Chapter 5: CPU Scheduling

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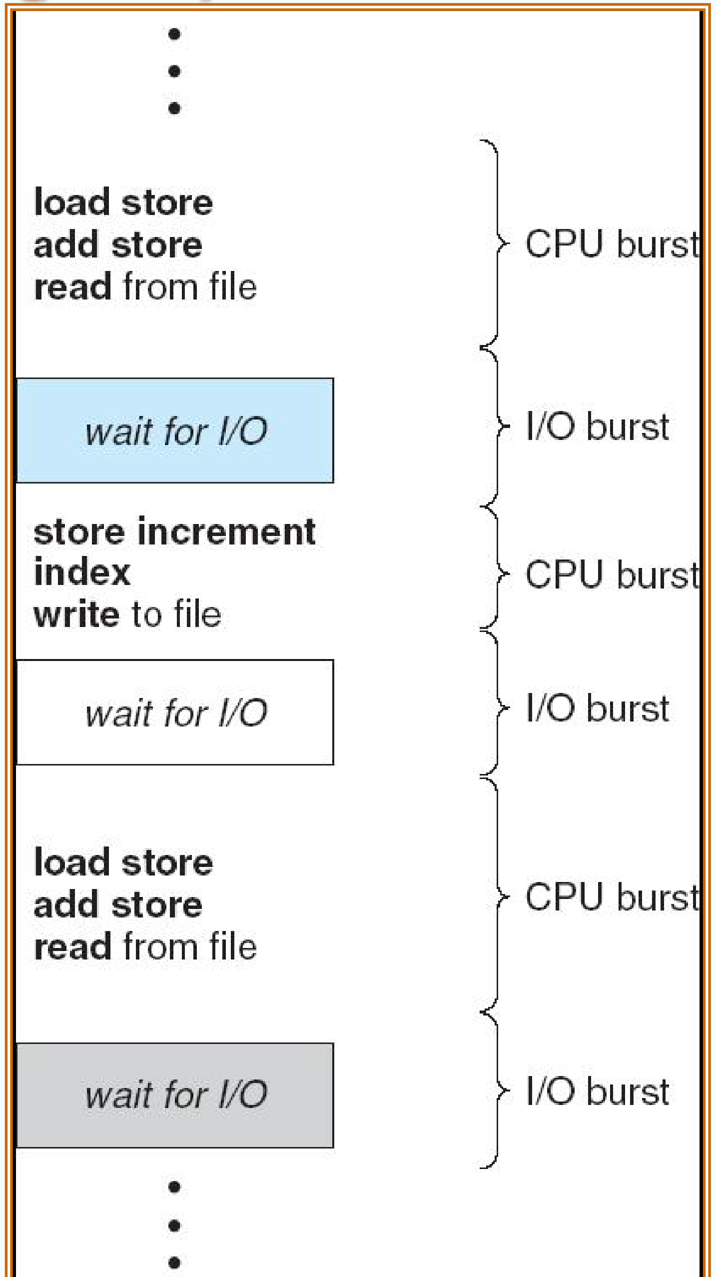
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Real-Time Scheduling
- Thread Scheduling
- Operating Systems Examples
- Java Thread Scheduling
- Algorithm Evaluation

Basic Concepts

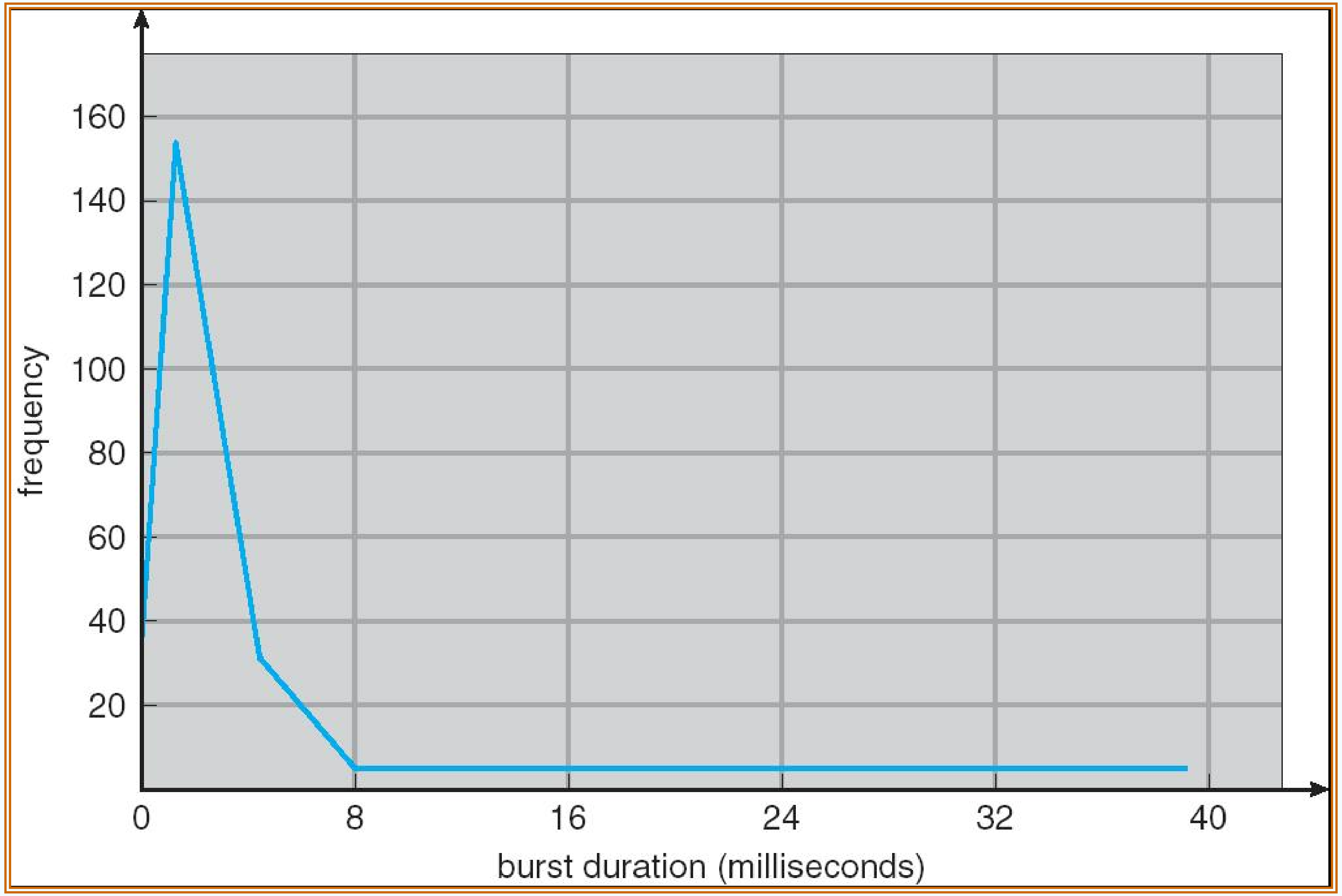
- Maximum CPU utilization obtained with multiprogramming
- CPU–I/O Burst Cycle – Process execution consists of a *cycle* of CPU execution and I/O wait
- CPU burst distribution

