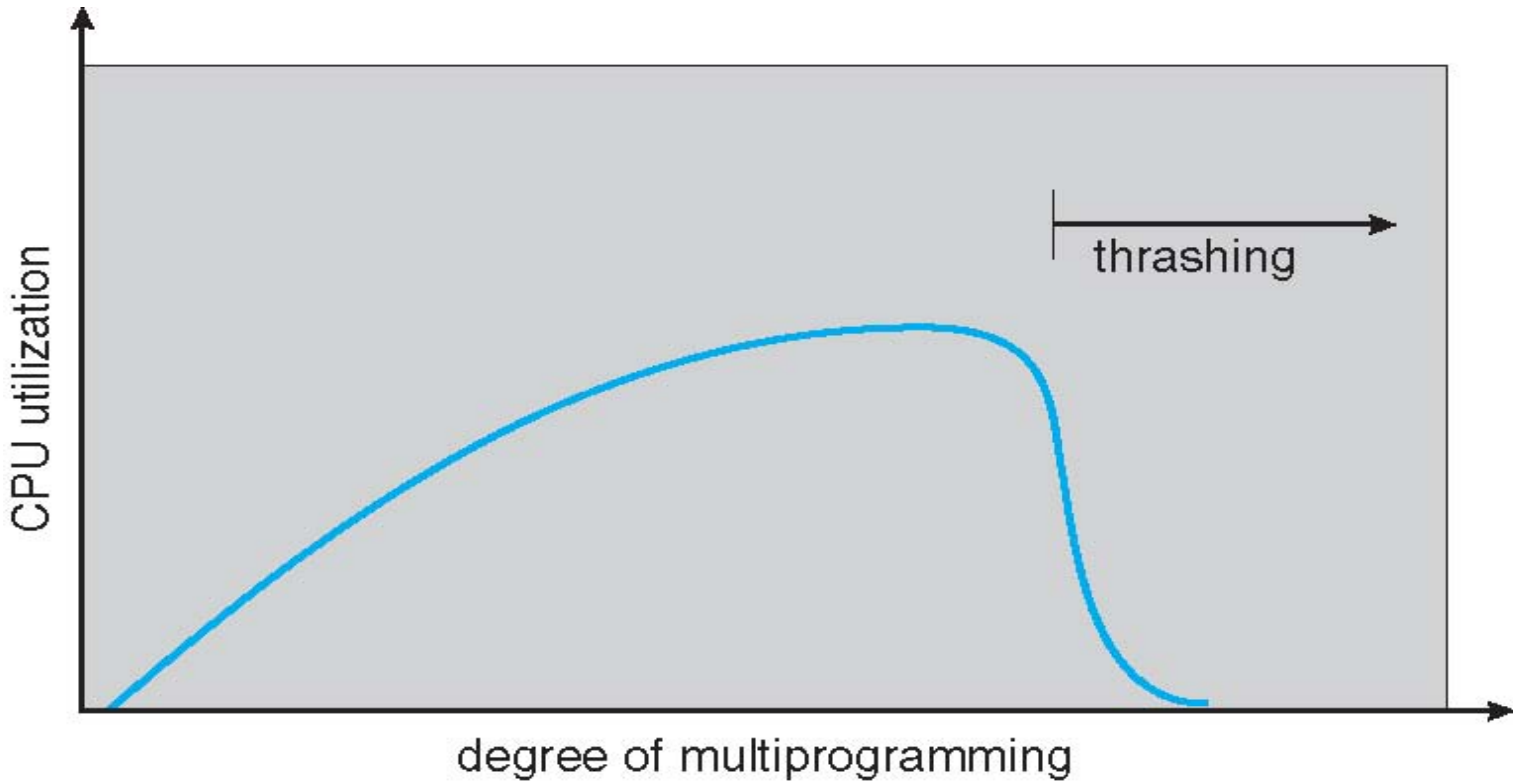
- **Global replacement – process selects a replacement frame from the set of *ALL* frames; one process can take a frame from another**
  - Process execution time can vary greatly due to another process stealing frames
  - Tends to have greater throughput (the number of processes that complete execution per unit time)
  - More common than local replacement
- **Local replacement – each process selects a replacement frame from only its own set of allocated frames**
  - Per-process performance is more consistent
  - But possibly underutilized memory

Thrashing

- **If a process does not have “enough” pages, the page-fault rate is very high**
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
  - This leads to:
    - Low CPU utilization
    - Operating system thinking 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 (spends more time paging than executing)**

Thrashing (Cont.)



Demand Paging and Thrashing

- **Why does demand 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
  - Limit effects by using local or priority page replacement

Locality In A Memory-Reference Pattern