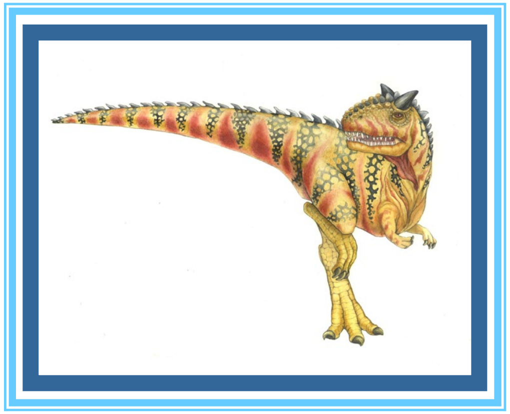
Chapter 6: CPU Scheduling



Chapter 6: CPU Scheduling

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples
- Algorithm Evaluation

Objectives

- To introduce CPU scheduling, which is the basis for multi-programmed operating systems, by switching the CPU among processes, the OS can make the computer more productive.
- To describe various CPU-scheduling algorithms
- To discuss evaluation criteria for selecting a CPU-scheduling algorithm for a particular system
- To examine the scheduling algorithms of several operating systems

Basic Concepts

- In a single-processor system, only one process can run at a time. Others must wait until the CPU is free.
- The objective of **multiprogramming** is to have some process running at all times, to **maximize CPU utilization**.
- The idea is relatively simple:
  - **A process is executed until it must wait for the completion of some I/O request.**
- One process has to wait, the OS takes the CPU away from that process and gives the CPU to another waiting process. This pattern continues is **multiprogramming**.
  - **This pattern continues.**
  - **Every time one process has to wait, another process can take over use of the CPU**.

Basic Concepts

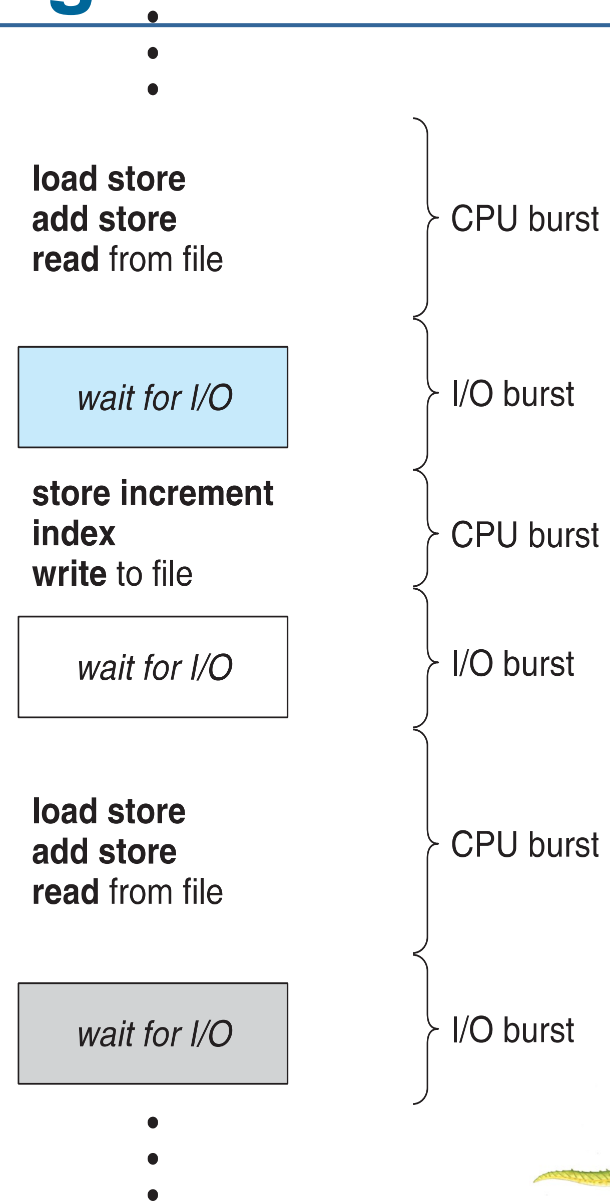
- **Scheduling** of this kind is a fundamental OS function.
- Almost all computer resources are **scheduled** before use.
- The **CPU** is, of course, one of the primary computer resources.
- Thus, **CPU scheduling** is central to an OS design.

CPU–I/O Burst

- The success of **CPU scheduling** depends on the following observed properties of processes:
  - A process **execution** consists of
    - (1) a **<u>cycle of CPU execution</u>** and
    - (2) **<u>I/O wait</u>.**
  - **Processes** alternate between these **two states**.
  - Process execution begins with a **CPU burst (means CPU involvement).**
- Process execution begins with a **CPU burst.** That is followed by an **I/O burst, which is followed by another CPU burst, then** another **I/O burst**, and so on.
- Eventually, the final CPU burst ends with a system request to **terminate execution** (**Figure 6.1**).

CPU–I/O Burst Figure 6.1

- **Maximum CPU utilization** obtained with multiprogramming
- **CPU–I/O Burst Cycle** – Process execution consists of a **cycle** of CPU execution and I/O wait
- **CPU burst** followed by **I/O burst**
- **CPU burst distribution** is of main concern



Process Scheduler

- To **schedule the CPU**, the **Process Scheduler** takes advantage of a common trait among most computer programs: they alternate between **CPU cycles** and **I/O cycles**:

```
{
printf("\nEnter the first integer: ");
scanf("%d", &a);
printf("\nEnter the second integer: ");
scanf("%d", &b);
```

I/O cycle

```
c = a+b
d = (a*b)-c
e = a-b
f = d/e
```

CPU cycle

```
printf("\n a+b= %d", c);
printf("\n (a*b)-c = %d", d);
printf("\n a-b = %d", e);
printf("\n d/e = %d", f);
}
```

I/O cycle

CPU–I/O Burst

- The durations of **CPU bursts** have been measured extensively.
  - Although a CPU burst vary from process to process and from computer to computer, it tends to have a **frequency curve** similar to that shown in **Figure 6.2.**
- The curve is generally characterized as *exponential* or *hyper-exponential*, with a large number of short CPU bursts and a small number of long CPU bursts.
  - An **I/O-bound program** typically has many *short CPU bursts*.
  - A **CPU-bound program** might have a few *long CPU bursts*.
  - This distribution can be important in the selection of an appropriate CPU-scheduling algorithm.

Histogram of CPU-burst Times Figure 6.2

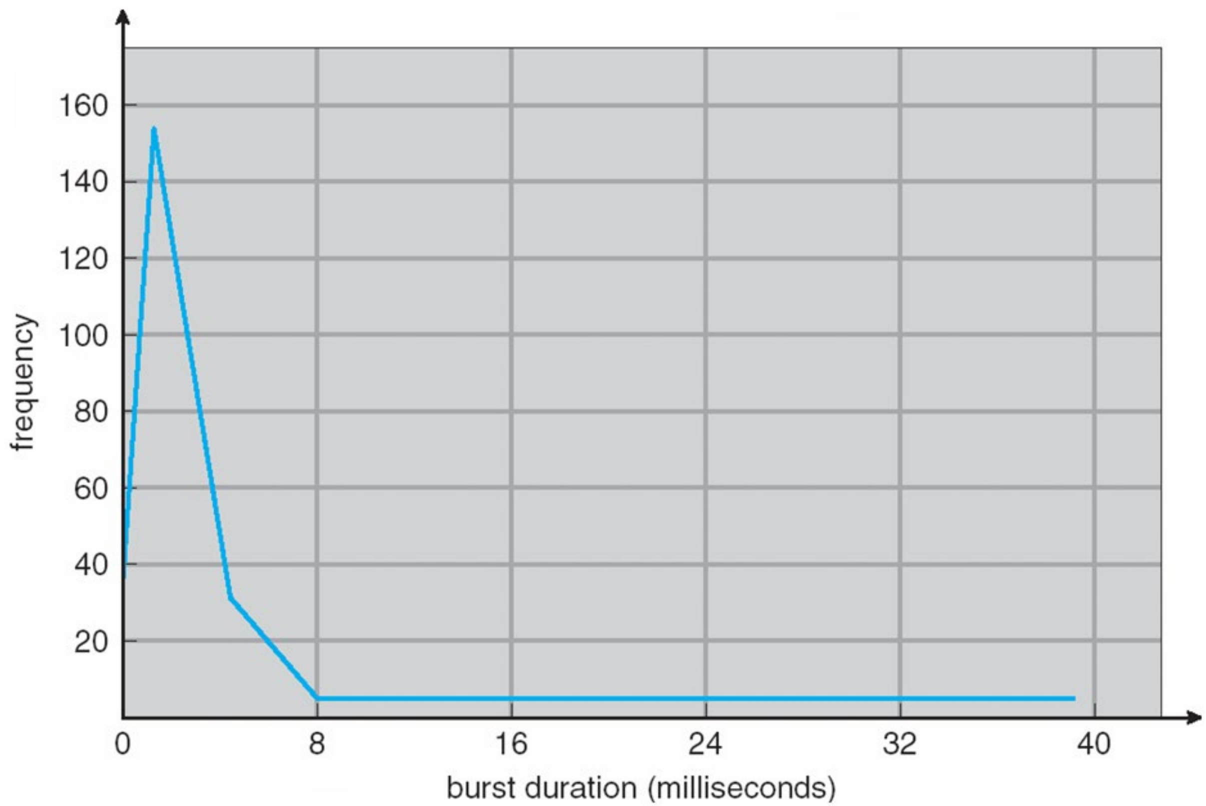


Figure 6.2.

