CS6401- Operating System

UNIT-III

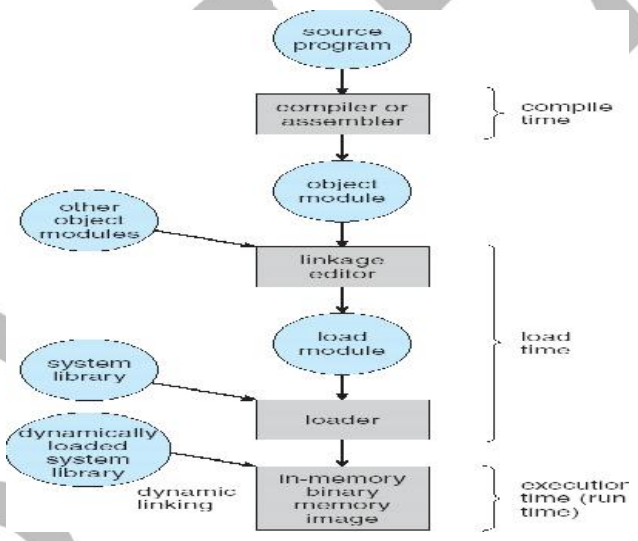
STORAGE MANAGEMENT

Memory Management: Background

- In general, to rum a program, it must be brought into memory.
- Input queue – collection of processes on the disk that are waiting to be brought into memory to run the program.
- User programs go through several steps before being run
- Address binding: Mapping of instructions and data from one address to another address in memory.

Three different stages of binding:

1. Compile time: Must generate absolute code if memory location is known in prior.
2. Load time: Must generate relocatable code if memory location is not known at compile time
3. Execution time: Need hardware support for address maps (e.g., base and limit registers).



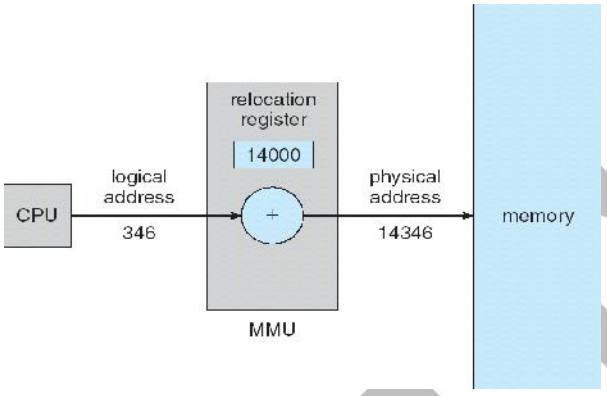
Logical vs. Physical Address Space

- **Logical address** – generated by the CPU; also referred to as **"virtual address"**
- **Physical address** – address seen by the memory unit.
- Logical and physical addresses are the **same** in —compile-time and load-time address-binding schemes‖
- Logical (virtual) and physical addresses **differ** in —execution-time address- binding scheme‖

Memory-Management Unit (MMU)

- It is a hardware device that maps virtual / Logical address to physical address
- In this scheme, the relocation register's value is added to Logical address generated by a user process.

- The user program deals with *logical* addresses; it never sees the *real* physical addresses
- Logical address range: 0 to max
- Physical address range: R+0 to R+max, where R—value in relocation register.



Dynamic Loading

- Through this, the routine is not loaded until it is called.
  - o Better memory-space utilization; unused routine is never loaded
  - o Useful when large amounts of code are needed to handle infrequently occurring cases
  - o No special support from the operating system is required implemented through program design

Dynamic Linking

- Linking postponed until execution time & is particularly useful for libraries
- Small piece of code called stub, used to locate the appropriate memory- resident library routine or function.
- Stub replaces itself with the address of the routine, and executes the routine
- Operating system needed to check if routine is in processes' memory address
- Shared libraries: Programs linked before the new library was installed will continue using the older library.

Swapping

- A process can be swapped temporarily out of memory to a backing store (SWAP OUT)and then brought back into memory for continued execution (SWAP IN).
- **Backing store** – fast disk large enough to accommodate copies of all memory images for all users & it must provide direct access to these memory images
- **Roll out, roll in –** swapping variant used for priority-based scheduling algorithms; lower-priority process is swapped out so higher-priority process can be loaded and executed
- **Transfer time:** Major part of swap time is transfer time. Total transfer time is directly proportional to the amount of memory swapped.

Example: Let us assume the user process is of size 1MB & the backing store is a standard hard disk with a transfer rate of 5MBPS.

Transfer time = 1000KB/5000KB per second
= 1/5 sec = 200ms

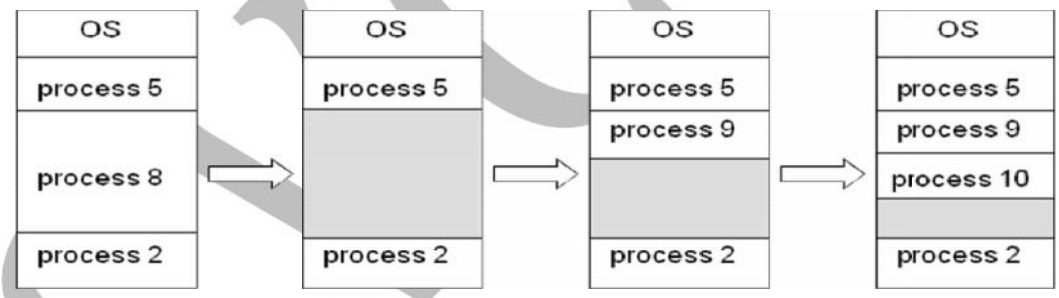
Contiguous Allocation

- Each process is contained in a single contiguous section of memory.
- There are two methods namely:

  Fixed – Partition Method

  Variable – Partition Method

  - **Fixed – Partition Method** :
    - o Divide memory into fixed size partitions, where each partition has exactly one process.
    - o The drawback is memory space unused within a partition is wasted.(eg.when process size < partition size)
  - **Variable-partition method:**
    - o Divide memory into variable size partitions, depending upon the size of the incoming process.
    - o When a process terminates, the partition becomes available for another process.
    - o As processes complete and leave they create holes in the main memory.
    - o ***Hole*** – block of available memory; holes of various size are scattered throughout memory.



Dynamic Storage- Allocation Problem:

How to satisfy a request of size ‗n' from a list of free holes?

Solution:

o First-fit: Allocate the first hole that is big enough.
o Best-fit: Allocate the smallest hole that is big enough; must search entire list, unless ordered by size. Produces the smallest leftover hole.
o Worst-fit: Allocate the largest hole; must also search entire list. Produces the largest leftover hole.

NOTE: First-fit and best-fit are better than worst-fit in terms of speed and storage utilization

- **Fragmentation:**

o **External Fragmentation** – This takes place when enough total memory space exists to satisfy a request, but it is not contiguous i.e, storage is fragmented into a large number of small holes scattered throughout the main memory.

o Internal Fragmentation – Allocated memory may be slightly larger than requested memory.

Example: hole = 184 bytes
Process size = 182 bytes.
We are left with a hole of 2 bytes.

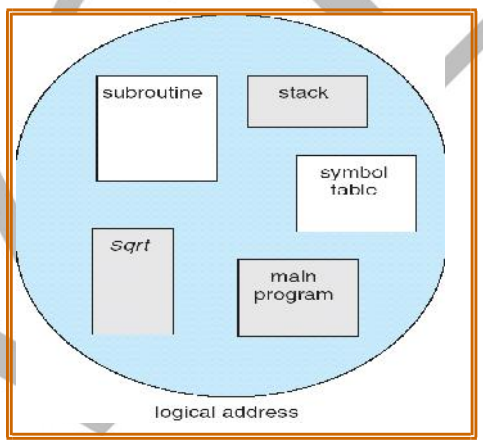
o Solutions

1. **Coalescing:** Merge the adjacent holes together.
2. **Compaction:** Move all processes towards one end of memory, hole towards other end of memory, producing one large hole of available memory. This scheme is expensive as it can be done if relocation is dynamic and done at execution time.
3. Permit the logical address space of a process to be **non-contiguous**. This is achieved through two memory management schemes namely **paging** and **segmentation**.

