Chapter 5: Process Scheduling

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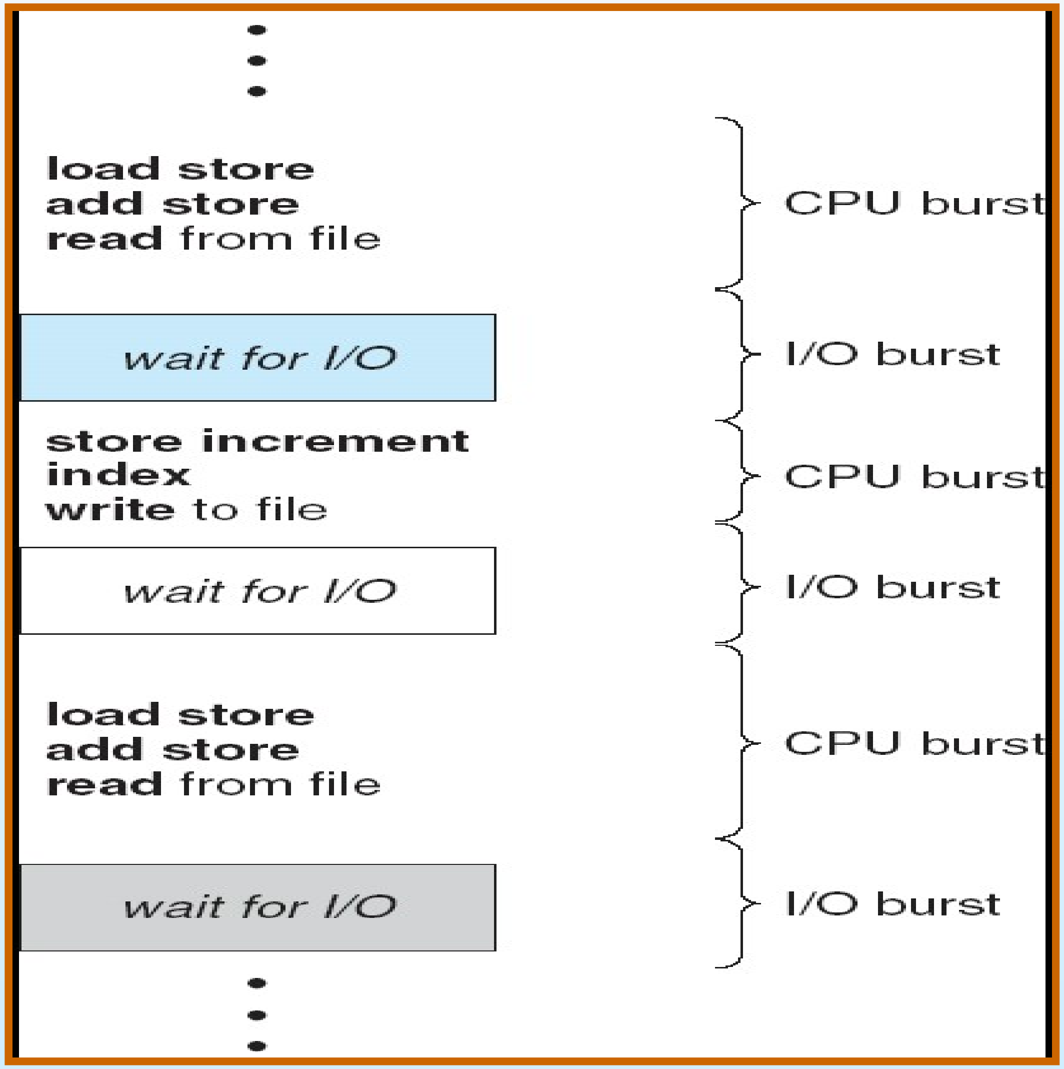
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Thread Scheduling
- Operating Systems Examples
- Algorithm Evaluation

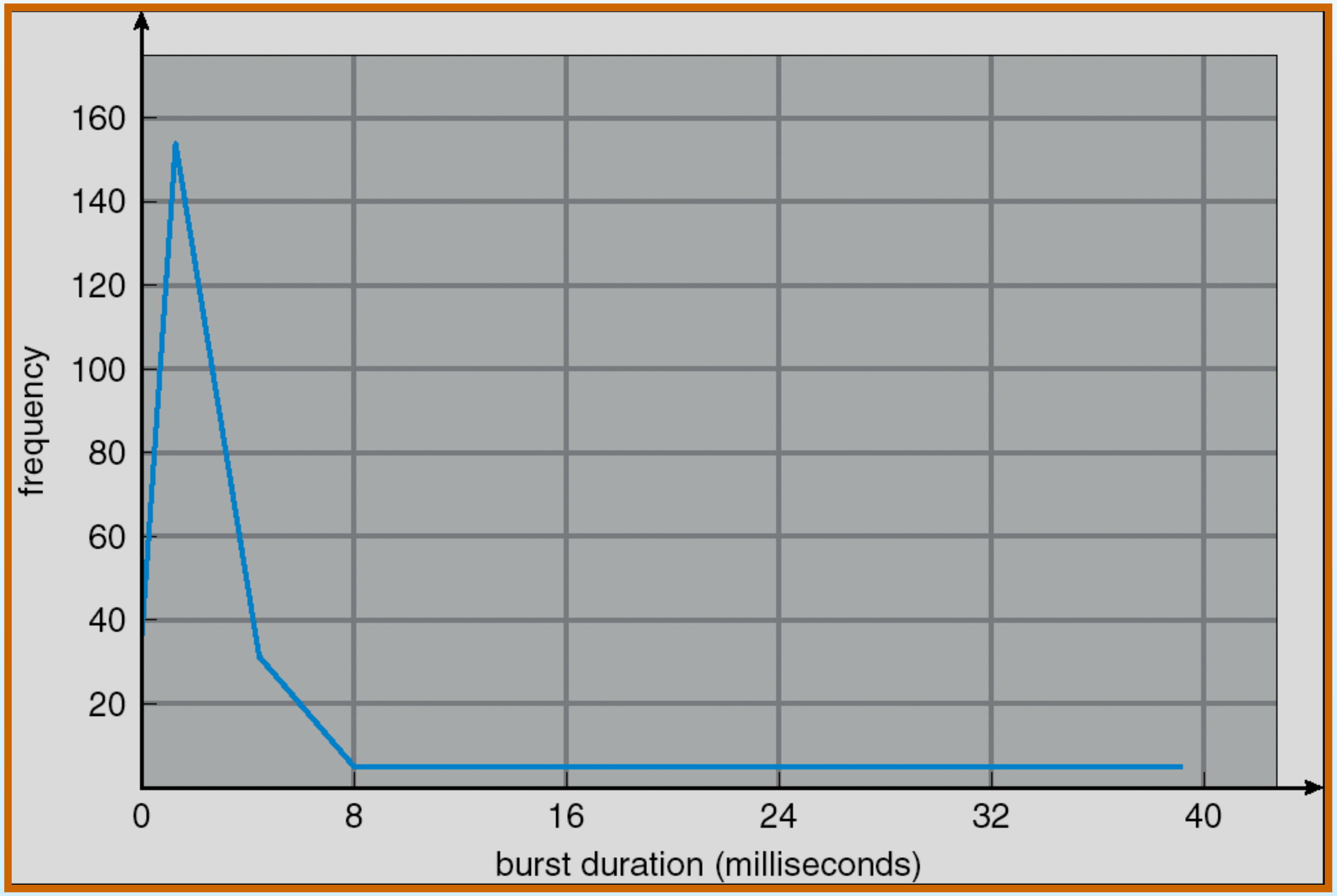
Basic Concepts

- The idea of multiprogramming:
  - Keep several processes in memory. Every time one process has to wait, another process takes over the use of the CPU
- CPU-I/O burst cycle: Process execution consists of a cycle of CPU execution and I/O wait (i.e., CPU burst and I/O burst).
  - Generally, there is a large number of short CPU bursts, and a small number of long CPU bursts.
  - An I/O-bound program would typically has many very short CPU bursts.
  - A CPU-bound program might have a few long CPU bursts

