Main Memory Management

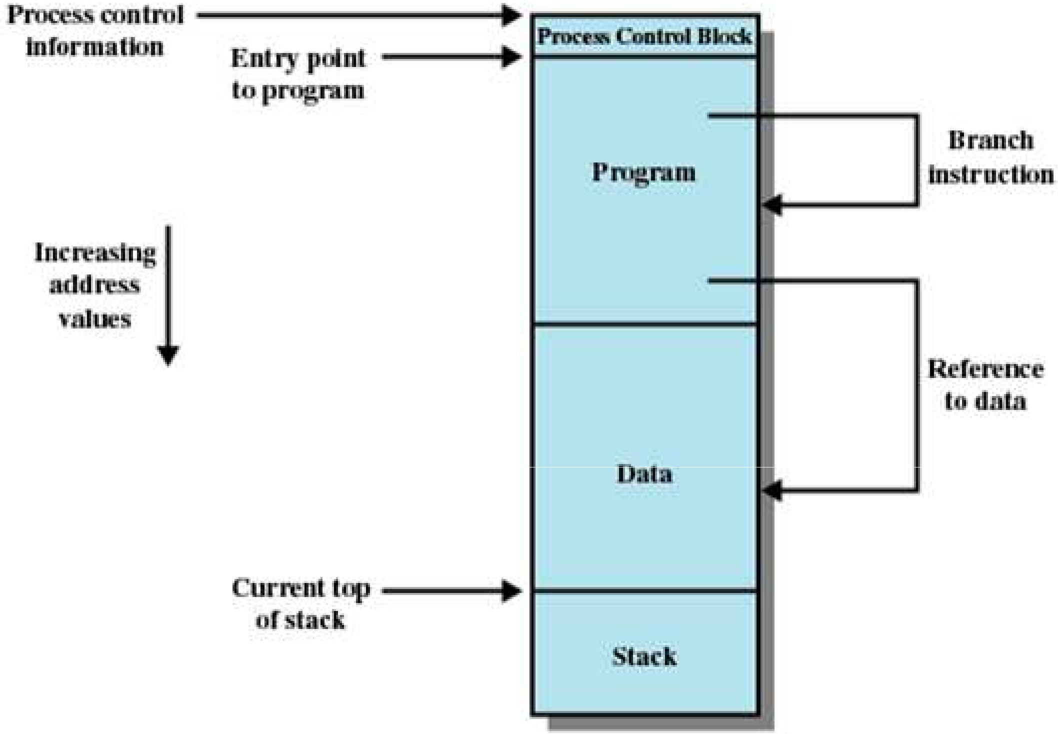
Reference – [Stallings] [Galvin]

Memory Management

- Subdividing memory to accommodate multiple processes
- Memory needs to be allocated to ensure a reasonable supply of ready processes to consume available processor time
- Features
  - Relocation
  - Protection
  - Sharing
  - Logical Organization
  - Physical Organization

Memory Management Requirements

- Relocation
  - Programmer does not know where the program will be placed in memory when it is executed
  - While the program is executing, it may be swapped to disk and returned to main memory at a different location (relocated)
  - Memory references must be translated in the code to actual physical memory address



Addressing Requirements for a Process

Memory Management Requirements

- Protection
  - Processes should not be able to reference memory locations in another process without permission
  - Impossible to check absolute addresses at compile time
  - Must be checked at run time
  - Memory protection requirement must be satisfied by the processor (hardware) rather than the operating system (software)
    - Operating system cannot anticipate all of the memory references a program will make

Memory Management Requirements

- Sharing
  - Allow several processes to access the same portion of memory
  - Better to allow each process access to the same copy of the program rather than have their own separate copy

Memory Management Requirements

- Logical Organization
  - Programs are written in modules
  - Modules can be written and compiled independently
  - Different degrees of protection given to modules (read-only, execute-only)
  - Share modules among processes

Memory Management Requirements

- Physical Organization
  - Two levels of memory (Main and Secondary)
  - Memory available for a program plus its data may be insufficient.
    - Overlaying (Programmer dependent) allows various modules to be assigned the same region of memory
  - Programmer does not know how much space will be available

Fixed Partitioning

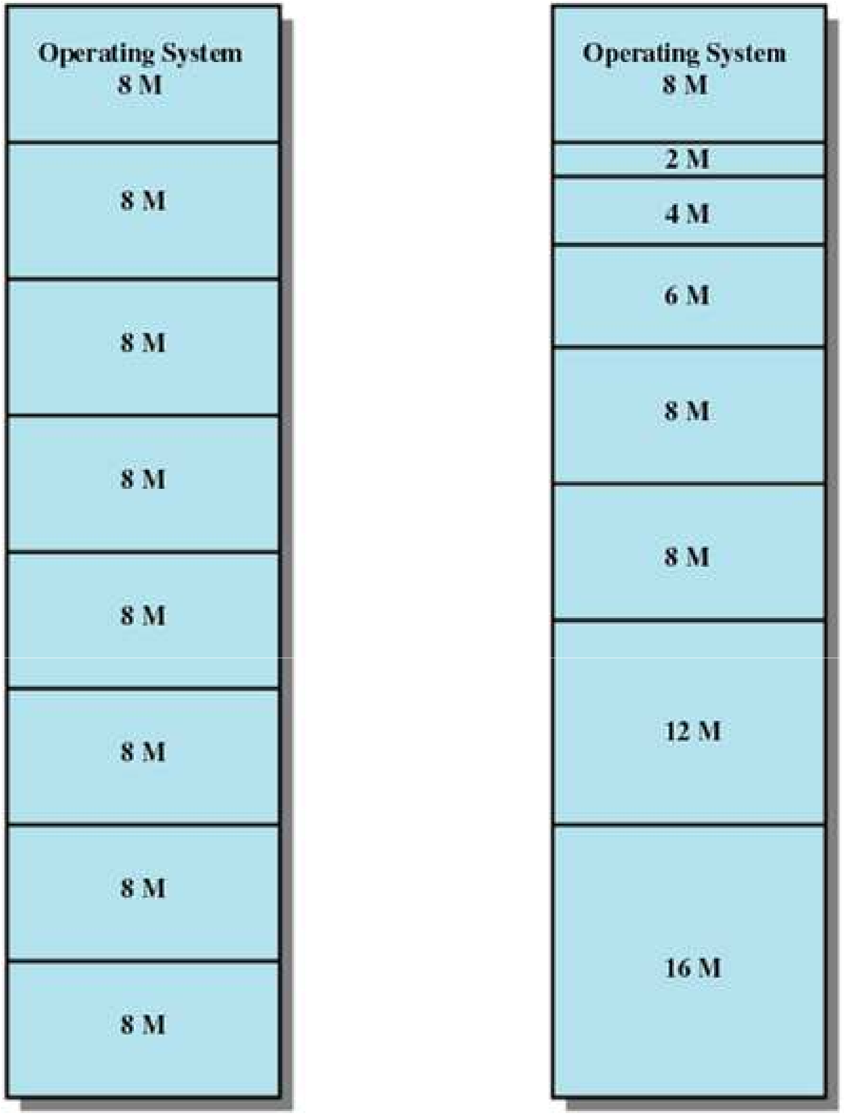
- Equal-size partitions
- Any process whose size is less than or equal to the partition size can be loaded into an available partition
  - If all partitions are full, the operating system can swap a process out of a partition

Difficulties

  - Bigger processes - Overlaying
  - Main memory use is inefficient. Any program, no matter how small, occupies an entire partition. This is called internal fragmentation
  - Fixed number of processes can be accommodated

Placement Algorithm with Partitions

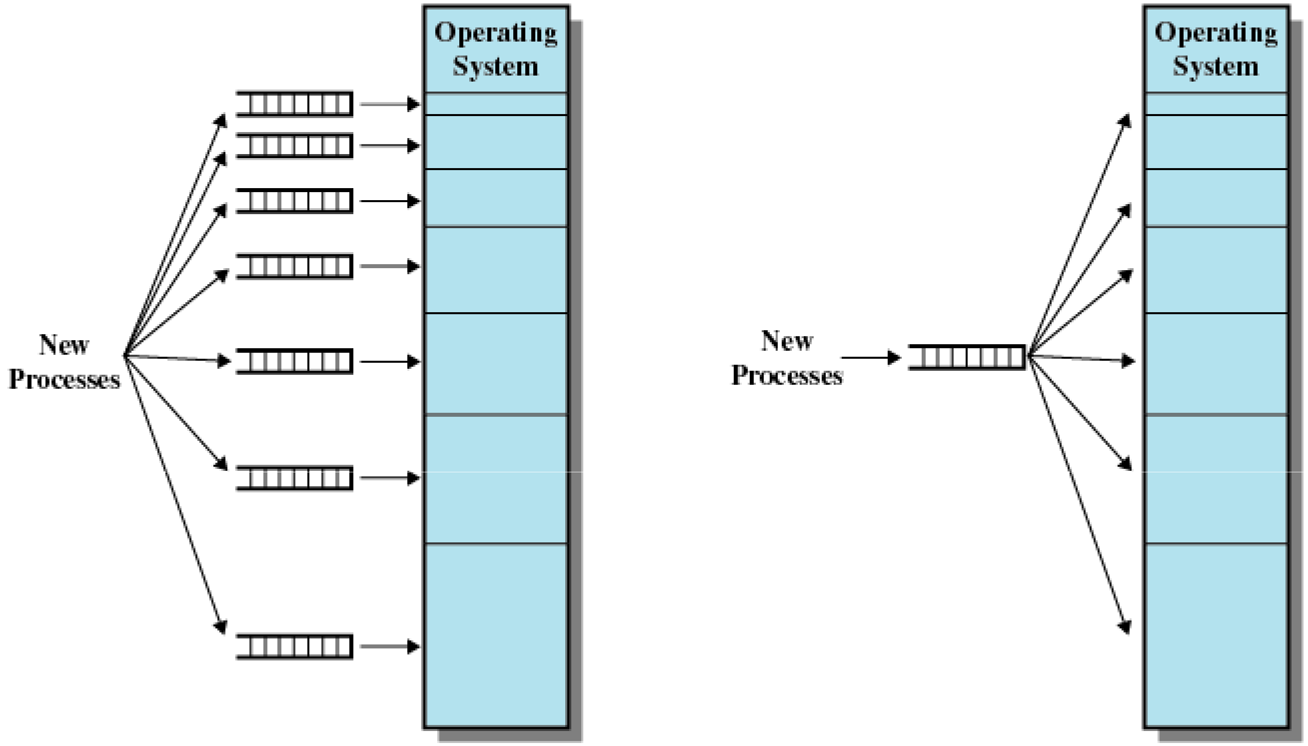
- Equal-size partitions
  - Because all partitions are of equal size, it does not matter which partition is used
- Unequal-size partitions
  - Can assign each process to the smallest partition within which it will fit
  - Queue for each partition
  - Processes are assigned in such a way as to minimize wasted memory within a partition