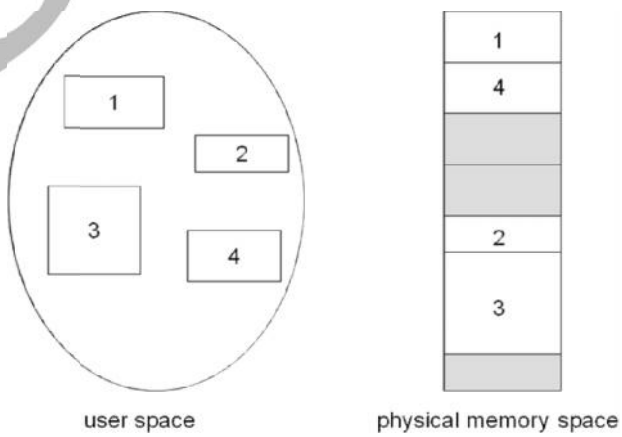
Segmentation

o Memory-management scheme that supports user view of memory

o A program is a collection of segments. A segment is a logical unit such as:Main program, Procedure, Function, Method, Object, Local variables, global variables, Common block, Stack, Symbol table, arrays

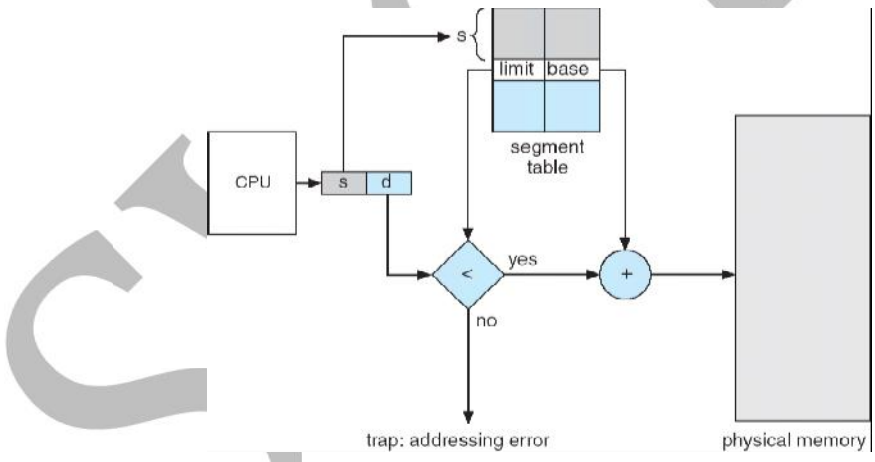


Logical View of Segmentation

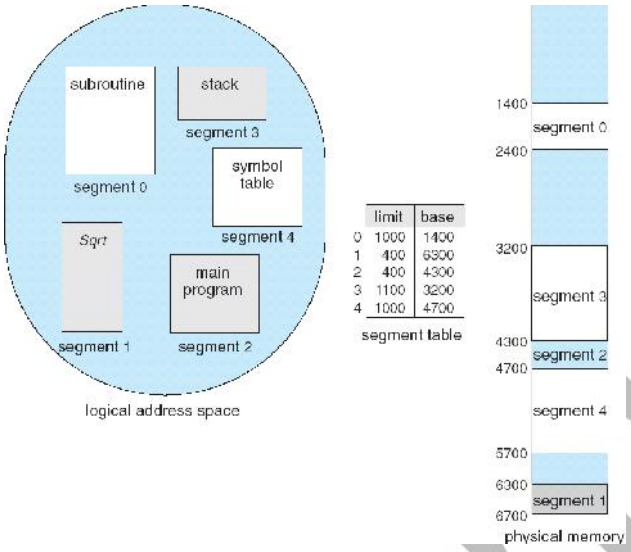


Segmentation Hardware

- o Logical address consists of a two tuple :
  <Segment-number, offset>
- o **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
- o ***Segment-table base register (STBR)*** points to the segment table's location in memory
- o ***Segment-table length register (STLR)*** indicates number of segments used by a program;
  Segment number=s' is legal, if *s* < STLR
- o **Relocation**.
  dynamic
  by segment table
- o **Sharing**.
  shared segments
  same segment number
- o **Allocation**.
  first fit/best fit
  external fragmentation
- o **Protection:** With each entry in segment table associate:
  validation bit = 0 illegal segment
  read/write/execute privileges
- o Protection bits associated with segments; code sharing occurs at segment level
- o Since segments vary in length, memory allocation is a dynamic storage- allocation problem
- o A segmentation example is shown in the following diagram



EXAMPLE:



o Another advantage of segmentation involves the sharing of code or data.

o Each process has a segment table associated with it, which the dispatcher uses to define the hardware segment table when this process is given the CPU.

o Segments are shared when entries in the segment tables of two different processes point to the same physical location.

Segmentation with paging

o The IBM OS/ 2.32 bit version is an operating system running on top of the Intel 386 architecture. The 386 uses segmentation with paging for memory management. The maximum number of segments per process is 16 KB, and each segment can be as large as 4 gigabytes.

o The local-address space of a process is divided into two partitions.

The first partition consists of up to 8 KB segments that are private to that process.

The second partition consists of up to 8KB segments that are shared among all the processes.

o Information about the first partition is kept in the **local descriptor table (LDT)**, information about the second partition is kept in the **global descriptor table (GDT)**.

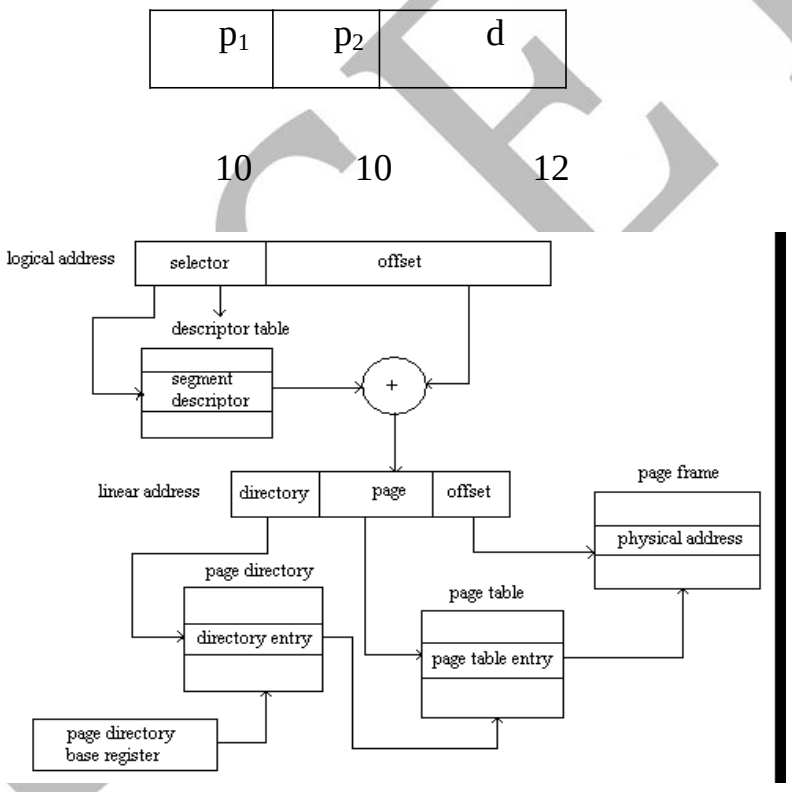
o Each entry in the LDT and GDT consist of 8 bytes, with detailed information about a particular segment including the base location and length of the segment.

The logical address is a pair (selector, offset) where the selector is a16-bit number:

s	g	p
13	1	2

Where s designates the segment number, g indicates whether the segment is in the GDT or LDT, and p deals with protection. The offset is a 32-bit number specifying the location of the byte within the segment in question.

- The base and limit information about the segment in question are used to generate a linear-address.
- First, the limit is used to check for address validity. If the address is not valid, a memory fault is generated, resulting in a trap to the operating system. If it is valid, then the value of the offset is added to the value of the base, resulting in a 32-bit linear address. This address is then translated into a physical address.
- The linear address is divided into a page number consisting of 20 bits, and a page offset consisting of 12 bits. Since we page the page table, the page number is further divided into a 10-bit page directory pointer and a 10-bit page table pointer. The logical address is as follows.



o To improve the efficiency of physical memory use. Intel 386 page tables can be swapped to disk. In this case, an invalid bit is used in the page directory entry to indicate whether the table to which the entry is pointing is in memory or on disk.

o If the table is on disk, the operating system can use the other 31 bits to specify the disk location of the table; the table then can be brought into memory on demand.

Paging

- It is a memory management scheme that permits the physical address space of a process to be noncontiguous.
- It avoids the considerable problem of fitting the varying size memory chunks on to the backing store.