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*

Preemptive Issues

- Inconsistent cases may occur: preemptive scheduling incurs a cost associated with access to shared data
- Affect the design of OS kernel: What happens if the process is preempted in the middle of critical changes (for instance, I/O queues) and the kernel (or the device driver) needs to read or modify the same structure?
  - Unix solution: **waiting** either for a system call to complete or for an I/O block to take place before doing a context switch
  - However, weak in supporting real-time computing and multiprocessing

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 – 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, **not** output (for time-sharing environment)

Optimization Criteria

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

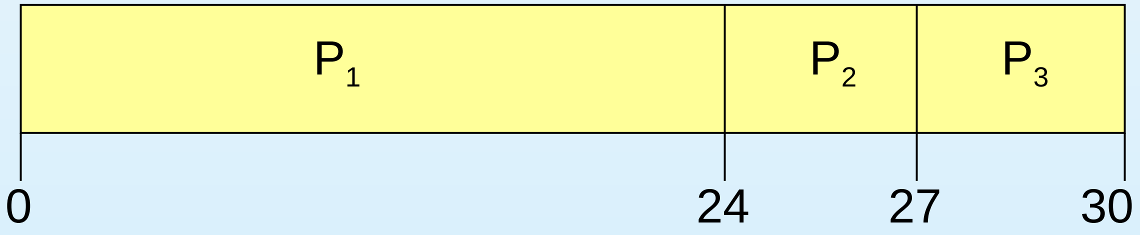
Scheduling Algorithms

- First-come, first-served (FCFS) scheduling
- Shortest-job-first (SJF) scheduling
- Priority scheduling
- Round-robin scheduling
- Multilevel queue scheduling
- Multilevel feedback queue scheduling

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:



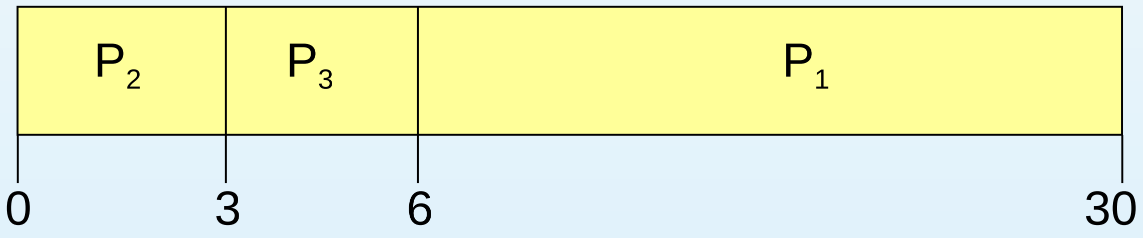
- Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
- Average waiting time: (0 + 24 + 27)/3 = 17

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

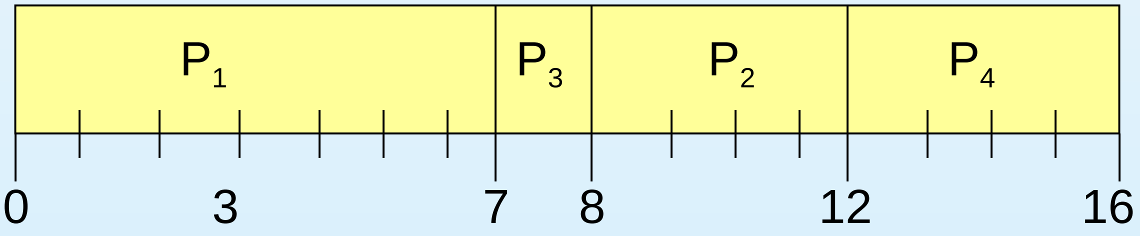
Shortest-Job-First (SJR) Scheduling

- 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)

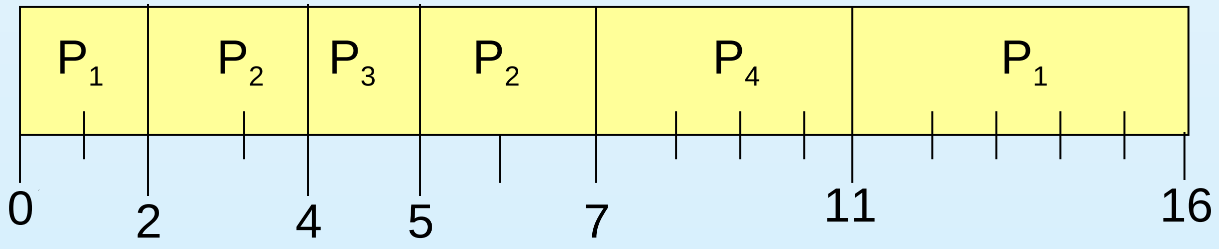


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

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

- Frequently used in long-term scheduling
  - A user is asked to estimate the job length. A lower value means faster response. Too low a value will cause timeout.
- **Approximate SJF**: the next burst can be predicted as an **exponential average** of the measured length of previous CPU bursts

$$\tau_{n+1} = \underset{\text{new one}}{\alpha t_n} + \overset{}{(1-\alpha)\tau_n} \longleftarrow \text{history}$$

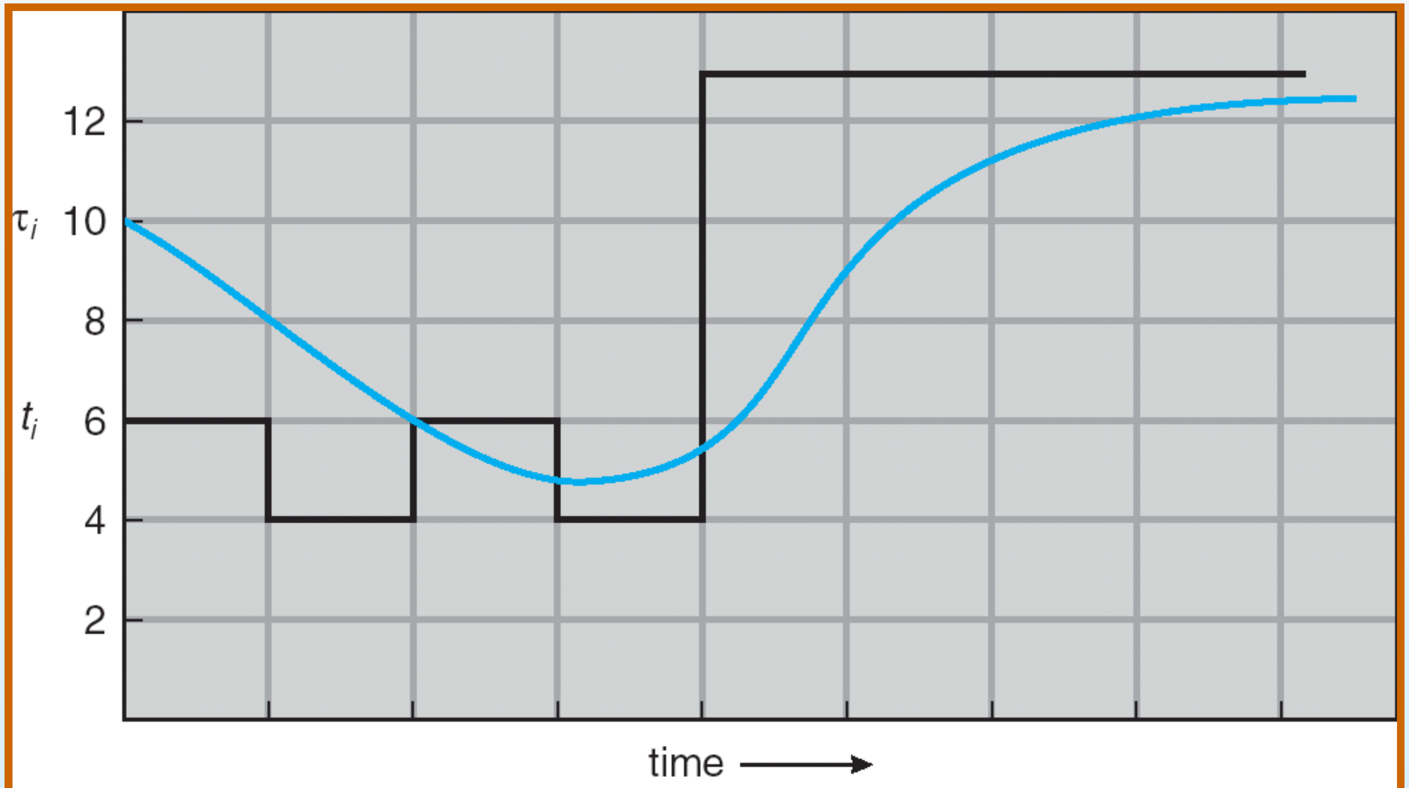
$$= \alpha t_n + (1-\alpha)\alpha t_{n-1} + (1-\alpha)^2 \alpha t_{n-2} + \ldots$$

