Chapter 5: CPU Scheduling

Chapter 5: Outline

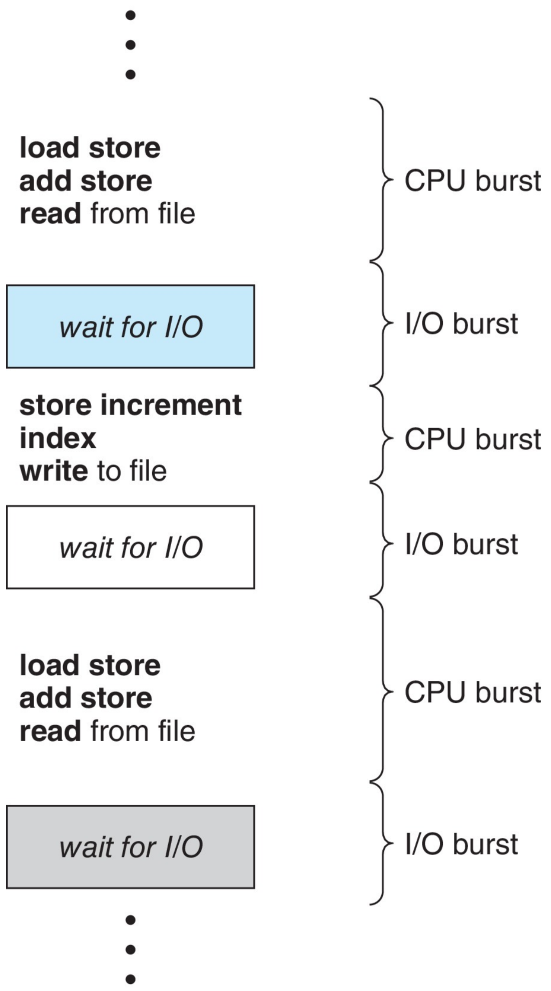
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multi-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples
- Algorithm Evaluation

Objectives

- Describe various *CPU scheduling algorithms*
- Assess CPU scheduling algorithms based on *scheduling criteria*
- Explain the issues related to *multiprocessor and multicore scheduling*
- Describe various *real-time scheduling algorithms*
- Describe the scheduling algorithms used in the **Windows**, **Linux**, and **Solaris** operating systems
- Apply *modeling* and *simulations* to evaluate CPU scheduling algorithms
- *Design a program* that implements several different CPU scheduling algorithms

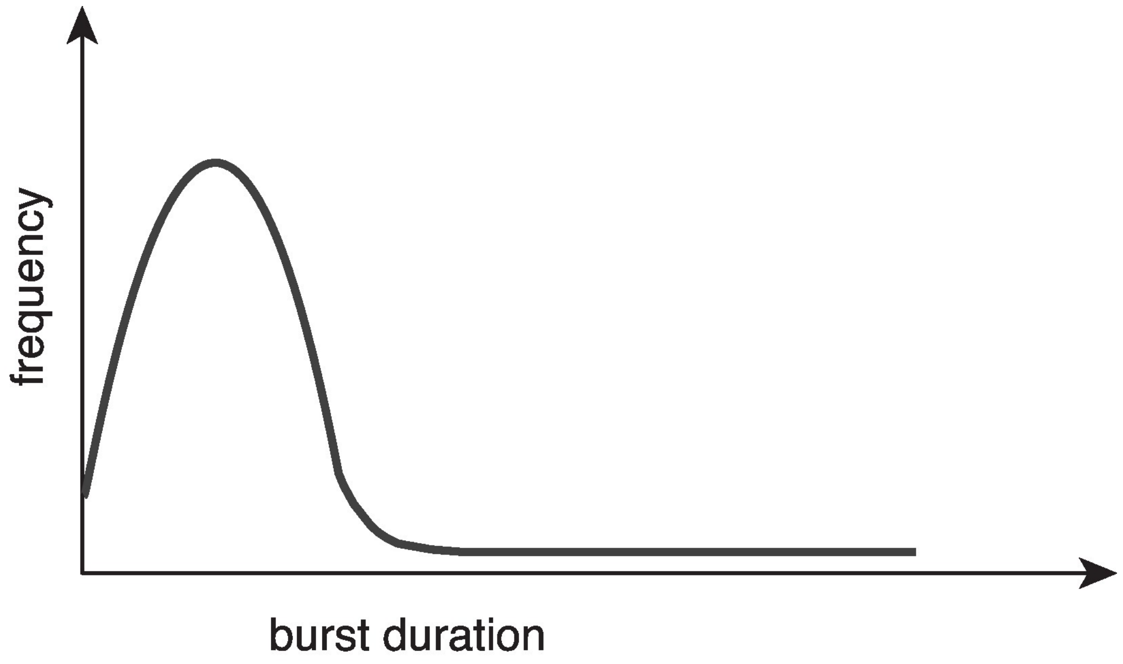
Basic Concepts

- Almost all computer resources are *scheduled* before use
- 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



Histogram of CPU-burst Times

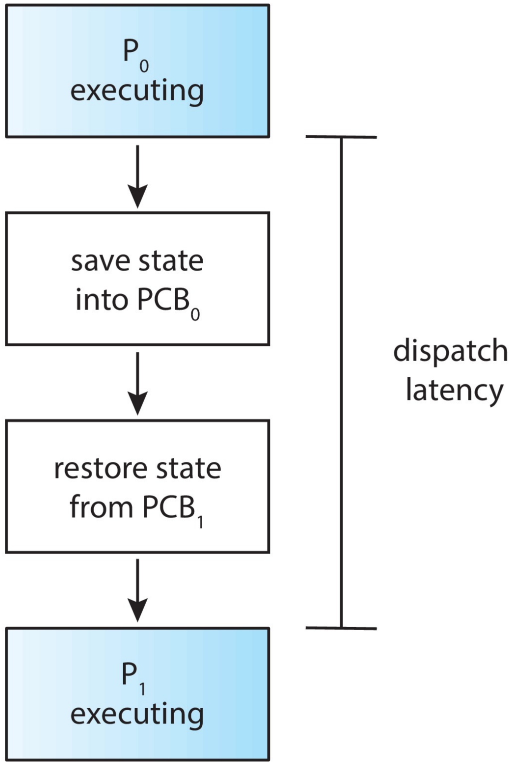
- Generally, frequency curve shows
  - Large number of *short bursts*
  - Small number of *longer bursts*



CPU Scheduler

- The *CPU scheduler* selects one process from among the processes in *ready queue*, and allocates the CPU core to it
  - Queue may be ordered in various ways: FIFO, priority, tree, linked list
- *CPU scheduling decisions* may take place when a process:
  1. switches from *running* to *waiting* state
  2. switches from *running* to *ready* state
  3. switches from *waiting* to *ready*
  4. terminates
- Scheduling under **1** and **4** is *non-preemptive*
  - No choice in terms of scheduling
- All other scheduling is *preemptive*, and can result in *race conditions*
  - Consider access to shared data
  - Consider preemption while in kernel mode
  - Consider interrupts occurring during crucial OS activities

Dispatcher



- **Dispatcher module** gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - switching context
    - The number of context switches can be obtained by using the **`#vmstat`** command or the **`/proc`** file system for a given process
  - switching to user mode
  - jumping to the proper location in the user program to resume that program
- **Dispatch latency** – time it takes for the dispatcher to stop one process and start another running

#vmstat

Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – number of processes that complete their execution per time unit

TAT = Waiting time + CPU burst

- **Turnaround time** – amount of time to execute a particular process
- **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 outputting the response (for time-sharing environment or in an interactive system)

#top

Scheduling Algorithm Optimization Criteria

- Max *CPU utilization*
- Max *Throughput*
- Min *Turnaround time*
- Min *Waiting time*
- Min *Response time*

- In most cases, it is necessary to *optimize the average measure*
- For interactive systems (such as a PC desktop or laptop system), it is more important to *minimize the variance* in the response time