(i) Basic Method:

o Divide logical memory into blocks of same size called **"pages"**. o Divide physical memory into fixed-sized blocks called **"frames"** o Page size is a power of 2, between 512 bytes and 16MB.

Address Translation Scheme

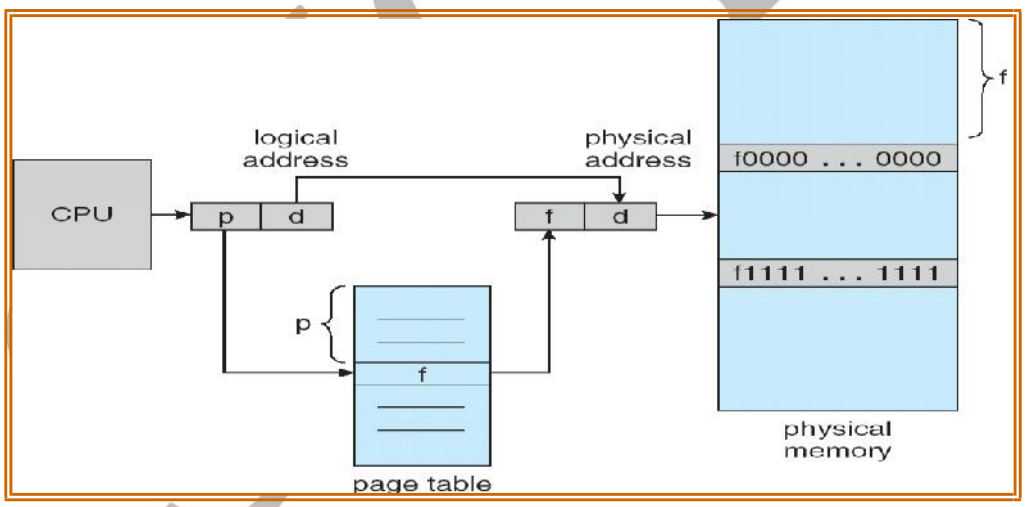
o Address generated by CPU(logical address) is divided into:

Page number *(p)* – used as an index into a page table which contains base address of each page in physical memory

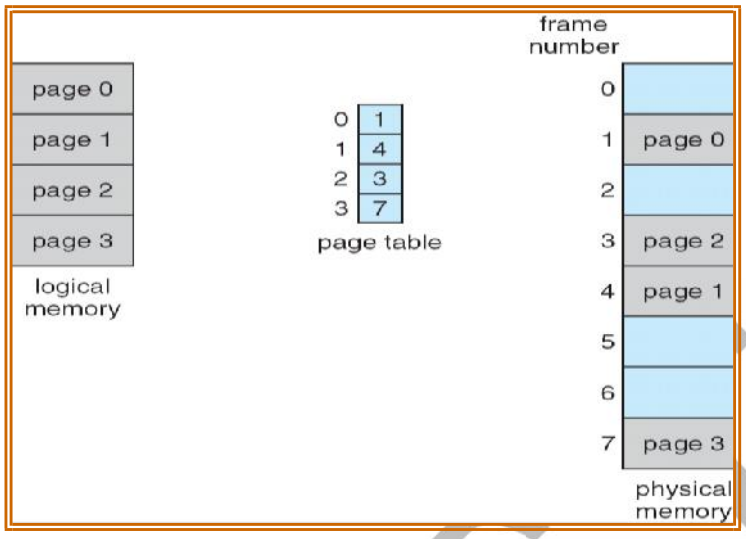
Page offset *(d)* – combined with base address to define the physical address i.e.,

Physical address = base address + offset

Paging Hardware



Paging model of logical and physical memory



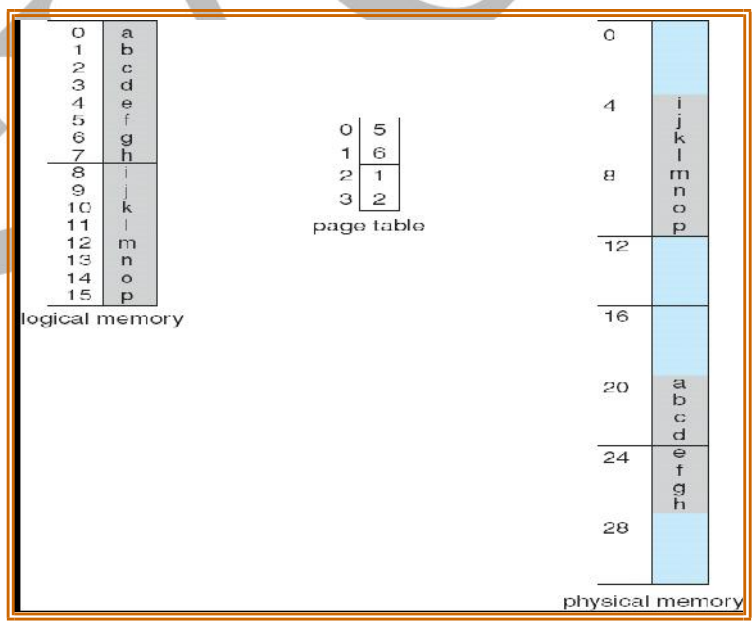
Paging example for a 32-byte memory with 4-byte pages

Page size = 4 bytes

Physical memory size = 32 bytes i.e (4 X 8 = 32 so, 8 pages)

Logical address ‗0' maps to physical address 20 i.e ((5 X 4) +0)

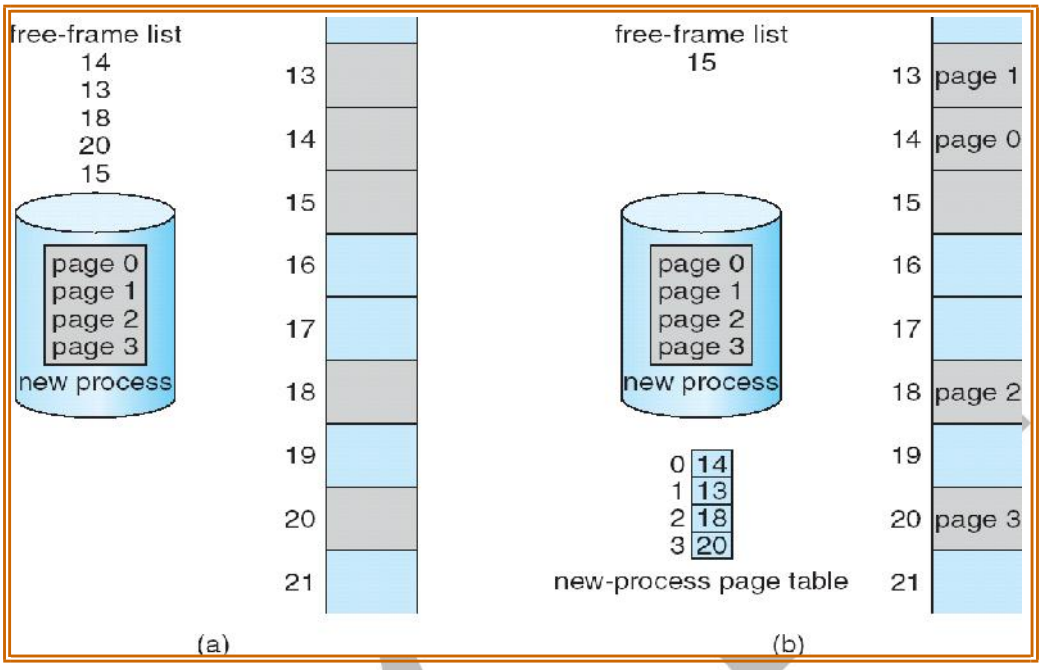
Where Frame no = 5, Page size = 4, Offset = 0



Allocation

- When a process arrives into the system, its size (expressed in pages) is examined.
- Each page of process needs one frame. Thus if the process requires ‗n' pages, at least ‗n' frames must be available in memory.

- If ‗n' frames are available, they are allocated to this arriving process.
- The 1st page of the process is loaded into one of the allocated frames & the frame number is put into the page table.
- Repeat the above step for the next pages & so on.



(a) Before Allocation (b) After Allocation

Frame table: It is used to determine which frames are allocated, which frames are available, how many total frames are there, and so on.(ie) It contains all the information about the frames in the physical memory.