Alternating Sequence of CPU And I/O Bursts



A burst is an instance of breaking

Histogram of CPU-burst Times



CPU Scheduler

Remember the long-term and short-term schedulers

- 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. When a process switches from the running state to the waiting state *(e.g. I/O request or an invocation of wait())*
  2. When a process switches from the running state to the ready state *(e.g., when an interrupt occurs)*
  3. When a process switches from the waiting state to the ready state *(e.g., at completion of I/O)*
  4. When a process 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

Dispatch Latency

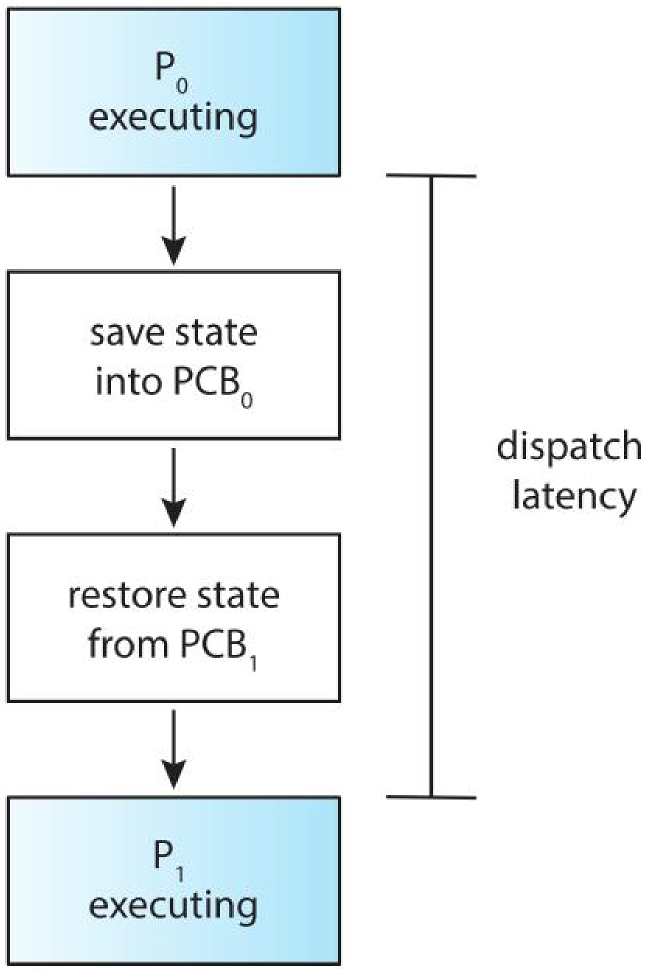


Figure 5.3 The role of the dispatcher.

Scheduling Criteria

- CPU utilization (CPU利用率) – keep the CPU as busy as possible
- Throughput (吞吐率)– # of processes that complete their execution per time unit
- Turnaround time (周转时间)– amount of time to execute a particular process
- Waiting time (等待时间)– amount of time a process has been waiting in the ready queue
- Response time (响应时间)– amount of time it takes from when a request was submitted until the *first* response is produced, **not** output (for time-sharing environment)

Not to confuse with 'waiting' state

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 (I/O-bound processes wait for the CPU-bound one)

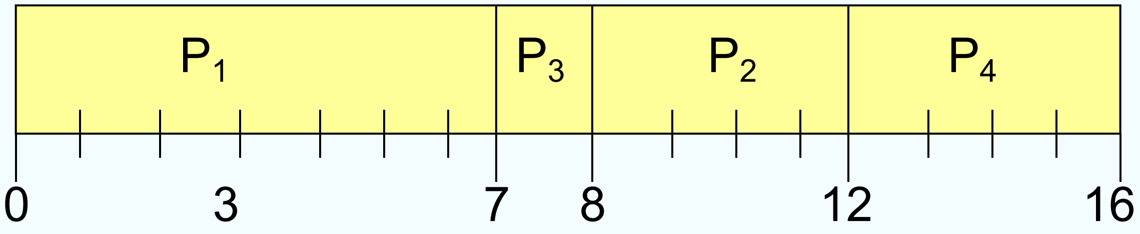
Shortest-Job-First (SJF) Scheduling

- 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 known 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)