Note: *For next examples of the comparison of various CPU-scheduling algorithms*

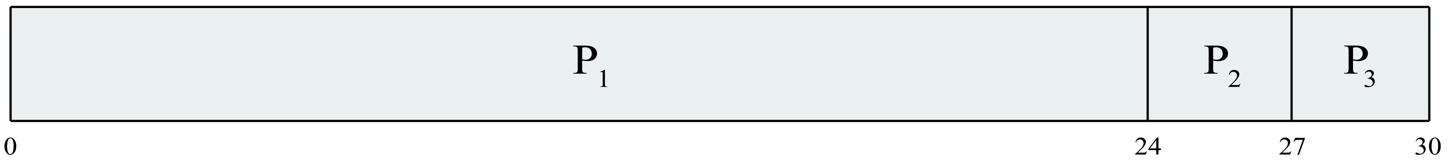
- Consider only *one CPU burst* (in milliseconds) per process
- The measure of comparison: **average waiting time**

First-Come, First-Served (FCFS) Scheduling

- **Motivation**: for simplicity, consider FIFO-like policy

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

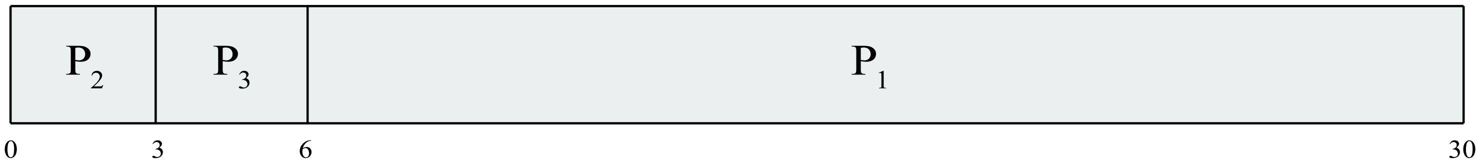
- Suppose that the processes arrive at time *0* in the order: P_1 , P_2 , P_3
- The *Gantt Chart* for the schedule is:



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

FCFS Scheduling (Cont.)

- Suppose that the processes arrive in the order: *P2 , P3 , P1*
- The *Gantt chart* for the schedule is:



  - Waiting time for *P1 = 6; P2 = 0; P3 = 3*
  - **Average waiting time** = *(6 + 0 + 3)/3 = 3*
  - Much better than previous case
- **Convoy effect** – short processes behind a long process, all the other processes wait for the one big process to get off the CPU
  - Consider one *CPU-bound* and *many I/O-bound* processes
  - Result in *lower* CPU and device utilization

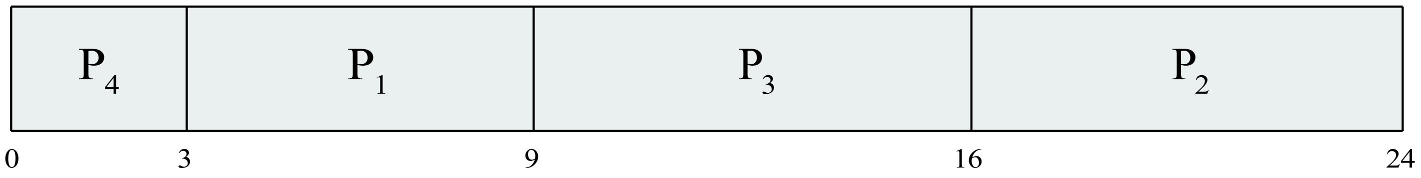
Shortest-Job-First (SJF) Scheduling

- **Motivation**: Moving a short process before a long one decreases the waiting time of the short process more than it increases the waiting time of the long process
  - The *shortest-next-CPU-burst* algorithm
- Associate with each process *the length of its next CPU burst*
  - When the CPU is available, it is assigned to the process that has the *smallest next CPU burst*
  - *FCFS scheduling* is used if the next CPU bursts of two processes are the same
- SJF is provably *optimal* – gives minimum average waiting time for a given set of processes
  - The difficulty is how to know the *length of the next CPU request*
  - Could ask the user

Example of SJF scheduling

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

- SJF scheduling *Gantt chart*



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

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
- Can be done by using *exponential averaging* of the measured lengths of previous CPU bursts as follows

  $\alpha \in [0,1]$

  τ_n: predicted value for the next CPU burst

  t_n: actual length of nth CPU burst

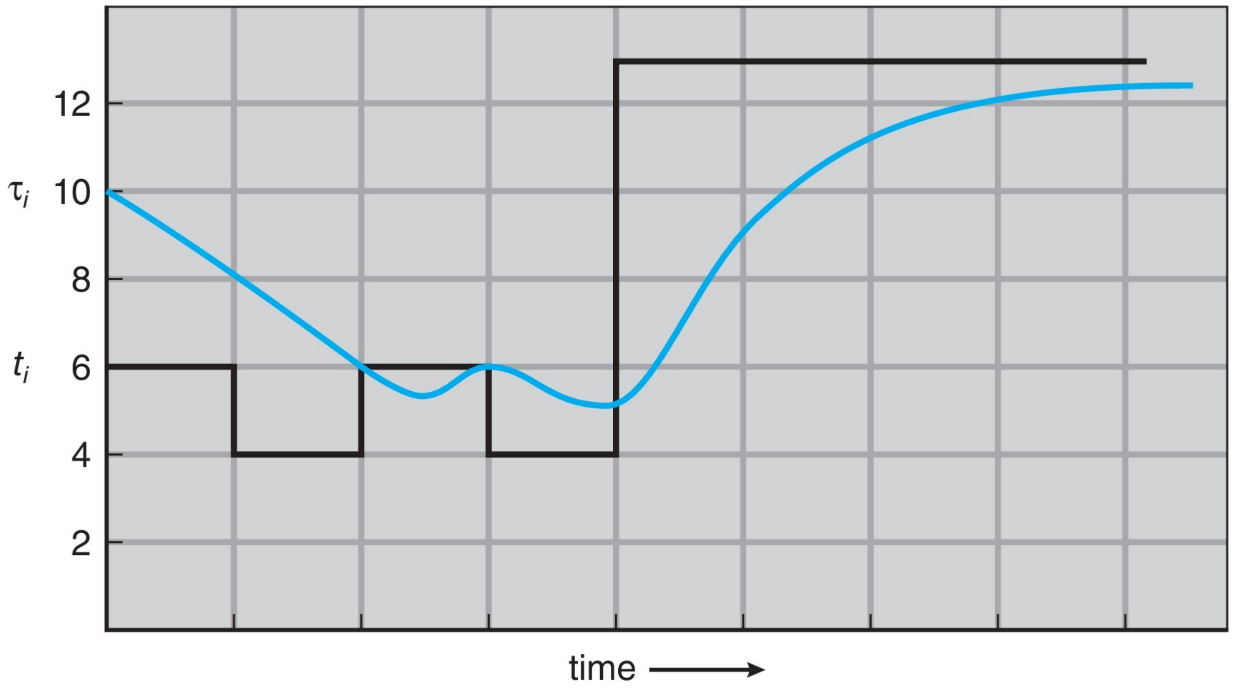
  $$\tau_{n+1} = \alpha . t_n + (1 - \alpha)\,\tau_n$$

- Commonly, *α* controls the relative weight of recent and past history in the prediction and *sets to ½*
- *Preemptive* version called *Shortest-Remaining-Time-First* (SRTF)

- A preemptive SJF algorithm will preempt the currently executing process,
- whereas a non- preemptive SJF algorithm will allow the currently running process to finish its CPU burst.
- Preemptive SJF scheduling is sometimes called **shortest-remaining-time-firs** scheduling.

