Formulae

FRL-General

- If number of forks = n:

> Total Number of processes created = 2^n
> Number of child processes = $2^n - 1$

```c
fork();
fork();
// ... n times
printf("Hello!");
```

… will print("Hello!") 2^n times.

- Number of frames = Main memory size / frame size

- Number of pages = Process size / Page size

FRL-Deadlock

- If a system has 3 processes each requiring 2 units of resources `R`. The solution to finding the minimum number of units of `R` such that no deadlock will occur is:
  - Allocate 1 less than the amount of resources needed to each process (1+1+1 here). Then add 1 to it (4). This is **the minimum number of resources** we need to prevent Deadlock.
  - Consequently, when we allocate 1 less than the amount of resources needed to each process, it becomes **the maximum number of resources** needed for Deadlock to occur.
- If a system has 3 processes that share 4 instances of the same resource type, and each process can request `k` instances of that resource, then to find the maximum value of `k` (to avoid deadlock), the following equation must be true: $Processes + Resources > Total\ Demand$
  - $R + n \leq \sum(i = 1\ to\ n)\ D_i$, for deadlock to occur
  - $R + n > \sum(i = 1\ to\ n)\ D_i$, to prevent deadlock

FRL Memory Management

- If each process consumes 4MB, and there is 8MB of primary memory available, we can accomodate 2 processes in the memory. If it does I/O operations for $K = 0.7$ ie 70% of it's time, CPU Utilization: $1 - K^2 = 1 - 0.49 = 0.51$ ie 51%.

Basics

Goals of an Operating System

- Provide convenience to the user.
- Provide user-friendliness.
- Provide an interface to allow users to use applications to access & instruct the hardware.
- Hardware management
- Process management: Manage all currently running processes in the system. CPU Scheduling algorithms are used to determine which process will be executed by the CPU.
- Memory management: Manage volatile memory, dynamically allocate storage to ensure efficient utilization of the available volatile memory.
- Storage management: Manage non-volatile storage, using File System.
- Security:
  - Provide a certain level of security, so only authorized users can unlock and use the computer system.
  - Processes cannot access each other's data. Processes can only use the segment of CPU & RAM allocated to them.

Types of Operating Systems

Batch OS

- During 1960's, computers weren't so common. So we needed to go to a particular place, which provided computing services, to get the job done.
- The jobs were first loaded offline to a physical storage device like punch card, paper tape, magnetic tape, etc.
- They were then submitted to the operator.
- The Operator sorted jobs into batches.
- The first batch was provided to the CPU for execution. All jobs were executed by the CPU one by one.
- Since only 1 job was executed at a time, if the job needed I/O time, the CPU would remain idle in that time. This was a major disadvantage.

- When the CPU had finished executing the job and produced the result, it was loaded in the physical storage again, and given back to the user.
- Later on, IBM launched FORTRAN & IBSYS709X, which provided monitors where the user could directly punch the punch card.

Multi-programming

- The objective is to bring as many processes to the volatile memory as possible.
- It's nature is **non-preemptive**, ie only 1 process is executed by the CPU at any time. If the process needs I/O, the processor will remain idle during that time.
- The CPU won't move to the next process unless the current process has either finished executing or until the process tells it to move on, by itself.

Multitasking / Time Sharing

- It's nature is **pre-emptive**, ie each process is allocated a specific time interval to execute itself, regardless of how much time it needs. After the time-quantum expires, it has to leave the CPU to make room for another process.
- It ensures that no process has to wait for a very long amount of time to execute itself. All processes are executed within a reasonable amount of time, and no process is left out.
- It results in more responsiveness, compared to a Multi-programming OS.

Process States

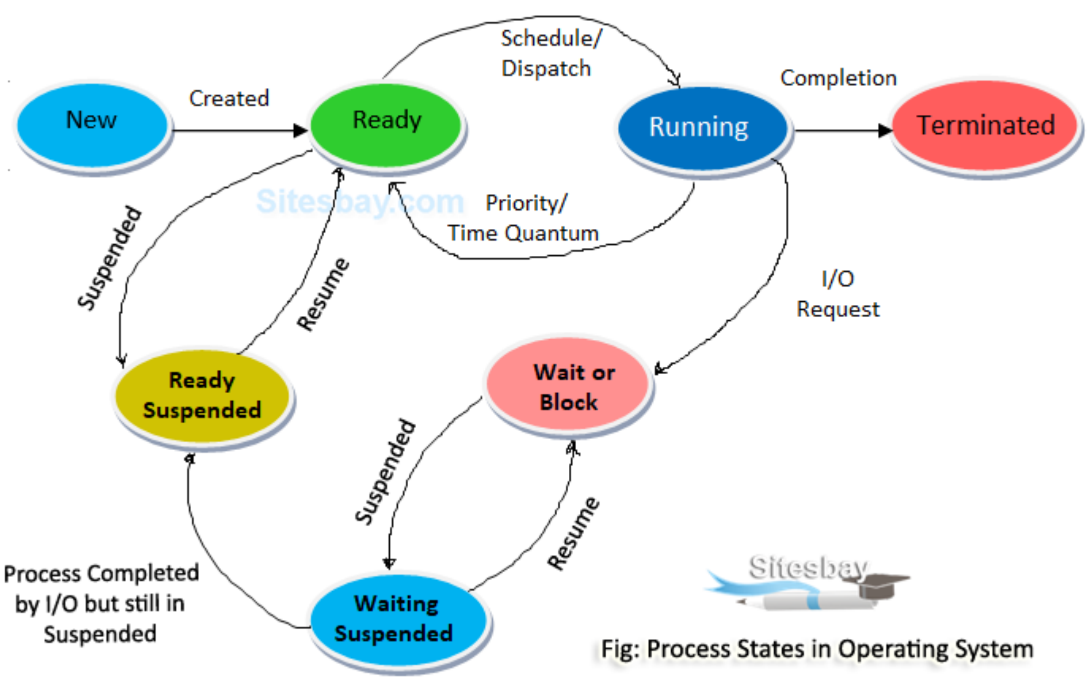


Fig: Process States in Operating System

Image taken from here

- There are **5 main states** & 2 suspend states: **New**, **Ready**, Suspend Ready, **Running**, **Wait/ Block**, Suspend Wait, **Terminated**.
- New <-> **Long-Term Scheduler (LTS)** <-> Ready
- Ready <-> **Short-Term Scheduler (STS)** <-> Running
- Ready / Wait <-> **Medium-Term Scheduler (MTS)** <-> Suspend Ready / Suspend wait
- **New**: At first, a new process is created.
- **Ready**:
  - The process is allocated memory & other resources as per needs.
  - The **LTS (Long-Term Scheduler)** is responsible for bringing processes in from the `New` state.
  - At the end of this state, it is ready to be executed.
- **Running, Wait**:
  - The Job Scheduler queues all the processes in the `Ready` state, and dispatches it to the CPU for executing.
  - The **STS (Short-Term Scheduler)** is responsible for moving processes back and forth the `Ready` & `Running` states.
  - During execution, sometimes the process is moved back to `Ready` queue:
    - if a higher priority Process `HP` arrives in the `Ready` queue, the currently running process `P` is moved to the `Ready` state to make room for process `P` .
    - If the `Ready` queue is already full, the MTS (Medium-Term Scheduler) moves some processes to the `Suspend Ready` queue to make room for Process `HP` .
    - when using time-quantum based algorithms like Round Robin. If the time-quantum is 2 seconds, it means that each running process will be given 2 seconds of CPU Time, after which it'll have to make room for another process.
    - CPU initiates this process.
  - During execution, sometimes the process requires some I/O operation. If that happens, it is moved to the `Wait/Block` state, where it can perform the operation it needs.
    - The secondary storage is usually much much slower than the CPU. This is done to reduce CPU idle time.
    - The process initiates this request.
    - After the I/O operation has finished, the CPU moves back to the `Ready` state.
  - If a lot of processes need to execute I/O operations at the same time, the I/O queue will get full. In such a case, some processes are swapped out to the secondary memory ie moved to the `suspend wait` queue.
    - The **MTS (Medium-Term Scheduler)** is responsible for swapping processes to and from

`Wait/Block` state and `Suspend Wait` state.
        - After the I/O operation is complete and the process is in the `Suspend Wait` state, it tries to get back to the `Wait` state. If the `Wait` queue is full for a significant amount of time, it is moved to the `Ready` queue. This is called `Backing Store`.
- **Terminated**: After the execution of the process is complete, all resources are de-allocated, and the process moves to the `Terminated` state.

User Mode & Kernel Mode

- By default, we use software/apps in **user-mode**.
- In user-mode, we don't have the rights to directly interact with the hardware. The kernel manages that part, as part of the operating system.
- When we want to communicate with or send information to hardware, we need to interact with the kernel, using `system calls`. We do that in **Kernel Mode**.
- A system call is used to invoke the kernel to perform operations on hardware, files, etc.
- **Mode bit**: 1 in user mode, 0 in kernel mode.

Types of System Calls

- **File-related**: During execution, if the process needs access to a particular file, it requests the kernel to provide it access, using file-related system calls. Example: `open()`, `read()`, `write()`, `close()`, create file.
- **Device-related**: We obtain the rights to access and talk to hardware, using these system calls. Example: read, write, reposition, `ioctl`.
- **Information-related**: We use these system calls when we want to get information about something. Example: `getPid`, attributes, system-wide time & date.
- **Process control**: These are used for managing processes. Example: `load()`, `execute()`, `abort()`, `fork()`, `nbit`, `signal`, `allocate`. `wait` & `signal` are used for process synchronization.
- **Communication**: These are used by processes to communicate among themselves. Example: `pipe()`, create/delete connections, `shmget()` [get value of the shared memeory].
- **Security**: Here, we're mostly concerned with security & permissions. Examples: `chmod`, `chown`, `umask`.

chmod (Change mode)

```
$ ls -lh  # Easiest way to display current permissions
total 12K
drwxr-xr-x 2 sayan sayan 4.0K Aug 13 20:39 dir1:
```

```
-           Directory?
 ---        Read, write, execute permissions for Owner / User who owns the file/directory
    ---     Read, write, execute permissions for Group
       ---  Read, write, execute permissions for Others (Everyone else)
```

Changing permissions:

- Can be done in 2 ways:
    - Method 1:
        - Permissions can either be defined specifically for `u/g/o`, or they can be combined together.
        - `o-x` means we're stripping the `execute` permission off `others`.
        - `ug+w` means we're providing `user` & `group` with the `write` permission.
        - `a+x` means we're giving everyone (ie user, group & others) the `execute` permission.
        - Example:

```
$ chmod o-x dir1  # Remove 'execute' permission for 'others'.
$ chmod o+w dir1  # Add 'write' permission for 'others'.
$ chmod a+x dir1  # Add 'write' permission for everyone (u,g as well as o).
$ chmod -R o+w dir1  # Add 'write' permission for 'others' recursively.
$ chown abcd dir1 # Transfer directory ownership to user 'abcd'.
$ chown -R abcd dir1 # Transfer directory ownership to user 'abcd' recursiv
```

    - Method 2 (octal): `chmod <user><group><other> file`, or `chmod ugo file`.
        - Meaning of the numbers: $r = 4,\ w = 2,\ x = 1$
        - Permissions are denoted by numbers like $1, 2, 4$ or a sum of any of the numbers, like $5, 6, 7$.
        - Permissions are defined in sequence, for `u`, `g` and `o`.
        - Example:

```
chmod 111 abcd  # u=x | g=x | o=x
chmod 666 abcd  # u=rw | g=rw | o=rw
chmod 421 abcd  # u=r | g=w | o=x
```

lseek()

- It is a system call that is used to change the location of the read/write pointer of the file descriptor.
- By default, pointer stays in the beginning, at index `0`.
- Syntax & example (input file = `1234567890abcdefghij`):

```
lseek(int file_descriptor,  offset, int whence)
```

```
lseek(n,10,SEEK_CUR) # It goes 10 bytes from character `1`, ie to `a`.
lseek(n,5,SEEK_SET)  # pointer is set at the position 5, ie at `5`.
```

- `file_descriptor` : The file descriptor of the pointer that is going to be moved.
- `offset` : The off-set of the pointer.
- `whence` : The method in which the offset will be interpreted. Possible values:
    - `SEEK_SET` : Set the off-set to the specified index.
    - `SEEK_CUR` : Off-set from current location of the pointer.
    - `SEEK_END` : Off-set from the end.

fork()

- It is used to create a child process, which is a clone of the parent process and has it's own PID.
- `fork()` returns different values depending on which process we're in:

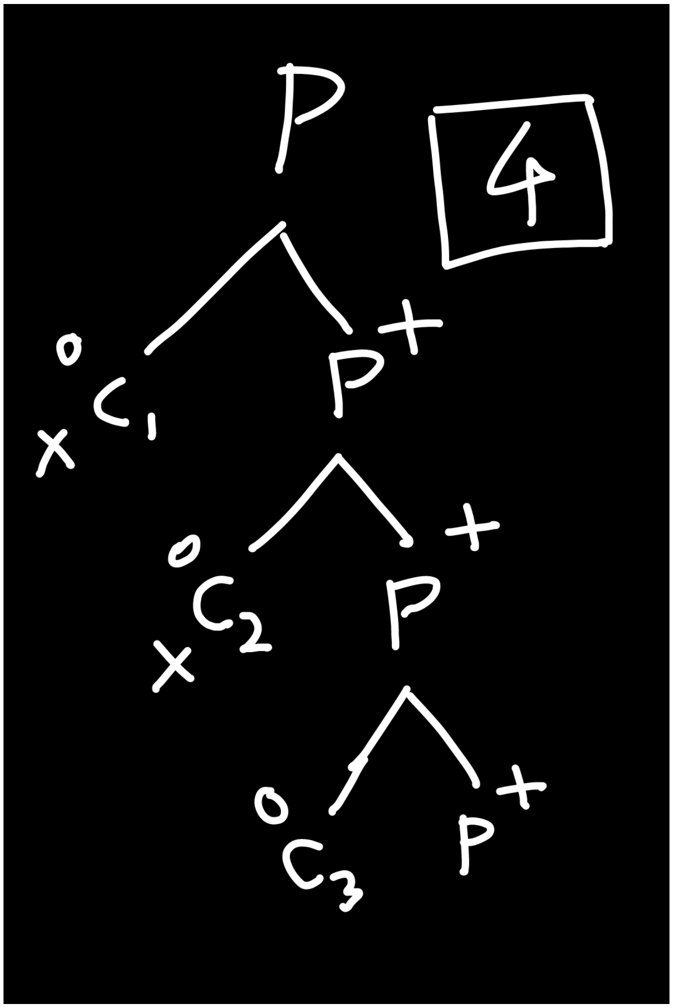
  > 0, if we're in the child process
  > +1/+ve number, ie the PID of the child process, if we're in the parent process.
  > -1/-ve number, if the child process couldn't be created.

