# CS420: Operating Systems

# CPU Scheduling

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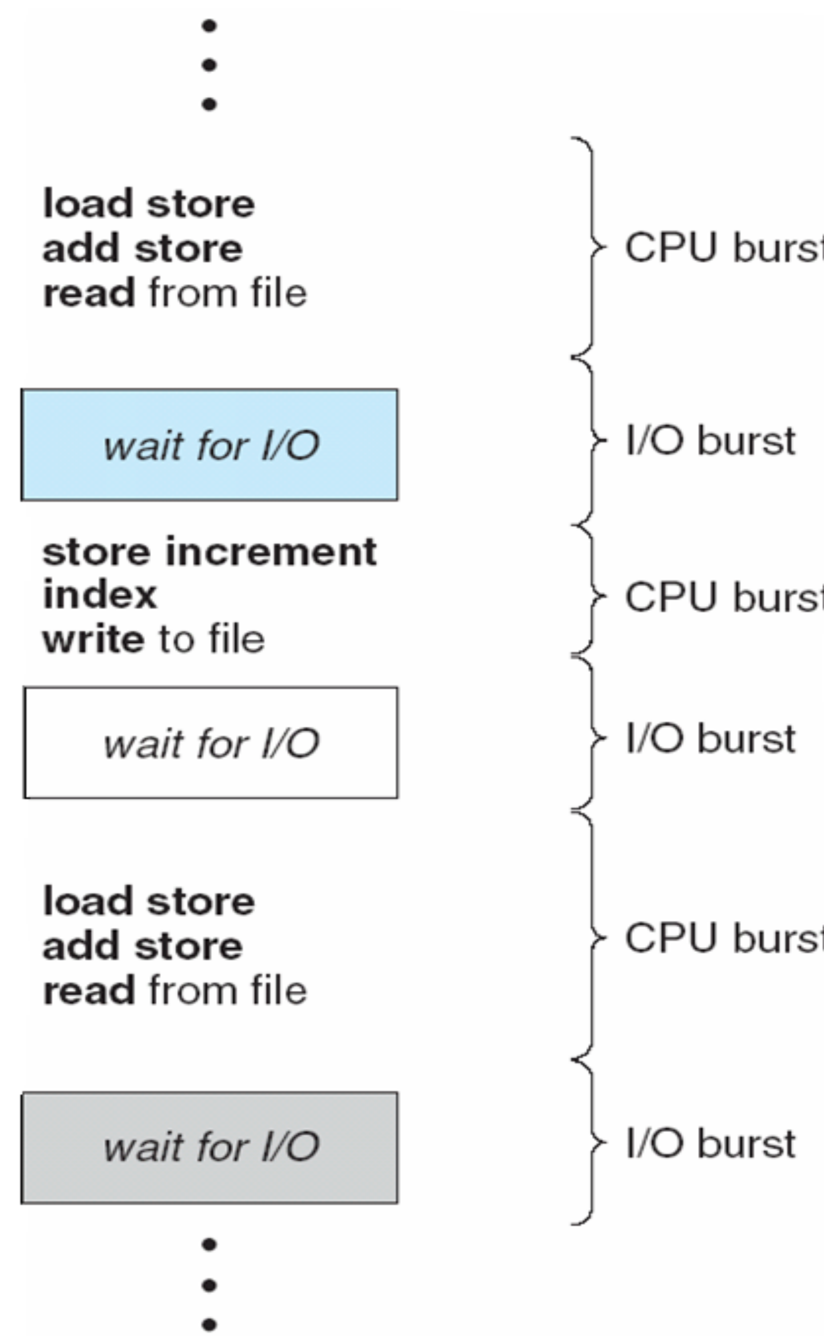
Based on Operating System Concepts, 9th Edition by Silberschatz, Galvin, Gagne

# Scheduling Concepts

- **Operating systems schedule kernel-level threads**
- **Maximum CPU utilization is obtained through multiprogramming**
  - Single process cannot keep CPU and I/O devices busy at all times
  - Multiprogramming attempts to ensure that the CPU always has something to execute
    - A process is executed until it must wait for something (typically I/O)
    - When waiting, the OS swaps another process onto the CPU for execution