CPU Scheduler

- Whenever the CPU becomes **idle** (*not working*), the OS must select one of the processes in the **ready queue** to be executed.
- The selection process is carried out by a **short-term scheduler** or **CPU scheduler.**
- The **short-term scheduler** selects from among the processes in **ready queue**, and allocates the CPU to one of them
  - **The scheduler selects a process** from the **ready queue** (processes in memory) that are ready to execute and allocates the CPU to that process.

CPU Scheduler

- **Short-term scheduler** selects the processes in **ready queue**, and then allocates the CPU to one of them
  - the **ready queue** is not necessarily a **first-in, first-out** (FIFO) queue
- **CPU scheduling decisions may take place when a process:**
  1. Switches from **running state** to **waiting state** (result of an I/O request)
  2. Switches from **running state** to **ready state** (when an interrupt occurs)
  3. Switches from **waiting state** to **ready state** (at completion of I/O)
  4. Terminates
- Scheduling under **1** and **4** is **non-preemptive**, there is no choice in terms of scheduling.
- This scheduling method was used by Microsoft **Windows 3.x.**

CPU Scheduler

- All other scheduling is **preemptive,** There is a choice, however, for situations **2** and **3**.
  - Consider access to **shared data**
  - Consider preemption while in **kernel mode**
  - Consider interrupts occurring during crucial OS activities
- **preemptive scheduling** can result in **race conditions** when data are shared among several processes:
  - Consider the case **of two processes that share data**. While one process is **updating** the data, it is **preempted** so that the second process can run. The second process then tries to read the data, which are in an **inconsistent state**.
- **Preemption also affects the design of the OS kernel**. During the processing of a **system call**, the **kernel** maybe busy with an activity on behalf of a process. Such activities may involve changing important kernel data (for instance, I/O queues).

CPU Scheduler

- **Windows 95** introduced **preemptive scheduling**, and all subsequent versions of Windows operating systems have used preemptive scheduling.
- The **Mac OS X** for the Macintosh also uses **preemptive scheduling**.

Dispatcher

- The **dispatcher** module gives control of the CPU to the process selected by the **short-term scheduler,** and this involves the following:
  - **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 process running

Scheduling Criteria

- Many criteria have been suggested for comparing **CPU-scheduling** algorithms. The criteria include the following:
- **CPU utilization** – keep the CPU as busy as possible (can range from 0 to 100 percent).
- **Throughput** – # of processes that complete their execution per time unit.
- **Turnaround time** – amount of time to execute a particular process (is the sum of the clock periods spent waiting to get into *memory*, waiting in the *ready queue*, *executing on the CPU*, and *doing I/O*).
- **Waiting time** – amount of time a process has been waiting in the **ready queue**
- **Response time** – amount of time it takes from when a request was submitted until the first response is produced–*is the time it takes to start responding.*

Scheduling Algorithm Optimization Criteria

The following are the **optimization criteria** of a CPU scheduling algorithm:

- **Max. CPU utilization**
- **Max. throughput**
- **Min. turnaround time**
- **Min. waiting time**
- **Min. response time**

Scheduling Algorithms

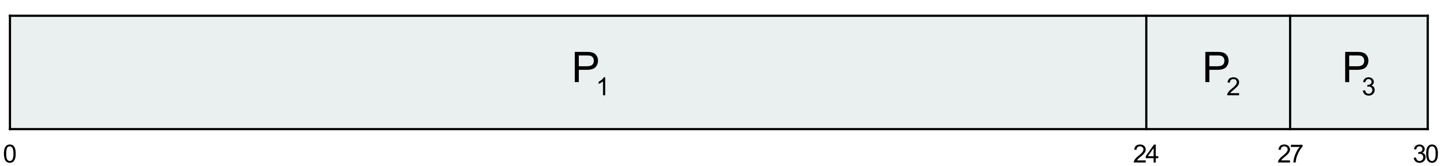
- **CPU scheduling** deals with the problem of deciding which of the processes in the **ready queue** is to be allocated the CPU.
- There are many different **CPU-scheduling algorithms**. This section describes the following:
  - **First-Come, First-Served Scheduling (FCFS)**
  - **Shortest-Job-First Scheduling (SJFS)**
  - **Priority Scheduling (PS)**
  - **Round-Robin Scheduling (RR)**
  - **Multilevel Queue Scheduling (MLQ)**
  - **Multilevel Feedback Queue Scheduling (MLFQ)**
  - **Thread Scheduling (TS)**

First- Come, First-Served (FCFS) Scheduling

Consider the following set of processes that arrive at time 0,with the length of the CPU burst given in milliseconds (ms):

Process	Burst Time(ms)
P_1	24
P_2	3
P_3	3

- Suppose that the **processes arrive in the order**: P_1 , P_2 , P_3
  The **Gantt Chart** for the schedule is:



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

FCFS Scheduling (Cont.)

Suppose that the processes arrive in the order:

$$P_2 , P_3 , P_1$$

- The Gantt chart for the schedule is:

- **Waiting time** for $P_1 = 6; P_2 = 0; P_3 = 3$
- **Average waiting time**: (6 + 0 + 3)/3 = 3 ms
- Much better than previous case
- **Convoy effect - short process** behind **long process** (in previous case)
  - Consider one CPU-bound and many I/O-bound processes
  - This effect results in lower CPU and device utilization

FCFS Scheduling (Cont.)

- The FCFS scheduling algorithm is a **non-preemptive** one.
- Once the CPU has been allocated to a process, that process keeps the CPU until it releases the CPU, either by terminating or by requesting I/O.
- The FCFS algorithm is thus particularly troublesome for **time-sharing** systems.

Shortest-Job-First (SJF) Scheduling

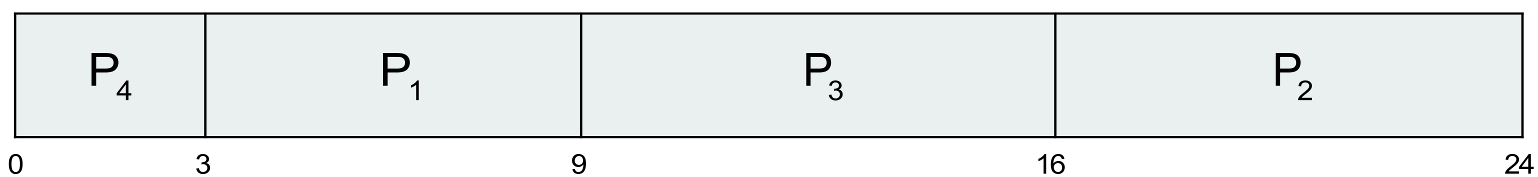
- In the **SJF algorithm** each process is associated with the length of its next CPU burst
  - Use these lengths to schedule the process with the **shortest time**
- **SJF is optimal** – it gives **minimum average waiting time** for a given set of processes
  - **The difficulty is knowing the length of the next CPU request**
  - **Could ask the user**

Example of SJF

Consider the following set of processes (in the ready queue) with the length of the CPU burst given in milliseconds:

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

- SJF scheduling chart



- **Waiting time** for P_4 = 0; P_1 = 3; P_3 = 9; P_2 = 16
- **Average waiting time** = (3 + 16 + 9 + 0) / 4 = 28/4 = 7 ms

