Lesson 4:
CPU Scheduling

Outline

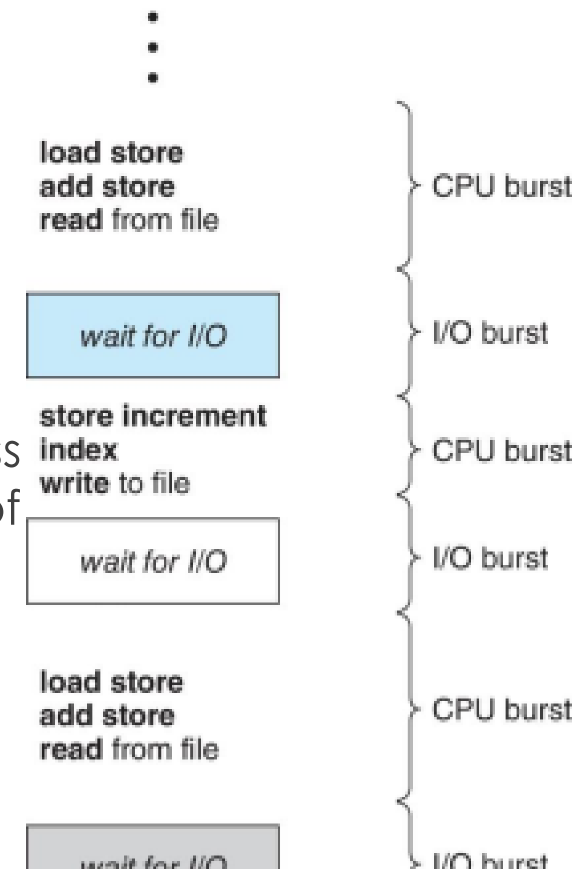
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multi-Processor Scheduling
- Real-Time CPU Scheduling

Objectives

- Describe various CPU scheduling algorithms
- Assess CPU scheduling algorithms based on scheduling criteria
- Explain the issues related to multiprocessor and multicore scheduling
- Describe Real-time CPU scheduling

Basic Concepts

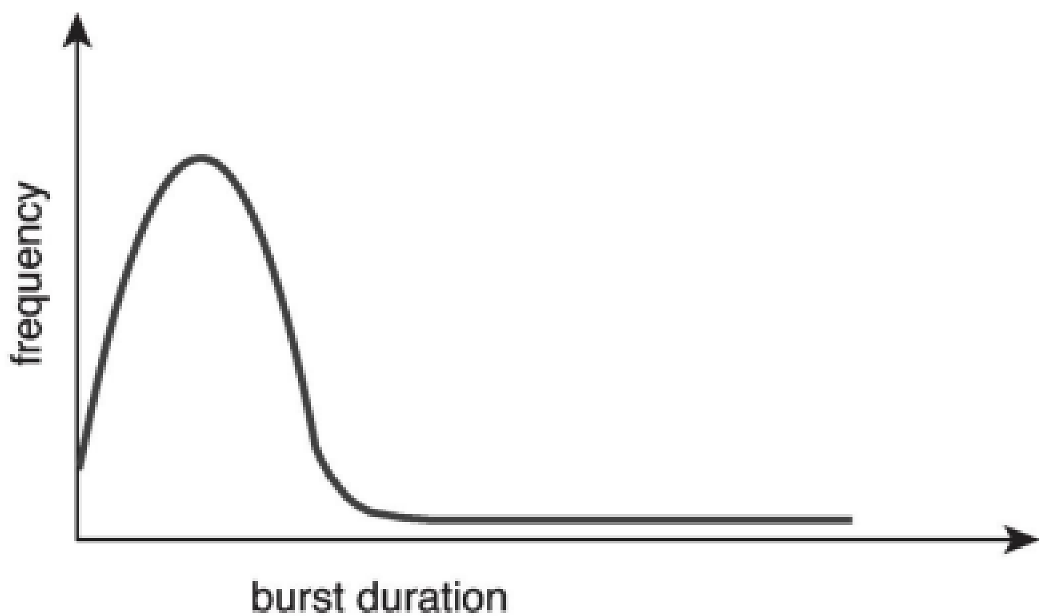
- Maximum CPU utilization obtained with multiprogramming
- CPU–I/O Burst Cycle – Process execution consists of a **cycle** of CPU execution and I/O wait
- **CPU burst** followed by **I/O burst**
- CPU burst distribution is of main concern