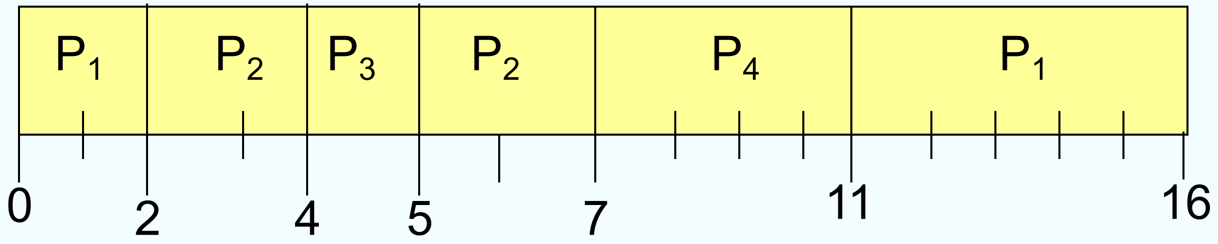


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

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

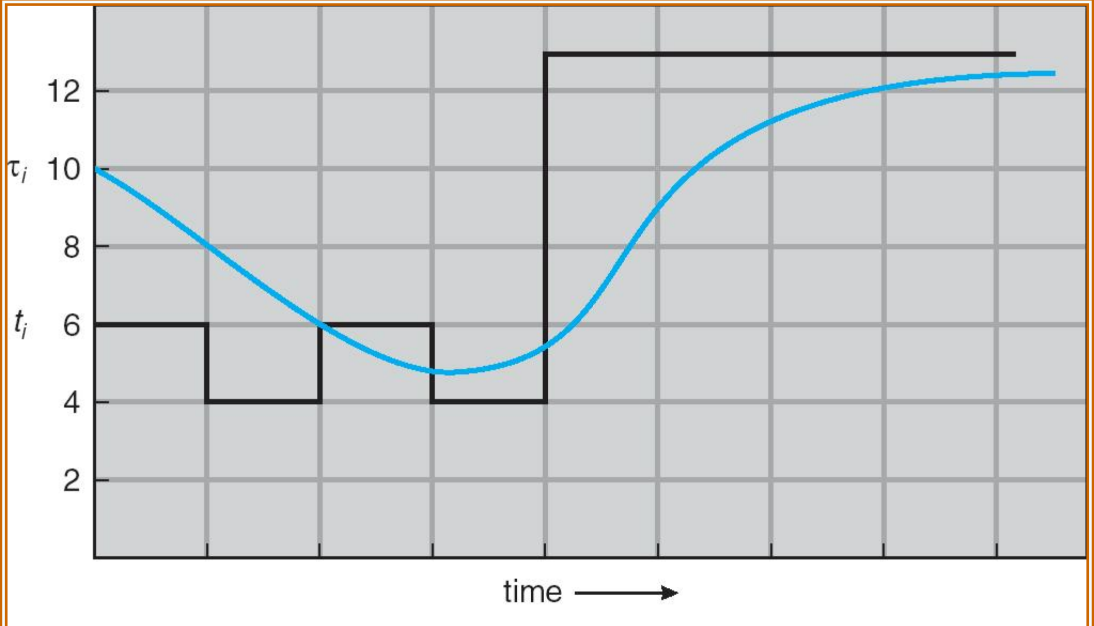
Determining Length of Next CPU Burst

- Unfortunately, no way to know the length of the next burst
- Can only estimate the length
- 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. $\alpha, 0 \le \alpha \le 1$
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

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$
  - 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:

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

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

Question

- Prove that SJF is Optimal in average waiting time. (Non-preemptive case)

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

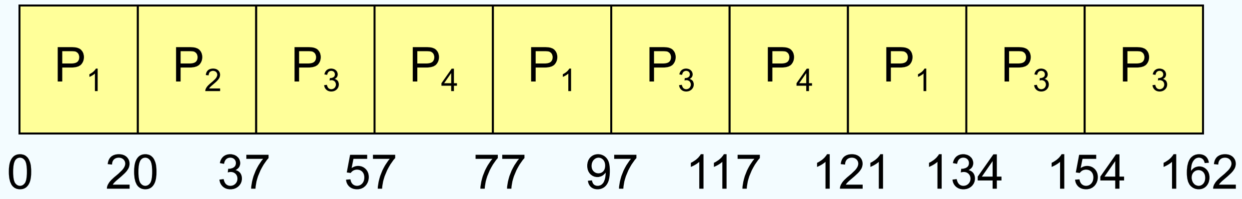
Round Robin (RR)

- 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 $\Rightarrow$ FIFO
  - q small $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high
- *Question: What are the waiting times of RR?*

Example of RR with Time Quantum = 20

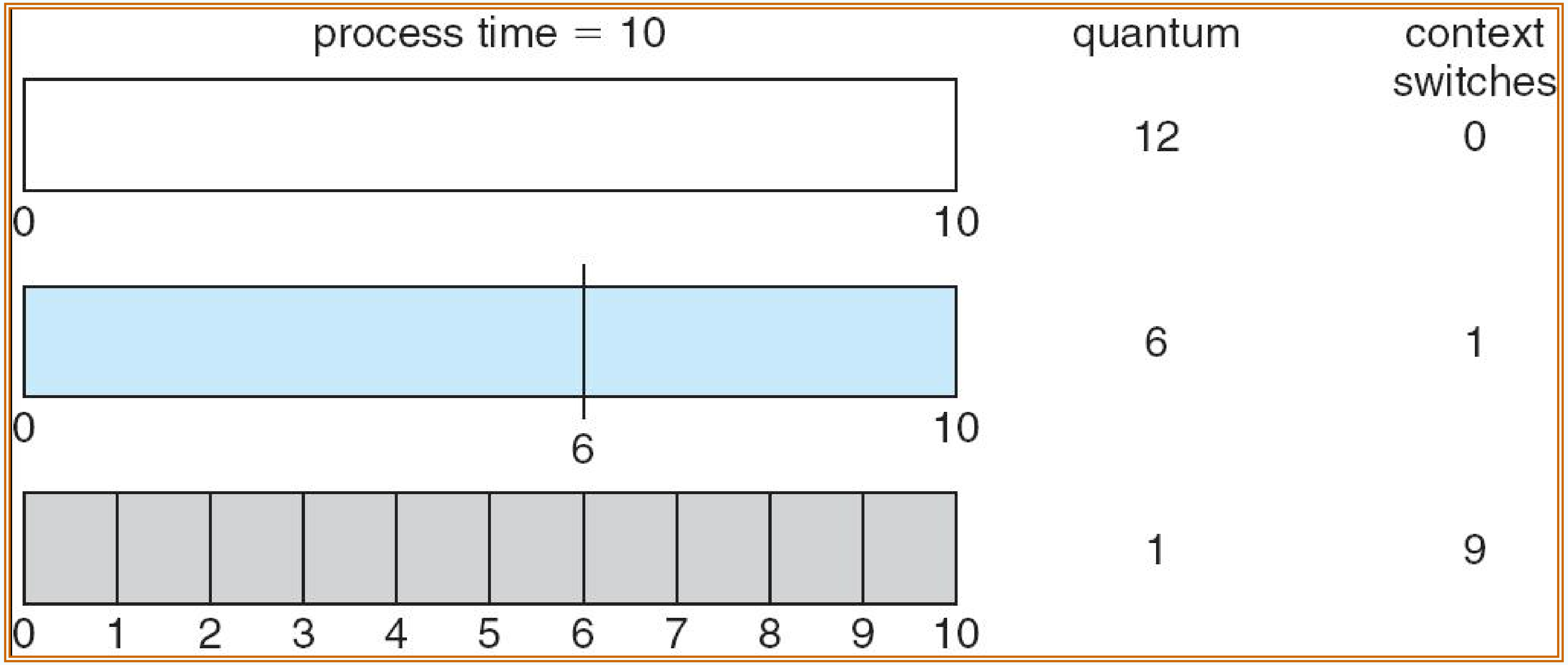
Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

- The Gantt chart is:

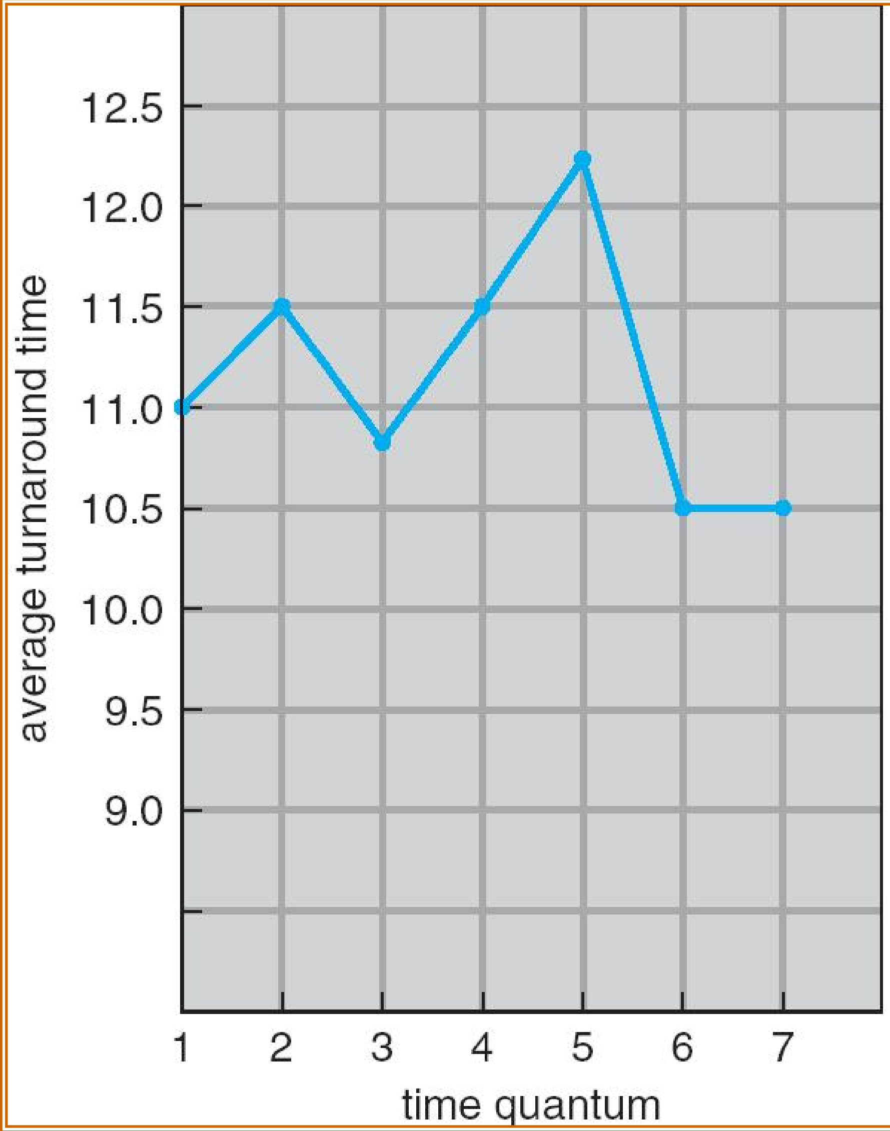


- Typically, higher average turnaround than SJF, but better *response*

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



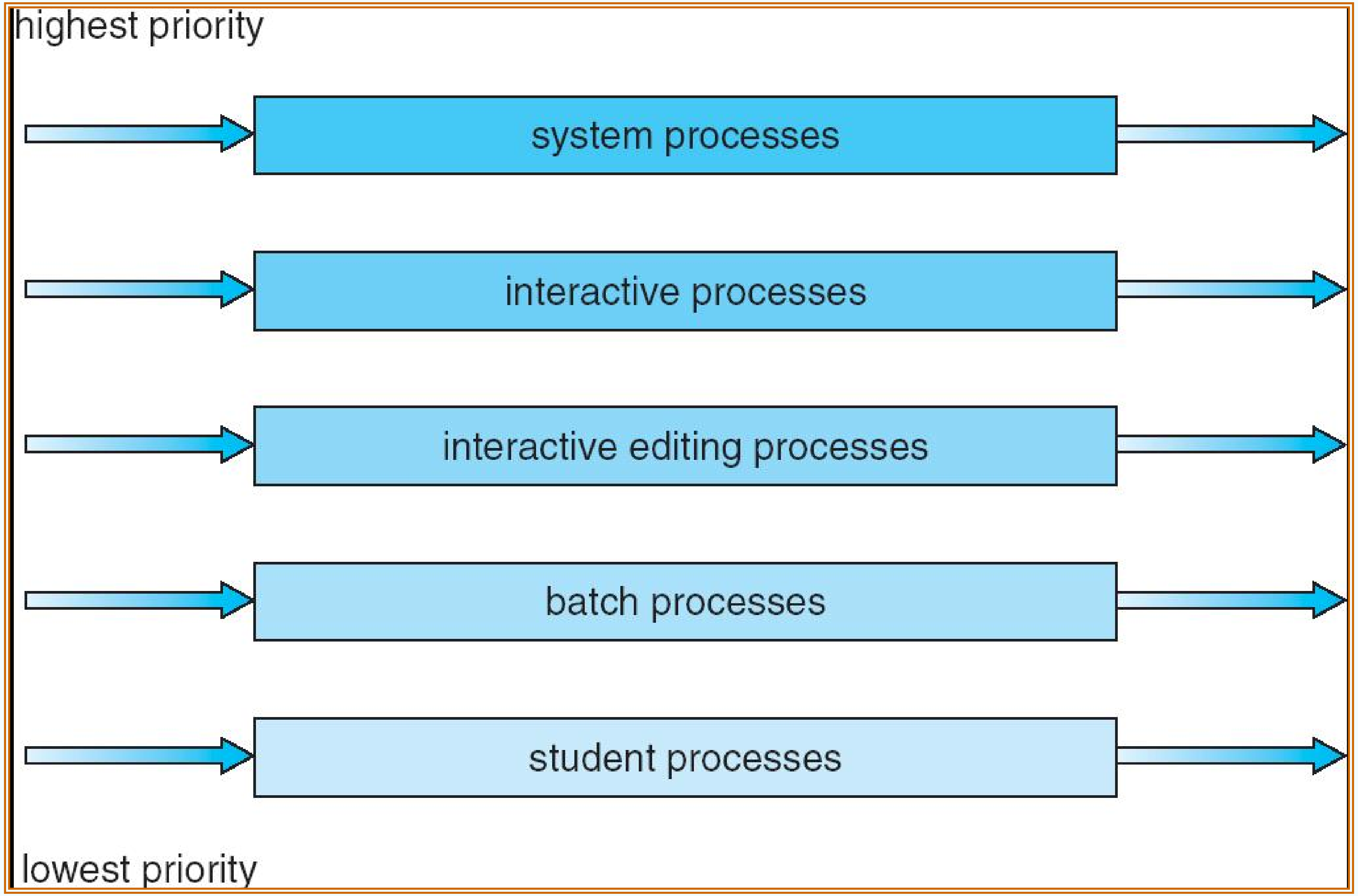
process	time
P_1	6
P_2	3
P_3	1
P_4	7

Question: what's the turnaround time for SJF?