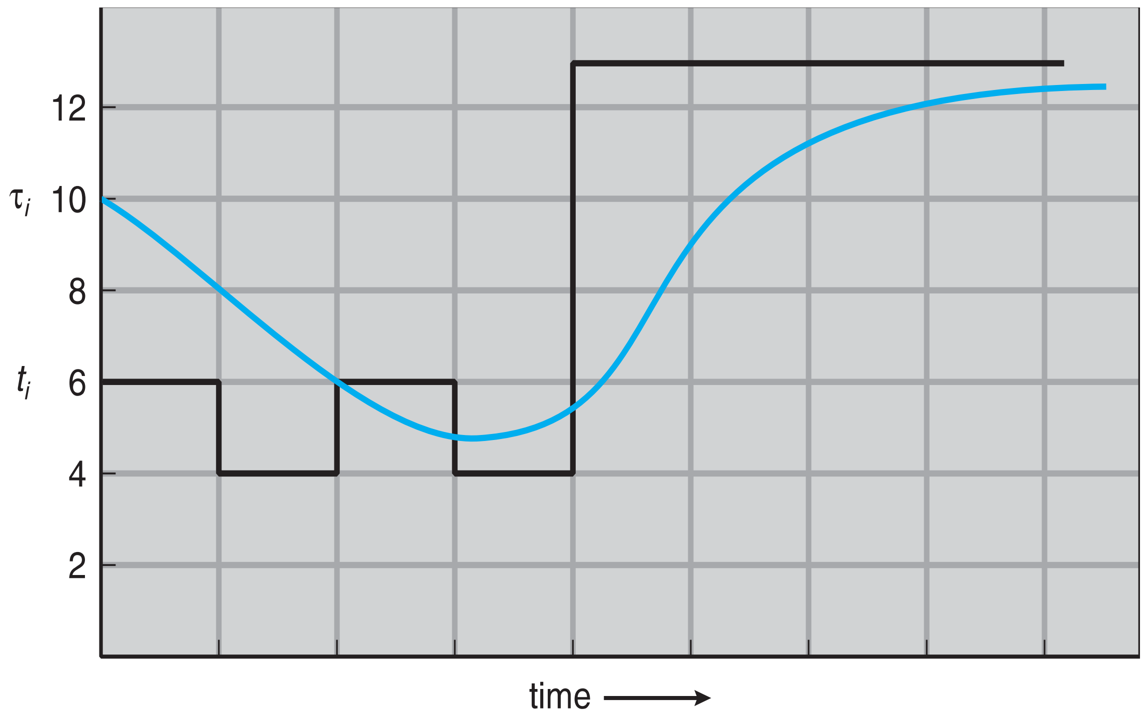
Determining Length of Next CPU Burst

- The real difficulty with the **SJF algorithm** is knowing **the length** of the next CPU request.
  - It can only estimate the length – should be similar to the previous one
  - Then pick process with **shortest predicted next CPU burst**
- Can be done by using the length of previous CPU bursts, using exponential averaging

1. $t_n =$ actual length of n^{th} CPU burst
2. $\tau_{n+1} =$ predicted value for the next CPU burst
3. $\alpha, 0 \le \alpha \le 1$ $\tau_{n=1} = \alpha\, t_n + (1-\alpha)\tau_n.$
4. Define :

- Commonly, α set to ½
- A **Preemptive SJF** algorithm is called **shortest-remaining-time-first (SRTF)**
- A **non-preemptive SJF** algorithm will allow the currently running process to finish its CPU burst.

Prediction of the Length of the Next CPU Burst



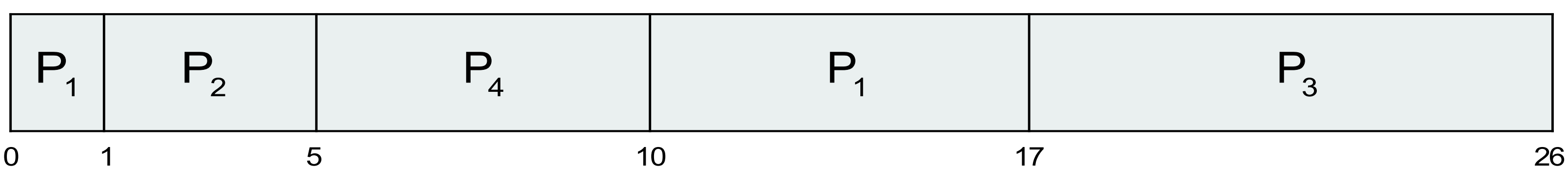
CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Shortest-remaining-time-first

- A **Preemptive** version **SJF** is called **shortest-remaining-time-first** (**SRTF**) algorithm
- Now we add the concepts of varying ***arrival times*** and ***preemption*** to the analysis

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

- ***Preemptive*** **SJF Gantt Chart**



- **Average waiting time** = [(10-1)+(1-1)+(17-2)+5-3)]/4 = 26/4 = 6.5 ms

Shortest-remaining-time-first

- Process *P1 is started at time 0, since it is the only process in the queue. Process P2 arrives at time 1. The remaining time for process P1 (7 ms) is* larger than the time required by process *P2 (4 ms), so process P1 is* preempted, and process *P2 is scheduled. The average waiting time for this* example is

  [(10 − 1) + (1 − 1) + (17 − 2) + (5 − 3)]/4 = 26/4 = 6.5 ms.

  P1 = final-start – initial start = 10 -1 = 9 ms

  P2 = start – arrival = 1-1 = 0 ms

  P3 = start – arrival = 17-2 = 15 ms

  P4 = start – arrival = 5-3 = 2 ms

  Total time /4 = (9 + 0 + 15 + 2)/4 = 26/4 = 6.5 ms

- **Non-preemptive SJF** scheduling would result in an average waiting time of 7.75 ms

Priority Scheduling

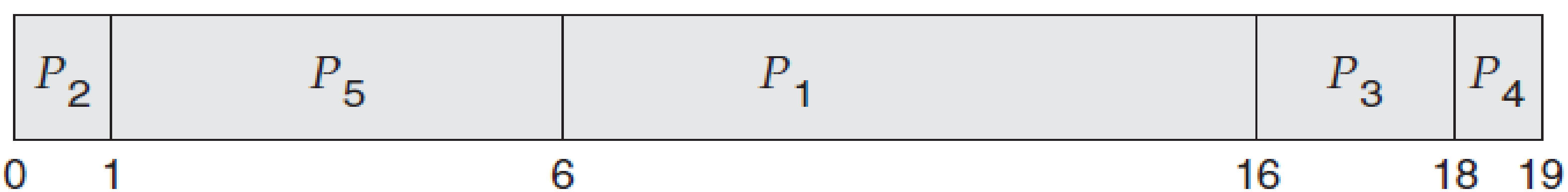
- A **priority number** (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (**smallest integer represents highest priority**)
  - **Preemptive**
  - **Non-preemptive**
- **Equal-priority processes** are scheduled in FCFS order
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time
- **<u>Problem</u>** ≡ **Starvation** – low priority processes may never execute
- **<u>Solution</u>** is **Aging** – as time progresses increase the priority of the process

Example of Priority Scheduling

Consider the following set of processes, assumed to have arrived at time 0 in the order *P1, P2, · · ·, P5, with the length of the CPU burst* given in ms:

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

- Priority scheduling Gantt Chart



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

Round Robin (RR) Scheduling

- The **round-robin (RR) scheduling algorithm** is designed especially for **timesharing** systems. It is similar to **FCFS** scheduling, but **preemption** is added to enable the system to switch between processes.
- *Each process gets a small unit of CPU time* (**time quantum *q***), usually 10-100 milliseconds. After this time has elapsed, the process is **preempted** and added to the end of the **ready queue**.
  - The **ready queue** is treated as a circular queue
- 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.
- **Timer interrupts** every quantum to schedule next process
- **Performance**
  - ***q* large** $\Rightarrow$ **FIFO**
  - ***q* small** $\Rightarrow$ *q* must be large with respect to context switch, otherwise overhead is too high

Round Robin (RR) Scheduling

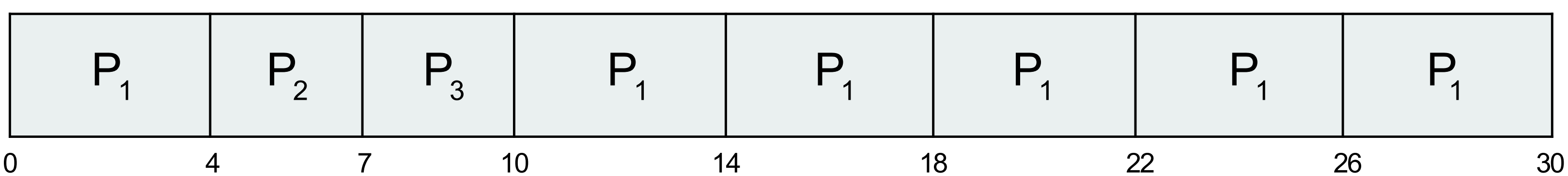
- The **ready queue** is treated as a **circular queue**. The *CPU scheduler* goes around the **ready queue**, allocating the CPU to each process for a time interval of up to **1 time quantum**.
- New processes are added to the tail of the **ready queue**. The *CPU scheduler* picks the first process from the **ready queue**, sets a timer to interrupt after **1 time quantum**, and **dispatches** the process.
- If the process have a CPU burst of **less than 1 time quantum**, then the process itself will release the CPU voluntarily. The scheduler will then proceed to the next process in the **ready queue**.
- If the CPU burst of the currently running process is **longer than 1 time quantum**, the timer will go off and will cause an interrupt to the operating system.
  - A context switch will be executed, and the process will be put at the tail of the **ready queue**. The CPU scheduler will then select the next process in the ready queue.