# CPU-I/O Burst Cycle

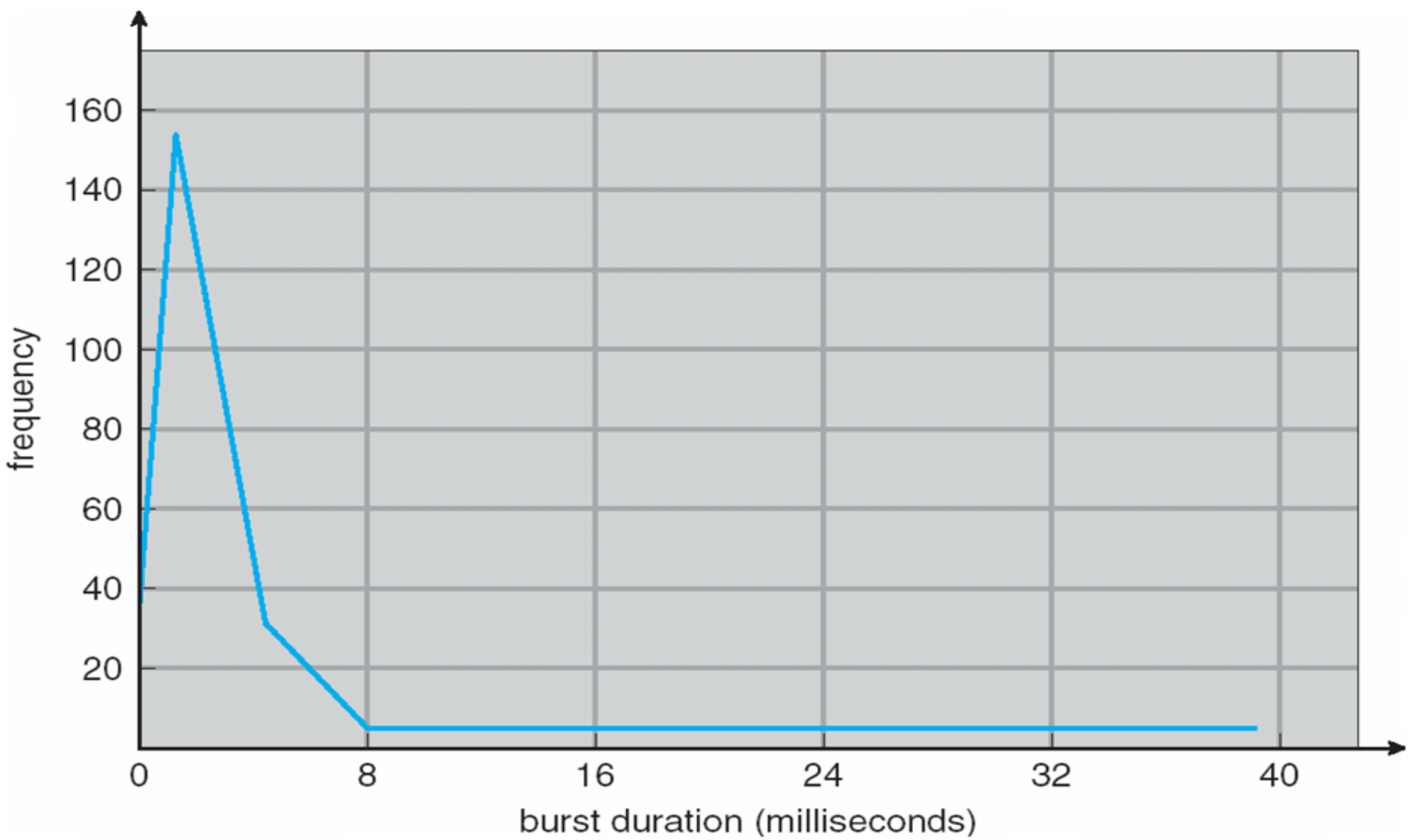
- **CPU scheduling works because of a property known as the CPU-I/O burst cycle**
  - A process cycles between the states of CPU execution and I/O wait
  - When a process enters the I/O wait state, another process can enter the CPU execution state




- **I/O-bound programs typically have a large number of short CPU bursts**
- **CPU-bound programs typically have only a few long CPU bursts**

# Histogram of CPU-burst Times

- **CPU-burst times for a typical program show a large number of short CPU bursts and only a small number of long CPU bursts**



# CPU Scheduler (i.e. short-term scheduler)

- **Selects from among the processes in the ready-queue, and allocates the CPU to one of them**
  - Queue may be ordered in various ways:
    - FIFO
    - Priority queue
    - Tree
- **Preemptive scheduling prioritizes processes -- the process with the highest priority should be the process utilizing the CPU**
  - A higher priority process may cause a lower priority process to be removed from the CPU (i.e. the lower priority process goes from the 'running' state back into the ready-queue)
- **In nonpreemptive scheduling, a process can run on the CPU until it voluntarily relinquishes control to another process (also called cooperative scheduling)**

# CPU Scheduler (Cont.)

- **In a system with nonpreemptive (cooperative) scheduling, scheduling decisions are only made when:**

  (1) A process **voluntarily** switches from a running state to a waiting state

  (2) A process terminates

- **In a system with preemptive scheduling, scheduling decisions may take place when:**

