Chapter 5: Process Scheduling

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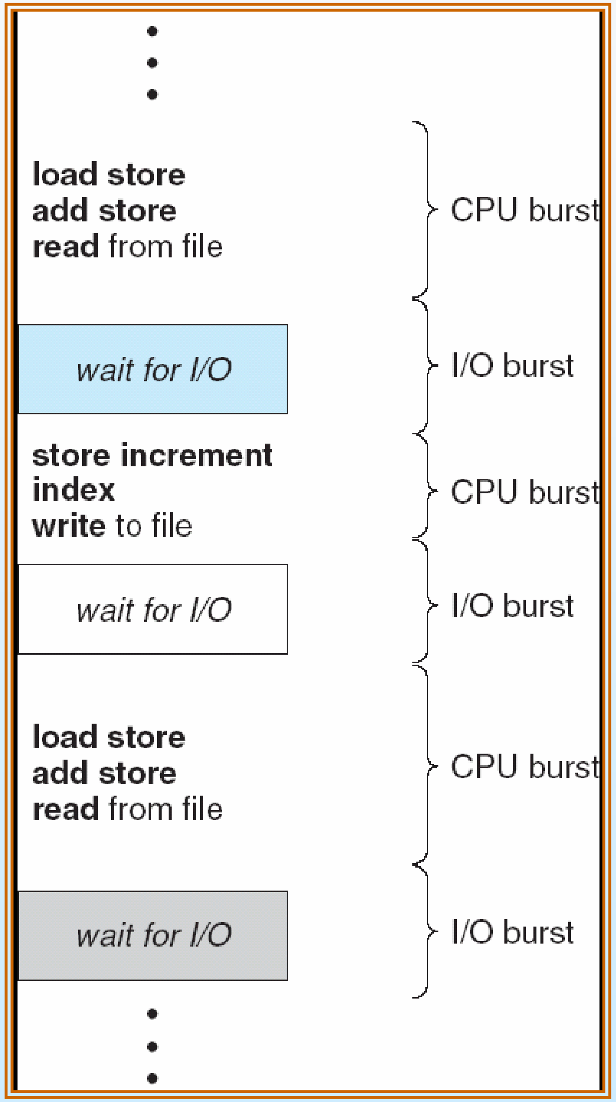
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Thread Scheduling
- Operating Systems Examples
- Algorithm Evaluation

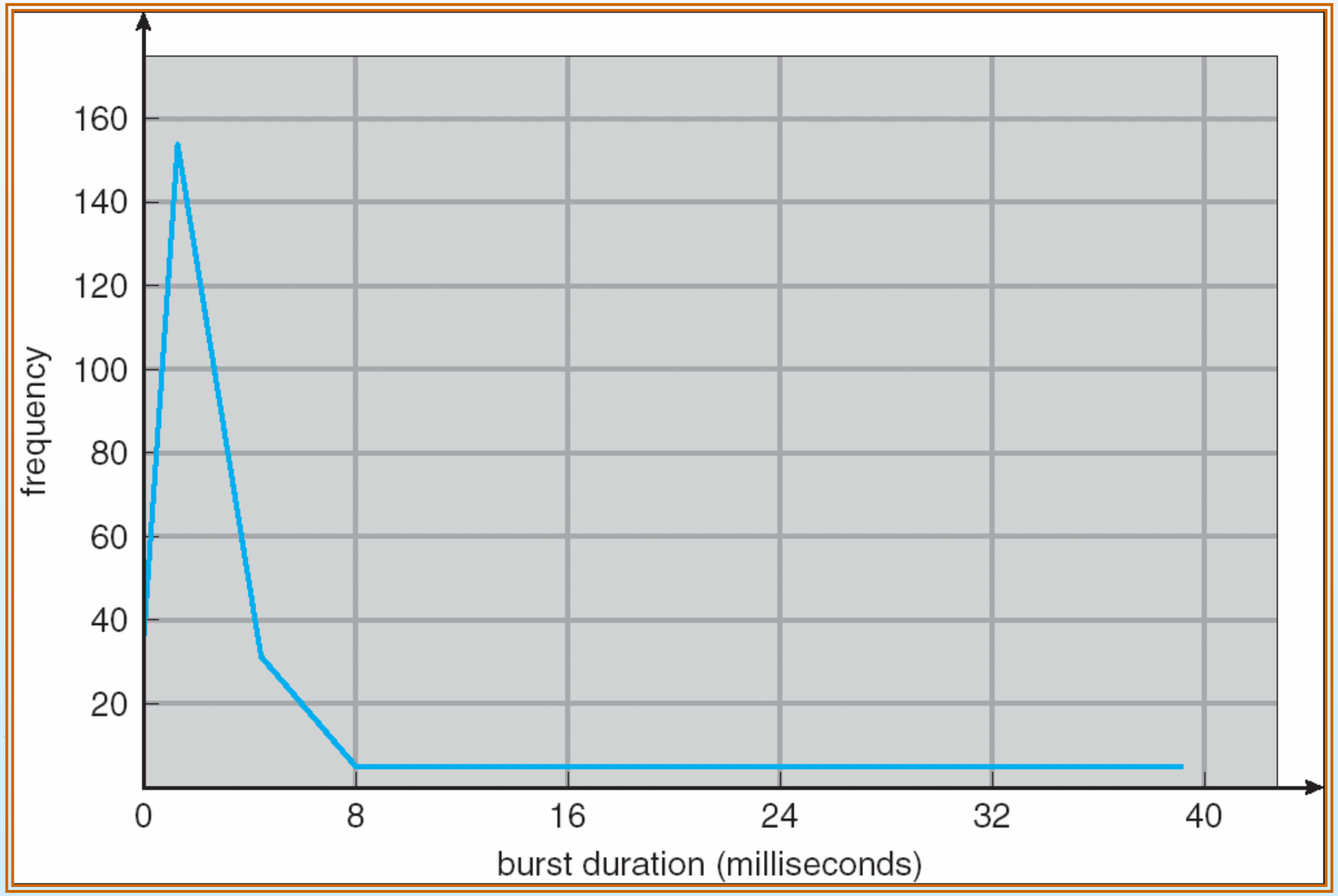
Basic Concepts

- 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 distribution

Alternating Sequence of CPU And I/O Bursts



Histogram of CPU-burst Times



CPU Scheduler

- Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them
- 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 *nonpreemptive*
- All other scheduling is *preemptive*

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

Scheduling Criteria

- CPU utilization – keep the CPU as busy as possible
- Throughput – # of processes that complete their execution per time unit
- Turnaround time – the interval from the time of submission of a process to the time of completion
- 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, **not** output (for time-sharing environment)

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:

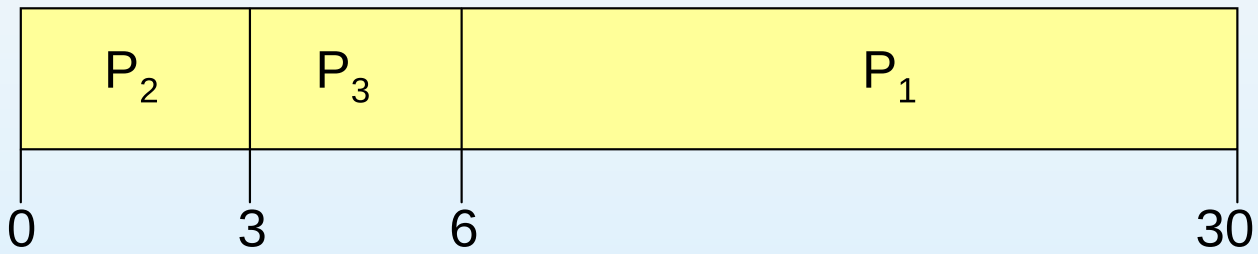
- Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
- Average waiting time: (0 + 24 + 27)/3 = 17

FCFS Scheduling (Cont.)