Prediction of the Length of the Next CPU Burst

- An exponential average with $\alpha = 1/2$ and $\tau_0 = 10$



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

Examples of Exponential Averaging

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- $\alpha = 1$
  - $\tau_{n+1} = t_n$
  - Only the actual last CPU burst counts
- If we expand the formula, we get:

$$\tau_{n+1} = \alpha t_n + (1 - \alpha)\alpha t_{n-1} + \dots$$
$$+ (1 - \alpha)^j \alpha t_{n-j} + \dots$$
$$+ (1 - \alpha)^{n+1} \tau_0.$$

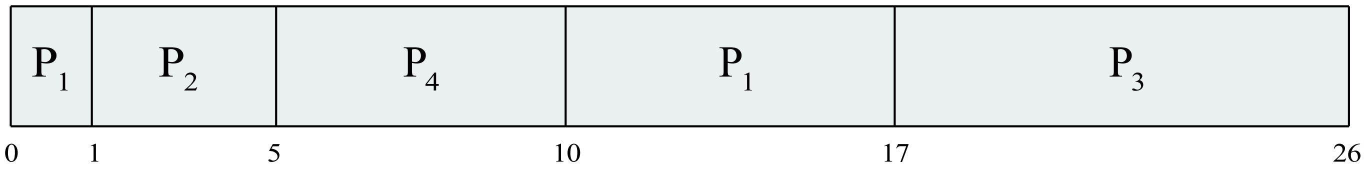
- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

Shortest-Remaining-Time-First (SRTF)

- **Motivation**: now, we add the concepts of *varying arrival times* and *preemption* to the analysis

Process	Arrival Time	Burst Time (ms)
P1	*0*	*8*
P2	*1*	*4*
P3	*2*	*9*
P4	*3*	*5*

- Preemptive SJF *Gantt Chart*

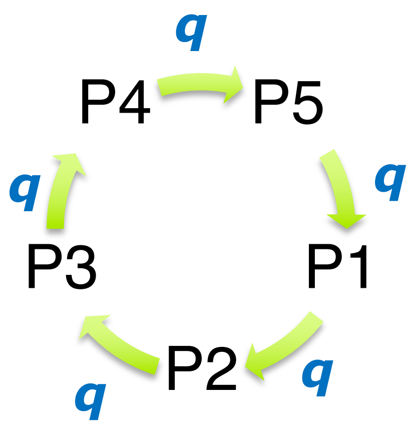


  - **Average waiting time** = *[(10-1)+(1-1)+(17-2)+(5-3)]/4 = 6.5*

- The value for *nonpreemptive SJF scheduling*?

Round Robin (RR) Scheduling

- **Motivation**: try scheduling algorithm 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
- 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



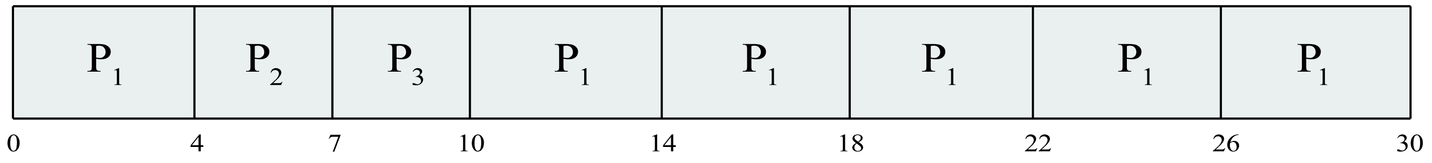
Round Robin (RR) Scheduling

- *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

Example of RR with Time Quantum q = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

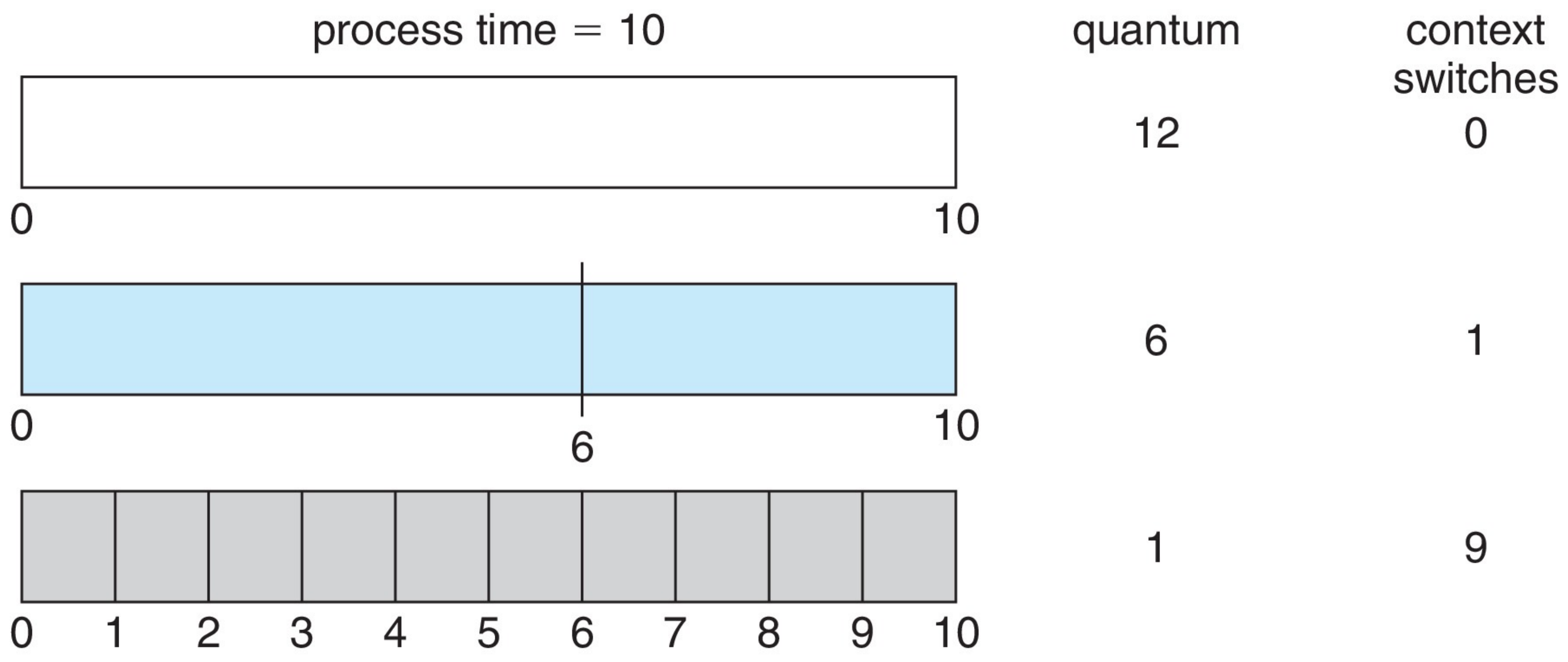
- The *Gantt chart* is:



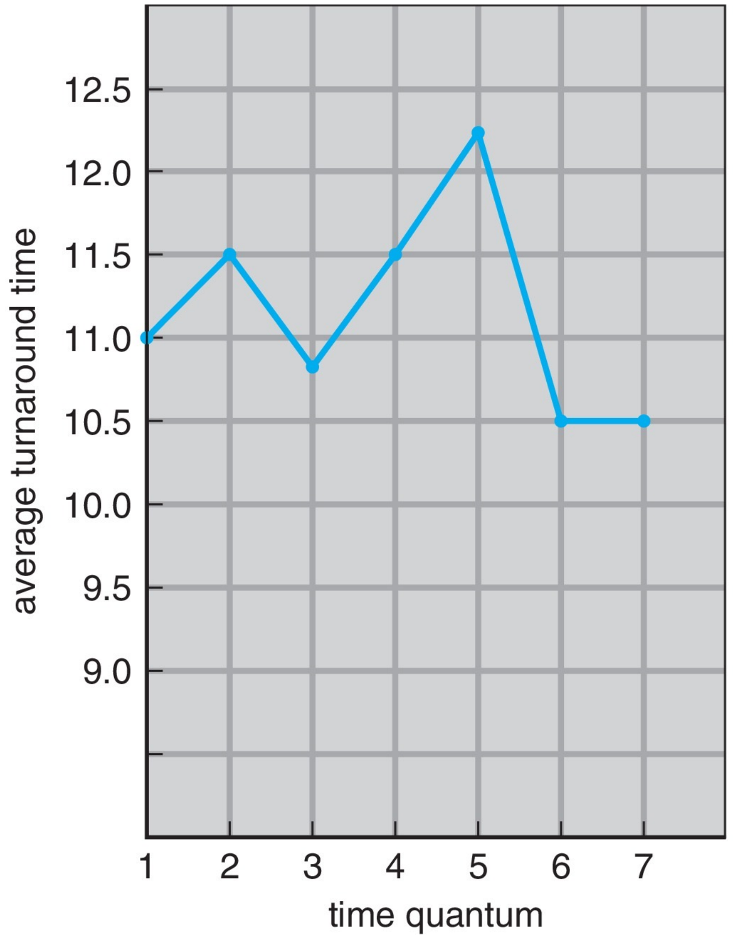
  - **Average waiting time** = ?

