Scan or click here for more resources

Memory Management in Operating System

The term Memory can be defined as a collection of data in a specific format. It is used to store instructions and processed data. The memory comprises a large array or group of words or bytes, each with its own location. The primary motive of a computer system is to execute programs. These programs, along with the information they access, should be in the main memory during execution. The CPU fetches instructions from memory according to the value of the program counter.

To achieve a degree of multiprogramming and proper utilization of memory, memory management is important. Many memory management methods exist, reflecting various approaches, and the effectiveness of each algorithm depends on the situation.

Here, we will cover the following memory management topics:

- *What is Main Memory*
- *What is Memory Management*
- *Why memory Management is required*
- *Logical address space and Physical address space*
- *Static and dynamic loading*
- *Static and dynamic linking*
- *Swapping*
- *Contiguous Memory allocation*
    - *Memory Allocation*
        - *First Fit*
        - *Best Fit*
        - *Worst Fit*
    - *Fragmentation*
        - *Internal Fragmentation*

- *External Fragmentation*
- *Paging*

What is Memory Management :

In a multiprogramming computer, the operating system resides in a part of memory and the rest is used by multiple processes. The task of subdividing the memory among different processes is called memory management. Memory management is a method in the operating system to manage operations between main memory and disk during process execution. The main aim of memory management is to achieve efficient utilization of memory.

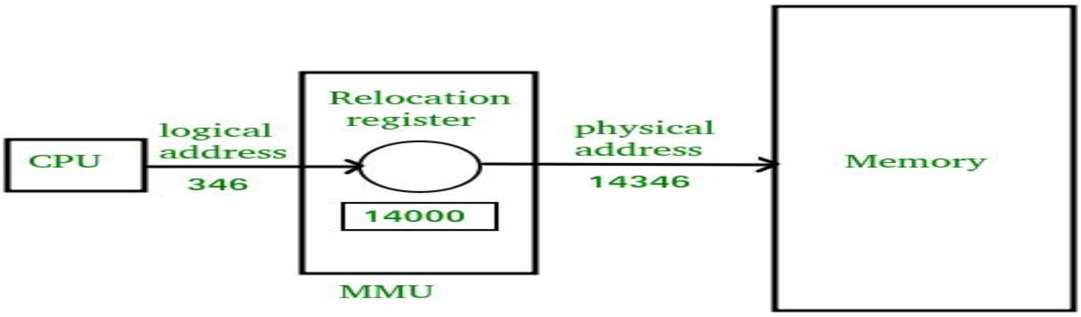
Why Memory Management is required:

- Allocate and de-allocate memory before and after process execution.
- To keep track of used memory space by processes.
- To minimize fragmentation issues.
- To proper utilization of main memory.
- To maintain data integrity while executing of process.

Logical and Physical Address Space:

Logical Address space: An address generated by the CPU is known as "Logical Address". It is also known as a Virtual address. Logical address space can be defined as the size of the process. A logical address can be changed.

Physical Address space: An address seen by the memory unit (i.e the one loaded into the memory address register of the memory) is commonly known as a "Physical Address". A Physical address is also known as a Real address. The set of all physical addresses corresponding to these logical addresses is known as Physical address space. A physical address is computed by MMU. The run-time mapping from virtual to physical addresses is done by a hardware device Memory Management Unit(MMU). The physical address always remains constant.



Comparison Chart:

Parameter	LOGICAL ADDRESS	PHYSICAL ADDRESS

Parameter	LOGICAL ADDRESS	PHYSICAL ADDRESS
Basic	generated by CPU	location in a memory unit
Address Space	Logical Address Space is set of all logical addresses generated by CPU in reference to a program.	Physical Address is set of all physical addresses mapped to the corresponding logical addresses.
Visibility	User can view the logical address of a program.	User can never view physical address of program.
Generation	generated by the CPU	Computed by MMU
Access	The user can use the logical address to access the physical address.	The user can indirectly access physical address but not directly.
Editable	Logical address can be change.	Physical address will not change.
Also called	virtual address.	real address.

Static and Dynamic Loading:

To load a process into the main memory is done by a loader. There are two different types of loading :

- **Static loading**:- loading the entire program into a fixed address. It requires more memory space.
- **Dynamic loading**:- The entire program and all data of a process must be in physical memory for the process to execute. So, the size of a process is limited to the size of physical memory. To gain proper memory utilization, dynamic loading is used. In dynamic loading, a routine is not loaded until it is called. All routines are residing on disk in a relocatable load format. One of the advantages of dynamic loading is that unused routine is never loaded. This loading is useful when a large amount of code is needed to handle it efficiently.

Static and Dynamic linking:

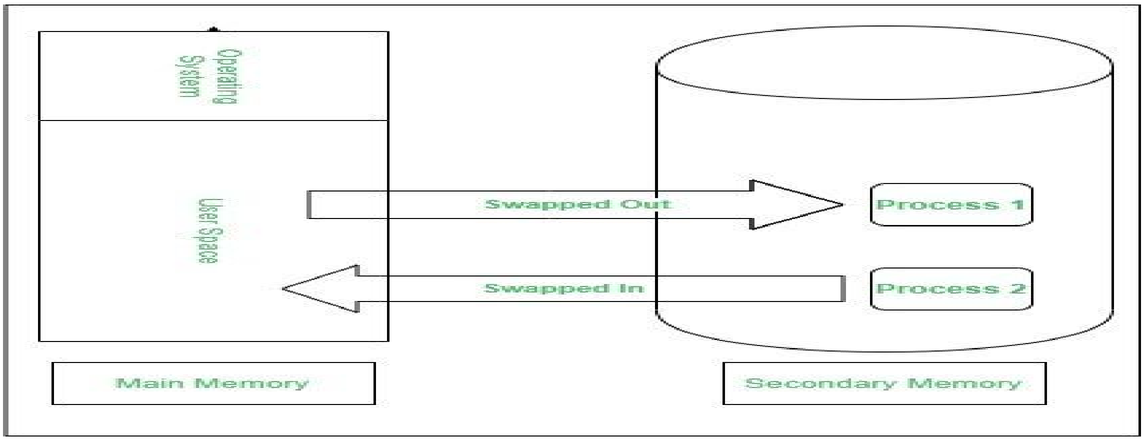
To perform a linking task a linker is used. A linker is a program that takes one or more object files generated by a compiler and combines them into a single executable file.

- **Static linking:** In static linking, the linker combines all necessary program modules into a single executable program. So there is no runtime dependency. Some operating systems support only static linking, in which system language libraries are treated like any other object module.

- **Dynamic linking:** The basic concept of dynamic linking is similar to dynamic loading. In dynamic linking, "Stub" is included for each appropriate library routine reference. A stub is a small piece of code. When the stub is executed, it checks whether the needed routine is already in memory or not. If not available then the program loads the routine into memory.

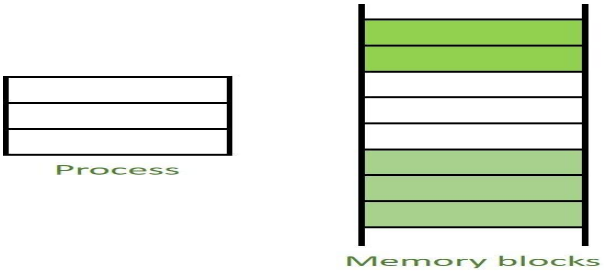
Swapping :

When a process is executed it must have resided in memory. Swapping is a process of swap a process temporarily into a secondary memory from the main memory, which is fast as compared to secondary memory. A swapping allows more processes to be run and can be fit into memory at one time. The main part of swapping is transferred time and the total time directly proportional to the amount of memory swapped. Swapping is also known as roll-out, roll in, because if a higher priority process arrives and wants service, the memory manager can swap out the lower priority process and then load and execute the higher priority process. After finishing higher priority work, the lower priority process swapped back in memory and continued to the execution process.



Contiguous Memory Allocation :

The main memory should oblige both the operating system and the different client processes. Therefore, the allocation of memory becomes an important task in the operating system. The memory is usually divided into two partitions: one for the resident operating system and one for the user processes. We normally need several user processes to reside in memory simultaneously. Therefore, we need to consider how to allocate available memory to the processes that are in the input queue waiting to be brought into memory. In adjacent memory allotment, each process is contained in a single contiguous segment of memory.



Contiguous Memory Allocation

Memory allocation:

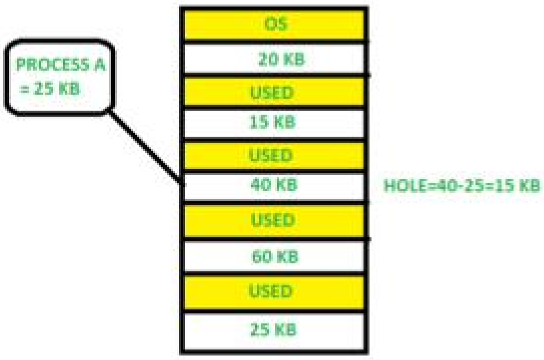
To gain proper memory utilization, memory allocation must be allocated efficient manner. One of the simplest methods for allocating memory is to divide memory into several fixed-sized partitions and each partition contains exactly one process. Thus, the degree of multiprogramming is obtained by the number of partitions.

Multiple partition allocation: In this method, a process is selected from the input queue and loaded into the free partition. When the process terminates, the partition becomes available for other processes.

Fixed partition allocation: In this method, the operating system maintains a table that indicates which parts of memory are available and which are occupied by processes. Initially, all memory is available for user processes and is considered one large block of available memory. This available memory is known as "Hole". When the process arrives and needs memory, we search for a hole that is large enough to store this process. If the requirement fulfills then we allocate memory to process, otherwise keeping the rest available to satisfy future requests. While allocating a memory sometimes dynamic storage allocation problems occur, which concerns how to satisfy a request of size n from a list of free holes. There are some solutions to this problem:

First fit:-

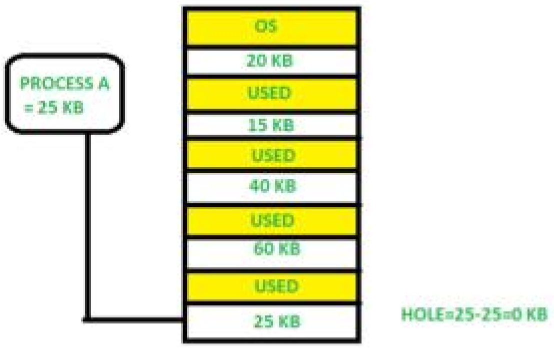
In the first fit, the first available free hole fulfills the requirement of the process allocated.



Here, in this diagram 40 KB memory block is the first available free hole that can store process A (size of 25 KB), because the first two blocks did not have sufficient memory space.

Best fit:-

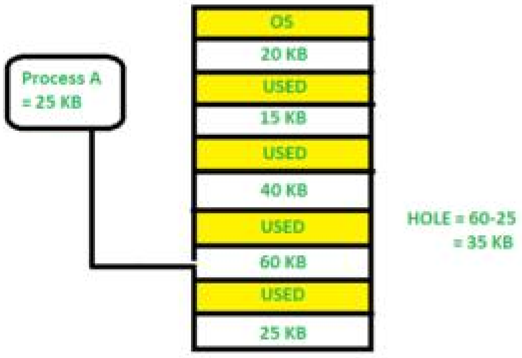
In the best fit, allocate the smallest hole that is big enough to process requirements. For this, we search the entire list, unless the list is ordered by size.