(a) Equal-size partitions

(b) Unequal-size partitions

Example of Fixed Partitioning of a 64-Mbyte Memory



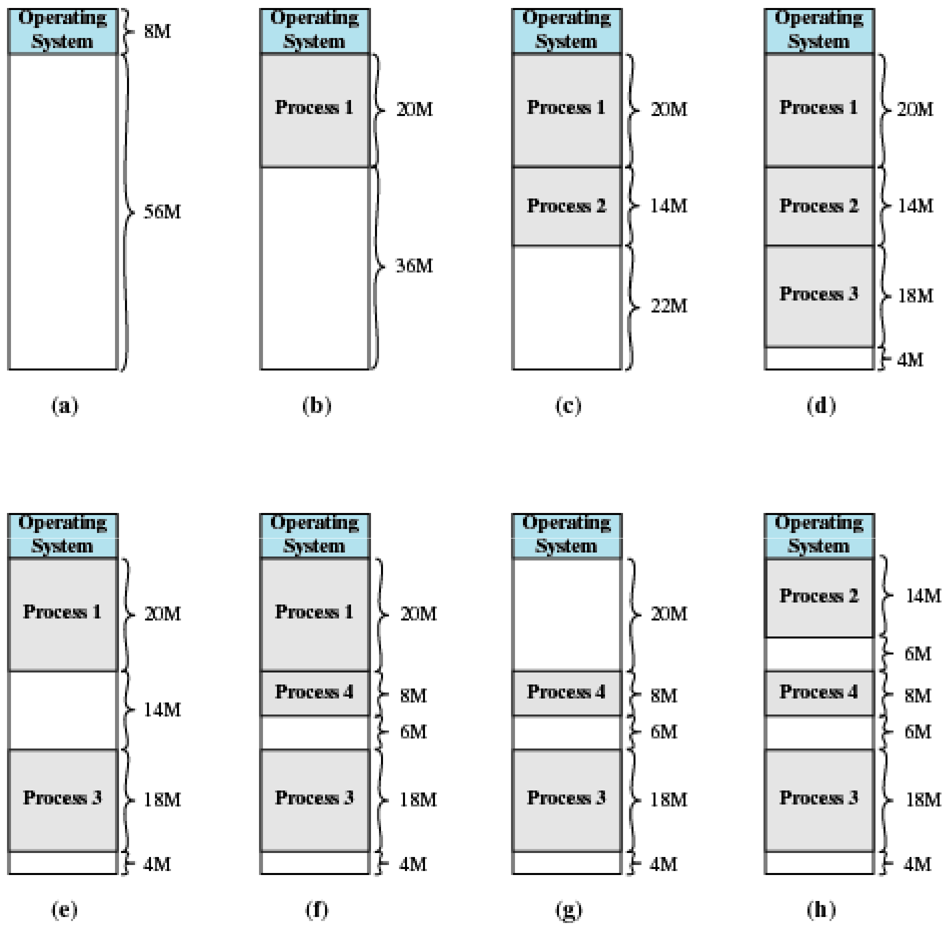
(a) One process queue per partition

(b) Single queue

Memory Assignment for Fixed Partitioning

Dynamic Partitioning

- Partitions are of variable length and number
- Process is allocated exactly as much memory as required (IBM Mainframes)
- Eventually get holes in the memory. This is called *external fragmentation*
- Must use *compaction* to shift processes so they are contiguous and all free memory is in one block



The Effect of Dynamic Partitioning

Dynamic Partitioning Placement Algorithm

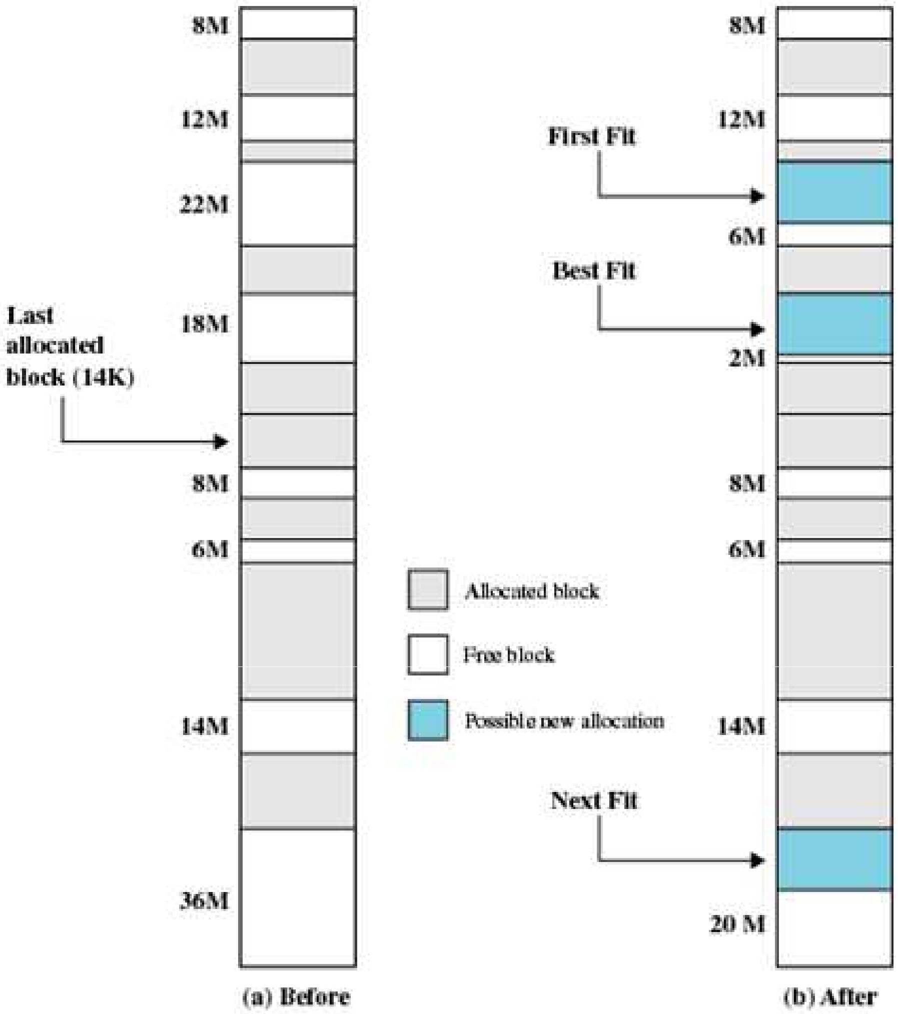
- Operating system must decide which free block to allocate to a process
- Best-fit algorithm
  - Chooses the block that is closest in size to the request
  - Worst performer overall
  - Since smallest block is found for process, the smallest amount of fragmentation is left
  - Memory compaction must be done more often

Dynamic Partitioning Placement Algorithm

- First-fit algorithm
  - Scans memory form the beginning and chooses the first available block that is large enough
  - Fastest
  - May have many process loaded in the front end of memory that must be searched over when trying to find a free block

Dynamic Partitioning Placement Algorithm

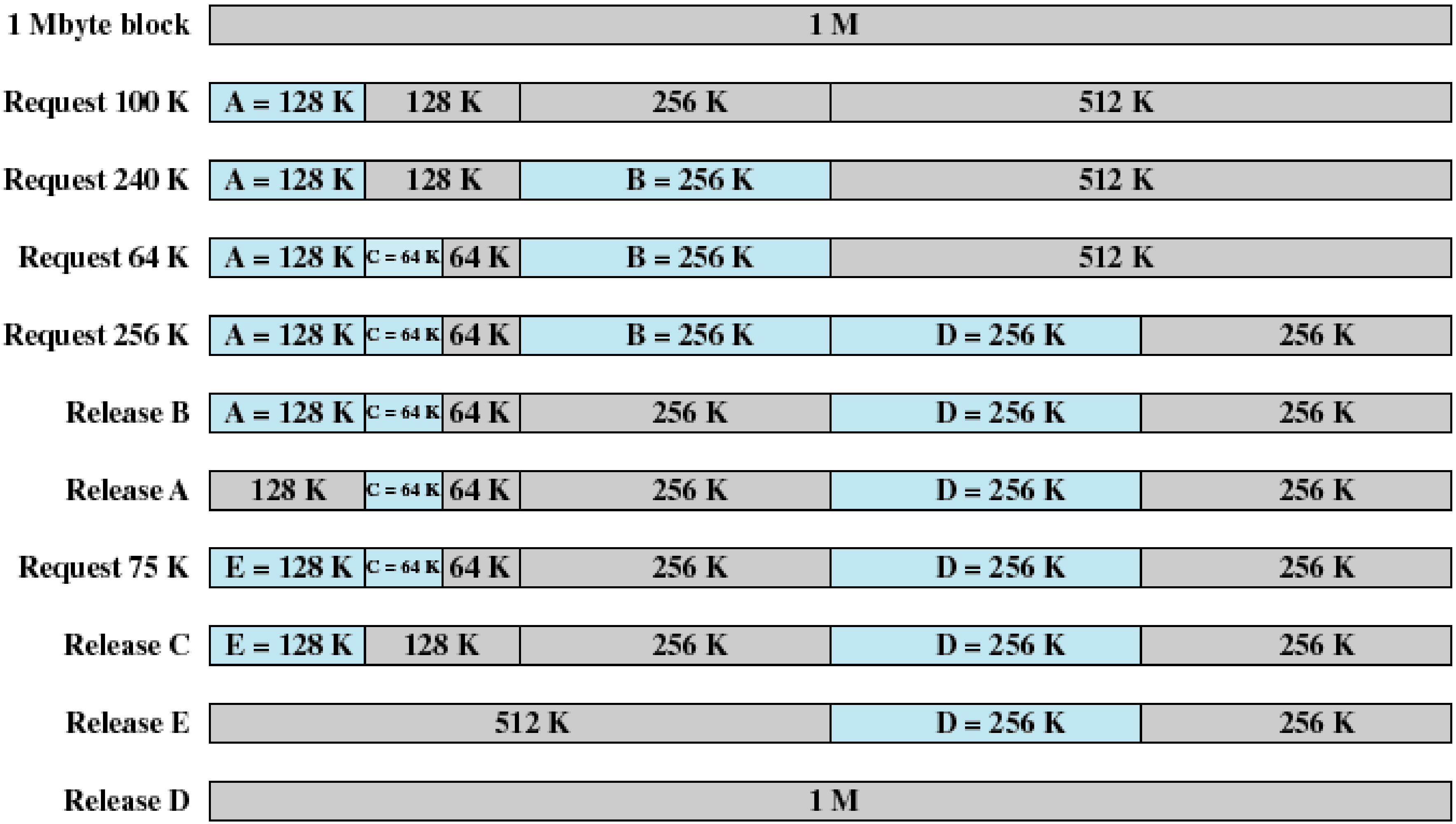
- Next-fit
  - Scans memory from the location of the last placement
  - More often allocate a block of memory at the end of memory where the largest block is found
  - The largest block of memory is broken up into smaller blocks
  - Compaction is required to obtain a large block at the end of memory