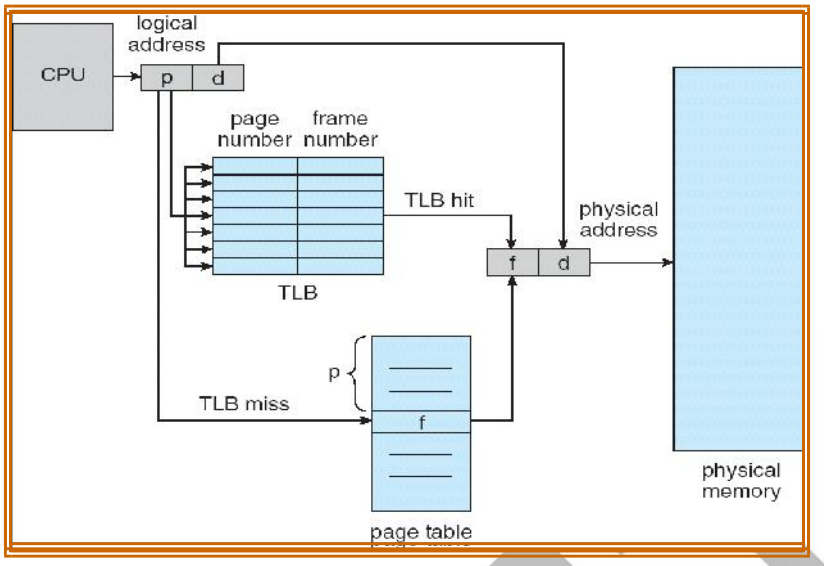
(ii) Hardware implementation of Page Table

- This can be done in several ways :
  1. Using PTBR
  2. TLB
- The simplest case is **Page-table base register (PTBR**), is an index to point the page table.

- **TLB (Translation Look-aside Buffer)**

  It is a fast lookup hardware cache.
  It contains the recently or frequently used page table entries.
  It has two parts: Key (tag) & Value.
  More expensive.

Paging Hardware with TLB



- When a logical address is generated by CPU, its page number is presented to TLB.
- **TLB hit**: If the page number is found, its frame number is immediately available & is used to access memory
- **TLB miss**: If the page number is not in the TLB, a memory reference to the page table must be made.
- **Hit ratio:** Percentage of times that a particular page is found in the TLB.

  For example hit ratio is 80% means that the desired page number in the TLB is 80% of the time.
- **Effective Access Time:**

  Assume hit ratio is 80%.

  If it takes 20ns to search TLB & 100ns to access memory, then the memory access takes 120ns(TLB hit)

  If we fail to find page no. in TLB (20ns), then we must 1st access memory for page table (100ns) & then access the desired byte in memory (100ns).

  Therefore Total = 20 + 100 + 100

  = 220 ns(TLB miss).

  Then Effective Access Time (EAT) = 0.80 X (120 + 0.20) X 220.

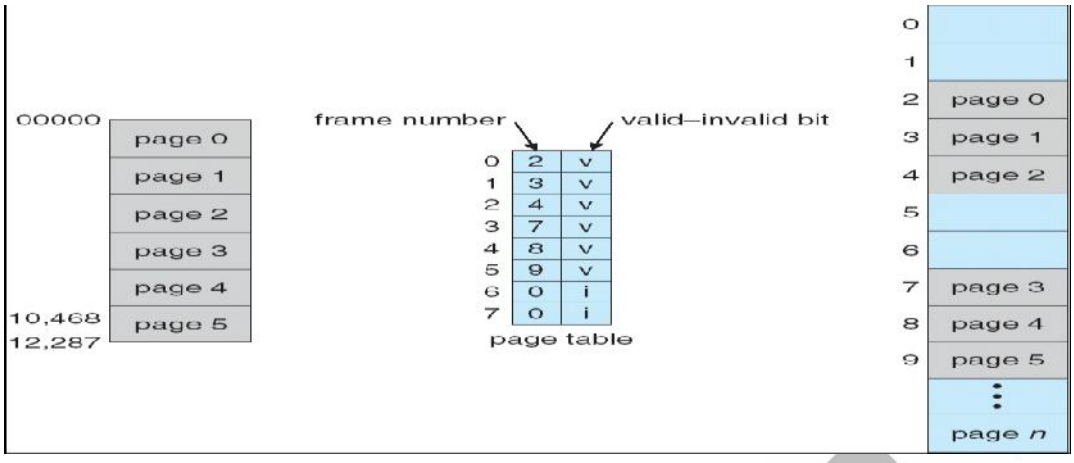
  = 140 ns.

(iii) Memory Protection

- Memory protection implemented by associating protection bit with each frame
- Valid-invalid bit attached to each entry in the page table:

  "valid (v)" indicates that the associated page is in the process' logical address space, and is thus a legal page

  "invalid (i)" indicates that the page is not in the process' logical address spaces



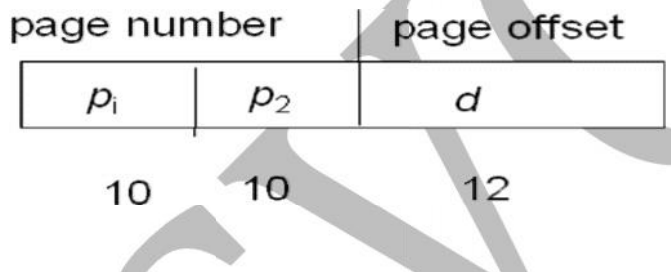
(iv) Structures of the Page Table

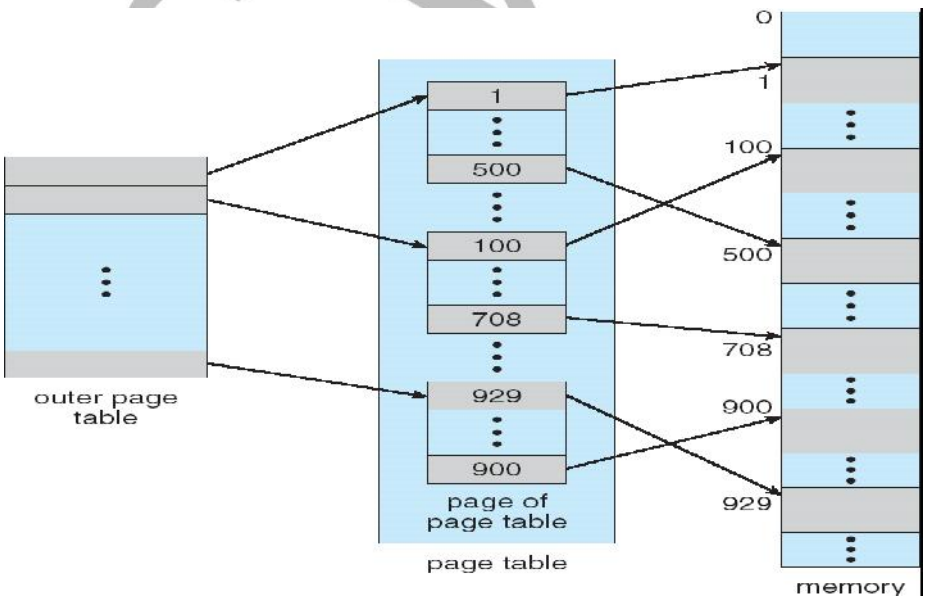
a) Hierarchical Paging b) Hashed Page Tables c) Inverte Page Tables

a) Hierarchical Paging

- Break up the Page table into smaller pieces. Because if the page table is too large then it is qui difficult to search the page number.