- If `fork()` is run n times, it will create 2^n total processes, including $2^n - 1$ child processes and 1 parent process.
- Child process runs parallely with the parent process.
- Example 0:

  ```
  main() {
      fork();
      printf("Hello");
  }
  ```

  … will print "Hello" 2 times.
- Example 1:

```c
#include<stdio.h>
#include<unistd.h>
int main() {
    if(fork() && fork()) {  // 0, 1
        fork();             // 2
    }
    printf("Hello");
    return 0;
}
```



- Here, at fork() `#0` , a child process c_1 is created.

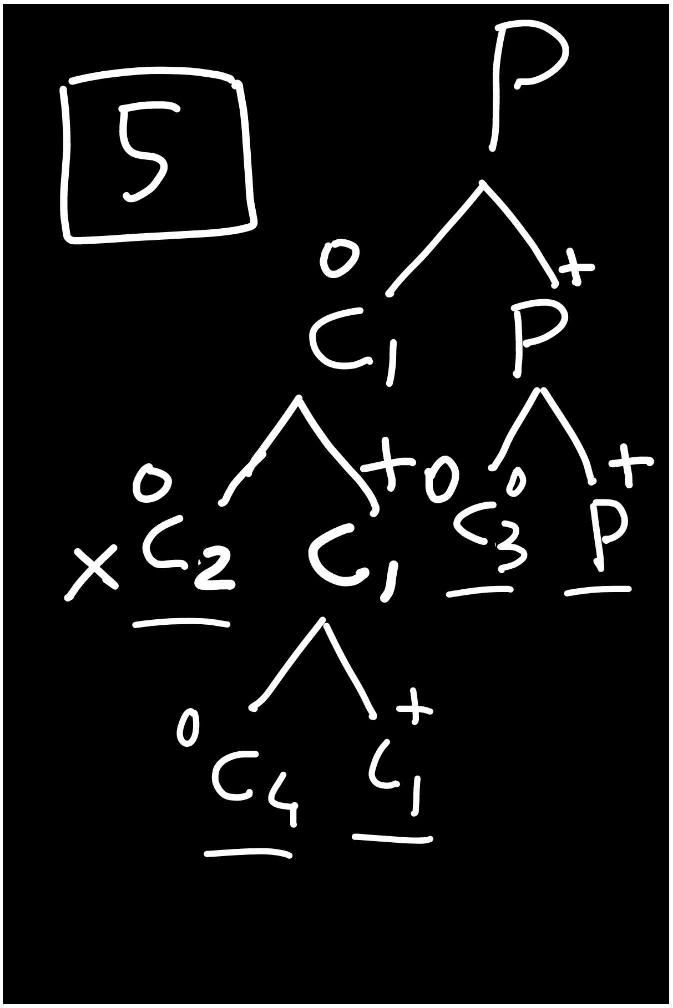
  > In the child process, it returns 0. The loop condition becomes false, and it exits.
  > In the parent process, it returns the PID of the child process. We proceed to fork() `#1` .

- In fork() `#1` , child process c_2 is created, which also returns 0. The loop exits. In the parent process, we go ahead and execute fork() `#2` . This forks another child process c_3.
- In total, there are 4 processes, and `Hello` is printed 4 times.

- Example 2:

```c
#include<stdio.h>
#include<unistd.h>
int main() {
    if(fork() || fork()) {  // 0, 1
```

```c
        fork();                 // 2
    }
    printf("Hello");
    return 0;
}
```



- Here, at fork() `#0` :

  > In the child process, it returns 0.
  >
  > In the parent process, it returns the PID of the child process.

- For the child process c_1, it will continue to check the 2nd sub-condition, which is fork() `#1` . That will fork another child process c_4.
- For the parent process, since the 1st condition is true, it won't even check the 2nd condition. It'll directly enter the loop, and execute fork() `#2` in it. That will fork another child process, c_2.
- Now, c_1 becomes the parent process. Since the condition is still true, it gets in the loop and executes `fork()` in it. This creates another child process, c_4.
- In total, there are 5 processes, and `Hello` is printed 5 times.

Processes & Threads

- Legend:

- [+] Process
- [-] User-level Thread

```
+ System call `fork()` is used to create a child process.
- No system calls involved.

+ OS treats different processes differently.
- All user-level threads are treated as a single process by the OS.

+ Forking multiple child processes creates a lot of overhead, since they all have their
- Creating multiple threads does not create much overhead since they all share code, da

+ Context switching is slower. Whenever a process is swapped out of the CPU, it's data
- Context switching is faster, since all threads share their stuff.

+ Blocking 1 child process does not affect the parent process or any other child process
- Blocking a thread will block the entire process, since the OS does not know that the

+ Processes are independent of each other.
- Threads are interdependent on each other.
```

User-level vs Kernel-level Thread

- Legend:
  - [+] User-level Thread
  - [-] Kernel-level Thread

```
+ Managed by User-level library.
- Managed by OS System Calls.

+ Typically faster.
- Typically slower.

+ Context switching is faster.
- Context switching is slower.

+ If blocked, the process is also blocked.
- If blocked, the other threads continue to function.
```

- Nowadays, we use hybrid systems, where one or more user-level threads is mapped to one or more kernel-level threads. This resolves the blocking problem.

Process Scheduling

- Used to move processes from the ready to running state.
- Important Terms:
  - Arrival Time: The time at which the process enters the **ready state**.
  - Burst Time: The total time duration needed to execute the process, from start to finish.
  - Completion time: The time at which the process completes execution.
  - Turn-around Time: {Completion Time - Arrival Time}
  - Waiting Time: {Turn-around Time - Burst Time}
  - Response Time: {Time at which process was first executed by the CPU - Arrival Time}
- Pre-emptive vs Non-preemptive:
  - [+] Pre-emptive
  - [-] Non-preemptive

```
+ Pre-emptive algorithms can interrupt the execution of a process to give CPU time
- Non-preemptive algorithms allow a process to complete its execution before anothe
+ Are more responsive to changing priorities and can provide better system utilizat
- May lead to longer response times for higher-priority processes if they are waiti
+ Require additional overhead to manage context switching and ensure fairness among
- Are simpler to implement and may be more suitable for real-time systems where pre
```

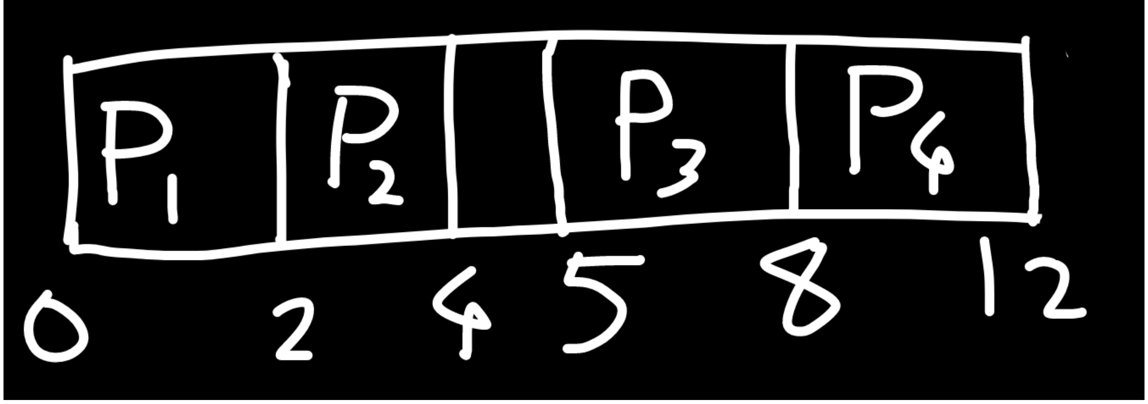
Non Pre-emptive Scheduling Algorithms

FCFS (First Come First Serve)

- **Criteria**: Arrival Time | **Mode**: Non-Preemptive
- Process which arrives first is executed first.
- `Response Time` is same as `Waiting Time`.
- Example 0:

Process No.	Arrival Time	Burst Time	Completion Time	Turn-around Time	Waiting Time	Response Time
P_1	0	2	2	2	0	0
P_2	1	2	4	3	1	1
P_3	5	3	8	3	0	0
P_4	6	4	12	6	2	2

  - Gantt Chart

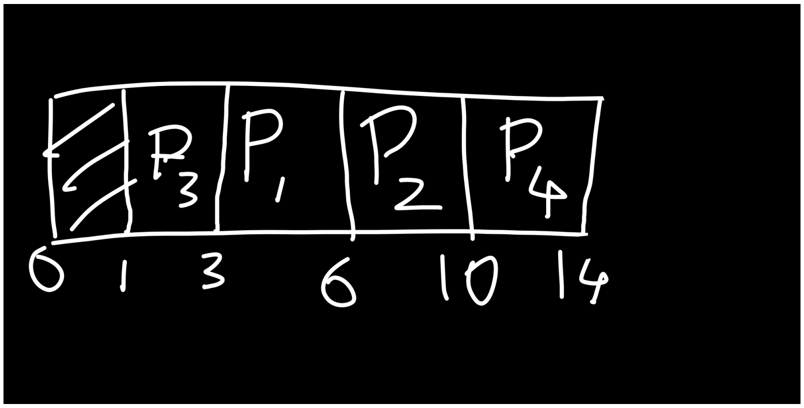


SJF (Shortest Job First)

- **Criteria**: Burst Time | **Mode**: Non-Preemptive
- Job with the shortest Burst Time is executed first.
- If Burst Time of 2 processes are same, the one that arrived earlier is executed first.
- Example 0:

Process No.	Arrival Time	Burst Time	Completion Time	Turn-around Time	Waiting Time	Response Time
P_1	1	3	6	5	2	2
P_2	2	4	10	8	4	4
P_3	1	2	3	2	0	0
P_4	4	4	14	10	6	6

  - Gantt Chart



Pre-emptive Scheduling Algorithms

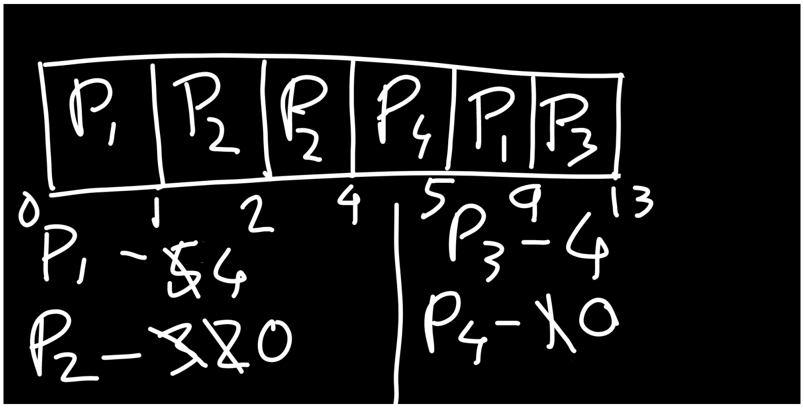
SRTF (Shortest Remaining Time First)

- **Criteria**: Burst Time | **Mode**: Pre-emptive

- Job with the shortest Remaining Burst Time is executed first, pre-emptively.
- At every step (ie unit of time), it checks if there's a process without a shorter burst time, in the ready queue.
- If Remaining Burst Time of 2 processes are same, the one that arrived earlier is executed first.
- Example 0:

Process No.	Arrival Time	Burst Time	Completion Time	Turn-around Time	Waiting Time	Response Time
P_1	0	5	9	9	4	0
P_2	1	3	4	3	0	0
P_3	2	4	13	11	7	7
P_4	4	1	5	1	0	0

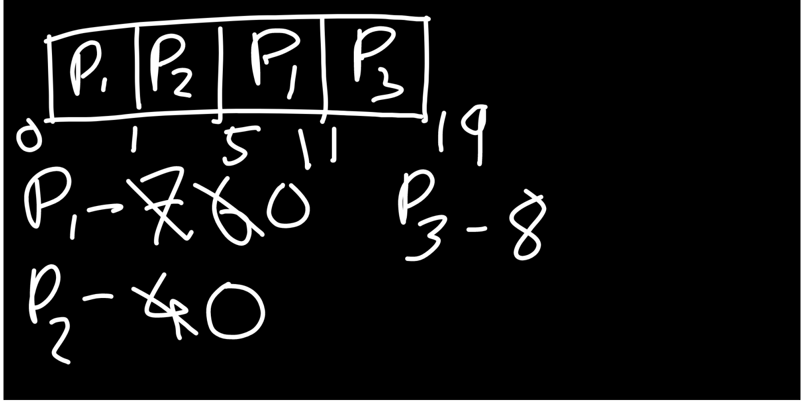
  - Gantt Chart



- Example 1:

Process No.	Arrival Time	Burst Time	Completion Time	Turn-around Time	Waiting Time	Response Time
P_1	0	7	11	11	4	0
P_2	1	4	5	4	0	1
P_3	2	8	19	17	9	9