Here in this example, first, we traverse the complete list and find the last hole 25KB is the best suitable hole for Process A(size 25KB).

In this method memory utilization is maximum as compared to other memory allocation techniques.

Worst fit:-In the worst fit, allocate the largest available hole to process. This method produces the largest leftover hole.



Here in this example, Process A (Size 25 KB) is allocated to the largest available memory block which is 60KB. Inefficient memory utilization is a major issue in the worst fit.

Fragmentation:

A Fragmentation is defined as when the process is loaded and removed after execution from memory, it creates a small free hole. These holes can not be assigned to new processes because holes are not combined or do not fulfill the memory requirement of the process. To achieve a degree of multiprogramming, we must reduce the waste of memory or fragmentation problem. In operating system two types of fragmentation:

Internal fragmentation:

Internal fragmentation occurs when memory blocks are allocated to the process more than their requested size. Due to this some unused space is leftover and creates an internal fragmentation problem.

Example: Suppose there is a fixed partitioning is used for memory allocation and the different size of block 3MB, 6MB, and 7MB space in memory. Now a new process p4 of size 2MB comes and demand for the block of memory. It gets a memory block of 3MB but 1MB block memory is a waste, and it can not be allocated to other processes too. This is called internal fragmentation.

External fragmentation:

In external fragmentation, we have a free memory block, but we can not assign it to process because blocks are not contiguous.

Example: Suppose (consider above example) three process p1, p2, p3 comes with size 2MB, 4MB, and 7MB respectively. Now they get memory blocks of size 3MB, 6MB, and 7MB allocated respectively. After allocating process p1 process and p2 process left 1MB and 2MB. Suppose a new process p4 comes and demands a 3MB block of memory, which is available, but we can not assign it because free memory space is not contiguous. This is called external fragmentation.

Both the first fit and best-fit systems for memory allocation affected by external fragmentation. To overcome the external fragmentation problem Compaction is used. In the compaction technique, all free memory space combines and makes one large block. So, this space can be used by other processes effectively.

Another possible solution to the external fragmentation is to allow the logical address space of the processes to be noncontiguous, thus permit a process to be allocated physical memory where ever the latter is available.

Compaction in Operating System

Compaction is a technique to collect all the free memory present in form of fragments into one large chunk of free memory, which can be used to run other processes.

It does that by moving all the processes towards one end of the memory and all the available free space towards the other end of the memory so that it becomes contiguous.

It is not always easy to do compaction. Compaction can be done only when the relocation is dynamic and done at execution time. Compaction can not be done when relocation is static and is performed at load time or assembly time.

Advantages of Compaction

- Reduces external fragmentation.
- Make memory usage efficient.
- Memory becomes contiguous.
- Since memory becomes contiguous more processes can be loaded to memory.

Disadvantages of Compaction

- System efficiency reduces.
- A huge amount of time is wasted in performing compaction.

- CPU sits idle for a long time.
- Not always easy to perform compaction.

Paging:

Paging is a memory management scheme that eliminates the need for contiguous allocation of physical memory. This scheme permits the physical address space of a process to be non-contiguous.

- Logical Address or Virtual Address (represented in bits): An address generated by the CPU
- Logical Address Space or Virtual Address Space (represented in words or bytes): The set of all logical addresses generated by a program
- Physical Address (represented in bits): An address actually available on a memory unit
- Physical Address Space (represented in words or bytes): The set of all physical addresses corresponding to the logical addresses

Example:

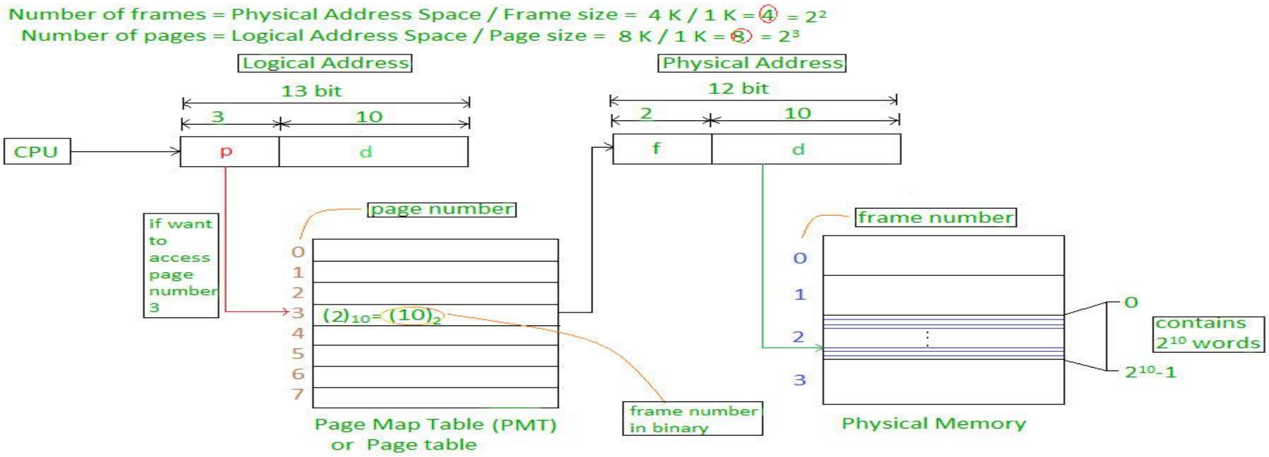
- If Logical Address = 31 bits, then Logical Address Space = 2_{31} words = 2 G words (1 G = 2_{30})
- If Logical Address Space = 128 M words = 2_{7} * 2_{20} words, then Logical Address = $\log_2 2_{27}$ = 27 bits
- If Physical Address = 22 bits, then Physical Address Space = 2_{22} words = 4 M words (1 M = 2_{20})
- If Physical Address Space = 16 M words = 2_{4} * 2_{20} words, then Physical Address = $\log_2 2_{24}$ = 24 bits

The mapping from virtual to physical address is done by the memory management unit (MMU) which is a hardware device and this mapping is known as the paging technique.

- The Physical Address Space is conceptually divided into several fixed-size blocks, called **frames**.
- The Logical Address Space is also split into fixed-size blocks, called **pages**.
- Page Size = Frame Size

Let us consider an example:

- Physical Address = 12 bits, then Physical Address Space = 4 K words
- Logical Address = 13 bits, then Logical Address Space = 8 K words
- Page size = frame size = 1 K words (assumption)


Number of frames = Physical Address Space / Frame size = 4 K / 1 K = 4 = 2²
Number of pages = Logical Address Space / Page size = 8 K / 1 K = 8 = 2³
Logical Address
13 bit
3
10
CPU
p
d
Physical Address
12 bit
2
10
f
d
if want to access page number 3
page number
0
1
2
3
4
5
6
7
(2)₁₀= (10)₂
Page Map Table (PMT) or Page table
frame number in binary
frame number
0
1
2
3
0
contains 2¹⁰ words
2¹⁰-1
Physical Memory

The address generated by the CPU is divided into

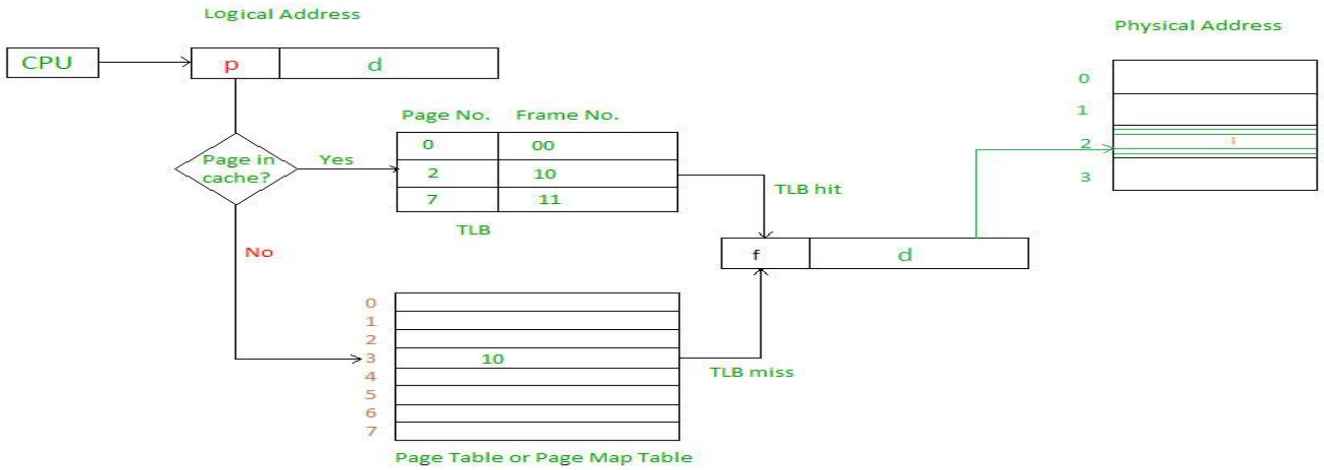
- **Page number(p):** Number of bits required to represent the pages in Logical Address Space or Page number
- **Page offset(d):** Number of bits required to represent a particular word in a page or page size of Logical Address Space or word number of a page or page offset.

Physical Address is divided into

- **Frame number(f):** Number of bits required to represent the frame of Physical Address Space or Frame number frame
- **Frame offset(d):** Number of bits required to represent a particular word in a frame or frame size of Physical Address Space or word number of a frame or frame offset.

The hardware implementation of the page table can be done by using dedicated registers. But the usage of register for the page table is satisfactory only if the page table is small. If the page table contains a large number of entries then we can use TLB(translation Look-aside buffer), a special, small, fast look-up hardware cache.

- The TLB is an associative, high-speed memory.
- Each entry in TLB consists of two parts: a tag and a value.
- When this memory is used, then an item is compared with all tags simultaneously. If the item is found, then the corresponding value is returned.



Main memory access time = m

If page table are kept in main memory,

Effective access time = m(for page table) + m(for particular page in page table)

Segmentation in Operating System

A process is divided into Segments. The chunks that a program is divided into which are not necessarily all of the same sizes are called segments. Segmentation gives user's view of the process which paging does not give. Here the user's view is mapped to physical memory.

