Scheduling Criteria

Each scheduling algorithm favors particular criteria:

- *CPU utilization* (maximize)
- *throughput*: number of processes which complete execution per time unit (maximize)
- *turnaround time* (TA): total amount of time to execute a particular process (minimize)
- *waiting time*: amount of time a process has been waiting in the ready queue (minimize)
- *response time*: amount of time it takes from when a request is submitted to when the response is produced (minimize); does not include the time for a response to be output

Some work is being done to minimize response time variance, to promote predictability.

CPU Scheduling Algorithms

- First-Come, First Serve (FCFS or FIFO) (non-preemptive)
- Priority Scheduling
- Shortest Job First (SJF; non-preemptive) or
- Shortest Remaining Time First (SRTF; preemptive)
- Round Robin (preemptive)
- Multi-level Queue
- Multi-level Feedback Queue

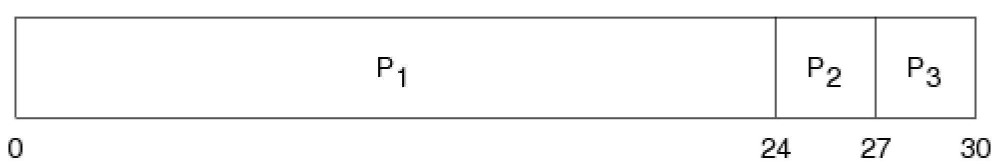
First-Come, First Serve

- non-preemptive scheduling management
- ready queue is managed as a FIFO queue

Example-1: 3 jobs arrive at time 0 in the following order (batch processing):

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	24	0	0	0	24	24
2	3	0	24	24	27	27
3	3	0	27	27	30	30

- Gantt chart:



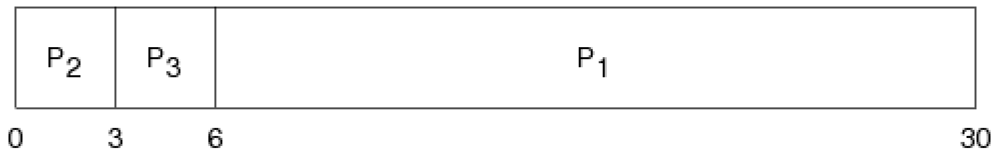
- average waiting time: (0+24+27)/3 = 17
- average turnaround time: (24+27+30)/3 = 27

Example-2:

- consider arrival order: 2, 3, 1

Process	Burst Time	Arrival	Start	Wait	Finish	TA
2	3	0	0	0	3	3
3	3	0	3	3	6	6
1	24	0	6	6	30	30

- Gantt chart:

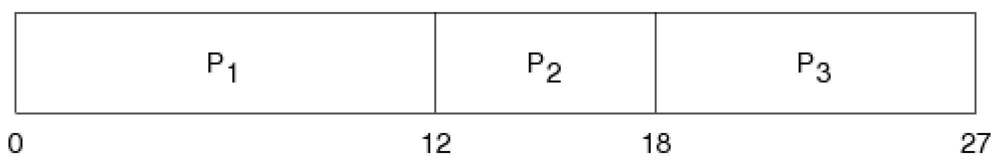


- average waiting time: (0+3+6)/3 = 3
- average turnaround time: (3+6+30) = 13

Example-3:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	12	0	0	0	12	12
2	6	1	12	11	18	17
3	9	4	18	14	27	23

- Gantt chart:

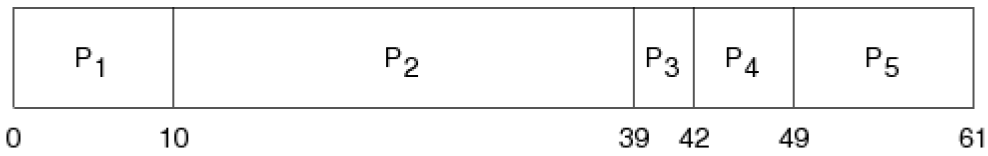


- average waiting time: (0+11+14)/3 = 8.33
- average turnaround time: (12+17+23) = 52/3 = 17.33