Suppose that the processes arrive in the order

$$P_2 , P_3 , P_1$$

- The Gantt chart for the schedule is:



- 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

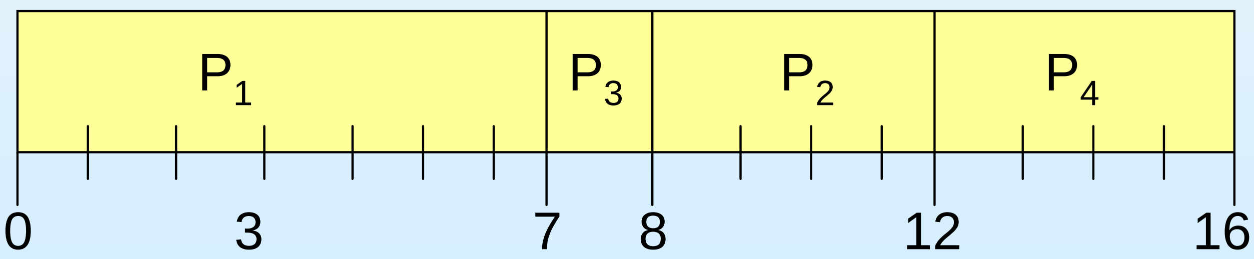
Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
- Two schemes:
  - nonpreemptive – once CPU given to the process it cannot be preempted until completes its CPU burst
  - preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is know as the Shortest-Remaining-Time-First (SRTF)
- SJF is optimal – gives minimum average waiting time for a given set of processes

Example of Non-Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (non-preemptive)

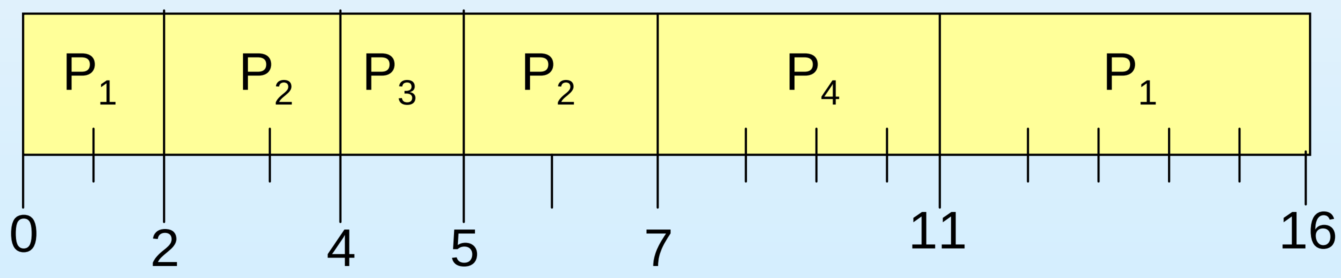


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Example of Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (preemptive)



- Average waiting time = (9 + 1 + 0 +2)/4 = 3

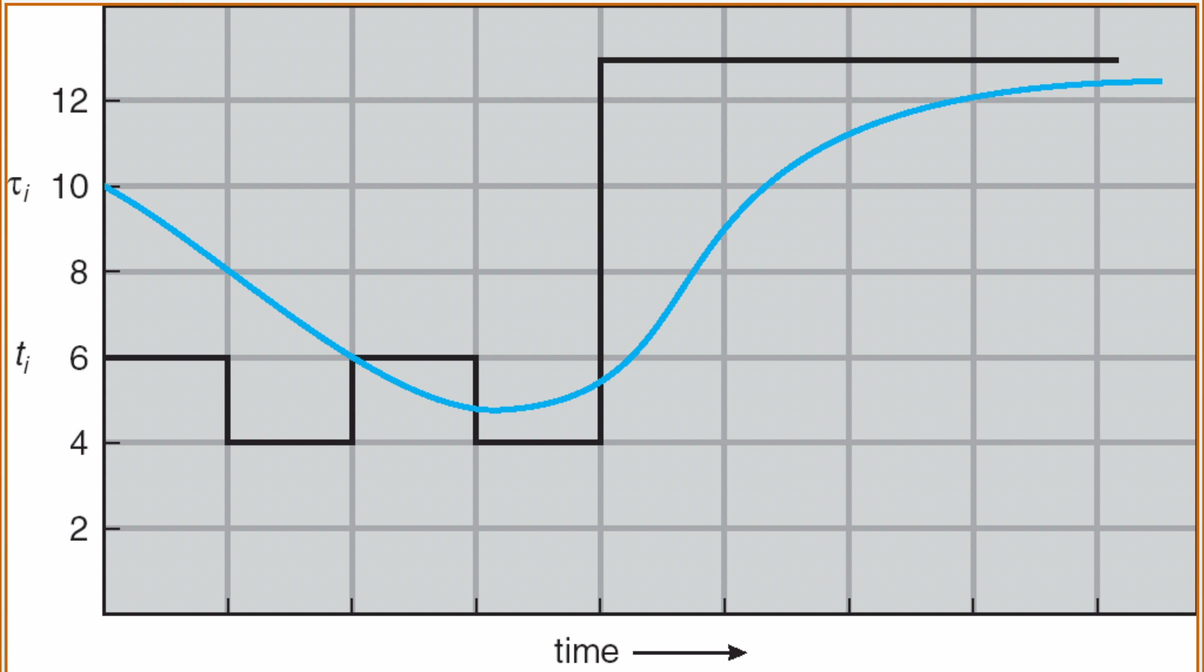
Determining Length of Next CPU Burst

- Can only estimate the length
- Can be done by using the length of previous CPU bursts, using exponential averaging

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

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

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

$$\begin{aligned}\tau_{n+1} = \alpha\ t_n &+ (1 - \alpha)\alpha\ t_{n-1} + \ldots \\ &+ (1 - \alpha)^j \alpha\ t_{n-j} + \ldots \\ &+ (1 - \alpha)^{n+1} \tau_0\end{aligned}$$

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

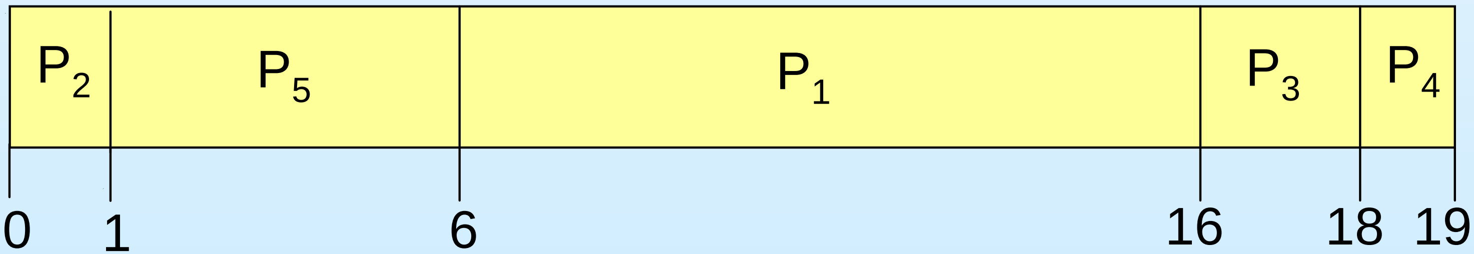
Priority Scheduling

- 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 a priority scheduling where priority is the 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