Example: "Two-Level Paging "

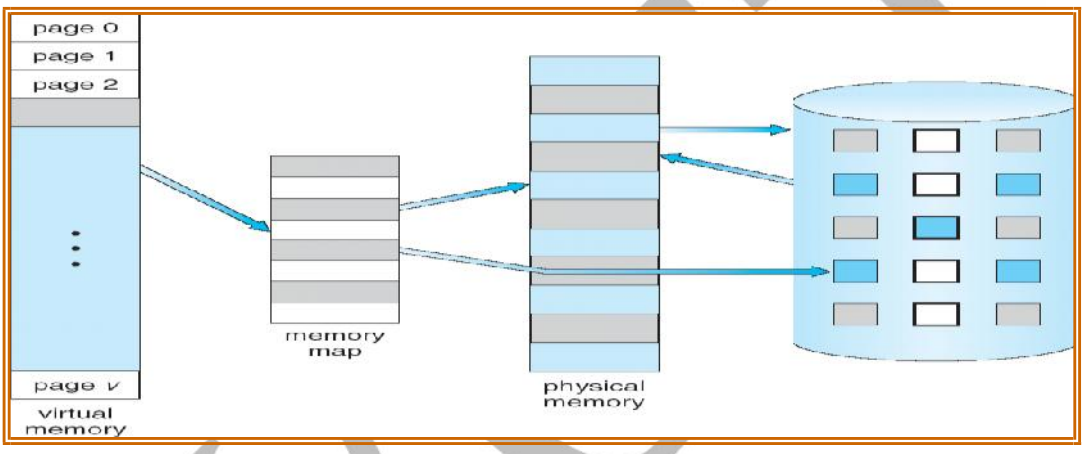




Virtual Memory

- It is a technique that allows the execution of processes that may not be completely in main memory.
- **Advantages:**
  - Allows the program that can be larger than the physical memory.
  - Separation of user logical memory from physical memory
  - Allows processes to easily share files & address space.
  - Allows for more efficient process creation.
- Virtual memory can be implemented using
  - Demand paging
  - Demand segmentation

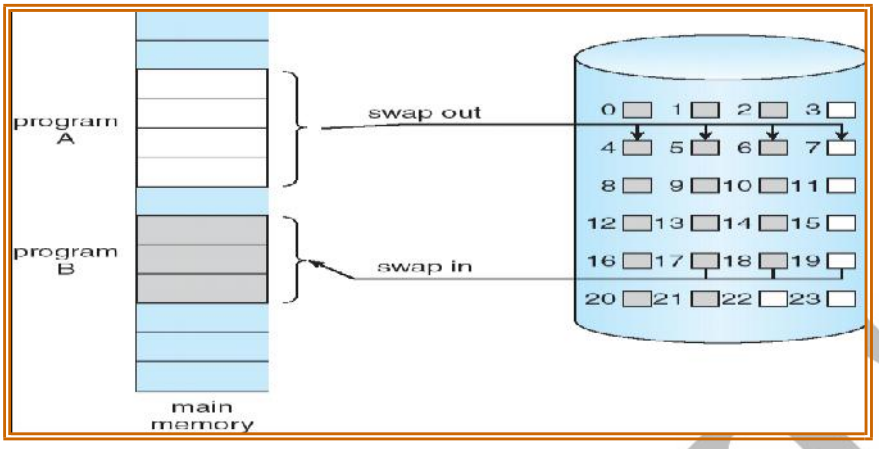
Virtual Memory That is Larger than Physical Memory



Demand Paging

- It is similar to a paging system with swapping.
- Demand Paging - Bring a page into memory only when it is needed
- To execute a process, swap that entire process into memory. Rather than swapping the entire process into memory however, we use –Lazy Swapper‖
- **Lazy Swapper** - Never swaps a page into memory unless that page will be needed.
- **Advantages**
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users

Transfer of a paged memory to contiguous disk space



Basic Concepts:

- Instead of swapping in the whole processes, the pager brings only those necessary pages into memory. Thus,
  1. It avoids reading into memory pages that will not be used anyway.
  2. Reduce the swap time.
  3. Reduce the amount of physical memory needed.
- To differentiate between those pages that are in memory & those that are on the disk we use the **Valid-Invalid bit**

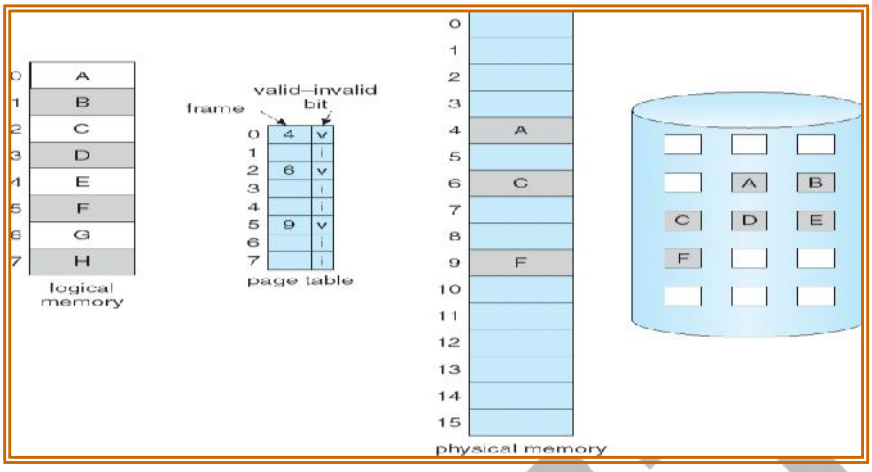
- A valid – invalid bit is associated with each page table entry.
- Valid associated page is in memory.

  In-Valid

  invalid page

  valid page but is currently on the disk

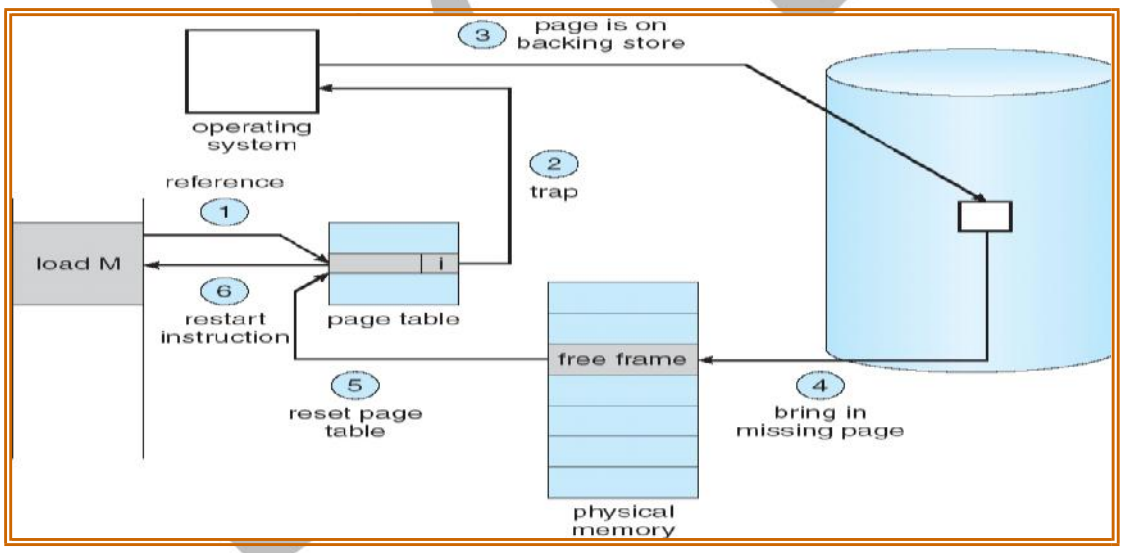
Page table when some pages are not in main memory



Page Fault

- Access to a page marked invalid causes a page fault trap**.**

Steps in Handling a Page Fault



1. Determine whether the reference is a valid or invalid memory access
2. a) If the reference is invalid then terminate the process.
   b) If the reference is valid then the page has not been yet brought into main memory.
3. Find a free frame.
4. Read the desired page into the newly allocated frame.
5. Reset the page table to indicate that the page is now in memory.
6. Restart the instruction that was interrupted .

Pure demand paging

- Never bring a page into memory until it is required.
- We could start a process with no pages in memory.
- When the OS sets the instruction pointer to the 1st instruction of the process, which is on the non-memory resident page, then the process immediately faults for the page.
- After this page is bought into the memory, the process continue to execute, faulting as necessary until every page that it needs is in memory.

Performance of demand paging

- Let p be the probability of a page fault 0 p 1
- Effective Access Time (EAT)

  EAT = $(1 - p)$ x ma + p x page fault time.