Example-4:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	10	0	0	0	10	10
2	29	0	10	10	39	39
3	3	0	39	39	42	42
4	7	0	42	42	49	49
5	12	0	49	49	61	61

- Gantt chart:



- average waiting time: (0+10+39+42+49)/5 = 28
- average turnaround time: (10+39+42+49+61)/5 = 40.2

Shortest Job First (SJF)

- associate with each process the length of its next CPU burst
- schedule the process with the shortest time
- two schemes
  - non-preemptive: once scheduled, a process continues until the end of its CPU burst
  - preemptive: preempt if a new process arrives with a CPU burst of less length than the *remaining time* of the currently executing process; known as the *Shortest Remaining Time First* (SRTF) algorithm
- SJF is provably optimal; it yields a minimum average waiting time for any set of processes
- however, we cannot always predict the future (i.e., we do not know the next burst length)
- we can only estimate its length
- an estimate can be formed by using the length of its previous CPU bursts:

T_n = actual length of the nth CPU burst

ψ_n = predicted value of nth CPU burst

$0 <= w <= 1$

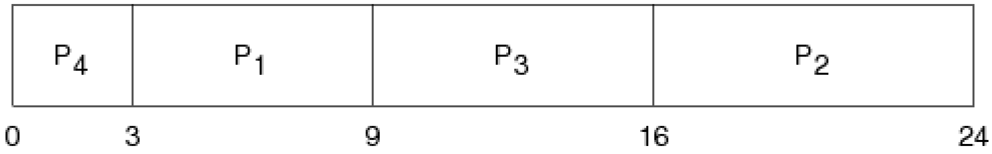
$\psi_{n+1} = w * T_n + (1-w) * \psi_n$

SJF (non-preemptive) examples

Example-1:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	6	0	3	3	9	9
2	8	0	16	16	24	24
3	7	0	9	9	16	16
4	3	0	0	0	3	3

- Gantt chart:

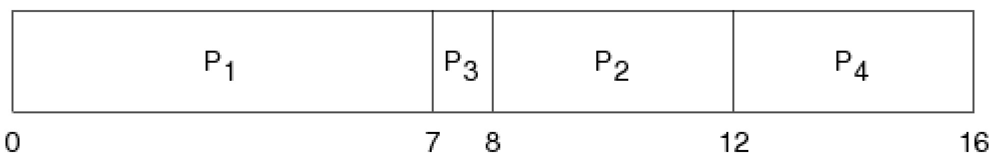


- average waiting time: (3+16+9+0)/4 = 7
- average turnaround time: (9+24+16+3)/4 = 13

Example-2:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	7	0	0	0	7	7
2	4	2	8	6	12	10
3	1	4	7	3	8	4
4	4	5	12	7	16	11

- Gantt chart:

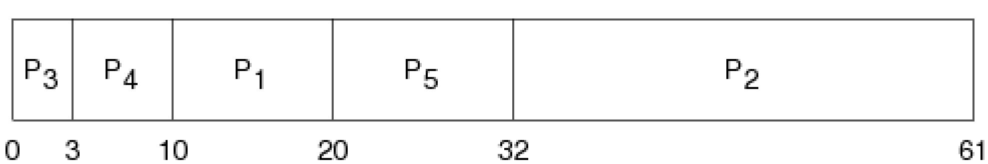


- average waiting time: (0+6+3+7)/4 = 4
- average turnaround time: (7+4+10+11)/4 = 8

Example-3:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	10	0	10	10	20	20
2	29	0	32	32	61	61
3	3	0	0	0	3	3
4	7	0	3	3	10	10
5	12	0	20	20	32	32

- Gantt chart:



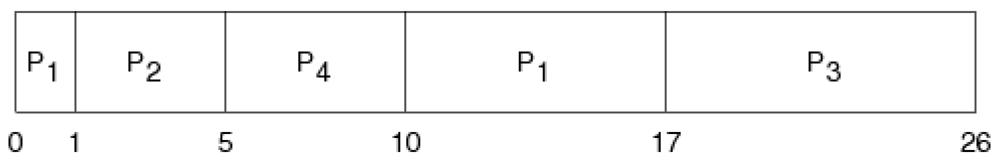
- average waiting time: (10+32+0+3+20)/5 = 13
- average turnaround time: (10+39+42+49+61)/5 = 25.2

SRTF (preemptive) examples

Example-1:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	8	0	0	9	17	17
2	4	1	1	0	5	4
3	9	2	17	15	26	24
4	5	3	5	2	10	7

- Gantt chart:

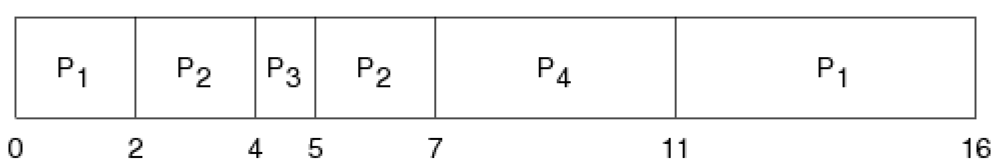


- average waiting time: (9+0+15+2)/4 = 6.5
- average turnaround time: (17+4+24+7)/4 = 13

Example-2:

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	7	0	0	9	16	16
2	4	2	2	1	7	5
3	1	4	4	0	5	1
4	4	5	7	2	11	6

- Gantt chart:



- average waiting time: (9+1+0+2)/4 = 3
- average turnaround time: (16+5+1+6)/4 = 7

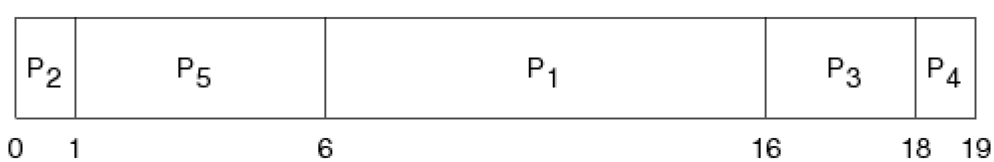
Priority Scheduling

- associate a priority with each process, allocate the CPU to the process with the highest priority
- any 2 processes with the same priority are handled FCFS
- SJF is a version of priority scheduling where the priority is defined using the predicted CPU burst length
- priorities are usually numeric over a range
- high numbers may indicate low priority (system dependent)
- internal (process-based) priorities: time limits, memory requirements, resources needed, burst ratio
- external (often political) priorities: importance, source (e.g., faculty, student)
- priority scheduling can be non-preemptive or preemptive
- problem: *starvation* --- low priority processes may never execute because they are waiting indefinitely for the CPU
- a solution: *aging* --- increase the priority of a process as time progresses
- `nice` in UNIX executes a utility with an altered scheduling priority
- `renice` in UNIX alters the priority of running processes

Priority Scheduling example

Process	Burst Time	Priority	Arrival	Start	Wait	Finish	TA
1	10	3	0	6	6	16	16
2	1	1	0	0	0	1	1
3	2	4	0	16	16	18	18
4	1	5	0	18	18	19	19
5	5	2	0	1	1	6	6

Gantt chart:



average waiting time: (6+0+16+18+1)/5 = 8.2

average turnaround time: (1+6+16+18+19)/5 = 12

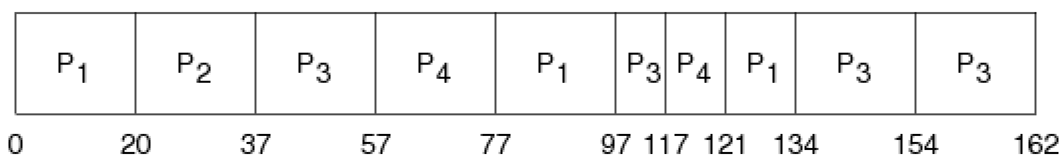
Round Robin

- time sharing (preemptive) scheduler where each process is given access to the CPU for 1 time quantum (slice) (e.g., 20 milliseconds)
- a process may block itself before its time slice expires
- if it uses its entire time slice, it is then preempted and put at the end of the ready queue
- the ready queue is managed as a FIFO queue and treated as a circular
- if there are n processes on the ready queue and the time quantum is q, then each process gets $1/n$ time on the CPU in chunks of at most q time units
- no process waits for more than $(n-1)q$ time units
- the choice of how big to make the time slice (q) is extremely important
    - if q is very large, Round Robin degenerates into FCFS
    - if q is very small, the context switch overhead defeats the benefits

Example-1 (q = 20):

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	53	0	0	?	134	134
2	17	0	20	?	37	37
3	68	0	37	?	162	162
4	24	0	57	?	121	121

- Gantt chart:

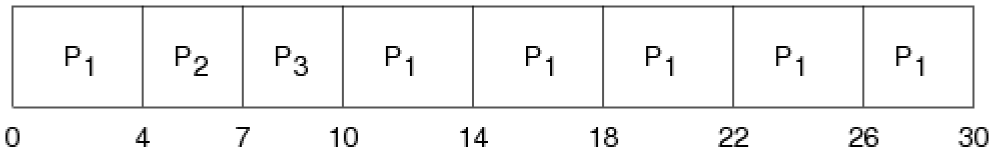


- waiting times:
    - p_1: (77-20) + (121-97) = 81
    - p_2: (20-0) = 20
    - p_3: (37-0) + (97-57) + (134-117) = 94
    - p_4: (57-0) + (117-77) = 97
- average waiting time: (81+20+94+97)/4 = 73

Example 2 (q = 4):

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	24	0	0	6	30	30
2	3	0	4	4	7	7
3	3	0	7	7	10	10

- Gantt chart:

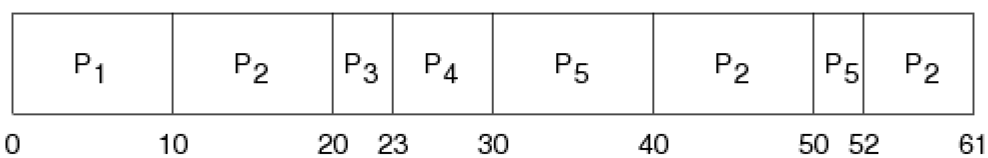


- average waiting time: (6+4+7)/3 = 5.67
- average turnaround time: (30+7+10)/3 = 15.67

Example 3 (q = 10):

Process	Burst Time	Arrival	Start	Wait	Finish	TA
1	10	0	0	0	10	10
2	29	0	10	32	61	61
3	3	0	20	20	23	23
4	7	0	23	23	30	30
5	12	0	30	40	52	52

- Gantt chart:



- average waiting time: (0+32+20+23+40)/5 = 23
- average turnaround time: (10+39+42+49+61)/5 = 35.2

Multilevel Queue

- the ready queue is managed as multiple queues based on various characteristics. For instance,
    - foreground (interactive)
    - background (batch)
- each queue uses a particular scheduling algorithm. For instance,
    - foreground (round robin)
    - background (FCFS)
- scheduling must be done between queues:
    - fixed priority (may lead to starvation) (e.g., foreground jobs have absolute priority over background jobs)
    - time slice per queue

Multilevel Feedback Queue

- processes move between the various queues
- a multilevel feedback queue is characterized by
    - number of queues
    - scheduling algorithm for each queue
    - method used to determine when to upgrade a process
    - method used to determine when to demote a process
    - method used to determine on which queue a process begins (each time it returns to the ready state)
- example:
    - 3 queues
    - fixed priority based on length of CPU burst
    - RR for 1st queue, FCFS for last queue
    - each process begins on top queue (quantum = 8)