- The Gantt chart for the schedule is:



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

Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum*), 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.
- Performance
  - q large $\Rightarrow$ FCFS
  - q small $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high
  - Rule of thumb: 80% of the CPU bursts should be shorter than the time quantum

Example of RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

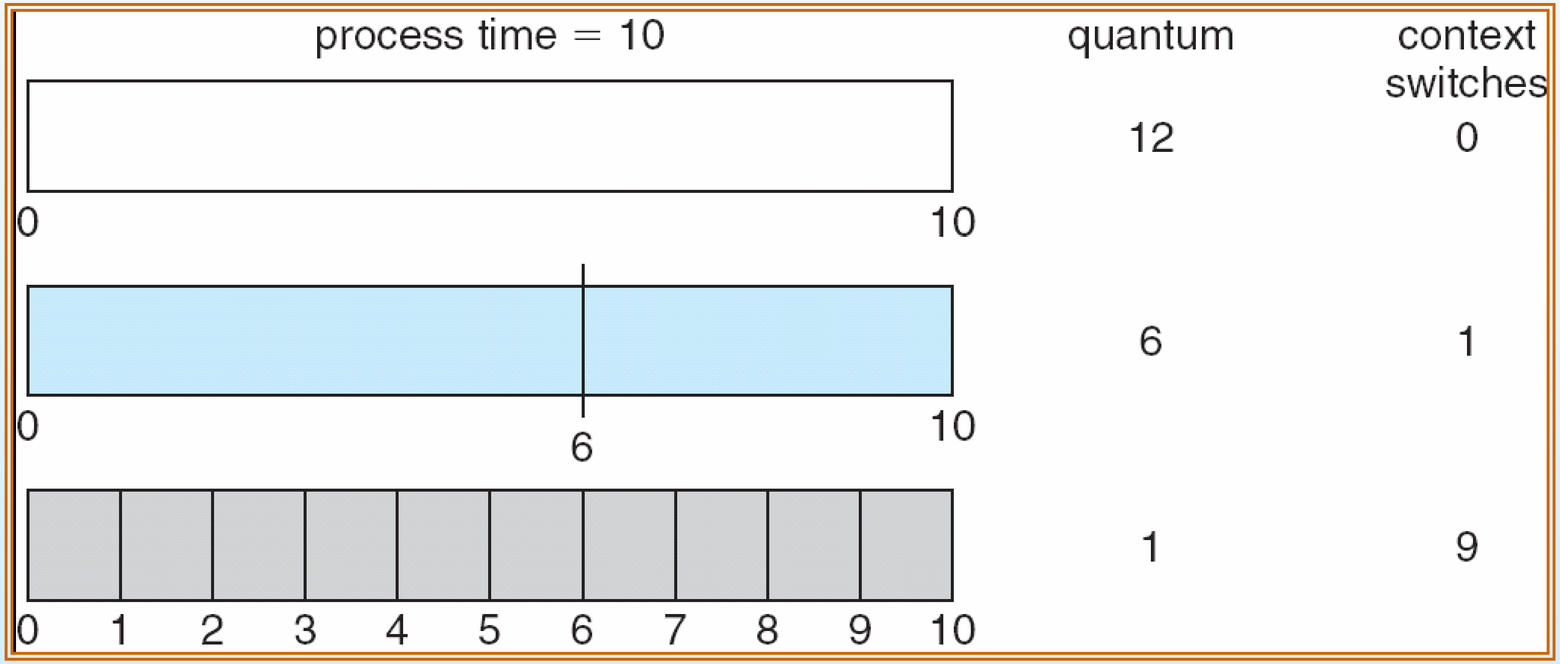
- The Gantt chart is:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

