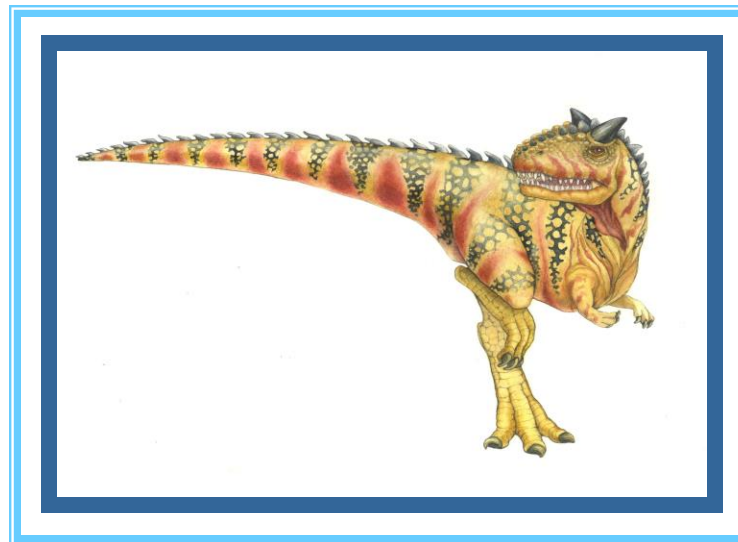# COMP3301: CPU Scheduling [Based on Chapter 6, OSC]

Chapter 6: CPU Scheduling

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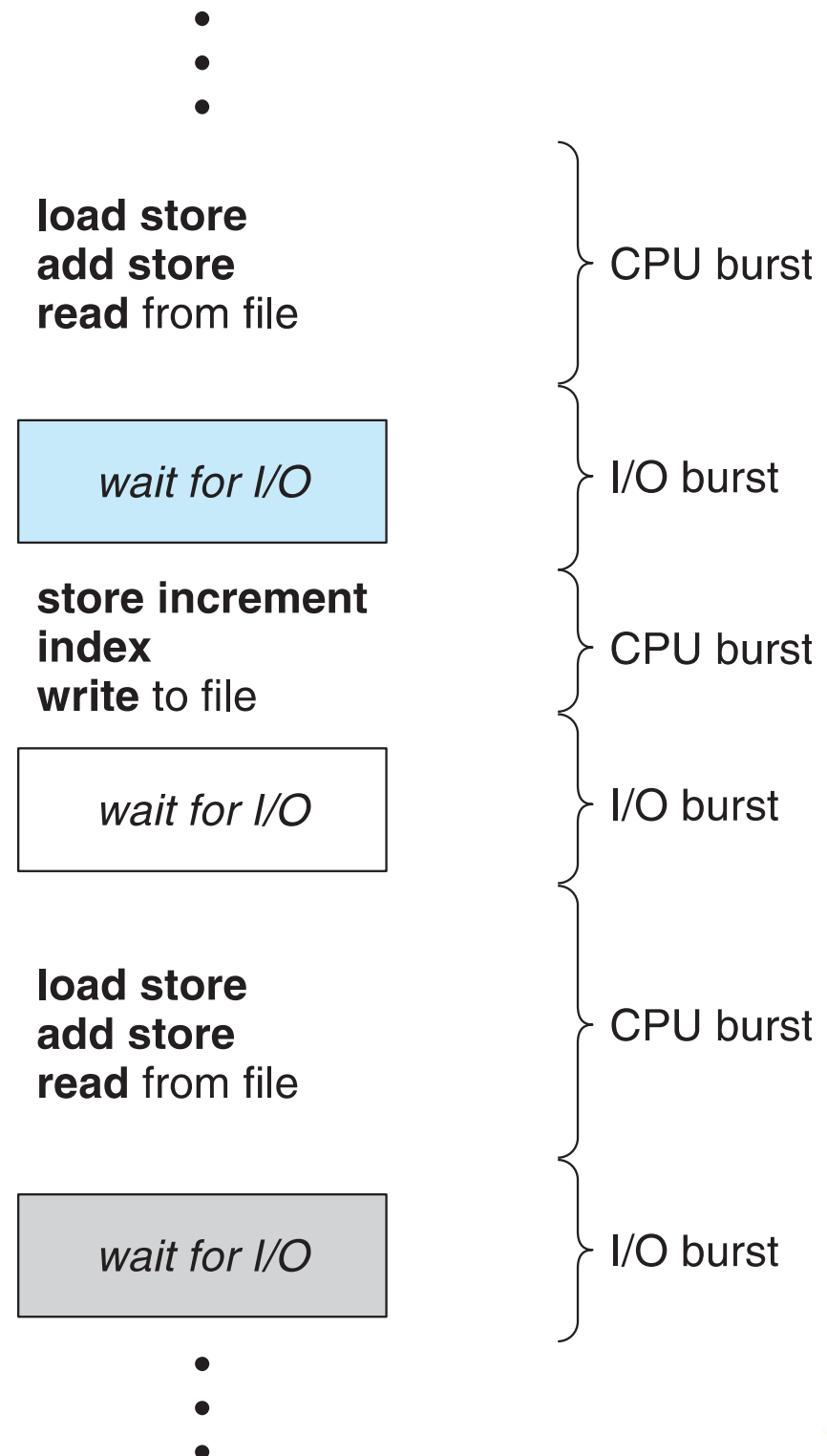- Algorithm Evaluation

Objectives

- To introduce CPU scheduling, which is the basis for multiprogrammed operating systems

- To describe various CPU-scheduling algorithms

- To discuss evaluation criteria for selecting a CPU-scheduling algorithm for a particular system

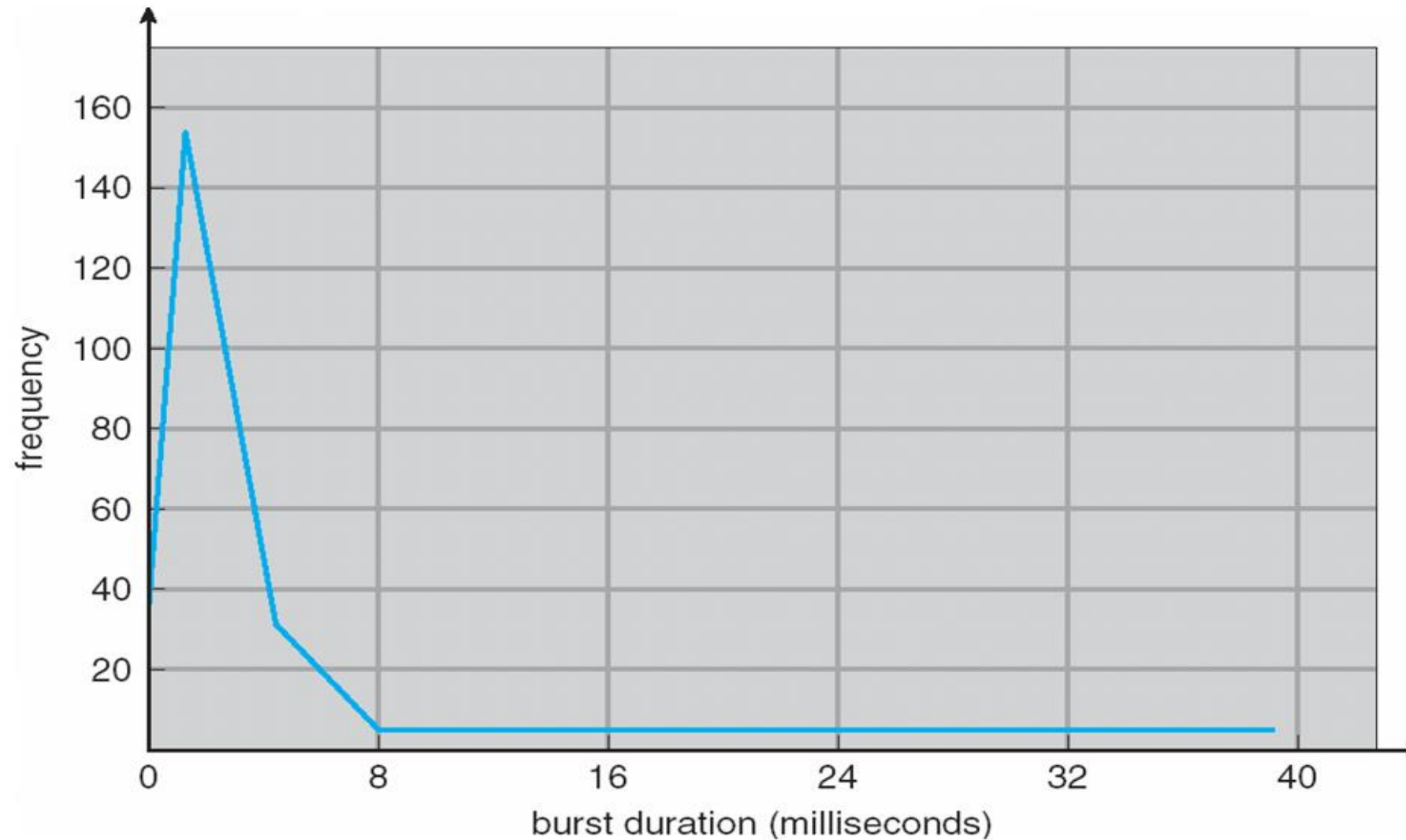- To examine the scheduling algorithms of several operating systems