Example of RR with Time Quantum = 4

Consider the following **set of processes that arrive at time 0**, with the length of the CPU burst given in ms (and the **time quantum** is 4 ms):

Process	Burst Time (ms)
P_1	24
P_2	3
P_3	3

- The Gantt chart is:



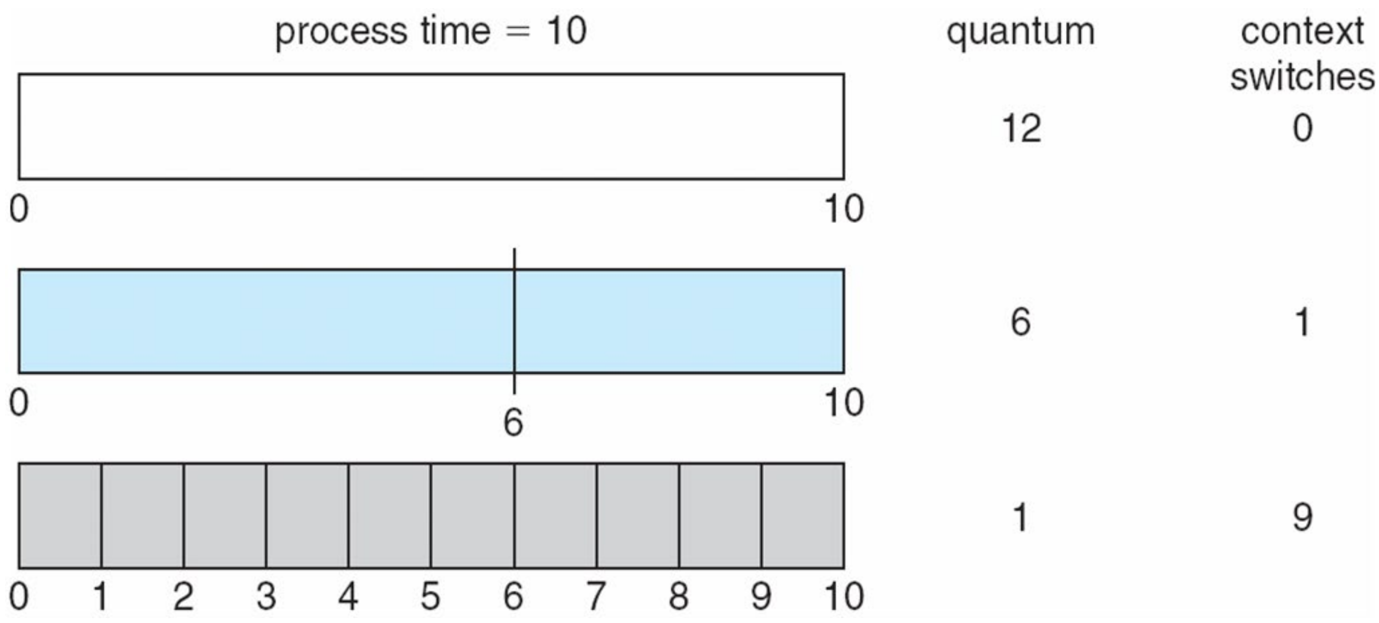
Let’s calculate the **average waiting time** for this schedule. P1 waits for 6 ms (10 - 4), P2 waits for 4 ms, and *P*3 *waits for* 7ms

- Thus, the **average waiting time** is (6+4+7)/3 = 17/3 = 5.66ms

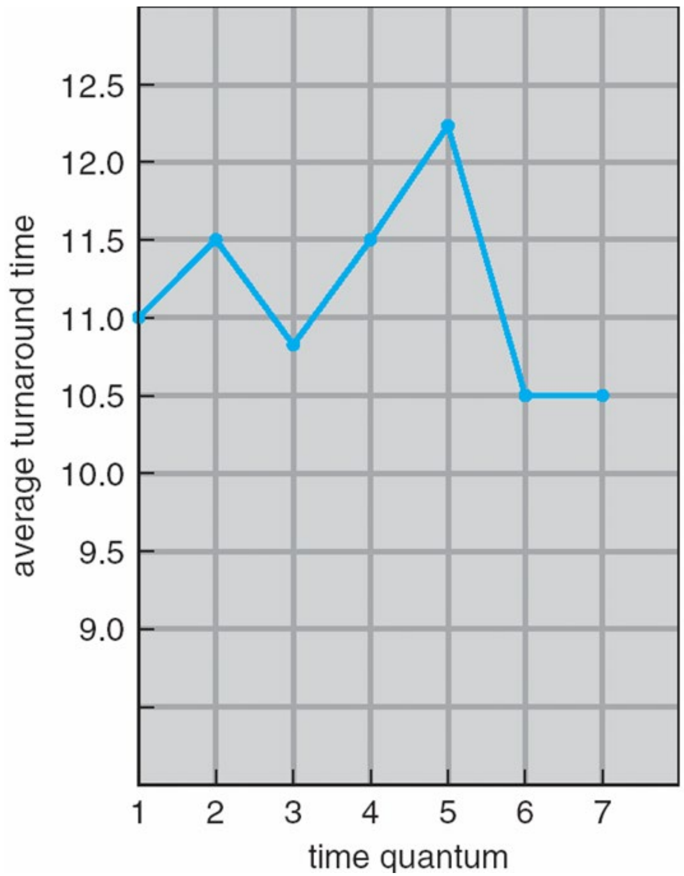
Example of RR with Time Quantum = 4

- If we use a time **quantum of 4 milliseconds**, then process *P1 gets the first 4* ms.
- Since it requires another 20 milliseconds, it is preempted after the first time quantum, and the CPU is given to the next process in the queue, process *P2. Process P2 does not need 4 milliseconds, so it quits before its time* quantum expires.
- The CPU is then given to the next process, process *P3. Once* each process has received 1 time quantum, the CPU is returned to process *P1* for an additional time quantum.
- Typically, higher average turnaround than SJF, but better ***response***
- The **time quantum, q should be large compared to context switch time**
  - **q** usually 10ms to 100ms, context switch < 10 μsec

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

80% of CPU bursts
should be shorter than q

Multilevel Queue

- The **Ready queue** is partitioned into separate queues, eg:
  - **foreground** (interactive) processes
  - **background** (batch) processes
- **foreground processes** may have higher priority (externally defined) over **background processes**.
- Each queue has its own scheduling algorithm:
  - **foreground – RR**
  - **background – FCFS**
- Scheduling must be done between the queues:
  - **Fixed priority scheduling**; (i.e., serve all from foreground then from background). Possibility of starvation.
  - **Time slice** – each queue gets a certain amount of CPU time which it can schedule amongst its processes; i.e., 80% to foreground in RR
  - 20% to background in FCFS

Multilevel Queue Scheduling

- A **multilevel queue scheduling algorithm** partitions the **ready queue** into several separate queues (**Figure 6.6**).
- The processes are permanently assigned to one queue, generally based on some property of the process, such as *memory size*, *process priority*, or *process type*.
- Each queue has its own **scheduling algorithm**. For example, separate queues might be used for **foreground** and **background** processes.
- The **foreground queue** might be scheduled by an **RR algorithm**, while the **background queue** is scheduled by an **FCFS algorithm**.
- The **foreground queue** may have absolute priority over the **background queue.**

Multilevel Queue Scheduling

- Let's look at an example of a **multilevel queue scheduling algorithm** with **five queues, listed below in their order of priority**:
  1. **System processes**
  2. **Interactive processes**
  3. **Interactive editing processes**
  4. **Batch processes**
  5. **Student processes**
- Each queue has absolute priority over lower-priority queues.
- No process in the batch queue, for example, could run unless the queues for system processes, interactive processes, and interactive editing processes were all empty.
- If an interactive editing process entered the ready queue while a batch process was running, the batch process would be preempted.