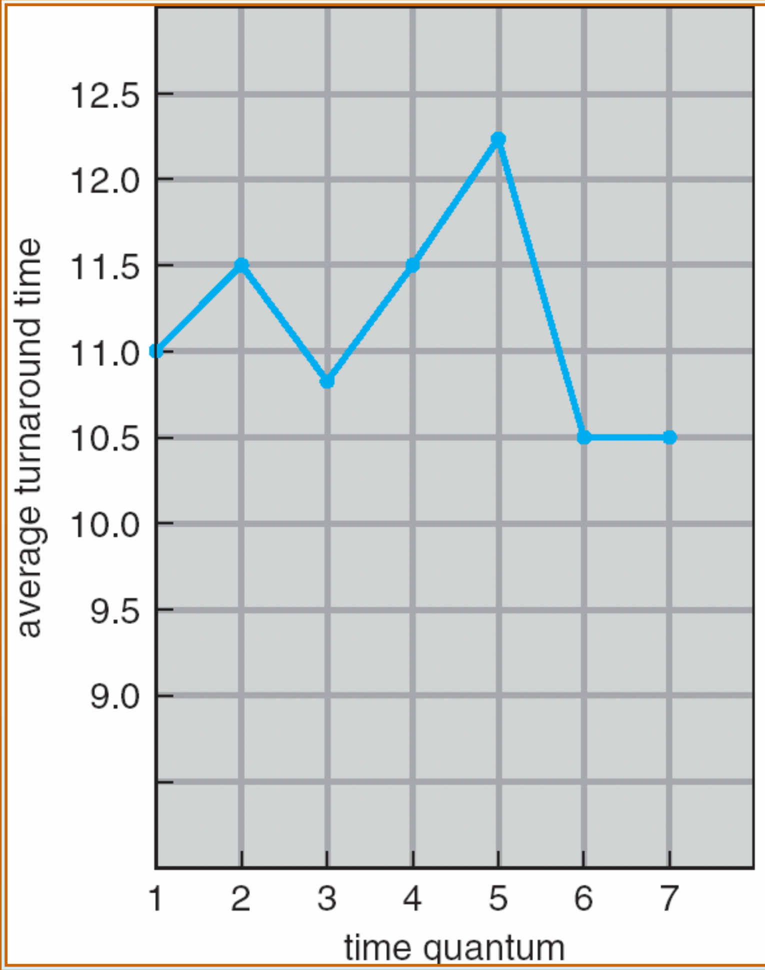
0 20 37 57 77 97 117 121 134 154 162

- Typically, higher average turnaround than SJF, but better *response*

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum

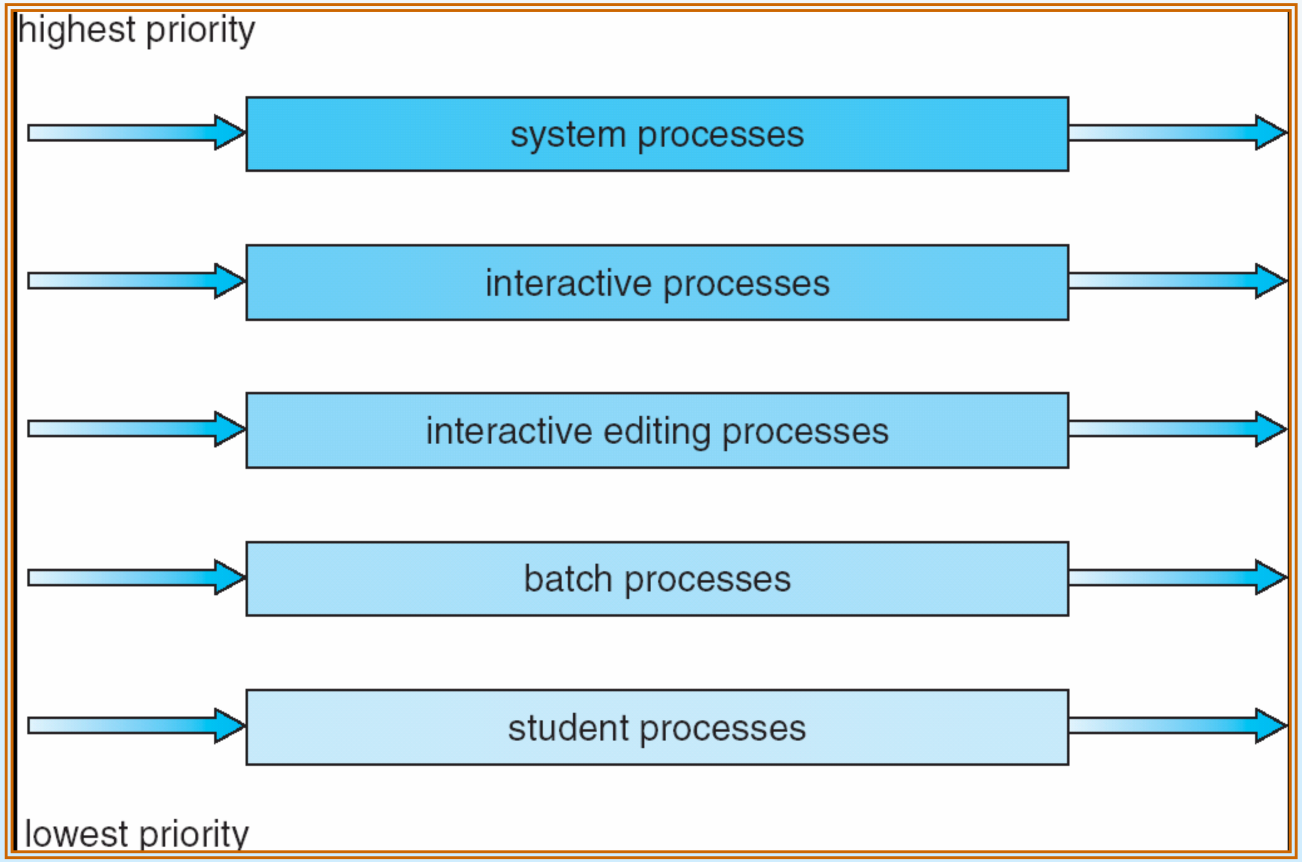


process	time
P_1	6
P_2	3
P_3	1
P_4	7

Multilevel Queue

- Ready queue is partitioned into separate queues:
  foreground (interactive)
  background (batch)
- 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, and 20% to background in FCFS

Multilevel Queue Scheduling



Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way
- The idea is to separate process according to the characteristics of their bursts
  - If a process uses too much CPU time, it will be moved to a low-priority queue.
    - This leaves I/O-bound and interactive processes in the higher-priority queues.
  - If a process waits too long in a low-priority queue, it may be moved to a higher-priority queue.
    - This prevents starvation.

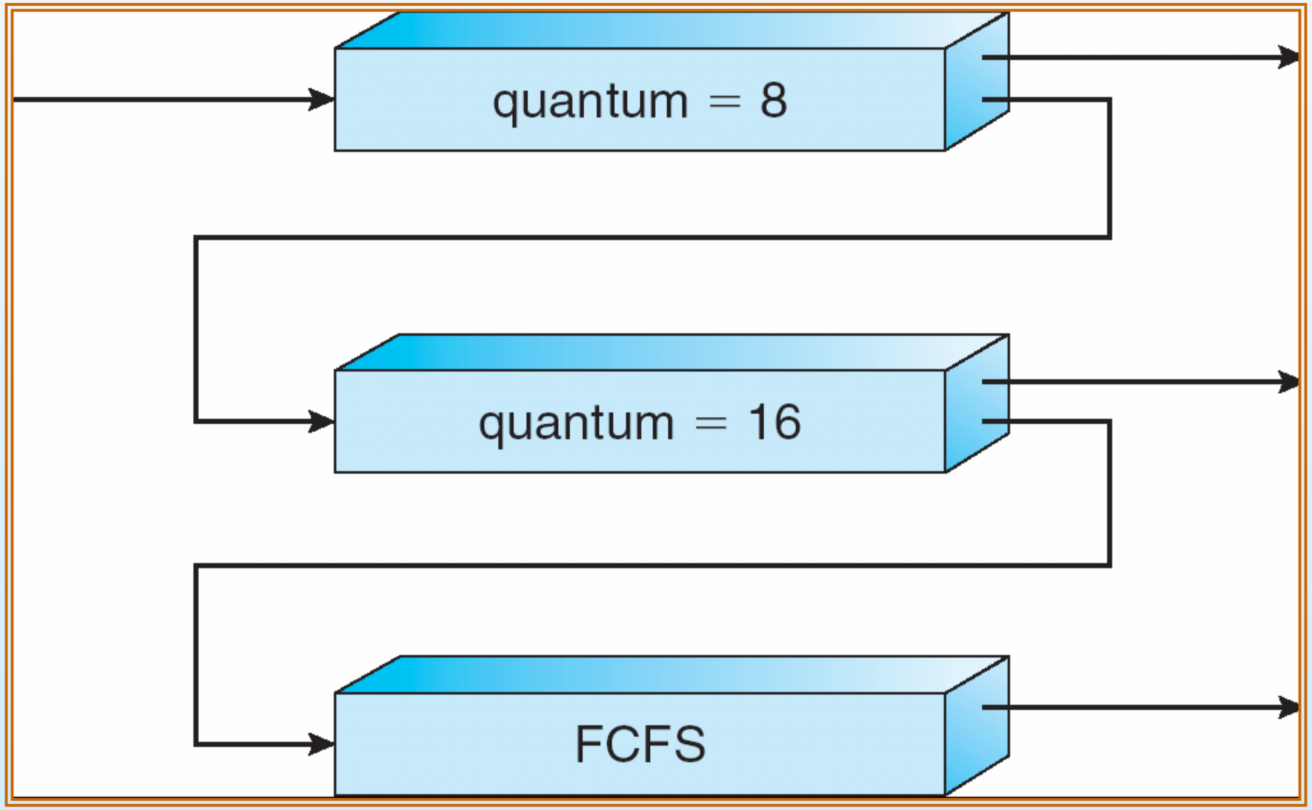
Multilevel Feedback Queue (Cont.)

- 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

Example of Multilevel Feedback Queue

- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds when Q_0 is empty
  - Q_2 – FCFS but only Q_0 and Q_1 are empty
- Scheduling
  - A new job enters queue Q_0. When it gains CPU, job receives 8 milliseconds. If it does not finish in 8 milliseconds, job is moved to queue Q_1.
  - At Q_1 job receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.