  (1) An interrupt occurs that must be handled by another process

  (2) A process switches from the waiting state and re-enters the ready-queue

  (3) [Blanket statement] Any change is made to the ready-queue

# CPU Scheduler (Cont.)

- **Special considerations when using a preemptive schedule**
  - Data shared between processes (i.e. shared memory) may be left in an inconsistent state if one of the processes is preempted while writing data
    - Consider a queue -- the current size is incremented, but the process is preempted before the data can actually be added into the queue
  - Low-level data structures (e.g. I/O queues) may be left in an unknown state if a process is preempted while in kernel mode due to a system call
    - If the process that caused the preemption needs to access those same low-level data structures, then bad things happen

# Dispatcher

- **Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:**
  - Switching context
  - Switching to user mode
  - Jumping to the proper location in the user program to restart that program

- **Dispatch latency -- time it takes for the dispatcher to stop one process and start another running**
  - Must be as small as possible since the dispatcher is invoked during every context switch

# Scheduling Criteria

- **Different CPU-scheduling algorithms have different properties**
  - Different algorithms may favor one type of process over another

- **Different criteria can be considered when comparing scheduling algorithms**
  - **CPU utilization** – desirable to maximize CPU utilization
  - **Throughput** – number of processes that complete their execution per time unit
  - **Turnaround time** – amount of time to execute a particular process from creation to termination; desirable to minimize turnaround time
  - **Waiting time** – amount of time a process spends waiting in the ready queue
  - **Response time** – amount of time it takes from when a request was submitted until the first response is produced, not output

# Scheduling Algorithm Optimization Criteria

- **Desirable to maximize:**
  - CPU utilization
  - Throughput
- **Desirable to minimize:**
  - Turnaround time
  - Waiting time
  - Response time

# Scheduling Algorithms

- **Many different scheduling algorithms exist -- each has its own method of determining which of the processes in the ready-queue will be assigned to the processor next**
  - First-Come, First-Served Scheduling
  - Shortest-Job-First Scheduling
  - Priority Scheduling
  - Round-Robin Scheduling
  - Multilevel Queue Scheduling
  - Multilevel Feedback Queue Scheduling

# First-Come, First-Served (FCFS) Scheduling

- **A very simple CPU-scheduling algorithm**
- **The process that requests the CPU first is allocated the CPU first**
- **Easily implemented with a standard FIFO**
  - Add the PCB of a process to the tail of the FIFO when added to the ready-queue
  - When the CPU is available, it is allocated to the process at the head of the FIFO
- **The average waiting time when using FCFS can be long**

# FCFS Scheduling (Cont.)

- **Consider the following three processes that all arrive at time *t=0* in the order $P_1$, $P_2$, $P_3$**

| Process | Burst Time (ms) |
|---|---|
| $P_1$ | 24 |
| $P_2$ | 3 |
| $P_3$ | 3 |


- **Waiting time for $P_1$ = 0; $P_2$ = 24; $P_3$ = 27**
- **Average waiting time = (0 + 24 + 27) / 3 = 17 milliseconds**

# FCFS Scheduling (Cont.)

- **Consider the same three processes that all arrive at time *t=0* in the order $P_2$, $P_3$, $P_1$**

| Process | Burst Time (ms) |
|---|---|
| $P_2$ | 3 |
| $P_3$ | 3 |
| $P_1$ | 24 |


- **Waiting time for $P_1$ = 6; $P_2$ = 0; $P_3$ = 3**
- **Average waiting time = (6 + 0 + 3) / 3 = 3 milliseconds**

# FCFS Scheduling (Cont.)

- **The average waiting time when using FCFS is generally not minimal and can vary substantially**
- **Consider a CPU-bound process followed by many I/O bound processes**
  - CPU-bound process consumes processor time while I/O bound processes wait in the ready-queue
  - If I/O bound processes were allowed to go first, they could be sitting in the I/O queues waiting for I/O instead while the CPU-bound process consumed the CPU
  - If CPU-bound process gets to I/O resources before the I/O bound processes, then the CPU is likely to be left idle
- **FCFS is nonpreemptive which means it is terrible for time-sharing systems as one process may hog CPU resources**