Histogram of CPU-burst Times

Large number of short bursts

Small number of longer bursts

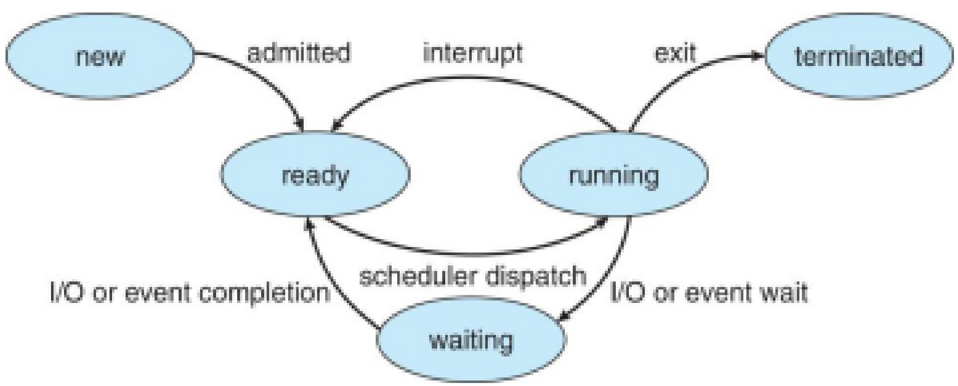


CPU Scheduler

- The **CPU scheduler** selects from among the processes in ready queue, and allocates a CPU core to one of them
- Queue may be ordered in various ways
- 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

- For situations 1 and 4, there is no choice in terms of scheduling. A new process (if one exists in the ready queue) must be selected for execution.
- For situations 2 and 3, however, there is a choice.



Preemptive and Nonpreemptive

Scheduling

- When scheduling takes place only under circumstances 1 and 4, the scheduling scheme is **nonpreemptive**.
- Otherwise, it is **preemptive**.
- Under Nonpreemptive scheduling, once the CPU has been allocated to a process, the process keeps the CPU until it releases it either by terminating or by switching to the waiting state.
  - Virtually all modern operating systems including Windows, MacOS, Linux, and UNIX use preemptive scheduling algorithms.

Preemptive Scheduling and Race Conditions

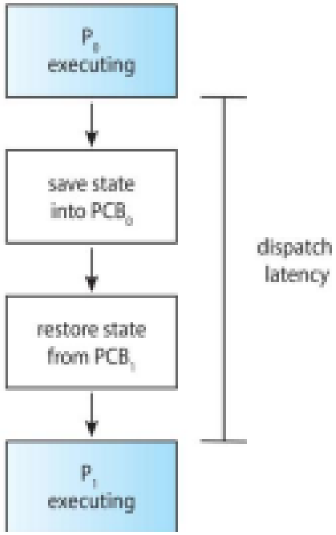
- Preemptive scheduling can result in race conditions when data are shared among several processes.
- Consider the case of two processes that share data. While

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.

- This issue will be explored in detail in Lesson 5.

Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the CPU 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

Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes that complete their execution per time unit
- **Turnaround time** – amount of time to execute a particular process
- **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.

Scheduling Algorithm Optimization Criteria

- Max CPU utilization
- Max throughput
- Min turnaround time

- Min waiting time
- Min response time

First- Come, First-Served (FCFS) Scheduling

Process	Burst Time
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:

P_1 P_2 P_3

0 24 27 30

- 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: P_2, P_3, P_1

- The Gantt chart for the schedule is:

P_1

P_2 P_3

0 3 6 30

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

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 time
- SJF is optimal – gives minimum average waiting time for a given set of processes
- Preemptive version called **shortest-remaining-time-first**
- How do we determine the length of the next CPU burst?
- Could ask the user
  - Estimate