Multilevel Feedback Queues



Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- *Homogeneous processors* within a multiprocessor system
- *Load sharing*
- *Asymmetric multiprocessing* – a single processor makes all scheduling decisions; the others execute only user code
  - only one processor accesses the system data structures, alleviating the need for data sharing

Multiple-Processor Scheduling (Cont.)

- Symmetric multiprocessing (SMP) – each processor is self-scheduling
  - Each process has its own queue or shares a common queue
  - Scheduling proceeds by having the scheduler for each processor examine the ready queue and select a process to execute
  - The scheduler must be programmed carefully
    - Ensure that two processors do not choose the same process and that processes are not lost from queue.
- Processor affinity
  - A process has an affinity for the processor on which it is currently running
  - To avoid migration of processes because of the high cost of invalidating and re-populating caches

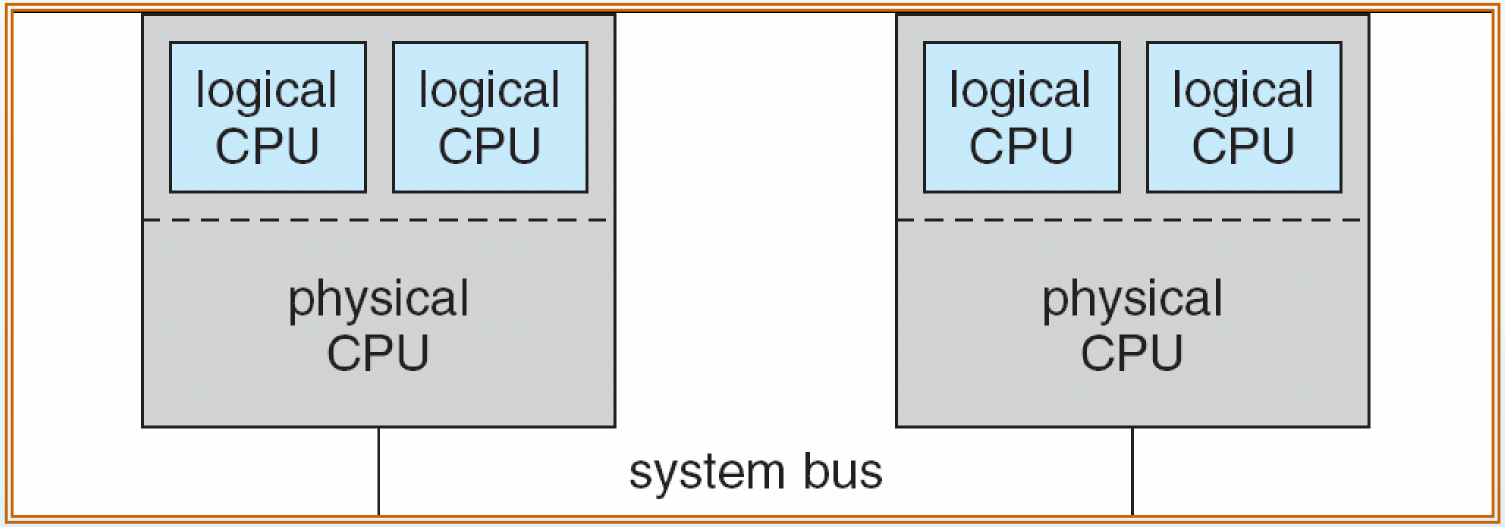
Load Balancing

- To keep the workload evenly distributed across all processors typically with own private ready queue
  - Push migration
    - A specific task periodically checks the load on each processor and evenly distributes the load if an imbalance is found
    - Linux – runs load-balancing algorithm every 200 ms
  - Pull migration
    - An idle processor pulls a waiting task from a busy processor
    - Linux
- Load balancing often counteracts the benefits of processor affinity
  - No absolute rule concerning what policy is best

Symmetric Multithreading

- Symmetric multithreading, SMT, or hyperthreading technology (Intel) provides multiple logical rather than processors
- Each logical processor has its own architecture state, including registers, and interrupt handling
- Each logical processor shares the resources of its physical processor, such as cache and buses
- From OS perspective, threads are scheduled on logical processors
- Note that SMT is a feature provided in hardware, not software
  - Hardware must provide the representation of the architecture state of each logical processor as well as interrupt handling
  - OS need not be designed differently if they are to run on an SMT system, but may be optimized

A Typical SMT Architecture



Real-Time Scheduling

- *Hard real-time* systems – required to complete a critical task within a guaranteed amount of time
- *Soft real-time* computing – requires that critical processes receive priority over less fortunate ones

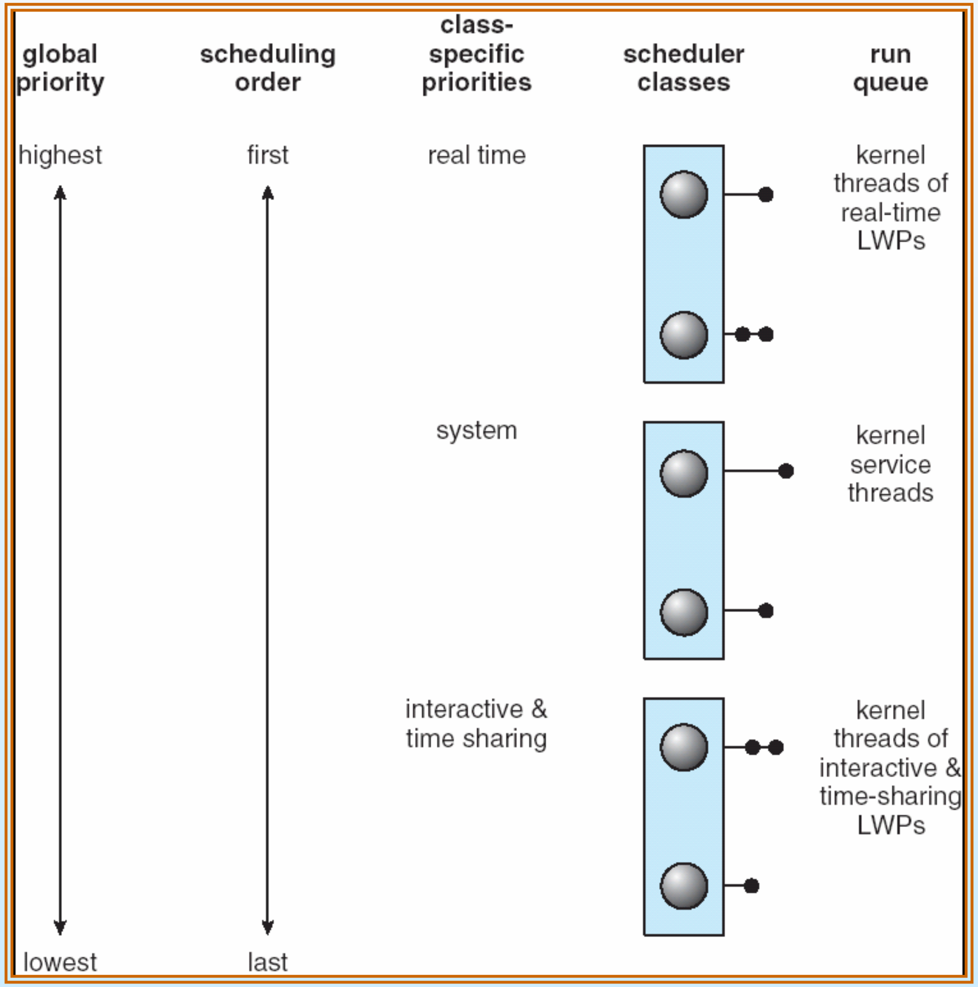
Thread Scheduling

- Local Scheduling – How the threads library decides which thread to put onto an available LWP
  - Process-contention scope (PCS)
- Global Scheduling – How the kernel decides which kernel thread to run next
  - System-contention scope (SCS)
- PCS is done via priority
  - PCS will typically preempt the running thread in favor of a higher-priority thread
  - No guarantee of time slicing among threads of equal priority