# Shortest-Job-First (SJF) Scheduling

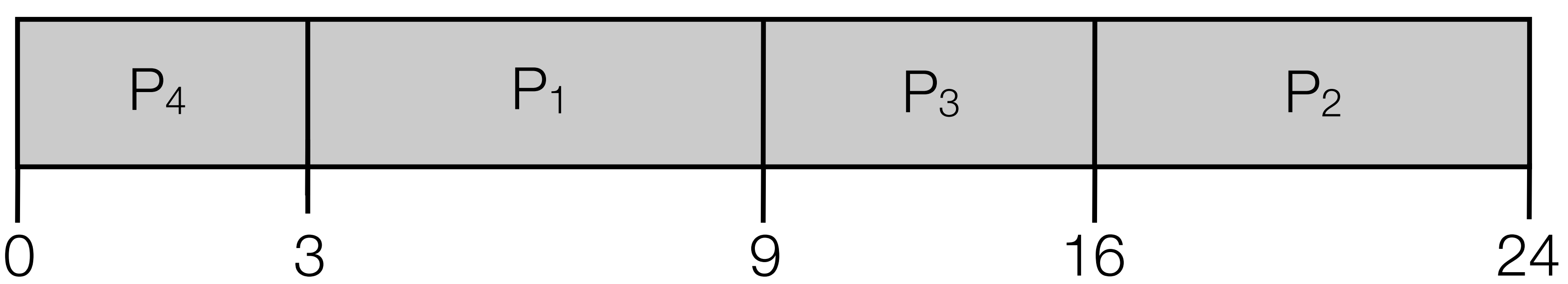
- **Associate with each process the length of its next CPU burst**
  - Use these lengths to schedule the process with the shortest burst time next
    - Note that the process is selected based on the length of its *next* CPU burst only, NOT the length of the entire process
  - If multiple processes have the same burst length, the tie is broken using FCFS

- **SJF is provably optimal – gives minimum average waiting time for a given set of processes (only when all jobs are available simultaneously)**
  - The difficulty is knowing the length of the next CPU request
    - Could ask the user
    - May be able to predict the length of the next CPU burst

# SJF Scheduling (Cont.)

- **Consider the following four processes that all arrive at time *t=0* in the order $P_1$, $P_2$, $P_3$, $P_4$**

| Process | Burst Time (ms) |
|---|---|
| $P_1$ | 6 |
| $P_2$ | 8 |
| $P_3$ | 7 |
| $P_4$ | 3 |




- **Average waiting time = (3 + 16 + 9 + 0) / 4 = 7 (provably minimal)**

# Determining Length of Next CPU Burst

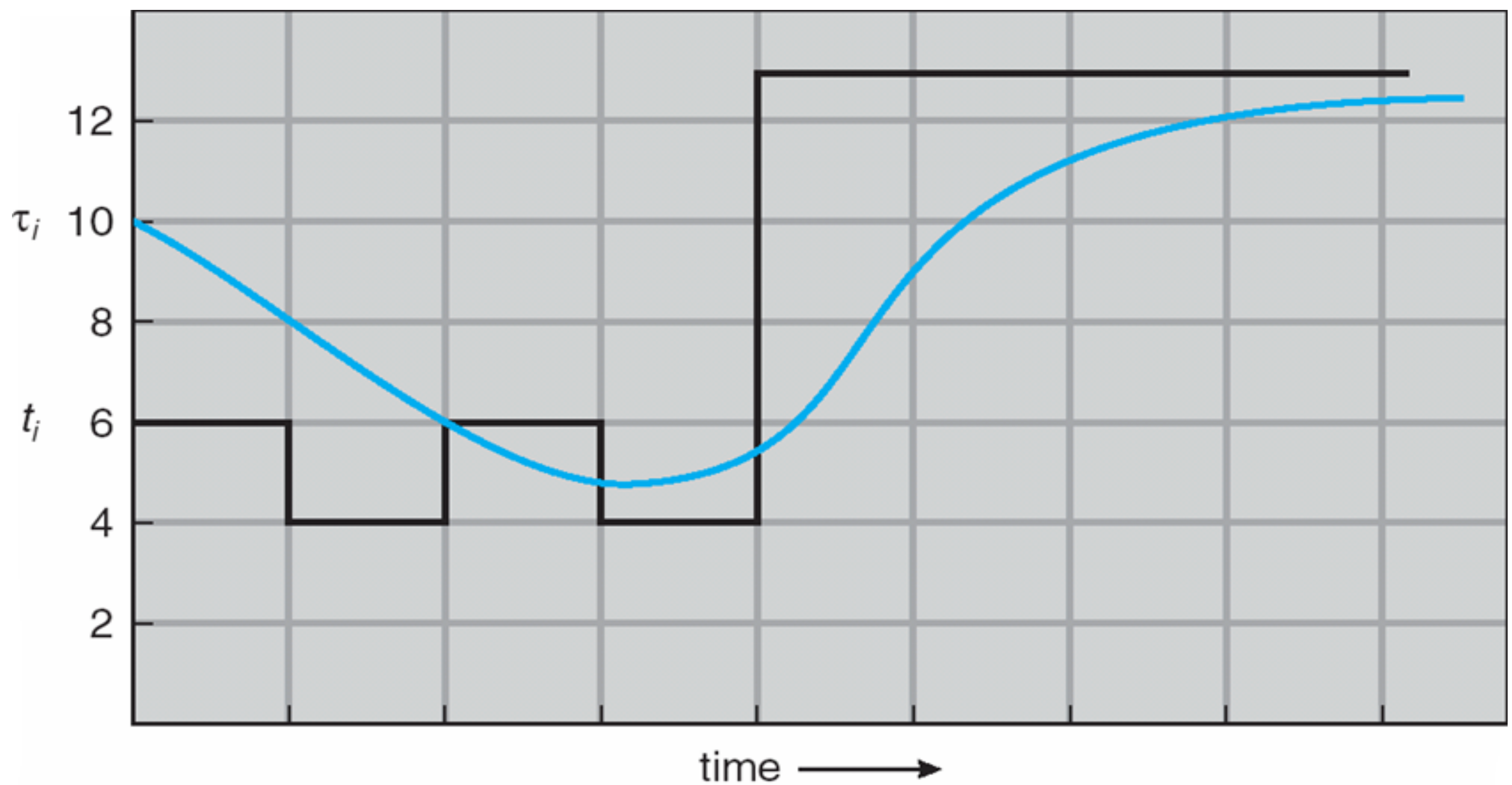
- **Can only estimate the length – should be similar to the previous one**
  - Then pick process with shortest predicted next CPU burst
- **Generally predicted as an exponential average of the measured lengths of previous CPU bursts**