  - Gantt Chart

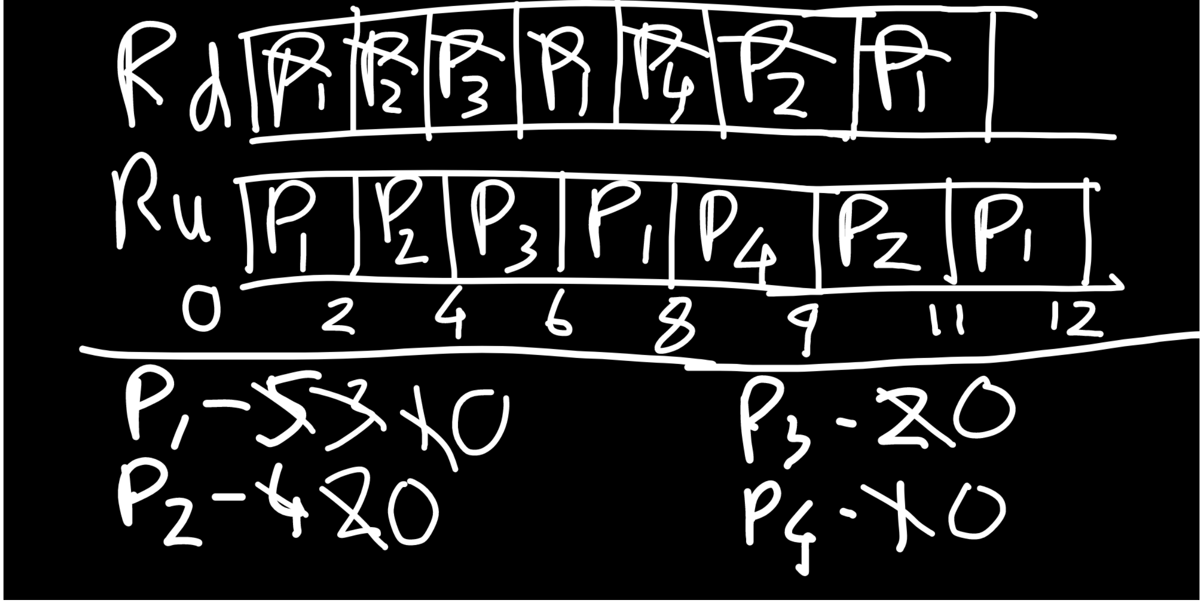


Round Robin

- **Criteria**: Time Quantum | **Mode**: Pre-emptive
- Jobs are executed according to the defined time quantum.
- Processes, which have never been executed, are added to the ready queue based on their arrival time.
- Whenever a process is pre-empted, but has remaining burst time, it is added back **to the end of the ready queue**.
- We should move the first process in the ready queue from the left to the running queue.
- Example 0 (Time Quantum: 2):

Process No.	Arrival Time	Burst Time	Completion Time	Turn-around Time	Waiting Time	Response Time
P_1	0	5	12	12	7	0
P_2	1	4	11	10	6	1
P_3	2	2	6	4	2	2
P_4	4	1	9	5	4	4

  - Gantt Chart



- Number of context switches: 6

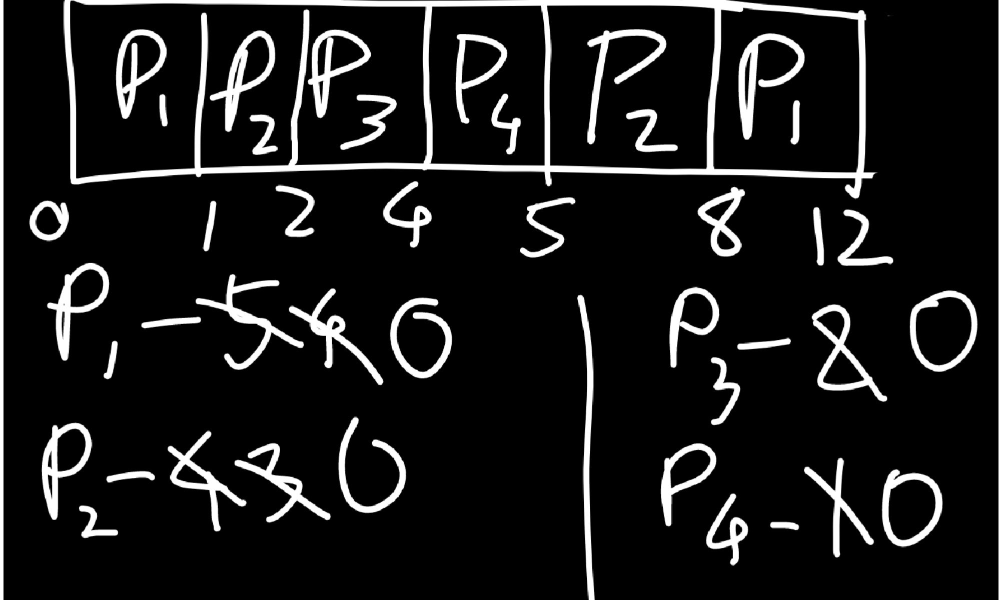
  > Calculate from Gantt Chart, excluding the first & last line in the running queue)

Priority

- **Criteria**: Priority | **Mode**: Pre-emptive
- Higher priority processes are executed first.
- Whenever a higher priority process arrives in the Ready queue, the currently running process is pre-empted in favour of that process.
- Example 0 (higher number = higher priority):

Priority	Process No.	Arrival Time	Burst Time	Completion Time	Turn-around Time	Waiting Time	Resp Tim
10	P_1	0	5	12	12	7	0
20	P_2	1	4	8	7	3	0
30	P_3	2	2	4	2	0	0
40	P_4	4	1	5	1	0	0

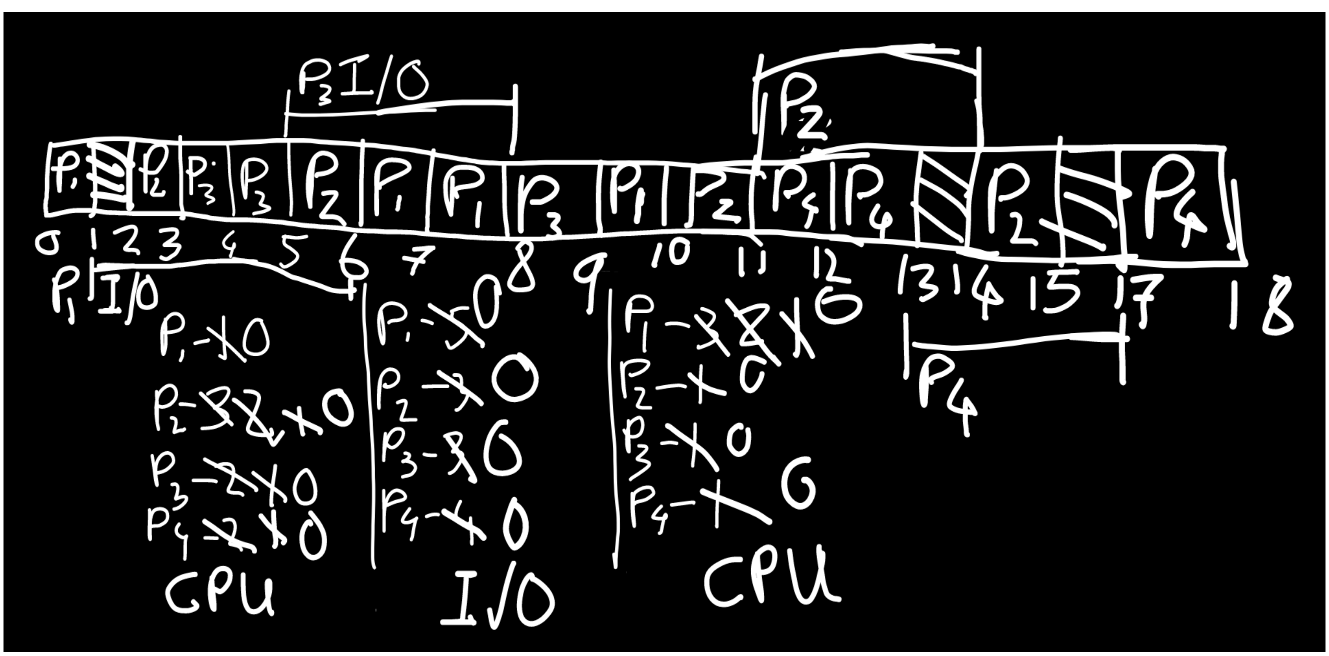
- Gantt Chart:



- Example 1 (lower number = higher priority):

Priority	Process No.	Arrival Time	CPU	I/O	CPU	Completion Time	Turn-around Time	Waiti Tim
2	P_1	0	1	5	3	10	10	0
3	P_2	2	3	3	1	15	13	0
1	P_3	3	2	3	1	9	6	0
4	P_4	3	2	4	1	18	15	8

  - Total CPU Idle Time: 4
  - Ratio of CPU Idle Time: $4 : 18 = 2 : 9$
  - Ratio of CPU Active Time: $14 : 18 = 7 : 9$
  - Gantt Chart:



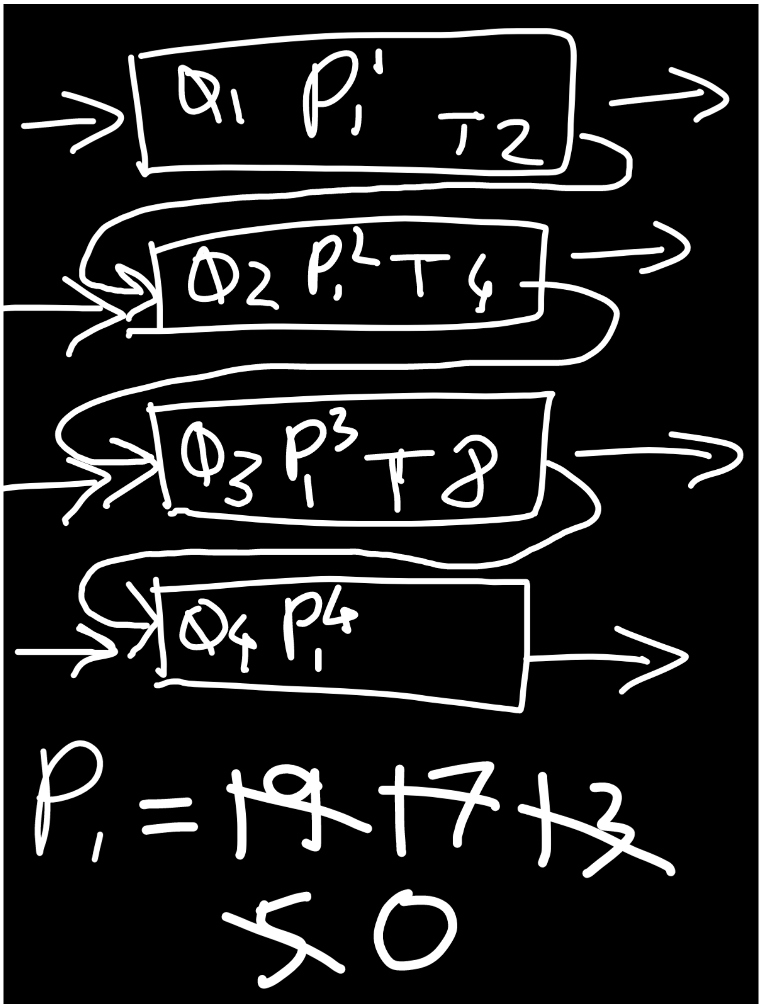
Multi-level Queue

- If there are different types of processes, there must also be different ready/running queues in the system, for accomodating them.
- These different queues have their own scheduling algorithms.
- The queues themselves are prioritized according to the kind of processes they house.
- Queue Priority:
    - **System Process**: Highest Priority, Round Robin algorithm
      > System calls, interrupts, etc.
    - **Interactive Process**: Medium Priority, Shortest Job First (SJF) algorithm
      > Processes related to software we're currently interacting with.
    - **Batch Process**: Lowest Priority, First Come First Serve (FCFS) algorithm
      > Background processes.
- The algorithms used for the jobs can differ based on the use-cases.
- LJF (Longest Job First)
- HRRN (Highest Response Ratio Next)
- Multi-level Queue
- Priority (exists as both pre-emptive and non-preemptive)
- LRTF (Longest Remaining Time First)

Multi-level Feedback Queue

- In a Multi-level Queue system, If there are a lot of processes in a higher priority queue, the processes in the lower priority queues will have to wait for a very long time to get executed. The `Multi-level Feedback Queue` aims to solve this problem.
- Steps:
    - A process first arrives in it's designated queue (Example, Q_1).
    - After it is executed once (as per the queue's algorithm), it is moved to the next higher priority queue (Q_2).
    - After it is executed here, it is again upgraded to a higher priority queue (Q_3). This process repeats till it has finished executing.
    - **Each higher priority queue has a time quantum higher than the previous one.**

- T: Time Quantum | Q_n: Queue ID



Process Synchronization

- **Co-operative process**: Processes whose execution affects other processes. Usually, this is because they share memory, code, variables, resources like scanner, printer, etc. with each other.
- **Independent processes**: Processes which run independently of each other.
- If co-operative processes are not synchronized properly, they can create conflicts or deadlock in the system.
- This problem is called `Race condition`.
- Example 0 (initially, $shared = 5$):

Row	Process 1	Process 2
1	int x=shared;	int y=shared;
2	x++;	y–;
3	sleep(1);	sleep(1);
4	shared=x;	shared=y;

i. Instructions `1` & `2` of process `1` will be executed. $x = 6$

ii. The CPU, upon receiving Instruction `3`, will pre-empt the process, and switch to process `2`.

iii. Instructions `1` & `2` of process `2` will be executed. $y = 4$

iv. The CPU, upon receiving Instruction `3`, will pre-empt the process, and switch back to process `1`.

v. Instruction `4` of process `1` will be executed. $shared = 6$.

vi. Process `1` ends, so the CPU will switch to process `2`.

vii. Instruction `4` of process `2` will be executed. $shared = 4$.

viii. So, the values of shared becomes `5`, then `6`, then finally `4`. But, it shoud've been `5`.

- Example 1 (Producer-Consumer problem):
  - $count = 0$, shared variable, represents the number of items in the buffer.
  - $n = 8$, stores the number of slots available in the buffer.
  - $in = 1$, stores the address of the next memory location, where the item produced by the producer, is stored.
  - `Producer` code:

```
void producer() {
    int itemp; // Item count of producer
    while (true) {
        produceItem(itemp); // Produce the item
        while(count==n);     // If buffer is full, do nothing
        buffer[in]=itemp;    // Store the item. Also check `DESC_buffer` below
        in=(in+1)%n;
        count=count+1;       // Check `DESC_count0` below
    }
}
```

  - `DESC_buffer`: `in`
  - `DESC_count0`: This is how CPU processes this line:
    - READ $R_p, m[count]$; // R_p = Register
    - INCREMENT R_p;
    - STORE $m[count], R_p$
  - $out = 1$, stores the address of the next memory location, where the item to be retrieved by the consumer, is stored.
  - `Consumer` code:

```
void consumer() {
    int itemc;
    while(true) {
        while(count==0);     // If buffer is empty, do nothing
        itemc=buffer[out];  // Retrieve the item. Also check `DESC_buffer` above
        out=(out+1)%n;
        count = count - 1; // Check `DESC_count1` below
    }
}
```

- `DESC_count1` : This is how CPU processes this line:
  - READ $R_c, m[count]$; // R_c = Register
  - DECREMENT R_c;
  - STORE $m[count], R_c$
- **Case 1**: `Producer` & `Consumer` code run one after the other.
  1. At the end of `Producer` code, $count = 1$ & $in = 1$.
  2. At the end of `Consumer` code, $count = 0$ & $out = 1$.