Commonly,

$\alpha = 1/2$ $\longrightarrow$

$$= (\frac{1}{2})t_n + (\frac{1}{2})^2 t_{n-1} + (\frac{1}{2})^3 t_{n-2} + \ldots$$

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

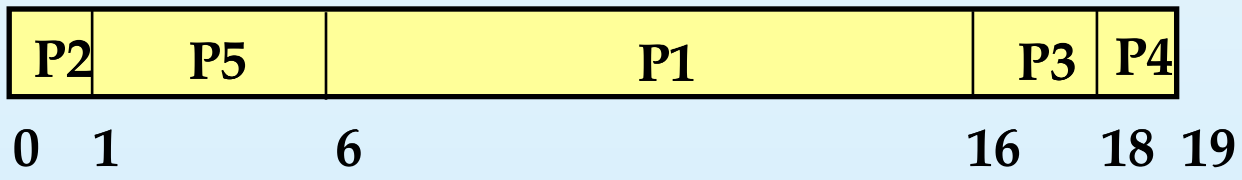
- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- $\alpha = 1$
  - $\tau_{n+1} = \alpha\, t_n = t_n$
  - Only the actual last CPU burst counts
- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

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

An Example

Process	Burst Time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2



AWT = (6+0+16+18+1)/5=8.2

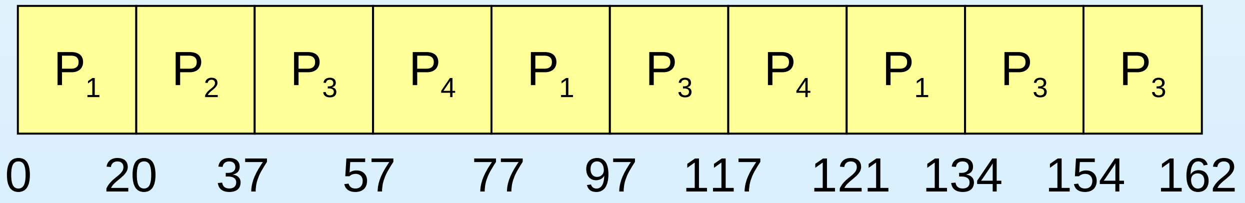
Round Robin (RR)

- 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 $\Rightarrow$ FIFO
  - *q* small $\Rightarrow$ *q* must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 20

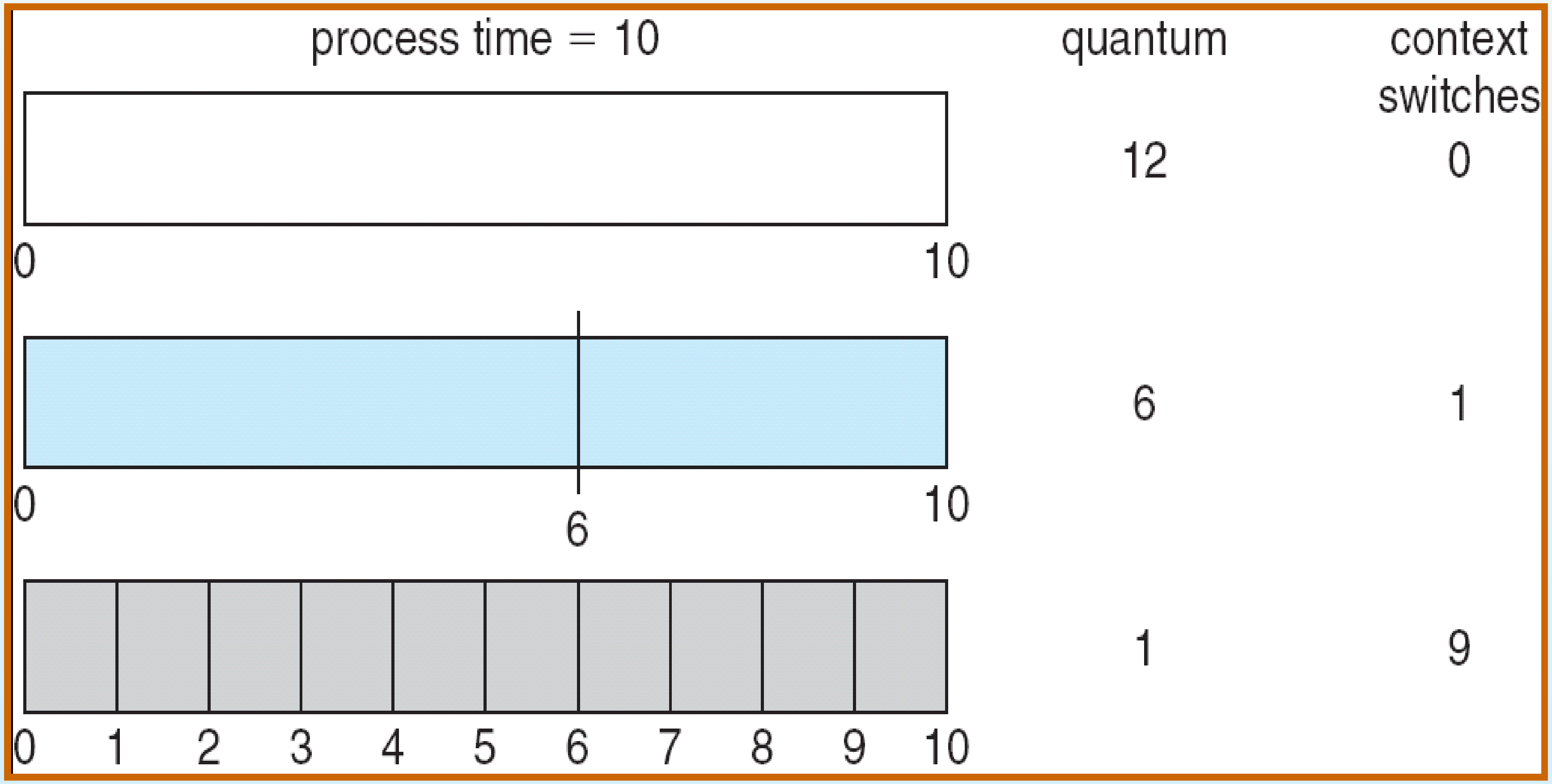
Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

- The Gantt chart is:

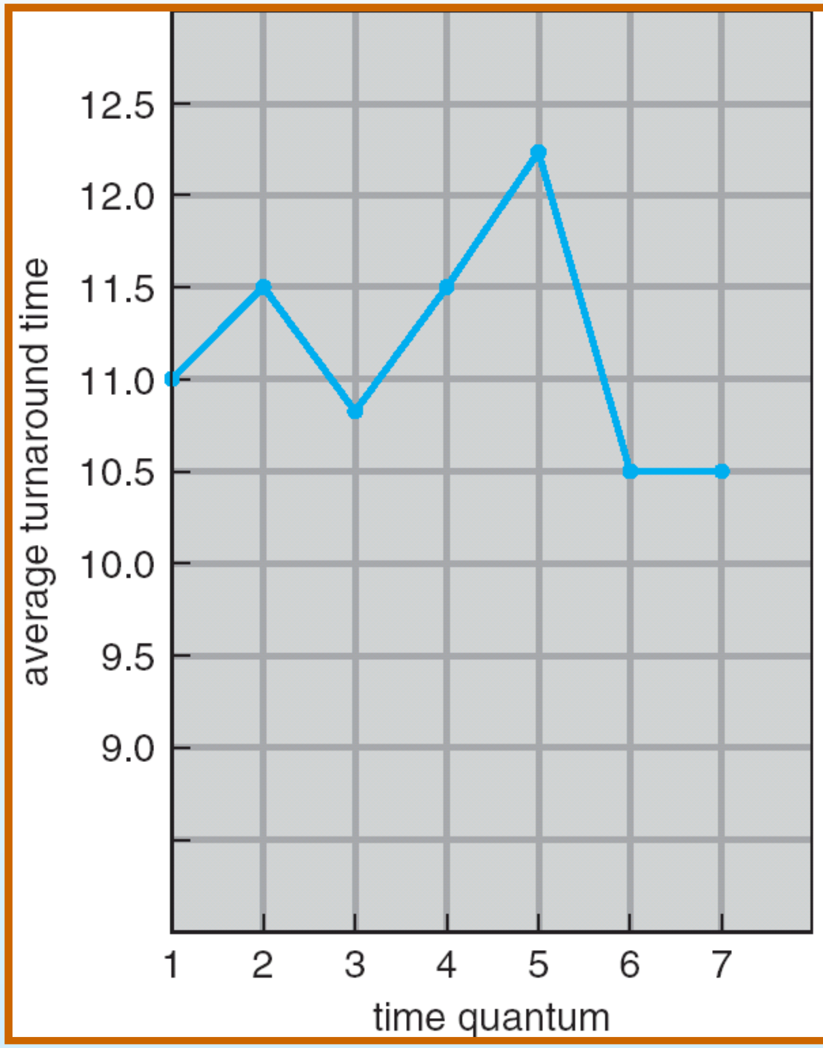


- Typically, higher average turnaround than SJF, but better *response*

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

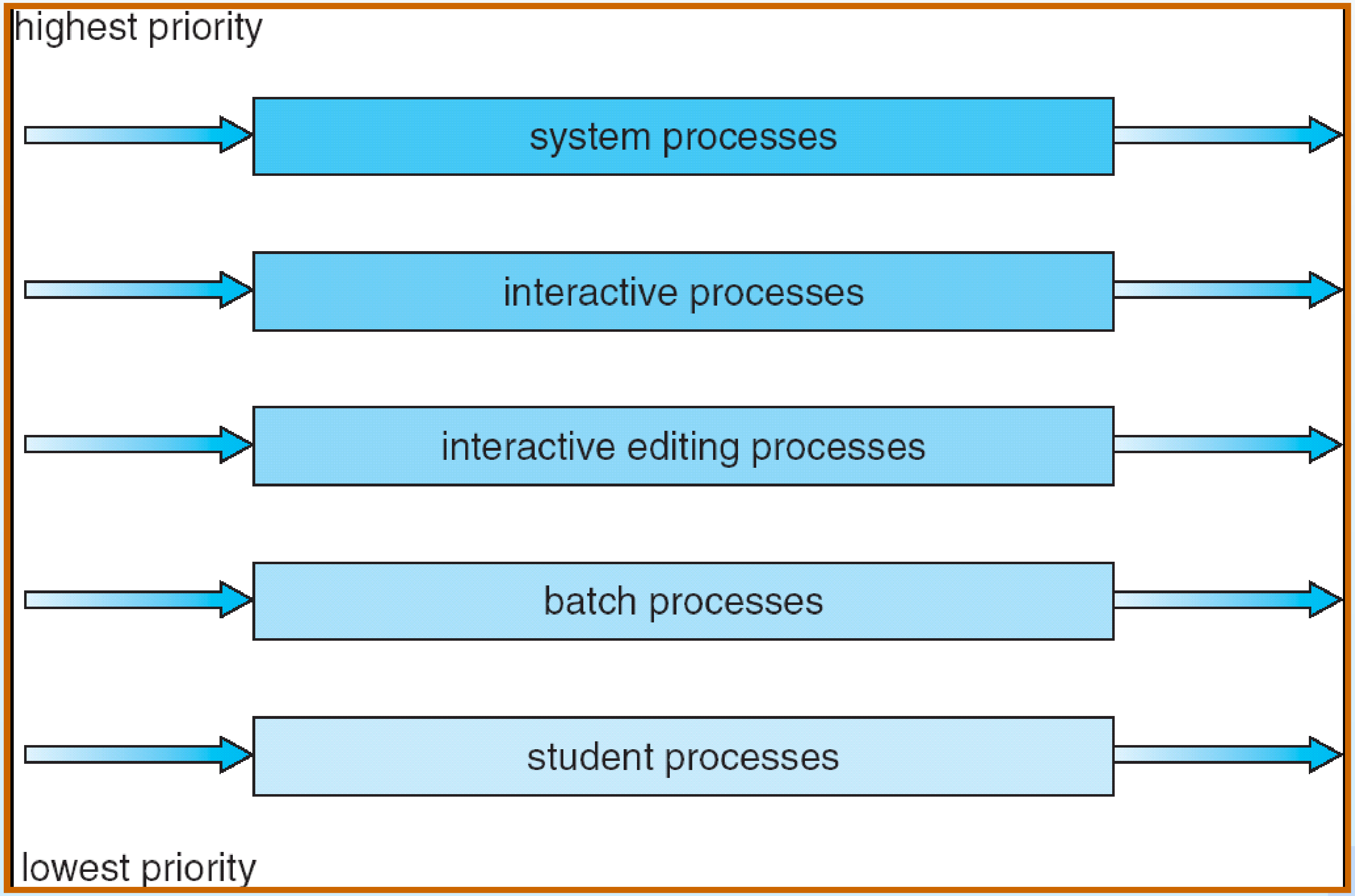
$p_1p_2p_3p_4p_1p_2p_4p_1p_2p_4p_1p_4p_1p_4p_1p_4p_4$