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

•
•
•

load store
add store
read from file   ⎫ CPU burst

wait for I/O   ⎫ I/O burst

store increment
index
write to file   ⎫ CPU burst

wait for I/O   ⎫ I/O burst

load store
add store
read from file   ⎫ CPU burst

wait for I/O   ⎫ I/O burst

•
•
•

Histogram of CPU-burst Times

CPU Scheduler

- **Short-term scheduler** selects from among the processes in ready queue, and allocates the CPU 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
- Scheduling under 1 and 4 is **nonpreemptive**
- All other scheduling is **preemptive**
    - 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
  - 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, (for time-sharing environment)

Scheduling Algorithm Optimization Criteria

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

- May be interested in AVERAGE or WORST CASE figures

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:

P₁	P₂	P₃

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$_2$	P$_3$	P$_1$

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
  - The difficulty is knowing the length of the next CPU request
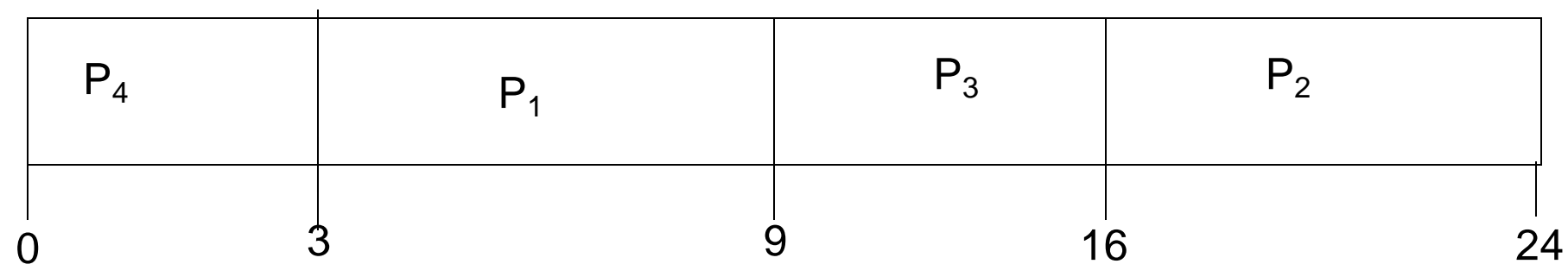 - Could ask the user

Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- SJF scheduling chart

P_4	P_1	P_3	P_2
0 3	9	16	24

- 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
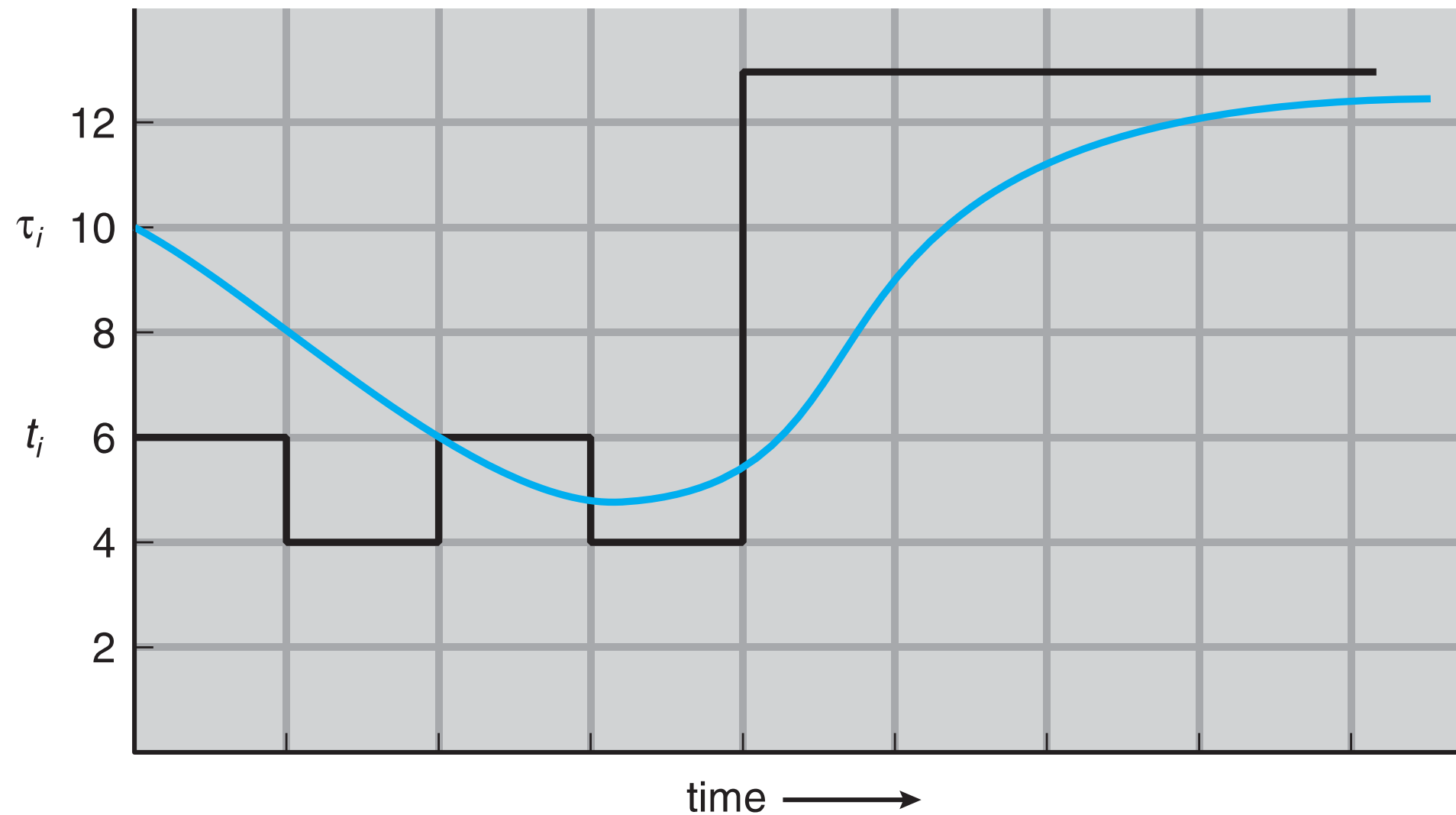
1. t_n = actual length of nth CPU burst
2. τ_{n+1} = predicted value for the next CPU burst
3. $\alpha, 0 \leq \alpha \leq 1$
4. Define : $\tau_{n=1} = \alpha\, t_n + (1-\alpha)\tau_n.$

- Commonly, α set to ½
- Preemptive version called **shortest-remaining-time-first**

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
- $\alpha = 1$
  - $\tau_{n+1} = \alpha\ t_n$
  - 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 successive term has less weight than its predecessor
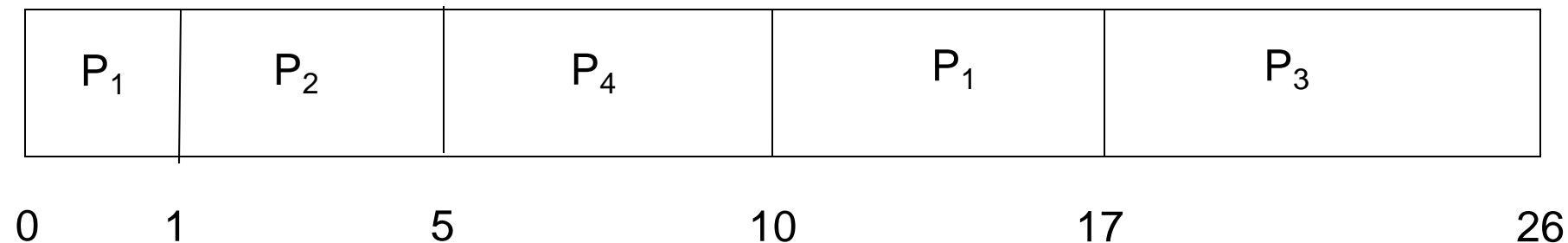
Example of Shortest-remaining-time-first

☐ 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_1	P_2	P_4	P_1	P_3

0   1   5   10   17   26

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

Priority Scheduling

- A priority number (integer) is associated with each process

- The CPU is allocated to the process with the highest priority (smallest integer $\equiv$ highest priority)
  - Preemptive
  - Nonpreemptive

- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time

- Problem $\equiv$ **Starvation** – low priority processes may never execute

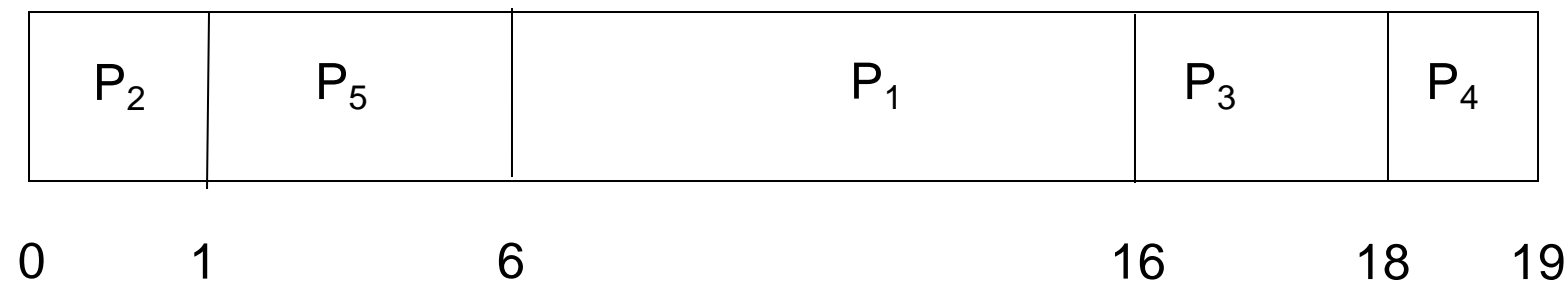- Solution $\equiv$ **Aging** – as time progresses increase the priority of the process

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

P₂	P₅	P₁	P₃	P₄

0   1   6   16   18   19

☐ Average waiting time = 8.2 msec

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

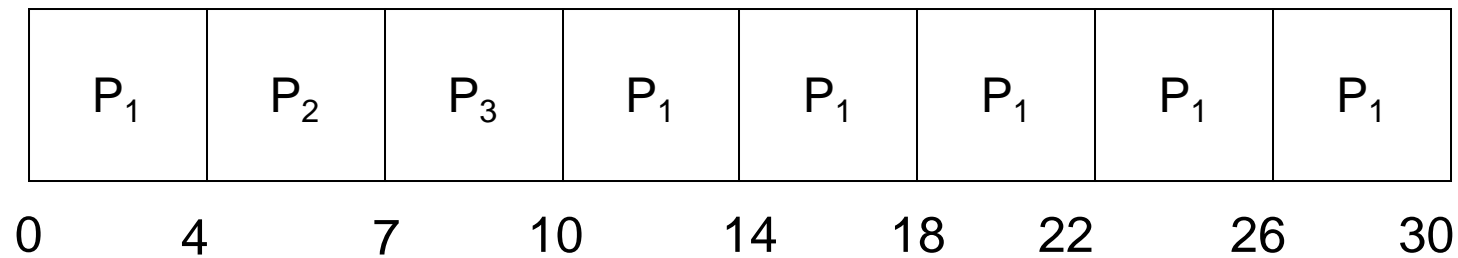 - q small $\Rightarrow q$ must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

- The Gantt chart is:

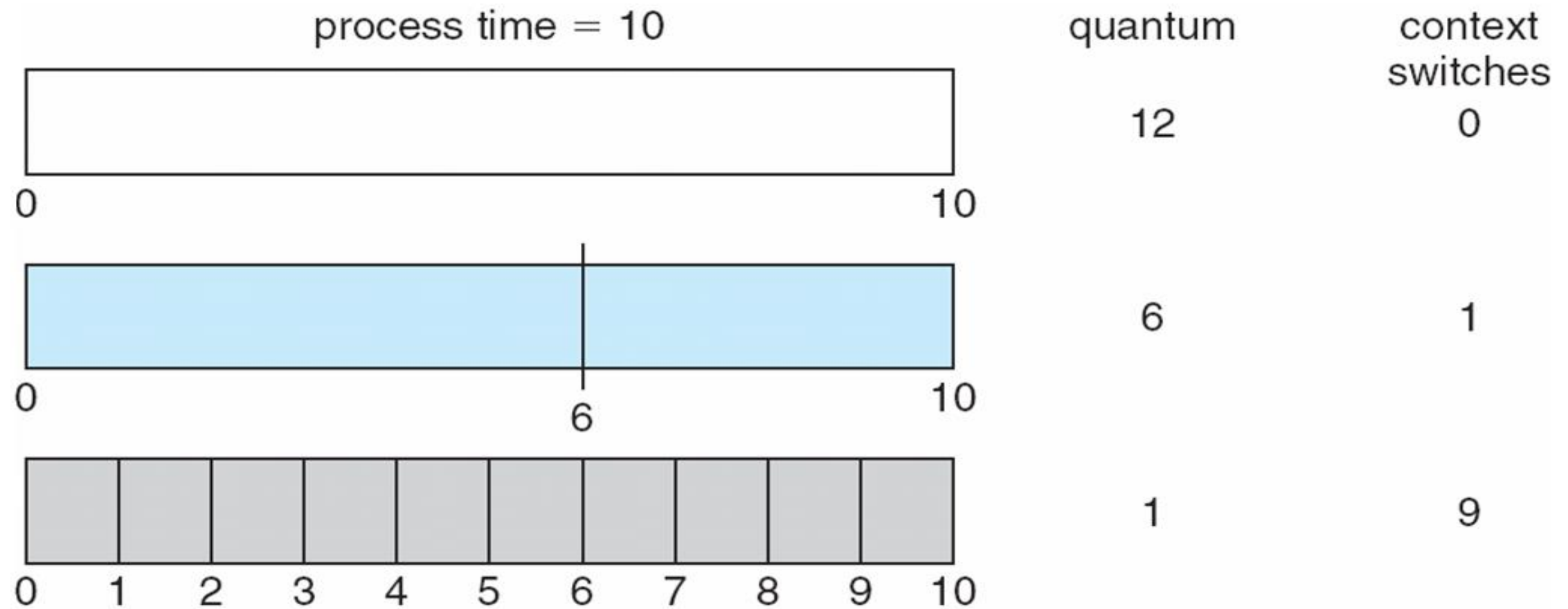| P_1	P_2	P_3	P_1	P_1	P_1	P_1	P_1

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
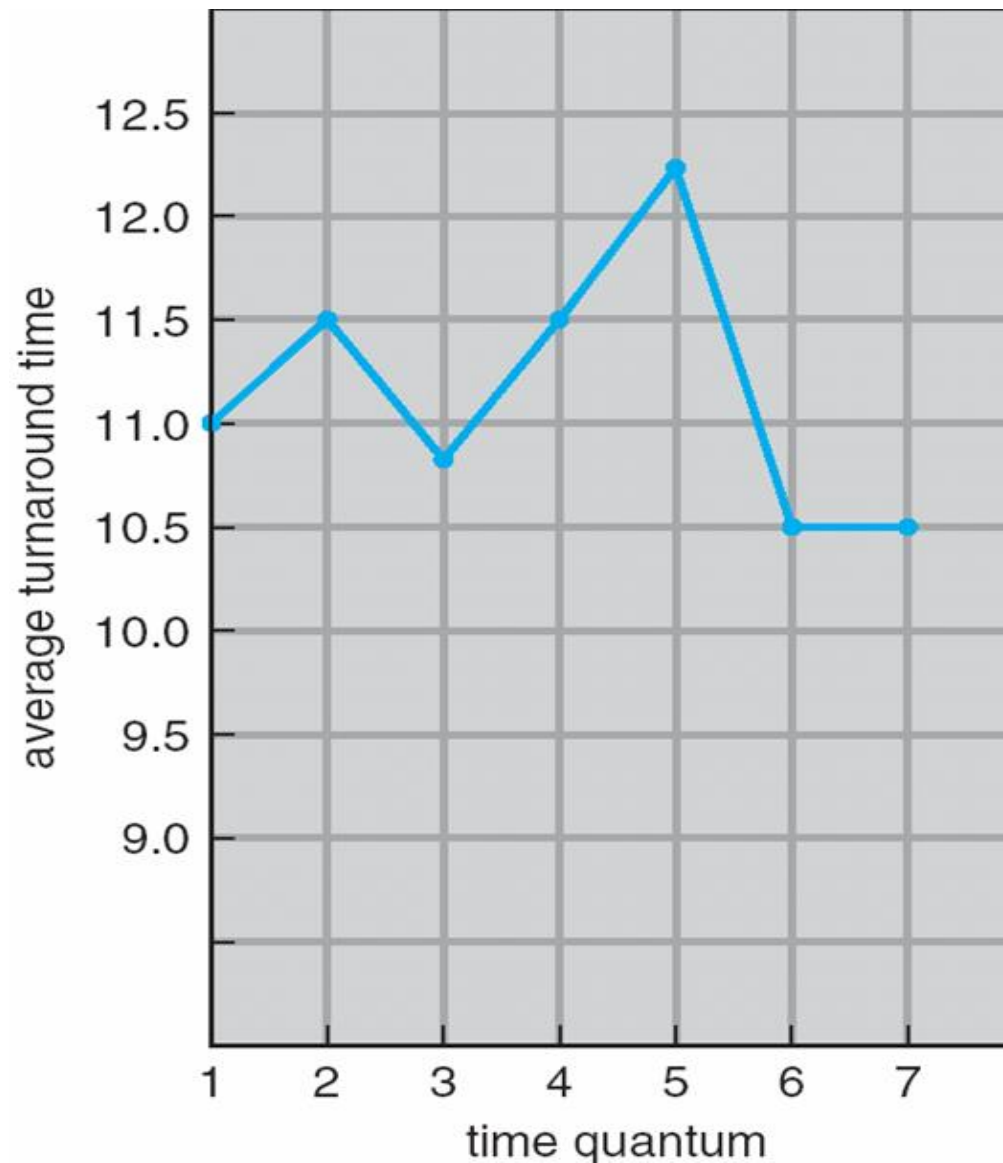- q usually 10ms to 100ms, context switch < 10 usec