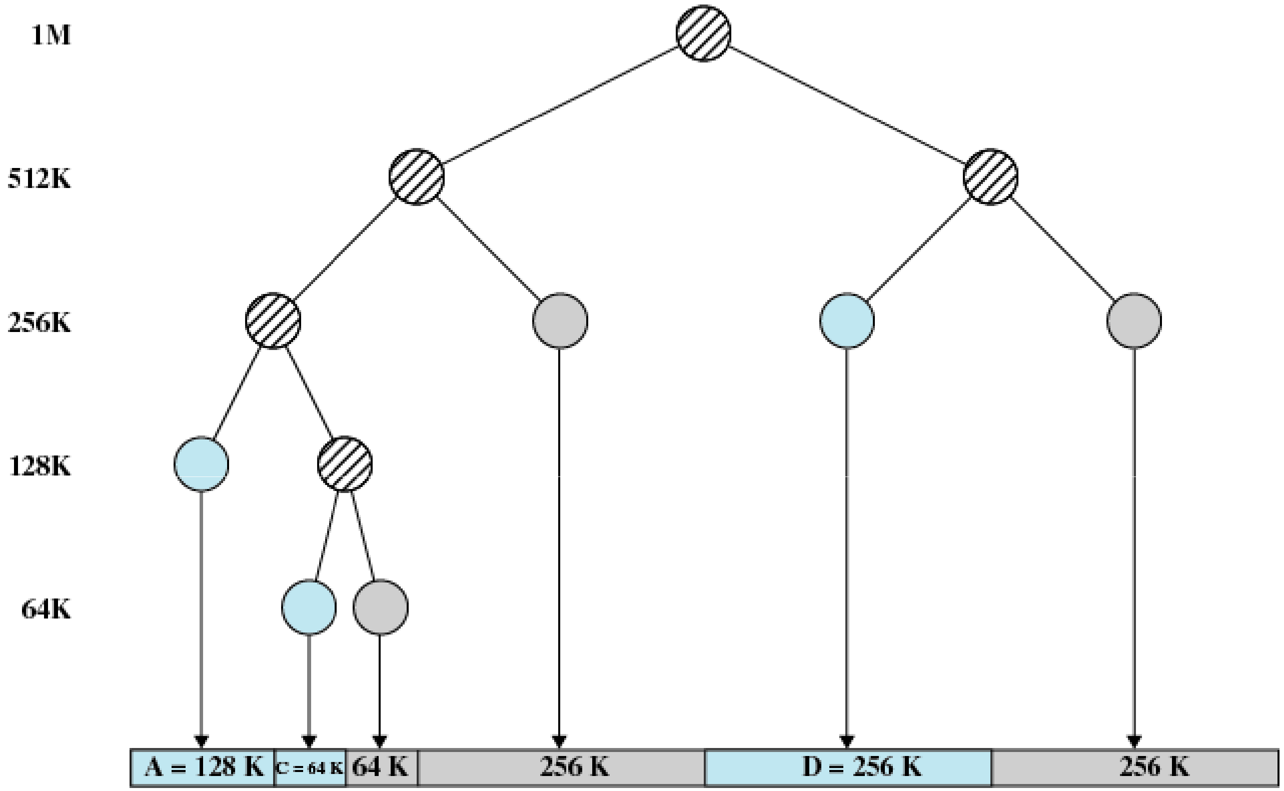
Example Memory Configuration Before and After Allocation of 16 Mbyte Block

Buddy System

- Entire space available is treated as a single block of 2^U
- If a request of size s such that $2^{U-1} < s <= 2^U$, entire block is allocated
  - Otherwise block is split into two equal buddies
  - Process continues until smallest block greater than or equal to s is generated
- Used for Parallel Systems



Example of Buddy System

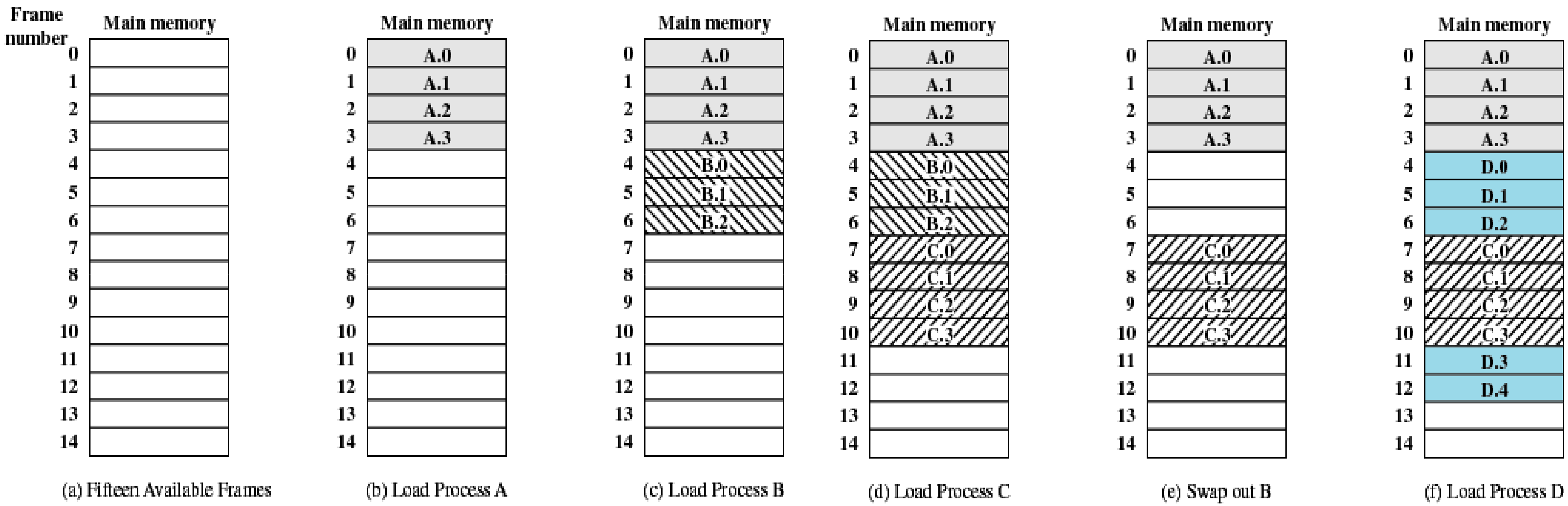


Tree Representation of Buddy System

Paging

- Partition memory into small equal fixed-size chunks and divide each process into the same size chunks
- The chunks of a process are called pages and chunks of memory are called frames
- Operating system maintains a page table for each process
  - Contains the frame location for each page in the process
  - Memory address consist of a page number and offset within the page

Assignment of Process Pages to Free Frames



Assignment of Process Pages to Free Frames

Page Tables for Example

0	0
1	1
2	2
3	3

Process A page table

0	Ñ
1	Ñ
2	Ñ

Process B page table

0	7
1	8
2	9
3	10

Process C page table

0	4
1	5
2	6
3	11
4	12

Process D page table

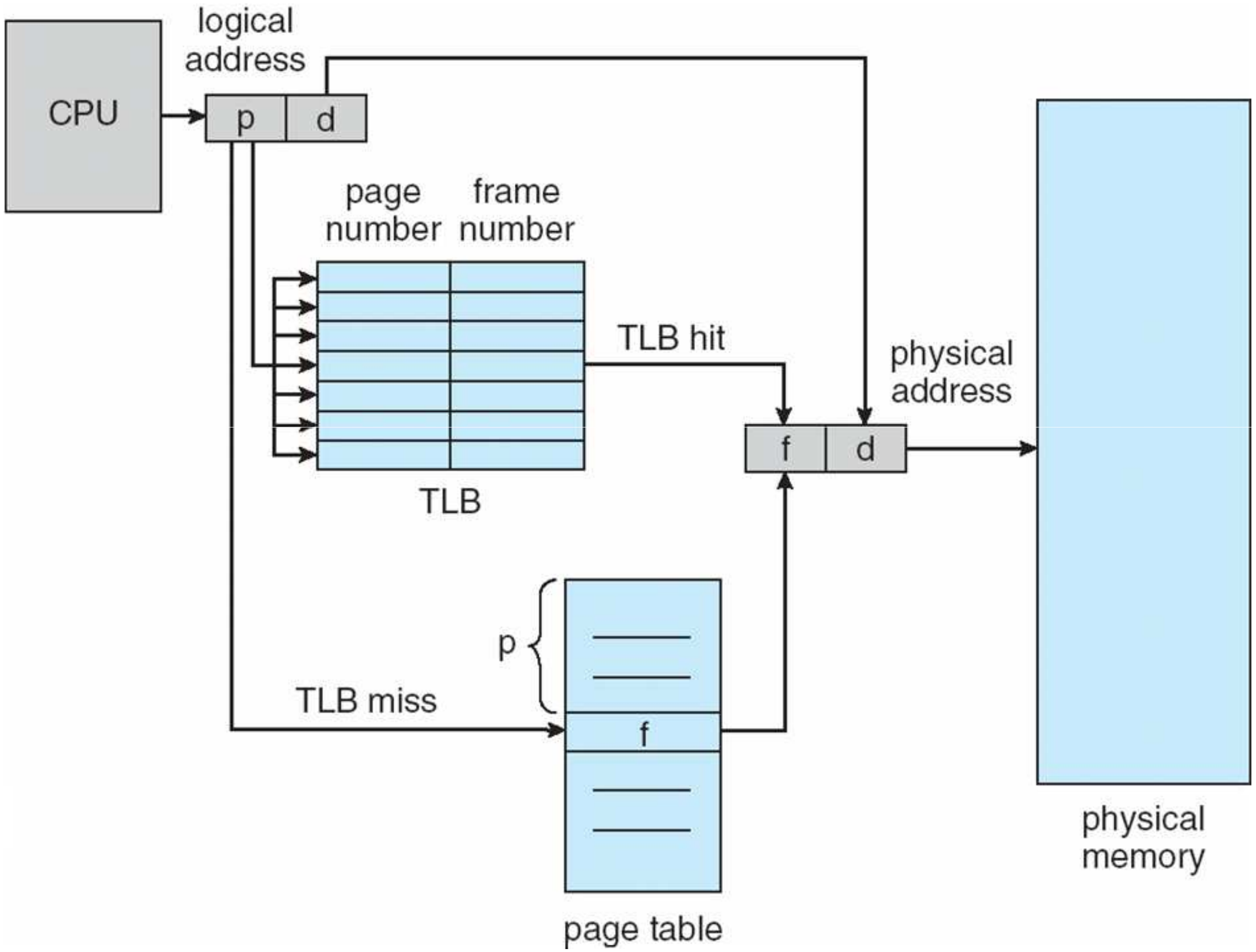
13
14

Free frame list

Implementation of Page Table

- Page table is kept in main memory
- **Page-table base register (PTBR)** points to the page table
- **Page-table length register (PRLR)** indicates size of the page table
- In this scheme every data/instruction access requires two memory accesses. One for the page table and one for the data/instruction.
- The two memory access problem can be solved by the use of a special fast-lookup hardware cache called **associative memory** or **translation look-aside buffers (TLBs)**
- Some TLBs store **address-space identifiers (ASIDs)** in each TLB entry – uniquely identifies each process to provide address-space protection for that process