Example of SJF

Process Burst Time

P_1 6

P_2 8

P_3 7

P_4 3

- SJF scheduling chart

P_3

P_2

P_4 P_1

0 3 24 9 16

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

Determining Length of Next CPU Burst

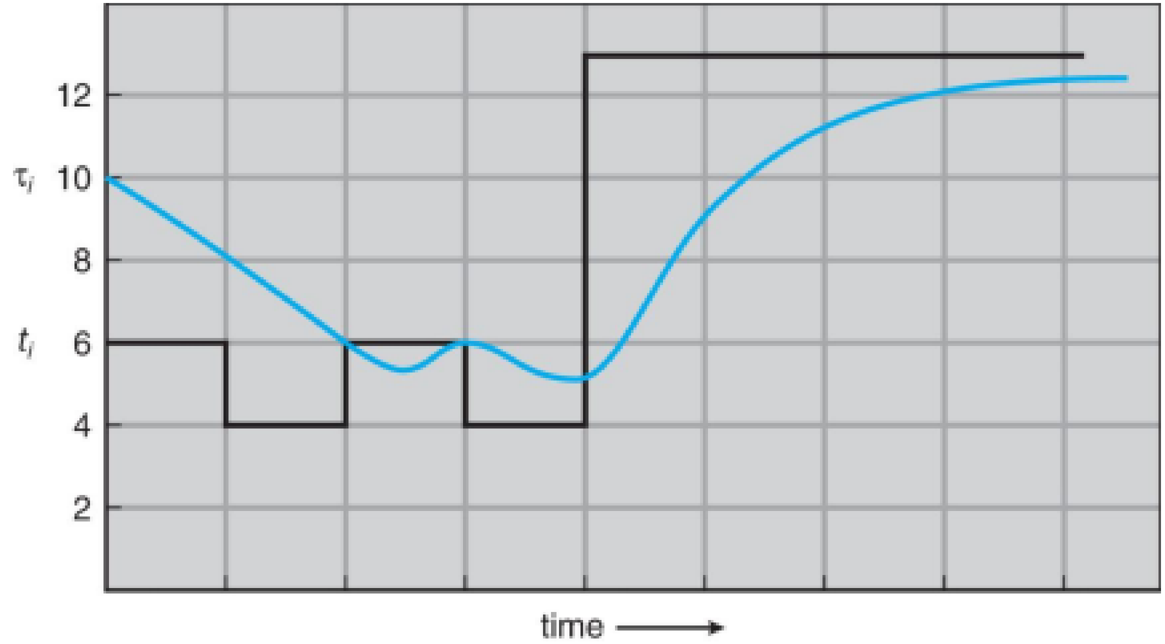
- Can only estimate the length – should be similar to the previous one
  - Then pick process with shortest predicted next CPU burst
- Can be done by using the length of previous CPU bursts, using exponential averaging

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

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

- Commonly, α set to ½

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	...

Examples of Exponential Averaging

- α =0
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count

- $\alpha = 1$
  - $\tau_{n+1} = \alpha\, t_n$
  - Only the actual last CPU burst counts
- If we expand the formula, we get:

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

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

Shortest Remaining Time First (SRTF)Scheduling

- SRTF is the preemptive version of SJF. The next CPU burst of the newly arrived process may be shorter than what is left of the currently executing process, the SRTF algorithm will preempt the currently executing process.
- Whenever a new process arrives in the ready queue, the

decision on which process to schedule next is redone using the SRTF algorithm.

- Is SRTF more “optimal” than SJF in terms of the minimum average waiting time for a given set of processes?

