Chapter - Five

Virtual Memory

Outline

- Introduction
- Virtual memory
- Page fault handling
- Virtual memory basic policy
- Page replacement algorithms

Chapter objectives

- To describe the benefits of virtual memory system
- To explain the concepts of demand paging, page-replacement algorithms, and allocation of page frames.

Introduction

- So far, we separated the programmer's view of memory from that of the operating system using a mapping mechanism.
- We have also seen protection and sharing of memory between processes.
- we also assumed that a user program had to be loaded completely into the memory before it could run.

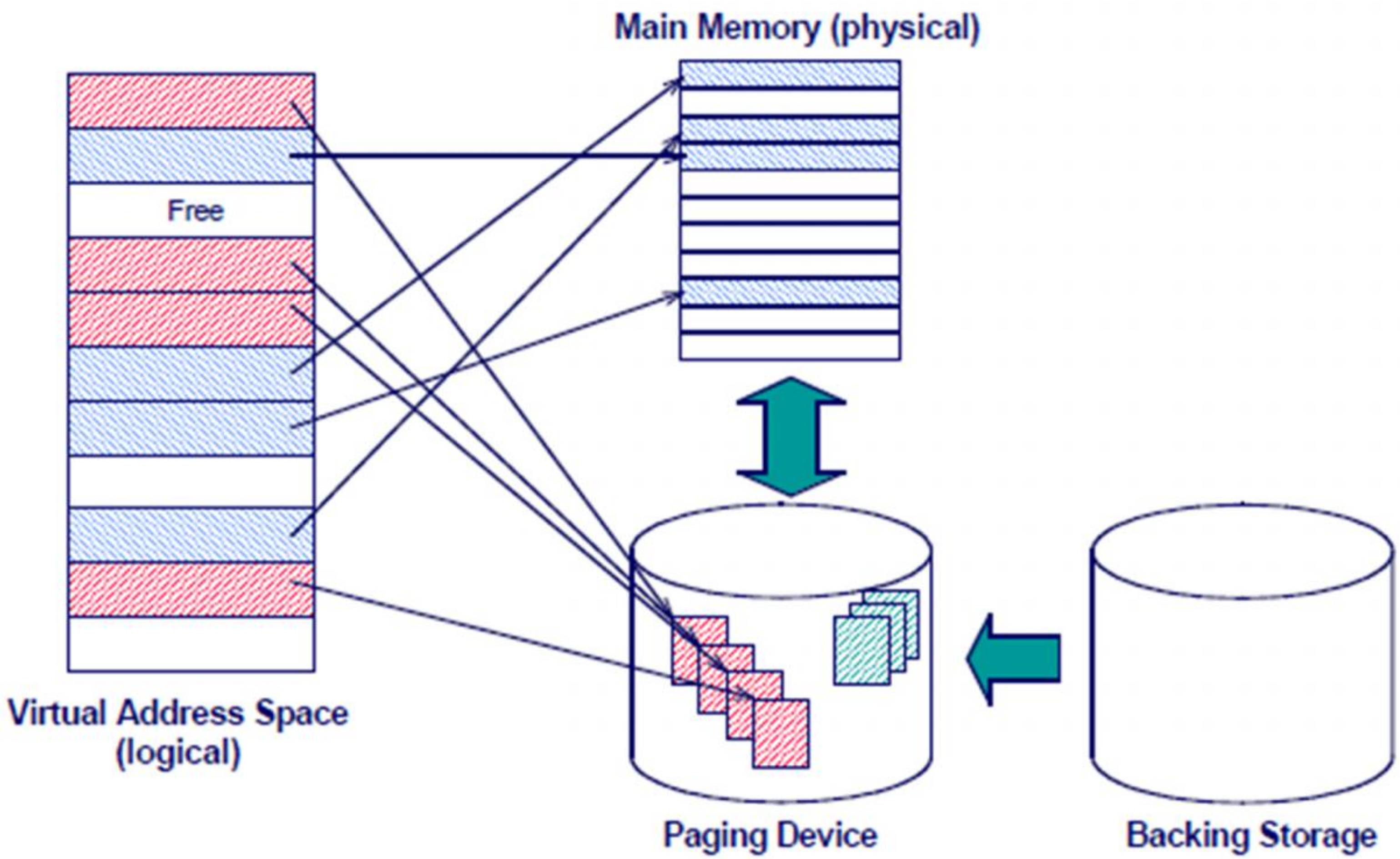
- Problem : Waste of memory, because a program only needs a small amount of memory at any given time.

- Solution : Virtual memory; a program can run with only some of its virtual address space in main memory.

Principles of operation

- The basic idea with virtual memory is to create an illusion of memory that is as large as a disk (in gigabytes) and as fast as memory (in nanoseconds).
- The key principle is locality of reference; a running program only needs access to a portion of its virtual address space at a given time.
- With virtual memory, a logical (virtual) address translates to:
  - Main memory (small but fast), or
  - Paging device (large but slow), or
  - None (not allocated, not used, free.)

A virtual view



Background

- 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 (program) can therefore be much larger than physical address space.
  - Allows address spaces to be shared by several processes.
  - Allows to share files easily and to implement shared memory.
  - Allows for more efficient process creation

Virtual memory can be implemented via:

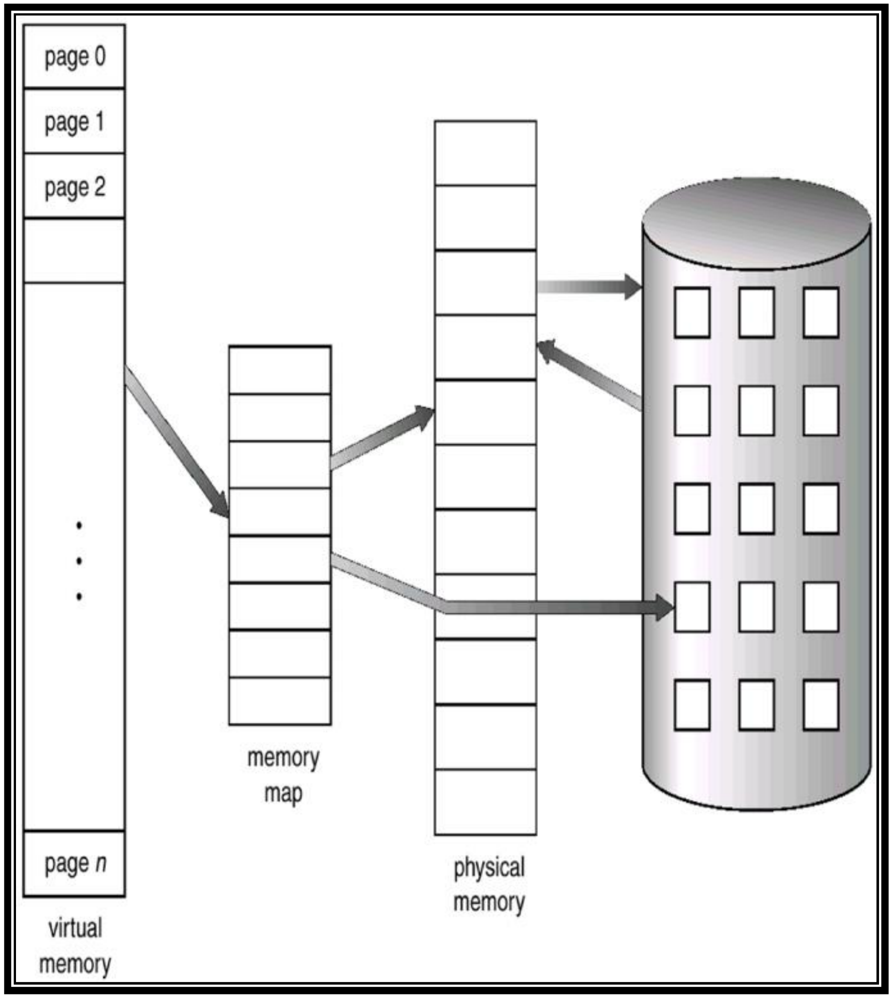
- Demand paging
- Demand segmentation

Background...

- In many cases, the entire program is not needed, for example:
  - Programs often have codes to handle unusual error conditions. This code may not be executed.
  - Arrays, lists, and tables are often allocated more memory than they actually need.
    - An array may be declared 100 by 100, but you may use only 10 by 10
  - Certain options and features of a program may be used rarely.
- Even in those cases where the entire program is needed, it may not all be needed at the same time.