Multilevel Queue

- Ready queue is partitioned into separate queues:
  foreground (interactive)
  background (batch)
- Each queue has its own scheduling algorithm, for example
  - 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



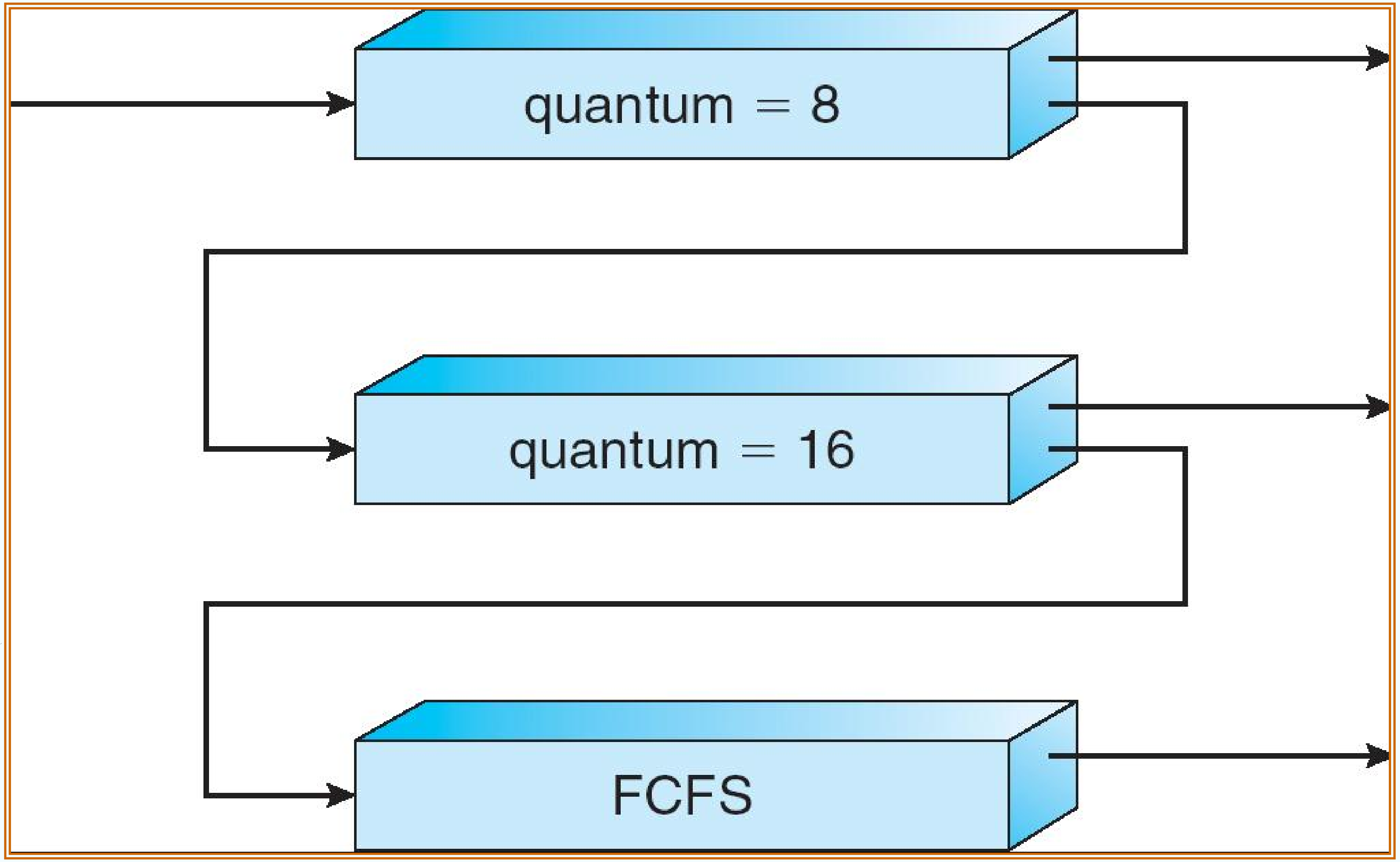
Multilevel Feedback Queue

- 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

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 job enters queue Q_0 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 Q_1.
  - At Q_1 job is again served FCFS and 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
- *Load balancing*
- *Asymmetric multiprocessing* – only one processor accesses the system data structures, alleviating the need for data sharing; others execute only user code.
- *Symmetric multiprocessing* (SMP) – each processor is self-scheduling. Multiple processors might access and update a common data structure.

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

- Also known as the Contention Scope

- Local Scheduling (Process-Contention Scope) – How the threads library decides which thread to put onto an available LWP

- Global Scheduling (System-Contention Scope) – How the kernel decides which kernel thread to run next

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, RR, 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);
```

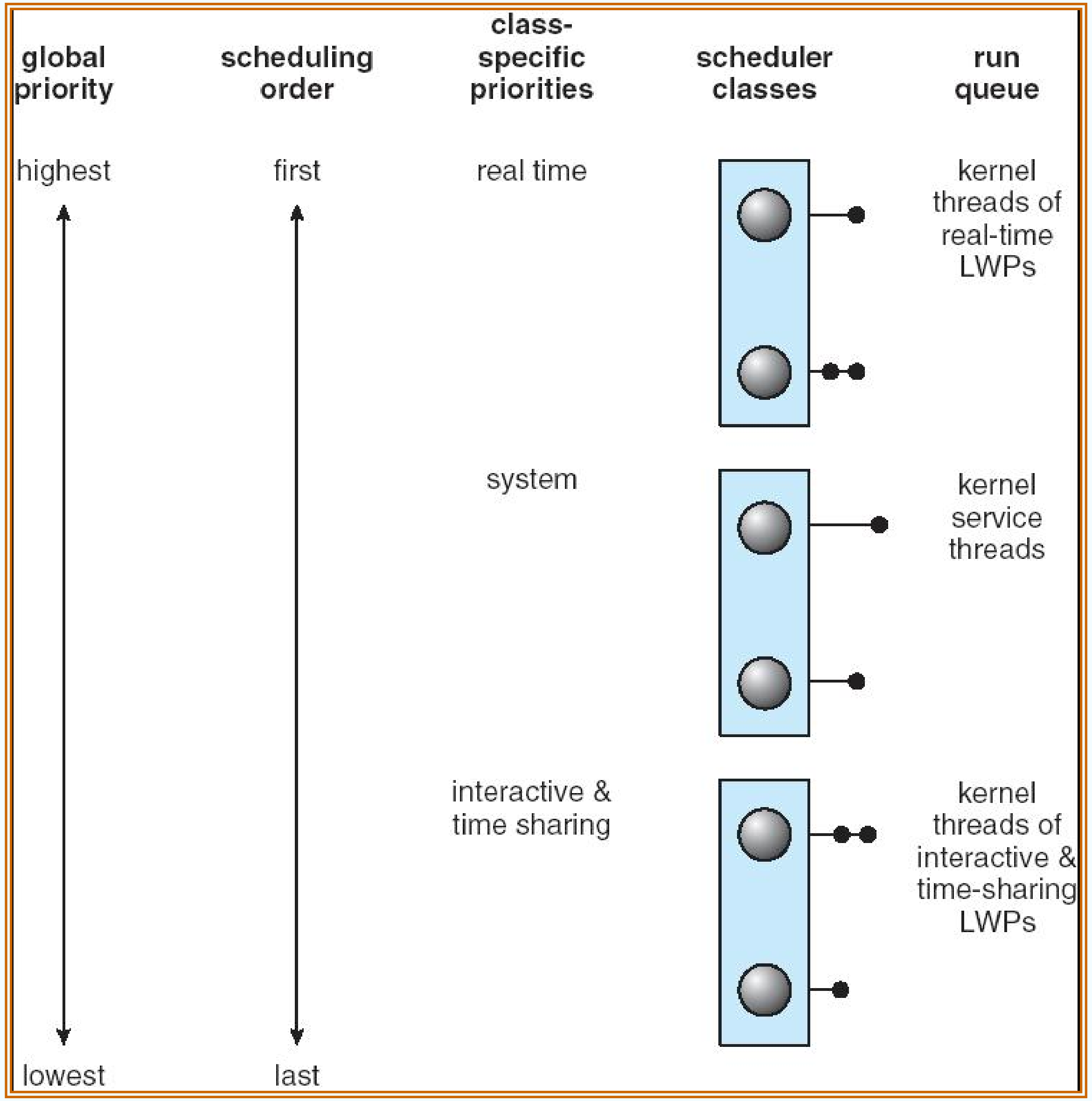
Pthread Scheduling API