1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7

Multilevel Queue

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

Multilevel Queue Scheduling



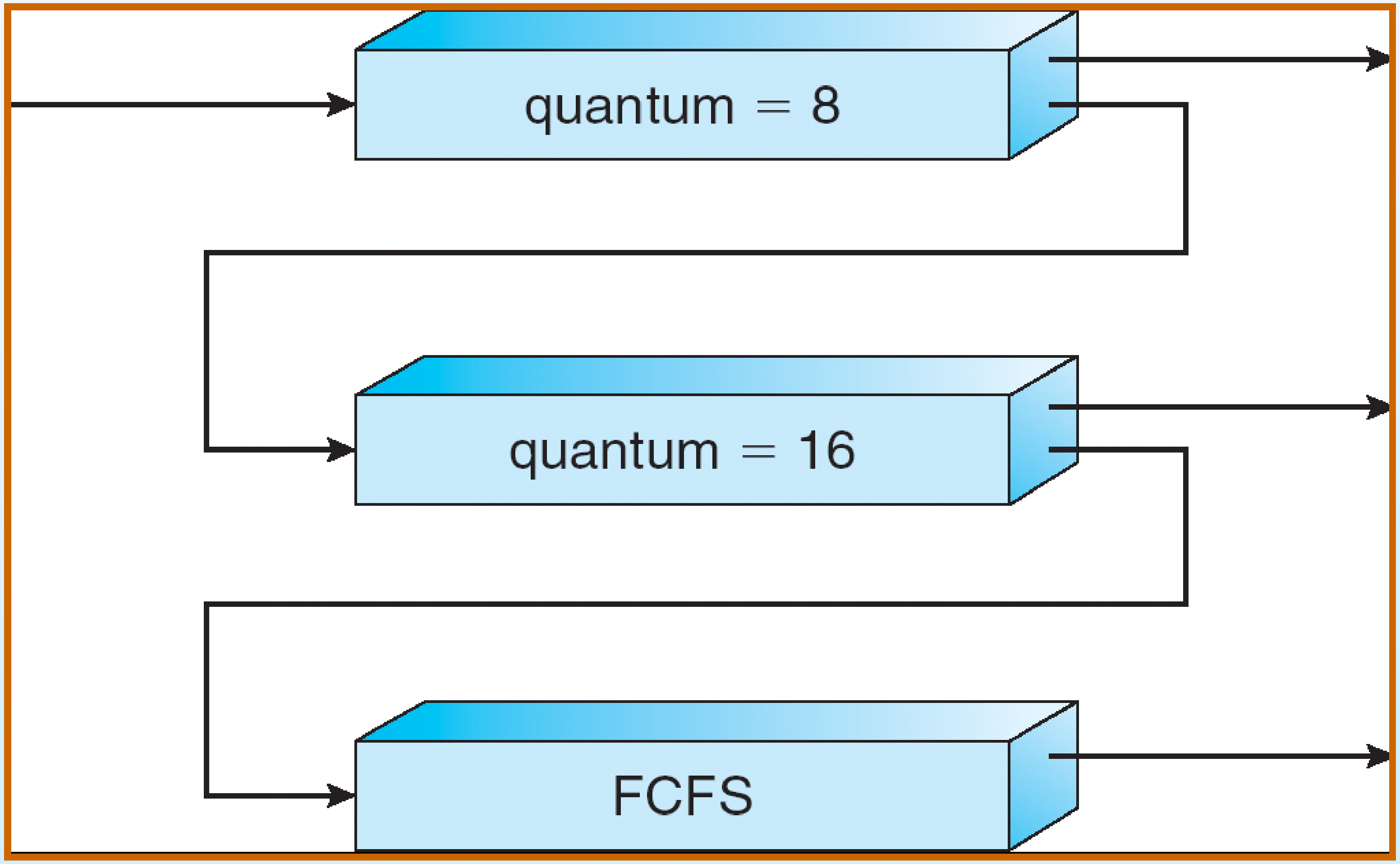
Multilevel Feedback Queue

- 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



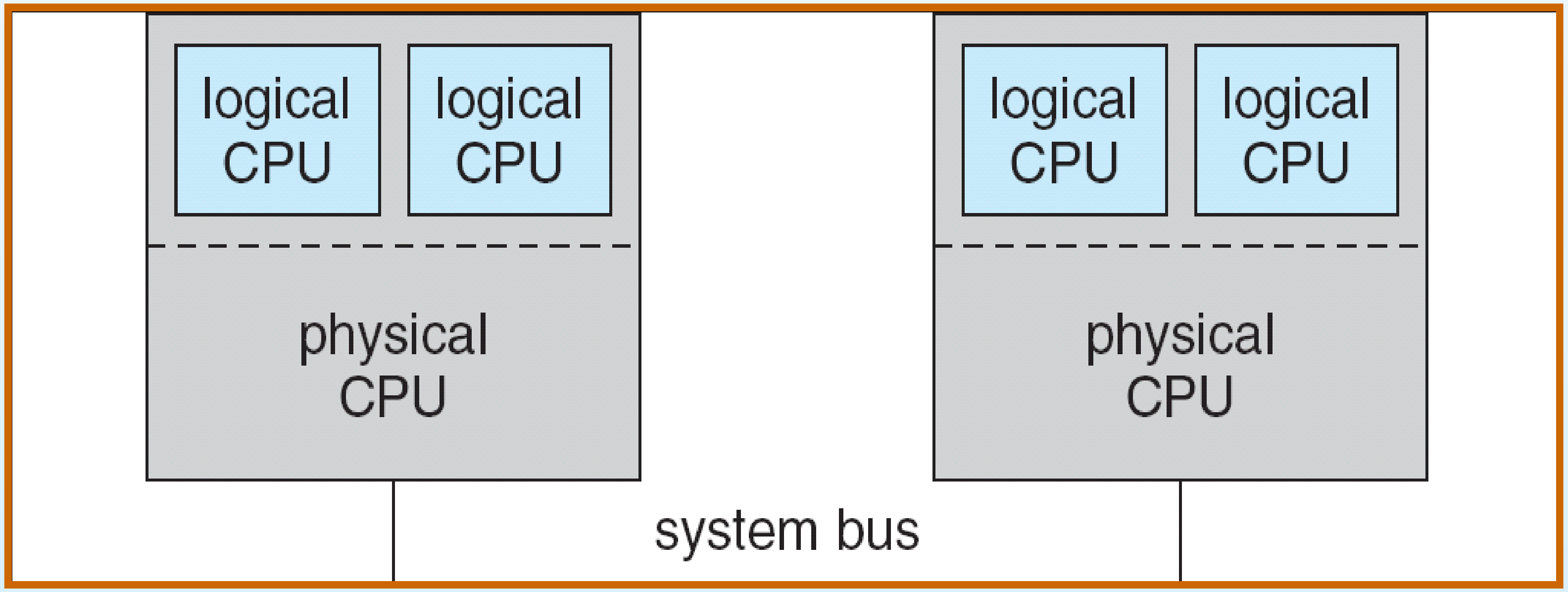
Multiple-Processor Scheduling

- Only **homogeneous** systems are discussed here
- **Symmetric multiprocessing**
  - Each processor is self-scheduling
  - All processes may be in a common ready queue or each processor have its own private queue
- Asymmetric multiprocessing: all system activities are handled by a processor, the others only execute user code (allocated by the master), which is far simple than **symmetric multiprocessing**
- **Processor affinity:** a process has an affinity for the processor on which it is currently running
  - Keep a process running on the same processor

SMT: Symmetric Multithreading

- SMP: Allow several threads to run concurrently by providing multiple physical processors (PPs).
- SMT: providing multiple logical processors (LPs) on the same PP.
- Each LP has its own architecture state, including general-purpose and machine-state registers.
  - LP is responsible for its own interrupt handling
- SMT is a feature provided by H/W (state, interrupt handling), not S/W.
  - Certain performance gain are possible if OS is aware that.
  - e.g., Consider a system with two PPs, both are idle. The scheduler should first try scheduling separate threads on each PP rather than on separate LPs on the same PP.

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
- Global Scheduling – How the kernel decides which kernel thread to run next

Thread Scheduling

- User-level threads are managed by a thread library, and the kernel is unaware of them. To run on a CPU, user-level threads are ultimately mapped to an associated kernel-level thread, or LWP.
  - **Process local scheduling**: Thread scheduling is done local to the application. The threads library schedules user-level threads to run on an available LWP
  - **System global scheduling**: The kernel decides which kernel thread to schedule