Virtual Memory That is Larger Than Physical Memory

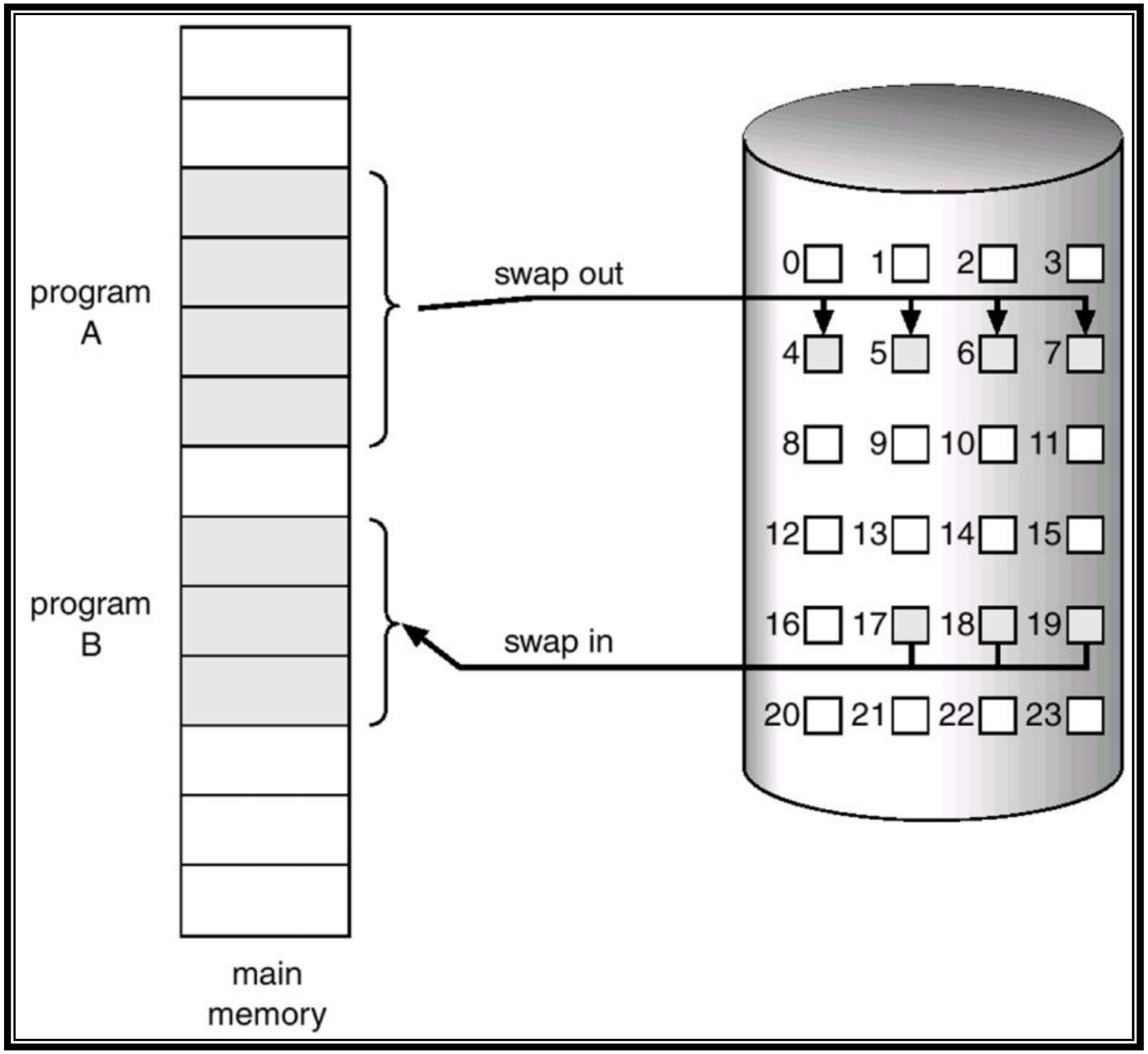
- The ability to execute a program that is only partially in memory would have many benefits.
  - A program would no longer be constrained by the amount of physical memory that is available.
  - Since each user program could take less physical memory, more programs could run at the same time, which increases CPU utilization and system throughput
  - Less I/O would be needed to load or swap each user program into memory.



Demand Paging

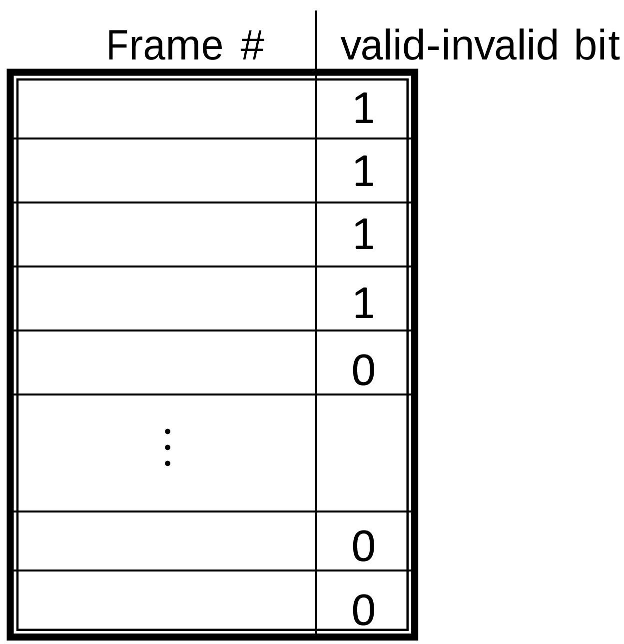
- Bring a page into memory only when it is needed.
- Pages that are never accessed are thus never loaded into physical memory.
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed $\Rightarrow$ reference to it
  - invalid reference $\Rightarrow$ abort
  - not-in-memory $\Rightarrow$ bring to memory

Transfer of a Paged Memory to Contiguous Disk Space



Valid-Invalid Bit

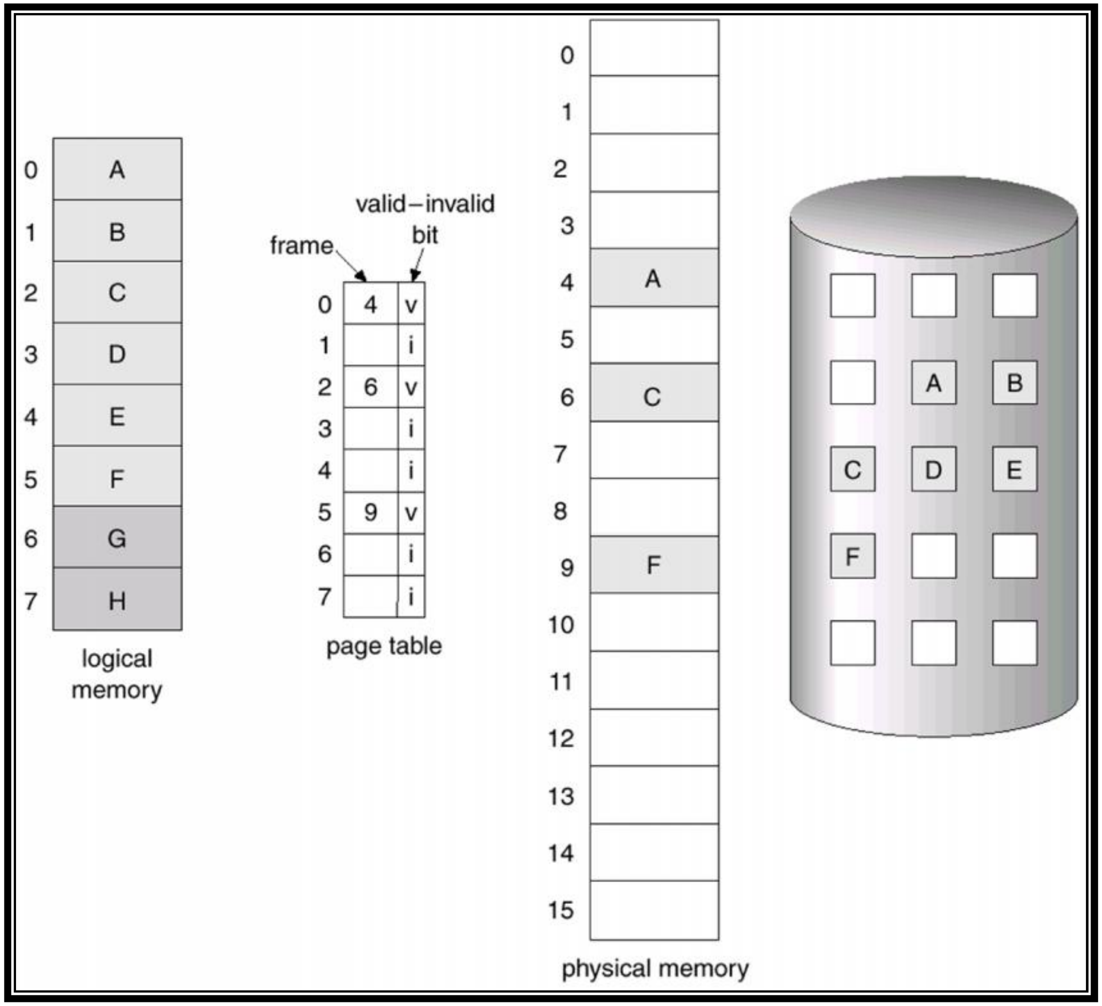
- With each page table entry a valid–invalid bit is associated ($1 \Rightarrow$ in-memory, $0 \Rightarrow$ not-in-memory)
- Initially valid–invalid but is set to 0 on all entries.
- Example of a page table snapshot.