```
    /* 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);
}
```

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 **low**	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	[illegible]
45	40	35	[illegible]
50	40	40	[illegible]
55	40	45	58
59 **high**	20	49	59

Higher priority for better interactivity

Priority lowered when quantum expired.

Windows XP Priorities

Priority classes

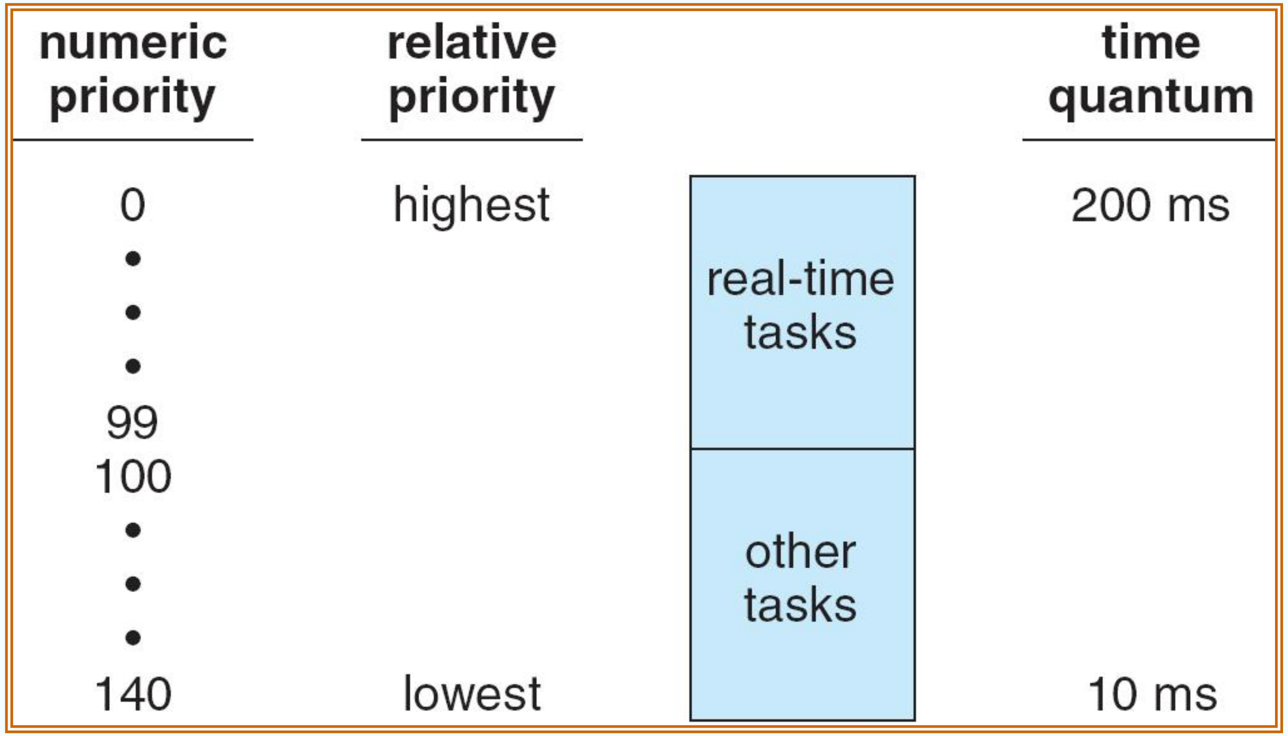
Relative Priorities

	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

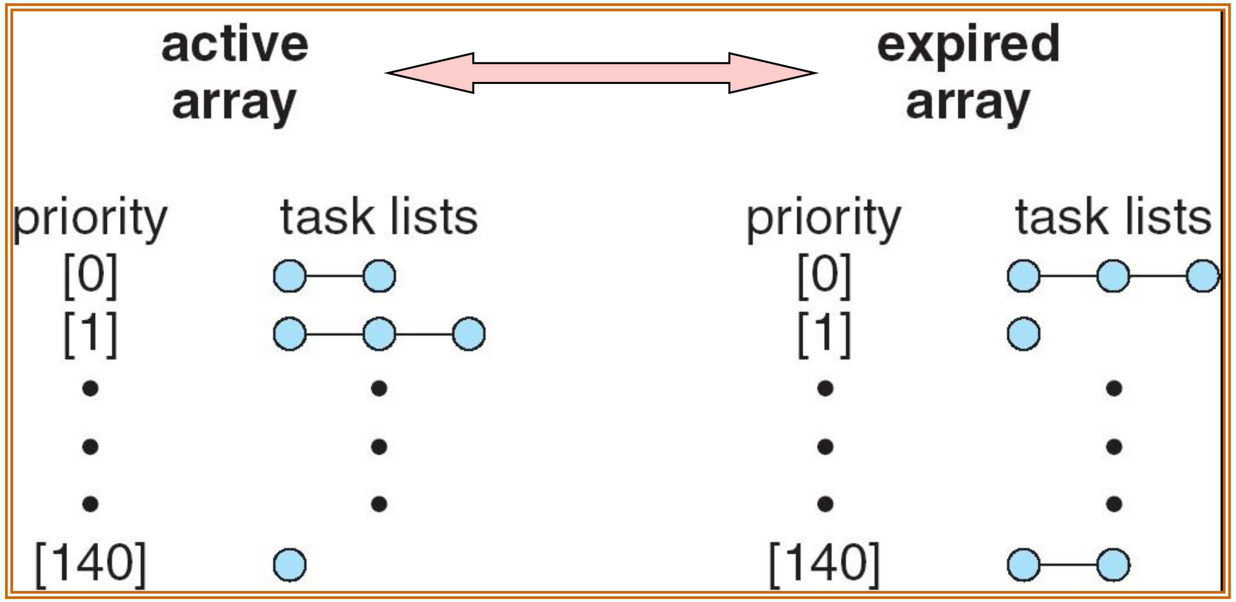
- Two algorithms: time-sharing and real-time
- Time-sharing
  - Prioritized credit-based – process with most credits is scheduled next