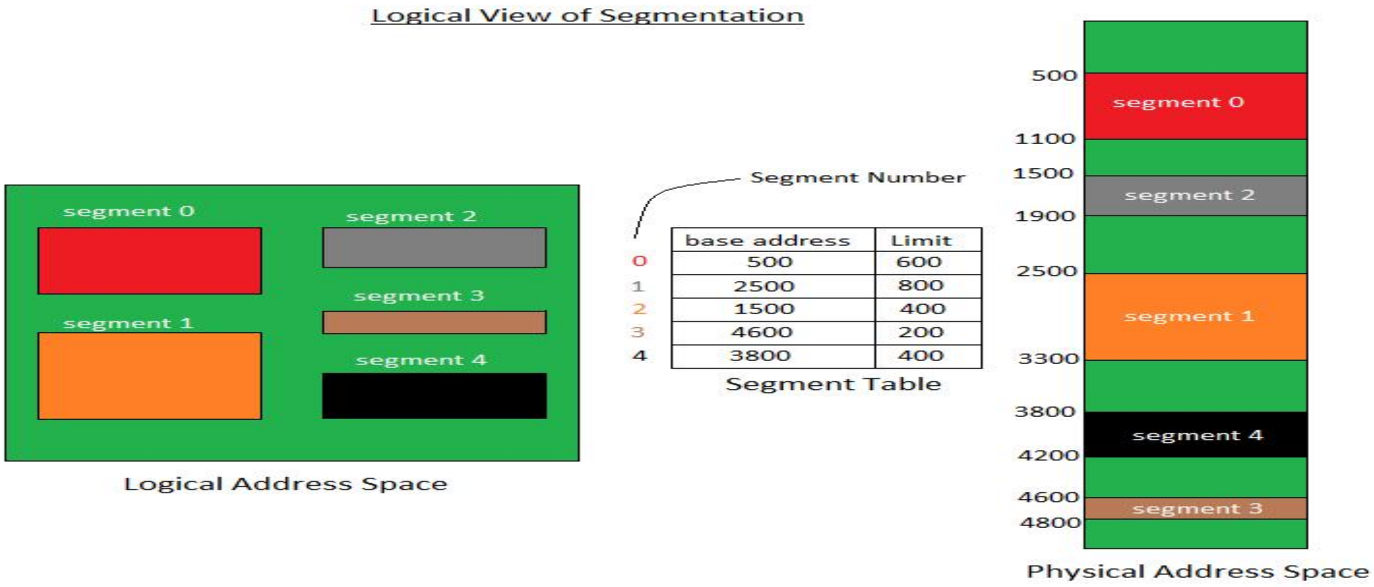
There are types of segmentation:

1. **Virtual memory segmentation –**
   Each process is divided into a number of segments, not all of which are resident at any one point in time.
2. **Simple segmentation –**
   Each process is divided into a number of segments, all of which are loaded into memory at run time, though not necessarily contiguously.

There is no simple relationship between logical addresses and physical addresses in segmentation. A table stores the information about all such segments and is called Segment Table.

Segment Table – It maps two-dimensional Logical address into one-dimensional Physical address. It's each table entry has:

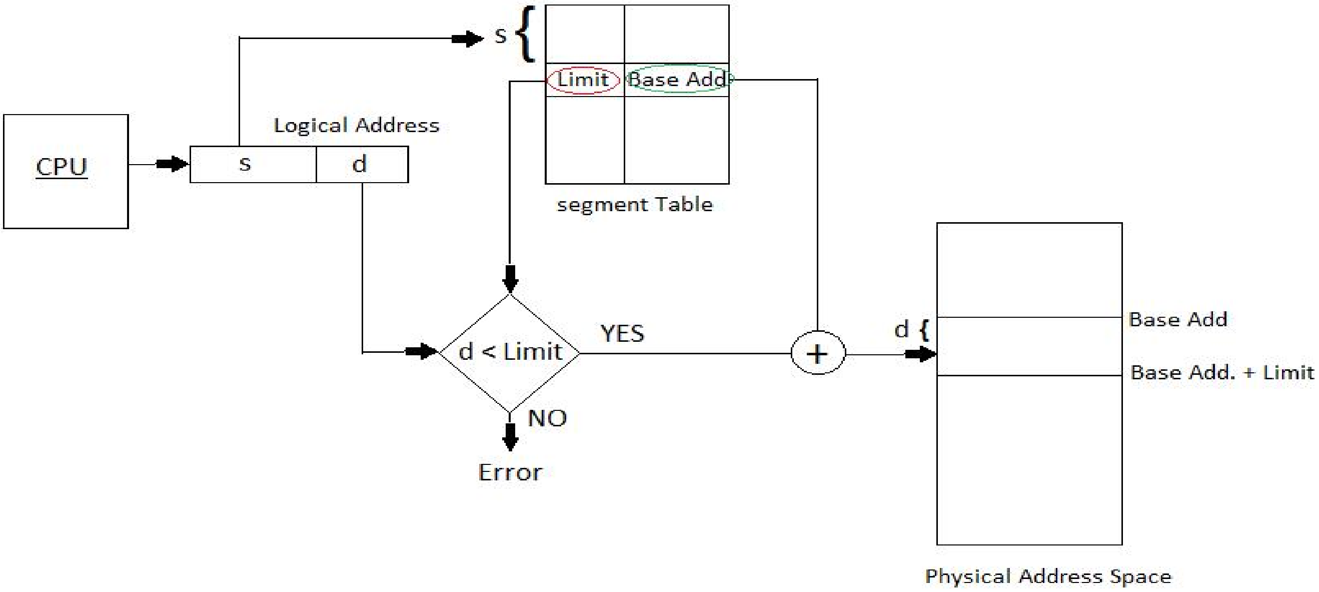
- **Base Address:** It contains the starting physical address where the segments reside in memory.
- **Limit:** It specifies the length of the segment.


Logical View of Segmentation

	base address	Limit
0	500	600
1	2500	800
2	1500	400
3	4600	200
4	3800	400

Segment Table

Translation of Two dimensional Logical Address to one dimensional Physical Address.



Address generated by the CPU is divided into:

- **Segment number (s)**: Number of bits required to represent the segment.
- **Segment offset (d)**: Number of bits required to represent the size of the segment.

Advantages of Segmentation –

- No Internal fragmentation.
- Segment Table consumes less space in comparison to Page table in paging.

Disadvantage of Segmentation –

- As processes are loaded and removed from the memory, the free memory space is broken into little pieces, causing External fragmentation.

Virtual Memory in Operating System

Virtual Memory is a storage allocation scheme in which secondary memory can be addressed as though it were part of the main memory. The addresses a program may use to reference memory are distinguished from the addresses the memory system uses to identify physical storage sites, and program-generated addresses are translated automatically to the corresponding machine addresses.

The size of virtual storage is limited by the addressing scheme of the computer system and the amount of secondary memory is available not by the actual number of the main storage locations.

It is a technique that is implemented using both hardware and software. It maps memory addresses used by a program, called virtual addresses, into physical addresses in computer memory.

1. All memory references within a process are logical addresses that are dynamically translated into physical addresses at run time. This means that a process can be swapped in and out of the main memory such that it occupies different places in the main memory at different times during the course of execution.

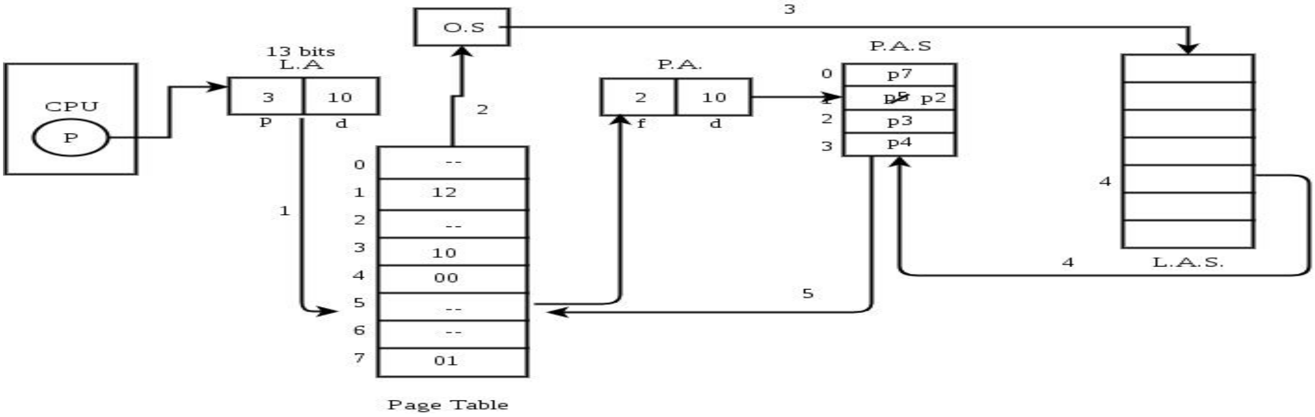
2. A process may be broken into a number of pieces and these pieces need not be continuously located in the main memory during execution. The combination of dynamic run-time address translation and use of page or segment table permits this.

If these characteristics are present then, it is not necessary that all the pages or segments are present in the main memory during execution. This means that the required pages need to be loaded into memory whenever required. Virtual memory is implemented using Demand Paging or Demand Segmentation.

Demand Paging :

The process of loading the page into memory on demand (whenever page fault occurs) is known as demand paging.

The process includes the following steps :



1. If the CPU tries to refer to a page that is currently not available in the main memory, it generates an interrupt indicating a memory access fault.
2. The OS puts the interrupted process in a blocking state. For the execution to proceed the OS must bring the required page into the memory.
3. The OS will search for the required page in the logical address space.
4. The required page will be brought from logical address space to physical address space. The page replacement algorithms are used for the decision-making of replacing the page in physical address space.
5. The page table will be updated accordingly.
6. The signal will be sent to the CPU to continue the program execution and it will place the process back into the ready state.

Hence whenever a page fault occurs these steps are followed by the operating system and the required page is brought into memory.

Advantages :

- More processes may be maintained in the main memory: Because we are going to load only some of the pages of any particular process, there is room for more processes. This leads to more efficient utilization of the processor because it is more likely that at least one of the more numerous processes will be in the ready state at any particular time.

- A process may be larger than all of the main memory: One of the most fundamental restrictions in programming is lifted. A process larger than the main memory can be executed because of demand paging. The OS itself loads pages of a process in the main memory as required.
- It allows greater multiprogramming levels by using less of the available (primary) memory for each process.

Page Replacement Algorithms in Operating Systems

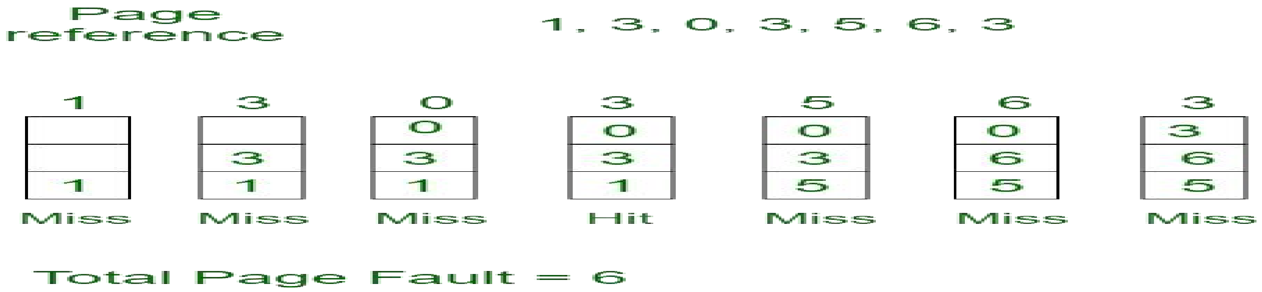
In an operating system that uses paging for memory management, a page replacement algorithm is needed to decide which page needs to be replaced when a new page comes in.

Page Fault – A page fault happens when a running program accesses a memory page that is mapped into the virtual address space but not loaded in physical memory.

Since actual physical memory is much smaller than virtual memory, page faults happen. In case of a page fault, Operating System might have to replace one of the existing pages with the newly needed page. Different page replacement algorithms suggest different ways to decide which page to replace. The target for all algorithms is to reduce the number of page faults.

Page Replacement Algorithms :

1. First In First Out (FIFO) –
This is the simplest page replacement algorithm. In this algorithm, the operating system keeps track of all pages in the memory in a queue, the oldest page is in the front of the queue. When a page needs to be replaced page in the front of the queue is selected for removal.
Example-1 Consider page reference string 1, 3, 0, 3, 5, 6, 3 with 3 page frames.Find the number of page faults.