- Typically, *higher average turnaround* than SJF, but *better response*
- ***q*** should be large compared to context switch time
- ***q*** usually *10ms* to *100ms*, context switch *< 10µsec*

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***

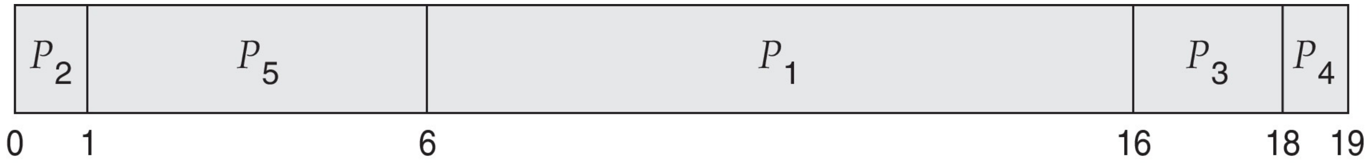
Priority Scheduling

- **Motivation**: A *priority number* (*integer*) is associated with each process
- The CPU is allocated to the process with the *highest priority* (*smallest integer ≡ highest priority*). Equal-priority processes are scheduled in **FCFS** or **RR**
  - Preemptive
  - Nonpreemptive
- **SJF** is priority scheduling where priority is the inverse of predicted next CPU burst time
- Problem ≡ *Starvation* – low priority processes may never execute
  - Solution ≡ *Aging* – as time progresses, increase the priority of the process

Example of Priority Scheduling

Process	Burst Time	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** = *8.2*

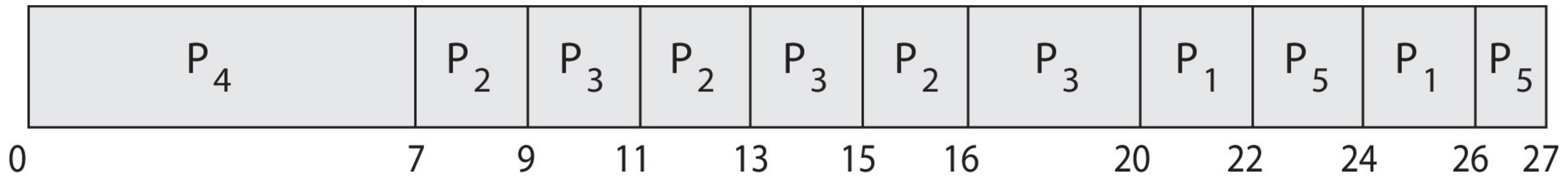
Priority Scheduling w/ Round-Robin

Process	Burst Time	Priority
P_1	4	3
P_2	5	2
P_3	8	2
P_4	7	1
P_5	3	3

- Run the process with the highest priority. Processes with the same priority run Round-Robin

Final point - Arrival time - Burst time = Waiting Time

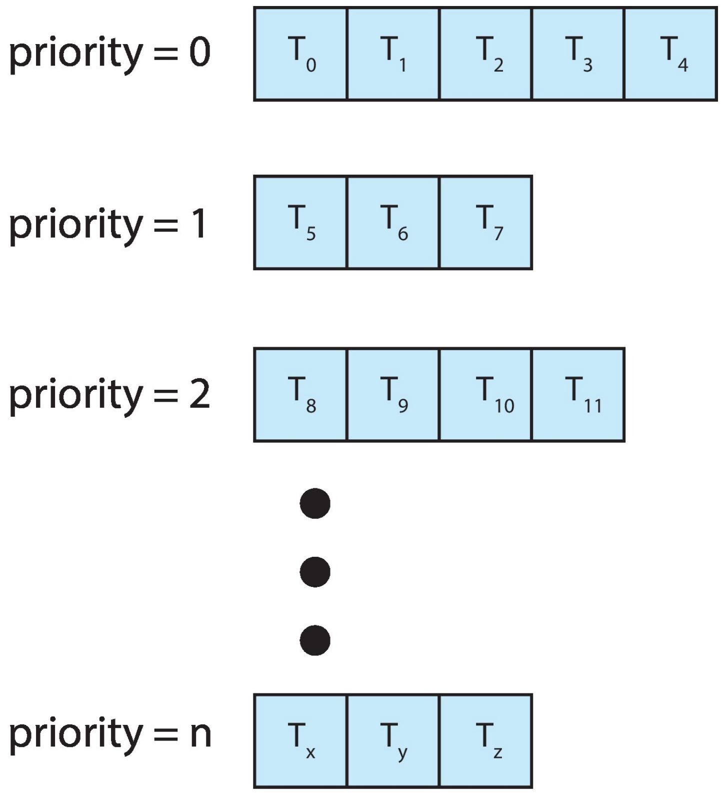
- *Gantt Chart* with time quantum *q = 2 ms*



  - **Average waiting time** = ?

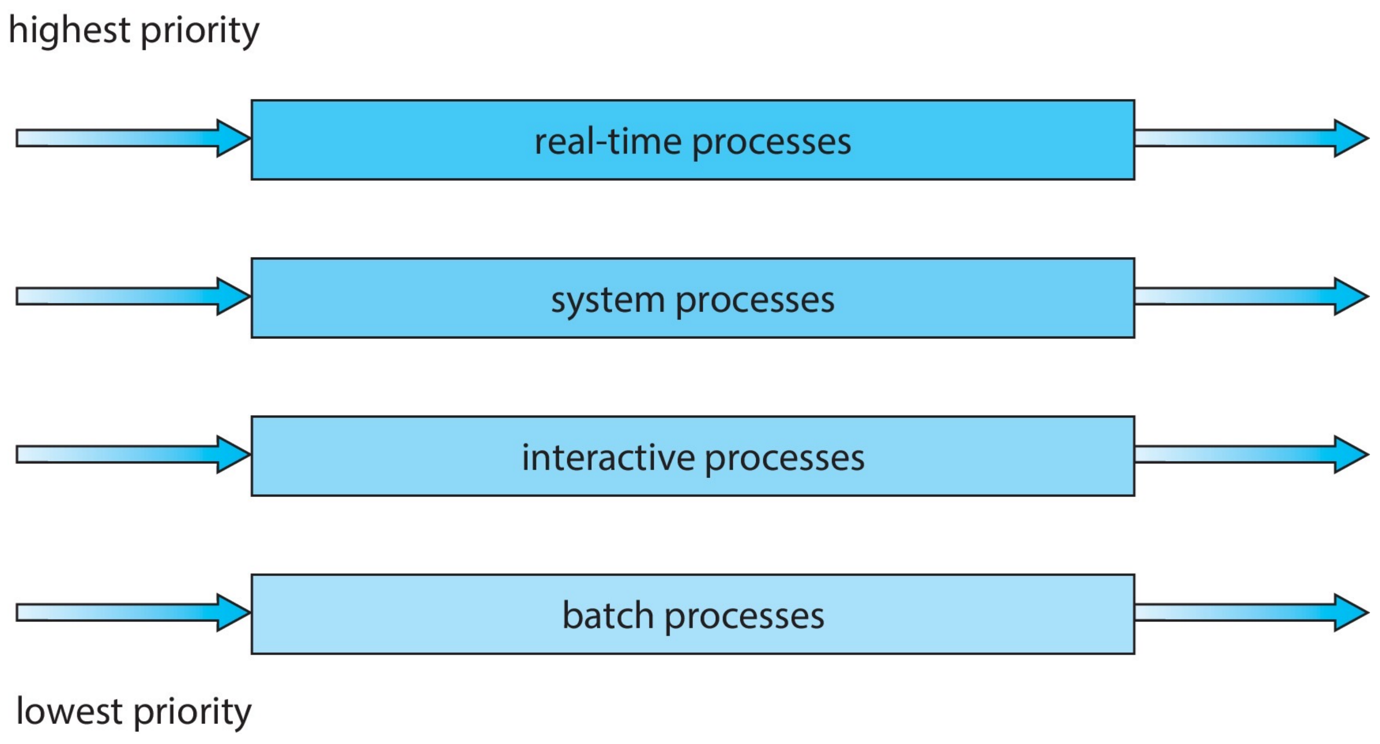
Multilevel Queue

- **Motivation**: with priority scheduling, have separate queues for each priority
- Schedule the process in the highest-priority queue!