Multilevel Queue Scheduling

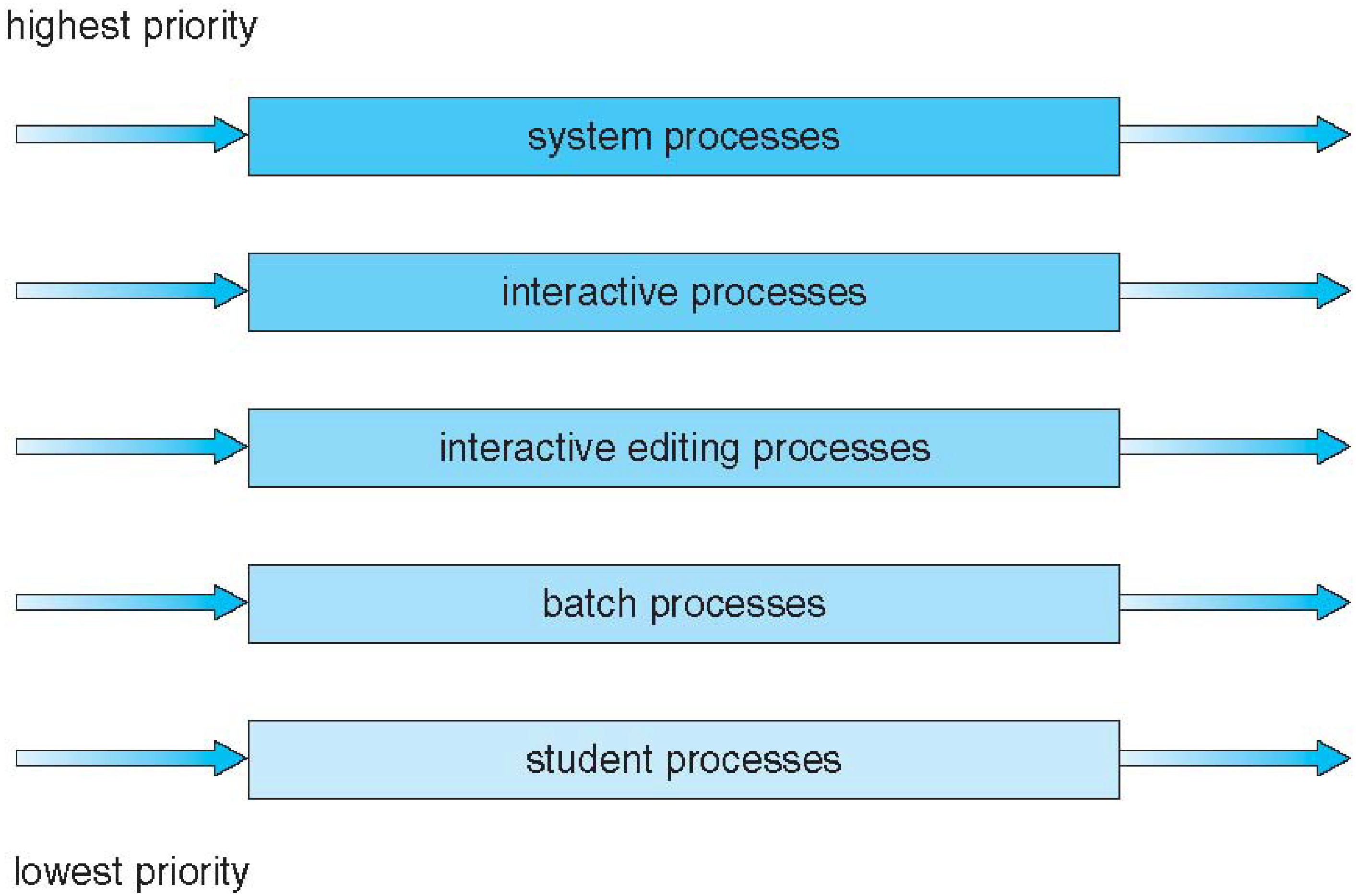


Figure 6.6 Multilevel queue scheduling.

Thread Scheduling

- We have seen the distinction between **user-level** and **kernel-level** threads
- As per operating systems **the kernel-level threads**—not processes—that are being scheduled by the operating system.
- **User-level threads** are managed by a **thread library**, and the kernel is unaware of them. To run on a CPU, **user-level threads** must ultimately be mapped to an associated **kernel-level thread**, although this mapping may be indirect and may use a **lightweight process (LWP)**.
- **Thread library schedules user-level threads to run on LWP**
  - Known as **process-contention scope (PCS)** since scheduling competition is within the process
  - Typically done via priority set by programmer
- **Kernel thread** scheduled onto available CPU is **system-contention scope (SCS)** – competition among all threads in system

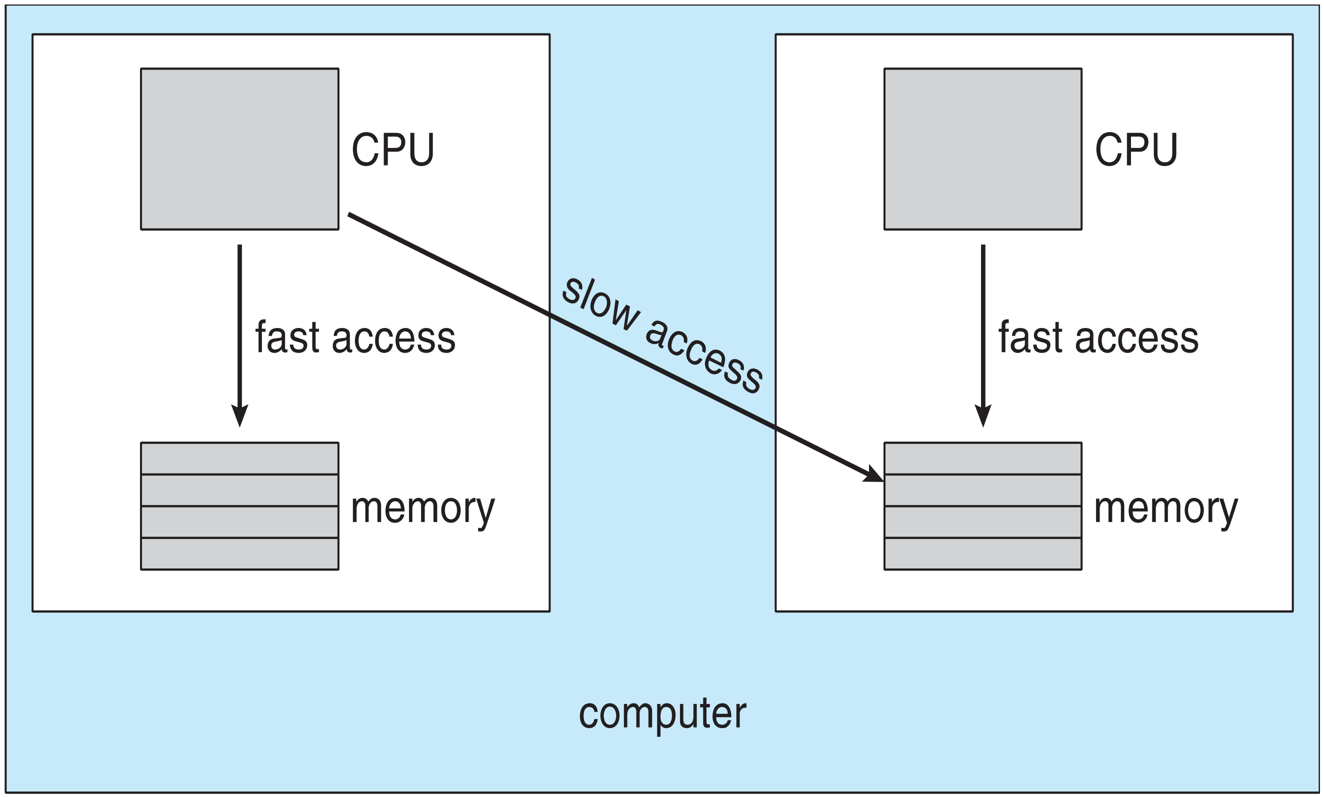
Thread Scheduling

- When we say the ***thread library*** schedules **user threads** onto available **LWP**s, we do not mean that the threads are actually running on a CPU.
- That would require the OS to schedule the **kernel thread** onto a physical CPU. To decide which **kernel-level thread** to schedule onto a CPU, the kernel uses **system-contention scope (SCS).**
- Typically, **process-contention scope (PCS)** is done according to priority—the scheduler selects the runnable thread with the highest priority to run.
- **User-level thread** priorities are set by the programmer and are not adjusted by the **thread library**, although some thread libraries may allow the programmer to change the priority of a thread.
- It is important to note that **PCS** will typically preempt the thread currently running in favor of a **higher-priority thread**.