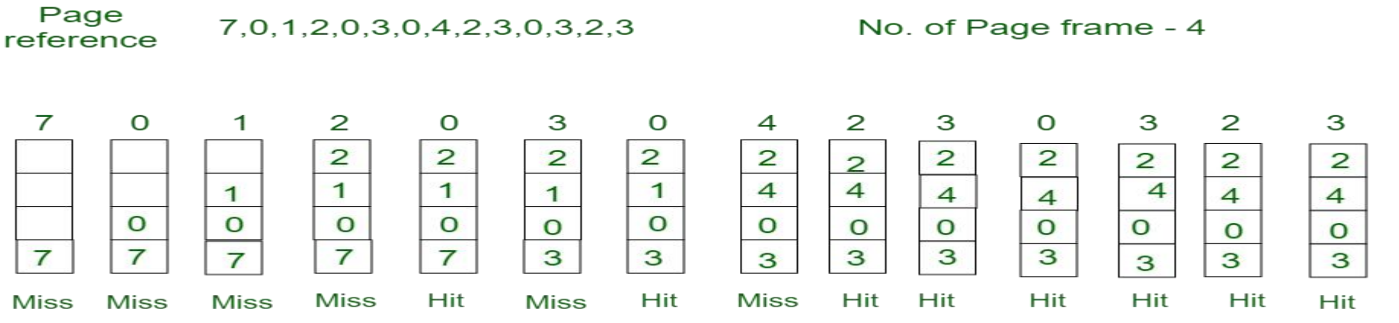
Initially, all slots are empty, so when 1, 3, 0 came they are allocated to the empty slots —> **3 Page Faults.**
when 3 comes, it is already in memory so —> **0 Page Faults.**
Then 5 comes, it is not available in memory so it replaces the oldest page slot i.e 1. —>**1 Page Fault.**
6 comes, it is also not available in memory so it replaces the oldest page slot i.e 3 —>**1 Page Fault.**
Finally, when 3 come it is not available so it replaces 0 **1 page fault**

Belady's anomaly – Belady's anomaly proves that it is possible to have more page faults when increasing the number of page frames while using the First in First Out (FIFO) page replacement algorithm. For example, if we consider reference string 3, 2, 1, 0, 3, 2, 4, 3, 2, 1, 0, 4 and 3 slots, we get 9 total page faults, but if we increase slots to 4, we get 10-page faults.

2. Optimal Page replacement –

In this algorithm, pages are replaced which would not be used for the longest duration of time in the future.

Example-2:*Consider the page references 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, with 4 page frame. Find number of page fault.*



Total Page Fault = 6

Initially, all slots are empty, so when 7 0 1 2 are allocated to the empty slots —> ***4 Page faults***

0 is already there so —> ***0 Page fault.***

*when 3 came it will take the place of 7 because it is not used for the longest duration of time in the future.—>****1 Page fault.***

0 is already there so —> ***0 Page fault..***

4 will takes place of 1 —> ***1 Page Fault.***

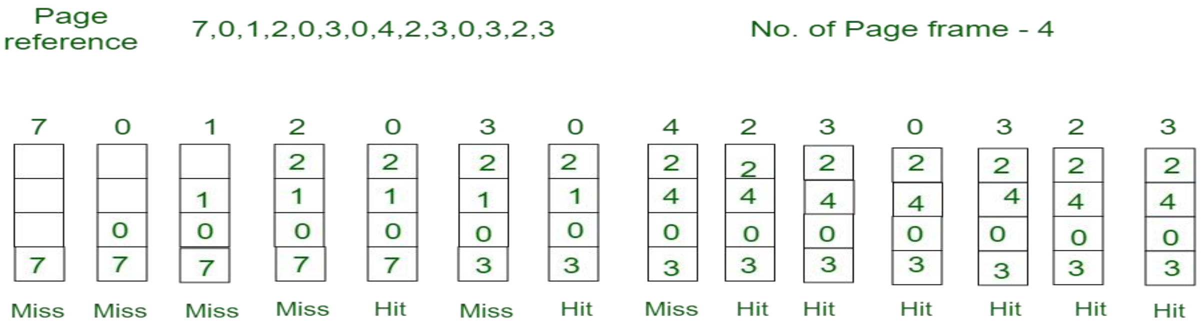
Now for the further page reference string —> ***0 Page fault*** *because they are already available in the memory.*

Optimal page replacement is perfect, but not possible in practice as the operating system cannot know future requests. The use of Optimal Page replacement is to set up a benchmark so that other replacement algorithms can be analyzed against it.

3. Least Recently Used –

In this algorithm, page will be replaced which is least recently used.

Example-3*Consider the page reference string 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2 with 4 page frames.Find number of page faults.*



Total Page Fault = 6

Here LRU has same number of page fault as optimal but it may differ according to question.

Initially, all slots are empty, so when 7 0 1 2 are allocated to the empty slots —> ***4 Page faults***

0 is already their so —> ***0 Page fault.***

when 3 came it will take the place of 7 because it is least recently used —>**1 Page fault**

0 is already in memory so —> **0 Page fault**.

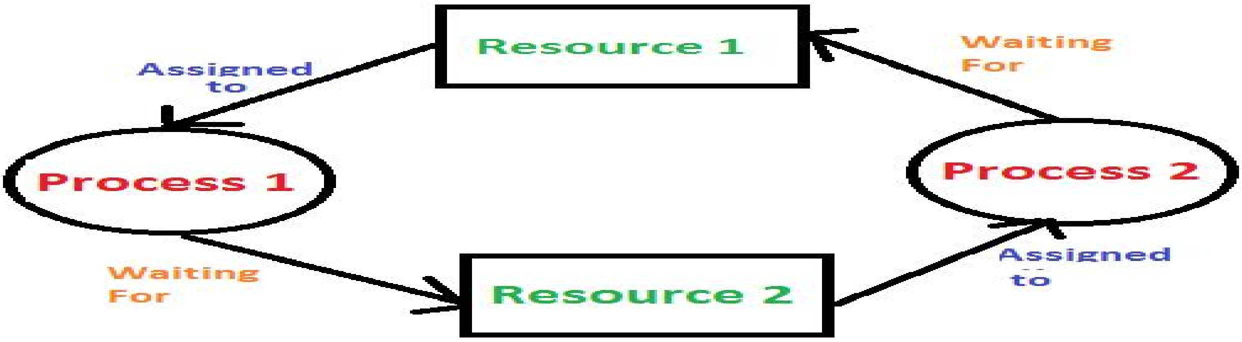
4 will takes place of 1 —> **1 Page Fault**

Now for the further page reference string —> **0 Page fault** because they are already available in the memory.

Introduction of Deadlock in Operating System

Deadlock is a situation where a set of processes are blocked because each process is holding a resource and waiting for another resource acquired by some other process.

Consider an example when two trains are coming toward each other on the same track and there is only one track, none of the trains can move once they are in front of each other. A similar situation occurs in operating systems when there are two or more processes that hold some resources and wait for resources held by other(s). For example, in the below diagram, Process 1 is holding Resource 1 and waiting for resource 2 which is acquired by process 2, and process 2 is waiting for resource 1.



Deadlock can arise if the **following four conditions hold simultaneously (Necessary Conditions)**

Mutual Exclusion: Two or more resources are non-shareable (Only one process can use at a time)

Hold and Wait: A process is holding at least one resource and waiting for resources.

No Preemption: A resource cannot be taken from a process unless the process releases the resource.

Circular Wait: A set of processes are waiting for each other in circular form.

Methods for handling deadlock

There are three ways to handle deadlock

1) Deadlock prevention or avoidance: The idea is to not let the system into a deadlock state.

One can zoom into each category individually, Prevention is done by negating one of above mentioned necessary conditions for deadlock.

Avoidance is kind of futuristic in nature. By using strategy of "Avoidance", we have to make an assumption. We need to ensure that all information about resources which process will need are known to us prior to execution of the process. We use Banker's algorithm (Which is in-turn a gift from Dijkstra) in order to avoid deadlock.

2) Deadlock detection and recovery: Let deadlock occur, then do preemption to handle it once occurred.

3) Ignore the problem altogether: If deadlock is very rare, then let it happen and reboot the system. This is the approach that both Windows and UNIX take.

Deadlock Detection Algorithm in Operating System

If a system does not employ either a deadlock prevention or deadlock avoidance algorithm then a deadlock situation may occur. In this case-

- Apply an algorithm to examine state of system to determine whether deadlock has occurred or not.
- Apply an algorithm to recover from the deadlock. For more refer- Deadlock Recovery

Deadlock Avoidance Algorithm/ Bankers Algorithm:

The algorithm employs several times varying data structures:

- **Available –**
  A vector of length m indicates the number of available resources of each type.
- **Allocation –**
  An n*m matrix defines the number of resources of each type currently allocated to a process. Column represents resource and rows represent process.
- **Request –**
  An n*m matrix indicates the current request of each process. If request[i][j] equals k then process P_i is requesting k more instances of resource type R_j.

This algorithm has already been discussed here

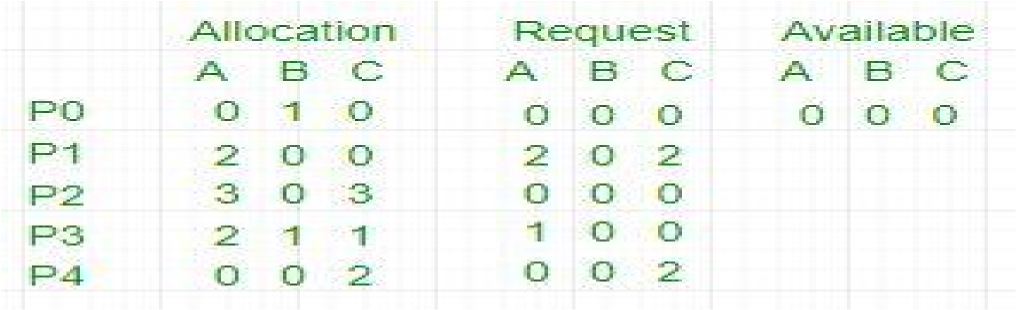
Now, Bankers algorithm includes a **Safety Algorithm / Deadlock Detection Algorithm**

The algorithm for finding out whether a system is in a safe state can be described as follows:

Steps of Algorithm:

1. Let *Work* and *Finish* be vectors of length m and n respectively. Initialize *Work= Available.* For *i=0, 1, …., n-1*, if $Request_i$ = 0, then *Finish[i]* = true; otherwise, *Finish[i]*= false.
2. Find an index i such that both
   a) *Finish[i] == false*
   b) $Request_i$ <= *Work*
   If no such *i* exists go to step 4.
3. *Work= Work+* $Allocation_i$
   Finish[i]= true
   Go to Step 2.
4. If *Finish[i]== false* for some i, 0<=i<n, then the system is in a deadlocked state. Moreover, if *Finish[i]==false* the process Pi is deadlocked.

For example,



	Allocation			Request			Available		
	A	B	C	A	B	C	A	B	C
P0	0	1	0	0	0	0	0	0	0
P1	2	0	0	2	0	2			
P2	3	0	3	0	0	0			
P3	2	1	1	1	0	0			
P4	0	0	2	0	0	2			

1. In this, Work = [0, 0, 0] &
Finish = [false, false, false, false, false]

2. i=0 is selected as both Finish[0] = false and [0, 0, 0]<=[0, 0, 0].