process time = 10	quantum	context switches
0 ———————————— 10	12	0
0 —————— 6 —————— 10	6	1
0 1 2 3 4 5 6 7 8 9 10	1	9

process	time
P_1	6
P_2	3
P_3	1
P_4	7

80% of CPU bursts should be shorter than q

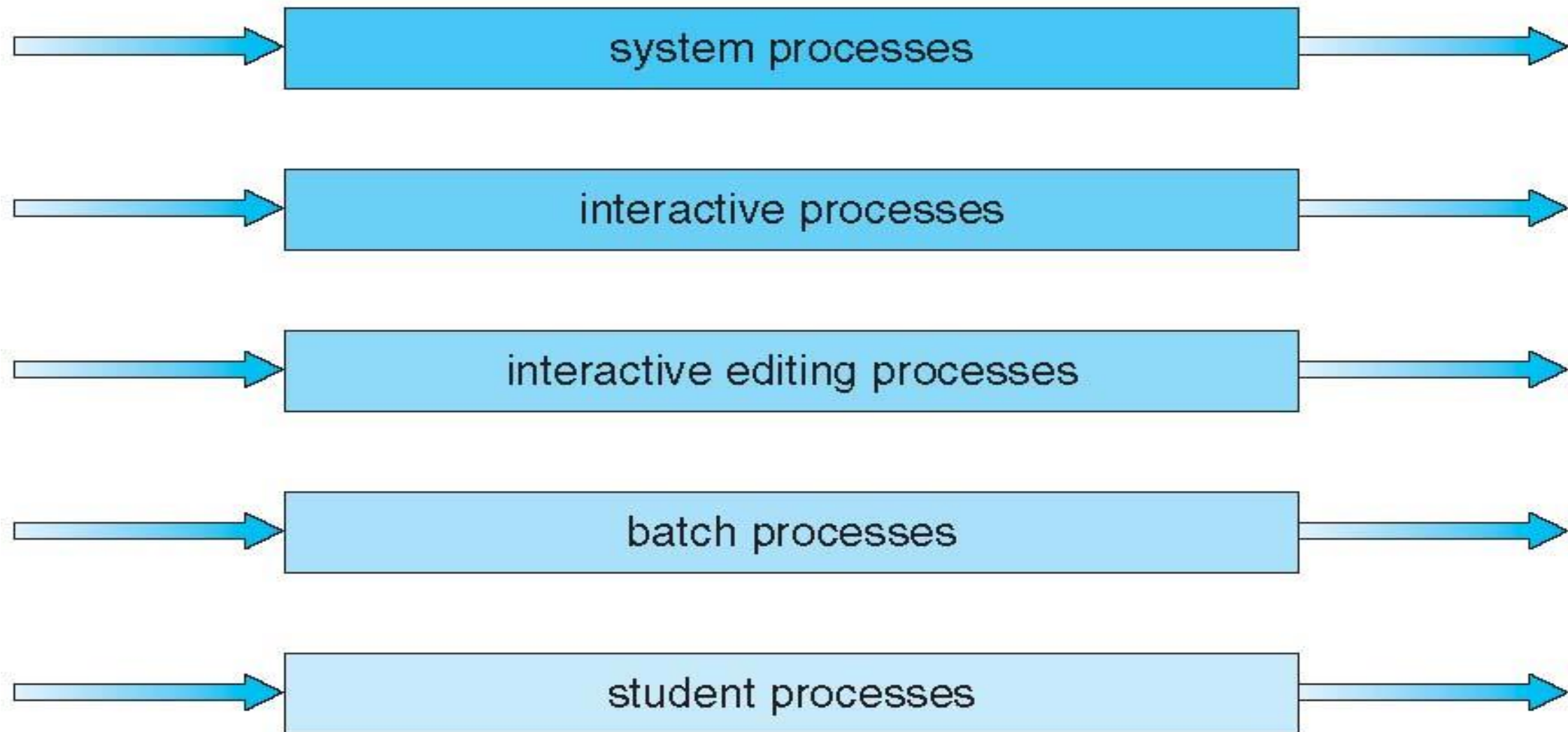# Questions?

Multilevel Queue

- Ready queue is partitioned into separate queues, eg:
  - **foreground** (interactive)
  - **background** (batch)
- Process permanently in a given queue

- 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 a
  - gst its processes; i.e., 80% to foreground in RR
  - 20% to background in FCFS

Multilevel Queue Scheduling

highest priority

→ system processes →

→ interactive processes →

→ interactive editing processes →

→ batch processes →

→ student processes →

lowest priority

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 (may be different)
  - 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

- Most general algorithm, but also most complicated

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
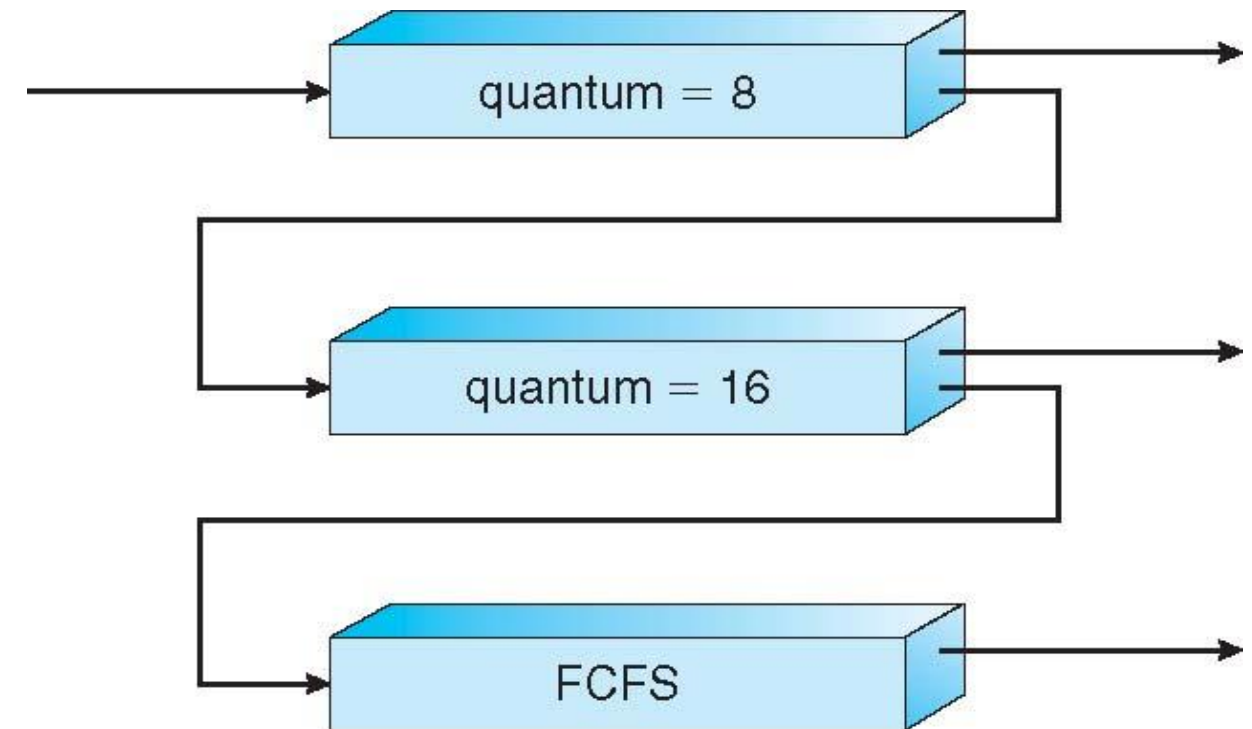
Thread Scheduling