Paging Hardware With TLB



Effective Access Time

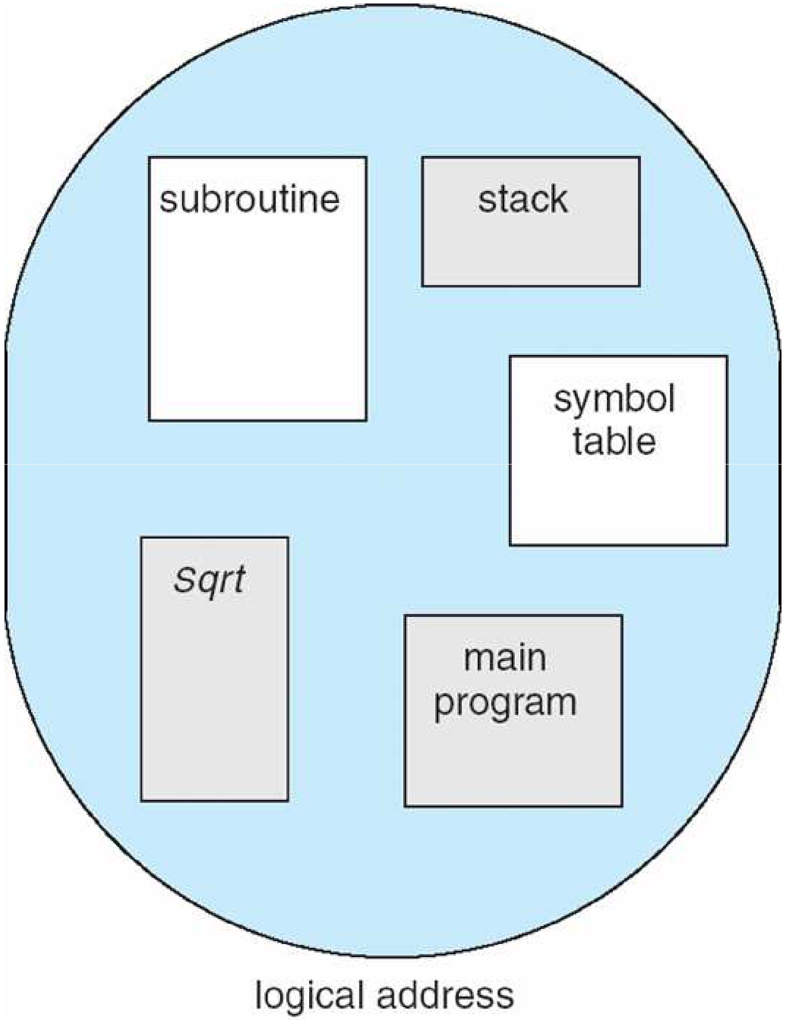
Time required

- if page is in TLB
  - HIT(T)= TLB(T)+MEM(T)
- if page is not available in TLB
  - MISS(T) = TLB(T)+ PAGE(T)+MEM(T)

- EAT = h*HIT(T) + m* MISS(T)

- h = hit ratio
- m= miss ratio or 1-hit ratio

User’s View of a Program



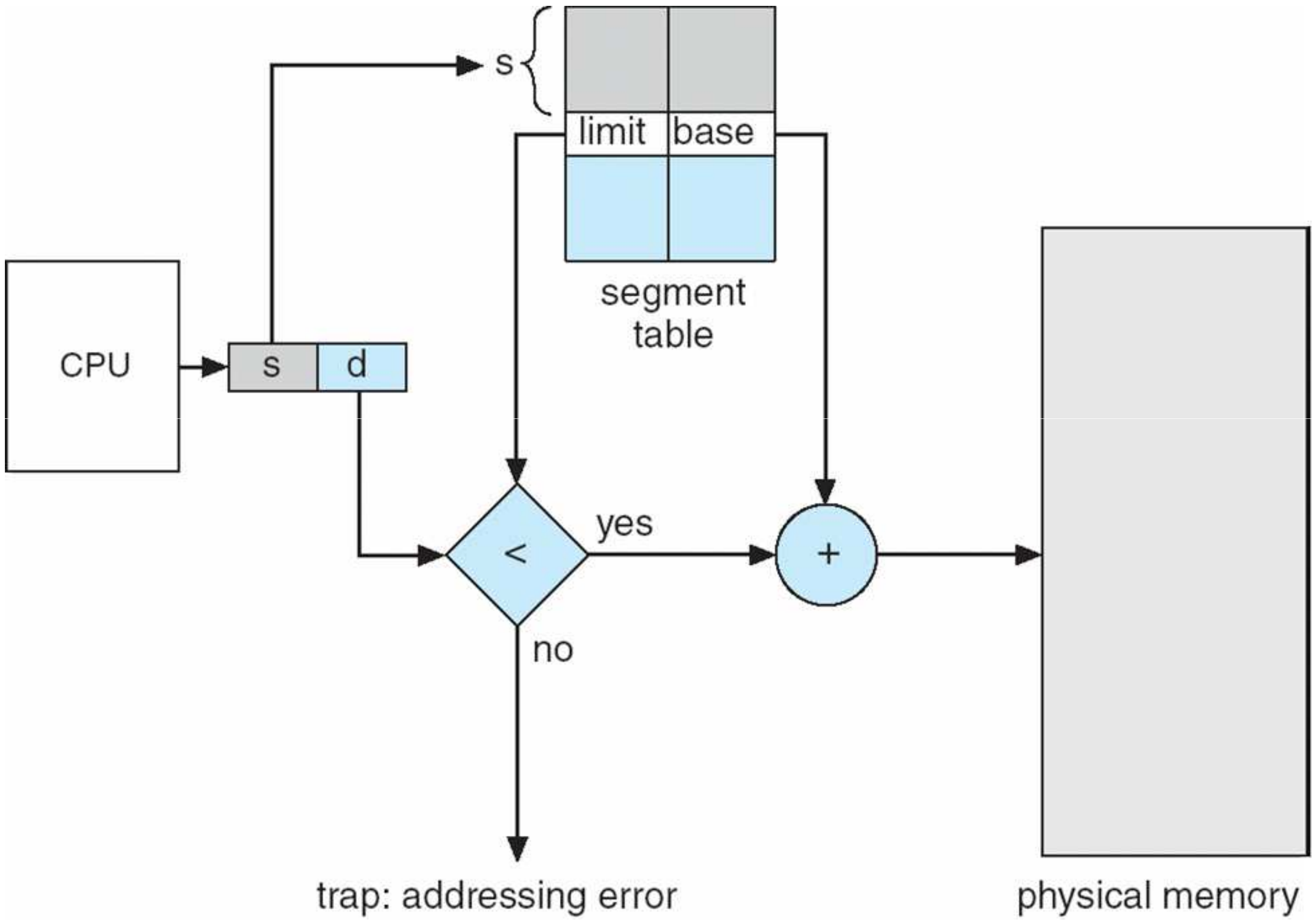
Segmentation Architecture

- Logical address consists of a two tuple:

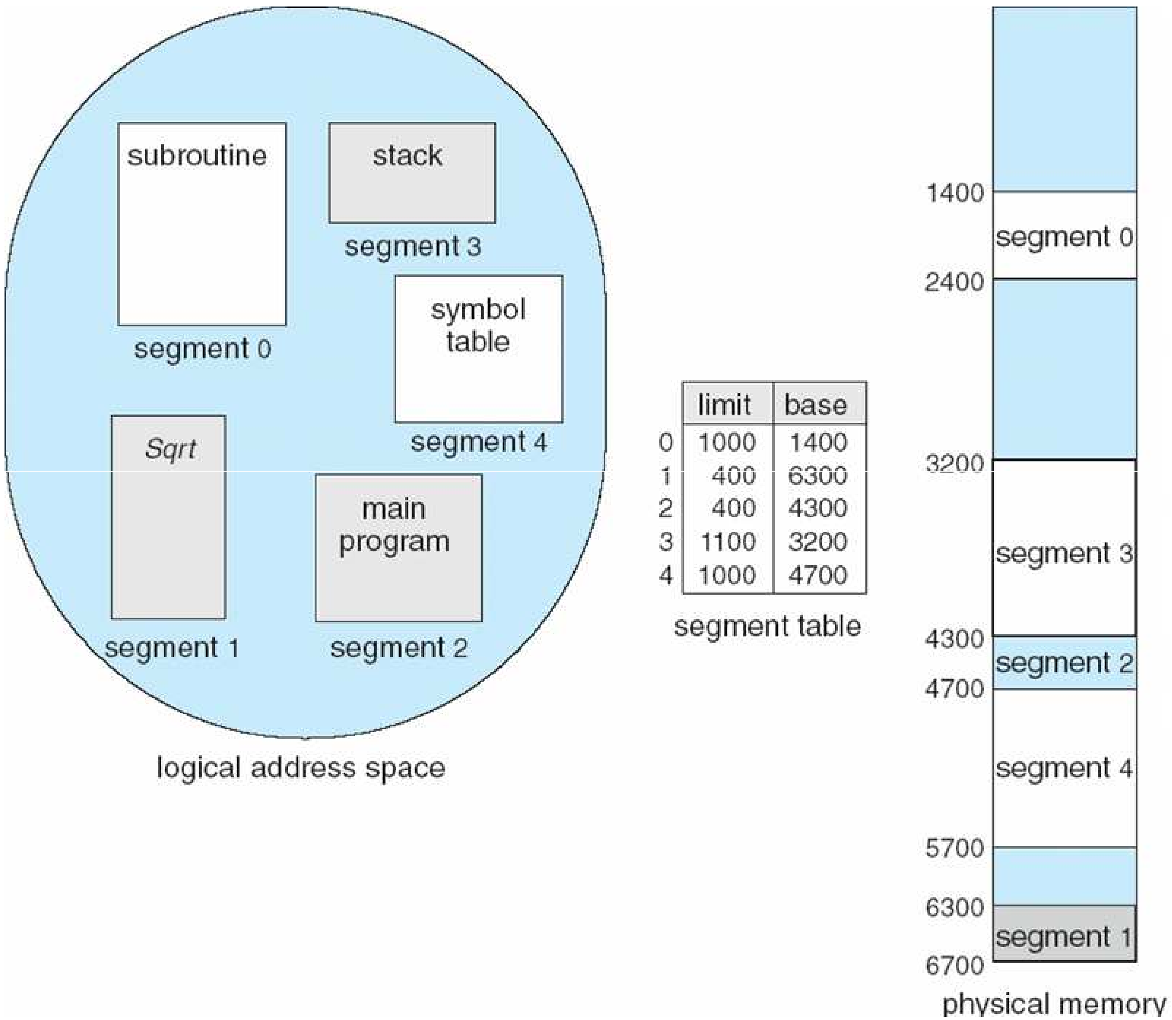
  $<$segment-number, offset$>$
- **Segment table** – maps two-dimensional physical addresses; each table entry has:
  - **base** – contains the starting physical address where the segments reside in memory
  - **limit** – specifies the length of the segment
- **Segment-table base register (STBR)** points to the segment table's location in memory
- **Segment-table length register (STLR)** indicates number of segments used by a program;