  > This won't cause problems because count is 0, so the consumer won't try to consume more products.

- **Case 2**: `Producer` code is pre-empted before it can increment the value of `count` . **Assume that producer has already produced `4` items.**
  1. `Producer` code starts running.
  2. Before being pre-empted, `Producer` code: $in = 4$ & $count = 3$. `count` could not be incremented.
  3. `Consumer` code runs from the start. Again, it is pre-empted before it could update the value of `count` . $out = 1$ & $count = 3$.
  4. Now, CPU goes back and executes `Consumer` code. $count = 4$.
  5. CPU goes back and executes `Producer` code. $count = 2$.

  > At this point, 3 items should be present in the buffer, but the `count` value says otherwise. This is a problem.

- Example 2 (Printer-Spooler problem):
  - The printer is a lot slower than the CPU, that's why there's a spooler directory in-between to store the print files and Instructions.
  - Whenever a process wants to print something, it puts it in the spooler directory. The printer takes the documents from the spooler directory, and prints them.
  - Code:

```
LOAD $R_i$, $m[in]$
STORE $SD[R_i]$, File-Name
INCR $R_i$
```

```
STORE $m[i]$, $R_i$
```

- $m[in]$: Stores the next empty slot in the spooler directory.
- **Case 1**: There is only 1 process P_1, trying to print file `f1.doc`
  1. Initially, $in = 0$. It is loaded onto the register.
  2. The file name is stored in position `in` ie `0`, in the spooler directory.
  3. Register R_i is incremented from `0` to `1`
  4. in is updated to `1`.
- **Case 2**: **2 co-operative processes, P_1 & P_2**, want to print documents. The spooler directory already contains 3 documents to print.
  1. P_1 executes first. Initially, in = 3. It is loaded onto the register.
  2. The file name is stored in position `in` ie `3`, in the spooler directory.
  3. Register R_i is incremented from `3` to `4`
  4. Before in can be updated to `4`, the process P_1 is pre-empted from the CPU.
  5. P_2 executes next. Initially, $in = 3$. It is loaded onto the register.
  6. The file name is stored in position `in` ie `3`, in the spooler directory. **It replaces the file P_1 had stored, resulting in Data Loss.**
  7. Register R_i is incremented from `3` to `4`
  8. Before in can be updated to `4`, the process P_2 is pre-empted from the CPU.
  9. CPU goes back and executes the remainder of P_1. $in = 4$. Process Terminates.
  10. CPU goes back and executes the remainder of P_2. $in = 4$. Process Terminates.
      - In this case, only P_2's document will be printed. Data loss occurs for P_1.

Critical Section

- The portion of the program where shared resources are accessed by various co-operative processes.
- If 1 program is executing it's Critical Section, no other program cannot execute their Critical Sections.
- Code syntax:

```
// Non-critical Section

// Entry Section
// Critical Section
// Exit Section

// Non-critical Section
```

- We have an `Entry Section` before the Critical Section. A program has to clear this section

to execute the Critical Section. If 1 program is executing it's Critical Section, we have to make sure that the others cannot clear their `Entry Sections`.
    - We also have an `Exit Section`, after the Critical Section. Once a code executed it's `Exit Section`, it means that it's finished executing it's Critical Section.
- These sections are used to achieve `Process Synchronization`.

Conditions for achieving Process Synchronization

- To achieve Process Synchronization, the code must fulfill these conditions:

1. **Mutual Exclusion**: Only one process can access a critical section (a portion of code where shared resources are accessed) at a time. This ensures that conflicting operations do not occur simultaneously, preventing data inconsistency or corruption.
2. **Progress**: If no process is executing in its critical section and some processes wish to enter their critical sections, then the selection of the next process to enter the critical section cannot be postponed indefinitely. In other words, progress ensures that processes do not remain indefinitely blocked, allowing eventual entry into their critical sections. This happens when the `Entry Section` of a program contains code that prevents other co-operative processes from executing, even at a time when the process itself is not in it's `Critical Section`.
3. **Bounded Wait**: There exists a limit on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted. This rule prevents a process from being indefinitely postponed in favor of other processes.
4. **No dependency on hardware, specifications, etc.**: The solution to the synchronization problem should be applicable to a wide range of hardware and system configurations. It should not rely on specific assumptions about the speed of execution, number of processes, or other hardware-related characteristics. This ensures portability and generality of the synchronization mechanism.

Solutions for achieving Process Synchronization

LOCK variable

- Scope: `Multiple processes`
- `Mutual Exclusion`: Not guaranteed. See Case 2.
- It executes in User Mode.
- Code:

```
while(LOCK==1);
LOCK=1;
// Critical Section
LOCK=0;
```

- **Case 1**: There are 2 processes in the system, each wanting to execute it's Critical Section.
    i. Initially, $LOCK = 0$. P_1 starts.
    ii. `while` condition is false.
    iii. $LOCK$ is set as 1. P_1 enters it's Critical Section.
    iv. Now, P_2 starts.
    v. `while` condition is true, and P_2 gets stuck in an infinite loop.
    vi. Until P_1 exits it's Critical Section and sets $LOCK = 0$ again, P_1 cannot enter it's Critical Section.
- **Case 2**: There are 2 processes in the system, each wanting to execute it's Critical Section. P_1 has higher priority than P_2 and it is a pre-emptive system.
    i. Initially, $LOCK = 0$. P_1 starts.
    ii. `while` condition is false.
    iii. Right before P_1 could set $LOCK = 1$, it is pre-empted from the CPU.
    iv. Now, P_2 starts.
    v. `while` condition is false, since $LOCK = 0$. It goes ahead, sets $LOCK = 1$, and enters it's Critical Section.
    vi. Meanwhile, P_1 returns. Since it's a higher priority process, P_2 is pre-empted and P_1 resumes.
    vii. P_1 sets $LOCK = 1$ and enters it's Critical Section.
    viii. So, now both P_1 and P_2 are in their Critical Section. So, **Mutual Exclusion is not obeyed**.

TEST and SET

- Scope: Multiple processes
- `Mutual Exclusion` : Guaranteed.
- `Bounded Wait` : Guaranteed.
- `Progress` : Not Guaranteed.
- The problem with the previous method is if a process gets pre-empted between the check and assignment statements, Mutual Exclusion does not happen. This method combines both the statements into 1.
- Code:

```
boolean test_and_set(boolean *target) {
    boolean r=*target;
    *target=TRUE;
    return r;
}

while(test_and_set(&LOCK));
// Critical Section
LOCK=FALSE;
```

- Initially, $LOCK = false$.
- When process P_1 executes the `while()` condition, the address of `LOCK` is taken as the input in `test_and_set()`.
- In `test_and_set()`, $r = false$. $*target = LOCK = true$. Finally, r is returned.
- Process P_1 gets $false$ as the output, so it can enter it's Critical Section.
- Now, if another process executes it's code: in `test_and_set()`, $r = true$. $*target = LOCK = true$. Finally, r is returned.
- Process P_2 gets $true$ as the output, so it has to wait.
- Here, the execution is same as the previous method, but there is no problem even if the process is pre-empted.

TURN variable

- Scope: 2 processes
- `Mutual Exclusion`: Guaranteed.
- `Progress`: Not Guaranteed. See point (1) below.
- `Bounded Wait`: Guaranteed. P_1 cannot execute multiple times in succession.
- Code:

```
// Process 1
while(turn!=0);
// Critical Section
turn=1;

// Process 2
while(turn!=1);
// Critical Section
turn=0;
```

1. If $turn = 0$ initially, P_1 can enter it's Critical Section. Then, it sets $turn = 1$. Then, P_2 can enter it's Critical Section. However, in case P_2 wants to enter the Critical Section before P_1, it cannot, even if there are no processes in their Critical Sections. **P_1 has to execute before P_2.**
2. If $turn = 1$ initially, P_2 can enter it's Critical Section. Then, it sets $turn = 0$. Then, P_1 can enter it's Critical Section. However, in case P_1 wants to enter the Critical Section before P_2, it cannot.

Semaphore

- `Semaphore` is an integer variable used in a Mutually Exclusive manner by various concurrent co-operative processes in order to achieve process synchronization.

- Synonyms for function in `Entry Section`: P(), Down(), Wait()

- Synonyms for function in `Exit Section` : V(), Up(), Signal(), Post(), Release()
- **Counting Semaphore**
  - Integer value can be anything from $-\infty$ to $+\infty$
  - Multiple processes run in their Critical Sections consurrently.
  - Code:

```
// Entry Section
Down(Semaphore S) {
    S.value = S.value-1;
    if(S.value<0) {
        // put process in suspended list
        sleep;
    } else {
        return;
    }
}

// Exit Section
Up(Semaphore S) {
    S.value = S.value+1;
    if($S.value <= 0$) {
        // select process from suspended list
        wake-up;
    } else {
        return;
    }
}
```

  - $S = 10$: 10 processes can run their Critical Sections, before they begin to be blocked.
  - $S = 0$: No process can enter their Critical Section, all subsequent processes will be blocked.
  - $S = -4$: 4 processes are currently blocked.
  - Example 0: Initially, $S = 10$.
    - 6 P() & 4 V() operations are run
    - Final $S = 10 - 6 = 4 + 4 = 8$
- **Binary Semaphore**:
  - Integer value can be 0 or 1
  - 0 means the resource is not available.
  - 1 means the resource is available.
  - Code:

```
// Entry Section
Down(Semaphore S) {
    if(S.value==1) {
        S.value=0;
```

```
            // Process enters Critical Section
        } else {
            // Block the process, place in suspend list
            sleep();
        }
    }
    // Exit Section
    Up(Semaphore S) {
        if(suspend list is empty) {
            S.value=1;
        } else {
            // select process from suspended list
            wake-up;
        }
    }
```

- In the `Entry Section`, we're checking if $S = 0$.
  - If it is, then process is allowed to enter it's Critical Section, and $S = 1$.
  - Otherwise, process is blocked.
- In the `Exit Section`, we're checking if there are any existing processes in the suspend list.
  - If there are, we will first wake up all those processes, and move them to the ready queue.
  - Otherwise, set $S = 1$, regardless of the previous value of S.
- Example 0: There are 10 co-operative processes. What is the maximum number of processes that can enter the `Critical Section` at any given time?

```
// For P1 through P9
p(mutex)
// Critical Section
v(mutex)

// For P10
v(mutex)
// Critical Section
v(mutex)
```

  i. Initially, $S = 1$. First, P_1 can enter. It sets $S = 0$, then enters Critical Section. P_2 through P_9 cannot enter anymore.
  ii. But P_{10} can enter it's Critical Section. It sets $S = 1$, then enters Critical Section. Now, another process amongst P_2 through P_9 can enter their Critical Section.
  iii. P_{10} exits it's Critical Section. $S = 1$.
  iv. P_2 sets $S = 0$, then enters Critical Section. Now, P_3 through P_9 cannot enter anymore. However, P_{10} can.
  v. P_{10} sets $S = 1$, then enters Critical Section. Now, another process amongst P_3 through P_9 can enter their Critical Section.
  vi. So, at the end, assuming the cycle goes like this, all 10 processes can be in their Critical

Sections. So, $result = 10$.

- Example 1: There are 10 co-operative processes. What is the maximum number of processes that can enter the `Critical Section` at any given time?

```
// For P1 through P9
p(mutex)
// Critical Section
v(mutex)

// For P10
v(mutex)
// Critical Section
p(mutex)
```

i. Initially, $S = 1$. First, P_1 can enter. It sets $S = 0$, then enters Critical Section. P_2 through P_9 cannot enter anymore.
ii. But P_{10} can enter it's Critical Section. It sets $S = 1$, then enters Critical Section. Now, another process amongst P_2 through P_9 can enter their Critical Section.
iii. P_2 sets $S = 0$, then enters Critical Section. Now, P_3 through P_9 cannot enter anymore. However, P_{10} can.
iv. P_{10} exits it's critical section. $S = 0$.
v. P_{10} cannot re-enter it's Critical Section repeatedly. The other 9 processes cannot enter either.
vi. So, a maximum of 3 processes can be in their Critical Sections at any point of time.

- Example 0 (Producer-Consumer):
  - $n = 8$ (number of slots):
  - Producer code (P_1):

```
produceItem(item p) {
    // Entry section
    Down(EMPTY);
    Down(S);
    // Critical Section
    buffer[in] = item p;
    in=(in+1)%n;
    // Exit Section
    Up(S);
    Up(FULL);
}
```

  - Consumer code (P_2):

```
consumeItem(item p) {
    // Entry section
    Down(FULL);
```

```
        Down(S);
        // Critical Section
        item p = buffer[out];
        out=(out+1)%n;
        // Exit Section
        Up(S);
        Up(EMPTY);
    }
```

- Case 1:
    i. Initially, $S=1$, $EMPTY=5$, $FULL=3$. P_1 runs.
    ii. $EMPTY=4$. P_1 gets pre-empted.
    iii. Now, $S=1$, $EMPTY=4$, $FULL=3$. P_2 arrives.
    iv. $FULL=2$, $S=0$. P_2 enters critical section.
    v. If, during execution of critical section, P_2 gets pre-empted, then P_1 will be switched back.
    vi. P_1 cannot execute `Down(S);` , because $S=0$. It'll get blocked and pre-empted again. P_2 will be executed again.
    vii. $S=1$, $EMPTY=5$, $FULL=2$. P_2 completes execution.
    viii. P_1 comes back to get executed. $S=0$. P_1 enters it's critical section.
    ix. $S=1$, $FULL=3$. P_1 finishes executing.
    x. $S=1$, $EMPTY=5$, $FULL=3$. $n=8$ is maintained.
    xi. Once $S=0$ is executed by a process, the other process can no longer execute it's critical section, thus maintaining consistency.