Operating System Examples

- Solaris scheduling
- Windows XP scheduling
- Linux scheduling

Solaris 2 Scheduling



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

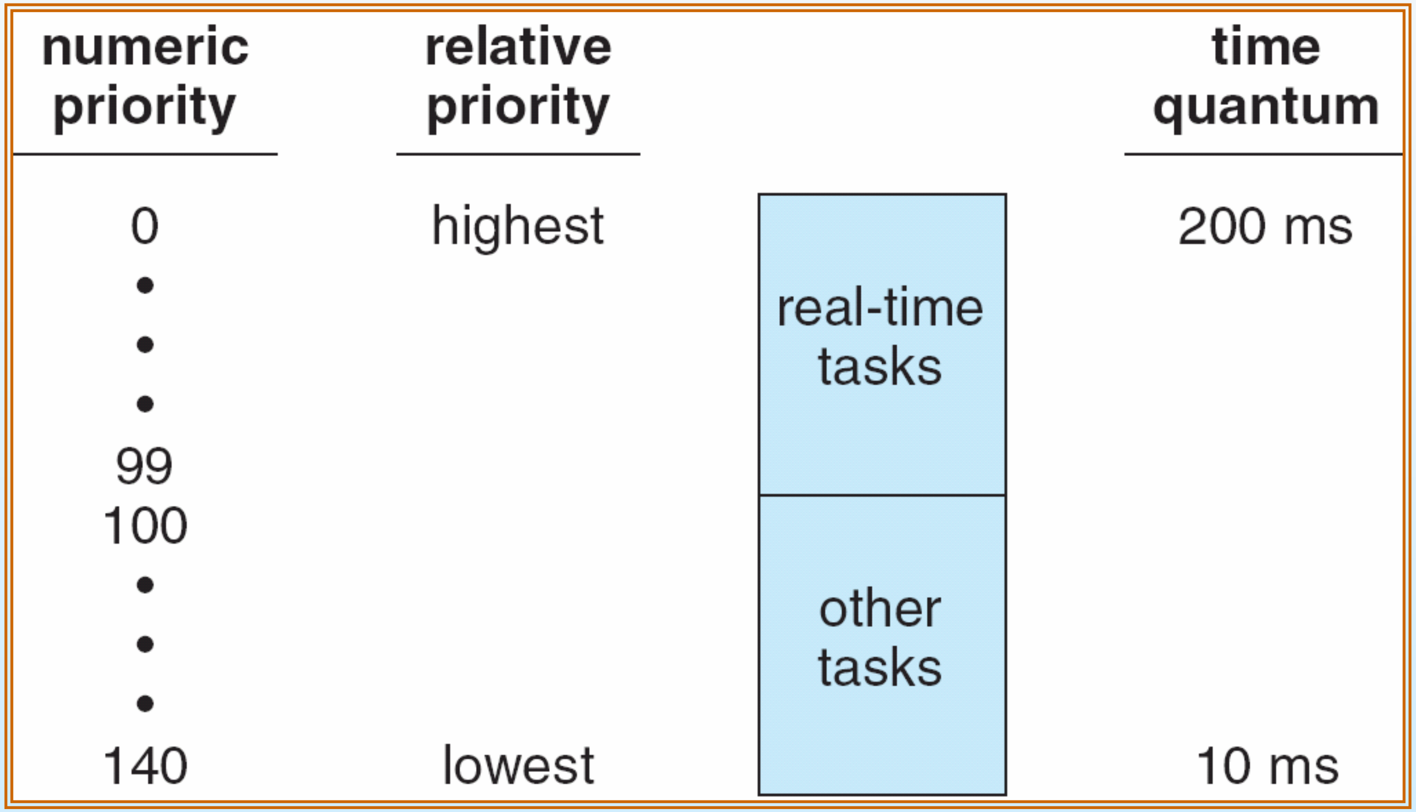
Windows XP Priorities

	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

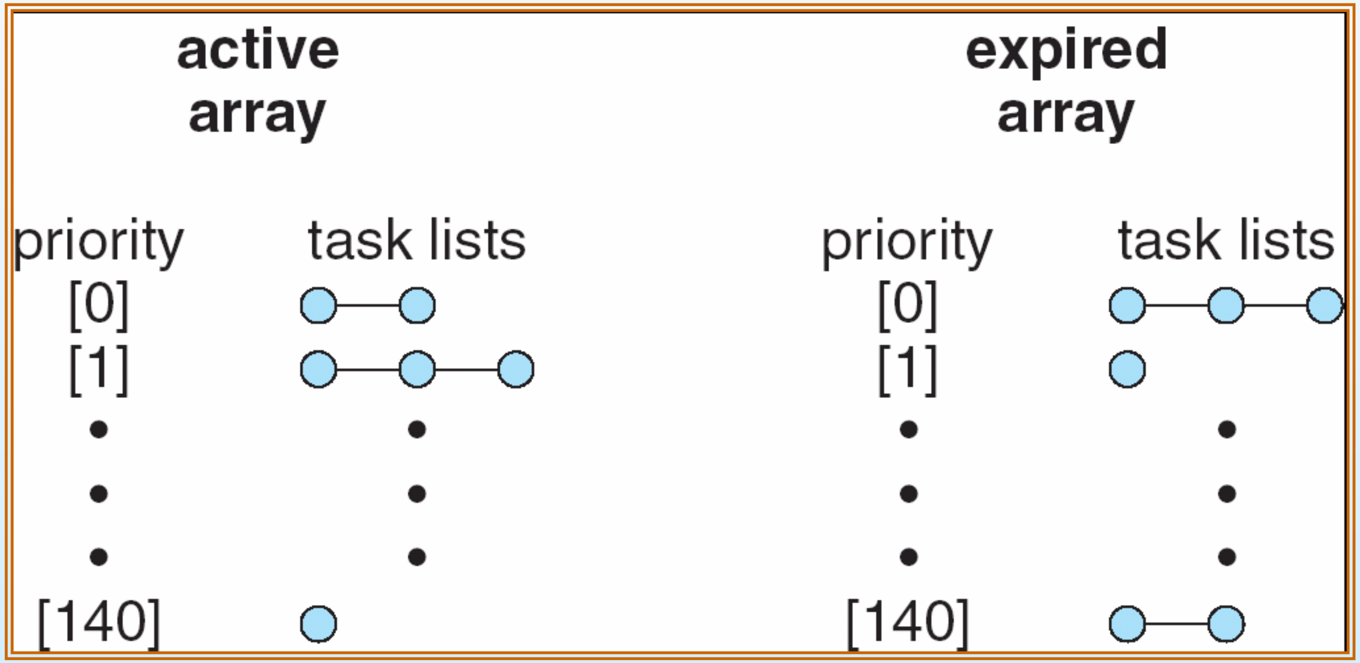
Linux Scheduling

- Two algorithms: time-sharing and real-time
- Time-sharing
  - Prioritized credit-based – process with most credits is scheduled next
  - Credit subtracted when timer interrupt occurs
  - When credit = 0, another process chosen
  - When all processes have credit = 0, recrediting occurs
    - Based on factors including priority and history
- Real-time
  - Soft real-time
  - Posix.1b compliant – two classes
    - FCFS and RR
    - Highest priority process always runs first