3. Work =[0, 0, 0]+[0, 1, 0] =>[0, 1, 0] &
Finish = [true, false, false, false, false].

4. i=2 is selected as both Finish[2] = false and [0, 0, 0]<=[0, 1, 0].
5. Work =[0, 1, 0]+[3, 0, 3] =>[3, 1, 3] &
Finish = [true, false, true, false, false].

6. i=1 is selected as both Finish[1] = false and [2, 0, 2]<=[3, 1, 3].
7. Work =[3, 1, 3]+[2, 0, 0] =>[5, 1, 3] &
Finish = [true, true, true, false, false].

8. i=3 is selected as both Finish[3] = false and [1, 0, 0]<=[5, 1, 3].
9. Work =[5, 1, 3]+[2, 1, 1] =>[7, 2, 4] &
Finish = [true, true, true, true, false].

10. i=4 is selected as both Finish[4] = false and [0, 0, 2]<=[7, 2, 4].

11. Work =[7, 2, 4]+[0, 0, 2] =>[7, 2, 6] &
Finish = [true, true, true, true, true].

12. Since Finish is a vector of all true it means **there is no deadlock** in this example.

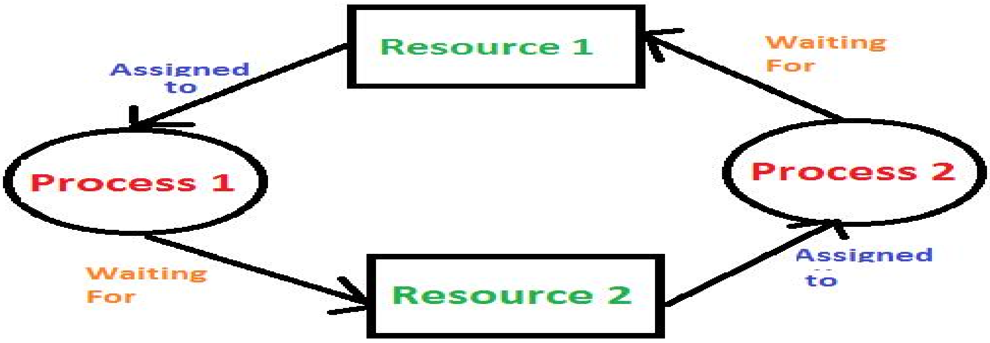
Deadlock Detection And Recovery

In the previous post, we have discussed Deadlock Prevention and Avoidance. In this post, the Deadlock Detection and Recovery technique to handle deadlock is discussed.

Deadlock Detection :

1. If resources have a single instance –

In this case for Deadlock detection, we can run an algorithm to check for the cycle in the Resource Allocation Graph. The presence of a cycle in the graph is a sufficient condition for deadlock.



2. In the above diagram, resource 1 and resource 2 have single instances. There is a cycle R1 → P1 → R2 → P2. So, Deadlock is Confirmed.

3. If there are multiple instances of resources –

Detection of the cycle is necessary but not sufficient condition for deadlock detection, in this case, the system may or may not be in deadlock varies according to different situations.

Deadlock Recovery :

A traditional operating system such as Windows doesn't deal with deadlock recovery as it is a time and space-consuming process. Real-time operating systems use Deadlock recovery.

1. **Killing the process –**

   Killing all the processes involved in the deadlock. Killing process one by one. After killing each process check for deadlock again keep repeating the process till the system recovers from deadlock. Killing all the processes one by one helps a system to break circular wait condition.

2. **Resource Preemption –**

   Resources are preempted from the processes involved in the deadlock, preempted resources are allocated to other processes so that there is a possibility of recovering the system from deadlock. In this case, the system goes into starvation.

Deadlock Prevention And Avoidance

Deadlock Characteristics

As discussed in the previous post, deadlock has following characteristics.

1. Mutual Exclusion
2. Hold and Wait
3. No preemption
4. Circular wait

Deadlock Prevention

We can prevent Deadlock by eliminating any of the above four conditions.

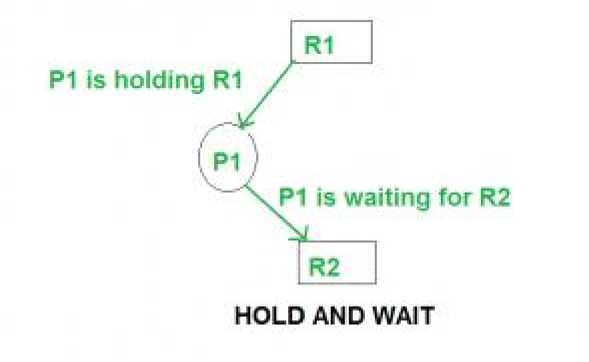
Eliminate Mutual Exclusion

It is not possible to dis-satisfy the mutual exclusion because some resources, such as the tape drive and printer, are inherently non-shareable.

Eliminate Hold and wait

1. Allocate all required resources to the process before the start of its execution, this way hold and wait condition is eliminated but it will lead to low device utilization. for example, if a process requires printer at a later time and we have allocated printer before the start of its execution printer will remain blocked till it has completed its execution.

2. The process will make a new request for resources after releasing the current set of resources. This solution may lead to starvation.



HOLD AND WAIT

Eliminate No Preemption

Preempt resources from the process when resources required by other high priority processes.

Eliminate Circular Wait

Each resource will be assigned with a numerical number. A process can request the resources increasing/decreasing. order of numbering.

For Example, if P1 process is allocated R5 resources, now next time if P1 ask for R4, R3 lesser than R5 such request will not be granted, only request for resources more than R5 will be granted.

Deadlock Avoidance

Deadlock avoidance can be done with Banker's Algorithm.

Banker's Algorithm

Bankers's Algorithm is resource allocation and deadlock avoidance algorithm which test all the request made by processes for resources, it checks for the safe state, if after granting request system remains in the safe state it allows the request and if there is no safe state it doesn't allow the request made by the process.

Inputs to Banker's Algorithm:

1. Max need of resources by each process.
2. Currently, allocated resources by each process.
3. Max free available resources in the system.

The request will only be granted under the below condition:

1. *If the request made by the process is less than equal to max need to that process.*
2. *If the request made by the process is less than equal to the freely available resource in the system.*

Example:

```
Total resources in system:
A B C D
6 5 7 6


Available system resources are:
A B C D
3 1 1 2


Processes (currently allocated resources):
    A B C D
P1  1 2 2 1
P2  1 0 3 3
P3  1 2 1 0


Processes (maximum resources):
    A B C D
P1  3 3 2 2
P2  1 2 3 4
P3  1 3 5 0


Need = maximum resources - currently allocated resources.
Processes (need resources):
    A B C D
P1  2 1 0 1
P2  0 2 0 1
P3  0 1 4 0
```

Note: *Deadlock prevention is more strict than Deadlock Avoidance.*

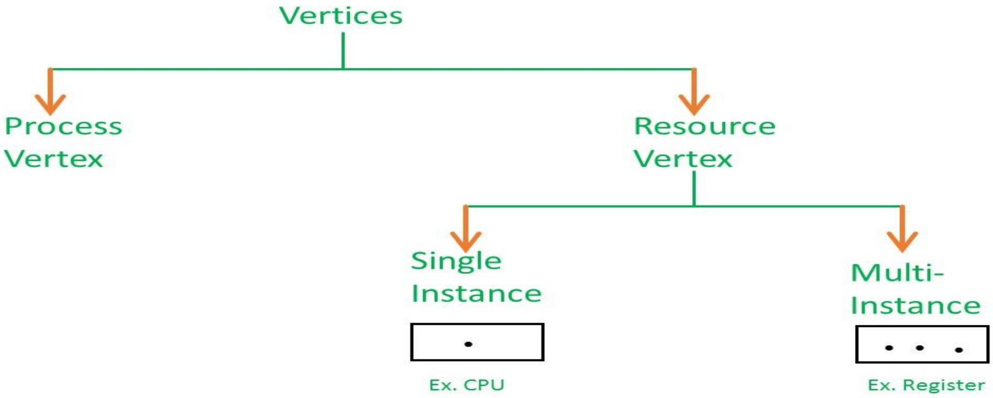
Resource Allocation Graph (RAG) in Operating System

As Banker's algorithm using some kind of table like allocation, request, available all that thing to understand what is the state of the system. Similarly, if you want to understand the state of the system instead of using those table, actually tables are very easy to represent and understand it, but then still you could even represent the same information in the graph. That graph is called **Resource Allocation Graph (RAG)**.

So, resource allocation graph is explained to us what is the state of the system in terms of **processes and resources**. Like how many resources are available, how many are allocated and what is the request of each process. Everything can be represented in terms of the diagram. One of the advantages of having a diagram is, sometimes it is possible to see a deadlock directly by using RAG, but then you might not be able to know that by looking at the table. But the tables are better if the system contains lots of process and resource and Graph is better if the system contains less number of process and resource.
We know that any graph contains vertices and edges. So RAG also contains vertices and edges. In RAG vertices are two type –

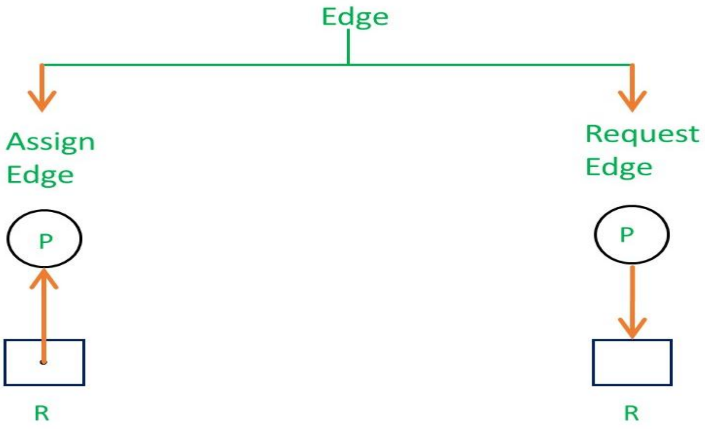
1. Process vertex – Every process will be represented as a process vertex.Generally, the process will be represented with a circle.
2. Resource vertex – Every resource will be represented as a resource vertex. It is also two type –

- **Single instance type resource –** It represents as a box, inside the box, there will be one dot.So the number of dots indicate how many instances are present of each resource type.
- **Multi-resource instance type resource –** It also represents as a box, inside the box, there will be many dots present.



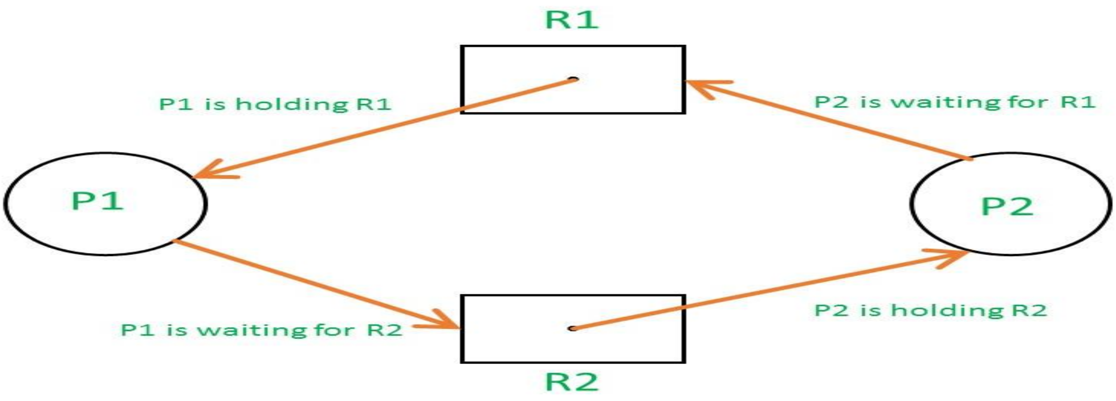
Now coming to the edges of RAG.There are two types of edges in RAG –

1. Assign Edge – If you already assign a resource to a process then it is called Assign edge.
2. Request Edge – It means in future the process might want some resource to complete the execution, that is called request edge.