- Example 1 (Reader-Writer):
    - Problems only occur if both operations are being done on the same data.
    - Can it cause problems?
        - Read-Write: yes
        - Write-Read: yes
        - Write-Write: yes
        - Read-Read: no
        - $P_1=R$, $P_2=W$
    - Code:

```
Semaphore mutex=1;
Semaphore db=1;
int rc=0;

void Reader(void) {
    while(true) {
        down(mutex);
        rc=rc+1;          // Read count
        if(rc==1) {
            down(db);
```

```
            }
            up(mutex);
            // Critical Section
            UseDB();
            down(mutex);
            rc=rc-1;
            if(rc==0) {
                up(db);
            }
        }
    }

    void Writer(void) {
        down(db);
        // Critical Section
        up(db);
        }
    }
```

- Case 1 (R-W):
  - $P_1 = R$, $P_2 = W$

  i. $rc = 0, mutex = 1, db = 1$. P_1 executes.

  ii. $rc = 1, mutex = 0$ then $mutex = 1, db = 0$. P_1 enters critical section.

  iii. Now, if P_2 wants to enter, it cannot. The line $down(db)$ will return an error, since $d = 0$. So, Mutual Exclusion is maintained.
- Case 2 (W-R):
  - $P_1 = R$, $P_2 = W$

  i. $rc = 0, mutex = 1, db = 1$. P_2 executes.

  ii. $rc = 0, mutex = 1, db = 0$. P_2 enters critical section.

  iii. Now, if P_1 wants to enter, it cannot. The line $down(db)$ will return an error, since $rc = 1$, but $d = 0$. So, Mutual Exclusion is maintained.
- Case 3 (W-W):
  - $P_1 = R$, $P_2 = W$, $P_3 = W$

  i. $rc = 0, mutex = 1, db = 1$. P_2 executes.

  ii. $rc = 0, mutex = 1, db = 0$. P_2 enters critical section.

  iii. Now, if P_3 wants to enter, it cannot. The line $down(db)$ will return an error, since $d = 0$. So, Mutual Exclusion is maintained.
- Case 4 (R-R):
  - $P_1 = R$, $P_2 = W$, $P_3 = R$

  i. $rc = 0, mutex = 1, db = 1$. P_1 executes.

  ii. $rc = 1, mutex = 0$ then $mutex = 1, db = 0$. P_1 enters critical section.

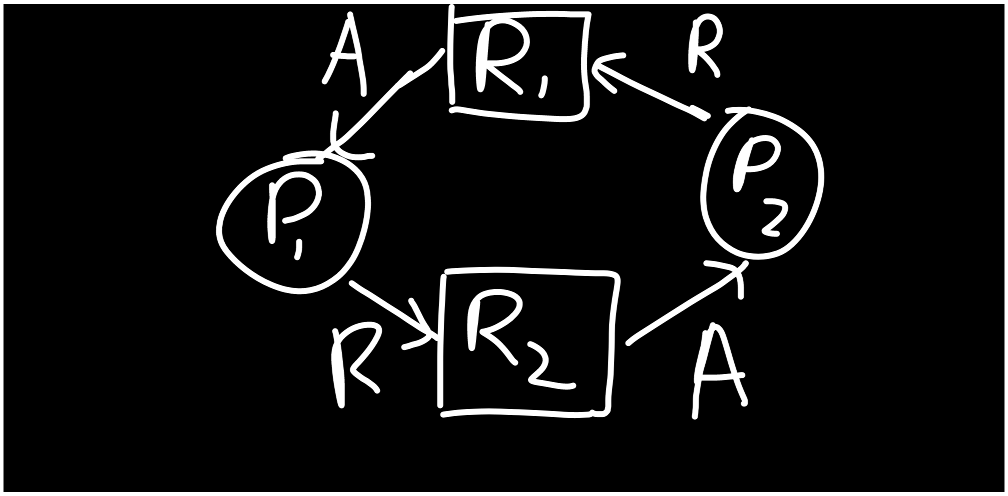
  iii. Now, P_3 wants to enter. $rc = 2, mutex = 0$ then $mutex = 1, db = 0$. Since, $rc \neq 1$, $down(db)$ is not executed. P_3 can enter the critical section, too.

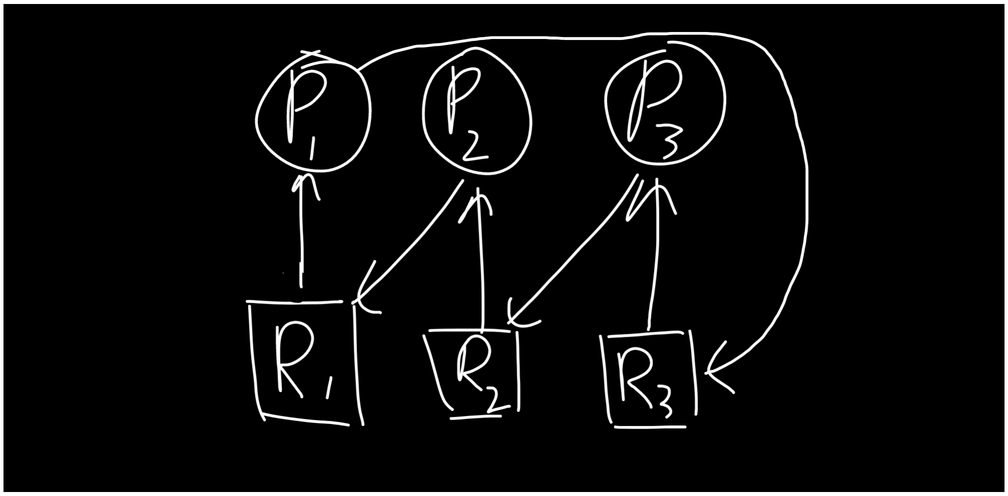
iv. So, in this case, all processes that want to read data can do so. It will not cause any problems. Mutual Exclusion doesn't need to be maintained.

Deadlock

- This situation occurs when 2 processes are waiting for some event, which will never happen.
- Example: P_1 already has resource R_1, and needs R_2 to execute. P_2 already has resource R_2, and needs R_1 to execute. Both processes are in a deadlock situation.
- All these Conditions must be true for deadlock to occur:

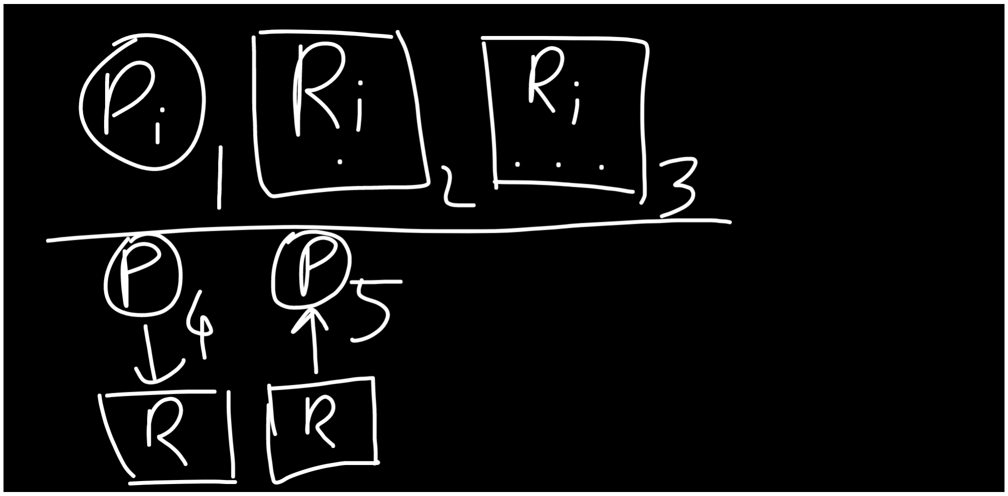
   i. Mutual Exclusion: The resource being used must only be used in a mutually exclusive manner, ie one by one.
   ii. No preemption: Processes cannot be forced to release the resource, and get pre-empted.
   iii. Hold & Wait: P_1 is holding on-to R_1, and waiting for R_2. P_2 is holding on-to R_2, and waiting for R_1.
   iv. Circular Wait: The Hold-Request graph forms a closed loop.



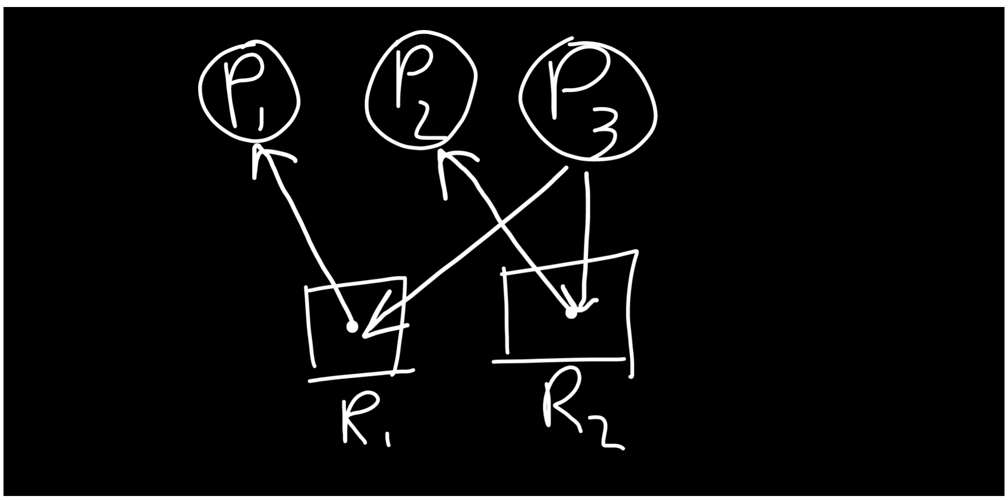


Resource Allocation Graph

- Used to represent the state of processes in the system.
- Vertices: Process (1) & Resource: Single-Instance (2) & Multi-Instance (3).
- Edges: Assign Edge (5) & Request Edge (4).
- In a Single-Instance Resource system, if Circular Wait is true, deadlock will mandatorily occur, but not in Multi-Instance system.

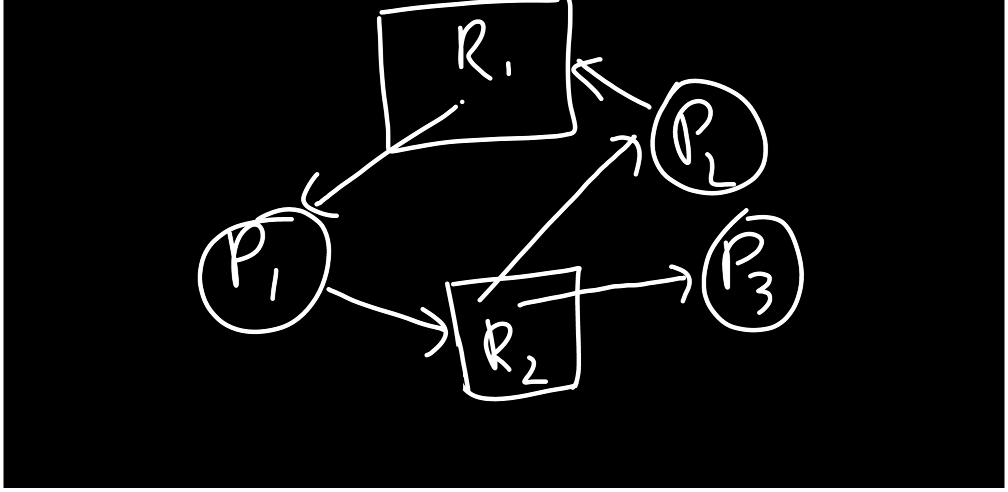


- Example 0:



Process	Allocate (R_1,R_2)	Request (R_1,R_2)
P_1	1,0	0,0
P_2	0,1	0,0
P_3	0,0	1,1

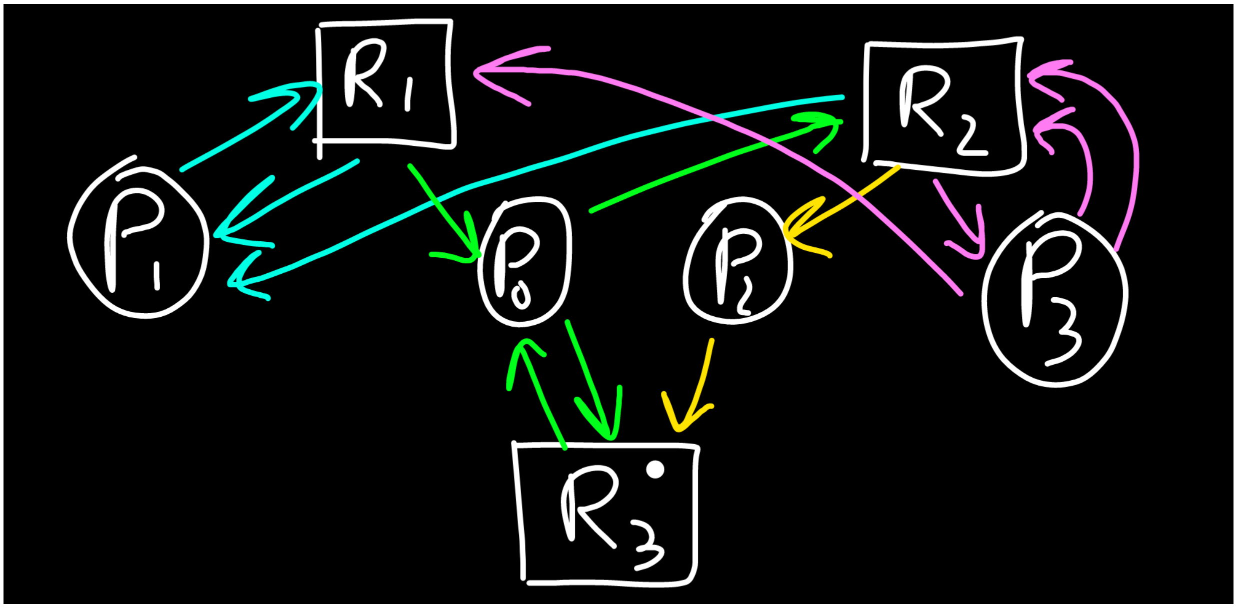
  - Availability (0): (0,0). In this case, P_1 will get executed. After getting terminated, and the resources will be released.
  - Availability (1): (1,0). P_2 will get executed, and terminate.
  - Availability (2): (1,1). P_3 will get executed, and terminate.
  - Availability (3): (1,1).
  - So, all processes can get executed and deadlock will not occur.
- Example 1:



Process	Allocate (R_1,R_2)	Request (R_1,R_2)
P_1	1,0	0,1
P_2	0,1	1,0
P_3	0,1	0,0

- Availability (0): (0,0). P_3 will get executed, and terminate.
- Availability (1): (0,1). P_1 will get executed, and terminate.
- Availability (2): (1,1). P_2 will get executed, and terminate.
- Availability (3): (1,1).
- So, all processes can get executed and deadlock will not occur.