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);
```

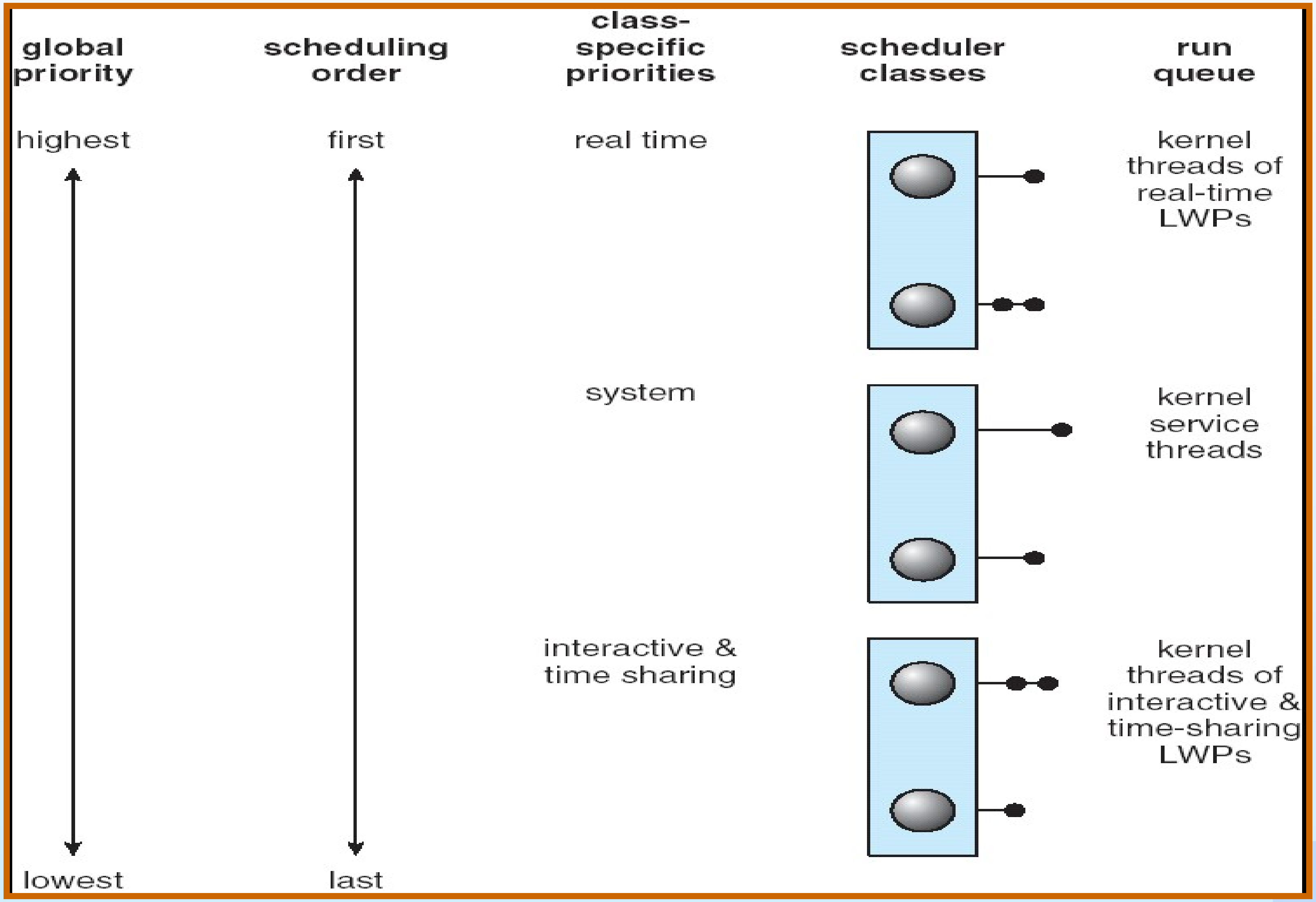
Pthread Scheduling API