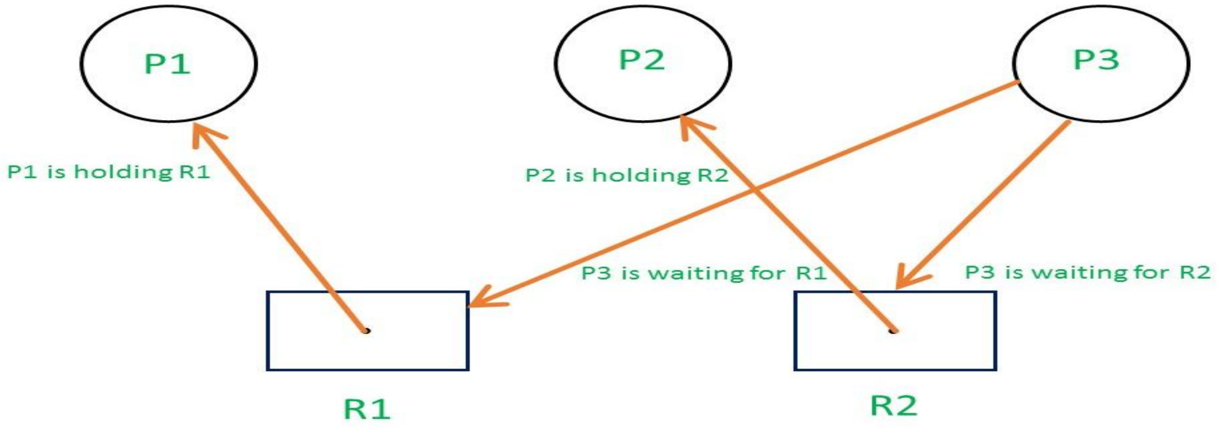
So, if a process is using a resource, an arrow is drawn from the resource node to the process node. If a process is requesting a resource, an arrow is drawn from the process node to the resource node.

Example 1 (Single instances RAG) –



SINGLE INSTANCE RESOURCE TYPE WITH DEADLOCK

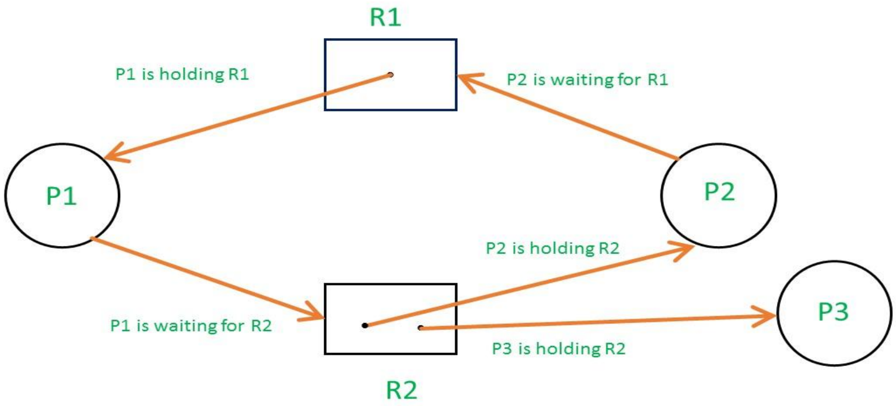
If there is a cycle in the Resource Allocation Graph and each resource in the cycle provides only one instance, then the processes will be in deadlock. For example, if process P1 holds resource R1, process P2 holds resource R2 and process P1 is waiting for R2 and process P2 is waiting for R1, then process P1 and process P2 will be in deadlock.



SINGLE INSTANCE RESOURCE TYPE WITHOUT DEADLOCK

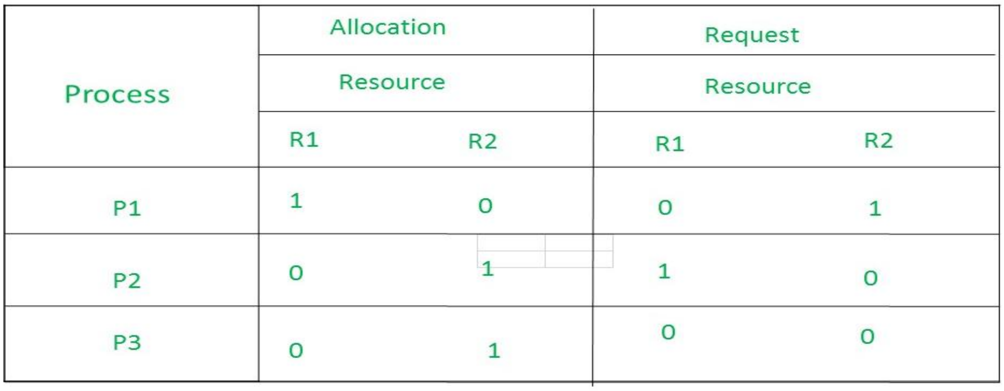
Here's another example, that shows Processes P1 and P2 acquiring resources R1 and R2 while process P3 is waiting to acquire both resources. In this example, there is no deadlock because there is no circular dependency.
So cycle in single-instance resource type is the sufficient condition for deadlock.

Example 2 (Multi-instances RAG) –



MULTI INSTANCES WITHOUT DEADLOCK

From the above example, it is not possible to say the RAG is in a safe state or in an unsafe state.So to see the state of this RAG, let's construct the allocation matrix and request matrix.



Process	Allocation		Request	
	Resource		Resource	
	R1	R2	R1	R2
P1	1	0	0	1
P2	0	1	1	0
P3	0	1	0	0

- The total number of processes are three; P1, P2 & P3 and the total number of resources are two; R1 & R2.

Allocation matrix –

- For constructing the allocation matrix, just go to the resources and see to which process it is allocated.

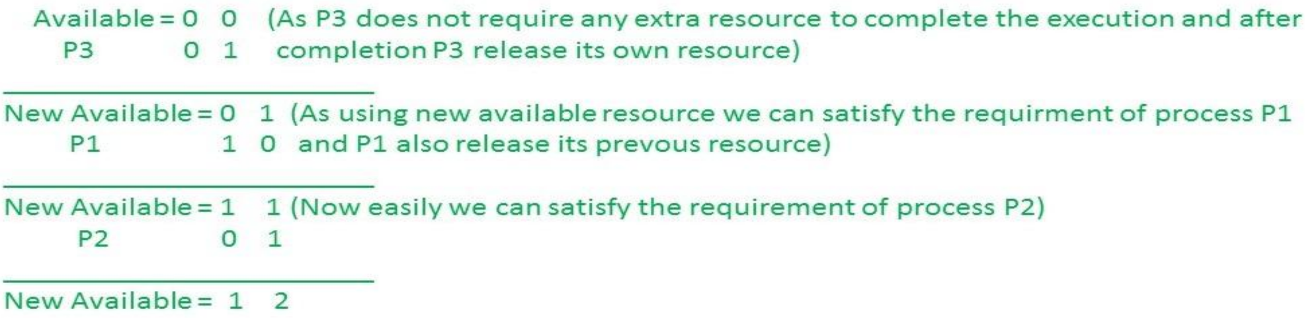
- R1 is allocated to P1, therefore write 1 in allocation matrix and similarly, R2 is allocated to P2 as well as P3 and for the remaining element just write 0.

Request matrix –

- In order to find out the request matrix, you have to go to the process and see the outgoing edges.
- P1 is requesting resource R2, so write 1 in the matrix and similarly, P2 requesting R1 and for the remaining element write 0.

So now available resource is = (0, 0).

Checking deadlock (safe or not) –



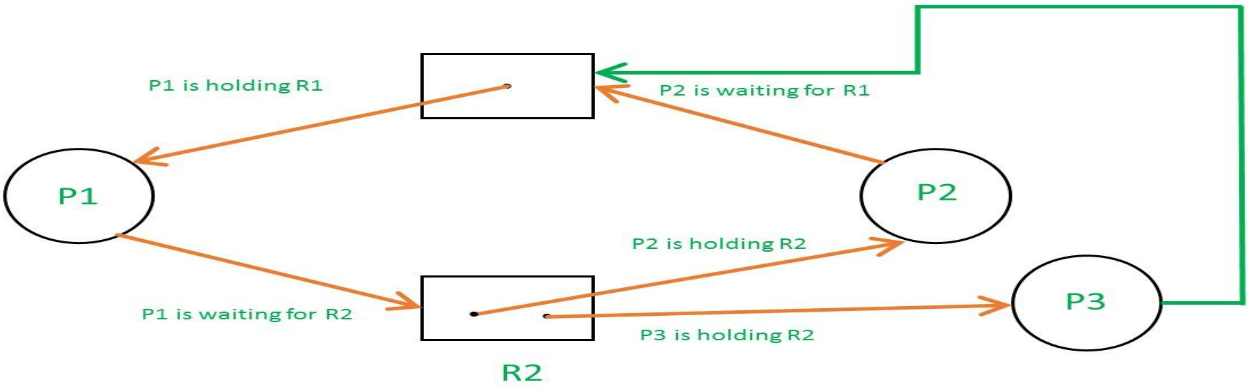
Available = 0 0 (As P3 does not require any extra resource to complete the execution and after
P3 0 1 completion P3 release its own resource)

New Available = 0 1 (As using new available resource we can satisfy the requirment of process P1
P1 1 0 and P1 also release its prevous resource)

New Available = 1 1 (Now easily we can satisfy the requirement of process P2)
P2 0 1

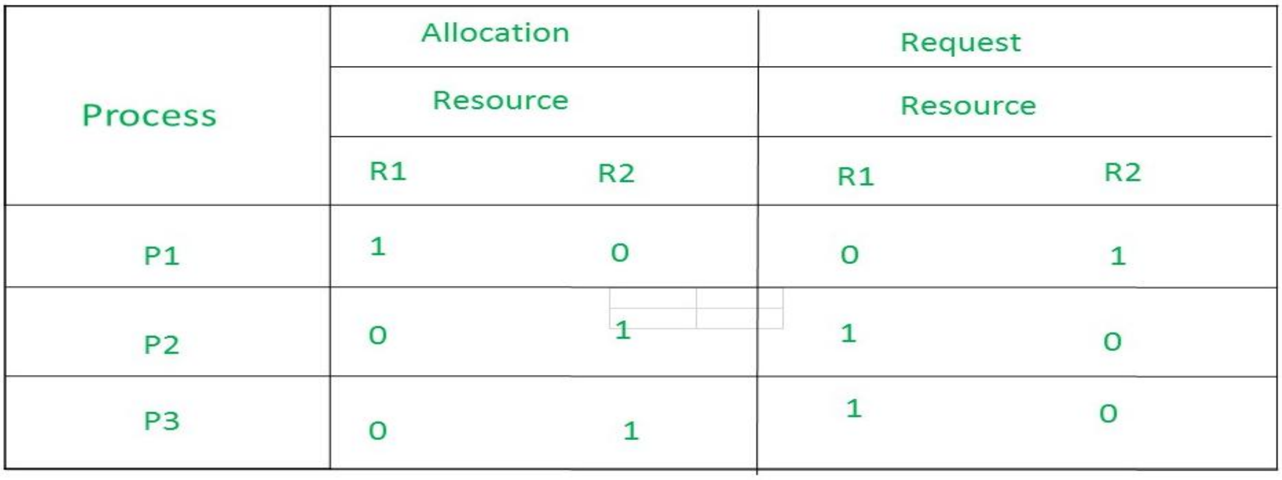
New Available = 1 2

So, there is no deadlock in this RAG.Even though there is a cycle, still there is no deadlock.Therefore in multi-instance resource cycle is not sufficient condition for deadlock.