- Example 2:



Process	Allocate (R_1,R_2,R_3)	Request (R_1,R_2,R_3)
P_0	1,0,1	0,1,1
P_1	1,1,0	1,0,0

Process	Allocate (R_1,R_2,R_3)	Request (R_1,R_2,R_3)
P_2	0,1,0	0,0,1
P_3	0,1,0	1,2,0

- Availability (0): (0,0,1). P_2 will get executed, and terminate.
- Availability (1): (0,1,1). P_0 will get executed, and terminate.
- Availability (2): (1,1,2). P_1 will get executed, and terminate.
- Availability (3): (2,2,2). P_3 will get executed, and terminate.
- Availability (4): (2,3,2).
- So, all processes can get executed and deadlock will not occur.

Deadlock Handling

- **Deadlock ignorance** (Ostrich method): Just ignore it.
  - Because deadlock occurs very rarely, it isn't worth writing code for it, which solves the issue. If a deadlock occurs, the solution is to reboot the kernel.
  - Also, if we include the solution for deadlock, the system will get more functionality but performance will degrade.
  - This solution is widely used.
  - Ostrict method: Whenever a sandstorm occurs, an Ostrich just puts it's head in it's feathers, and *tries to ignore* the sandstorm.
- **Deadlock Prevention**: Preventing the deadlock before it can occur, ie preventing any or all 4 deadlock conditions from occuring.
  - Mutual Exclusion: Make all resources shareable.

    ```
    - Not all resources can be made shareable. Examples are printer, etc.
    ```

  - No pre-emption: Make preemption mandatory.

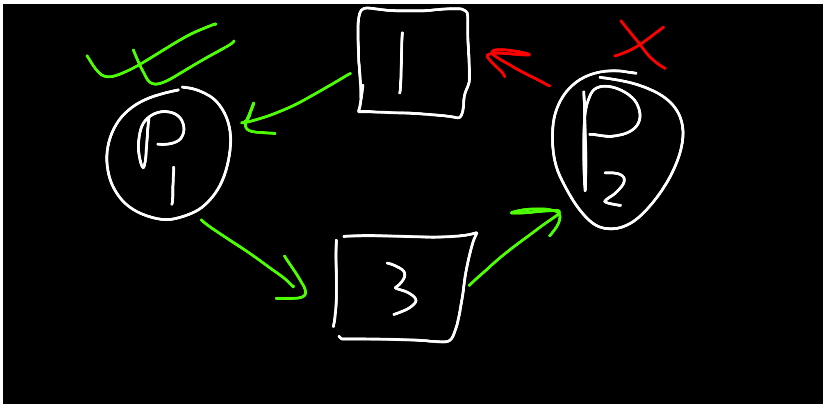
    ```
    + When a process is pre-empted, it will release it's resources, which can then
    ```

  - Hold & Wait: Before a process starts executing, allocate all resources it needs, so it doesn't have to request for anything later on.

    ```
    - Not practical.
    - Can lead to starvation of other processes, because of insufficient resources.
    ```

  - Circular Wait: Order/Prioritize resources. A process can only request for a resource of a priority lower than the one it has allocated to it. If it has 3 assigned, it can only request for $>$

3, not < 3.



- **Deadlock Avoidance**: We try to avoid the deadlock. This is done using **Banker's Algorithm**.
  - Safe Sequence: There is no possibility of deadlock if processes are executed in this order.
  - Unsafe Sequence: There is a possibility of deadlock if processes are executed in any other order.
  - Example 0: Banker's Algorithm

Process	Allocation	Max Need	Available	Remaining Need
P_1	0 | 1 | 0	7 | 5 | 3	3 | 3 | 2	7 | 4 | 3
P_2	2 | 0 | 0	3 | 2 | 2	5 | 3 | 2	1 | 2 | 2
P_3	3 | 0 | 2	9 | 0 | 2	7 | 4 | 3	6 | 0 | 0
P_4	2 | 1 | 1	4 | 2 | 2	7 | 4 | 5	2 | 1 | 1
P_5	0 | 0 | 2	5 | 3 | 3	7 | 5 | 5	5 | 3 | 1
null	null	null	10 | 5 | 7	null

i. Calculate the `Available` amount of resources: `Total Allocation` : 7,2,5. `Available` : 10,5,7 - 7,2,5= 3,3,2.
ii. Calculate the `Remaining Need` , which is `Max Need - Allocation` .
iii. With the amount of resources we have available (based on difference between `Available` and `Remaining Need`), we can fulfill the request of P_2 & P_4. We will let P_2 execute.
iv. After P_2 terminates, `Available` , which is `Current Available + Allocation` , is 3,3,2 + 2,0,0 = 5,3,2
v. Next, we can fulfill the request of P_4.
vi. After P_4 terminates, `Available` : 5,3,2 + 2,1,1 = 7,4,3
vii. Next, we fulfill the request of P_5.
viii. After P_5 terminates, `Available` : 7,4,3 + 0,0,2 = 7,4,5
ix. Next, we fulfill the request of P_1.
x. After P_1 terminates, `Available` : 7,4,5 + 0,1,0 = 7,5,5

xi. Lastly, we fulfill the request of P_3.
xii. After P_3 terminates, `Available` : 7,5,5 + 3,0,2 = 10,5,7.
xiii. Check for correctness: `Final Available` = `Initial Available` = 10,5,7
xiv. Safe Sequence: $P_2 > P_4 > P_5 > P_1 > P_3$.

> There is no possibility of deadlock if processes are executed in this order.

- In real life, processes don't have static needs, rather their needs keep changing as they're running. Banker's Algorithm provides a base for solutions that can be implemented in practical scenarios.

- Example 1: Banker's Algorithm

Process	Allocation	Max Need	Available	Remaining Need
P_0	1 | 0 | 1	4 | 3 | 1	3 | 3 | 0	3 | 3 | 0
P_1	1 | 1 | 2	2 | 1 | 4	4 | 3 | 1	1 | 0 | 2
P_2	1 | 0 | 3	1 | 3 | 3	5 | 3 | 4	0 | 3 | 0
P_3	2 | 0 | 0	5 | 4 | 1	6 | 4 | 6	3 | 4 | 1
null	null	null	8 | 4 | 6	null

i. Calculate the `Remaining Need` , which is `Max Need` - `Allocation` .
ii. With the amount of resources we have available (based on difference between `Available` and `Remaining Need`), we can fulfill the request of P_0 & P_2. We will let P_0 execute.
iii. After P_2 terminates, `Available` , which is `Current Available` + `Allocation` , is 3,3,0 + 1,0,0=4,3,1
iv. Next, we can fulfill the request of P_2.
v. After P_2 terminates, `Available` : 1,3,1 + 1,0,3 = 5,3,4
vi. Next, we can fulfill the request of P_1.
vii. After P_2 terminates, `Available` : 5,3,4 + 1,1,2 = 6,4,6
viii. Next, we can fulfill the request of P_3.
ix. After P_3 terminates, `Available` : 6,4,6 + 2,0,0 = 8,4,6
x. Safe Sequence: $P_0 > P_2 > P_1 > P_3$

- Example 2: Deadlock. A system is having 3 processes each requiring 2 units of resources `R` . The minimum number of units of `R` such that no deadlock will occur:
  - 3
  - 5
  - 6
  - 4

i. Focus on the word '**minimum**'.

ii. If we have `6` resources, we can allow `2` each to all processes, and they'll be fine. But we need '**minimum**' here.
iii. If we have `3` resources, we can allocate `2` to P_1, then `2` to P_2, and so on. But we need to check for all cases.
iv. If we allocate `1` resource each to each process, then deadlock will occur.
v. If we have `4` resources, then we can allocate `1` resource each to each process, and still have 1 left. So we can allocate the remaining resource to any of the processes, and let them execute. There will be no deadlock in any case.
vi. $Answer : 4$
   - Check Formulae.

- Example 3: Deadlock. A system is having 3 processes. P_1 requires 3 instances of Resource R, P_2 requires 4 instances, P_3 requires 5 instances. What is the minimum number of units of `R` such that no deadlock will occur?
  - Processes need $\{3, 4, 5\}$ resources. Allocate $\{2, 3, 4\}$ resources. We need 1 more instance to break the deadlock. $Answer : 10$.
  - Maximum number of resources needed for Deadlock to occur: 9
- Example 4: Deadlock. Consider a system with 3 processes that share 4 instances of the same resource type. Each process can request `k` instances of that resource. What can the maximum value of `k` be, to avoid deadlock?
  i. Assume that each process needs `1` instance of the resource ($k = 1$). If we give `1` each to each process, we are left with `1` instance, and the processes execute successfully.
  ii. Now, assume that each process needs `2` instances of the resource ($k = 2$). If we give `1` instance to each process, we're left with `1` instance, which we can give to any of the processes, and deadlock will not occur.
  iii. Now, $k = 3$. Now, if we give `1` instance to each process, we're left with `1` instance, but we cannot execute any process with it.
  iv. $Answer : k = 2$
   - Check Formulae.

- **Deadlock Detection & Recovery**: Try to detect a deadlock, and then try to recover from it. Recovery method:
  - Kill the deadlocked processes: Kill 1 of the processes, check for deadlock, then kill another (if needed). Continue this till deadlock is no longer present.
  - Pre-empt the resources: Pre-empt all the resources a process is holding.

Memory Management

- Check Formulae
- Register, cache and primary memory (RAM) is directly connected to the CPU.

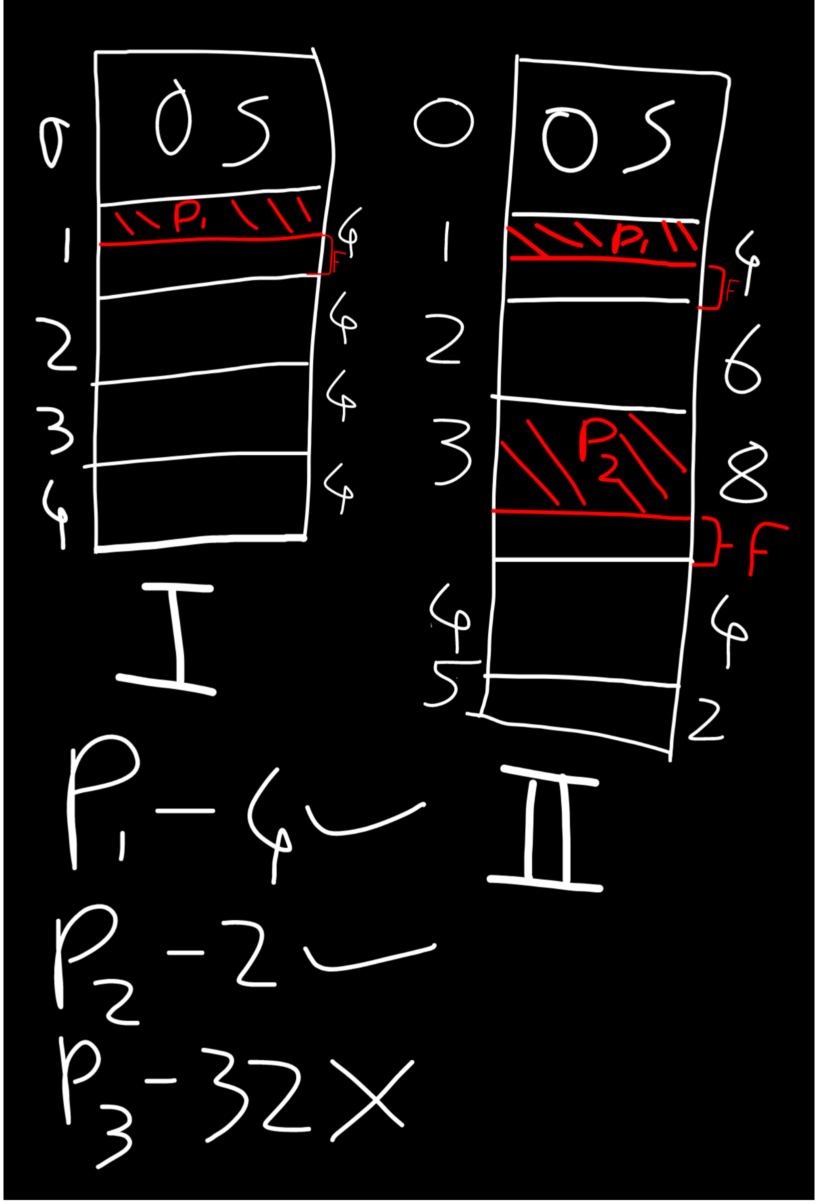
- Programs are stored in the secondary memory. Whenever a process needs to be executed, it is transferred to the primary memory.
- Degree of Multi-programming: Keep more and more processes in the System RAM.
- CPU Utilization increases with an increase in the size of the system memory.
- Example 0:
    - If each process consumes 4MB, and there is 4MB of primary memory available, we can only accomodate 1 process in the memory. If it does I/O operations for $K = 70\%$ of it's time, CPU Utilization: $1 - K^1 = 1 - 0.7 = 0.3$ ie 30%.
    - If each process consumes 4MB, and there is 8MB of primary memory available, we can accomodate 2 processes in the memory. If it does I/O operations for $K = 70\%$ of it's time, CPU Utilization: $1 - K^2 = 1 - 0.49 = 0.51$ ie 51%.
    - Similarly, if there is 16MB of primary memory available, we can accomodate 4 processes. I/O Operation time duration: 70% ie 0.7, so CPU Utilization: $1 - k^4 = 1 - 0.7^4 = 1 - 0.2401 = 0.7599$ ie 76%.
- Techniques:
    - Contiguous: We allocate processes in continuous partitions in the memory. Example: Fixed & Dynamic Partition
    - Non-Contiguous: We allocate processes in random places in the memory.