- 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 (lightweight processes)
    - 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
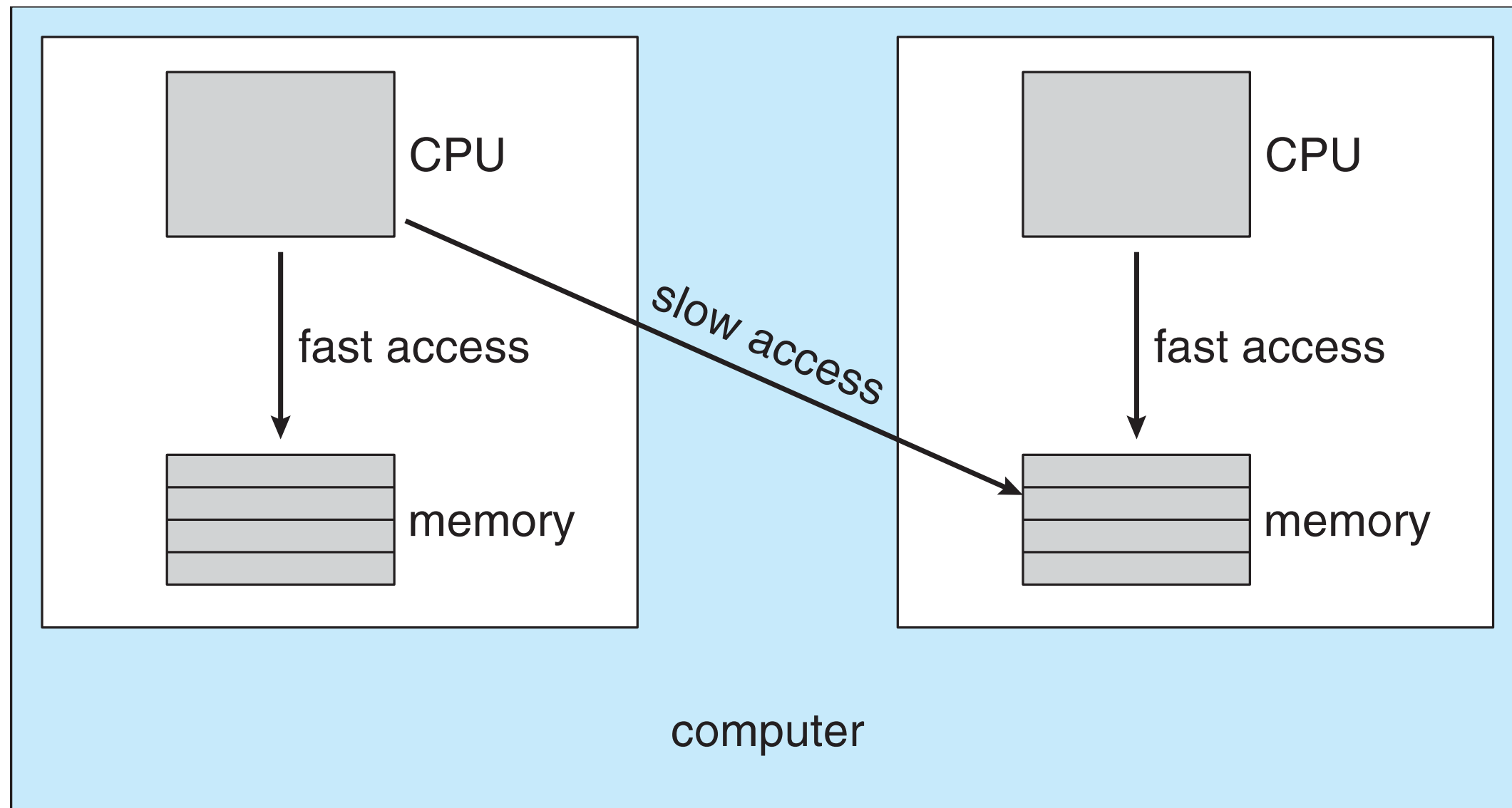
Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available

- **Homogeneous processors** within a multiprocessor

- **Asymmetric multiprocessing** – only one processor accesses the system data structures, alleviating the need for data sharing

- **Symmetric multiprocessing** (**SMP**) – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
  - Currently, most common

- **Processor affinity** – process has affinity for processor on which it is currently running
  - **soft affinity**
  - **hard affinity**
  - Variations including **processor sets**

NUMA and CPU Scheduling

CPU

fast access

memory

slow access

CPU

fast access

memory

computer

Note that memory-placement algorithms can also consider affinity

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
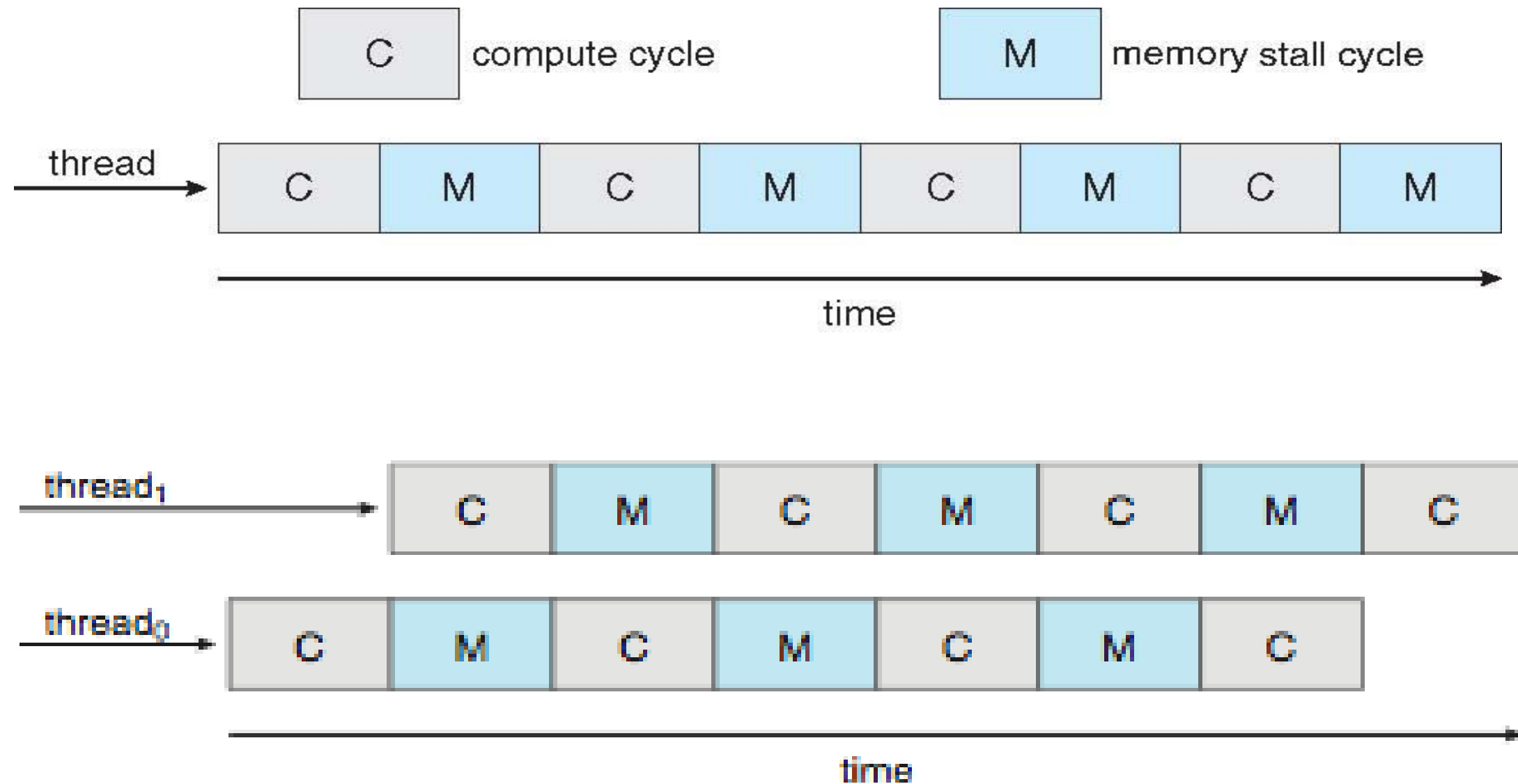
Multicore Processors

- Recent trend to place multiple processor cores on same physical chip

- Faster and consumes less power than multiple chips

- Multiple threads per core also growing
    - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

Questions?