$t_n$ = actual length of $n^{th}$ CPU burst
$\tau_{n+1}$ = predicted value for next CPU burst
$\alpha,\ 0 \le \alpha \le 1$
Define:

$$\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n$$

- **Commonly, $\alpha$ set to ½ -- determines the relative weight of recent and past history**
  - If $\alpha=0$, then recent history has no effect
  - If $\alpha=1$, then only the most recent CPU bursts matter

# Prediction of the Length of the Next CPU Burst




| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CPU burst ($t_i$) | | 6 | 4 | 6 | 4 | 13 | 13 | 13 | ... |
| "guess" ($\tau_i$) | 10 | 8 | 6 | 5 | 6 | 9 | 11 | 12 | ... |

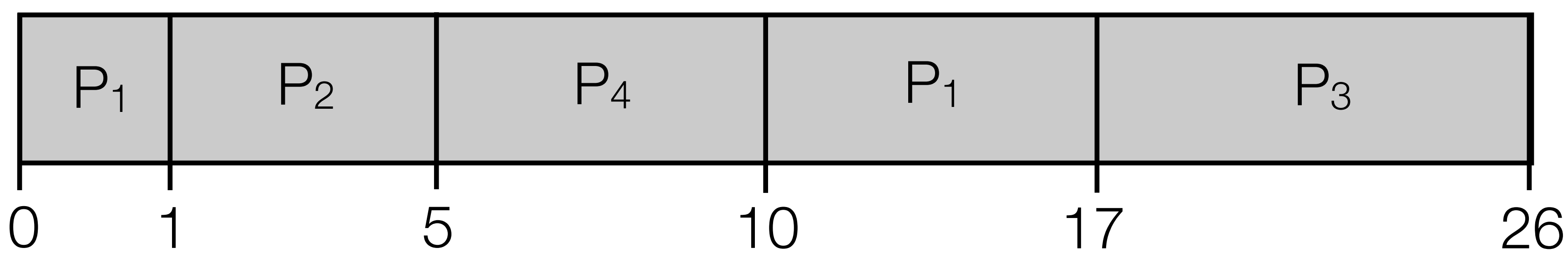
# SJF Scheduling

- **SJF scheduling can be either nonpreemptive or preemptive**
  - If a new process enters the ready-queue while a previous process is still executing, should the new process preempt the currently running process if its next CPU burst is shorter than the currently executing process?
    - A nonpreemptive version will allow the currently executing process to finish
    - A preemptive version will allow the new process with the shorter CPU burst to preempt the currently executing process
- **Preemptive version is typically called shortest-remaining-time-first**

# Example of Shortest-Remaining-Time-First

- **Consider the following four processes with the specified arrival times and burst times**

| Process | Arrival Time | Burst Time (ms) |
|---|---|---|
| $P_1$ | 0 | 8 |
| $P_2$ | 1 | 4 |
| $P_3$ | 2 | 9 |
| $P_4$ | 3 | 5 |




- **Average waiting time = [(10-1)+(1-1)+(17-2)+(5-3)] / 4 = 26/4 = 6.5 milliseconds**
  - $P_1$ arrived at *t=0* and ran immediately, then it waited from *t=1* to *t=10*;
    $P_2$ arrived at *t=1* and never waited;
    $P_3$ arrived at *t=2* and waited until *t=17* to run;
    $P_4$ arrived at *t=3* and ran at *t=5*