Fixed Partitioning

- Type: Contiguous
- Number of partitions: Fixed.
- Size of partitions: May not be Fixed.
- We have to fit the entire process within the same partition. Spanning between partitions is not allowed.
- Facts:

```
- Internal Fragmentation: If partition size is 4MB and we want to accomodate a 2MB
- External Fragmentation: Happens when free memory is split into small blocks and s
- If maximum partition size is 8MB, we cannot bring in processes larger than 8MB in
- If number of partitions is 4, we cannot bring in more than 4 processes to memory.
+ Easy to implement.
```

- Diagram:



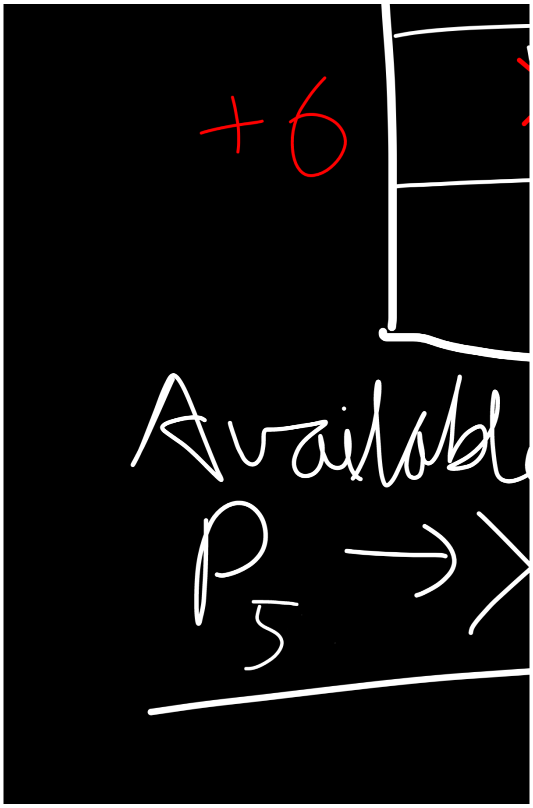
Dynamic Partitioning

- Type: Contiguous
- Number of partitions: Not Fixed.
- Size of partitions: Not Fixed.

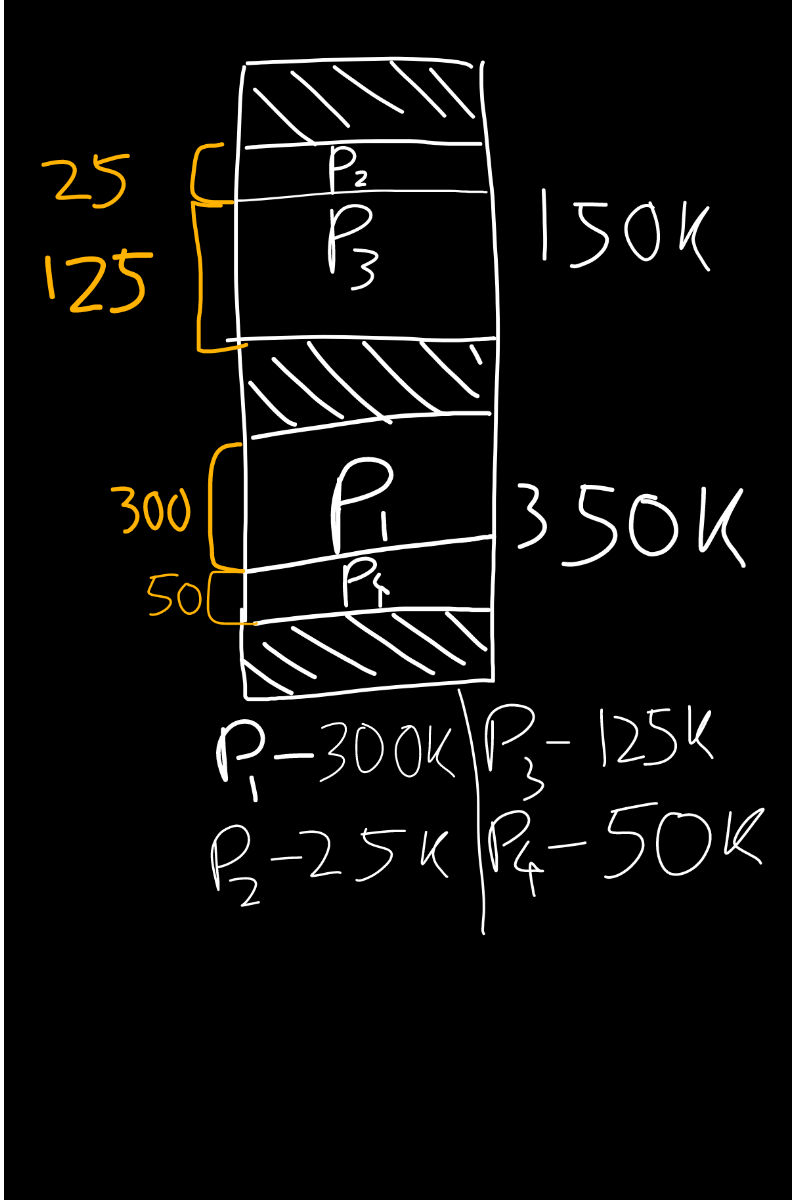
```
+ Partitions are allocated at runtime.
+ No limitation on process size.
+ No Internal Fragmentation: Since memory is allocated as processes arrive.
- External Fragmentation: After processes leave the memory, holes are created in it. Th
```

- **Compacting**: We may use this method to resolve External Fragmentation. We move all processes to one end of the memory, and all the free space to the other end. Then we can accomodate new processes in memory.
  - We have to stop processes before re-allocating memory.
  - It consumes a lot of time.

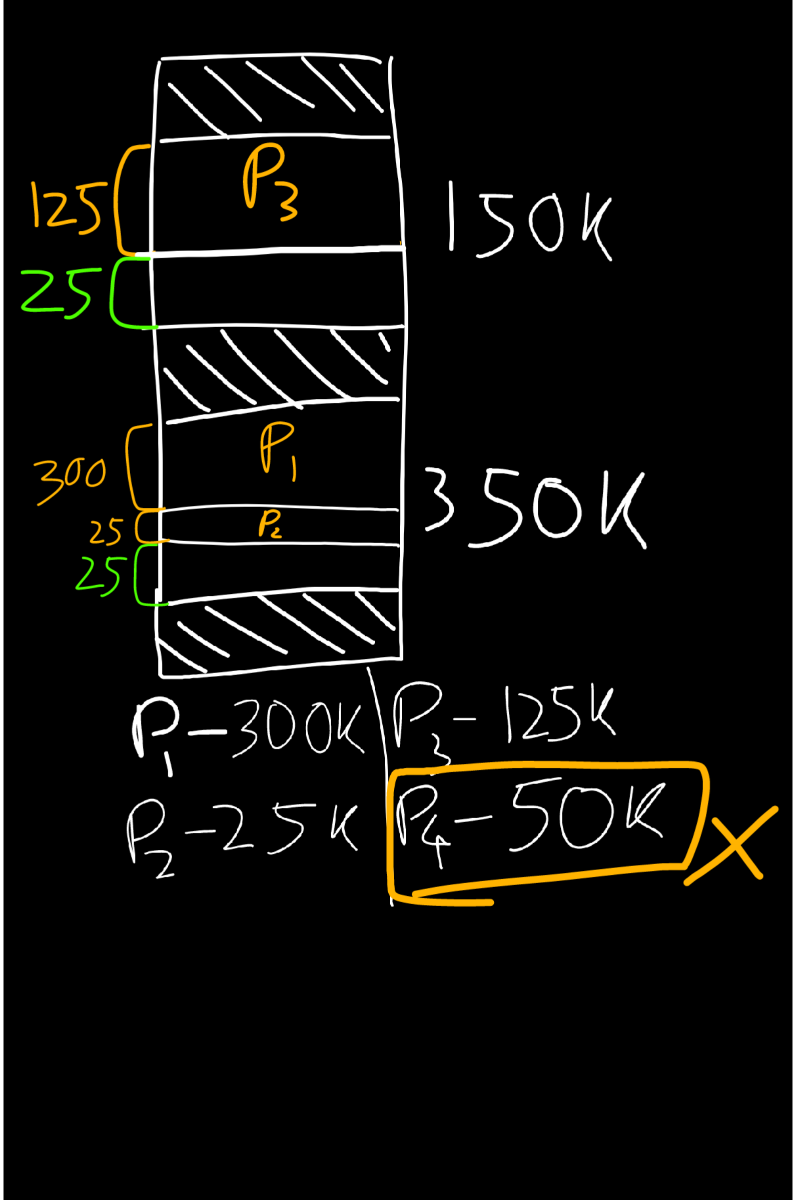
- Diagram:



- How memory is allocated:
    - **First Fit**: Processes are allocated the first slot of memory that is sufficient for it.

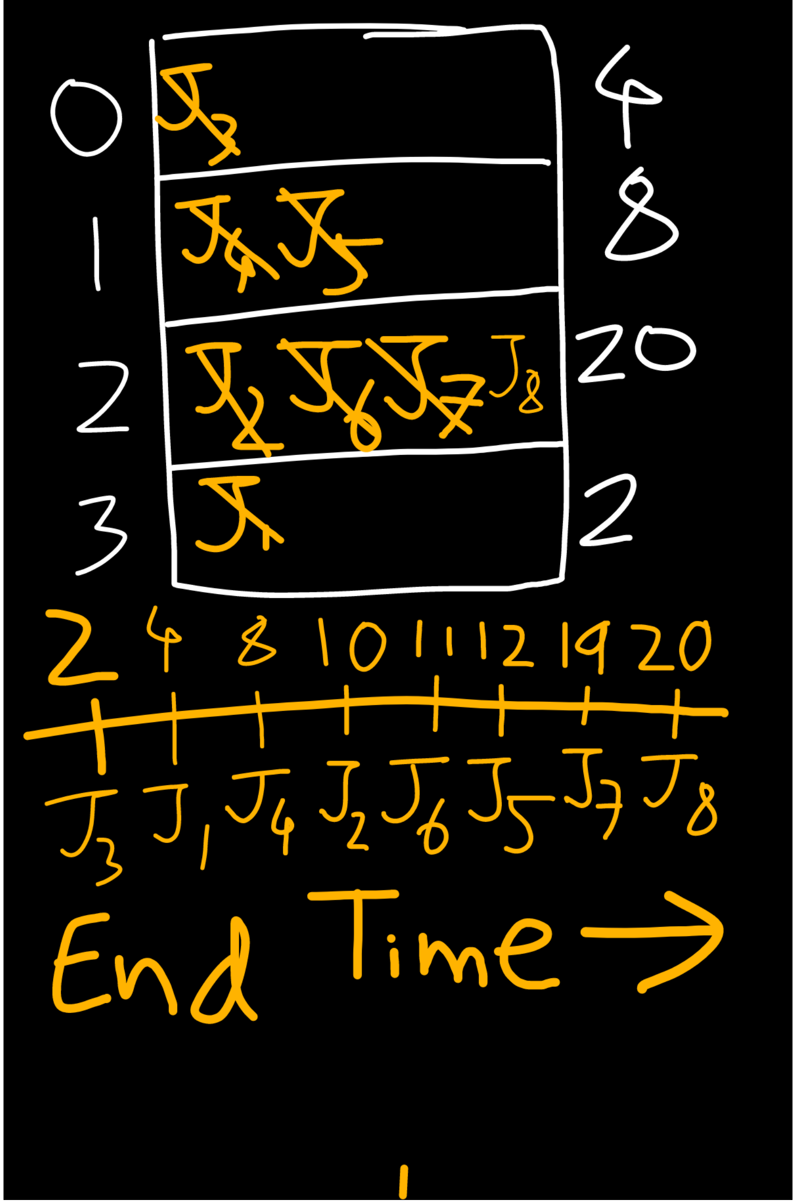


- **Best Fit**: We allocate the memory in such a way that the remaining available space in the slot should be minimum.

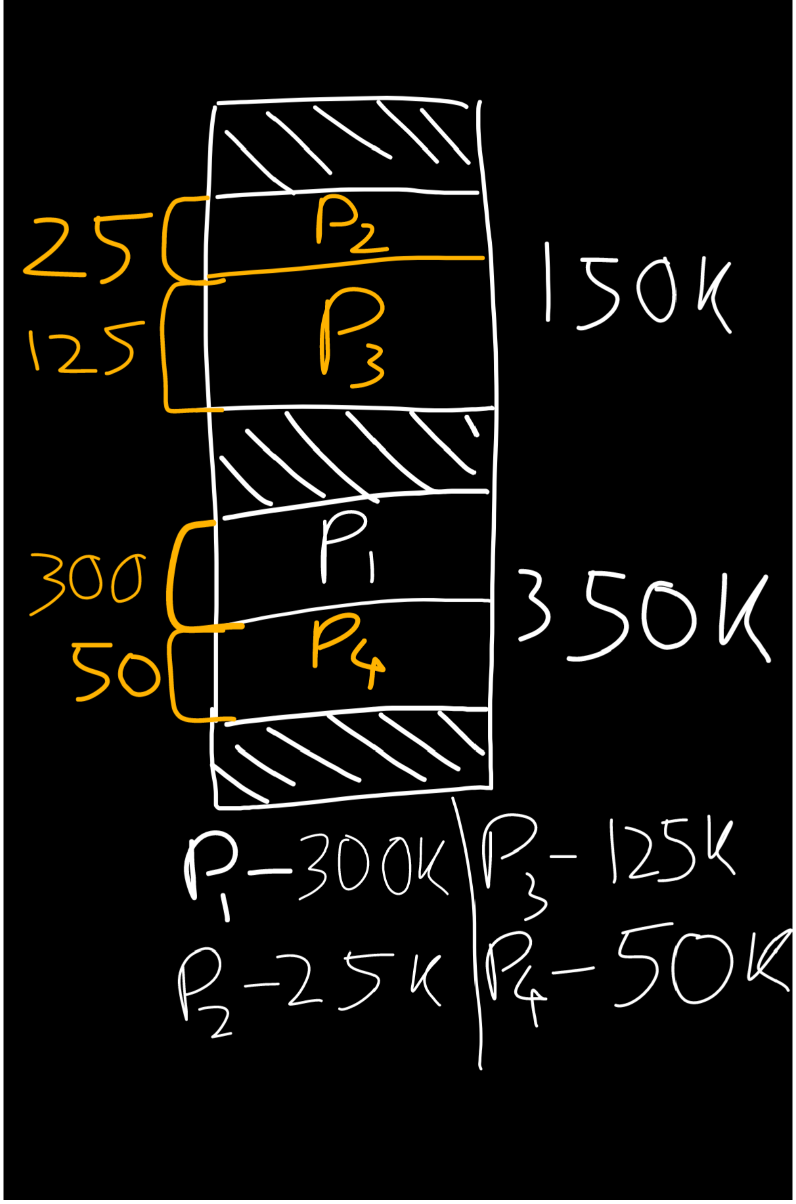


- **Example 0**: Calculate the time at which J_7 will be completed.