  segment number ***s*** is legal if ***s*** < **STLR**

Segmentation Hardware



Example of Segmentation

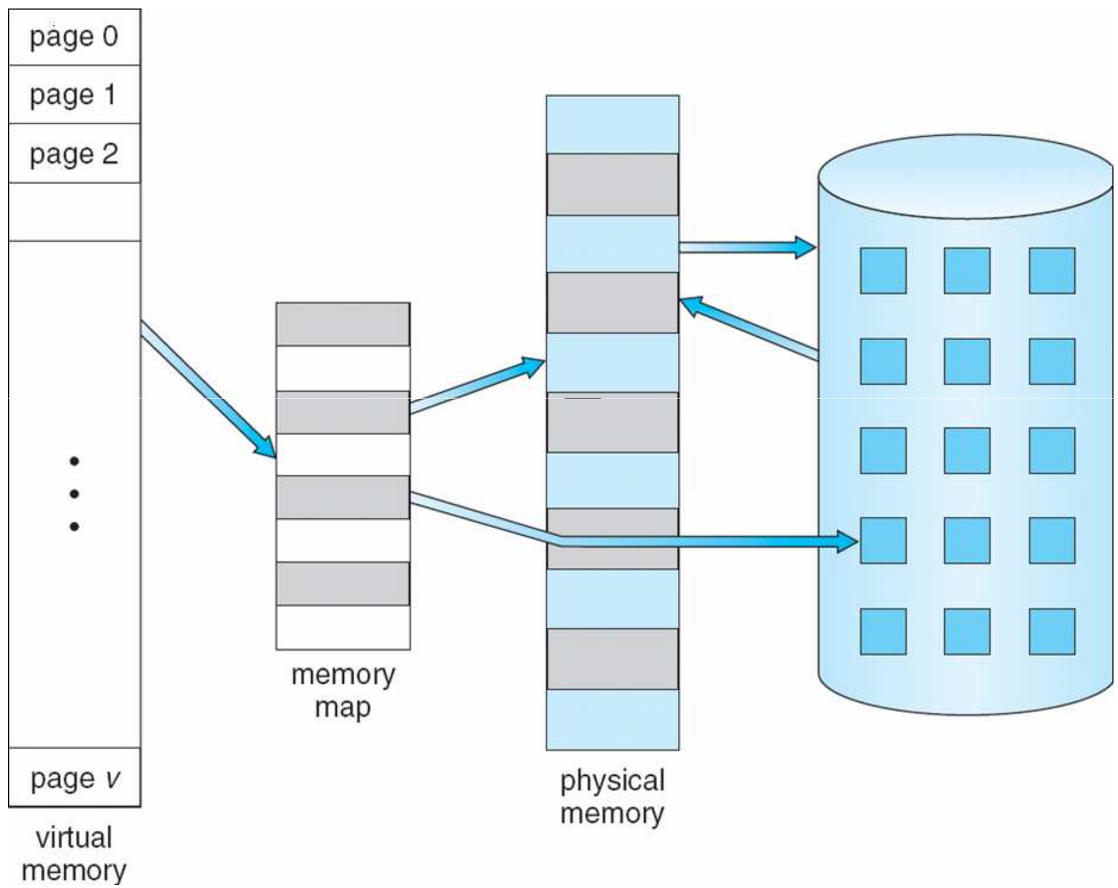


Background

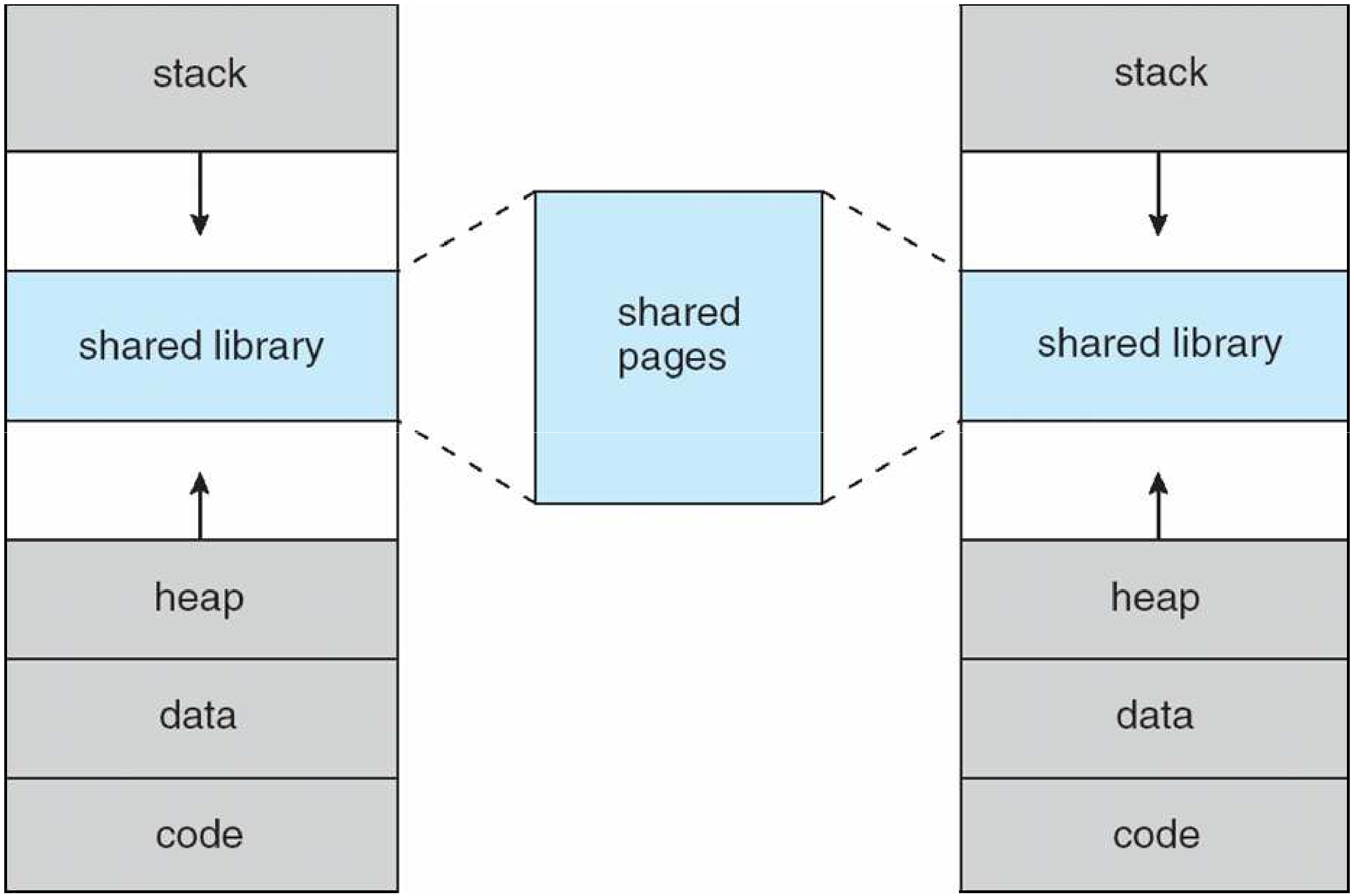
- **Virtual memory** – separation of user logical memory from physical memory.
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation

- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

Virtual Memory That is Larger Than Physical Memory



Shared Library Using Virtual Memory



Demand Paging

- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users

- Page is needed ⇒ reference to it
  - invalid reference ⇒ abort
  - not-in-memory ⇒ bring to memory
- **Lazy swapper** – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a **pager**

Valid-Invalid Bit

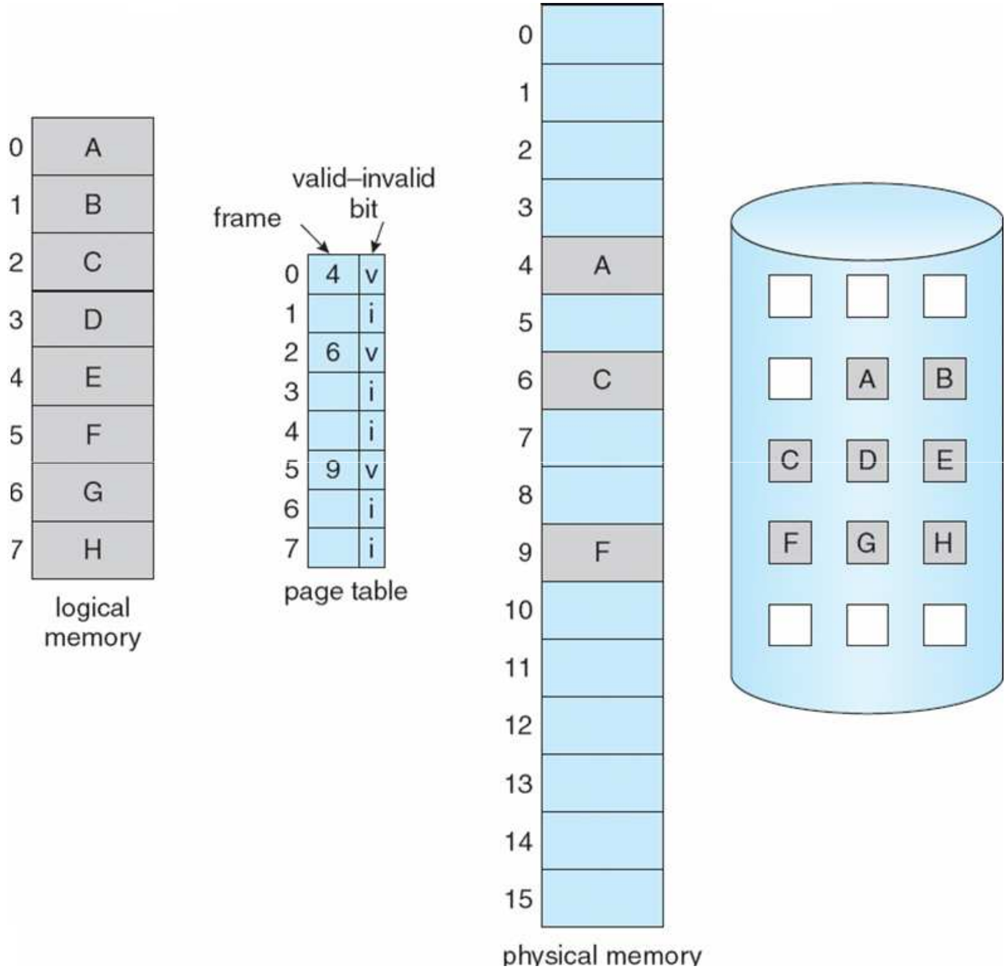
- With each page table entry a valid–invalid bit is associated
  (**v** ⇒ in-memory, **i** ⇒ not-in-memory)
- Initially valid–invalid bit is set to **i** on all entries
- Example of a page table snapshot:

Frame #	valid-invalid bit
	v
	v
	v
	v
	i
….	
	i
	i

page table

- During address translation, if valid–invalid bit in page table entry
- is **I** ⇒ page fault

Page Table When Some Pages Are Not in Main Memory

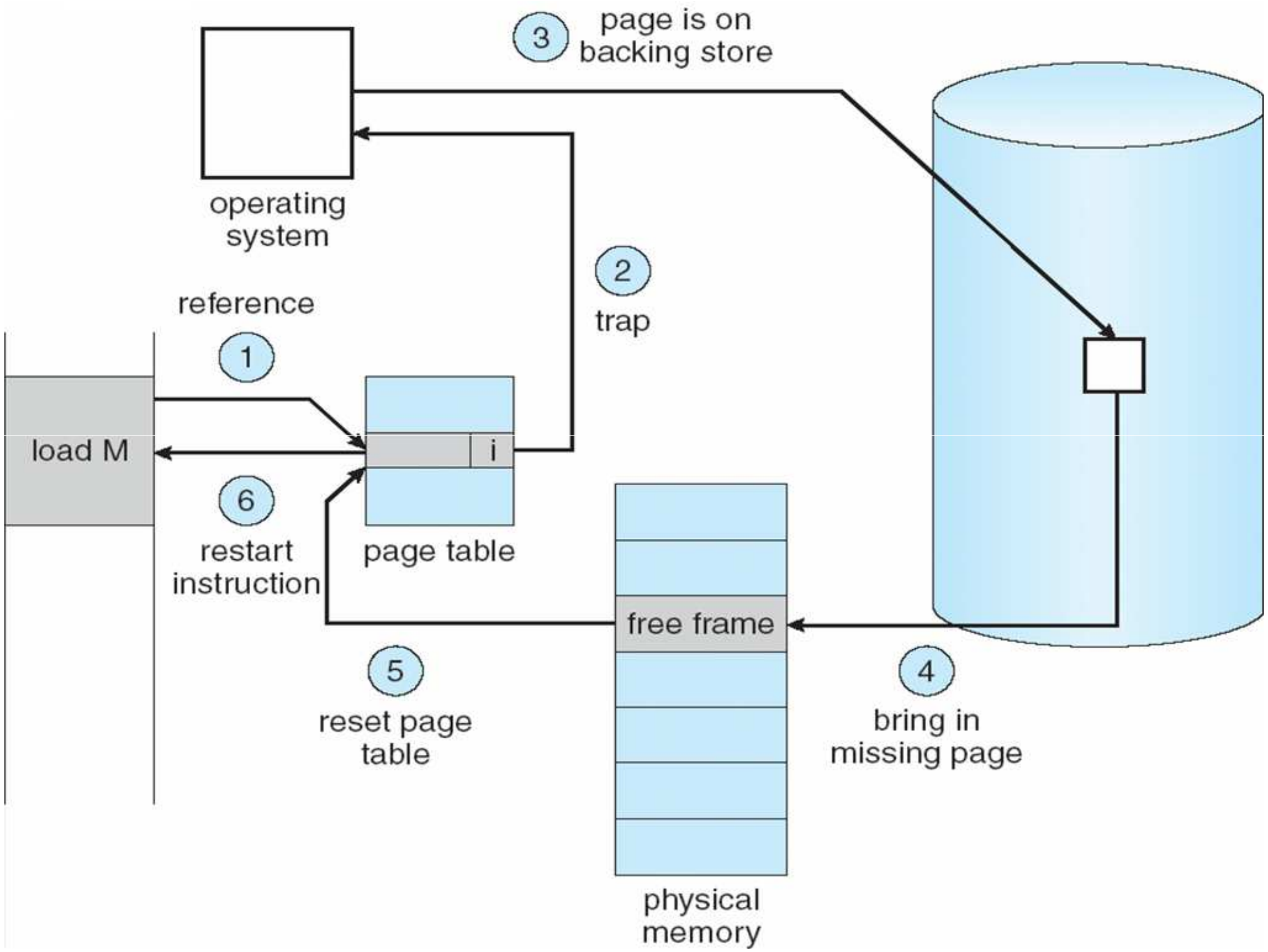


Page Fault

If there is a reference to a page, first reference to that page will trap to operating system: **page fault**

1. Operating system looks at another table to decide:
   - Invalid reference $\Rightarrow$ abort
   - Just not in memory
2. Get empty frame
3. Swap page into frame
4. Reset tables
5. Set validation bit = **v**
6. Restart the instruction that caused the page fault

Steps in Handling a Page Fault



Performance of Demand Paging

- 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)

$$
\begin{aligned}
\text{EAT} = {} & (1 - p) \text{ x memory access} \\
& + p \text{ (page fault overhead} \\
& \qquad + \text{swap page out} \\
& \qquad + \text{swap page in} \\
& \qquad + \text{restart overhead} \\
& \qquad)
\end{aligned}
$$

Demand Paging Example

- Memory access time = 200 nanoseconds

- Average page-fault service time = 8 milliseconds

- EAT = (1 – p) x 200 + p (8 milliseconds)
  = (1 – p x 200 + p x 8,000,000
  = 200 + p x 7,999,800

- If one access out of 1,000 causes a page fault, then
  EAT = 8.2 microseconds.
  This is a slowdown by a factor of 40!!

Process Creation

- Virtual memory allows other benefits during process creation:

  - Copy-on-Write

Copy-on-Write

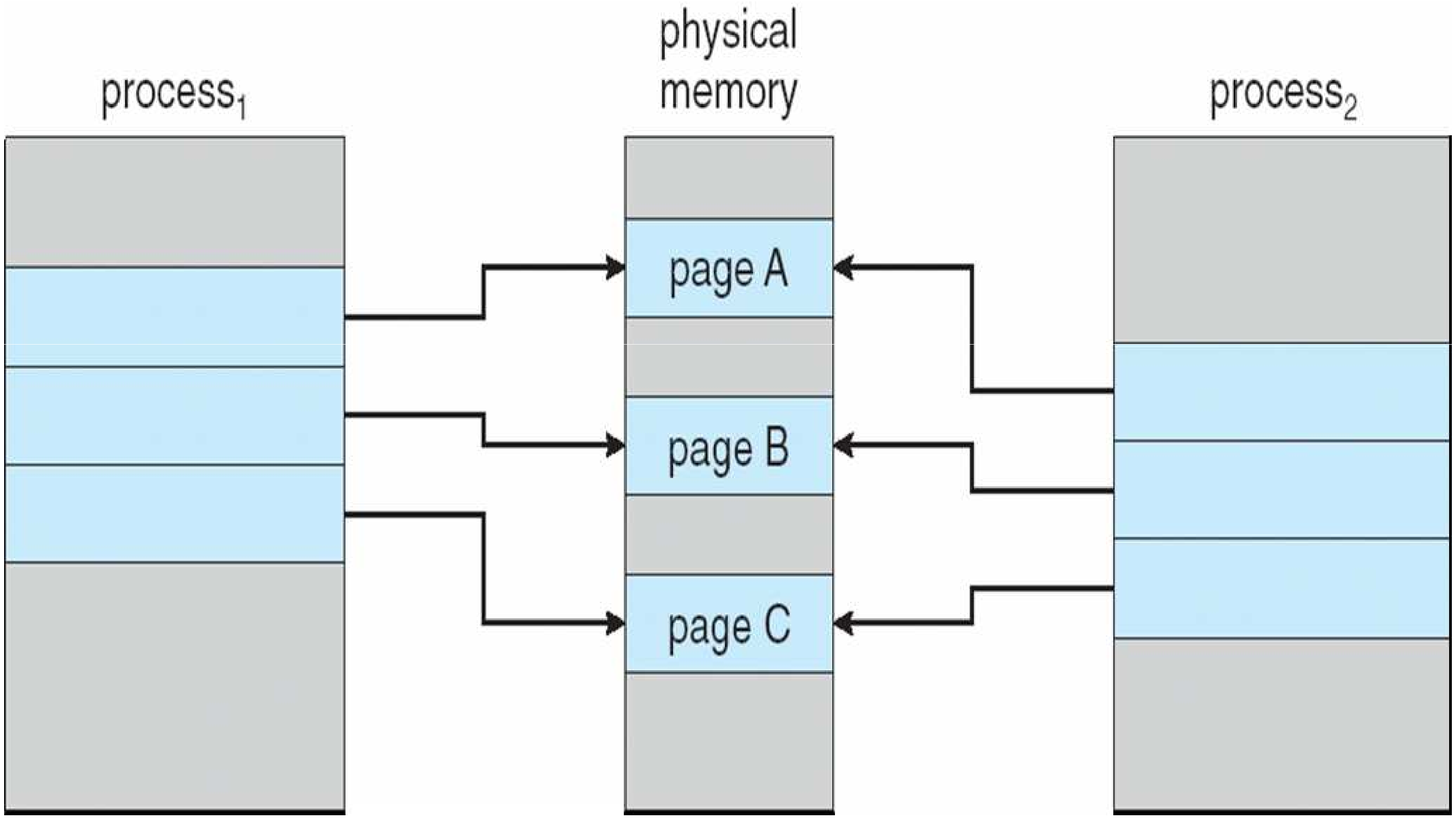
- Copy-on-Write allows both parent and child processes to initially *share* the same pages in memory