# Priority Scheduling

- **A priority number (integer) is associated with each process**

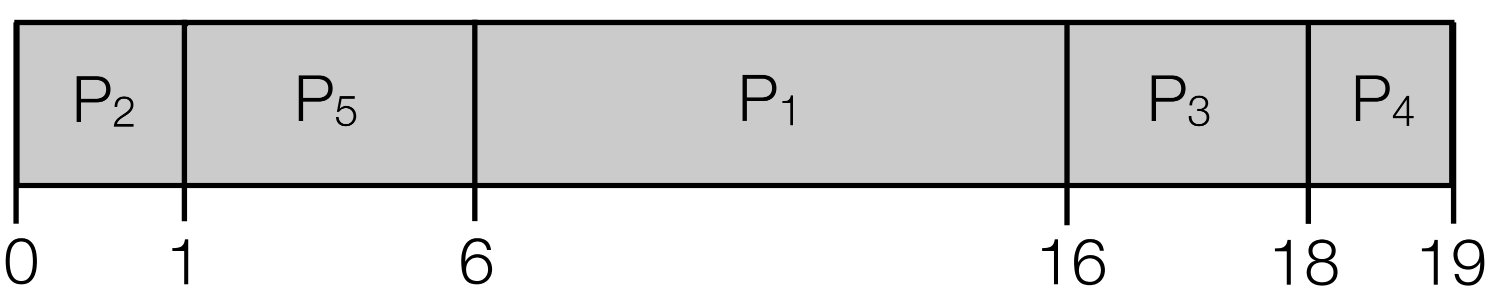
- **The CPU is allocated to the process with the highest priority (smallest integer usually the highest priority)**
  - Can be preemptive or nonpreemptive

- **SJF is a method of priority scheduling where the priority is the inverse of next predicted CPU burst time**

# Example of Priority Scheduling

- **Consider the following five processes that all arrive at time *t=0* in the order $P_1$, $P_2$, $P_3$, $P_4$, $P_5$ -- (nonpreemptive version)**

| Process | Burst Time (ms) | Priority |
|---|---|---|
| $P_1$ | 10 | 3 |
| $P_2$ | 1 | 1 |
| $P_3$ | 2 | 4 |
| $P_4$ | 1 | 5 |
| $P_5$ | 5 | 2 |




- **Average waiting time = (6 + 0 + 16 + 18 + 1) / 5 = 8.2 milliseconds**

# Priority Scheduling

- **One problem with priority scheduling is something called starvation**
  - A low-priority process never gets allocated the CPU because there are always higher priority processes in the ready-queue

- **One possible solution to the problem of starvation is called aging**
  - As time progresses the priority of a process increases
  - A low-priority process gradually becomes a higher priority process
  - The rate at which a process ages can be tuned

# Round Robin (RR) Scheduling

- **Each process gets a small unit of CPU time (called a time quantum or time slice), usually 10-100 milliseconds**
- **Processes are stored in the ready queue which is implemented as a simple FIFO**
- **When the CPU is available, it is allocated to the process at the head of the ready queue**
- **The process is run for some period of time (the time quantum) after which it is preempted by a timer, added back to the tail of the ready queue and the next process in the ready queue is dispatched**

# RR Scheduling (Cont.)

- **Designed especially for time-sharing systems**

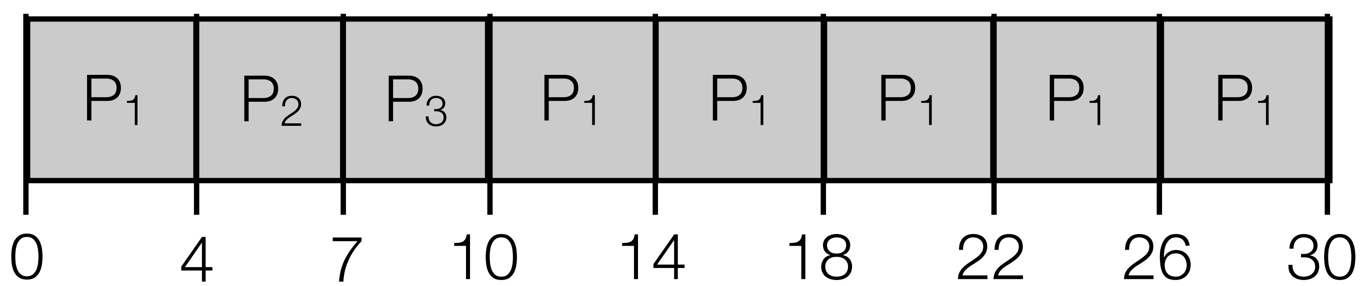
- **Similar to FCFS, but with preemption**
  - If time quantum is very large, then RR scheduling behaves identically to FCFS