MULTI INSTANCES WITH DEADLOCK

Above example is the same as the previous example except that, the process P3 requesting for resource R1.
So the table becomes as shown in below.



Process	Allocation		Request	
	Resource		Resource	
	R1	R2	R1	R2
P1	1	0	0	1
P2	0	1	1	0
P3	0	1	1	0

- So,the Available resource is = (0, 0), but requirement are (0, 1), (1, 0) and (1, 0).So you can't fulfill any one requirement.Therefore, it is in deadlock.
- Therefore, every cycle in a multi-instance resource type graph is not a deadlock, if there has to be a deadlock, there has to be a cycle.So, in case of RAG with multi-instance resource type, the cycle is a necessary condition for deadlock, but not sufficient.
-

Banker's Algorithm in Operating System

The banker's algorithm is a resource allocation and deadlock avoidance algorithm that tests for safety by simulating the allocation for predetermined maximum possible amounts of all resources, then makes an "s-state" check to test for possible activities, before deciding whether allocation should be allowed to continue.

Why Banker's algorithm is named so?

Banker's algorithm is named so because it is used in banking system to check whether loan can be sanctioned to a person or not. Suppose there are n number of account holders in a bank and the total sum of their money is S. If a person applies for a loan then the bank first subtracts the loan amount from the total money that bank has and if the remaining amount is greater than S then only the loan is sanctioned. It is done because if all the account holders comes to withdraw their money then the bank can easily do it.

In other words, the bank would never allocate its money in such a way that it can no longer satisfy the needs of all its customers. The bank would try to be in safe state always.

Following **Data structures** are used to implement the Banker's Algorithm:

Let **'n'** be the number of processes in the system and **'m'** be the number of resources types.

Available :

- It is a 1-d array of size **'m'** indicating the number of available resources of each type.
- Available[j] = k means there are **'k'** instances of resource type **Rj**

Max :

- It is a 2-d array of size **'n*m'** that defines the maximum demand of each process in a system.
- Max[i, j] = k means process **Pi** may request at most **'k'** instances of resource type **Rj**.

Allocation :

- It is a 2-d array of size **'n*m'** that defines the number of resources of each type currently allocated to each process.
- Allocation[i, j] = k means process **P_i** is currently allocated **'k'** instances of resource type **R_j**

Need :

- It is a 2-d array of size **'n*m'** that indicates the remaining resource need of each process.
- Need [i,   j] = k means process **P_i** currently need **'k'** instances of resource type **R_j**
- Need [i,   j] = Max [i,   j] – Allocation [i,   j]

$Allocation_i$ specifies the resources currently allocated to process P_i and $Need_i$ specifies the additional resources that process P_i may still request to complete its task.

Banker's algorithm consists of Safety algorithm and Resource request algorithm

Safety Algorithm

The algorithm for finding out whether or not a system is in a safe state can be described as follows:

```
1) Let Work and Finish be vectors of length 'm' and 'n' respectively.
Initialize: Work = Available
Finish[i] = false; for i=1, 2, 3, 4….n
2) Find an i such that both
a) Finish[i] = false
b) $Need_i$ <= Work
if no such i exists goto step (4)
3) Work = Work + Allocation[i]
Finish[i] = true
goto step (2)
4) if Finish [i] = true for all i
then the system is in a safe state
```

Resource-Request Algorithm

Let $Request_i$ be the request array for process P_i. $Request_i$ [j] = k means process P_i wants k instances of resource type R_j. When a request for resources is made by process P_i, the following actions are taken:

1) If $Request_i$ <= $Need_i$

Goto step (2) ; otherwise, raise an error condition, since the process has exceeded its maximum claim.

2) If $Request_i$ <= Available

Goto step (3); otherwise, P_i must wait, since the resources are not available.

3) Have the system pretend to have allocated the requested resources to process Pi by modifying the state as follows:

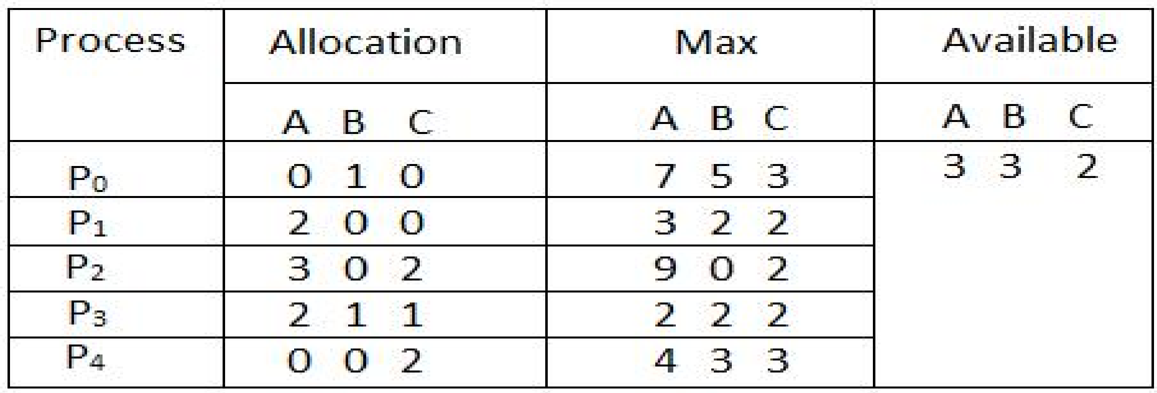
Available = Available – Requesti

Allocationi = Allocationi + Requesti

Needi = Needi– Requesti

Example:

Considering a system with five processes P0 through P4 and three resources of type A, B, C. Resource type A has 10 instances, B has 5 instances and type C has 7 instances. Suppose at time t0 following snapshot of the system has been taken:

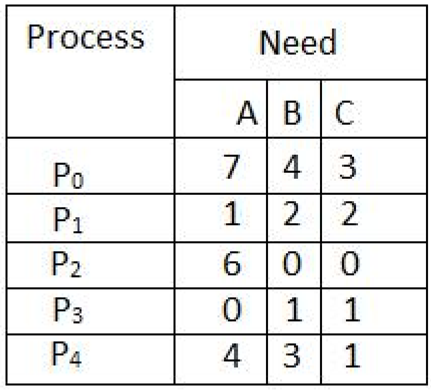


Process	Allocation	Max	Available
	A B C	A B C	A B C
P0	0 1 0	7 5 3	3 3 2
P1	2 0 0	3 2 2	
P2	3 0 2	9 0 2	
P3	2 1 1	2 2 2	
P4	0 0 2	4 3 3	

Question1. What will be the content of the Need matrix?

Need [i, j] = Max [i, j] – Allocation [i, j]

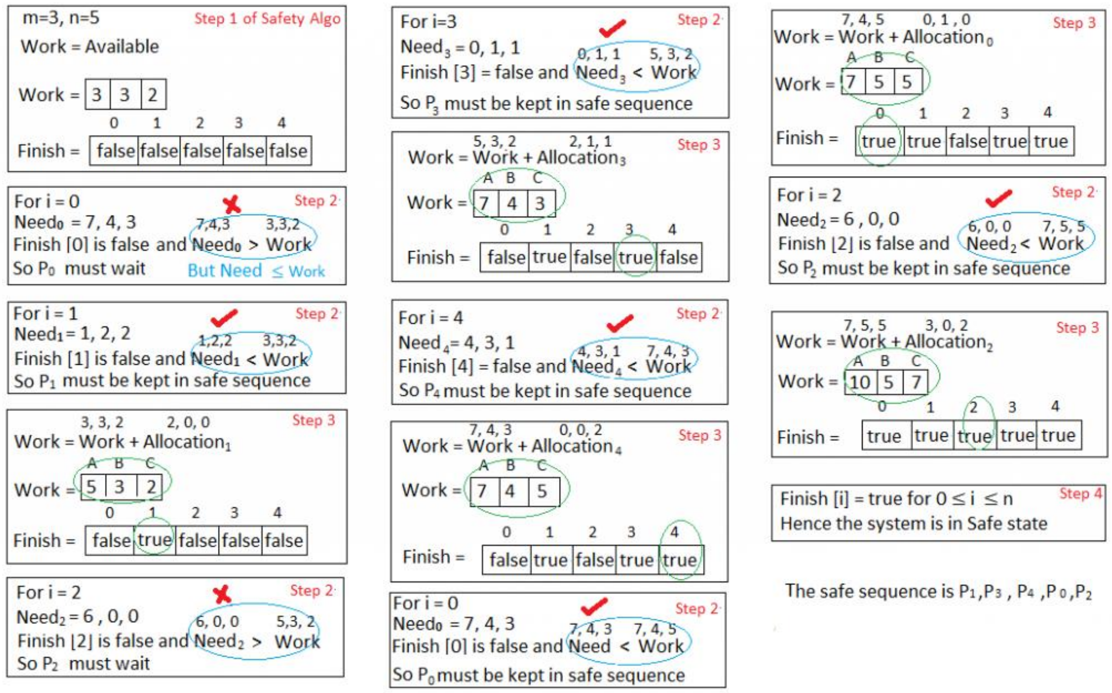
So, the content of Need Matrix is:



Process	Need		
	A	B	C
P0	7	4	3
P1	1	2	2
P2	6	0	0
P3	0	1	1
P4	4	3	1

Question2. Is the system in a safe state? If Yes, then what is the safe sequence?