Example of Multilevel Queue

- Prioritization based upon process type

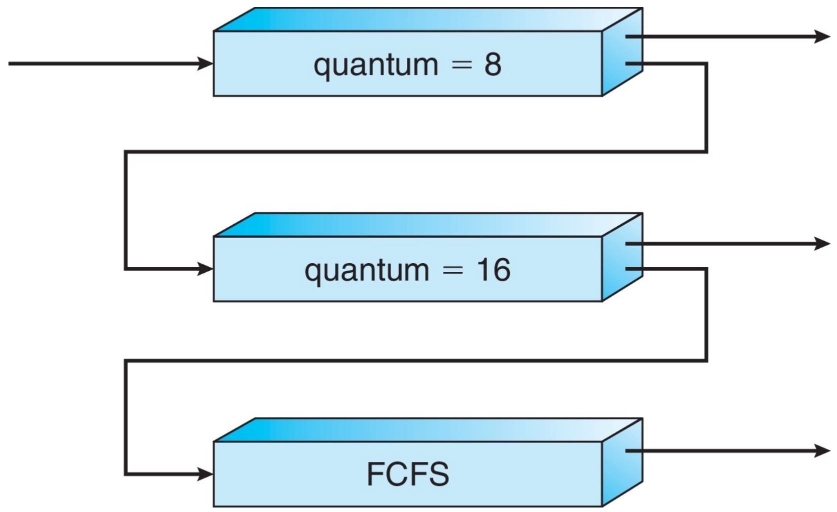


Multilevel Feedback Queue

- **Motivation**: A process can move between the various queues; *aging* can be implemented this way
- **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
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service
- This scheme leaves I/O-bound and interactive processes — which are typically characterized by short CPU bursts — in the higher-priority queues and a process that waits too long in a lower-priority queue *may be moved to a higher-priority queue*

Example of Multilevel Feedback Queue

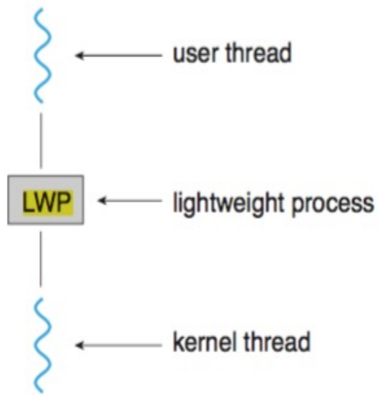
- Three queues:
  - **Q0** – RR with time quantum 8 milliseconds
  - **Q1** – RR with time quantum 16 milliseconds
  - **Q2** – FCFS



- Scheduling
  - A new job enters queue **Q0** which is served FCFS
    - When it gains CPU, job receives *8* milliseconds
    - If it does not finish in *8* milliseconds, job is moved to queue **Q1**
  - At **Q1** job is again served FCFS and receives *16* additional milliseconds
    - If it still does not complete, it is preempted and moved to queue **Q2**

Thread Scheduling

- Distinction between *user-level* and *kernel-level* threads
- When threads supported, *threads scheduled, not processes*
- Many-to-one and many-to-many models, thread library schedules user-level threads to run on *Light-Weight Process* (**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



POSIX Pthread Scheduling

- API allows specifying either PCS or SCS during thread creation
  - **PTHREAD_SCOPE_PROCESS** schedules threads using PCS scheduling
  - **PTHREAD_SCOPE_SYSTEM** schedules threads using SCS scheduling
- Can be limited by OS – Linux and macOS only allow **PTHREAD_SCOPE_SYSTEM**
- Pthread IPC (Inter-process Communication) provides two functions for setting
  - `pthread attr setscope(pthread attr t *attr, int scope)`
  - `pthread attr getscope(pthread attr t *attr, int *scope)`

Pthread Scheduling API

```
#include <pthread.h>

#include <stdio.h>

#define NUM_THREADS 5
```

```
int main(int argc, char *argv[]) {

   int i, scope;
   pthread_t tid[NUM THREADS];

   pthread_attr_t attr;

   /* get the default attributes */

   pthread_attr_init(&attr);

   /* first inquire on the current scope */
   if (pthread_attr_getscope(&attr, &scope) != 0)

      fprintf(stderr, "Unable to get scheduling scope\n");

   else {

      if (scope == PTHREAD_SCOPE_PROCESS)

         printf("PTHREAD_SCOPE_PROCESS");

      else if (scope == PTHREAD_SCOPE_SYSTEM)

         printf("PTHREAD_SCOPE_SYSTEM");

      else
         fprintf(stderr, "Illegal scope value.\n");

   }
```

Pthread Scheduling API (Cont.)

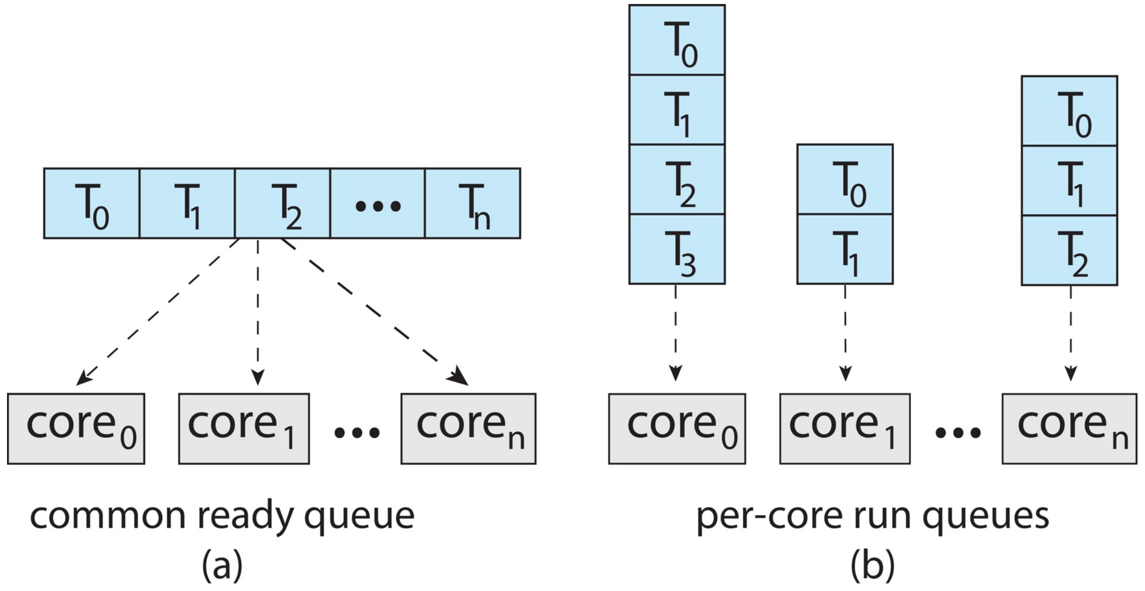
```
   /* set the scheduling algorithm to PCS or SCS */

   pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM);

   /* create the threads */
   for (i = 0; i < NUM_THREADS; i++)

      pthread_create(&tid[i],&attr,runner,NULL);

   /* now join on each thread */
   for (i = 0; i < NUM_THREADS; i++)

      pthread_join(tid[i], NULL);

}

/* Each thread will begin control in this function */

void *runner(void *param)
{

   /* do some work ... */

   pthread_exit(0);

}
```

Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- *Multiprocessor* may be any one of the following architectures:
  - Multicore CPUs
  - Multithreaded cores
  - NUMA systems
  - Heterogeneous multiprocessing
- *Multiprocessor scheduling*
  - There is no one best solution

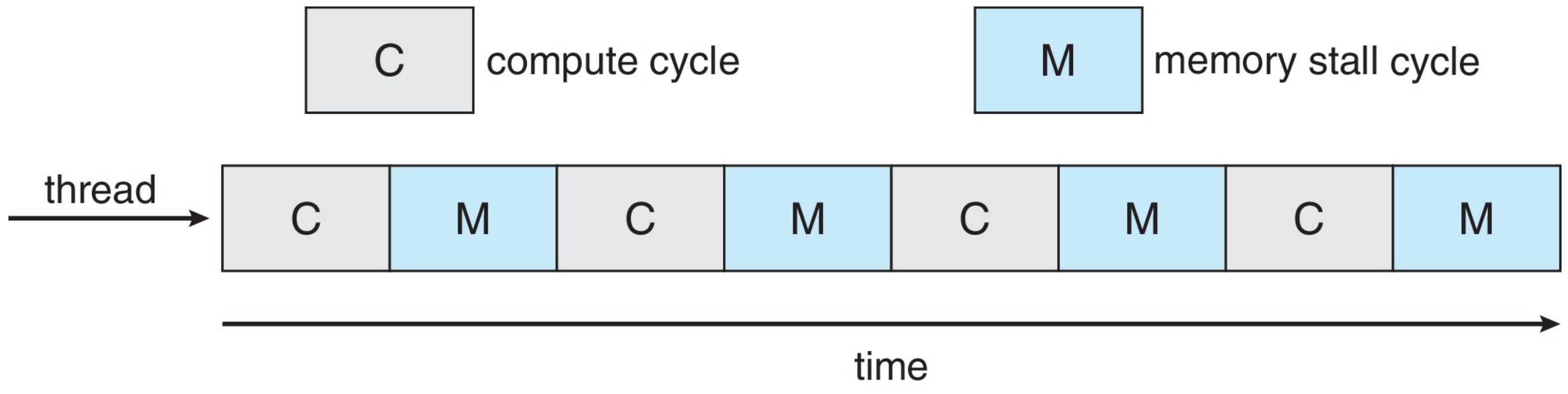
Multiple-Processor Scheduling (Cont.)

- *Symmetric multiprocessing* (**SMP**) is where each processor is self-scheduling
- Two possible strategies
  - All threads may be in a common ready queue (Fig. a)
  - Each processor may have its own private queue of threads (Fig. b)



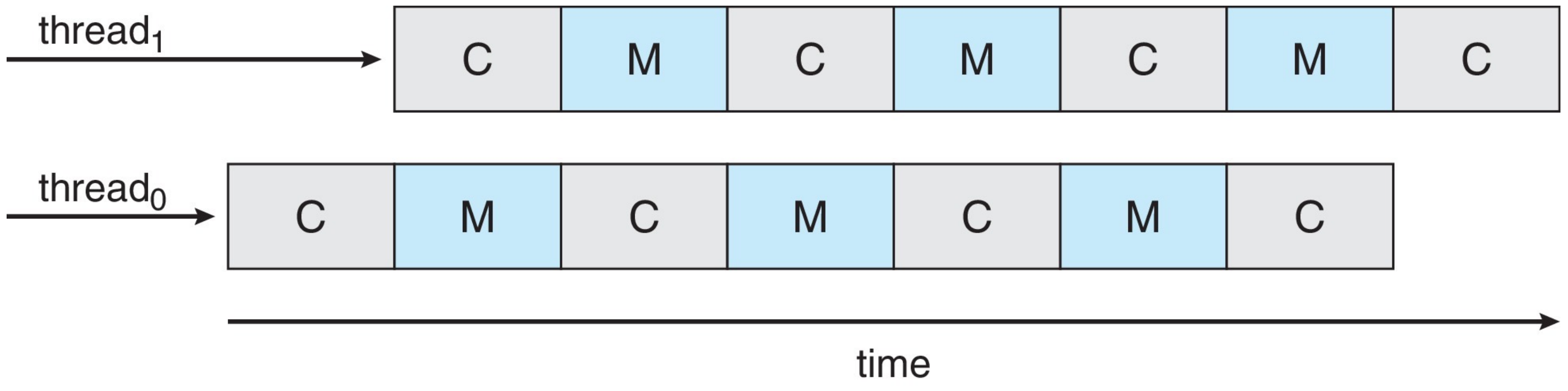
Multicore Processors

- 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

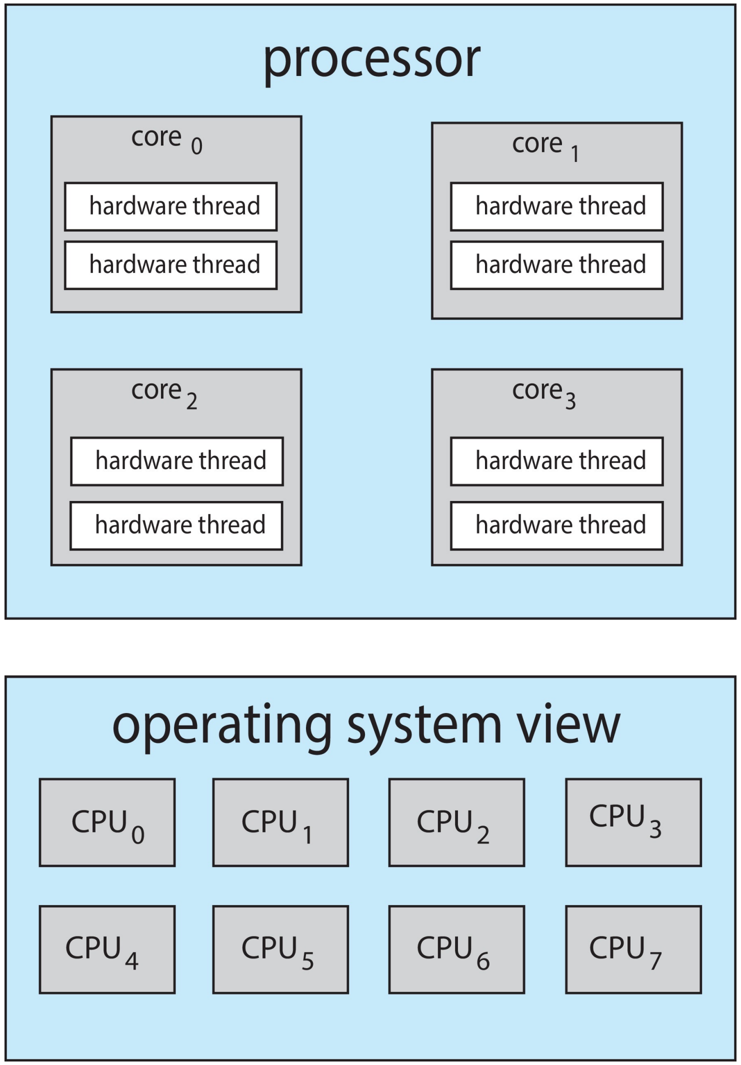


Multithreaded Multicore System

- Each core has > 1 hardware threads.
- If one thread has a memory stall, switch to another thread!