The Relationship Between Priorities and Time-slice length



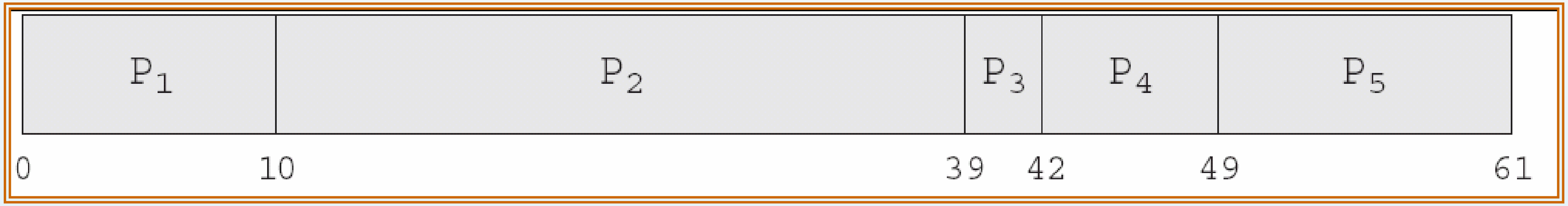
List of Tasks Indexed According to Priorities



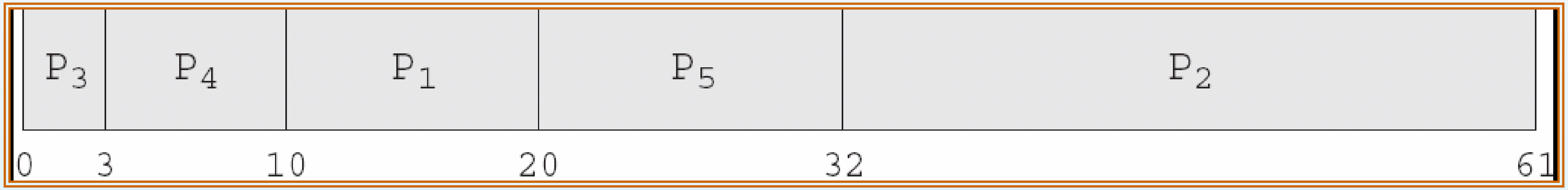
Algorithm Evaluation

- Deterministic modeling – takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Queueing models
- Simulation
- Implementation

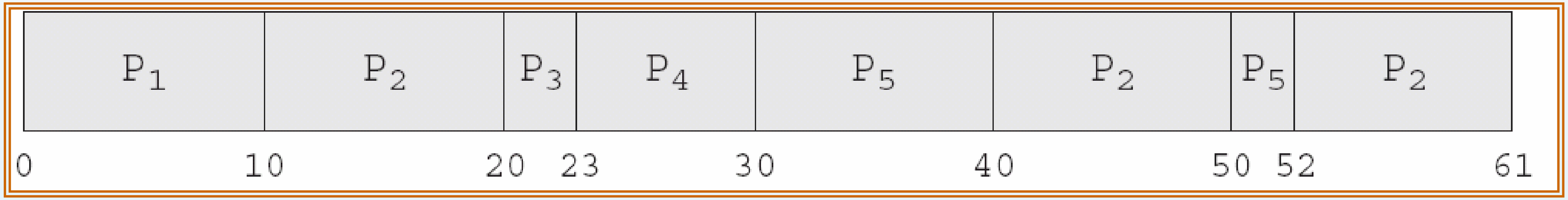
In-5.7



In-5.8



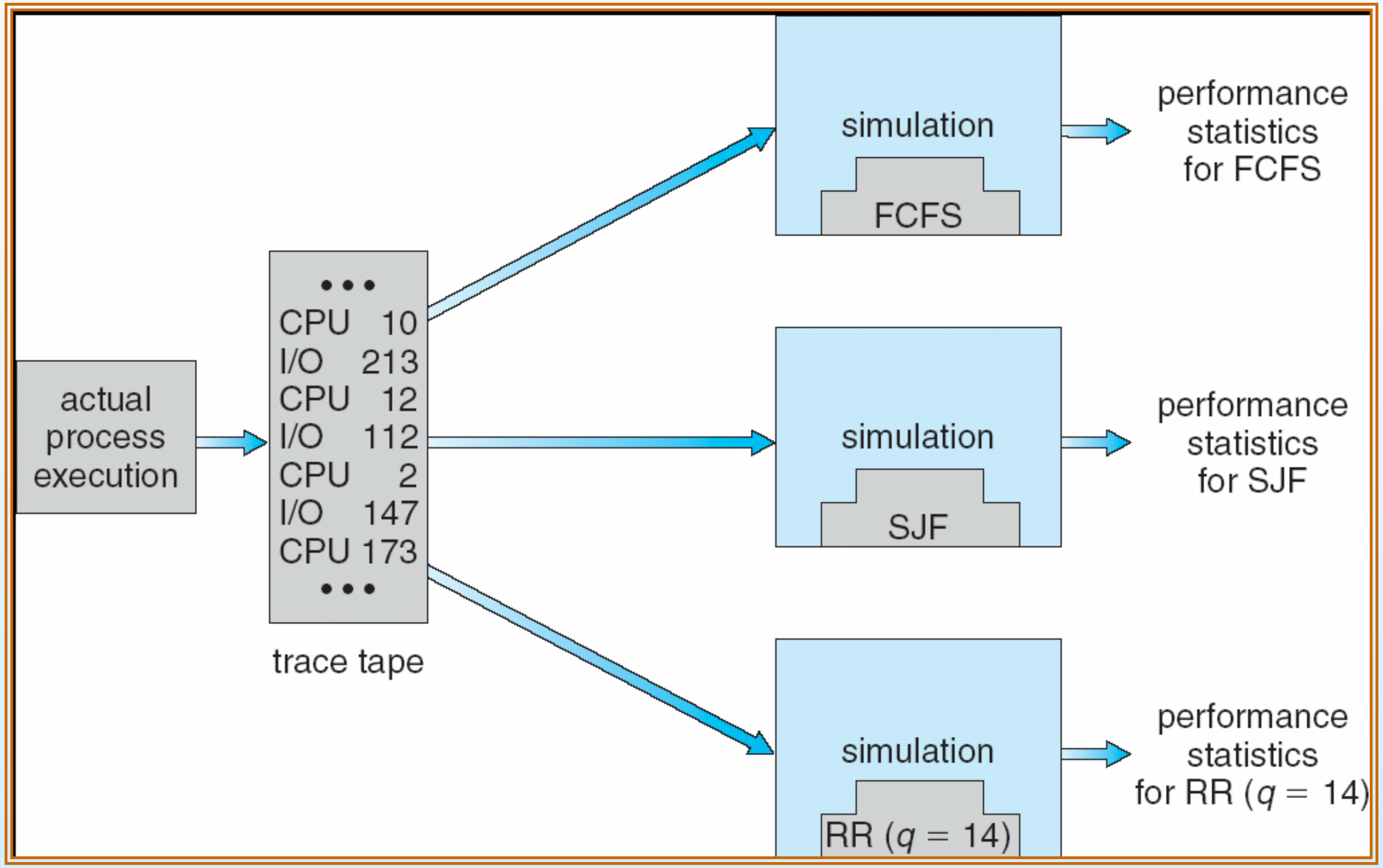
In-5.9



Queueing Models

- Model the computer system as a network of servers
  - Each server has a queue of waiting processes
- Knowing arrival rates and service rates
  - Utilization, queue length, wait time, and so on can be obtained
- A lot of math
- Arrival and service distributions may not by accurate, which are often defined in mathematically tractable but unrealistic ways.