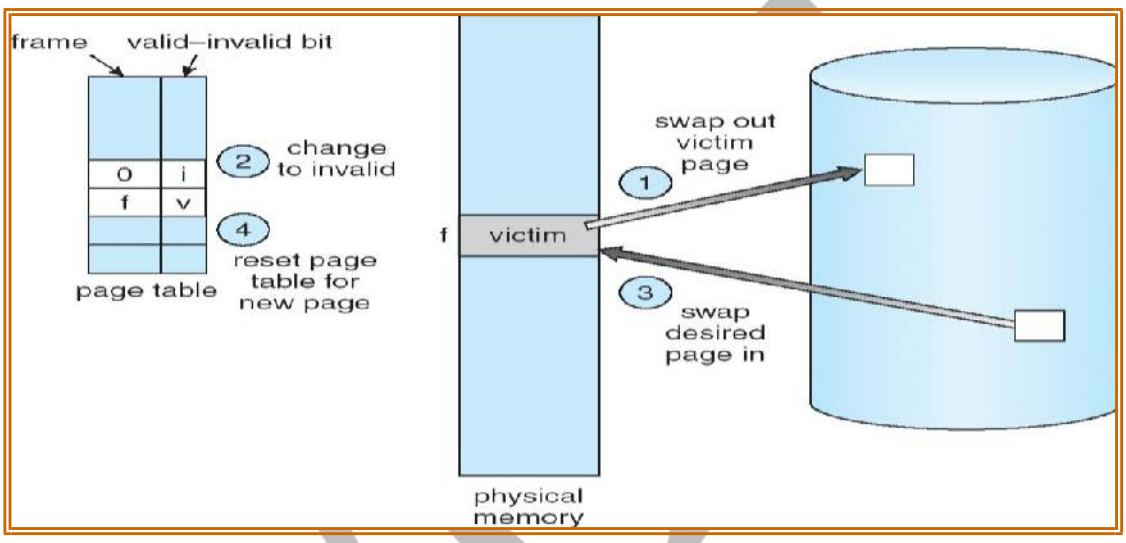
  Where ma memory access, p Probability of page fault $(0 \le p \le 1)$
- The memory access time denoted ma is in the range 10 to 200 ns.
- If there are no page faults then EAT = ma.
- To compute effective access time, we must know how much time is needed to service a page fault.
- A page fault causes the following sequence to occur:
  1. Trap to the OS
  2. Save the user registers and process state.
  3. Determine that the interrupt was a page fault.
  4. Check whether the reference was legal and find the location of page on disk.
  5. Read the page from disk to free frame.
     a. Wait in a queue until read request is serviced. b. Wait for seek time and latency time.
     c. Transfer the page from disk to free frame.
  6. While waiting ,allocate CPU to some other user.
  7. Interrupt from disk.
  8. Save registers and process state for other users.
  9. Determine that the interrupt was from disk.
  7. Reset the page table to indicate that the page is now in memory.
  8. Wait for CPU to be allocated to this process again.
  9. Restart the instruction that was interrupted .

Page Replacement

- If no frames are free, we could find one that is not currently being used & free it.
- We can free a frame by writing its contents to swap space & changing the page table to indicate that the page is no longer in memory.
- Then we can use that freed frame to hold the page for which the process faulted.

Basic Page Replacement

1. Find the location of the desired page on disk
2. Find a free frame
   - If there is a free frame , then use it.
   - If there is no free frame, use a page replacement algorithm to select a **victim** frame
   - Write the victim page to the disk, change the page & frame tables accordingly.
3. Read the desired page into the (new) free frame. Update the page and frame tables.
4. Restart the process



Page Replacement Algorithms

1. FIFO Page Replacement
2. Optimal Page Replacement
3. LRU Page Replacement
4. LRU Approximation Page Replacement
5. Counting-Based Page Replacement

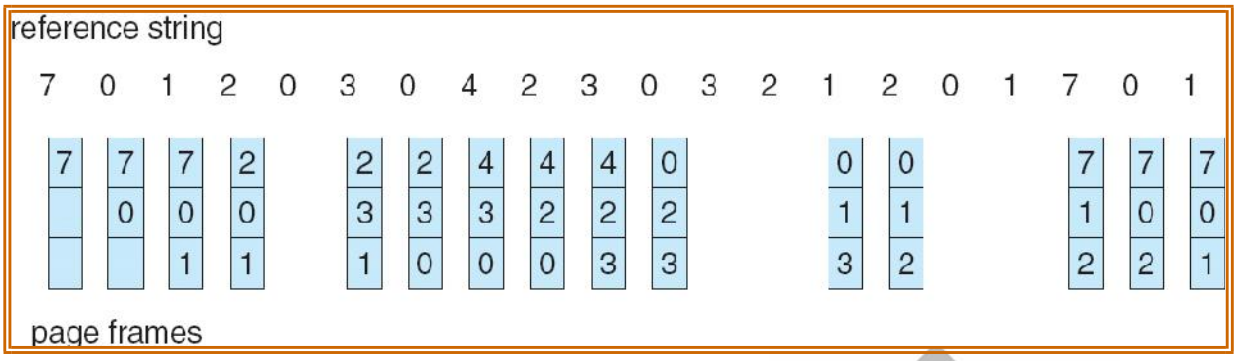
(a) FIFO page replacement algorithm

- **Replace the oldest page.**
- This algorithm associates with each page ,the time when that page was brought in.

Example:

Reference string: 7,0,1,2,0,3,0,4,2,3,0,3,2,1,2,0,1,7,0,1

No.of available frames = 3 (3 pages can be in memory at a time per process)



No. of page faults = 15

Drawback:

- FIFO page replacement algorithm _s performance is not always good.
- To illustrate this, consider the following example:

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

- If No.of available frames -= 3 then the no.of page faults =9
- If No.of available frames =4 then the no.of page faults =10
- Here the no. of page faults increases when the no.of frames increases .This is called as **Belady's Anomaly.**

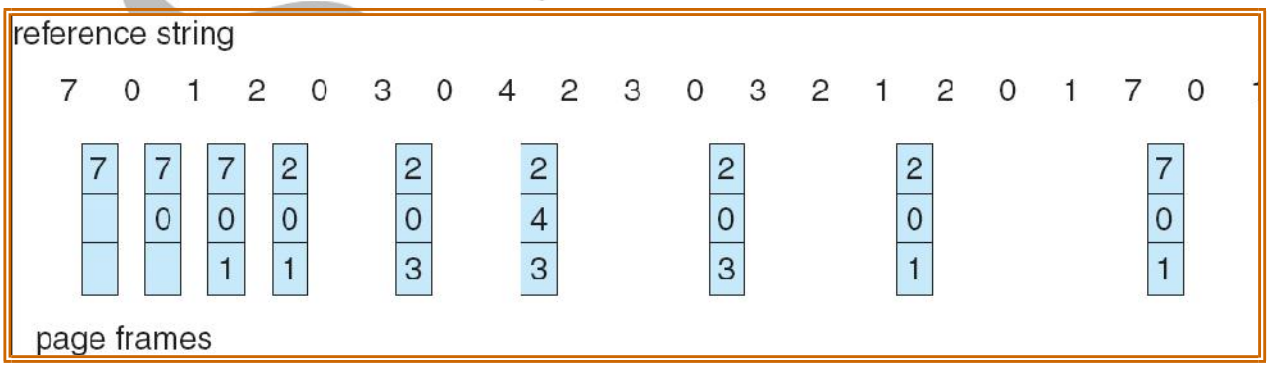
(b) Optimal page replacement algorithm

- **Replace the page that will not be used for the longest period of time.**

Example:

Reference string: 7,0,1,2,0,3,0,4,2,3,0,3,2,1,2,0,1,7,0,1

No.of available frames = 3



No. of page faults = 9

Drawback:

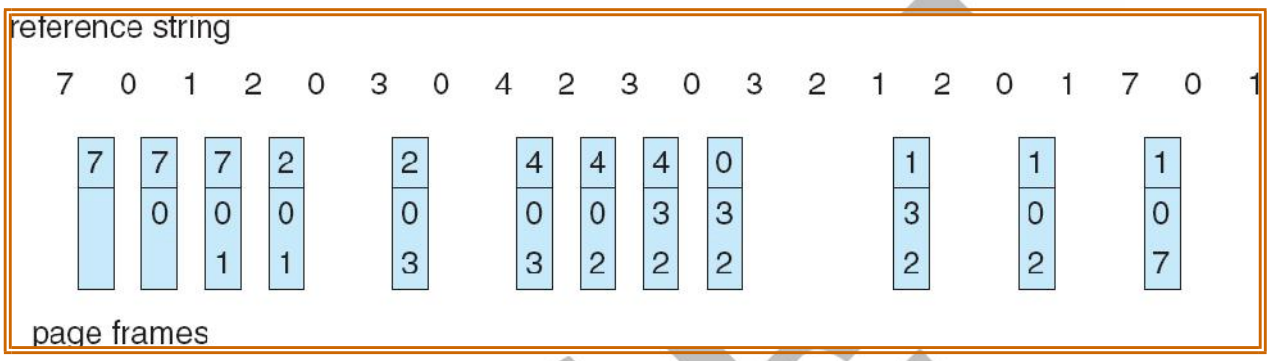
o It is difficult to implement as it requires future knowledge of the reference string.