Example of

Shortest-remaining-time-first

- Now we add the concepts of varying arrival times and preemption to the analysis

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

- *Preemptive* SJF Gantt Chart

P_4

P_1 P_2 P_1 P_3

0 1 26 5 17

10

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

Round Robin (RR)

- 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.
- Timer interrupts every quantum to schedule next process
- Performance
  - *q* large $\Rightarrow$ FIFO (FCFS)
  - *q* small $\Rightarrow$ RR
- Note that q must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 4

Process Burst Time

P_1 24

P_2 3

P_3 3

- The Gantt chart is:

P_1 P_1 P_1

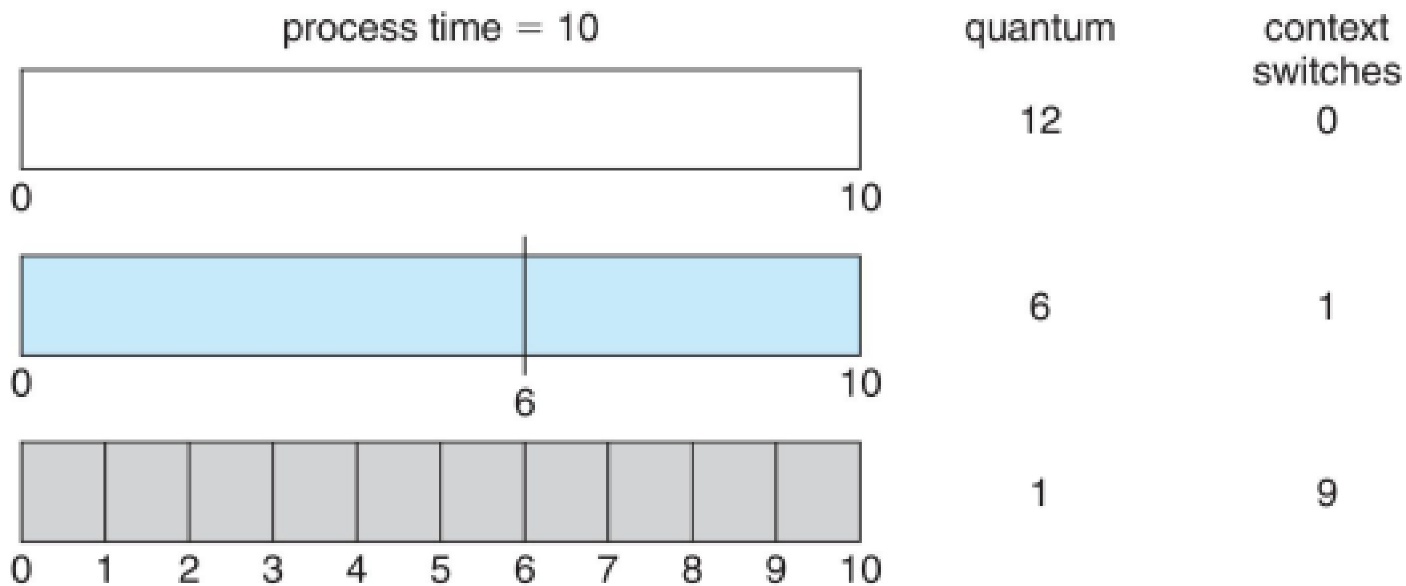
P_2 P_3 P_1 P_1 P_1

0 4 7 10 14 18 22 26 30

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

Time Quantum and Context Switch

Time



Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer ≡ highest priority)

- 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

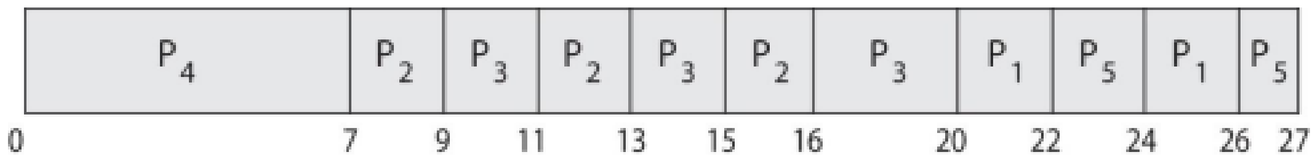
- Average waiting time = 8.2

Priority Scheduling w/ Round-Robin

- Run the process with the highest priority. Processes with the same priority run round-robin
- Example:

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

- Gantt Chart with time quantum = 2

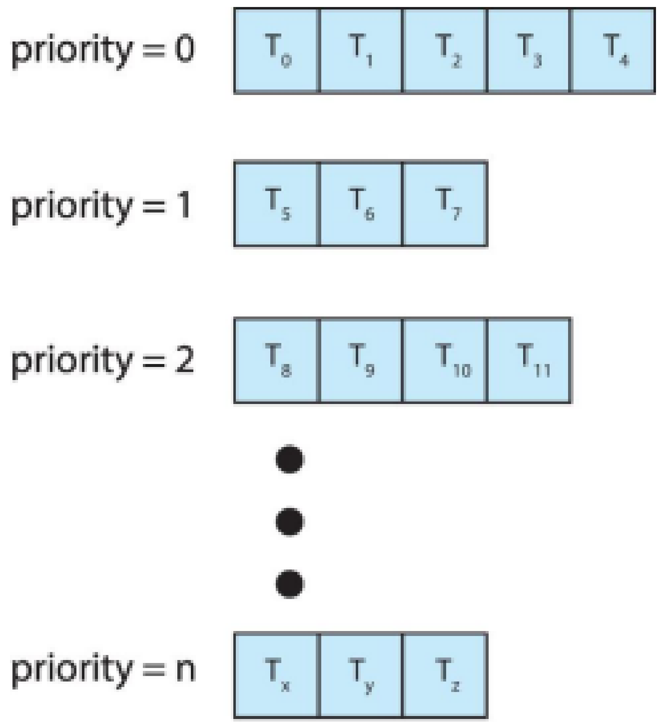


Multilevel Queue

- The ready queue consists of multiple queues
- Multilevel queue scheduler defined by the following parameters:
  - Number of queues
  - Scheduling algorithms for each queue
  - Method used to determine which queue a process will enter when that process needs service
  - Scheduling among the queues

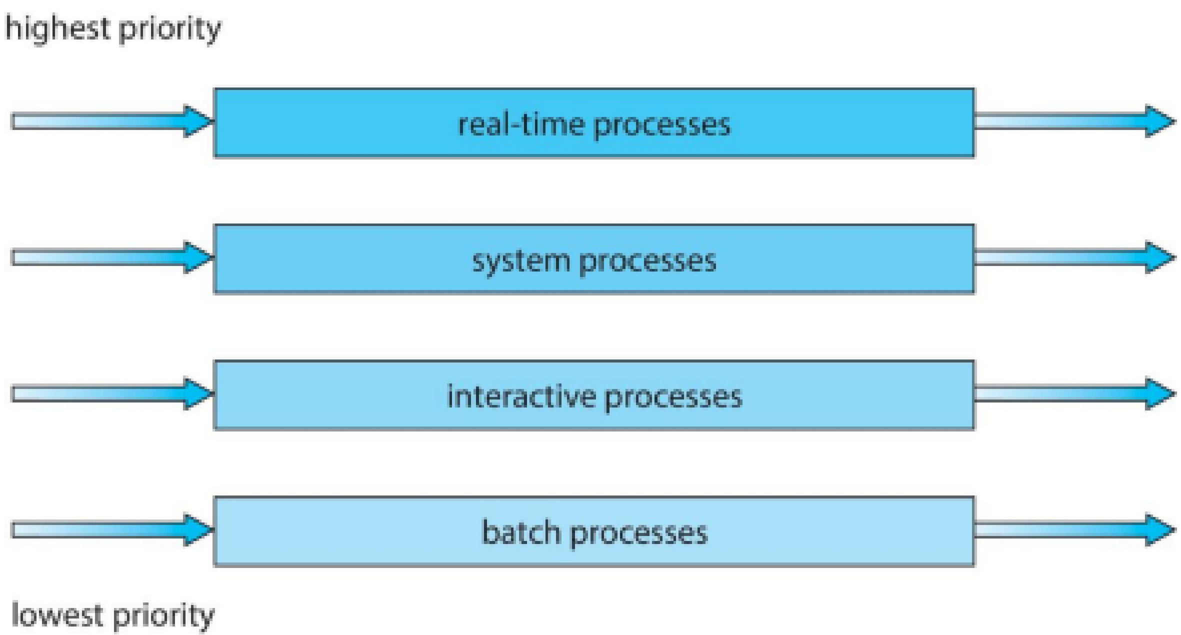
Multilevel Queue(Cont.)