Simulation


actual
process
execution
• • •
CPU 10
I/O 213
CPU 12
I/O 112
CPU 2
I/O 147
CPU 173
• • •
trace tape
simulation
FCFS
performance
statistics
for FCFS
simulation
SJF
performance
statistics
for SJF
simulation
RR (q = 14)
performance
statistics
for RR (q = 14)

Implementation

- The only completely accurate way to evaluate a scheduling algorithm
  - Code it, put in the system and see how it work
- Expensive

End of Chapter 5

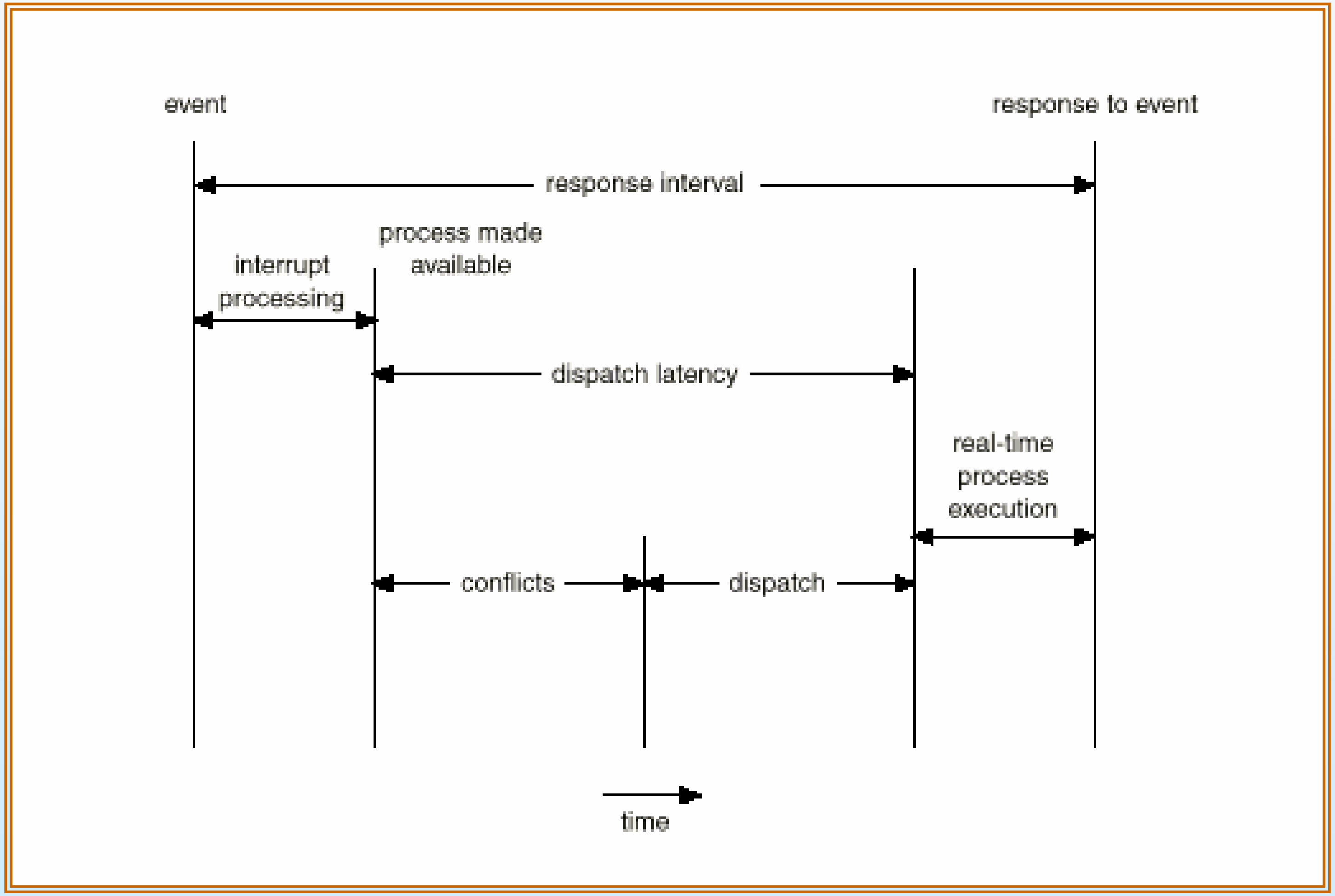
Pthread Scheduling API

```
#include <pthread.h>
#include <stdio.h>
#define NUM THREADS 5
int main(int argc, char *argv[])
{
         int i;
        pthread t tid[NUM THREADS];
        pthread attr t attr;
        /* get the default attributes */
        pthread attr init(&attr);
        /* set the scheduling algorithm to PROCESS or SYSTEM */
        pthread attr setscope(&attr, PTHREAD SCOPE SYSTEM);
        /* set the scheduling policy - FIFO, RT, or OTHER */
        pthread attr setschedpolicy(&attr, SCHED OTHER);
        /* create the threads */
        for (i = 0; i < NUM THREADS; i++)
                  pthread create(&tid[i],&attr,runner,NULL);
```

Pthread Scheduling API

```
        /* 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)
{
        printf("I am a thread\n");
        pthread exit(0);
}
```

Dispatch Latency



Java Thread Scheduling

- JVM Uses a Preemptive, Priority-Based Scheduling Algorithm

- FIFO Queue is Used if There Are Multiple Threads With the Same Priority

Java Thread Scheduling (cont)

JVM Schedules a Thread to Run When:

1. The Currently Running Thread Exits the Runnable State
2. A Higher Priority Thread Enters the Runnable State

* Note – the JVM Does Not Specify Whether Threads are Time-Sliced or Not

Time-Slicing

Since the JVM Doesn't Ensure Time-Slicing, the yield() Method May Be Used:

```
while (true) {
        // perform CPU-intensive task
        . . .
        Thread.yield();
}
```

This Yields Control to Another Thread of Equal Priority

Thread Priorities

Priority	**Comment**
Thread.MIN_PRIORITY	Minimum Thread Priority
Thread.MAX_PRIORITY	Maximum Thread Priority
Thread.NORM_PRIORITY	Default Thread Priority

Priorities May Be Set Using setPriority() method:

```
setPriority(Thread.NORM_PRIORITY + 2);
```