  If either process modifies a shared page, only then is the page copied

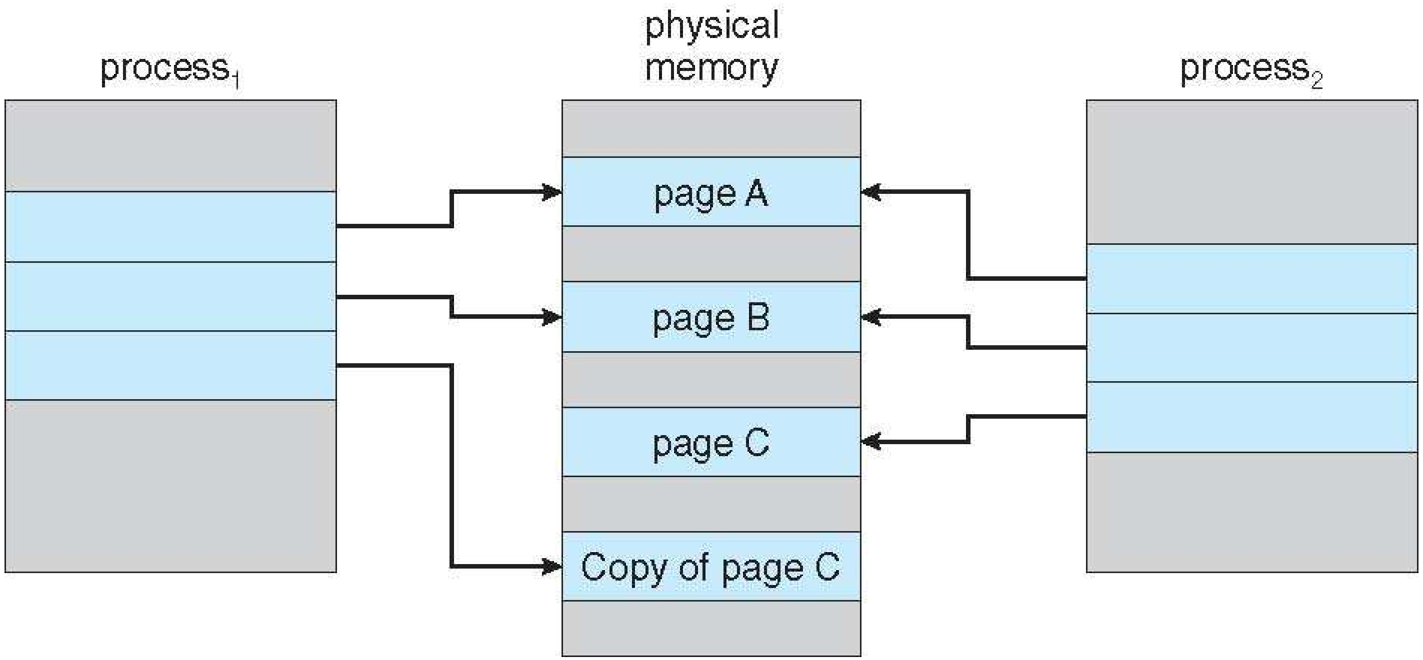
- It allows more efficient process creation as only modified pages are copied

- Free pages are allocated from a **pool** of zeroed-out pages

Before Process 1 Modifies Page C



After Process 1 Modifies Page C



Page Replacement Algorithms

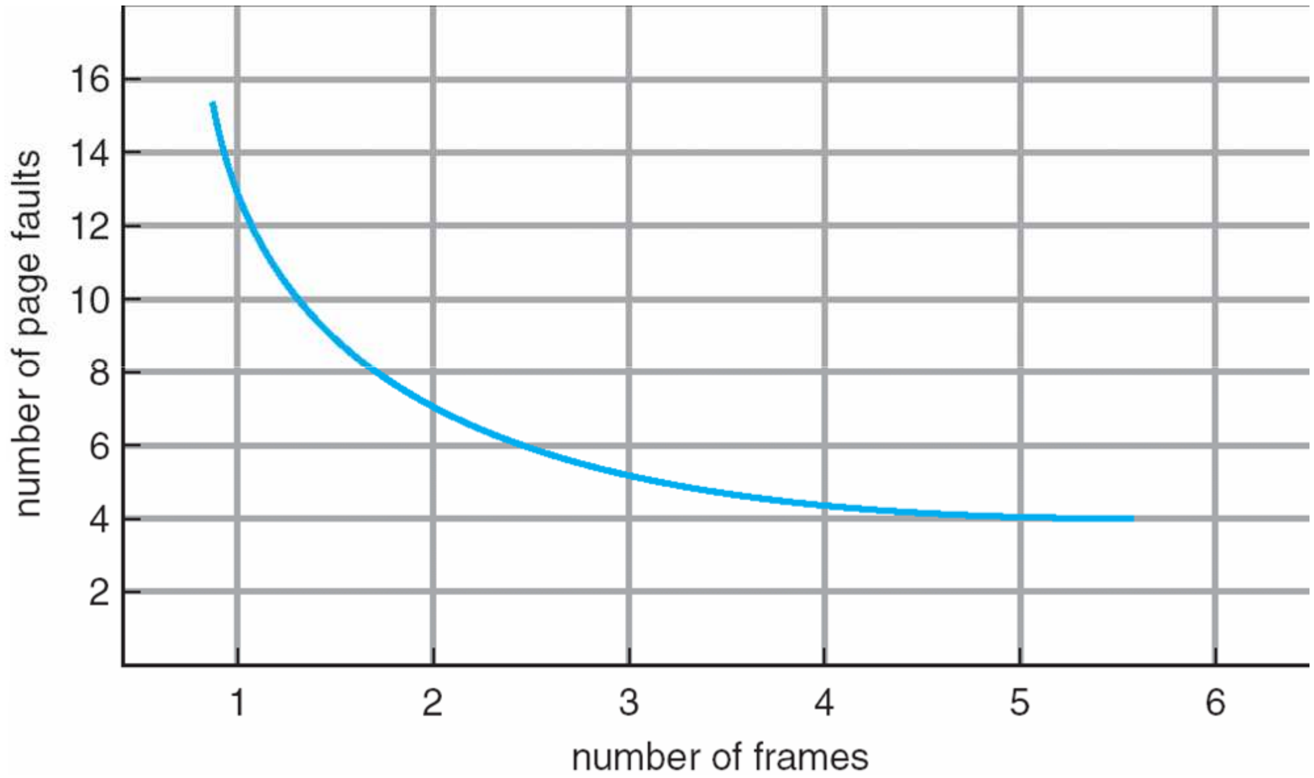
- Want lowest page-fault rate

- 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

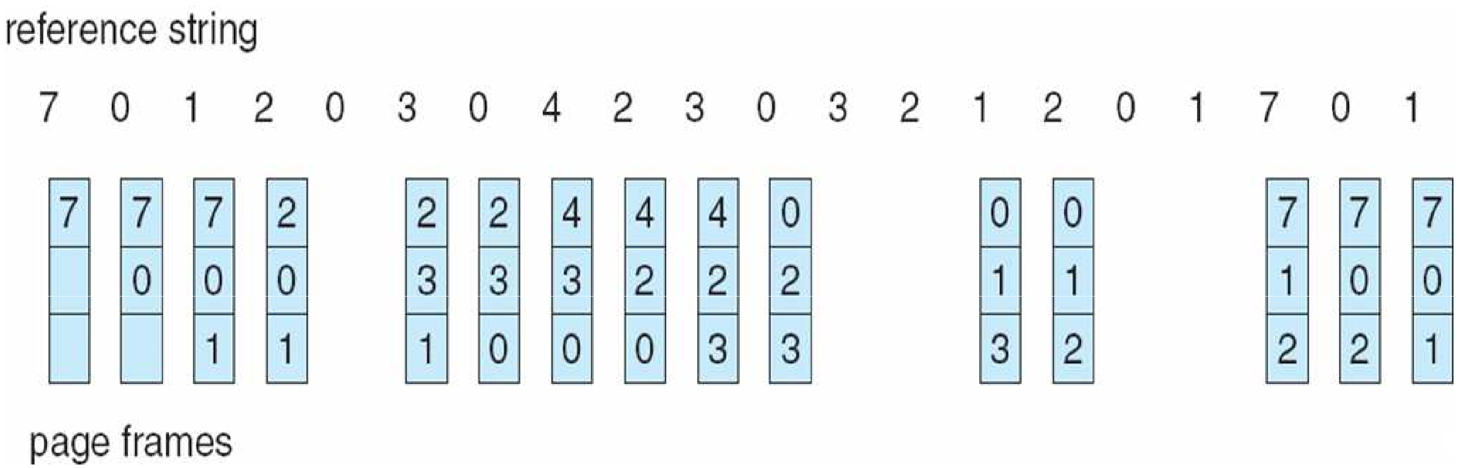
Graph of Page Faults Versus The Number of Frames



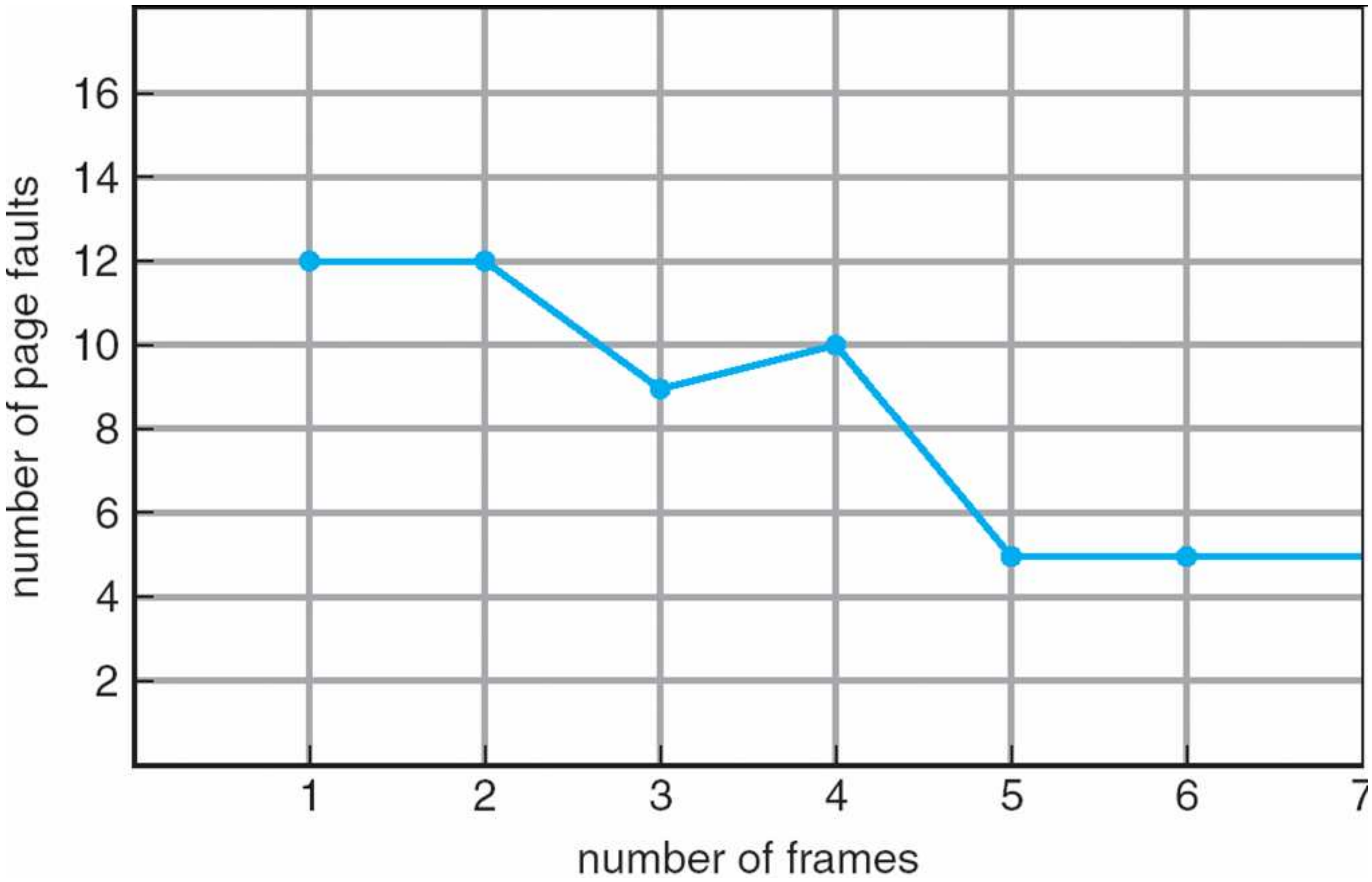
First-In-First-Out (FIFO) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- Belady's Anomaly