page table

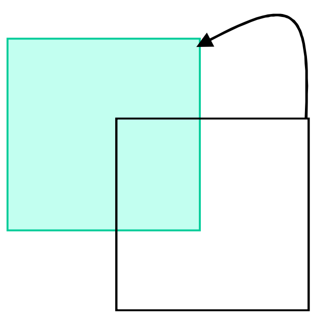
- During address translation, if valid–invalid bit in page table entry is $0 \Rightarrow$ page fault.

Page Table When Some Pages Are Not in Main Memory



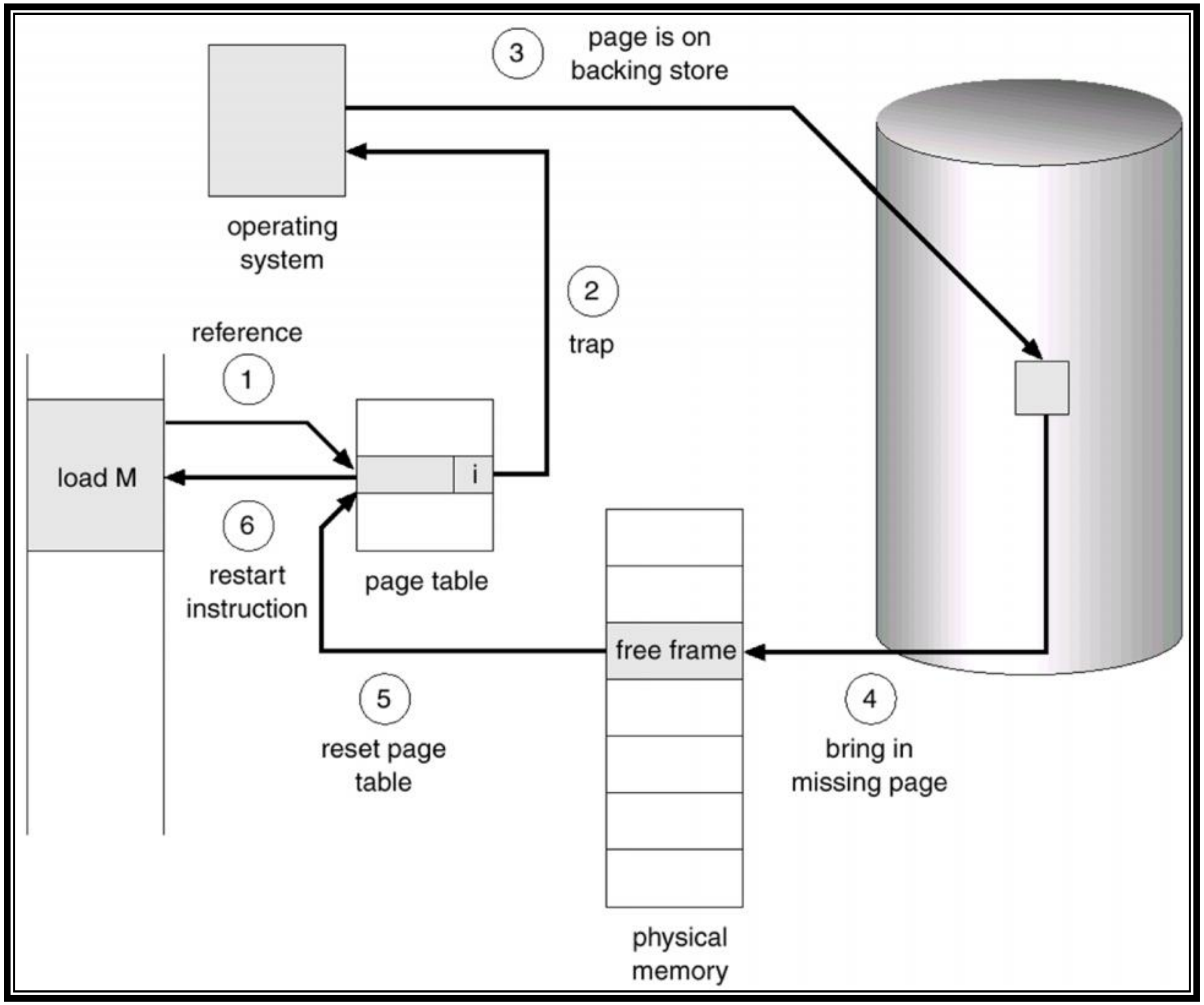
Page Fault

- If there is ever a reference to a page, first reference will trap to OS $\Rightarrow$ page fault
- OS looks at another table to decide:
  - Invalid reference $\Rightarrow$ abort.
  - Just not in memory.
- Get empty frame.
- Swap page into frame.
- Reset tables, validation bit = 1.
- Restart instruction: Least Recently Used
  - block move



  - auto increment/decrement location

Steps in Handling a Page Fault



Virtual memory...

- Virtual memory system can be implemented as an extension of paged or segmented memory management or sometimes as a combination of both.
- In this scheme, the operating system has the ability to execute a program which is only partially loaded in memory.

Missing pages

- What happens when an executing program references an address that is not in main memory?
- Here, both hardware (H/W) and software (S/W) cooperate and solve the problem:

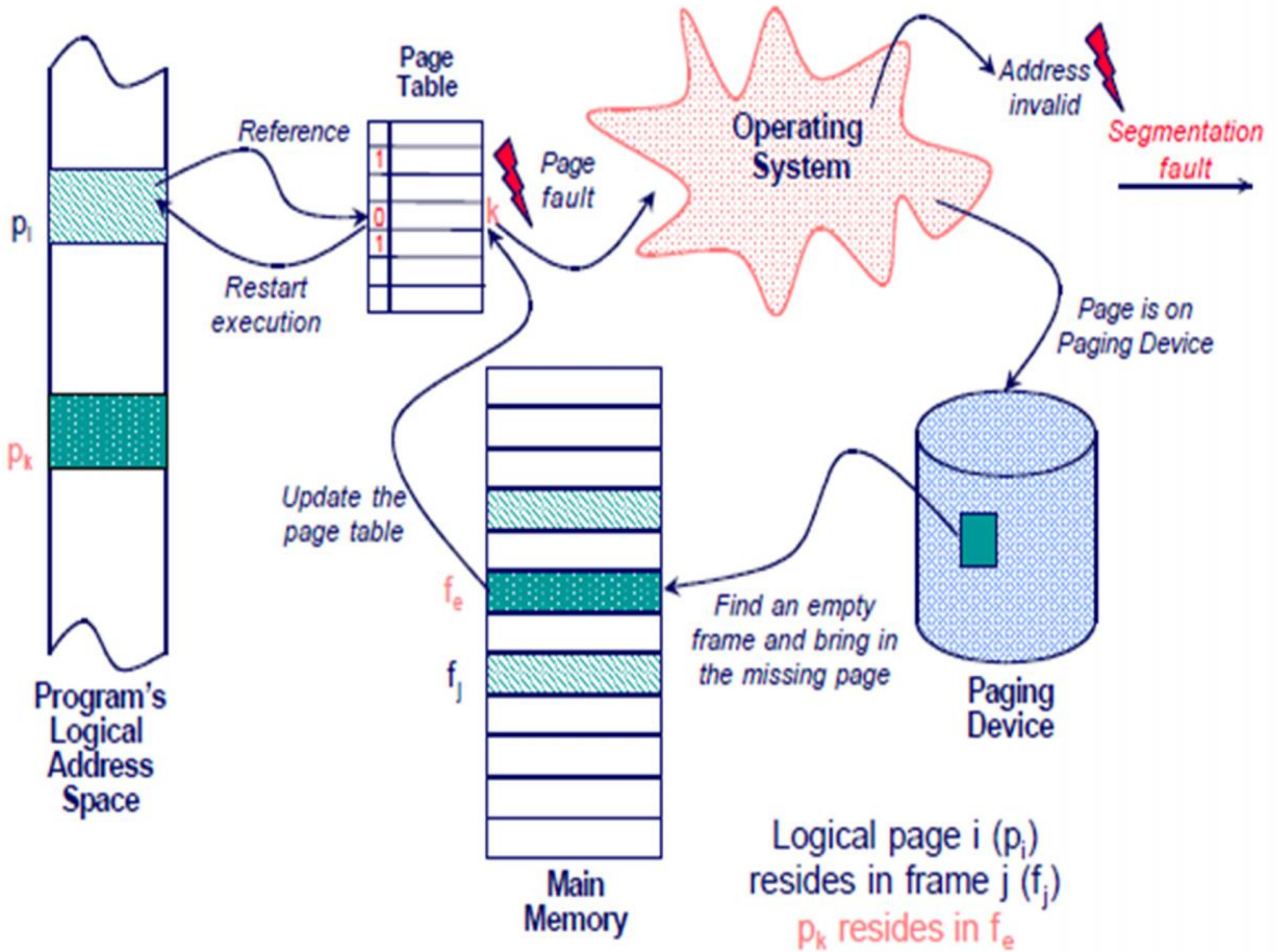
Missing pages...

- The page table is extended with an extra bit, present. Initially, all the present bits are cleared (H/W and S/W).
- While doing the address translation, the MMU checks to see if this bit is set.
- Access to a page whose present bit is not set causes a special hardware trap, called page fault (H/W).
- When a page fault occurs the operating system:
  - brings the page into memory,
  - sets the corresponding present bit, and
  - restarts the execution of the instruction (S/W).
- Most likely, the page carrying the address will be on the paging device,

Page fault handling—by words

- When a page fault occurs, the system:
  - ✓ marks the current process as blocked (waiting for a page),
  - ✓ finds an empty frame or make a frame empty in main memory,
  - ✓ determines the location of the requested page on paging device,
  - ✓ performs an I/O operation to fetch the page to main memory
  - ✓ triggers a " page fetched'' event (e.g., special form of I/O completion interrupt) to wake up the process.

Page fault handling—by picture



Basic policies

- The operating system must make several decisions:
  - Allocation — how much real memory to allocate to each (ready) program?
  - Fetching — when to bring the pages into main memory?
  - Placement — where in the memory the fetched page should be loaded?
  - Replacement — what page should be removed from main memory?

Allocation Policy

- In general, the allocation policy deals with conflicting requirements:
  - The fewer the frames allocated for a program, the higher the page fault rate.
  - The fewer the frames allocated for a program, the more programs can reside in memory; thus, decreasing the need of swapping.
  - Allocating additional frames to a program beyond a certain number results in little or only moderate gain in performance.
  - The number of allocated pages (also known as resident set size) can be fixed or can be variable during the execution of a program.

Fetch Policy

- Demand paging
  - Start a program with no pages loaded; wait until it references a page; then load the page (this is the most common approach used in paging systems).
- Request paging
  - Similar to overlays, let the user identify which pages are needed (not practical, leads to over estimation and also user may not know what to ask for.)
- Pre-paging
  - Start with one or a few pages pre-loaded. As pages are referenced, bring in other (not yet referenced) pages too.

- Opposite to fetching, the cleaning policy deals with determining when a modified (dirty) page should be written back to the paging device.

Placement Policy

- This policy usually follows the rules about paging and segmentation discussed earlier.
- Given the matching sizes of a page and a frame, placement with paging is straightforward.
- Segmentation requires more careful placement, especially when not combined with paging.
- Placement in pure segmentation is an important issue and must consider “free” memory management policies.
- With the recent developments in non-uniform memory access (NUMA) distributed memory multiprocessor systems, placement becomes a major concern.

What happens if there is no free frame?

- Page replacement – find some page in memory, but not really in use, swap it out.
  - algorithm
  - performance – want an algorithm which will result in minimum number of page faults.
- Same page may be brought into memory several times.

Performance of Demand Paging

- For most computer systems, memory access time ranges from 10 to 200 nanoseconds
- Page Fault Rate $0 \le p \le 1.0$
  - if p = 0 no page faults
  - if p = 1, every reference is a fault
- Effective Access Time (EAT)

EAT = (1 – p) x memory access
+ p (page fault overhead
+ [swap page out]
+ swap page in
+ restart overhead)

Demand Paging Example

- Memory access time = 1 microsecond

- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out.

- Swap Page Time = 10 msec = 10,000 msec

$$EAT = (1 - p) \times 1 + p\ (15000)$$

$$1 + 15000P \qquad \text{(in msec)}$$

Process Creation

- Virtual memory allows other benefits during process creation:

  - Copy-on-Write

  - Memory-Mapped Files

Copy-on-Write

- 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.
- All unmodified pages can be shared by the parent and child processes.
- Free pages are allocated from a pool of zeroed-out pages.