Request No.	Request Size	Usage Time
J_1	2K	4
J_2	14K	10
J_3	3K	2
J_4	6K	8
J_5	6K	4
J_6	10K	1
J_7	7K	8
J_8	20K	1



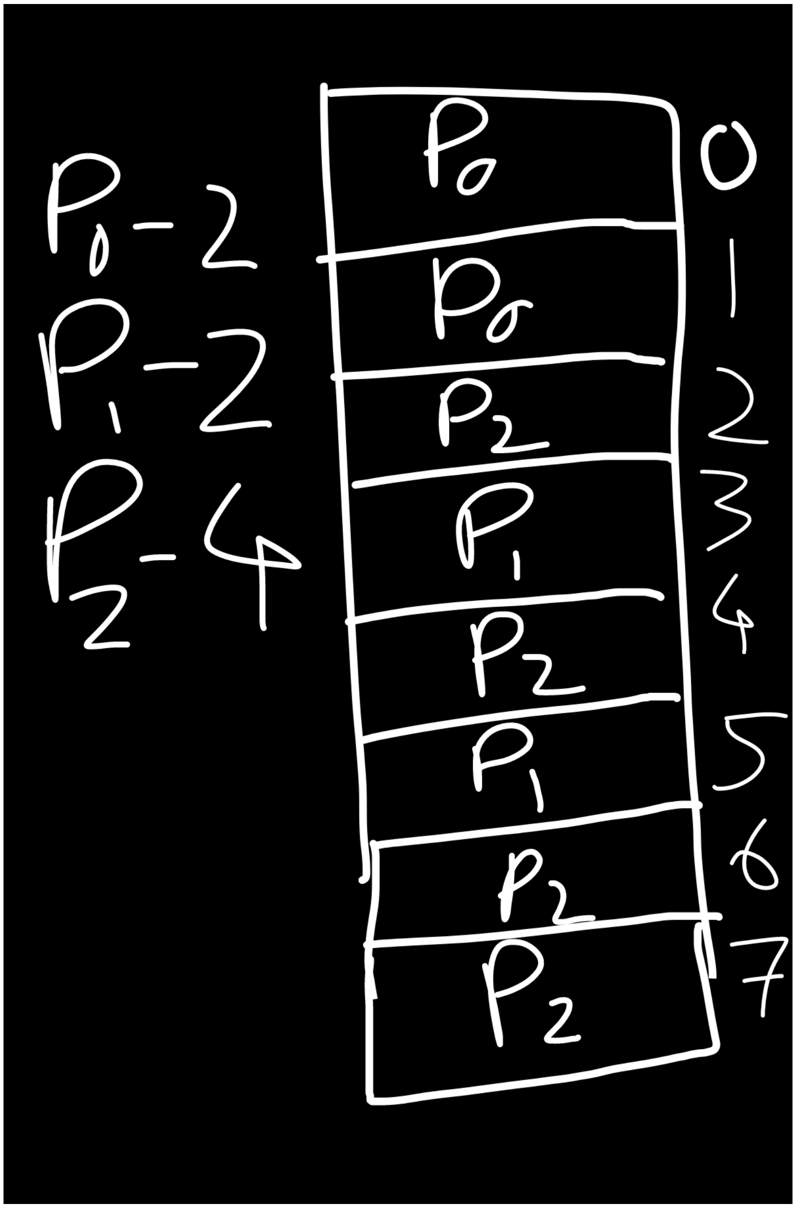
   - $Result = 19$, and J_7 will enter at 11
- **Worst Fit**: We allocate the memory in such a way that the remaining available space in the slot should be maximum.



Paging

- Also known as: non-Continguous memory allocation
- Processes are divided into pages, and then allocated space in the main memory so that they can take advantage of the scattered free spaces in the main memory.
- You don't have to allocate memory space individually.
- It's a time consuming process, because determining all free spaces that are available, checking for suitability, etc. takes time.
- Process is divided into pages, Memory is divided into frames.
- Each entry in the Page Table has frame number in it.
- Page size = Frame size.
- If frame size = $1KB$, memory size = $8KB$, number of frames = 8

- Number of frames = Main memory size / frame size
- Number of pages = Process size / Page size



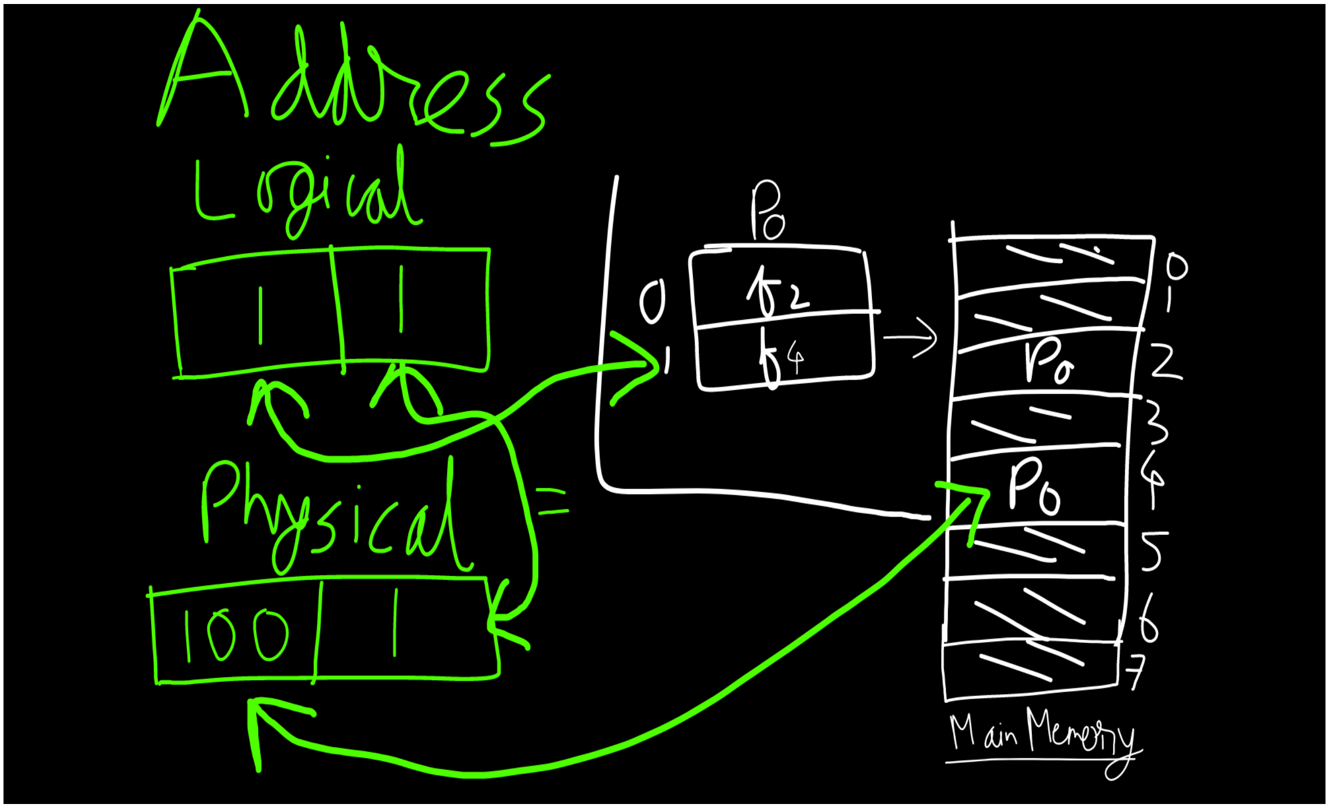
- CPU is not aware of any occurence of paging.
- **Logical Address**: The address CPU generates.
  - Format: Page Number | Page offset
  - Size: If a process has 2 pages of 2 bytes each, then: Page Number: $2^1 = 2$ ie 1 byte. Page Off-set: $2^1 = 2$ ie 1 byte.

    > Page Number: The number of the page we need to go to.
    > Page offset: The bit we need to go to, within that page number.

- **Absolute Address**: The actual address of the data in memory.
  - Format: Frame Number | Frame offset
  - Size: If a memory has 8 frames of 2 bytes each, then: Frame Number: $2^3 = 8$ ie 3 bytes. Frame Off-set: $2^1 = 2$ ie 1 byte.

> Frame Number: The number of the frame we need to go to.
> Frame offset: The bit we need to go to, within that frame number.

- **Memory Management Unit (MMU)** converts the logical address to it's absolute address.
  - MMU uses a paging table for this. Every process has it's own page table.
  - Page Table contains the frame number per page.



- Example 0: Logical Address Space: 4GB, Physical Address Space: 64MB, Page Size: 4KB. What is the: Number of pages, Number of frames, Number of entries in the Page Table, Size of Page Table?

> $4GB = 2^2 * 2^{30}$ bytes, $2KB = 2^1 * 2^{10}$ bytes

i. Logical Address Space: $4GB = 2^2 * 2^{30} = 2^{32}$ bytes.

> Total size of logical address: 32 bytes.

ii. Page Size: $4KB = 2^2 * 2^{10} = 2^{12}$ bytes.

> Size of page offset: 12 bytes. So, $32 - 12 = 20$ bytes is the size of page number.

iii. Number of pages: $2^{20} = 1048576$

iv. Physical Address Space: $64MB = 2^6 * 2^{20} = 2^{26}$ bytes.

> Total size of logical address: 26 bytes.

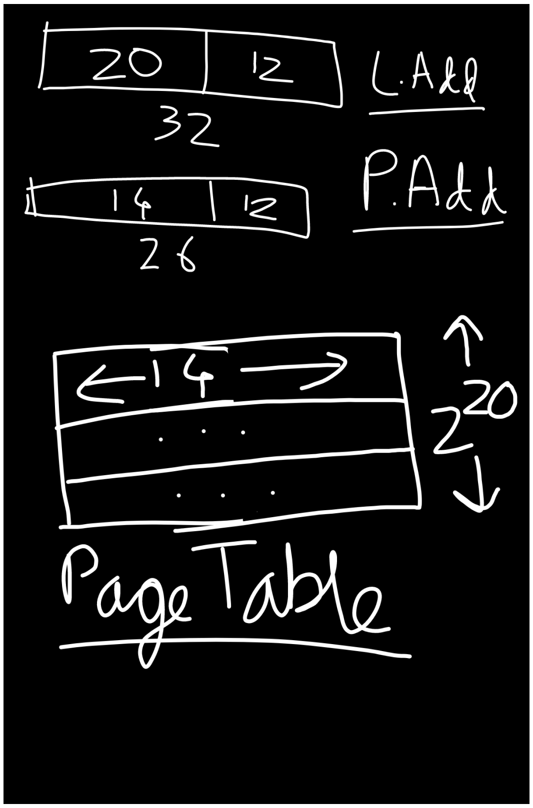
v. Frame Size (= Page Size): $4KB = 2^2 * 2^{10} = 2^{12}$ bytes.

> Size of frame offset: 12 bytes. So, $26 - 12 = 14$ bytes is the size of frame number.

vi. Number of frames: $2^{14} = 16384$

vii. Number of entries in the Page Table: Number of pages: $2^{20} = 1048576$

viii. Size of Page Table: $2^{20} * 14 = 14680064$ bytes.

> Each entry in the Page Table has frame number in it. Each frame number is 14 bytes, and there are a total of 2^{20} pages in the table.
>
> 
>

- **Page Table**: Format: | Frame Number | Valid/Invalid (0/1) | Protection (RWX) | Reference (0/1) | Caching | Dirty (0/1)?
  - Frame Number: **Mandatory**.
  - Valid/Invalid (1/0): Is the page present? Sometimes the page is swapped out to secondary memory, in which case it can be absent from main memory.
  - Protection (RWX): Permissions
  - Reference (0/1): If we had brought the page to main memory before.
  - Caching: Caching means putting the data to cache memory. If this is enabled, the data can be cached by the CPU.
  - Dirty?: If some value is modified, we will set this as 1.
- **Multi-level Paging**:
  - Example 0:Physical Address Space: $256MB$, Logical Address Space: $4GB$, Page Size = Frame Size = $4KB$
    i. Frame: $256MB = 2^8 * 2^{20} = 2^{28}$ | Frame Number size: 16
    ii. Frame Size: $4KB = 2^2 * 2^{10} = 2^{12}$ | Frame Offset size: 12
    iii. Physical Address Format: $16 + 12 = 28$
    iv. Number of frames: $2^{28} - 2^{12} = 2^{16} = 65536$
    v. Page: $4GB = 2^2 * 2^{30} = 2^{32}$ | Page Number size: 32

vi. Frame Size: $4KB = 2^2 * 2^{10} = 2^{12}$ | Frame Offset size: 12

vii. Logical Address Format: $20 + 12 = 32$

viii. Number of pages: $2^{32} - 2^{12} = 2^{20} = 1048576$

- Page Table stores frames. Each partition mandatorily has the frame number.

i. A frame has a size of 16 bits. There are 2^{20} pages in it. So, total size: $2^{20} * (16/8) = 2MB$

ii. Obviously, we cannot store 2MB in the main memory partition of size 4KB. This is why we need **Multi-level Paging**.