  - Credit subtracted when timer interrupt occurs
  - When credit = 0, another process chosen
  - When all processes have credit = 0, recrediting occurs
    - Based on 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 Prorities

The runqueue data structure



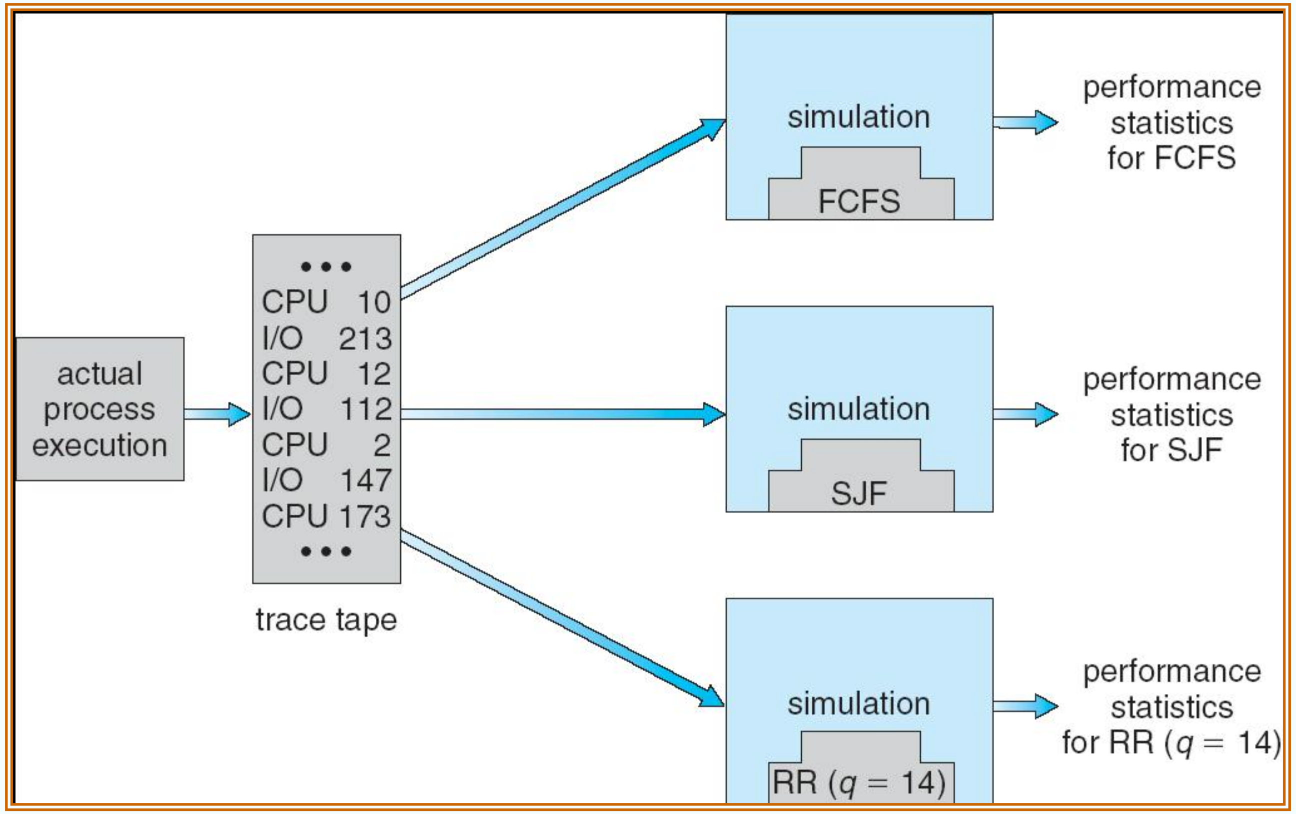
Algorithm Evaluation

- Deterministic modeling(确定性模型) – takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Queueing models

  Little's Law: $$n = \lambda \cdot W$$

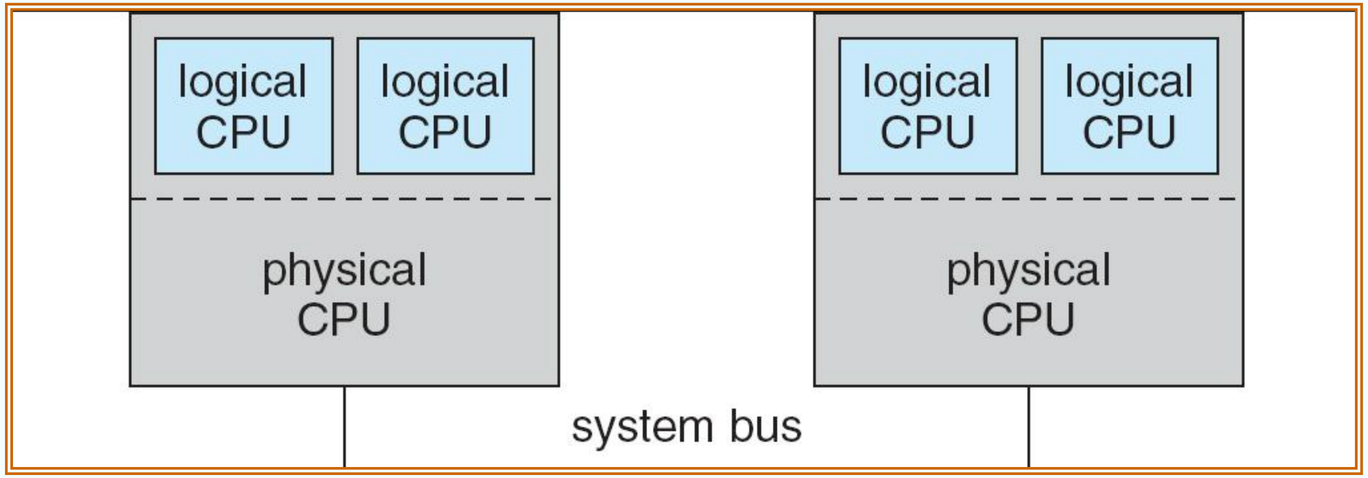
  which states that the long-term average number *L* of customers in a stationary system is equal to the long-term average effective arrival rate *λ* multiplied by the average time *W* that a customer spends in the system.