Multithreaded Multicore System



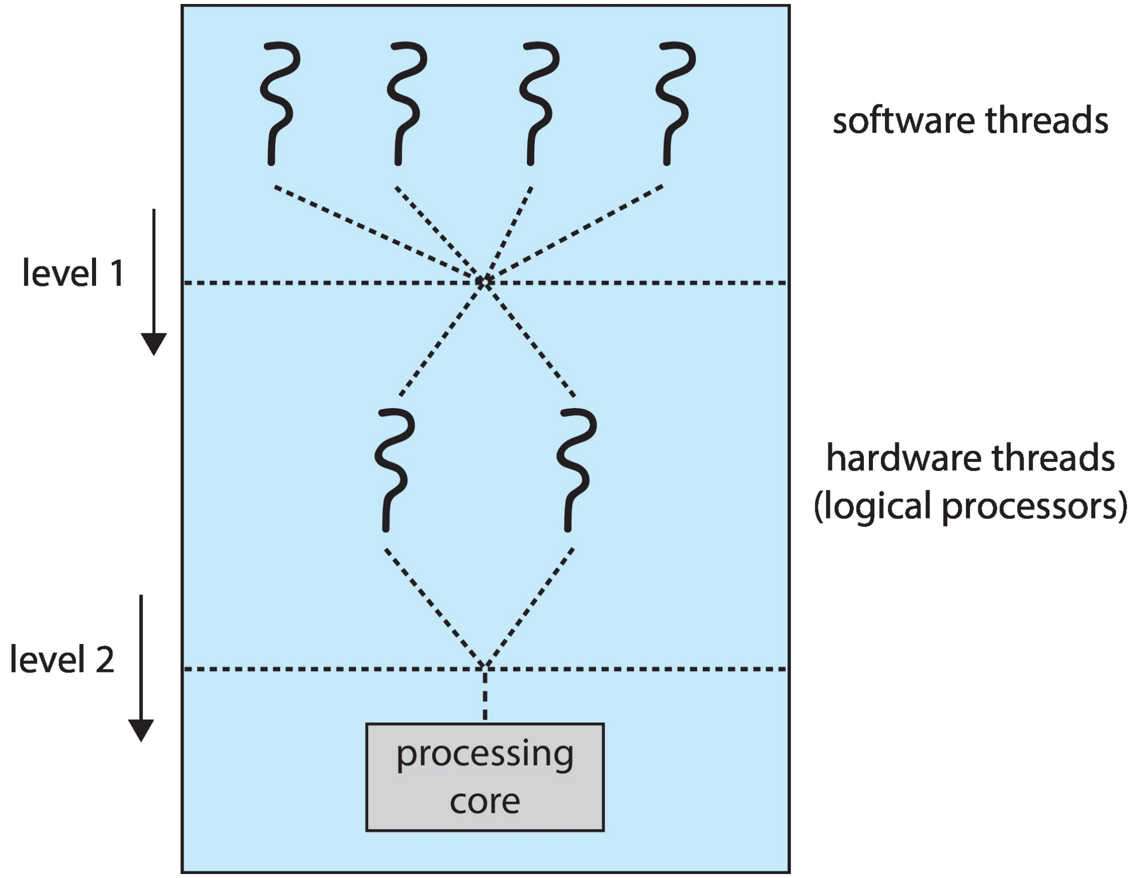
- *Chip-multithreading* (**CMT**) assigns each core multiple hardware threads (Intel refers to this as *hyperthreading*)
- Each hardware thread maintains its architectural state, such as *instruction pointer* and *register set*
- On a quad-core system with 2 hardware threads per core (e.g., Intel i7), the operating system sees 8 logical processors

Multithreaded Multicore System

- Two levels of scheduling:

1. The operating system deciding which software thread to run on a logical CPU

2. How each core decides which hardware thread to run on the physical core.



Multiple-Processor Scheduling – Load Balancing

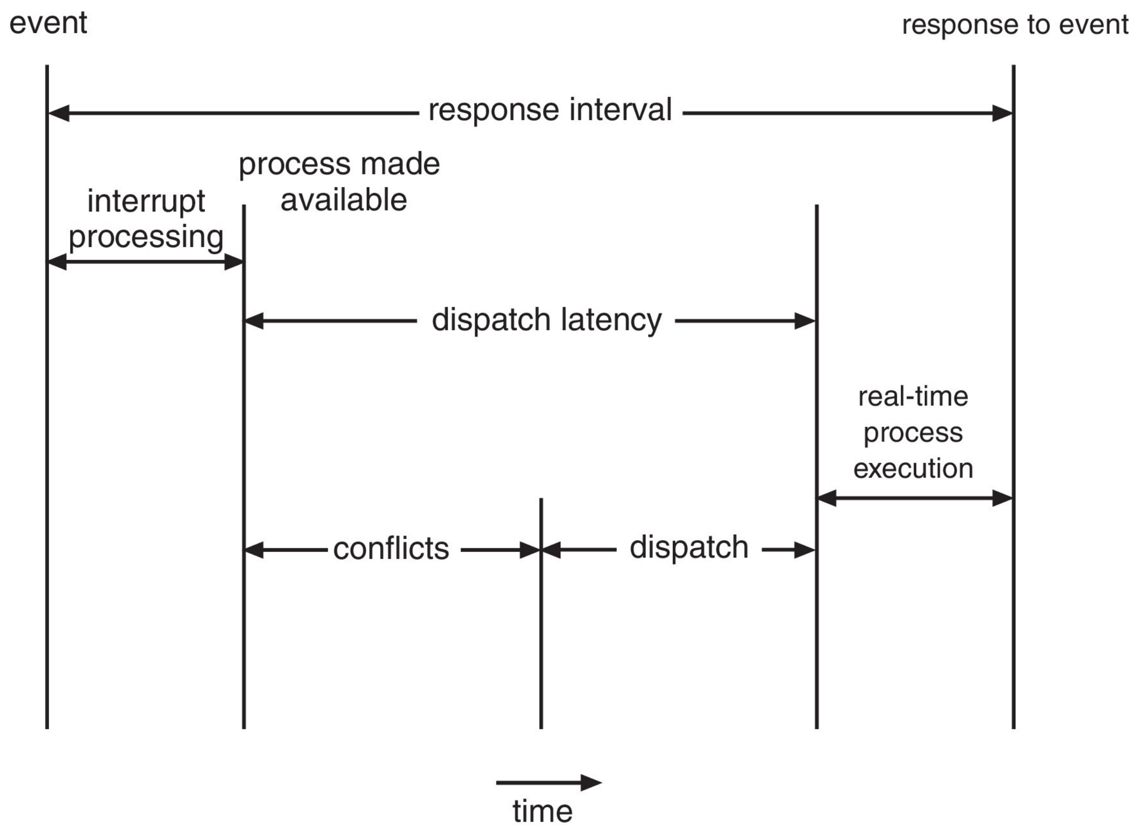
- If SMP, need to keep all CPUs loaded for efficiency
- *Load balancing* attempts to keep workload evenly distributed
- *Push migration* – periodic task checks load on each processor, and if found, pushes task from overloaded CPU to other CPUs
- *Pull migration* – idle processors pulls waiting task from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

Multiple-Processor Scheduling – Processor Affinity

- When a thread has been running on one processor, the cache contents of that processor stores the memory accesses by that thread.
- We refer to this as a thread having *affinity* for a processor (i.e. "processor affinity")
- *Load balancing* may affect processor affinity as a thread may be moved from one processor to another to balance loads, yet that thread loses the contents of what it had in the cache of the processor it was moved off of.
- *Soft affinity* – the operating system attempts to keep a thread running on the same processor, but no guarantees.
- *Hard affinity* – allows a process to specify a set of processors it may run on.