Multiple-Processor Scheduling

- **CPU scheduling** more complex when multiple CPUs are available
- <u>**Multi-core system:**</u> **Homogeneous processors** within a **multiprocessor**
- **Asymmetric multiprocessing** – only one processor (master) accesses the system data structures, alleviating the need for data sharing
- **Symmetric multiprocessing (SMP)** – each processor is self-scheduling, all processes in **common ready queue**, or each has its own private queue of ready processes
  - Currently, most common
- **Processor affinity** (liking) – process has affinity for processor on which it is currently running
  - **soft affinity**
  - **hard affinity**
  - Variations including **processor sets**

NUMA and CPU Scheduling



Note that memory-placement algorithms can also consider affinity (NUMA → Non Uniform Memory Access)

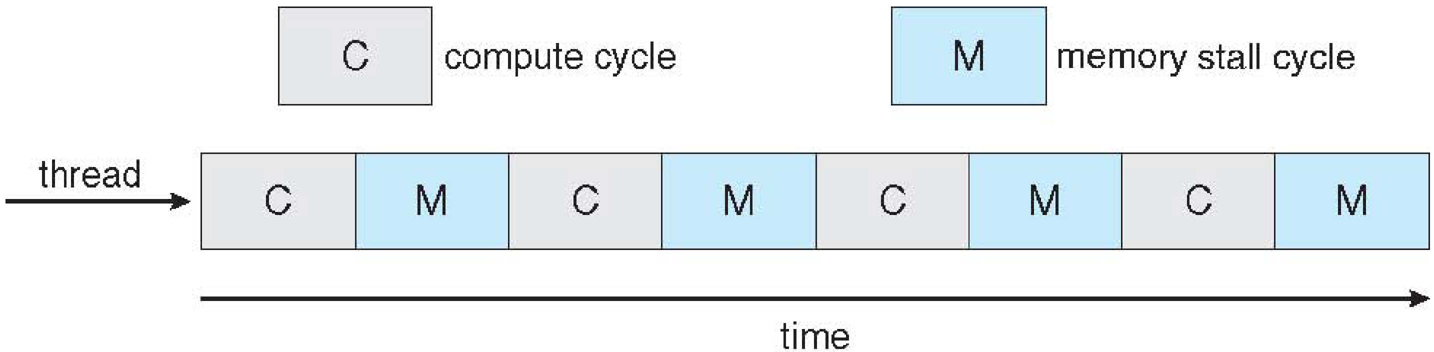
Multiple-Processor Scheduling – Load Balancing

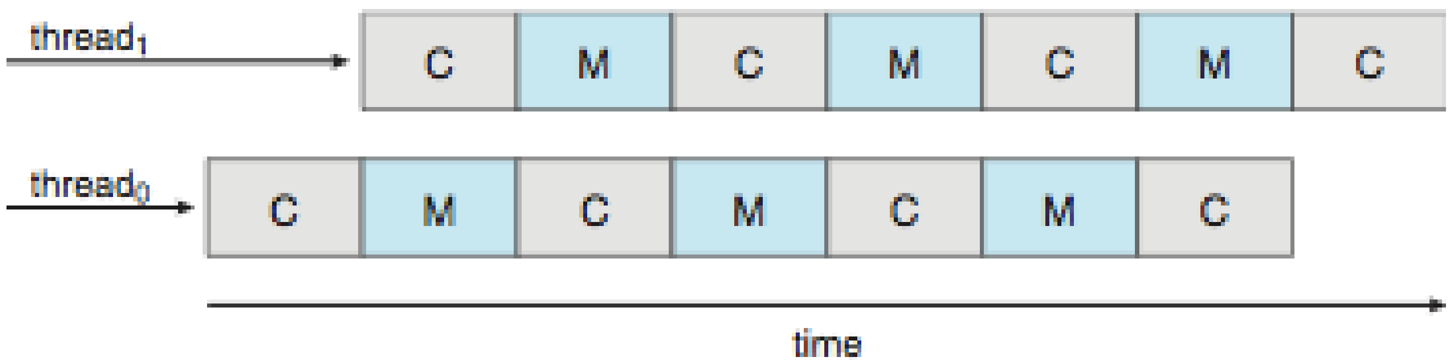
- If SMP, need to keep all CPUs loaded for efficiency
- **Load balancing** attempts to keep workload evenly distributed
- **Push migration** – periodic task checks load on each processor, and if found pushes task from overloaded CPU to other CPUs
- **Pull migration** – idle processors pulls waiting task from busy processor

Multicore Processors

- Recent trend to place **multiple processor cores** on same physical chip
- Faster and consumes less power
- **Multiple threads** per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

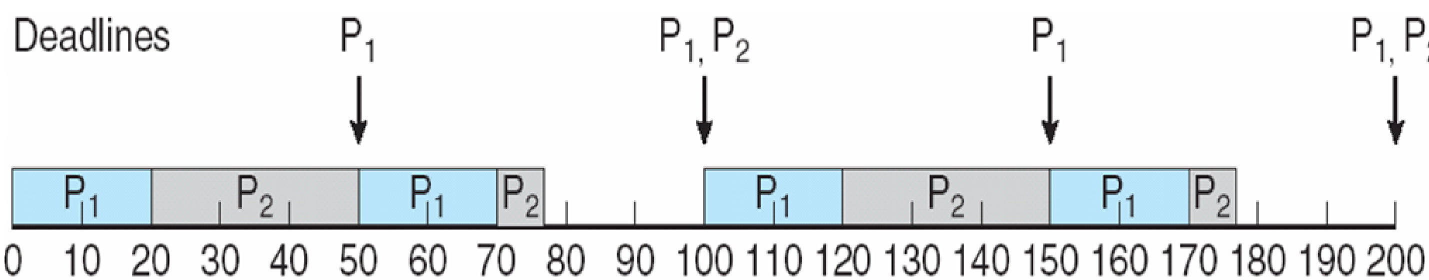
Multithreaded Multicore System



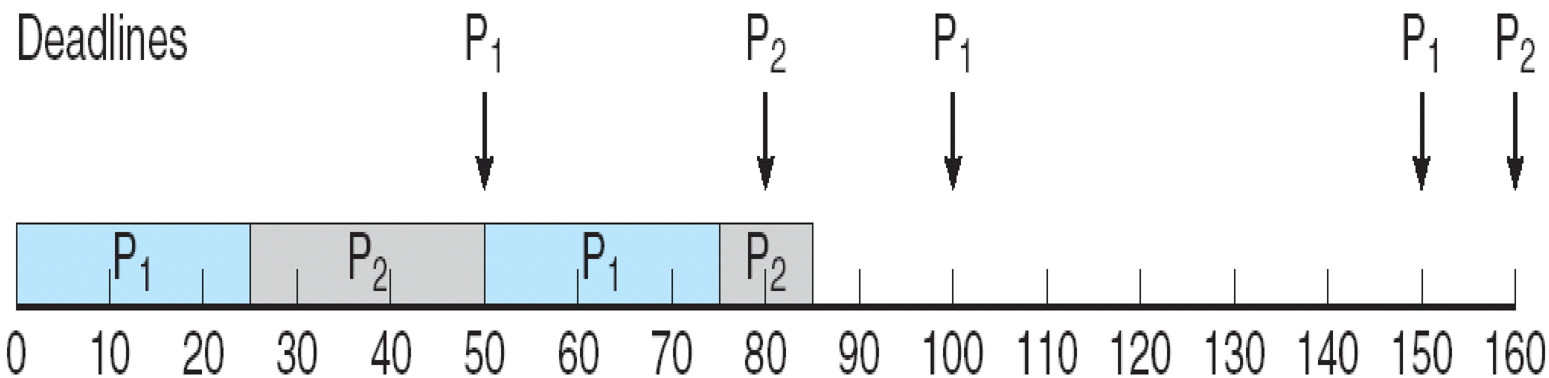


Rate Montonic Scheduling

- A priority is assigned based on the inverse of its period
- Shorter periods = higher priority;
- Longer periods = lower priority
- P_1 is assigned a higher priority than P_2.