- **If there are n processes in the ready queue and the time quantum is q, then each process gets 1/n of the CPU time in chunks of at most q time units at once.**
  - No process waits more than (n-1)*q time units between CPU bursts
  - No process is allocated the CPU for more than 1 time quantum in a row (unless it is the only runnable process)

# Example of RR with Time Quantum = 4

- **Consider the following three processes that all arrive at time *t=0* in the order $P_1$, $P_2$, $P_3$ -- the time quantum = 4 milliseconds**

| Process | Burst Time (ms) |
|---|---|
| $P_1$ | 24 |
| $P_2$ | 3 |
| $P_3$ | 3 |




- **Average waiting time = (6 + 4 + 7) / 3 = 5.67 milliseconds**

# Performance of RR Scheduling

- **Typically, higher average turnaround time than SJF, but better response**
  - Good response time makes it well-suited for time-sharing systems

- **Size of time quantum can dramatically impact the performance of RR scheduling**
  - If time quantum is too large, then RR starts to look like FCFS
  - If time quantum is too small and context switching occurs too often, then there is a high overhead for context switching

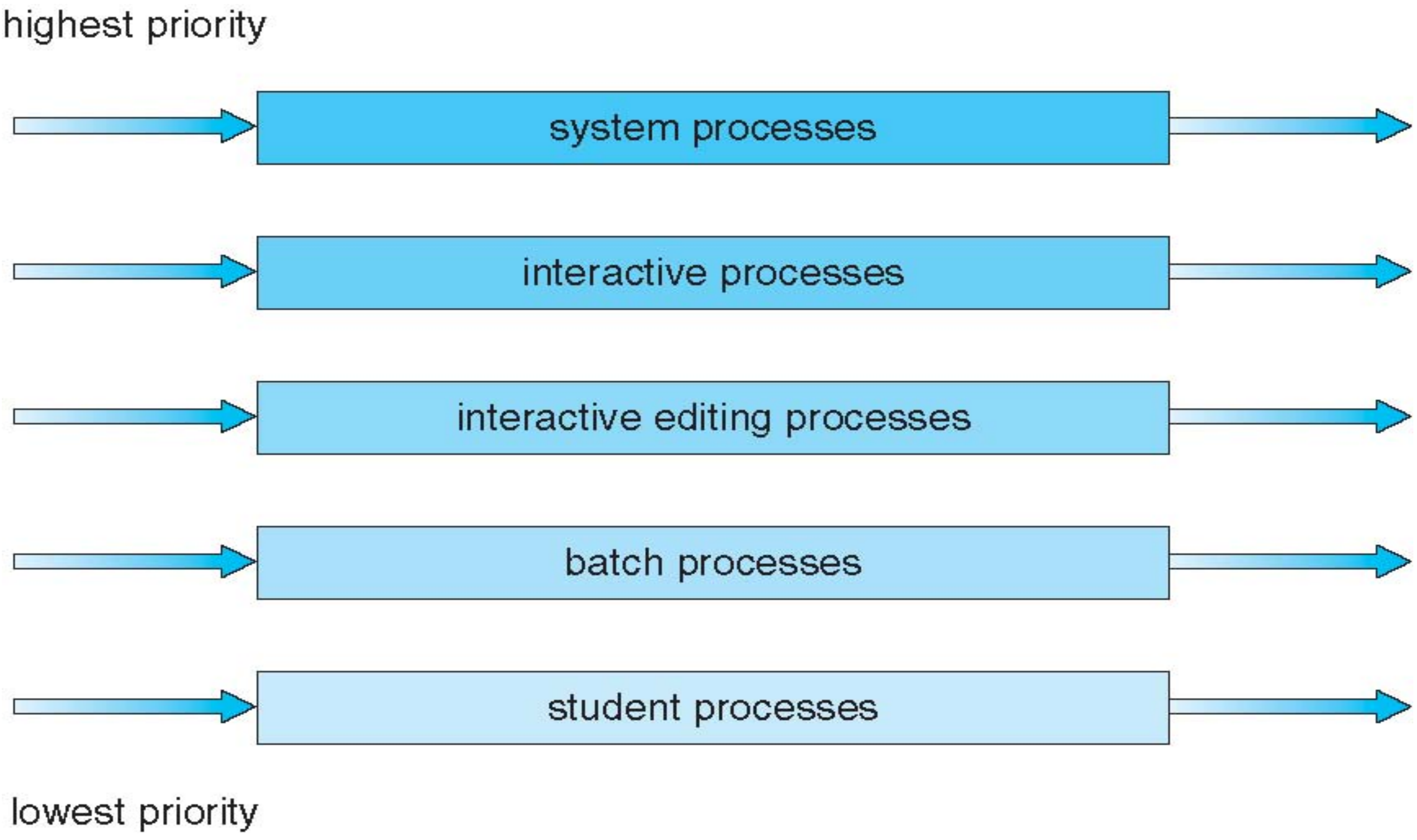
# Multilevel Queue Scheduling

- **Created for situations in which processes are easily classified into different groups (i.e. interactive processes / background processes)**
  - Different types of processes may have different scheduling requirements
- **Ready queue is partitioned into separate queues for different types of processes**
- **A process is permanently assigned to a specific queue**
- **Each queue has its own scheduling algorithm**
  - Interactive processes may be scheduled using RR scheduling
  - Background processes may be scheduled using FCFS scheduling

# Multilevel Queue Scheduling

- **Scheduling must also be done between the various queues**