```
   /* 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);
}
```

Operating System Examples

- Solaris scheduling
- Windows XP scheduling
- Linux scheduling

Solaris 2 Scheduling


global priority
scheduling order
class-specific priorities
scheduler classes
run queue
highest
first
real time
kernel threads of real-time LWPs
system
kernel service threads
interactive & time sharing
kernel threads of interactive & time-sharing LWPs
lowest
last

Solaris Scheduling

- Four classes of scheduling: real-time -> system -> interactive -> time sharing.
- A process starts with one LWP and is able to create new LWPs as needed. Each LWP inherits the scheduling class and priority of the parent process. Default : time sharing (multilevel feedback queue)
- Inverse relationship between priorities and time slices: the high the priority, the smaller the time slice.
- Interactive processes typical have a higher priority; CPU-bound processes have a lower priority.

Solaris Scheduling

- Uses the system class to run kernel processes, such as the scheduler and paging daemon. The system class is reserved for kernel use only. User process running in kernel mode are not in the system class.
- Threads in the real-time class are given the highest priority to run among all classes.
- There is a set of priorities within each class. However, the scheduler converts the class-specific priorities into global priorities. (round-robin queue)

Solaris Dispatch Table (for interactive and time-sharing threads)

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

Dispatch Table

- Priority: a higher number indicates a higher priority
- Time quantum: the lower priority has the higher time quantum
- Time quantum expired: the new priority of a thread that has used its entire time quantum without blocking. Such threads are considered CPU-intensive. Lower priority of these thread
- Return from sleep: the priority of a thread that is returning from sleeping (such as waiting for I/O). Its priority is boosted to between 50 and 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

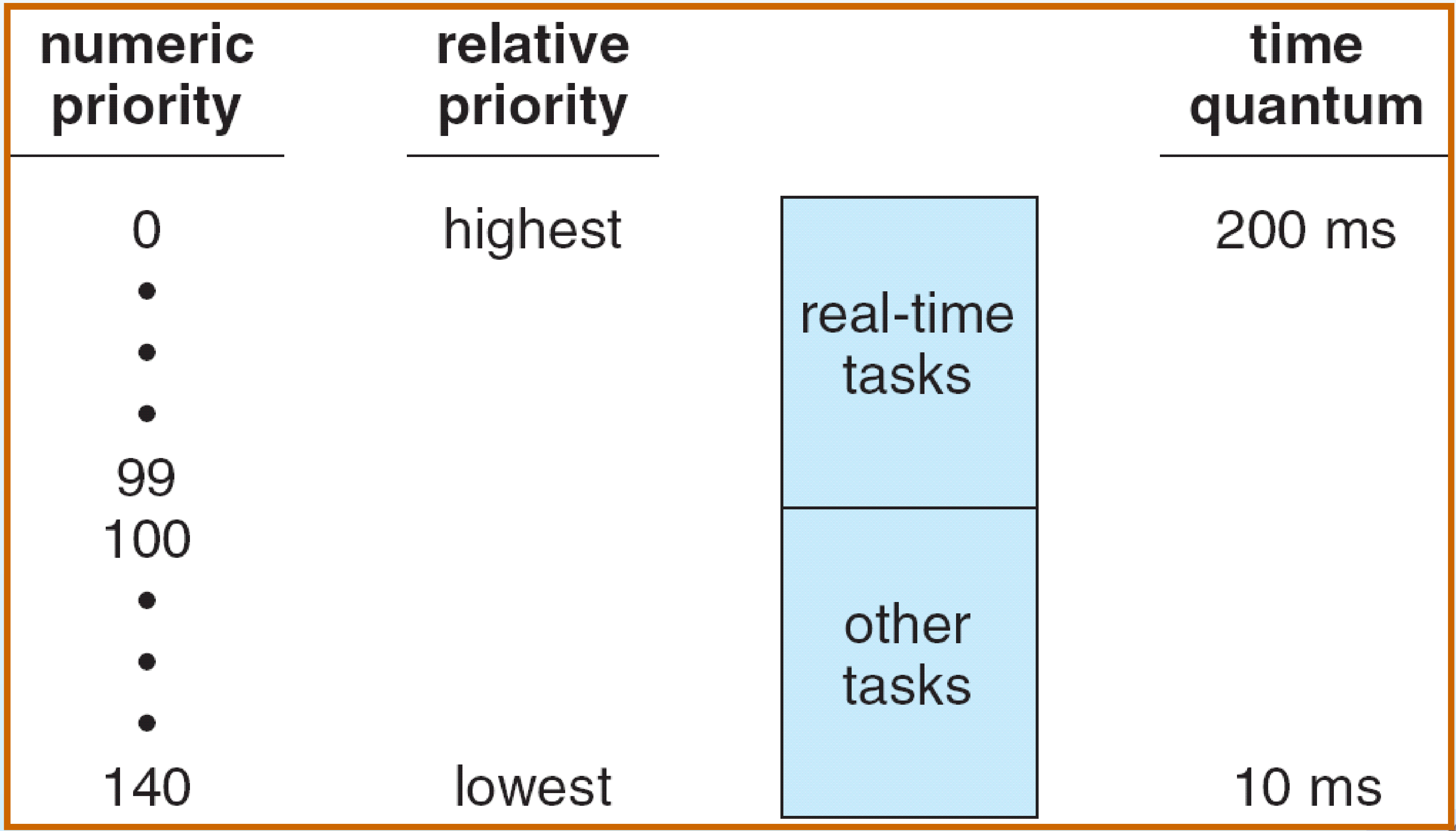
Windows XP Scheduling

- Using a priority-based, preemptive scheduling algorithm
- There are 32-level priority which are divided into two classes
    - The variable class contains priorities from 1 to 15
    - The real-time class contains threads from 16 to 31
- Within each of the priority classes is a relative priority
- The priority of each thread is based on the priority class it belongs to and its relative priority within that class.

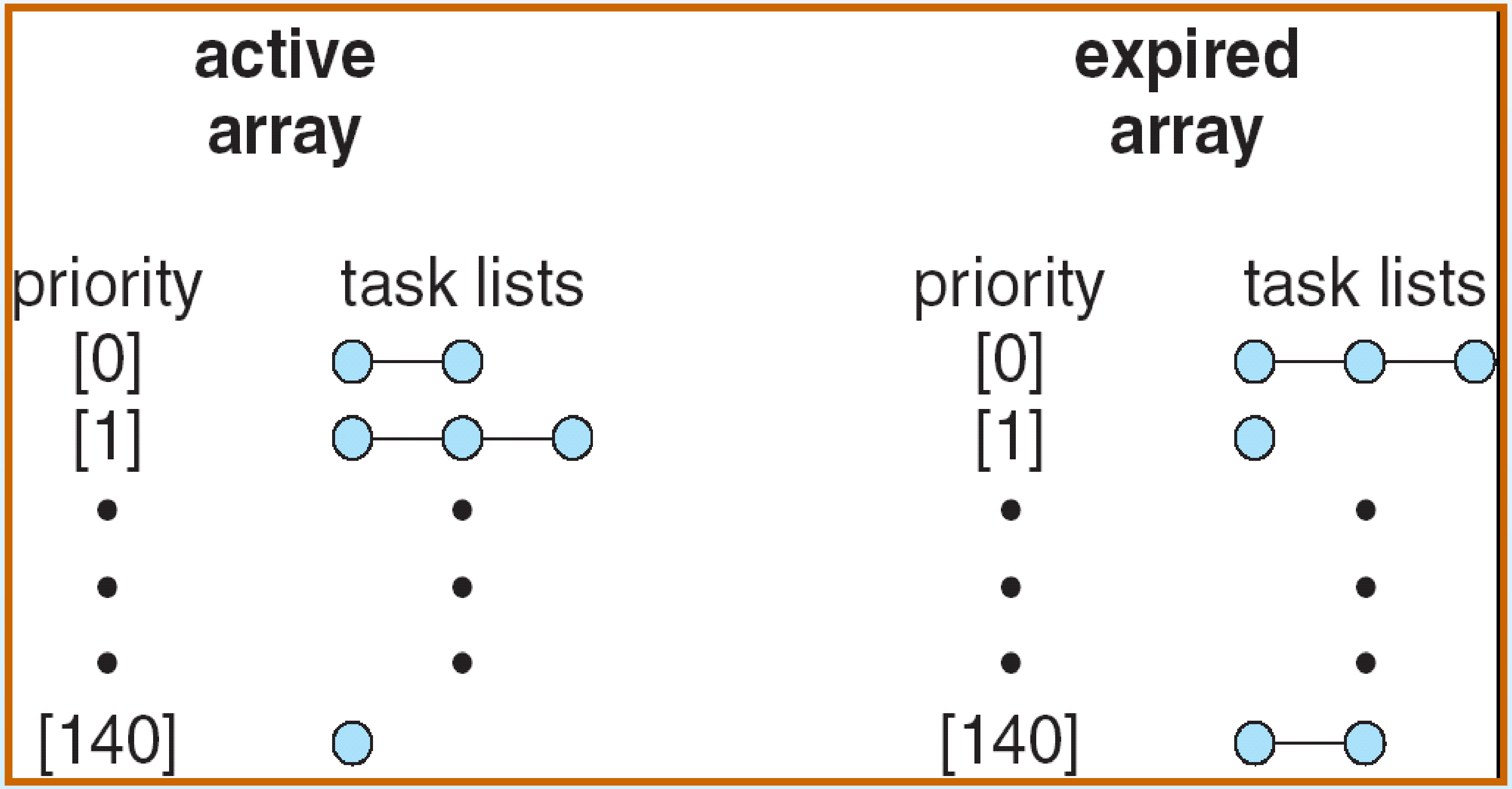
Linux Scheduling – preemptive & priority

- Version 2.5: support SMP, Load balancing & Processor affinity
- Time-sharing (100-140) and Real-time (0-99)
- Higher priority with longer time quanta
- 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



Algorithm Evaluation

- Criteria to select a CPU scheduling algorithm may include several measures, such as:
  - Maximize CPU utilization under the constraint that the maximum response time is 1 second