Missed Deadlines with Rate Monotonic Scheduling

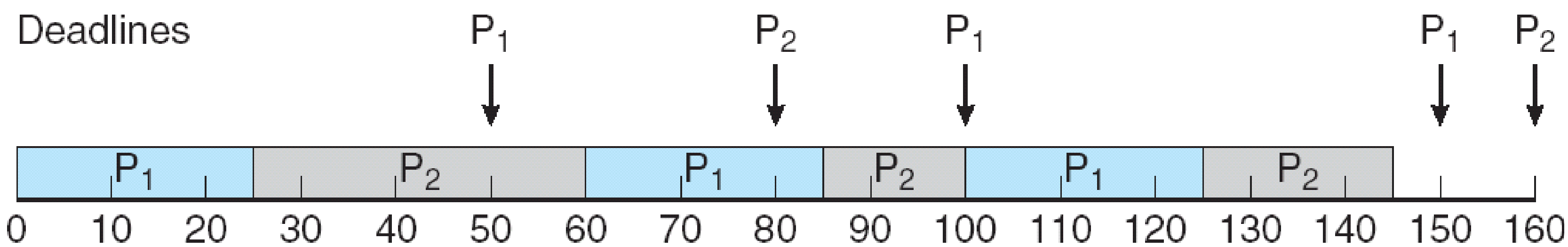


Earliest Deadline First Scheduling (EDF)

- Priorities are assigned according to deadlines:

  the earlier the deadline, the higher the priority;

  the later the deadline, the lower the priority



Scheduling in Operating Systems

- Linux scheduling
- Windows scheduling
- Solaris scheduling

Linux Scheduling Through Version 2.5

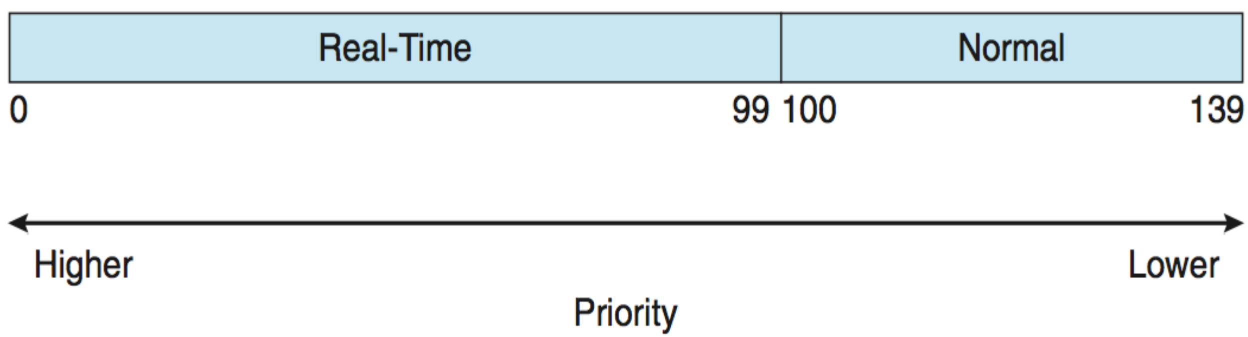
- Prior to kernel version 2.5, ran variation of standard UNIX scheduling algorithm
- Version 2.5 moved to constant order *O*(1) scheduling time
  - Preemptive, priority based
  - Two priority ranges: time-sharing and real-time
  - **Real-time** range from 0 to 99 and **nice** value from 100 to 140
  - Map into global priority with numerically lower values indicating higher priority
  - Higher priority gets larger q
  - Task run-able as long as time left in time slice (**active**)
  - If no time left (**expired**), not run-able until all other tasks use their slices
  - All run-able tasks tracked in per-CPU **runqueue** data structure
    - Two priority arrays (active, expired)
    - Tasks indexed by priority
    - When no more active, arrays are exchanged
  - Worked well, but poor response times for interactive processes

Linux Scheduling in Version 2.6.23 +

- ***Completely Fair Scheduler*** (CFS)
- **Scheduling classes**
  - Each has specific priority
  - Scheduler picks highest priority task in highest scheduling class
  - Rather than quantum based on fixed time allotments, based on proportion of CPU time
  - 2 scheduling classes included, others can be added: **default** and **real-time**
- Quantum calculated based on **nice value** from -20 to +19
  - Lower value is higher priority
  - Calculates **target latency** – interval of time during which task should run at least once
  - Target latency can increase if say number of active tasks increases
- CFS scheduler maintains per task **virtual run time** in variable **`vruntime`**
  - Associated with decay factor based on priority of task – lower priority is higher decay rate and Normal default priority yields virtual run time = actual run time
- To decide next task to run, scheduler picks task with lowest virtual run time

Linux Scheduling (Cont.)

- Real-time scheduling according to POSIX.1b
  - Real-time tasks have static priorities
- Real-time plus normal map into global priority scheme
- Nice value of -20 maps to global priority 100
- Nice value of +19 maps to priority 139



Windows Scheduling

- Windows uses priority-based preemptive scheduling
- Highest-priority thread runs next
- **Dispatcher** is scheduler
- Thread runs until (1) blocks, (2) uses time slice, (3) preempted by higher-priority thread
- Real-time threads can preempt non-real-time
- 32-level priority scheme
- **Variable class** is 1-15, **real-time class** is 16-31
- Priority 0 is memory-management thread
- Queue for each priority
- If no run-able thread, runs **idle thread**

Windows Priority Classes

- **Win32 API** identifies several priority classes to which a process can belong
  - REALTIME_PRIORITY_CLASS, HIGH_PRIORITY_CLASS, ABOVE_NORMAL_PRIORITY_CLASS,NORMAL_PRIORITY_CLASS, BELOW_NORMAL_PRIORITY_CLASS, IDLE_PRIORITY_CLASS
  - All are variable except REALTIME
- A thread within a given priority class has a relative priority
  - TIME_CRITICAL, HIGHEST, ABOVE_NORMAL, NORMAL, BELOW_NORMAL, LOWEST, IDLE
- Priority class and relative priority combine to give numeric priority
- Base priority is NORMAL within the class
- If quantum expires, priority lowered, but never below base

Windows Priority Classes (Cont.)

- If wait occurs, priority boosted depending on what was waited for
- Foreground window given 3x priority boost
- Windows 7 added **user-mode scheduling** (**UMS**)
  - Applications create and manage threads independent of kernel
  - For large number of threads, much more efficient
  - UMS schedulers come from programming language libraries like C++ **Concurrent Runtime** (ConcRT) framework

Windows Priorities

	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

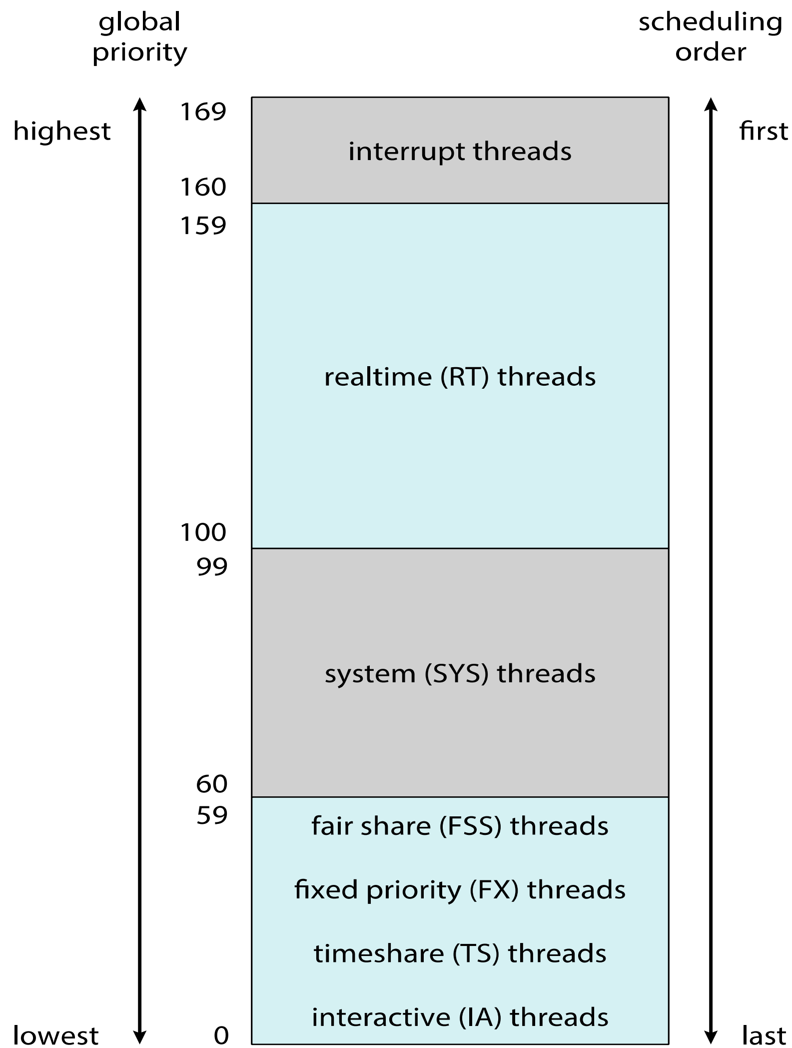
Solaris

- Priority-based scheduling
- Six classes available
  - **Time sharing (default) (TS)**
  - **Interactive (IA)**
  - **Real time (RT)**
  - **System (SYS)**
  - **Fair Share (FSS)**
  - **Fixed priority (FP)**
- Given thread can be in one class at a time
- Each class has its own scheduling algorithm
- Time sharing is multi-level feedback queue
  - Loadable table configurable by sys.admin