  - One method uses fixed priority preemptive scheduling
    - Serve all processes from interactive process queue, then serve processes from the background process queue
      - Possibility of starvation for background processes
  - Another method assigns time slices to each queue
    - Each queue gets a certain amount of CPU time which it can schedule amongst its processes
      - 80% of time slice may go to interactive processes which are scheduled in RR fashion
      - 20% of time slice may go to background processes which are scheduled in FCFS fashion

# Multilevel Queue Scheduling



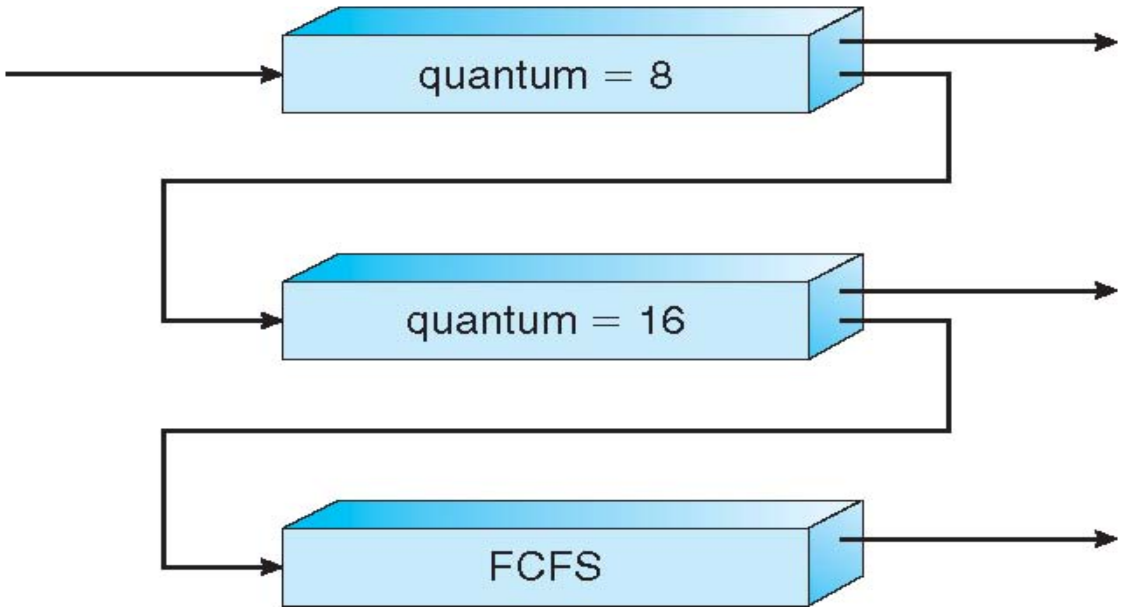
# Multilevel Feedback Queue Scheduling

- **Similar to Multilevel Queue Scheduling, but processes may move between the various queues**

- **Multilevel Feedback Queue scheduler defined by the following parameters:**
  - Number of queues
  - Scheduling algorithms for each queue
  - Method used to determine when to upgrade a process to a higher priority queue
  - Method used to determine when to demote a process to a lower priority queue
  - Method used to determine which queue a process will enter when that process needs service

# Example of Multilevel Feedback Queue Scheduling

- **Three queues:**
  - Q0 – RR with time quantum 8 milliseconds
  - Q1 – RR time quantum 16 milliseconds
  - Q2 – FCFS




- **Scheduling**
  - A new process enters queue Q0 which is served with RR scheduling
    - When it gains the CPU, the process receives 8 milliseconds
    - If it does not finish in 8 milliseconds, it is preempted and moved to queue Q1
  - At Q1 the process is again served with RR scheduling and receives 16 additional milliseconds (only if Q0 is empty)
    - If it still does not complete, it is preempted and moved to queue Q2
  - Once in Q2, a process is able to utilize whatever CPU cycles are left over from Q0 and Q1