(c) LRU(Least Recently Used) page replacement algorithm

o **Replace the page that has not been used for the longest period of time.**
Example:

Reference string: 7,0,1,2,0,3,0,4,2,3,0,3,2,1,2,0,1,7,0,1

No.of available frames = 3



No. of page faults = 12

o LRU page replacement can be implemented using

1. **Counters**

Every page table entry has a time-of-use field and a clock or counter is associated with the CPU.

The counter or clock is incremented for every memory reference.

Each time a page is referenced , copy the counter into the time- of-use field.

When a page needs to be replaced, replace the page with the smallest counter value.

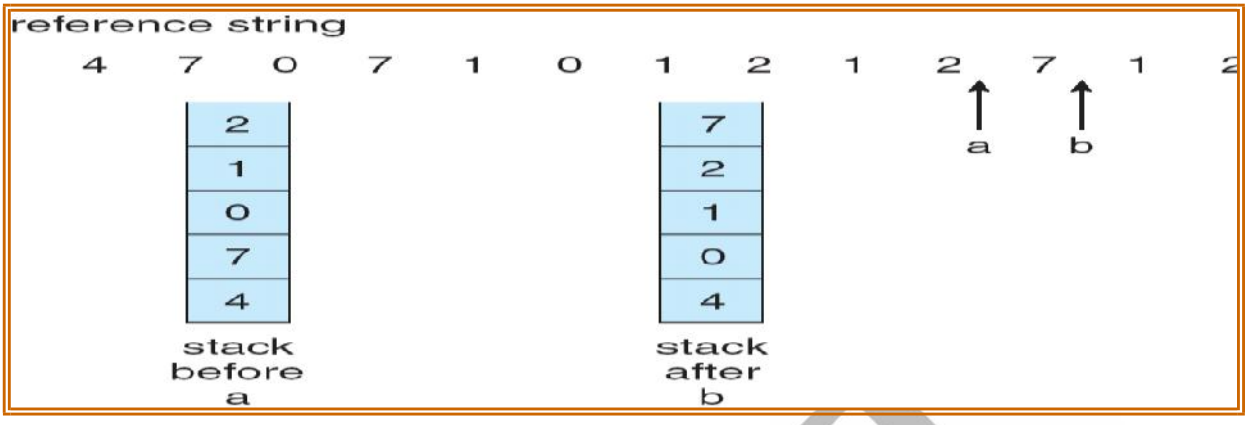
2. **Stack**

Keep a stack of page numbers

Whenever a page is referenced, remove the page from the stack and put it on top of the stack.

When a page needs to be replaced, replace the page that is at the bottom of the stack.(LRU page)

Use of A Stack to Record The Most Recent Page References



(d) LRU Approximation Page Replacement

- Reference bit
  - With each page associate a reference bit, initially set to 0
  - When page is referenced, the bit is set to 1
- When a page needs to be replaced, replace the page whose reference bit is 0
- The order of use is not known , but we know which pages were used and which were not used.

(i) Additional Reference Bits Algorithm

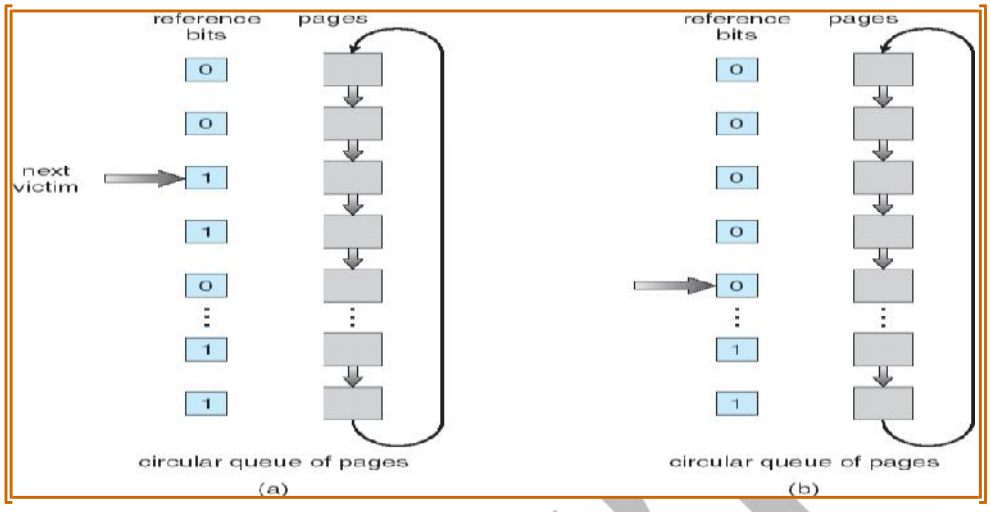
- Keep an 8-bit byte for each page in a table in memory.
- At regular intervals , a timer interrupt transfers control to OS.
- The OS shifts reference bit for each page into higher- order bit shifting the other bits right 1 bit and discarding the lower-order bit.

Example:

- If reference bit is 00000000 then the page has not been used for 8 time periods.
- If reference bit is 11111111 then the page has been used atleast once each time period.
- If the reference bit of page 1 is 11000100 and page 2 is 01110111 then page 2 is the LRU page.

(ii) Second Chance Algorithm

- Basic algorithm is FIFO
- When a page has been selected , check its reference bit.
  - If 0 proceed to replace the page
  - If 1 give the page a second chance and move on to the next FIFO page.
  - When a page gets a second chance, its reference bit is cleared and arrival time is reset to current time.
  - Hence a second chance page will not be replaced until all other pages are replaced.



(iii) Enhanced Second Chance Algorithm o Consider both reference bit and modify bit o There are four possible classes

1. (0,0) – neither recently used nor modified Best page to replace
2. (0,1) – not recently used but modified page has to be written out before replacement.
3. (1,0) - recently used but not modified page may be used again
4. (1,1) – recently used and modified page may be used again and page has to be written to disk

(e) Counting-Based Page Replacement

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

1. **Least Frequently Used (LFU)Algorithm**: replaces page with smallest count
2. **Most Frequently Used (MFU)Algorithm**: replaces page with largest count

It is based on the argument that the page with the smallest count was probably just brought in and has yet to be used

Page Buffering Algorithm

o These are used along with page replacement algorithms to improve their performance

Technique 1:

o A pool of free frames is kept.
o When a page fault occurs, choose a victim frame as before.
o Read the desired page into a free frame from the pool
o The victim frame is written onto the disk and then returned to the pool of free frames.

Technique 2:

- Maintain a list of modified pages.
- Whenever the paging device is idles, a modified is selected and written to disk and its modify bit is reset.

Technique 3:

- A pool of free frames is kept.
- Remember which page was in each frame.
- If frame contents are not modified then the old page can be reused directly from the free frame pool when needed

Allocation of Frames

- There are two major allocation schemes
  - Equal Allocation
  - Proportional Allocation
- **Equal allocation**
  - If there are n processes and m frames then allocate m/n frames to each process.
  - **Example:** If there are 5 processes and 100 frames, give each process 20 frames.
- **Proportional allocation**
  - Allocate according to the size of process
  - Let s_i be the size of process i.
  - Let m be the total no. of frames
  - Then $S = \sum s_i$
  - $a_i = s_i / S * m$
  - where a_i is the no.of frames allocated to process i.

Global vs. Local Replacement

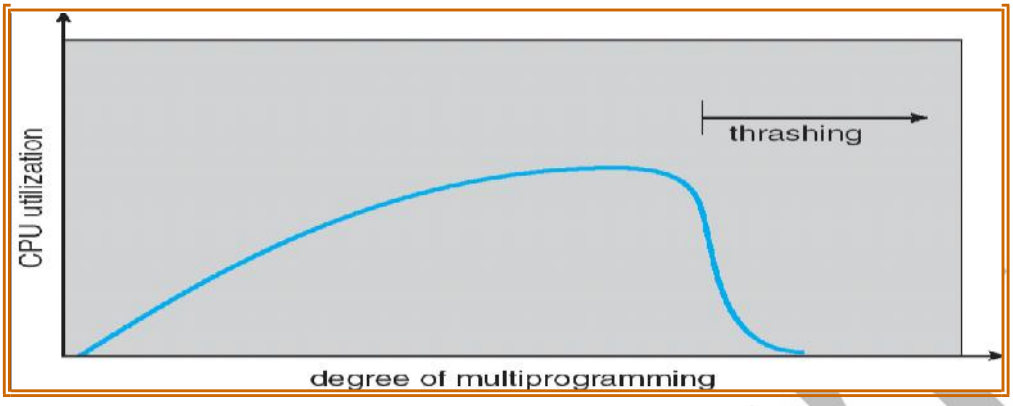
- **Global replacement** – each process selects a replacement frame from the set of all frames; one process can take a frame from another.
- **Local replacement** – each process selects from only its own set of allocated frames.