- With priority scheduling, have separate queues for each priority.
- Schedule the process in the highest-priority queue!



Multilevel Queue(Cont.)

- Prioritization based upon process type



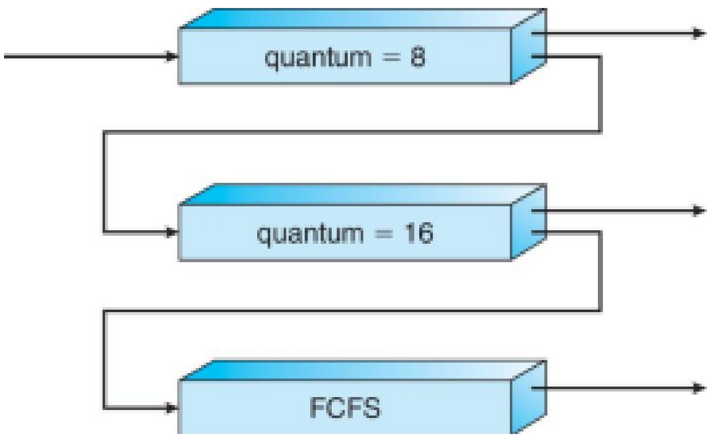
Multilevel Feedback Queue

- A process can 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
  - Method used to determine when to demote a process
  - Method used to determine which queue a process will enter when that process needs service
- Aging can be implemented using multilevel feedback queue

Example of Multilevel Feedback Queue

- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds

- Q_1 – RR time quantum 16 milliseconds
- Q_2 – FCFS



- Scheduling
  - A new process enters queue Q_0 which is served in RR
    - When it gains CPU, the process receives 8 milliseconds
    - If it does not finish in 8 milliseconds, the process is moved to queue Q_1
  - At Q_1 job is again served in RR and receives 16 additional milliseconds
    - If it still does not complete, it is preempted and moved to queue Q_2

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 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

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 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