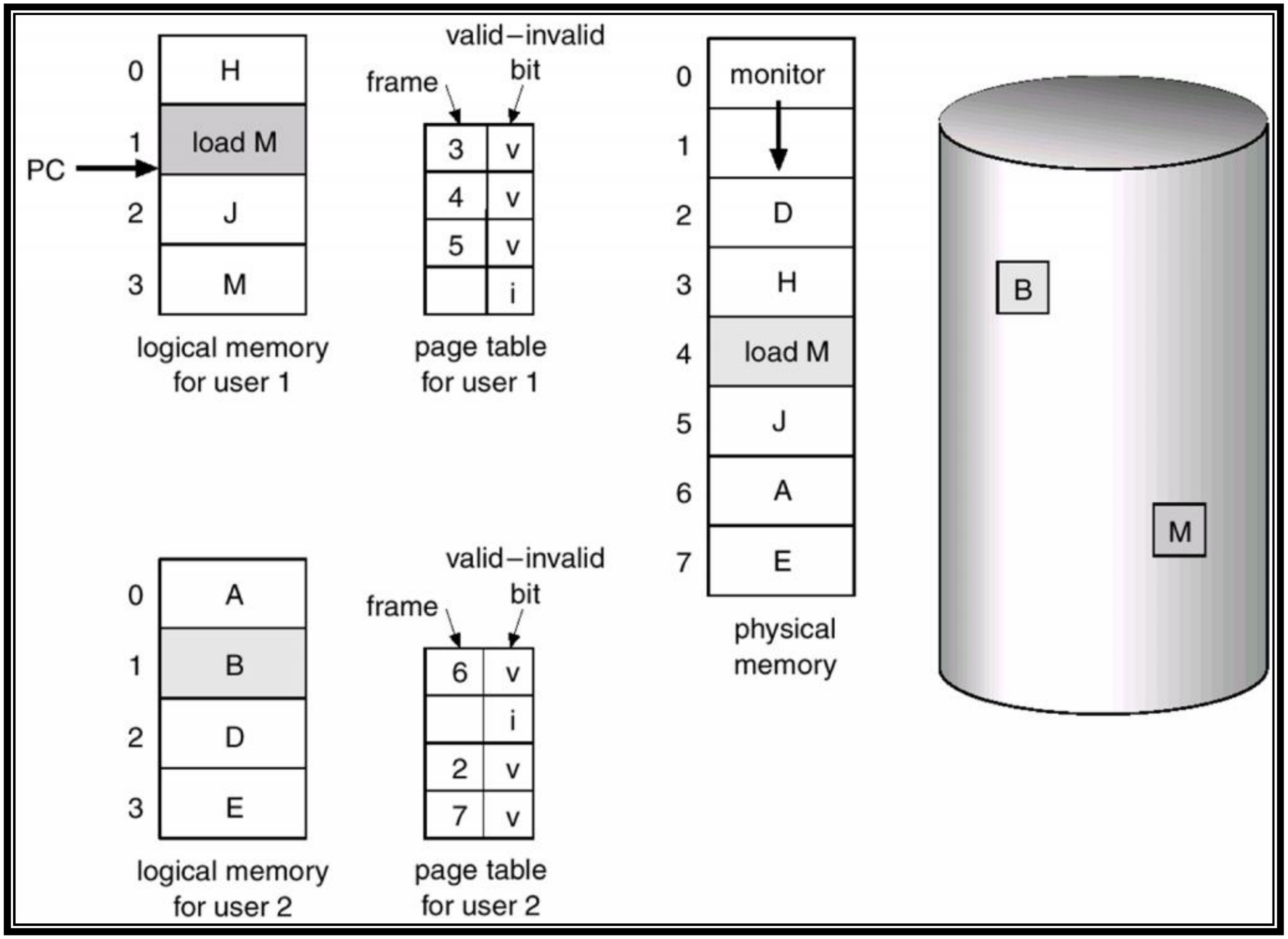
Replacement Policy

- The most studied area of the memory management is the replacement policy or victim selection to satisfy a page fault:
  - FIFO—the frames are treated as a circular list; the oldest (longest resident) page is replaced.
  - LRU—the frame whose contents have not been used for the longest time is replaced.
  - OPT—the page that will not be referenced again for the longest time is replaced (prediction of the future; purely theoretical, but useful for comparison.)
  - Random—a frame is selected at random.

Page Replacement

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement.
- Use modify (dirty) bit to reduce overhead of page transfers – only modified pages are written to disk.
- Page replacement completes separation between logical memory and physical memory
  - large virtual memory can be provided on a smaller physical memory.

Need For Page Replacement



Basic Page Replacement

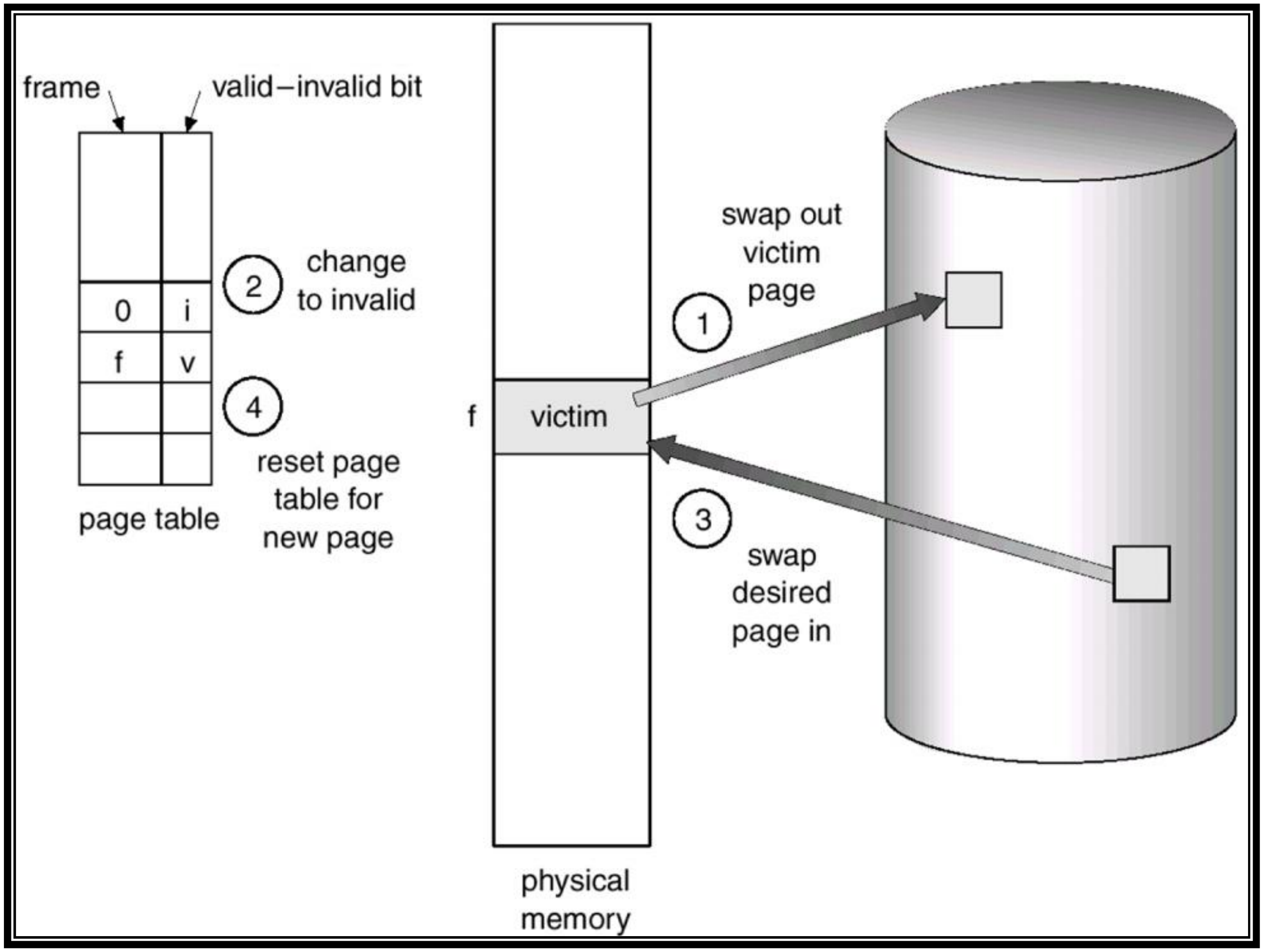
1. Find the location of the desired page on disk.

2. Find a free frame:
   - If there is a free frame, use it.
   - If there is no free frame, use a page replacement algorithm to select a victim frame.

3. Read the desired page into the (newly) free frame. Update the page and frame tables.

4. Restart the process.

Page Replacement



Page Replacement Algorithms

- Want lowest page-fault rate.
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string.
- In all our examples, the reference string is

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

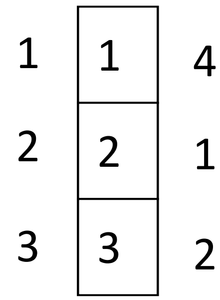
Graph of Page Faults Versus The Number of Frames

First-In-First-Out (FIFO) Algorithm

- The frames are treated as a circular list; the oldest (longest resident) page is replaced.
- The OS maintains a list of all pages currently in memory, with:
  - the page at the head of the list the oldest one and
  - the page at the tail the most recent arrival.
- On a page fault, the page at the head is removed and the new page added to the tail of the list.

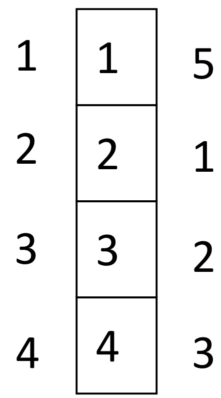
First-In-First-Out (FIFO) Algorithm...