Applying the Safety algorithm on the given system,



m=3, n=5 Step 1 of Safety Algo

Work = Available

Work = 3 3 2

0 1 2 3 4

Finish = false false false false false

For i = 0 ✗ Step 2

$Need_0$ = 7, 4, 3 7,4,3 3,3,2

Finish [0] is false and $Need_0$ > Work

So P_0 must wait But Need ≤ Work

For i = 1 ✓ Step 2

$Need_1$ = 1, 2, 2 1,2,2 3,3,2

Finish [1] is false and $Need_1$ < Work

So P_1 must be kept in safe sequence

3, 3, 2 2, 0, 0 Step 3

Work = Work + $Allocation_1$

A B C

Work = 5 3 2

0 1 2 3 4

Finish = false true false false false

For i = 2 ✗ Step 2

$Need_2$ = 6, 0, 0 6, 0, 0 5,3, 2

Finish [2] is false and $Need_2$ > Work

So P_2 must wait

For i=3 ✓ Step 2

$Need_3$ = 0, 1, 1 0, 1, 1 5, 3, 2

Finish [3] = false and $Need_3$ < Work

So P_3 must be kept in safe sequence

5, 3, 2 2, 1, 1 Step 3

Work = Work + $Allocation_3$

A B C

Work = 7 4 3

0 1 2 3 4

Finish = false true false true false

For i = 4 ✓ Step 2

$Need_4$ = 4, 3, 1 4, 3, 1 7, 4, 3

Finish [4] = false and $Need_4$ < Work

So P_4 must be kept in safe sequence

7, 4, 3 0, 0, 2 Step 3

Work = Work + $Allocation_4$

A B C

Work = 7 4 5

0 1 2 3 4

Finish = false true false true true

For i = 0 ✓ Step 2

$Need_0$ = 7, 4, 3 7, 4, 3 7, 4, 5

Finish [0] is false and Need < Work

So P_0 must be kept in safe sequence

7, 4, 5 0, 1, 0 Step 3

Work = Work + $Allocation_0$

A B C

Work = 7 5 5

0 1 2 3 4

Finish = true true false true true

For i = 2 ✓ Step 2

$Need_2$ = 6, 0, 0 6, 0, 0 7, 5, 5

Finish [2] is false and $Need_2$ < Work

So P_2 must be kept in safe sequence

7, 5, 5 3, 0, 2 Step 3

Work = Work + $Allocation_2$

A B C

Work = 10 5 7

0 1 2 3 4

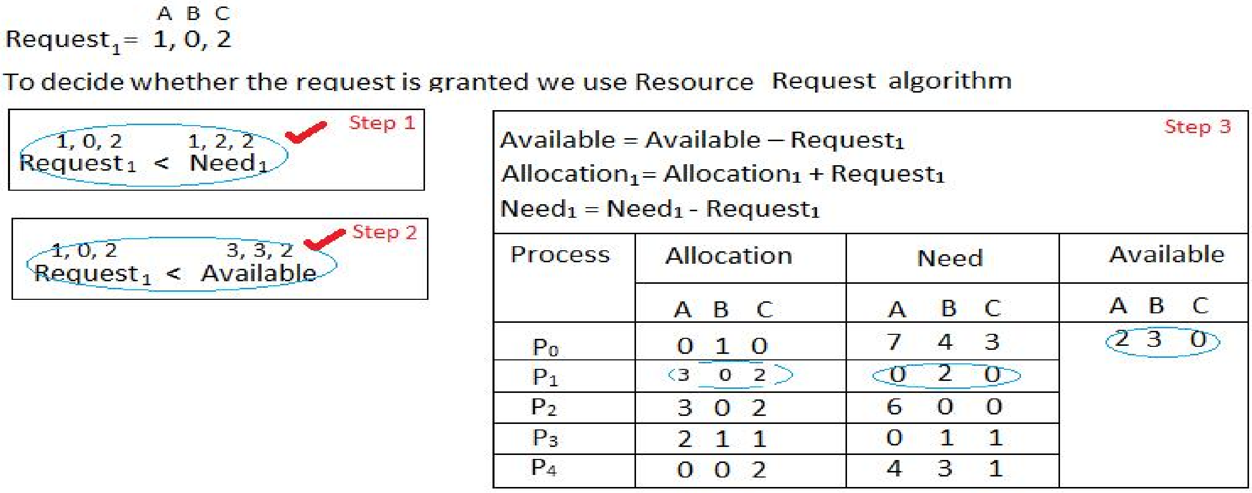
Finish = true true true true true

Finish [i] = true for 0 ≤ i ≤ n Step 4

Hence the system is in Safe state

The safe sequence is P_1,P_3 , P_4 ,P_0,P_2

Question3. What will happen if process P1 requests one additional instance of resource type A and two instances of resource type C?



$$Request_1 = \overset{A}{1}, \overset{B}{0}, \overset{C}{2}$$

To decide whether the request is granted we use Resource Request algorithm

Step 1 ✓

$Request_1$ < $Need_1$ (1, 0, 2 < 1, 2, 2)

Step 2 ✓

$Request_1$ < Available (1, 0, 2 < 3, 3, 2)

Step 3

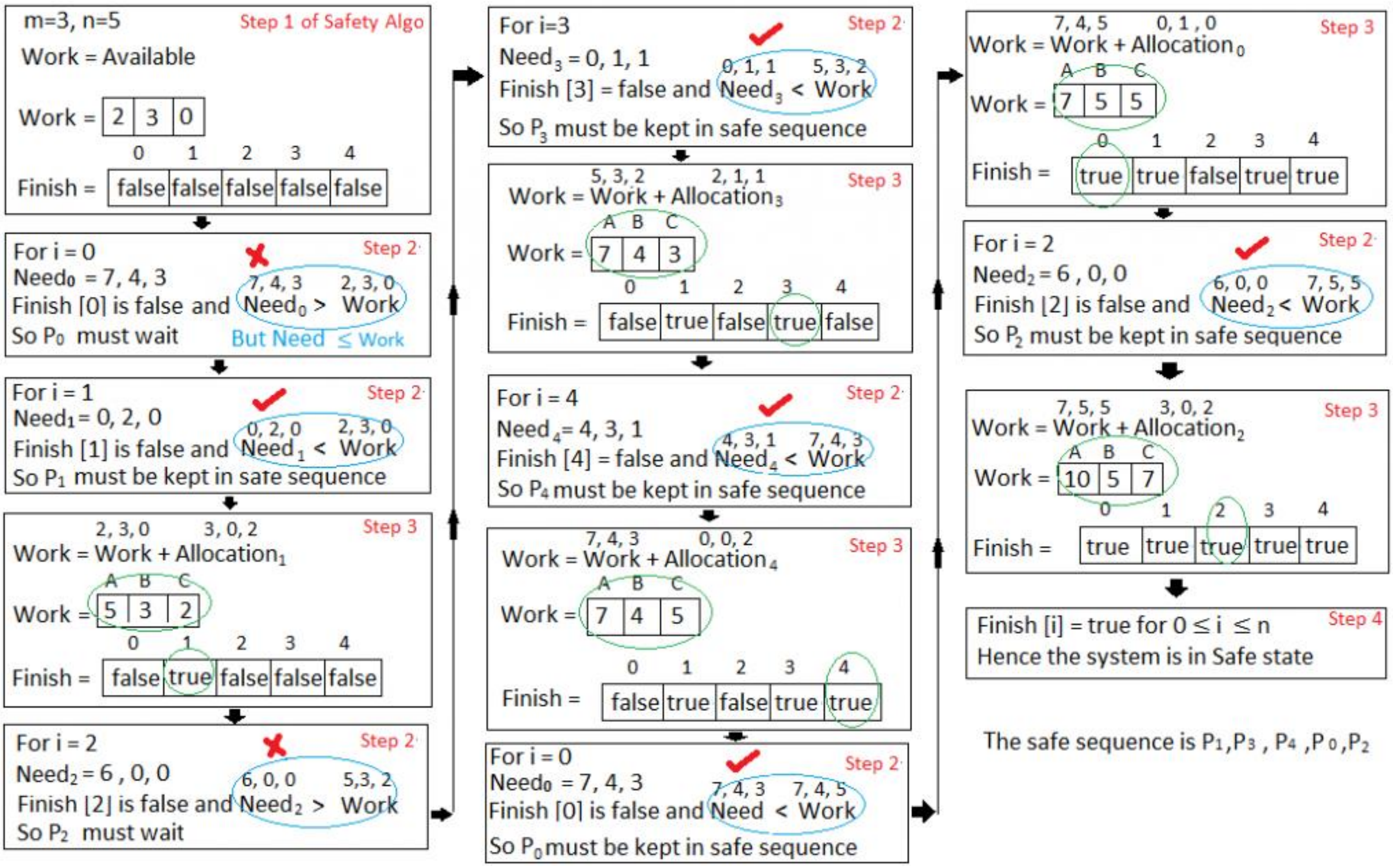
Available = Available – $Request_1$

$Allocation_1$ = $Allocation_1$ + $Request_1$

$Need_1$ = $Need_1$ - $Request_1$

Process	Allocation	Need	Available
	A B C	A B C	A B C
P_0	0 1 0	7 4 3	2 3 0
P_1	3 0 2	0 2 0	
P_2	3 0 2	6 0 0	
P_3	2 1 1	0 1 1	
P_4	0 0 2	4 3 1	

We must determine whether this new system state is safe. To do so, we again execute Safety algorithm on the above data structures.



m=3, n=5 Step 1 of Safety Algo

Work = Available

Work =

2	3	0

Finish =

0	1	2	3	4
false	false	false	false	false

For i = 0 Step 2

$Need_0$ = 7, 4, 3

Finish [0] is false and $\overset{7,\,4,\,3}{Need_0} > \overset{2,\,3,\,0}{Work}$

So P_0 must wait But Need ≤ Work

For i = 1 Step 2

$Need_1$ = 0, 2, 0

Finish [1] is false and $\overset{0,\,2,\,0}{Need_1} < \overset{2,\,3,\,0}{Work}$

So P_1 must be kept in safe sequence

$Work = \overset{2,\,3,\,0}{Work} + \overset{3,\,0,\,2}{Allocation_1}$ Step 3

Work =

A	B	C
5	3	2

Finish =

0	1	2	3	4
false	true	false	false	false

For i = 2 Step 2

$Need_2$ = 6 , 0, 0

Finish [2] is false and $\overset{6,\,0,\,0}{Need_2} > \overset{5,3,\,2}{Work}$

So P_2 must wait

For i=3 Step 2

$Need_3$ = 0, 1, 1

Finish [3] = false and $\overset{0,\,1,\,1}{Need_3} < \overset{5,\,3,\,2}{Work}$

So P_3 must be kept in safe sequence

$Work = \overset{5,\,3,\,2}{Work} + \overset{2,\,1,\,1}{Allocation_3}$ Step 3

Work =

A	B	C
7	4	3

Finish =

0	1	2	3	4
false	true	false	true	false

For i = 4 Step 2

$Need_4$= 4, 3, 1

Finish [4] = false and $\overset{4,\,3,\,1}{Need_4} < \overset{7,\,4,\,3}{Work}$

So P_4 must be kept in safe sequence

$Work = \overset{7,\,4,\,3}{Work} + \overset{0,\,0,\,2}{Allocation_4}$ Step 3

Work =

A	B	C
7	4	5

Finish =

0	1	2	3	4
false	true	false	true	true

For i = 0 Step 2

$Need_0$ = 7, 4, 3

Finish [0] is false and $\overset{7,\,4,\,3}{Need} < \overset{7,\,4,\,5}{Work}$

So P_0 must be kept in safe sequence

$Work = \overset{7,\,4,\,5}{Work} + \overset{0,\,1\,,\,0}{Allocation_0}$ Step 3

Work =

A	B	C
7	5	5

Finish =

0	1	2	3	4
true	true	false	true	true

For i = 2 Step 2

$Need_2$ = 6 , 0, 0

Finish [2] is false and $\overset{6,\,0,\,0}{Need_2} < \overset{7,\,5,\,5}{Work}$

So P_2 must be kept in safe sequence

$Work = \overset{7,\,5,\,5}{Work} + \overset{3,\,0,\,2}{Allocation_2}$ Step 3

Work =

A	B	C
10	5	7

Finish =

0	1	2	3	4
true	true	true	true	true

Finish [i] = true for 0 ≤ i ≤ n Step 4

Hence the system is in Safe state

The safe sequence is P_1, P_3 , P_4 , P_0 , P_2