Solaris Dispatch Table

priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Solaris Scheduling



Solaris Scheduling (Cont.)

- Scheduler converts class-specific priorities into a per-thread global priority
  - Thread with highest priority runs next
  - Runs until (1) blocks, (2) uses time slice, (3) preempted by higher-priority thread
  - Multiple threads at same priority selected via RR

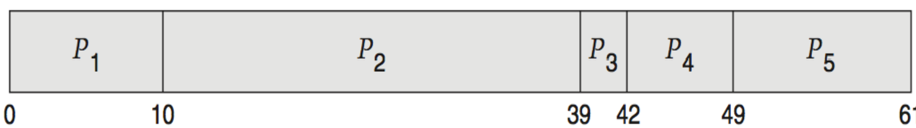
Algorithm Evaluation

- How to select CPU-scheduling algorithm for an OS?
- Determine criteria, then evaluate algorithms
- **Deterministic modeling**
  - Type of **analytic evaluation**
  - Takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Consider 5 processes arriving at time 0:

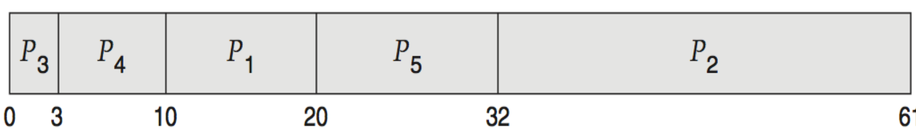
Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

Deterministic Evaluation

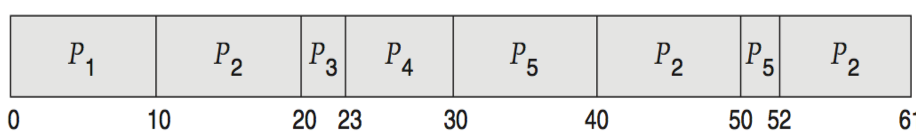
- For each algorithm, calculate minimum average waiting time
- Simple and fast, but requires exact numbers for input, applies only to those inputs
  - FCS is 28ms:



  - Non-preemptive SFJ is 13ms:



  - RR is 23ms:



Queueing Models

- Describes the arrival of processes, and CPU and I/O bursts probabilistically
  - Commonly exponential, and described by mean
  - Computes average throughput, utilization, waiting time, etc
- Computer system described as network of servers, each with queue of waiting processes
  - Knowing arrival rates and service rates
  - Computes utilization, average queue length, average wait time, etc

Little's Formula

- n = average queue length
- W = average waiting time in queue
- λ = average arrival rate into queue
- Little's law – in steady state, processes leaving queue must equal processes arriving, thus:

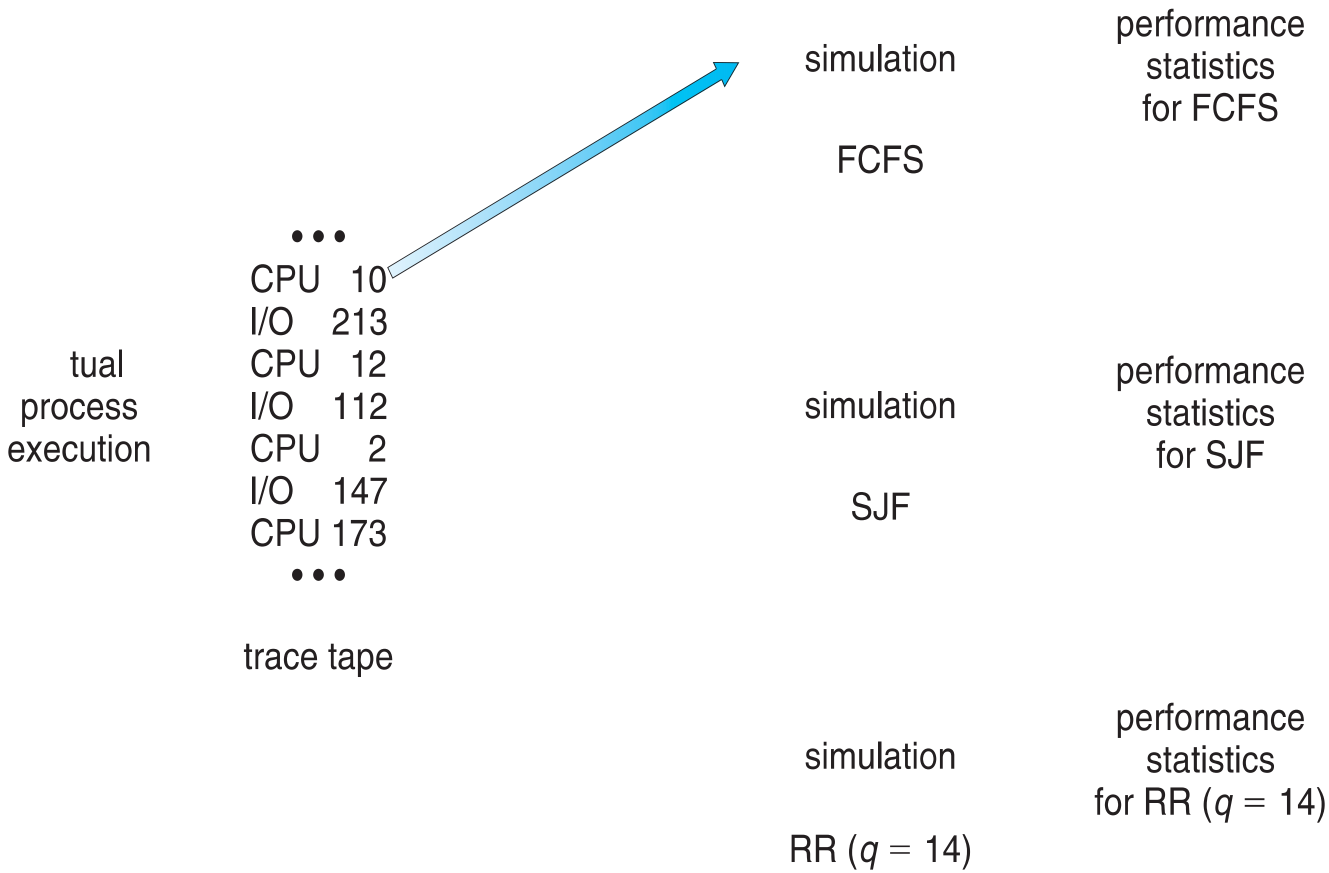
  $$n = \lambda \times W$$

  - Valid for any scheduling algorithm and arrival distribution
- For example, if on average 7 processes arrive per second, and normally 14 processes in queue, then average wait time per process = 2 seconds

Simulations

- Queueing models limited
- **Simulations** more accurate
  - Programmed model of computer system
  - Clock is a variable
  - Gather statistics indicating algorithm performance
  - Data to drive simulation gathered via
    - Random number generator according to probabilities
    - Distributions defined mathematically or empirically
    - Trace tapes record sequences of real events in real systems

Evaluation of CPU Schedulers by Simulation



Implementation

- Even simulations have limited accuracy
- Just implement new scheduler and test in real systems
  - High cost, high risk
  - Environments vary
- Most flexible schedulers can be modified per-site or per-system
- Or APIs to modify priorities
- But again environments vary

End of Chapter 6