Thrashing

- High paging activity is called **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 is added to the system
- When the CPU utilization is low, the OS increases the degree of multiprogramming.
- If global replacement is used then as processes enter the main memory they tend to steal frames belonging to other processes.
- Eventually all processes will not have enough frames and hence the page fault rate becomes very

high.

- Thus swapping in and swapping out of pages only takes place.
- This is the cause of thrashing.



- To **limit thrashing**, we can use a **local replacement** algorithm.
- To prevent thrashing, there are two methods namely ,

Working Set Strategy
Page Fault Frequency

1. Working-Set Strategy

- It is based on the assumption of the model of locality.
- Locality is defined as the set of pages actively used together.
- Working set is the set of pages in the most recent page references
- is the working set window.

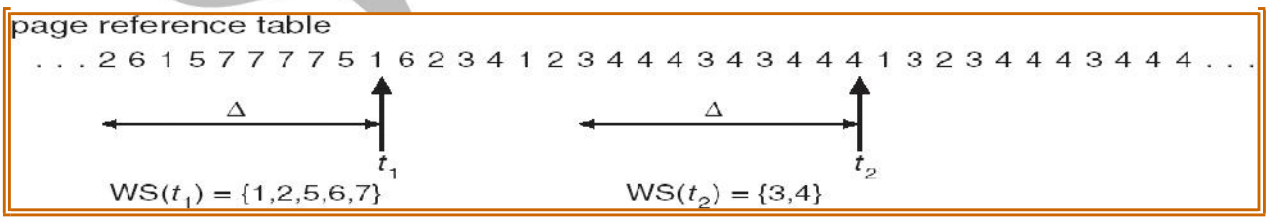
if too small , it will not encompass entire locality
if too large ,it will encompass several localities
if = it will encompass entire program

- $D = WSS_i$

Where WSS_i is the working set size for process i.

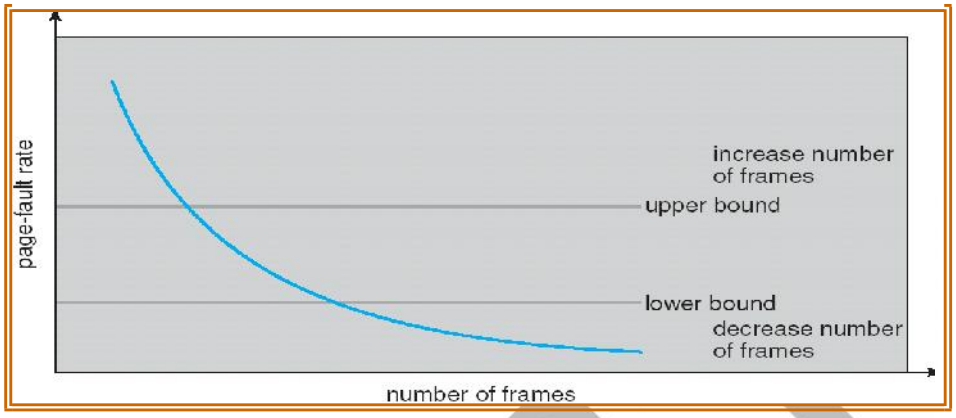
D is the total demand of frames

- if $D > m$ then Thrashing will occur.



2. Page-Fault Frequency Scheme

- If actual rate too low, process loses frame
- If actual rate too high, process gains frame



Other Issues

- **Prepaging**

  To reduce the large number of page faults that occurs at process startup

  Prepage all or some of the pages a process will need, before they are referenced

  But if prepaged pages are unused, I/O and memory are wasted

- **Page Size**

  Page size selection must take into consideration:

  - fragmentation
  - table size
  - I/O overhead
  - locality

- **TLB Reach**

  TLB Reach - The amount of memory accessible from the TLB

  TLB Reach = (TLB Size) X (Page Size)

  Ideally, the working set of each process is stored in the TLB. Otherwise there is a high degree of page faults.

  Increase the Page Size. This may lead to an increase in fragmentation as not all applications require a large page size

  Provide Multiple Page Sizes. This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation.

- **I/O interlock**

  Pages must sometimes be locked into memory

  Consider I/O. Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm.

Allocating Kernel Memory

When a process running in user mode requests additional memory, pages are allocated from the list of free page frames maintained by the kernel. This list is typically populated using a page-replacement algorithm such as those discussed in Section 9.4 and most likely contains free pages scattered throughout physical memory, as explained earlier. Remember, too, that if a user process requests a single byte of memory, internal fragmentation will result, as the process will be granted an entire page frame.

Kernel memory is often allocated from a free-memory pool different from the list used to satisfy ordinary user-mode processes. There are two primary reasons for this:

1. The kernel requests memory for data structures of varying sizes, some of which are less than a page in size. As a result, the kernel must use memory conservatively and attempt to minimize waste due to fragmentation. This is especially important because many operating systems do not subject kernel code or data to the paging system.

2. Pages allocated to user-mode processes do not necessarily have to be in contiguous physical memory. However, certain hardware devices interact directly with physical memory—without the benefit of a virtual memory interface—and consequently may require memory residing in physically contiguous pages.

Buddy System

The buddy system allocates memory from a fixed-size segment consisting of physically contiguous pages. Memory is allocated from this segment using a **power-of-2 allocator**, which satisfies requests in units sized as a power of 2 (4KB,8KB,16KB, and so forth). A request in units not appropriately sized is rounded up to the next highest power of 2. For example, a request for 11 KB is satisfied with a 16K segment

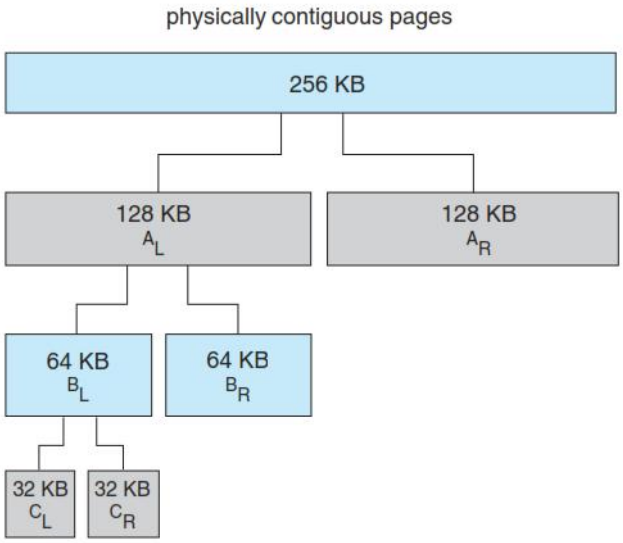


Figure 9.26 Buddy system allocation.

OS Examples

Windows

Windows implements virtual memory using demand paging with clustering. Clustering handles page faults by bringing in not only the faulting page but also several pages following the faulting page. When a process is first created, it is assigned a working-set minimum and maximum. The **working-set minimum** is the minimum number of pages the process is guaranteed to have in memory.

If sufficient memory is available, a process may be assigned as many pages as its **working-set maximum**. (In some circumstances, a process may be allowed to exceed its working-set maximum.) The virtual memory manager maintains a list of free page frames. Associated with this list is a threshold value that is used to indicate whether sufficient free memory is available. If a page fault occurs for a process that is below its working-set maximum, the virtual memory manager allocates a page from this list of free pages. If a process that is at its working-set maximum incurs a page fault, it must select a page for replacement using a local LRU page-replacement policy.

Solaris

In Solaris, when a thread incurs a page fault, the kernel assigns a page to the faulting thread fromthe list of free pages it maintains. Therefore, it is imperative that the kernel keep a sufficient amount of free memory available. Associated with this list of free pages is a parameter— lotsfree—that represents a threshold to begin paging. The lotsfree parameter is typically set to 1/64 the size of the physical memory. Four times per second, the kernel checks whether the amount of free memory is less than lotsfree. If the number of free pages falls below lotsfree, a process known as a **pageout** starts up. The pageout process is similar to the second

Figure 9.29 Solaris page scanner.