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames (3 pages can be in memory at a time per process)



9 page faults

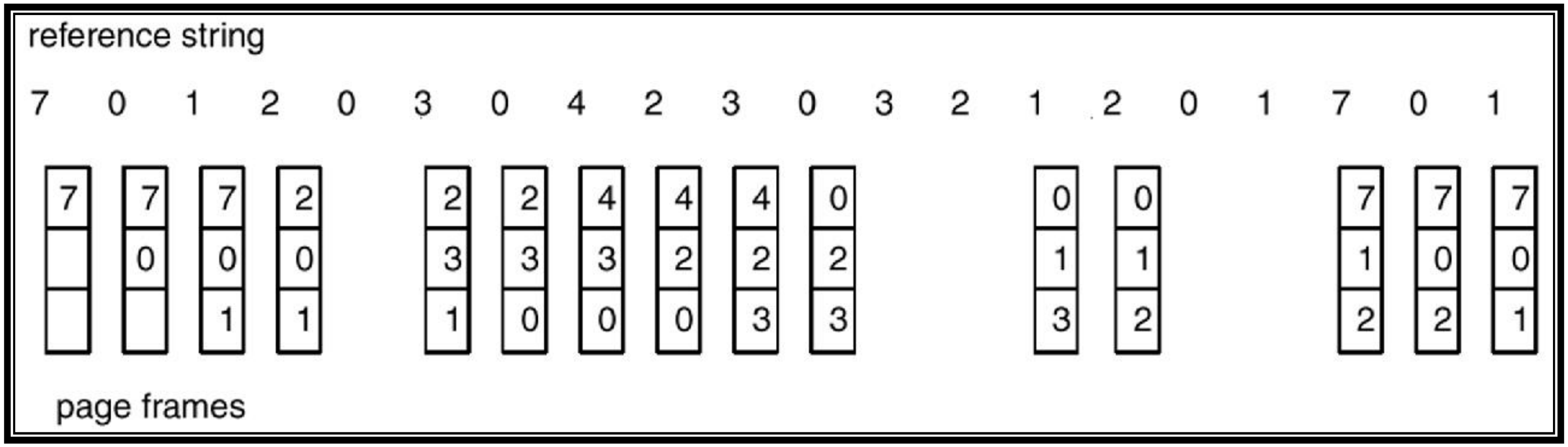
- 4 frames



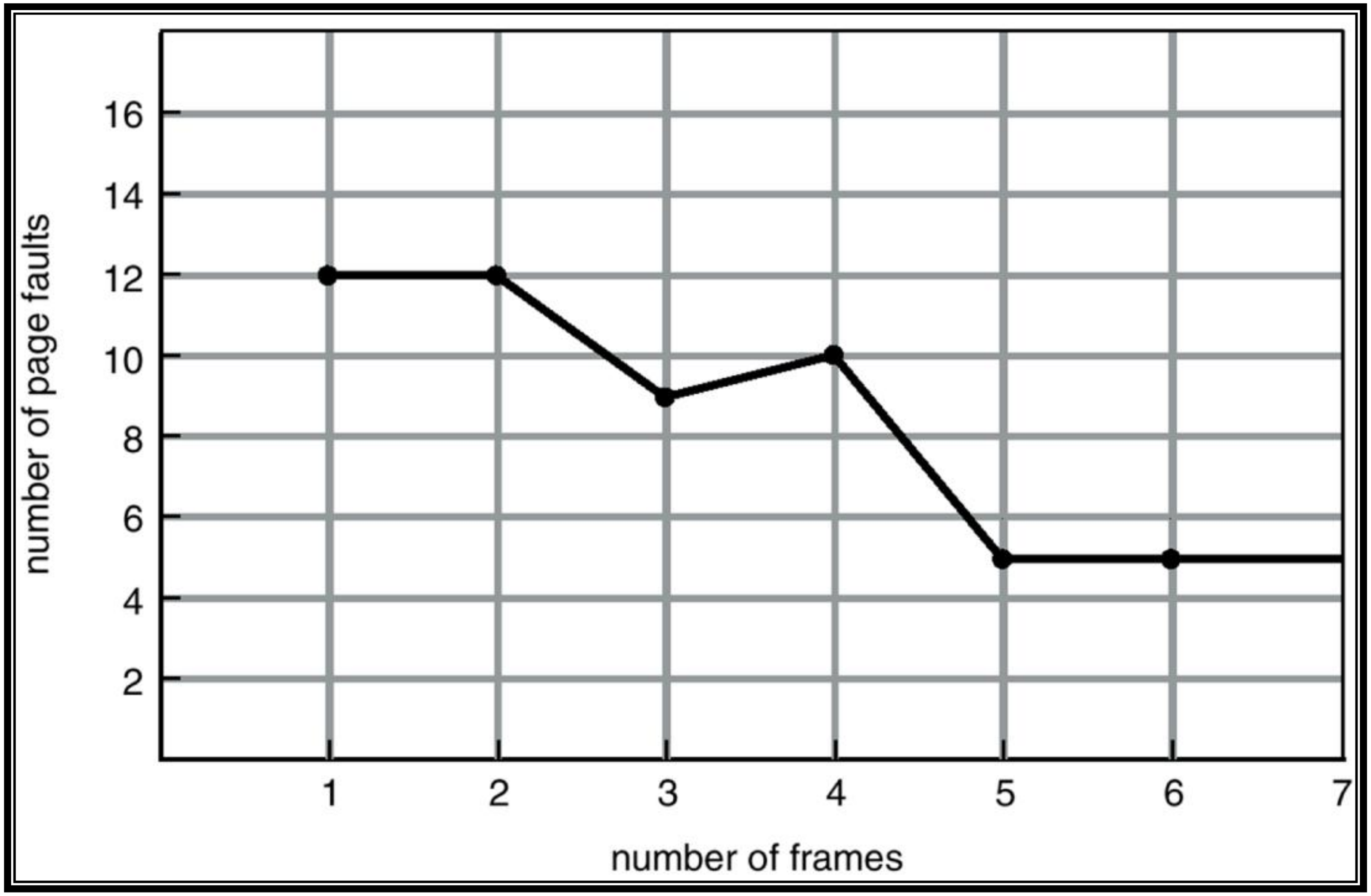
10 page faults

- FIFO Replacement – Belady's Anomaly
  - more frames ⇒ less page faults

FIFO Page Replacement



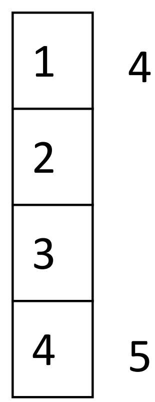
FIFO Illustrating Belady's Anamoly



Optimal Algorithm

- Replace page that will not be used for longest period of time.
- 4 frames example

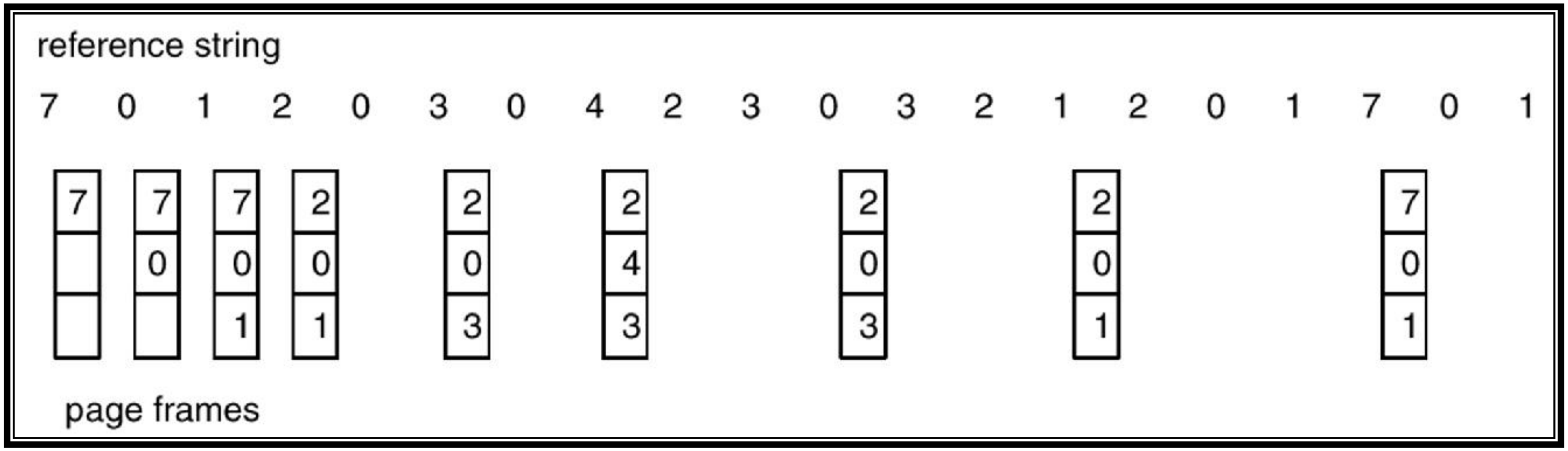
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



6 page faults

- How do you know this?
- Used for measuring how well your algorithm performs.