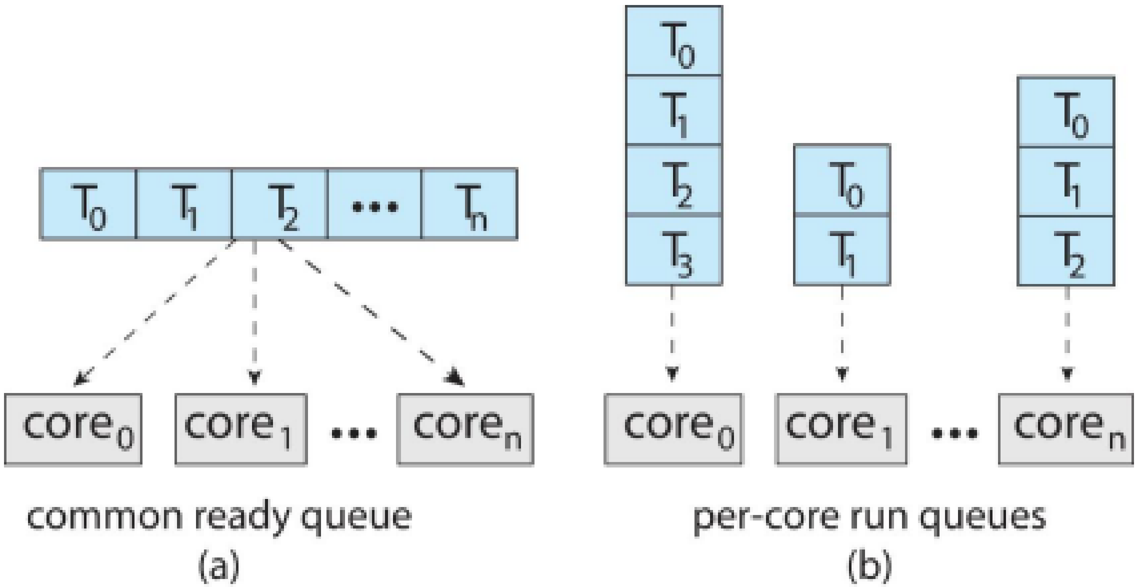
```
    /* set the scheduling algorithm to PCS or SCS */
    pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM);
    /* create the threads */
    for (i = 0; i < NUM_THREADS; i++)
       pthread_create(&tid[i],&attr,runner,NULL);
    /* now join on each thread */
    for (i = 0; i < NUM_THREADS; i++)
       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
- Multiprocess may be any one of the following architectures: - Multicore CPUs
  - Multithreaded cores
  - NUMA (non-uniform memory access) systems
  - Heterogeneous multiprocessing

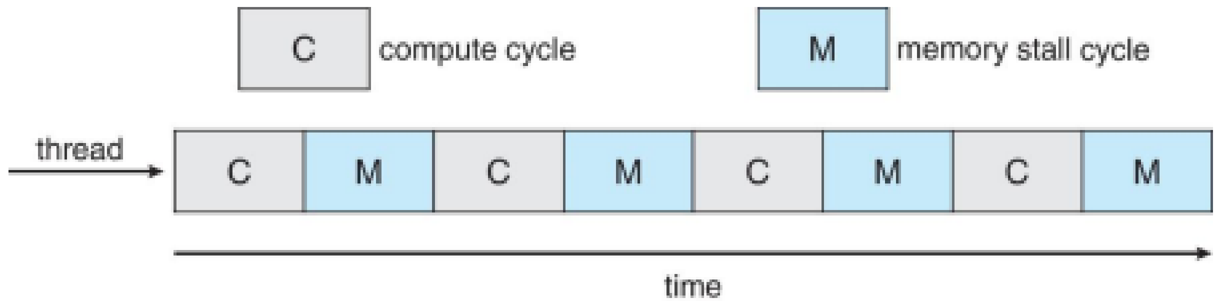
Multiple-Processor Scheduling

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

- **Chip-multithreading** (CMT) assigns each core multiple hardware threads. (Intel refers
to this as **hyperthreading**.)

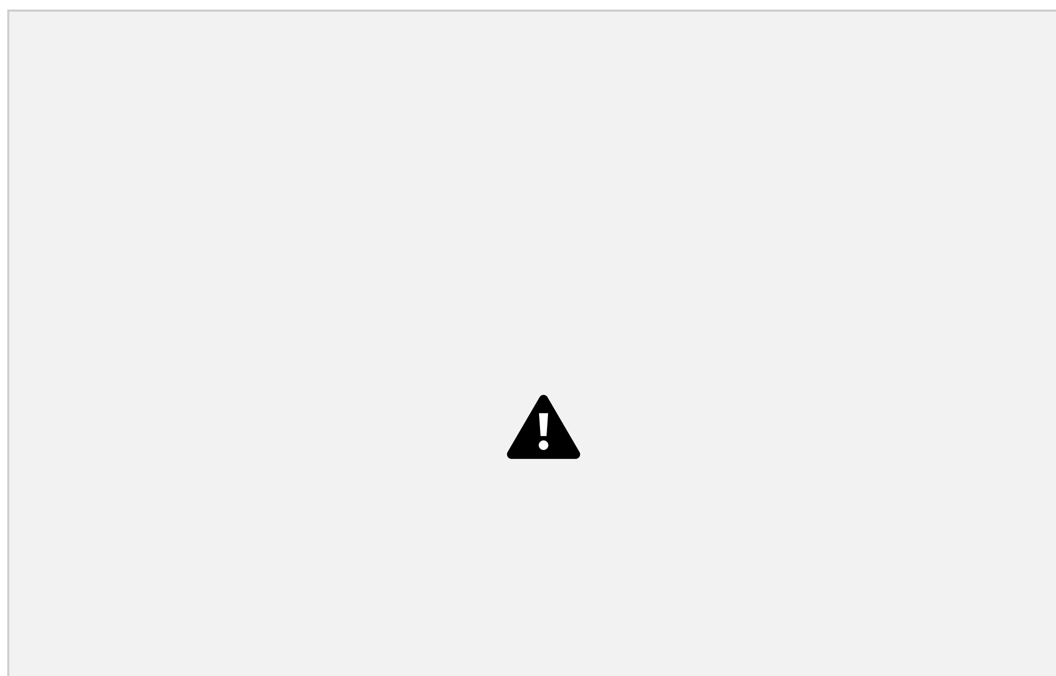
- On a quad-core system with 2 hardware threads per core, the operating system sees 8 logical processors.

Multithreaded Multicore System (Cont.)