- Simulations
- Implementation

Fig 5.15 simulations

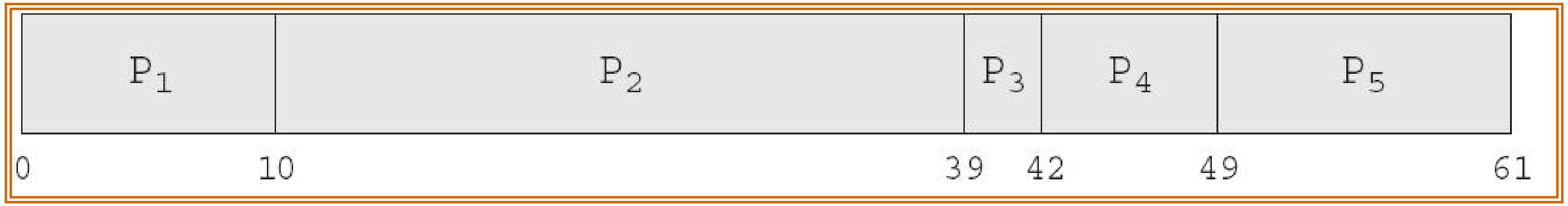


End of Chapter 5

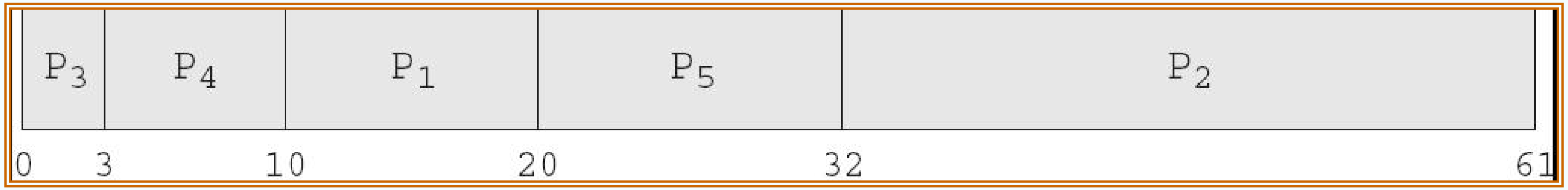
5.08


logical CPU
logical CPU
logical CPU
logical CPU
physical CPU
physical CPU
system bus

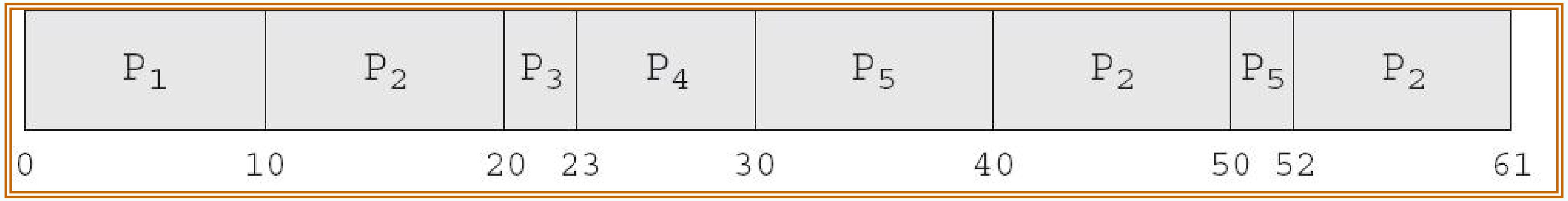
In-5.7



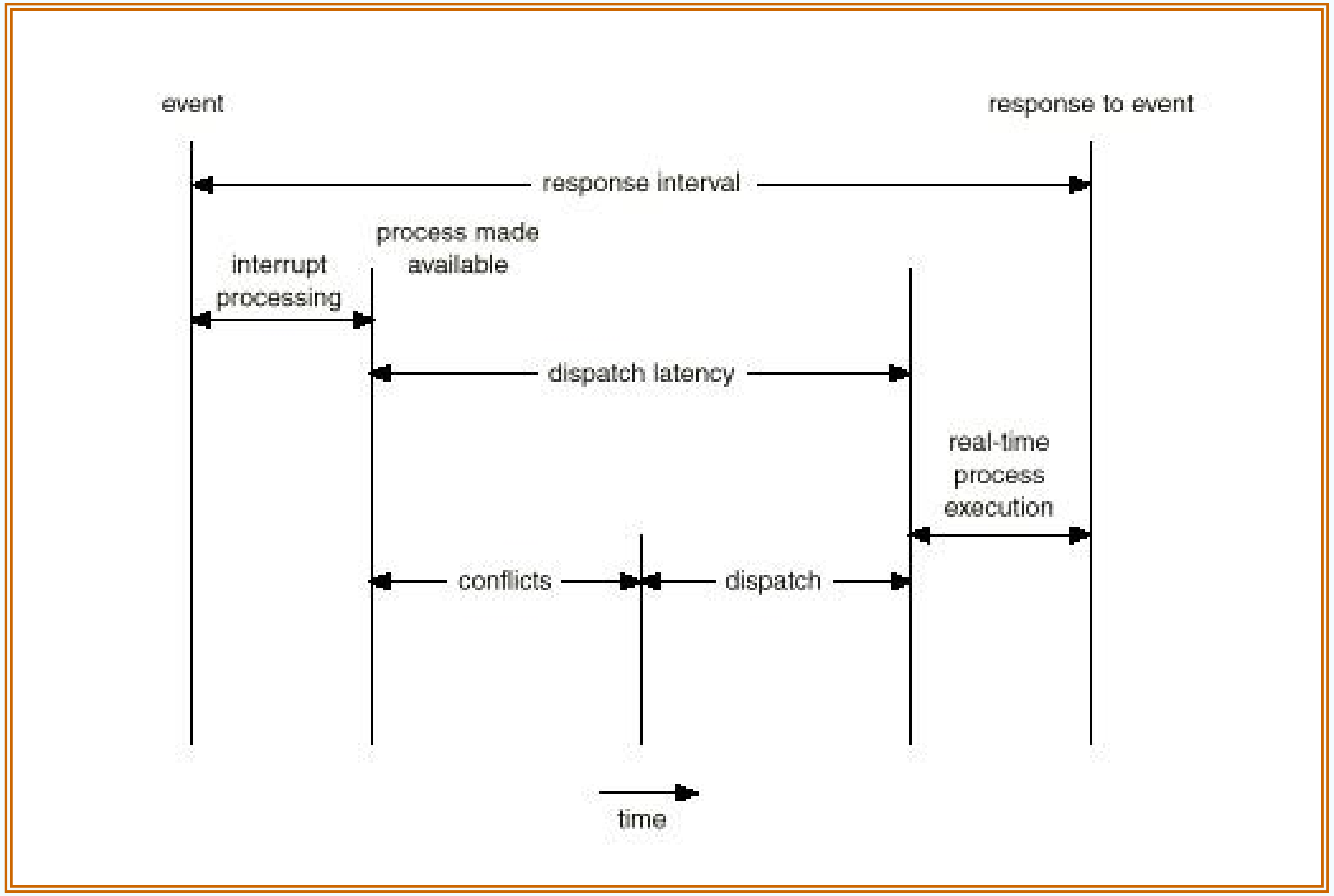
In-5.8



In-5.9



Dispatch Latency



The conflict phase of dispatch latency has two components:

1. Preemption of any process running in the kernel
2. Release resources from low-priority process for the high-priority process

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);
```