Optimal Page Replacement



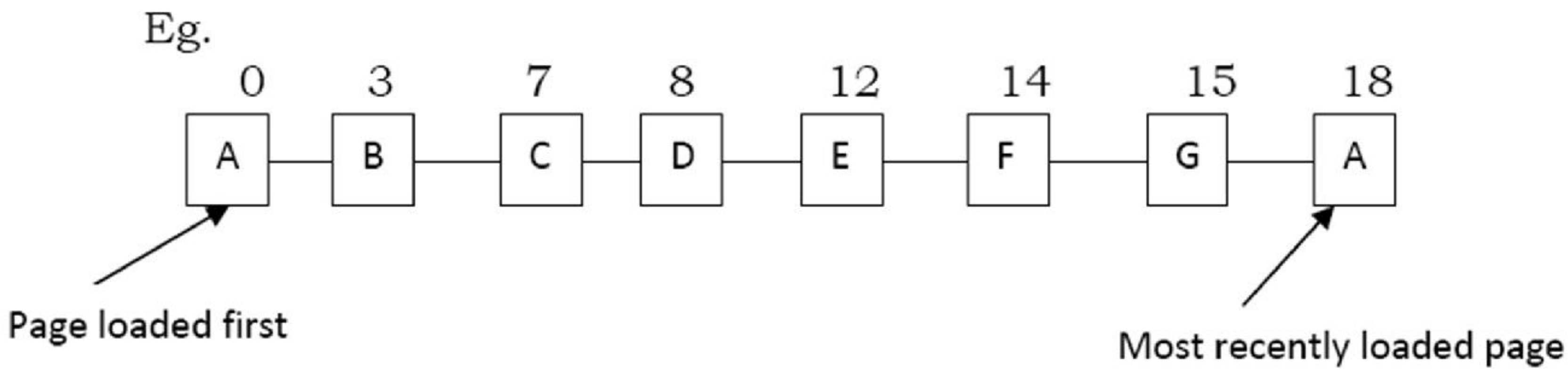
The Second Chance Page Replacement algorithm

- A simple modification to FIFO that avoids the problem of throwing out a heavily used page is to inspect the R bit of the oldest page.

-If R→0, then the page is both old and unused, so it is replaced immediately.

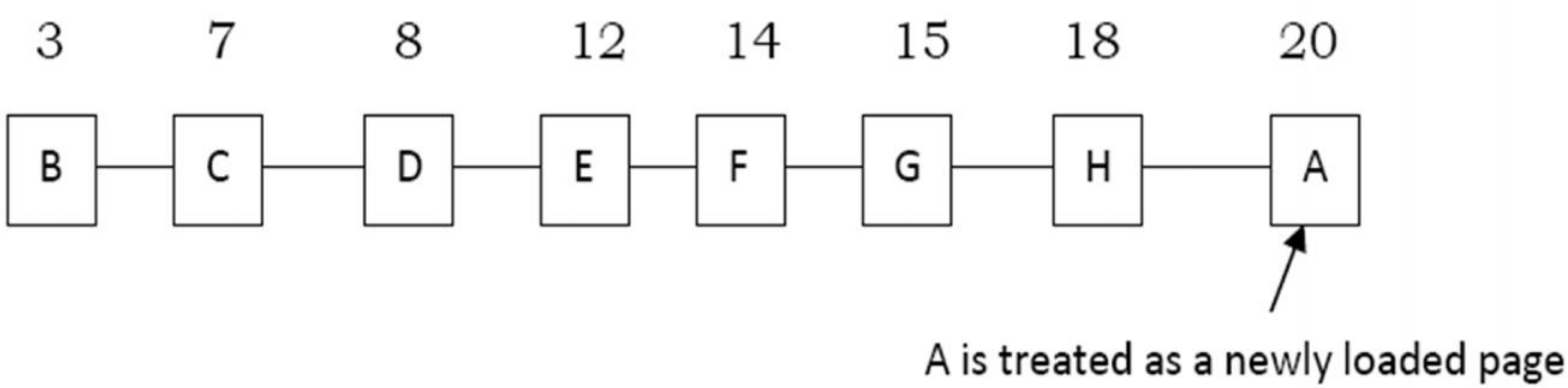
- If R→1,
  - the bit is cleared,
  - the page is put onto the end of the list of pages, and
  - its load time is updated as though it had just arrived in memory. Then the search continues.

- The operation of this algorithm is called second chance.



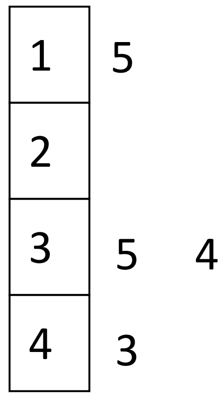
- Suppose a page fault occurs at time 20. Oldest page is A=>, Check for R bit.

- If A has the R bit cleared, it is evicted from memory.
- If R bit set to 1, A is put onto the end of the list and its “load time” is reset to the current time (20). R is also cleared.



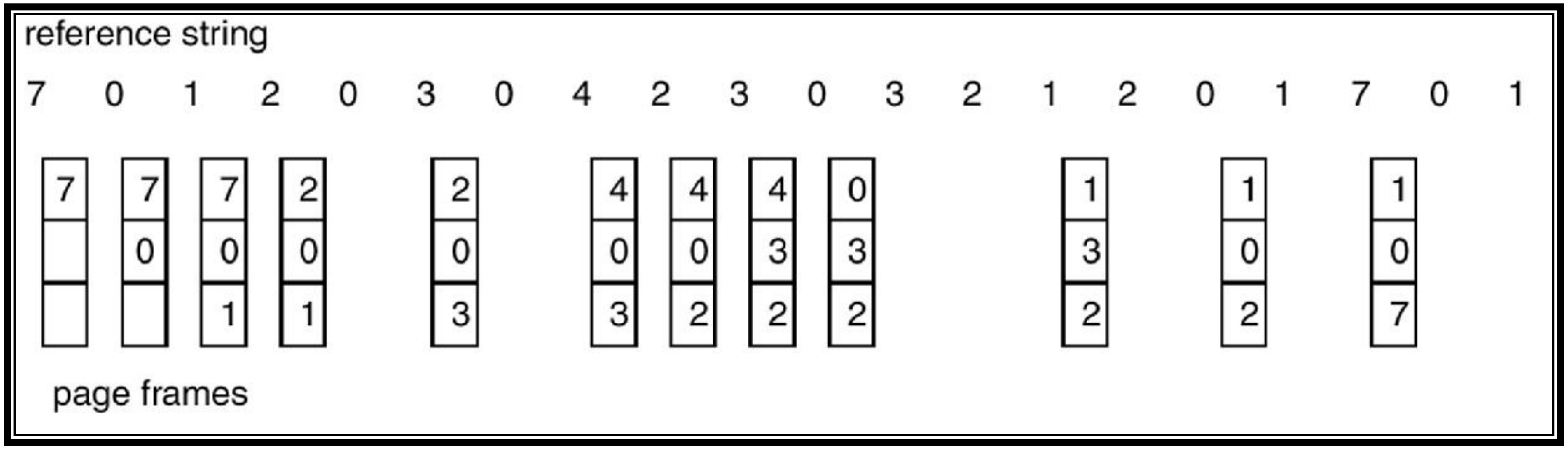
Least Recently Used (LRU) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



- 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 determine which are to change.