- 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



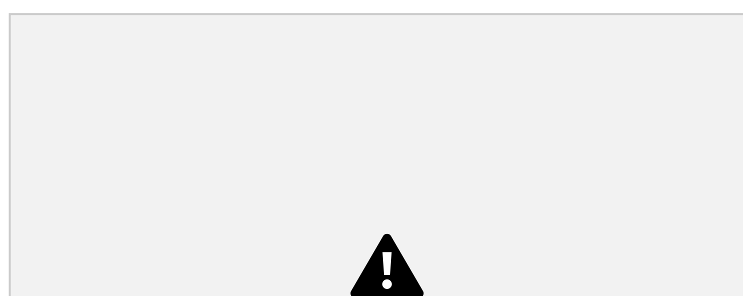
run on the physical
core.

Real-Time CPU Scheduling

- Can present obvious challenges
- **Soft real-time systems** – Critical real-time tasks have the highest priority, but no guarantee as to when tasks will be scheduled
- **Hard real-time systems – task must be serviced by its deadline**

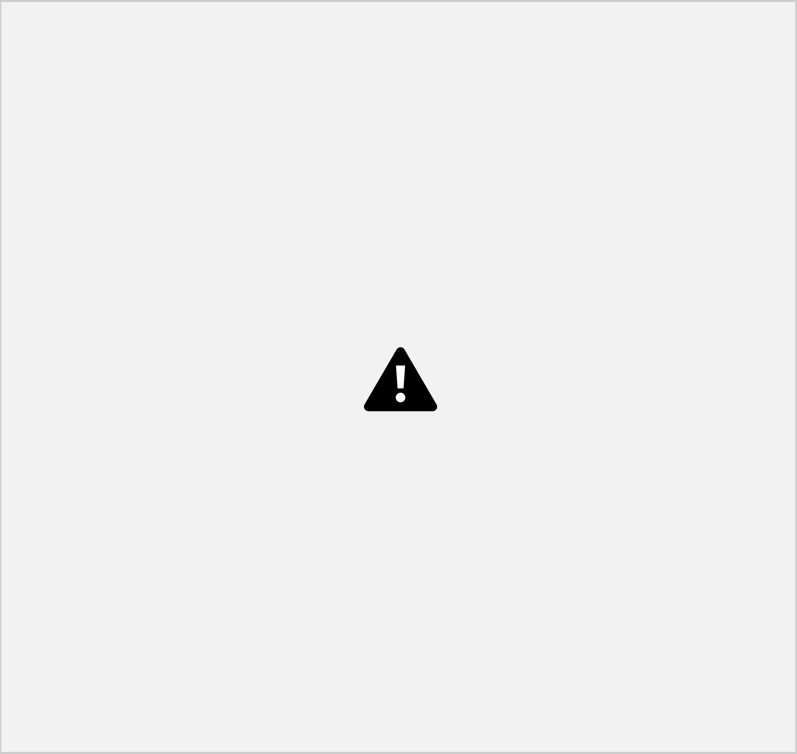
Real-Time CPU Scheduling: Latency

- Event latency – the amount of time that elapses from when an event occurs to when it is serviced.
- Two types of latencies affect performance



1. **Interrupt latency** – time from arrival of interrupt to start of routine that services interrupt
2. **Dispatch latency** – time for schedule to take current process off CPU and switch to another

Interrupt Latency



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

Homework 1

- Read and report:
  - Linux scheduling
  - Windows scheduling

Homework 2

- Deploying program in slides 34, 35

Homework 3

- Do exercises 5.17 and 5.18 in the textbook

End of Lesson 4