FIFO Page Replacement



FIFO Illustrating Belady's Anomaly



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

1
2
3
4

6 page faults

- Future knowledge
- Used for measuring how well your algorithm performs

Least Recently Used (LRU) Algorithm

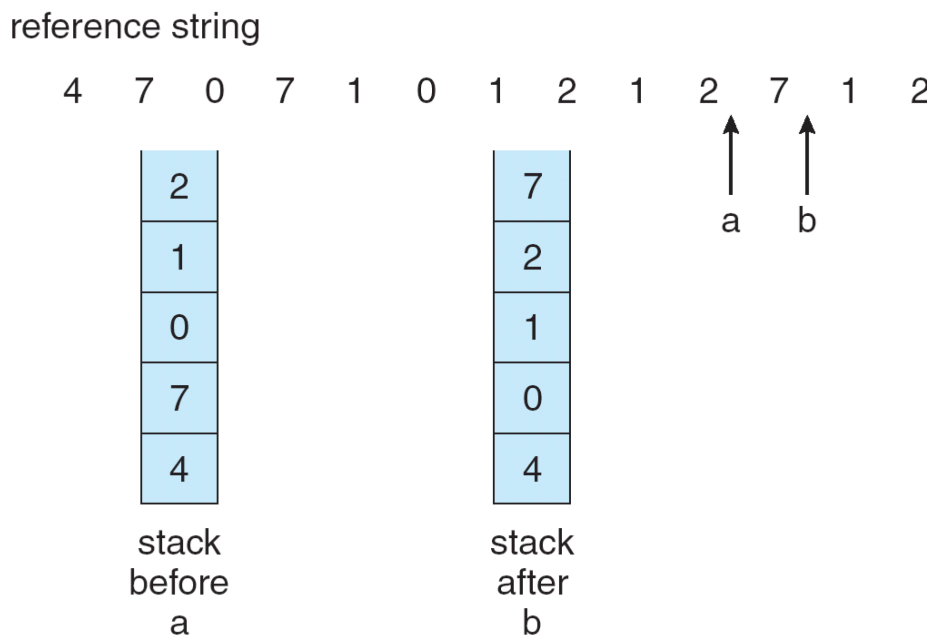
- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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

- 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 Algorithm (Cont.)

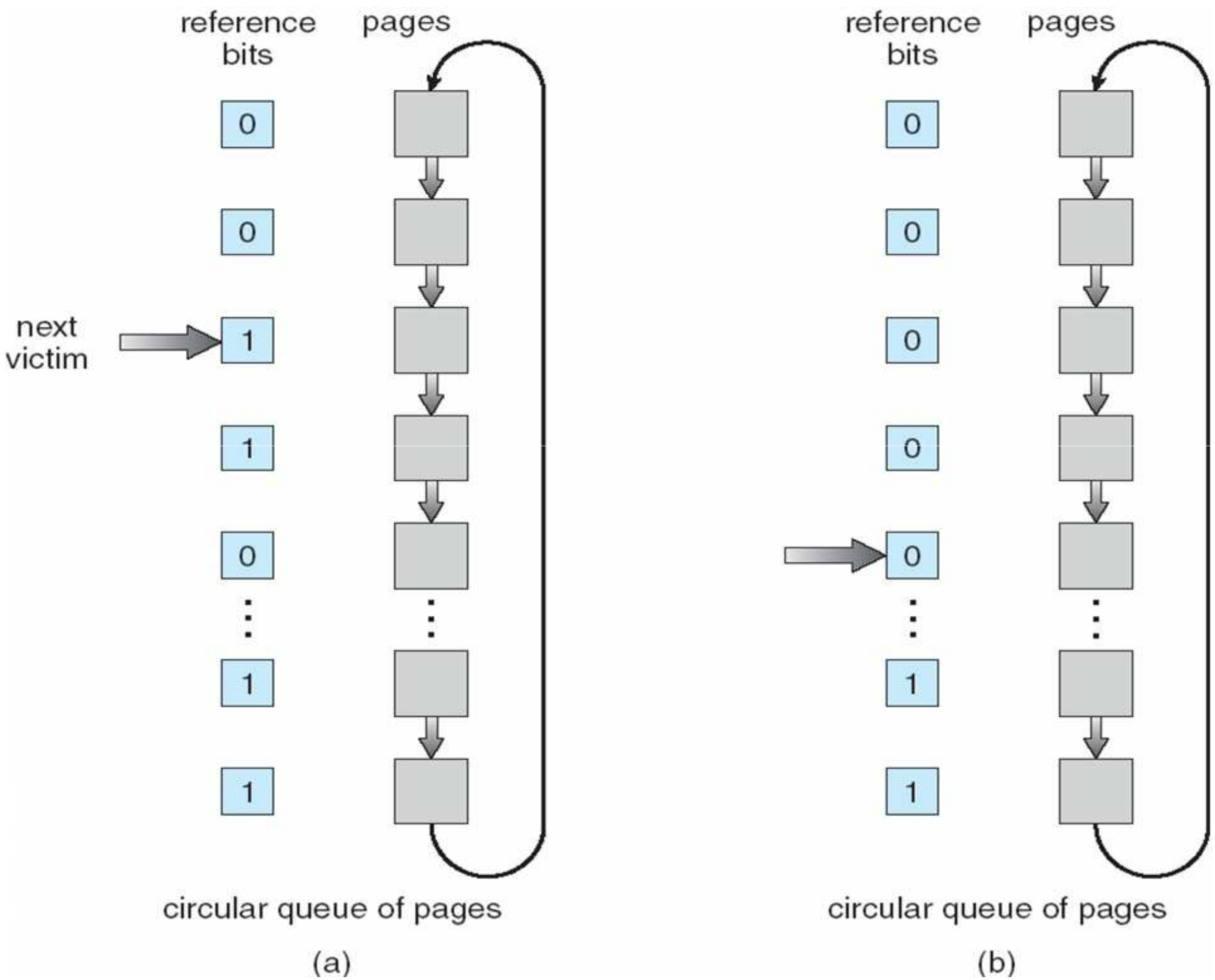
- Stack implementation – keep a stack of page numbers in a double link form:
  - Page referenced:
    - move it to the top
    - requires 6 pointers to be changed
  - No search for replacement



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

Allocation

- Equal allocation – For example, if there are 100 frames and 5 processes, give each process 20 frames.
- Proportional allocation – Allocate according to the size of process

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

$$m = 64$$
$$s_i = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 64 \approx 5$$
$$a_2 = \frac{127}{137} \times 64 \approx 59$$

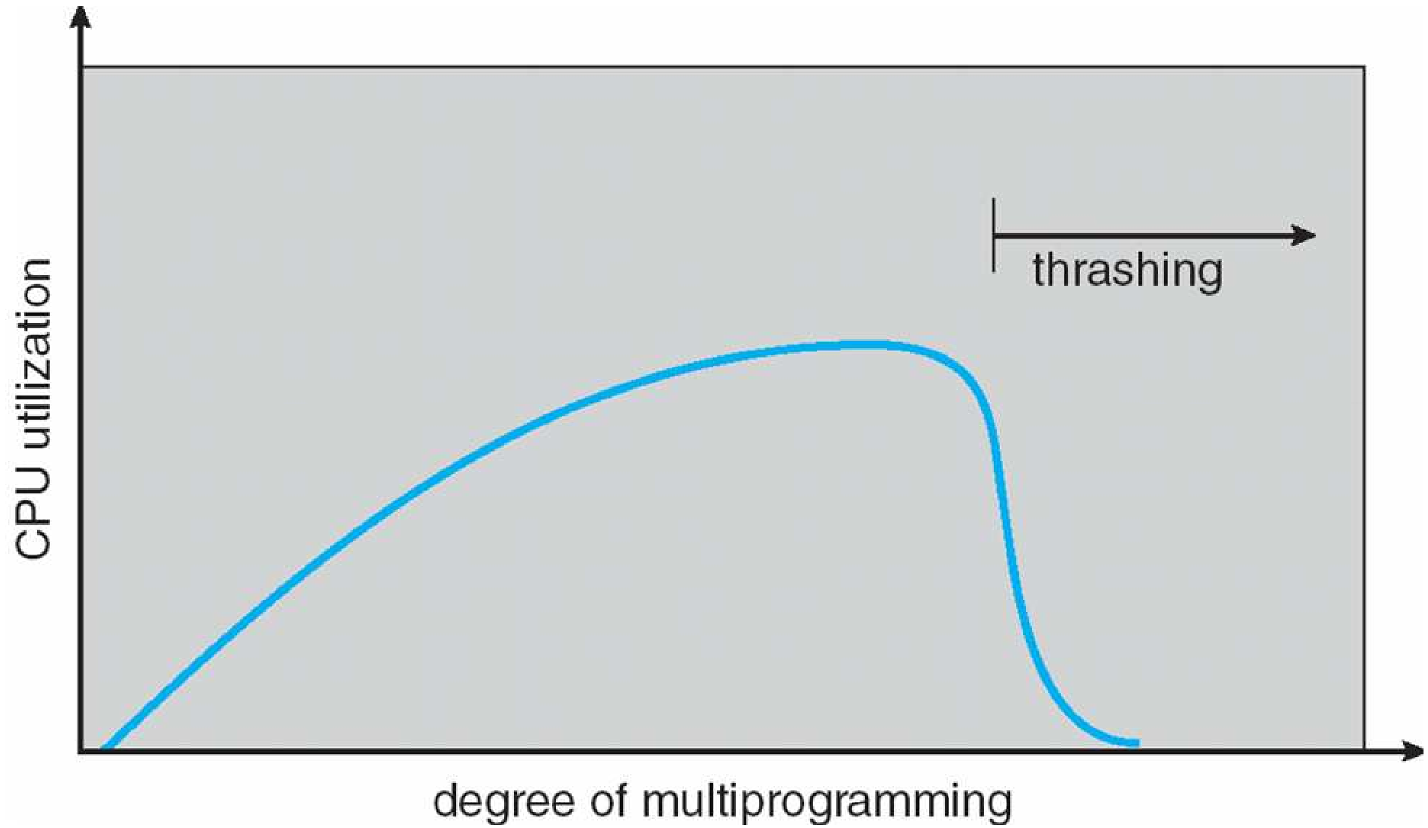
Priority Allocation

- 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

Thrashing



Thrashing

- If a process does not have "enough" pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system thinks 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

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

Working-Set Model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  Example: 10,000 instruction
- WSS_i (working set of Process P_i) =
  total number of pages referenced in the most recent Δ (varies in time)
  - if Δ too small will not encompass entire locality
  - if Δ too large will encompass several localities
  - if $\Delta = \infty \Rightarrow$ will encompass entire program
- $D = \Sigma\ WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
- Policy if $D >$ m, then suspend one of the processes

Working-set model