Virtualization and Scheduling

- Virtualization software schedules multiple guests onto CPU(s)

- Each guest doing its own scheduling

  - Not knowing it doesn't own the CPUs

  - Can result in poor response time

  - Can effect time-of-day clocks in guests

- Can undo good scheduling algorithm efforts of guests

Real-Time CPU Scheduling

- Can present obvious challenges

- **Soft real-time systems** – no guarantee as to when critical real-time process will be scheduled

- **Hard real-time systems** – task must be serviced by its deadline

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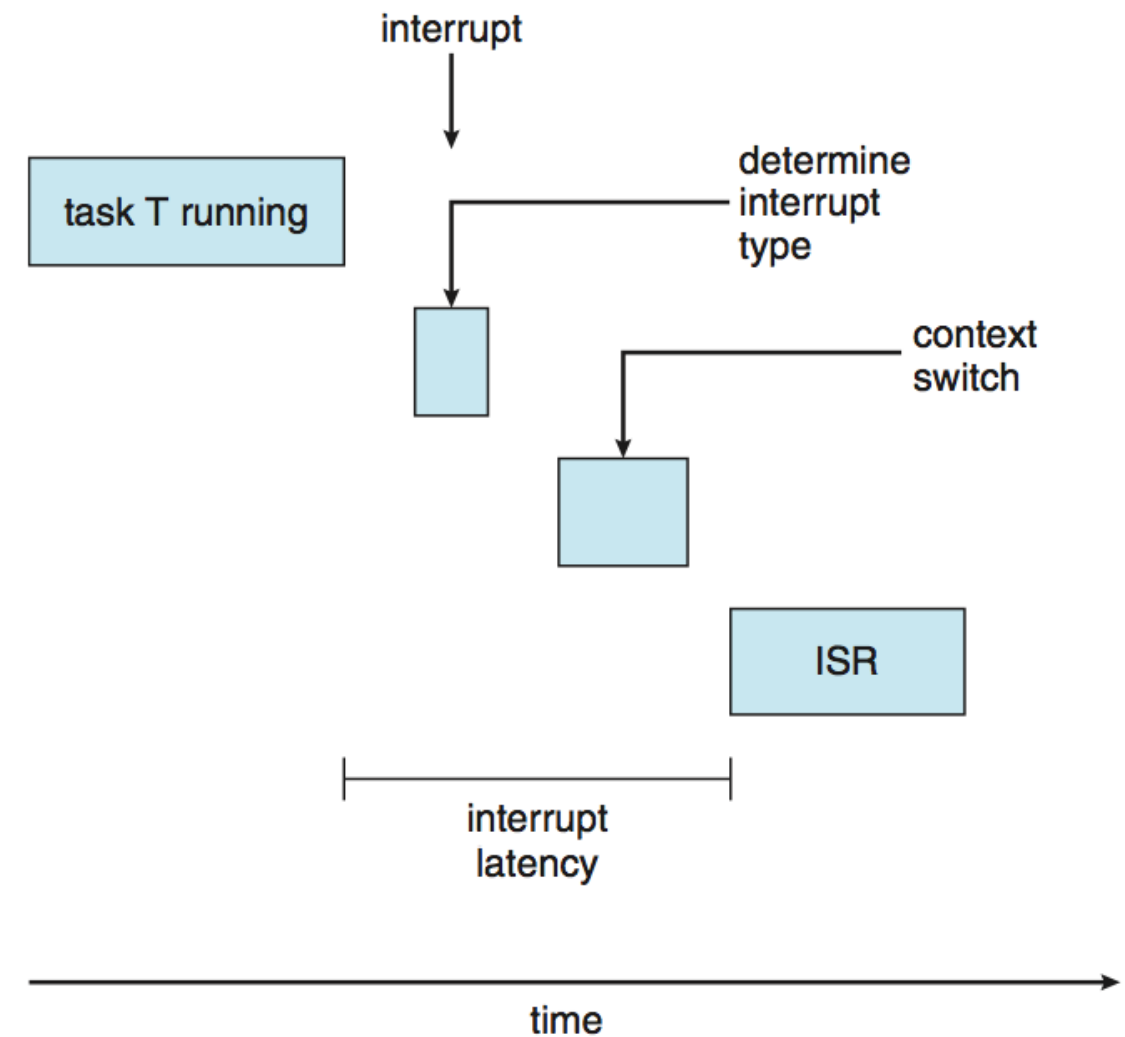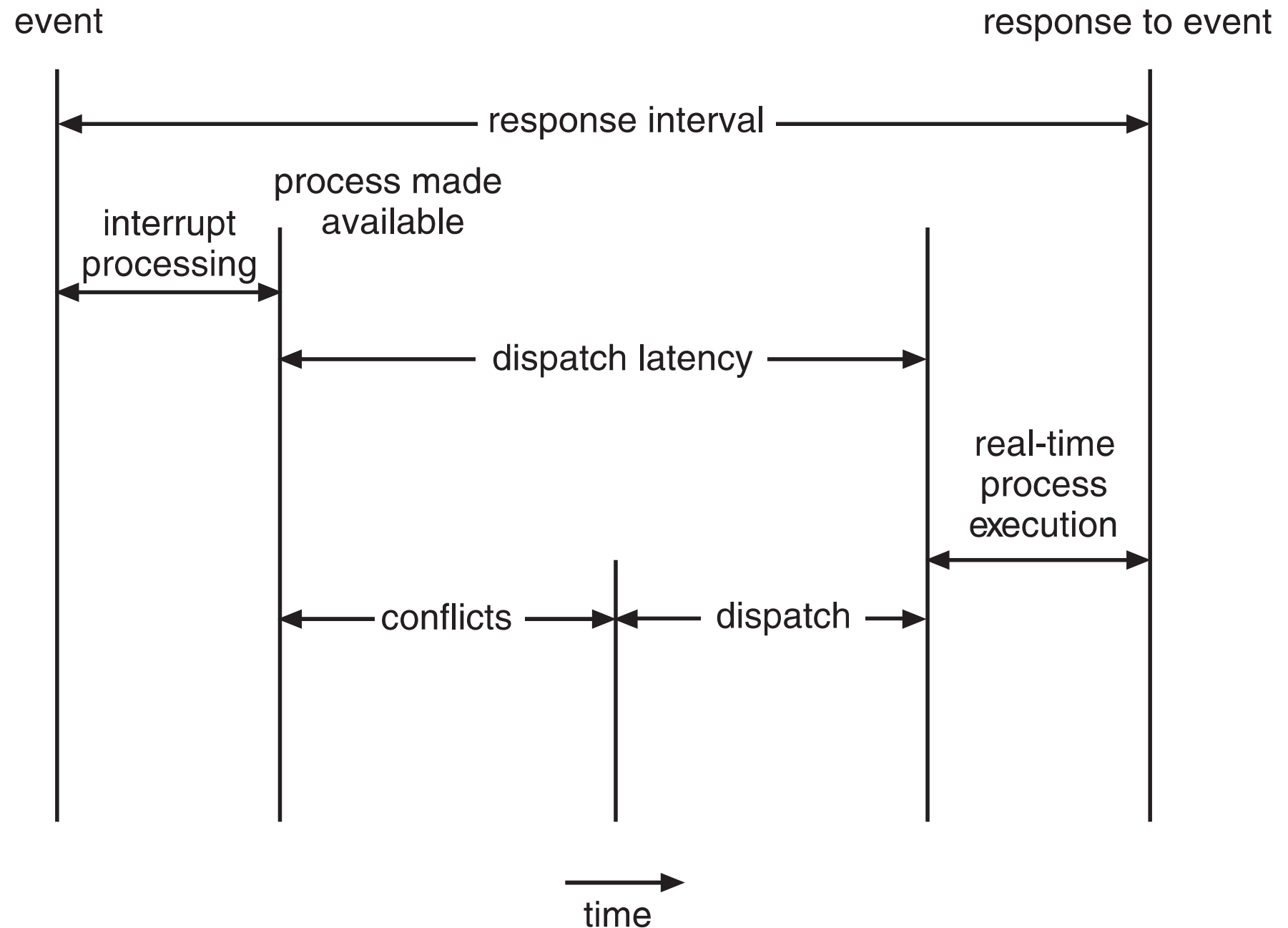
- Conflict phase of dispatch latency:
  1. Preemption of any process running in kernel mode
  2. Release by low-priority process of resources needed by high-priority processes