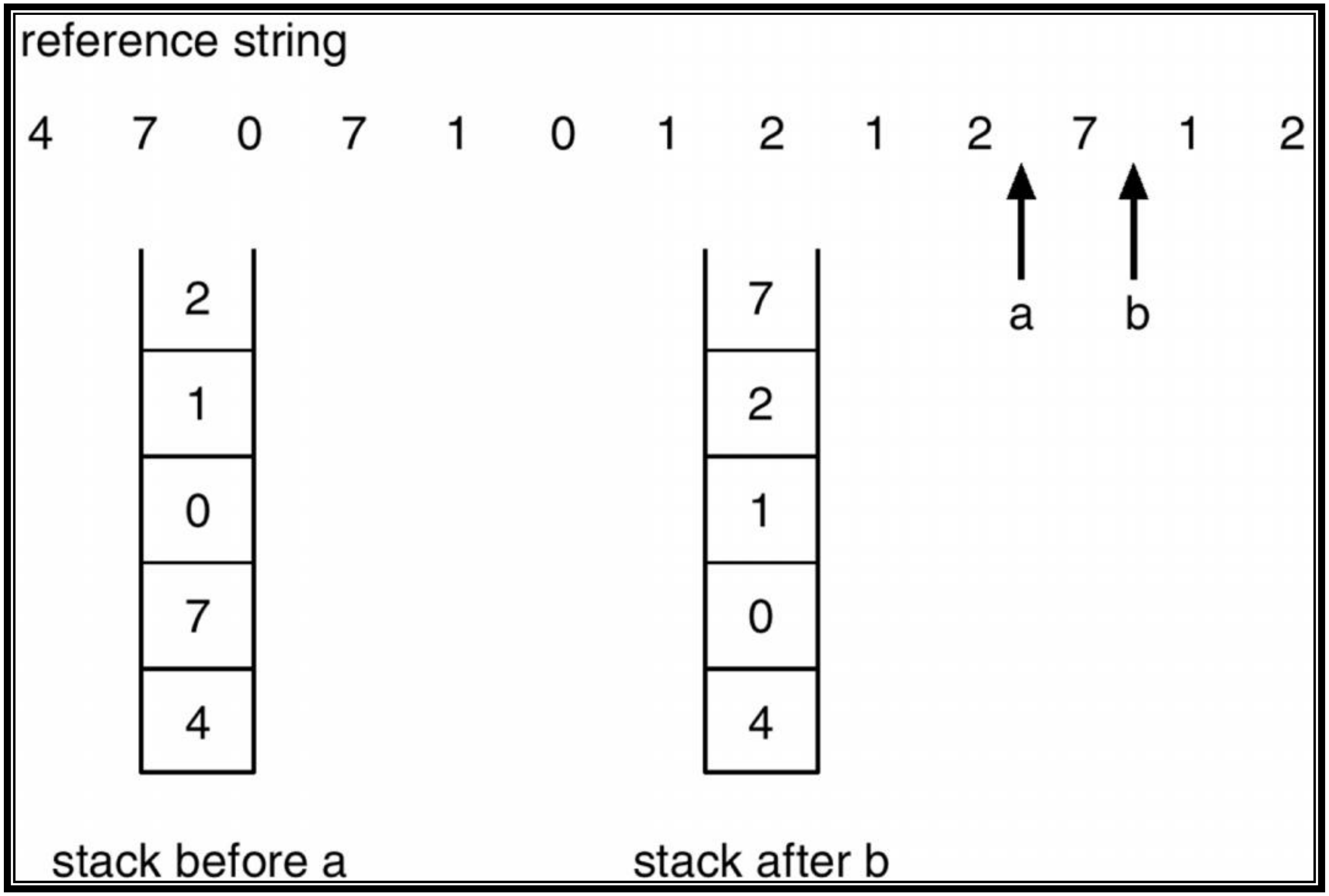
LRU Page Replacement



LRU Algorithm (Cont.)

- Stack implementation – keep a stack of page numbers in a double link form:
  - Page referenced:
    - move it to the top
    - requires 6 pointers to be changed
  - No search for replacement

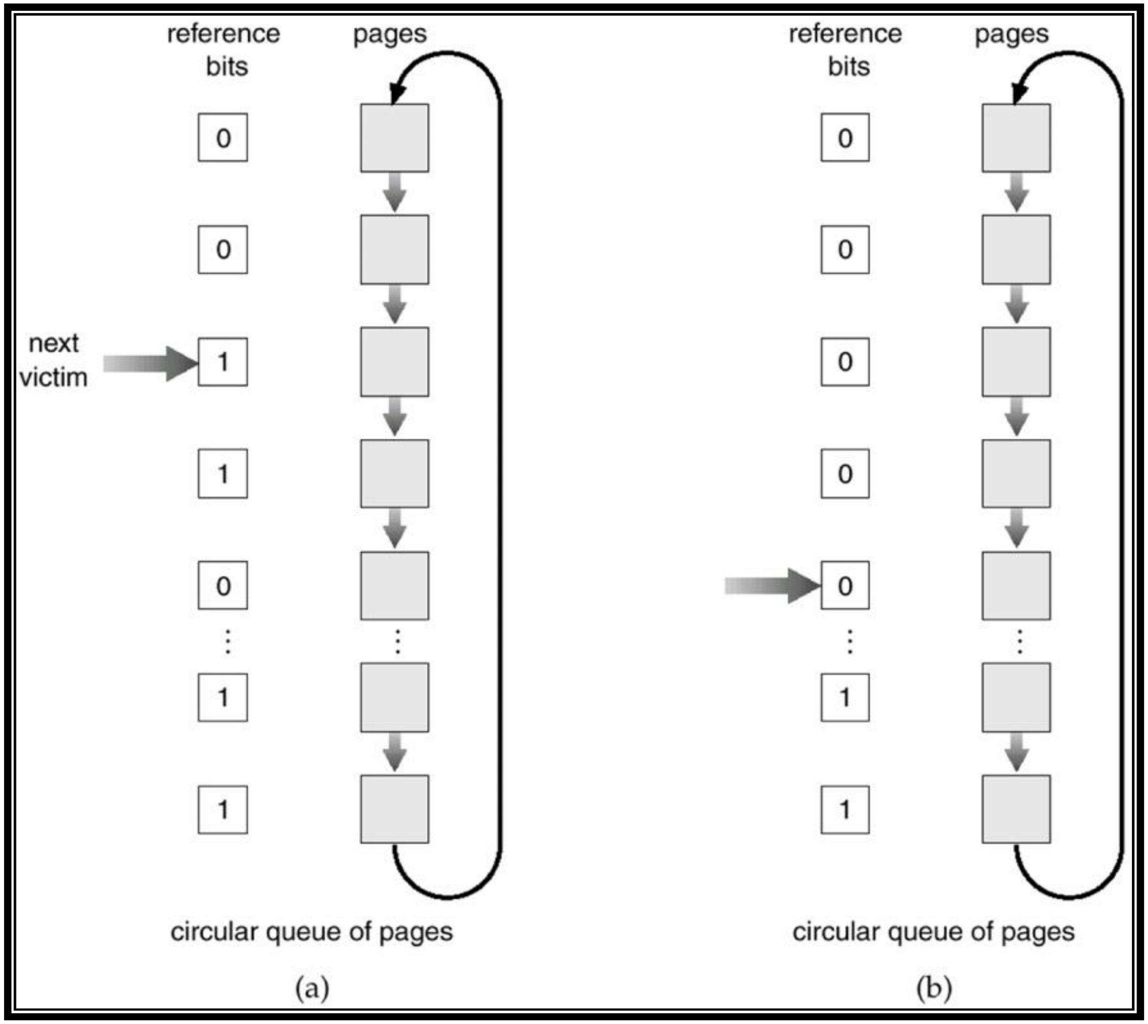
Use Of A Stack to Record The Most Recent Page References



LRU Approximation Algorithms

- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1.
  - Replace the one which is 0 (if one exists). We do not know the order, however.
- Second chance
  - Need reference bit.
  - Clock replacement.
  - If page to be replaced (in clock order) has reference bit = 1. then:
    - set reference bit 0.
    - leave page in memory.
    - replace next page (in clock order), subject to same rules.

Second-Chance (clock) Page-Replacement Algorithm



Counting Algorithms

- Keep a counter of the number of references that have been made to each page.

- LFU Algorithm: replaces page with smallest count.

- MFU Algorithm: based on the argument that the page with the smallest count was probably just brought in and has yet to be used.

Allocation of Frames

- Each process needs minimum number of pages.
- Example: IBM 370 – 6 pages to handle SS MOVE instruction:
  - instruction is 6 bytes, might span 2 pages.
  - 2 pages to handle from.
  - 2 pages to handle to.
- Two major allocation schemes.
  - fixed allocation
  - priority allocation

Fixed Allocation

- Equal allocation – e.g., if 100 frames and 5 processes, give each 20 pages.
- Proportional allocation – Allocate according to the size of process.
  - $s_i = \text{size of process } p_i$
  - $S = \sum s_i$
  - $m = \text{total number of frames}$
  - $a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$

$$m = 64$$

$$s_i = 10$$

$$s_2 = 127$$

$$a_1 = \frac{10}{137} \times 64 \approx 5$$

$$a_2 = \frac{127}{137} \times 64 \approx 59$$

Priority Allocation

- Use a proportional allocation scheme using priorities rather than size.

- If process P_i generates a page fault,
  - select for replacement one of its frames.
  - select for replacement a frame from a process with lower priority number.

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.

- Local replacement – each process selects from only its own set of allocated frames.