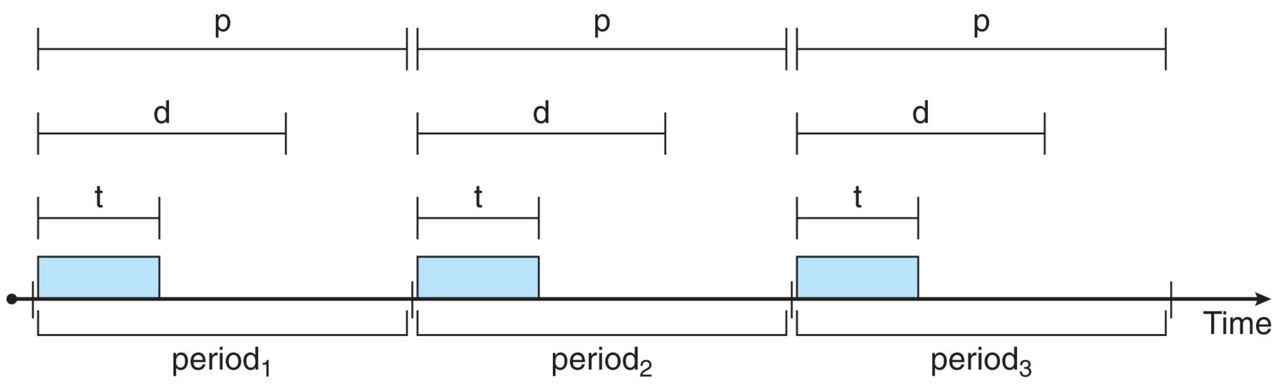
Dispatch Latency

- Conflict phase of dispatch latency:
  1. *Preemption* of any process running in kernel mode
  2. *Release* by low-priority process of resources needed by high-priority processes



Priority-based Scheduling

- For real-time scheduling, scheduler must support *preemptive*, *priority-based scheduling*
  - But only guarantees soft real-time
- For hard real-time, it must also provide ability to meet deadlines
- Processes have new characteristics: *periodic* ones require CPU at constant intervals
  - Has processing time *t*, deadline *d*, period *p*
  - $0 \leq t \leq d \leq p$
  - *Rate of periodic task* is 1/*p*



Proportional Share Scheduling

- T shares are allocated among all processes in the system
- An application receives N shares where $N < T$
- This ensures each application will receive N / T of the total processor time

POSIX Real-Time Scheduling

- The *POSIX.1b* standard
- API provides functions for managing real-time threads
- Defines two scheduling classes for real-time threads:
  - **SCHED_FIFO** – threads are scheduled using a FCFS strategy with a FIFO queue. There is no time-slicing for threads of equal priority
  - **SCHED_RR** – similar to SCHED_FIFO except time-slicing occurs for threads of equal priority
- Defines two functions for getting and setting scheduling policy:
  - `pthread_attr_getsched_policy(pthread_attr_t *attr, int *policy)`
  - `pthread_attr_setsched_policy(pthread_attr_t *attr, int policy)`

Summary

- *CPU scheduling* is the task of selecting a waiting process from the ready queue and allocating the CPU to it. The CPU is allocated to the selected process by the dispatcher.
- *Scheduling algorithms* may be either *preemptive* (where the CPU can be taken away from a process) or *nonpreemptive* (where a process must voluntarily relinquish control of the CPU). Almost all modern operating systems are preemptive.
- Scheduling algorithms can be evaluated according to the following five criteria: (1) *CPU utilization*, (2) *throughput*, (3) *turnaround time*, (4) *waiting time*, and (5) *response time*.
- *First-come, first-served* (**FCFS**) scheduling is the simplest scheduling algorithm, but it can cause short processes to wait for very long processes.

Summary (Cont.)

- *Shortest-job-first* (**SJF**) scheduling is provably optimal, providing the shortest average waiting time. Implementing SJF scheduling is difficult, how- ever, because predicting the length of the next CPU burst is difficult.
- *Round-robin* (**RR**) scheduling allocates the CPU to each process for a time quantum. If the process does not relinquish the CPU before its time quantum expires, the process is preempted, and another process is scheduled to run for a time quantum.
- *Priority scheduling* assigns each process a priority, and the CPU is allocated to the process with the highest priority. Processes with the same priority can be scheduled in FCFS order or using RR scheduling.

Summary (Cont.)

- *Multilevel queue scheduling* partitions processes into several separate queues arranged by priority, and the scheduler executes the processes in the highest-priority queue. Different scheduling algorithms may be used in each queue.
- *Multilevel feedback queues* are similar to multilevel queues, except that a process may migrate between different queues.
- *Multicore processors* place one or more CPUs on the same physical chip, and each CPU may have more than one hardware thread. From the perspective of the operating system, each hardware thread appears to be a logical CPU.
- *Load balancing* on multicore systems equalizes loads between CPU cores, although migrating threads between cores to balance loads may invalidate cache contents and therefore may increase memory access times.

Summary (Cont.)

- *Soft real-time scheduling* gives priority to real-time tasks over non-real- time tasks. Hard real-time scheduling provides timing guarantees for real- time tasks,
- *Rate-monotonic real-time scheduling* schedules periodic tasks using a static priority policy with preemption.
- *Earliest-deadline-first* (**EDF**) scheduling assigns priorities according to deadline. The earlier the deadline, the higher the priority; the later the deadline, the lower the priority.
- *Proportional share scheduling* allocates *T* shares among all applications. If an application is allocated *N* shares of time, it is ensured of having N□T of the total processor time.

Summary (Cont.)

- *Modeling and simulations* can be used to evaluate a CPU scheduling algorithm.

Exercise 1

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

- Considering all three algorithms FCFS, SJF, and RR (quantum time = 10)
- What is the average turnaround time for these processes with corresponding algorithm?
- What is the average waiting time for these processes with corresponding algorithm?

Exercise 2

Process	Burst Time	Arrival time	Priority
P_1	10	0	3
P_2	29	2	2
P_3	3	3	4
P_4	7	5	1
P_5	12	6	0

- Considering all five algorithms FCFS, SJF, SRTF, Preemptive Priority, Non-preemptive Priority, and RR (**quantum time = 10**)
- What is the **average waiting time** for these processes with corresponding algorithm?
- What is the **average turnaround time** for these processes with corresponding algorithm?

Exercise 3

Process	Burst Time	Arrival time
P_1	10	0
P_2	29	2
P_3	3	5
P_4	7	3
P_5	12	6

- Considering RR (quantum time = 5)
- What is the average waiting time for these processes?

Exercise 4

Process	Burst Time	Arrival time
P_1	11	0
P_2	12	3
P_3	13	9

- Using MLF for process scheduling with 3 queues:
  - Q0: RR (4ms)
  - Q1: RR (6ms)
  - Q2: FCFS

Compute average process waiting time.

End of Chapter 5

Operating System Examples (seff-study)

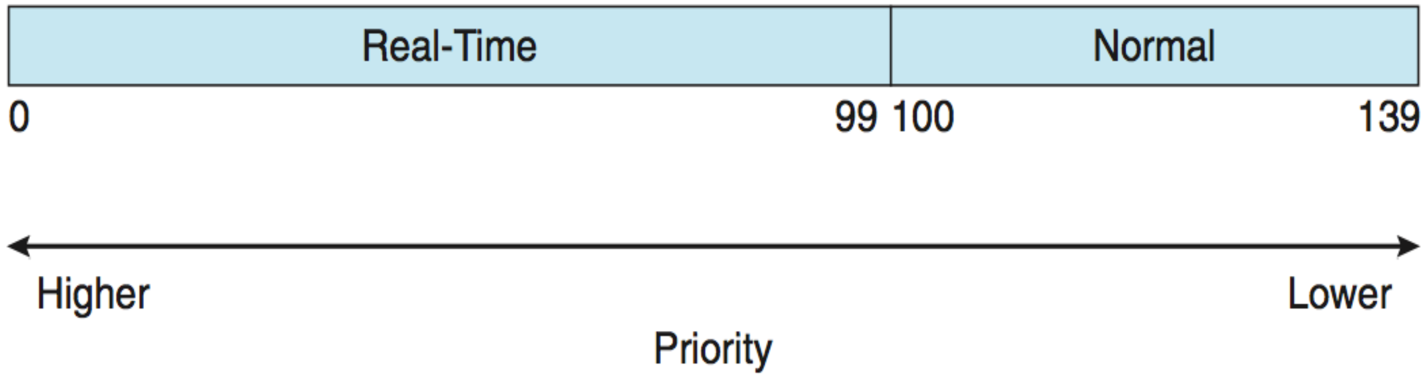
- Linux scheduling
- Windows scheduling

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 139
  - Map into global priority with numerically lower values indicating higher priority
  - Higher priority gets larger *q*
  - Task runnable as long as time left in time slice (*active*)
  - If no time left (*expired*), not runnable until all other tasks use their slices
  - All runnable tasks tracked in per-CPU *run-queue 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 Real-time Scheduling

- 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 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