event   response to event

response interval

process made available

interrupt processing

dispatch latency

real-time process execution

conflicts   dispatch
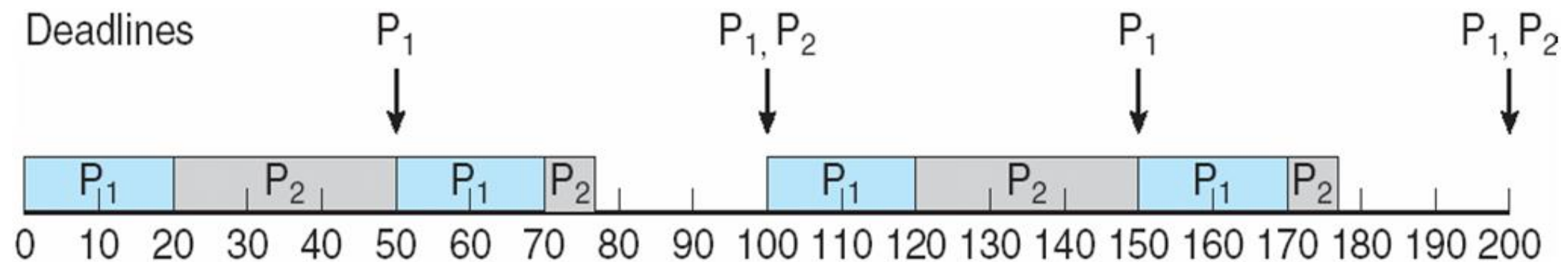
time

Priority-based Scheduling

- For real-time scheduling, scheduler must support preemptive, priority-based scheduling
    - But only guarantees soft real-time
- For hard real-time 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
    - $0 \leq t \leq d \leq p$
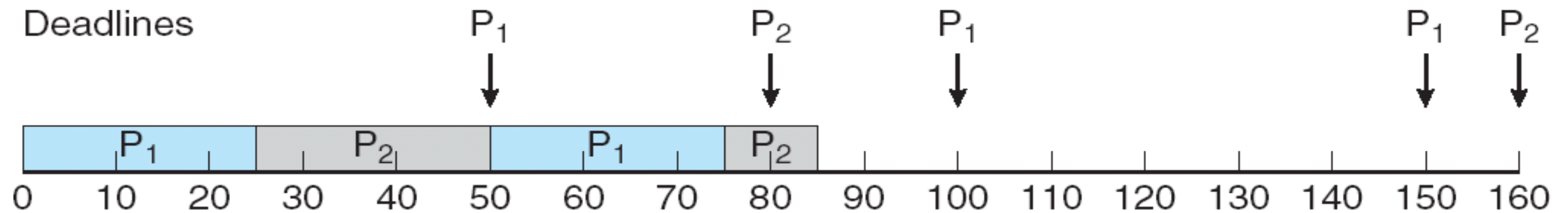   - **Rate** of periodic task is $1/p$
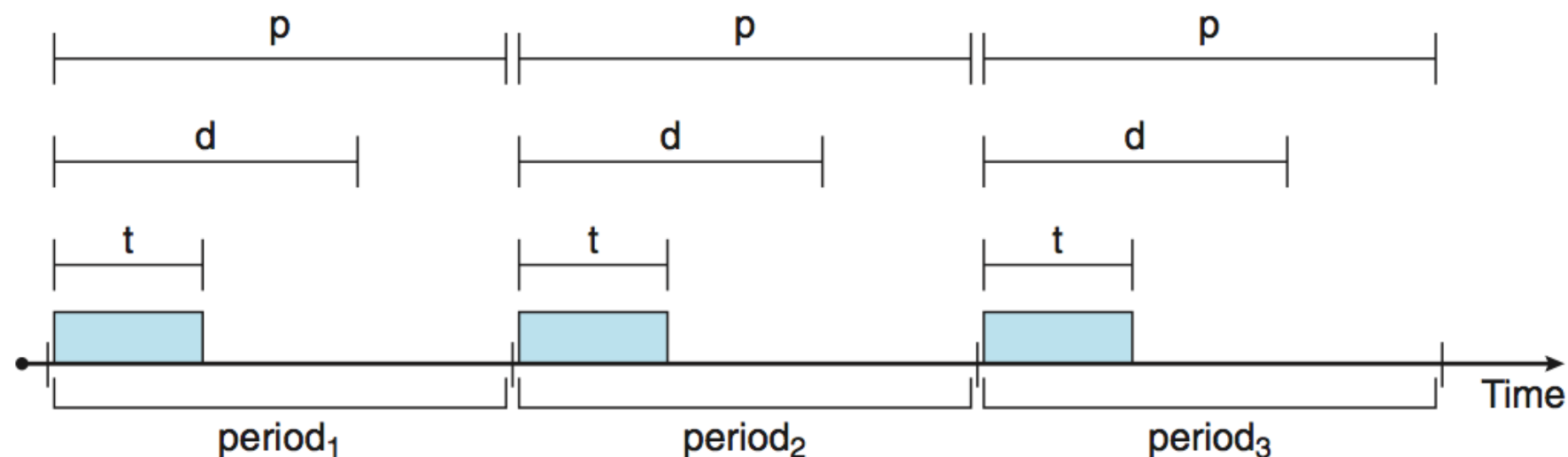
Rate Monotonic Scheduling

- A priority is assigned based on the inverse of its period

- Shorter periods = higher priority;

- Longer periods = lower priority

- P_1 is assigned a higher priority than P_2.

Maximum CPU utilization to guarantee schedule for N tasks is

$$N(2^{1/N} - 1)$$
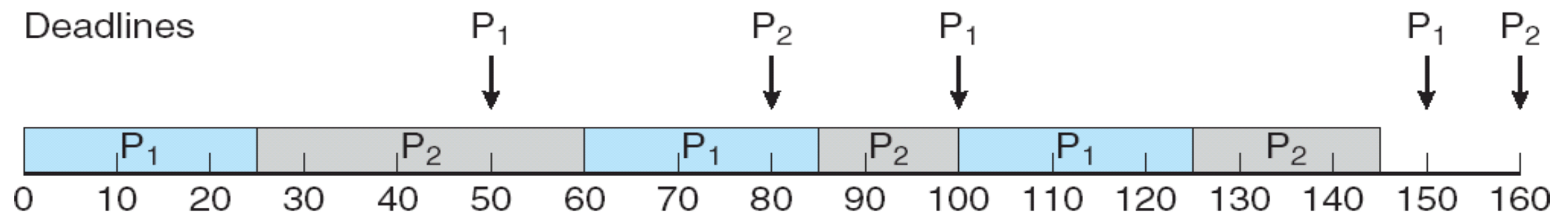
= 83% for two tasks
~ 69% for many tasks

Earliest Deadline First Scheduling (EDF)

- Priorities are assigned according to deadlines:

  the earlier the deadline, the higher the priority;

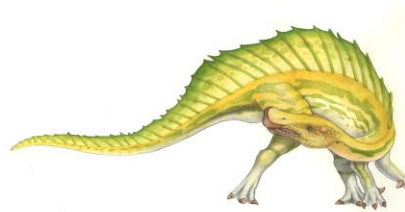 the later the deadline, the lower the priority

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

Questions?

Operating System Examples

- Linux scheduling

- Windows scheduling

- Solaris scheduling

Linux Scheduling in Version 2.6.23 +

- *Completely Fair Scheduler* (CFS)
- **Scheduling classes**
  - Each has specific priority
  - Scheduler picks highest priority task in highest scheduling class
  - Rather than quantum based on fixed time allotments, based on proportion of CPU time
  - 2 scheduling classes included, others can be added
    1. default
    2. real-time
- Quantum calculated based on **nice value** from -20 to +19
  - Lower value is higher priority
  - Calculates **target latency** – interval of time during which task should run at least once
  - Target latency can increase if say number of active tasks increases
- CFS scheduler maintains per task **virtual run time** in variable `vruntime`
  - Associated with decay factor based on priority of task – lower priority is higher decay rate
  - Normal default priority yields virtual run time = actual run time
- To decide next task to run, scheduler picks task with lowest virtual run time