  - Maximize throughput such that turnaround time is (on average) linearly proportional to total execution time
- Evaluation methods ?
  - deterministic modeling
  - queuing models
  - simulations
  - implementation

Deterministic Modeling

- Analytic evaluation

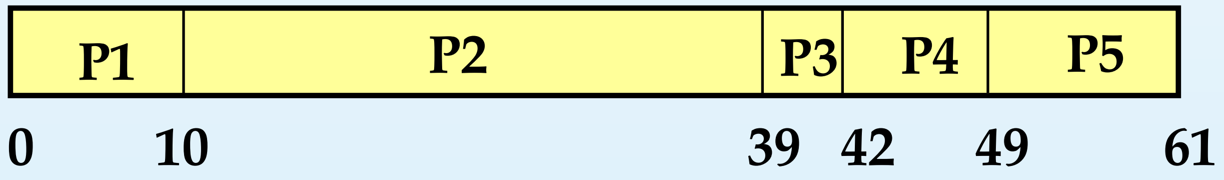
  Input: a given algorithm and a system workload to

  Output: performance of the algorithm for that workload
- Deterministic modeling
  - Taking a particular predetermined workload and defining the performance of each algorithm for that workload.

Deterministic Modeling

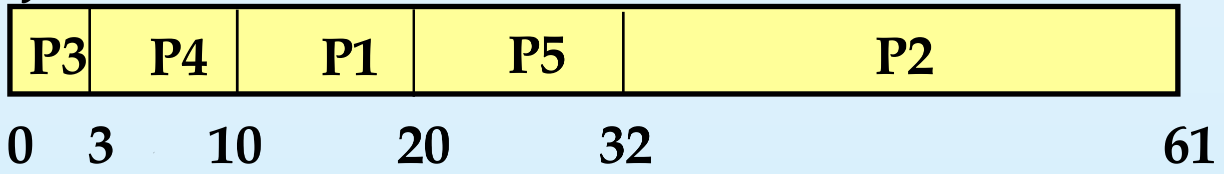
Process	Burst Time
P1	10
P2	29
P3	3
P4	7
P5	12

- FCFS



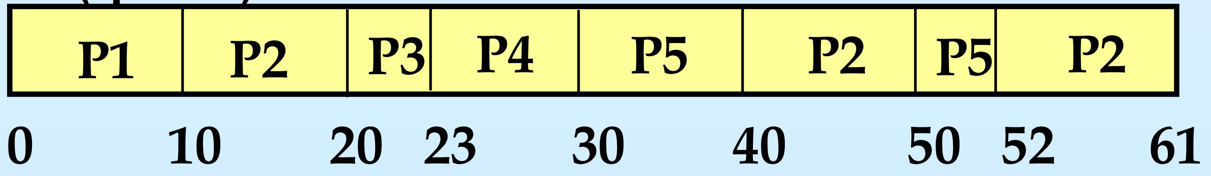
AWT = 28 ms

- SJF



AWT = 13 ms

- RR (q = 10)



AWT = 23 ms

Deterministic Modeling

- A simple and fast method. It gives the exact numbers, allows the algorithms to be compared.
- It requires exact numbers of input, and its answers apply to only those cases. In general, deterministic modeling is too specific, and requires too much exact knowledge, to be useful.
- Usage
  - Describing algorithm and providing examples
  - A set of programs that may run over and over again
  - Indicating the trends that can then be proved

Queuing Models

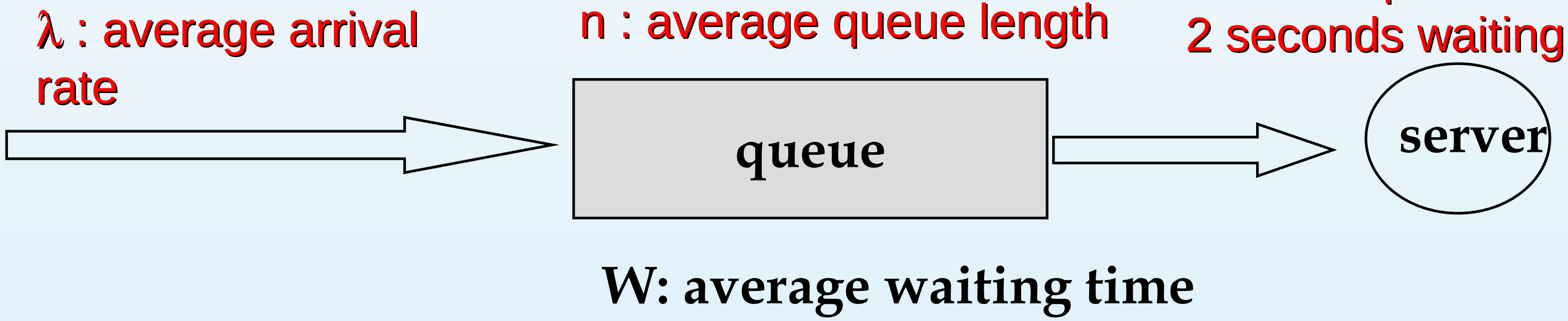
- Queuing network analysis
  - Using
    - the distribution of service times (CPU and I/O bursts)
    - the distribution of process arrival times
  - The computer system is described as a network of servers. Each server has a queue of waiting processes.
  - Determining
    - utilization, average queue length, average waiting time, and so on

Queuing Models

- Little's formula (for a stable system):

$$n = \lambda \times W$$

14 persons in queue =
7 arrives/per second ×
2 seconds waiting

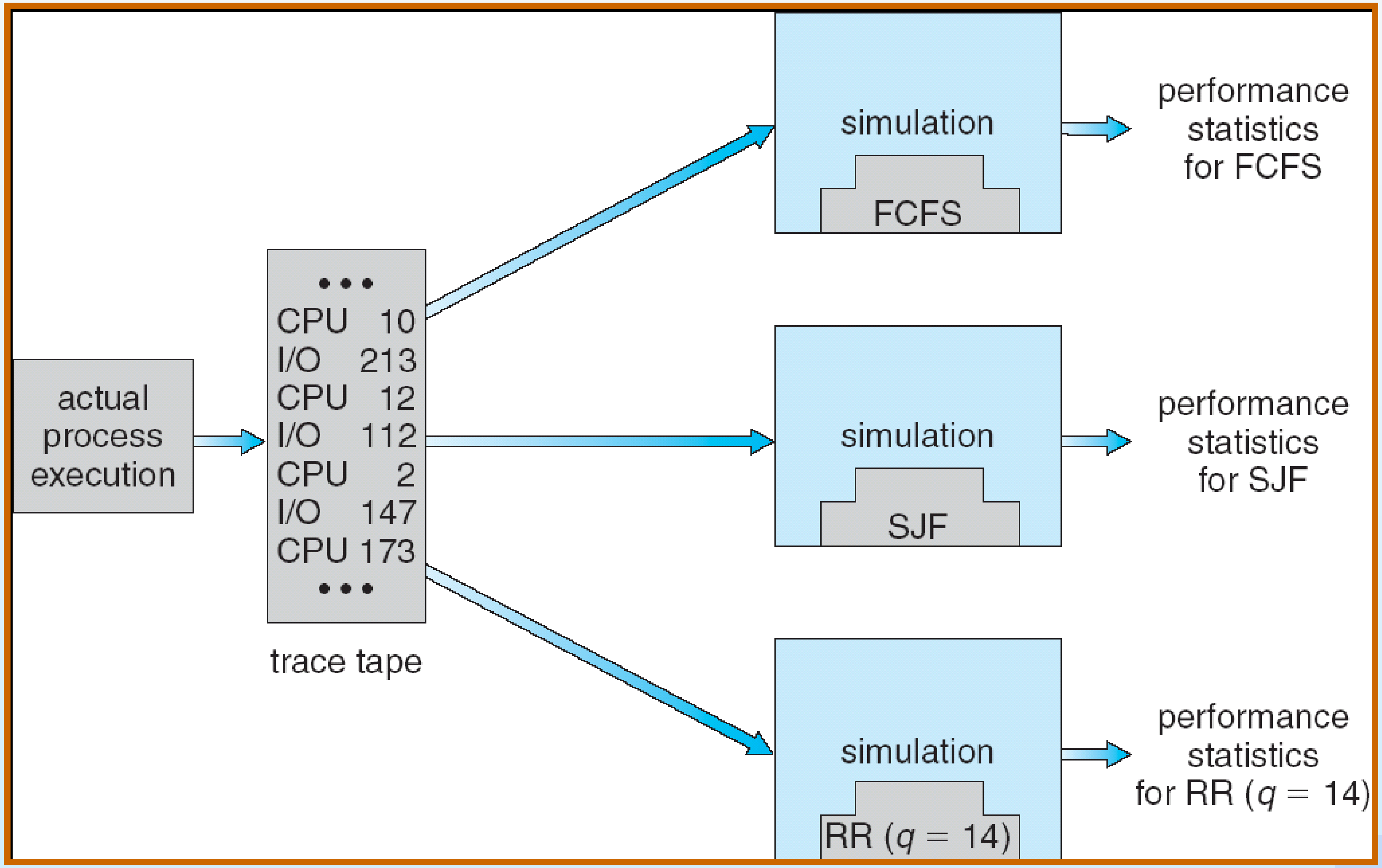


- Queuing analysis can be useful in comparing scheduling algorithms, but it also has limitations.
- Queuing model is only an approximation of a real system. Thus, the result is questionable.
  - The arrival and service distributions are often defined in unrealistic, but mathematically tractable, ways.
  - Besides, independent assumptions may not be true.

Simulations

- Simulations involve programming a model of the system. Software data structures represent the major components of the system.
- Simulations get a more accurate evaluation of scheduling algorithms.
  - expensive (several hours of computer time).
  - large storage
  - coding a simulator can be a major task
- Generating data to drive the simulator
  - a random number generator.
  - trace tapes: created by monitoring the real system, recording the sequence of actual events.

Evaluation of CPU Schedulers by Simulation



Implementation

- Put data into a real system and see how it works.
- The only accurate way
  - cost is too high
  - environment will change (All methods have this problem!)
  - e.g., To avoid moving to a lower priority queue, a user may output a meaningless character on the screen regularly to keep itself in the interactive queue.

Home Works

- 2, 3, 5, 7, 9
- First exam.: Nov. 3 (10:10 ~ 11:30)

End of Chapter 5