CFS Performance

The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Each runnable task is placed in a red-black tree—a balanced binary search tree whose key is based on the value of `vruntime`. This tree is shown below:
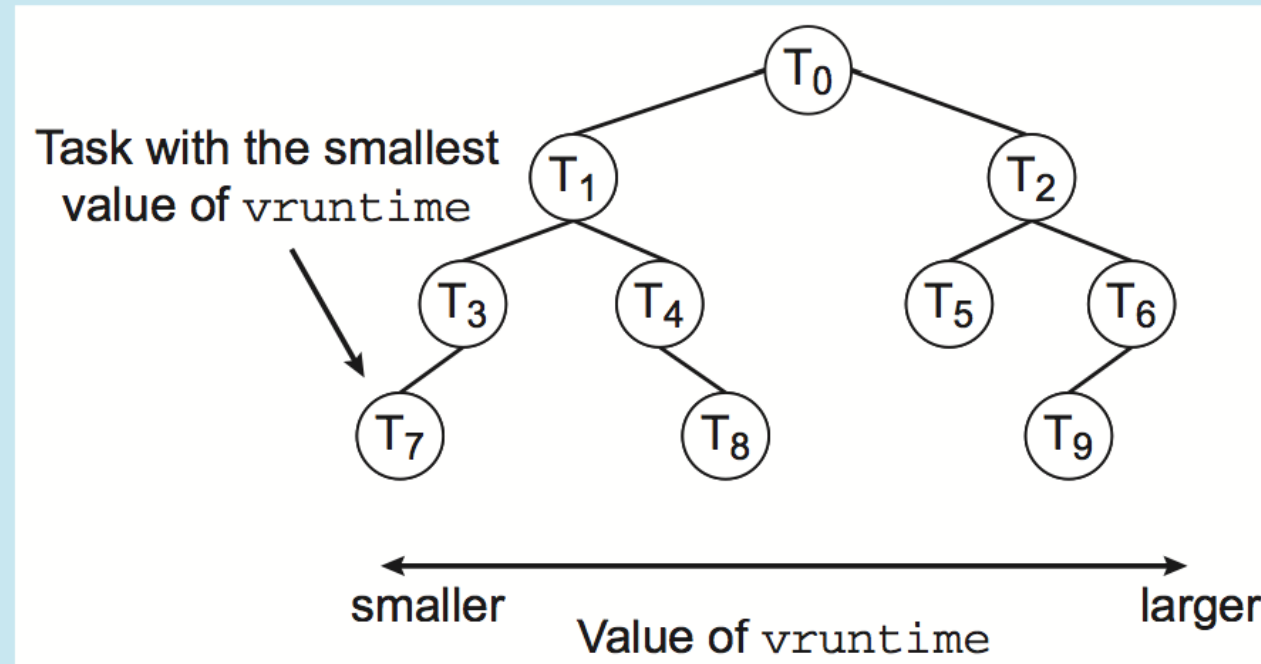

When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable (for example, if it is blocked while waiting for I/O), it is removed. Generally speaking, tasks that have been given less processing time (smaller values of `vruntime`) are toward the left side of the tree, and tasks that have been given more processing time are on the right side. According to the properties of a binary search tree, the leftmost node has the smallest key value, which for the sake of the CFS scheduler means that it is the task with the highest priority. Because the red-black tree is balanced, navigating it to discover the leftmost node will require $O(lg N)$ operations (where N is the number of nodes in the tree). However, for efficiency reasons, the Linux scheduler caches this value in the variable `rb_leftmost`, and thus determining which task to run next requires only retrieving the cached value.

Linux Scheduling (Cont.)

- 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

Real-Time	Normal
0 99	100 139

Higher ←————————————————————————→ Lower
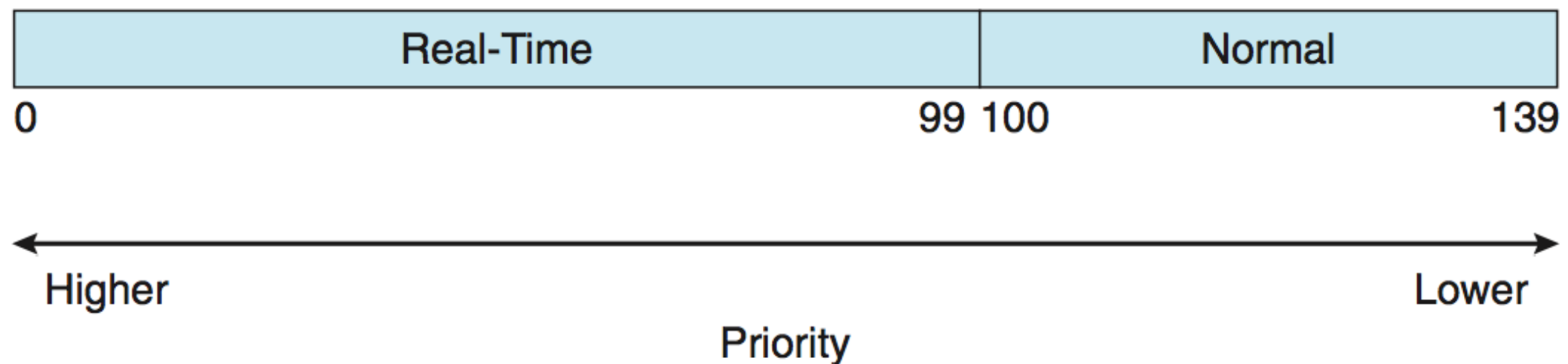
Priority

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**

Solaris

- Priority-based scheduling
- Six classes available
    - Time sharing (default) (TS)
    - Interactive (IA)
    - Real time (RT)
    - System (SYS)
    - Fair Share (FSS)
    - Fixed priority (FP)
- Given thread can be in one class at a time
- Each class has its own scheduling algorithm
- Time sharing is multi-level feedback queue
    - Loadable table configurable by sysadmin

Algorithm Evaluation

- How to select CPU-scheduling algorithm for an OS?
- Determine criteria, then evaluate algorithms
- **Deterministic modeling**
    - Type of **analytic evaluation**
    - Takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Consider 5 processes arriving at time 0:

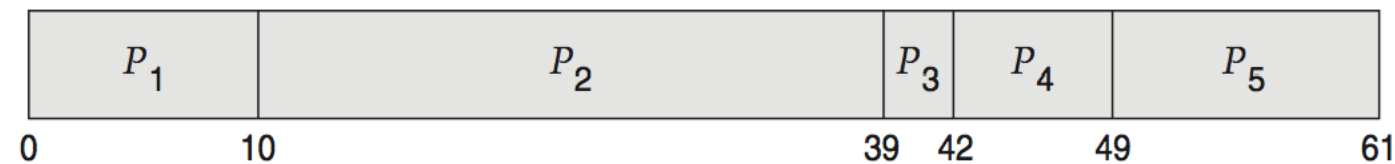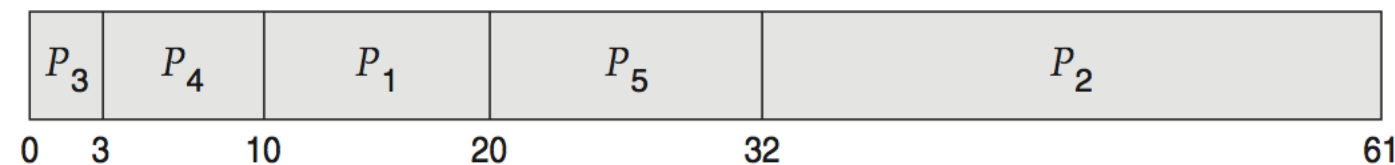| Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

Deterministic Evaluation

n   For each algorithm, calculate minimum average waiting time

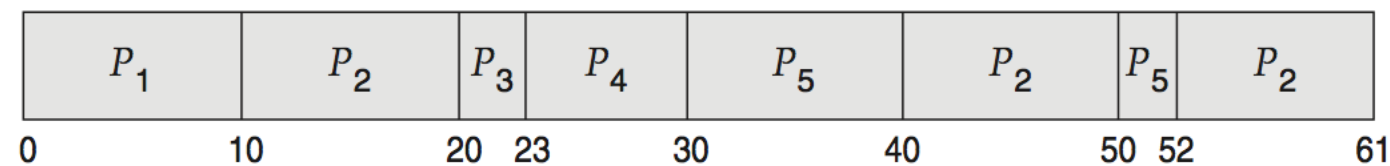n   Simple and fast, but requires exact numbers for input, applies only to those inputs

l   FCS is 28ms:

P_1	P_2	P_3	P_4	P_5

0   10   39 42   49   61

l   Non-preemptive SFJ is 13ms:

P_3	P_4	P_1	P_5	P_2

0 3   10   20   32   61

l   RR is 23ms:

P_1	P_2	P_3	P_4	P_5	P_2	P_5	P_2

0   10   20 23   30   40   50 52   61

Queueing Models

- Describes the arrival of processes, and CPU and I/O bursts probabilistically
    - Commonly exponential, and described by mean
    - Computes average throughput, utilization, waiting time, etc
- Computer system described as network of servers, each with queue of waiting processes
    - Knowing arrival rates and service rates
    - Computes utilization, average queue length, average wait time, etc

Little's Formula

- n = average queue length

- W = average waiting time in queue

- λ = average arrival rate into queue

- Little's law – in steady state, processes leaving queue must equal processes arriving, thus
  $n = \lambda \times W$

  - Valid for any scheduling algorithm and arrival distribution

- For example, if on average 7 processes arrive per second, and normally 14 processes in queue, then average wait time per process = 2 seconds

Simulations

- Queueing models limited

- **Simulations** more accurate
  - Programmed model of computer system
  - Clock is a variable
  - Gather statistics indicating algorithm performance
  - Data to drive simulation gathered via
    - Random number generator according to probabilities
    - Distributions defined mathematically or empirically
    - Trace tapes record sequences of real events in real systems

Implementation

- Even simulations have limited accuracy
- Just implement new scheduler and test in real systems
  - High cost, high risk
  - Environments vary
- Most flexible schedulers can be modified per-site or per-system
- Or APIs to modify priorities
- But again environments vary

Questions ?