Operating System Concepts

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Contents

1. Introduction
2. System Structures
3. Process Concept
4. Multithreaded Programming
5. Process Scheduling
6. Synchronization
7. Deadlocks
8. Memory-Management Strategies
9. Virtual-Memory Management
10. File System
11. Implementing File Systems
12. Secondary-Storage Systems

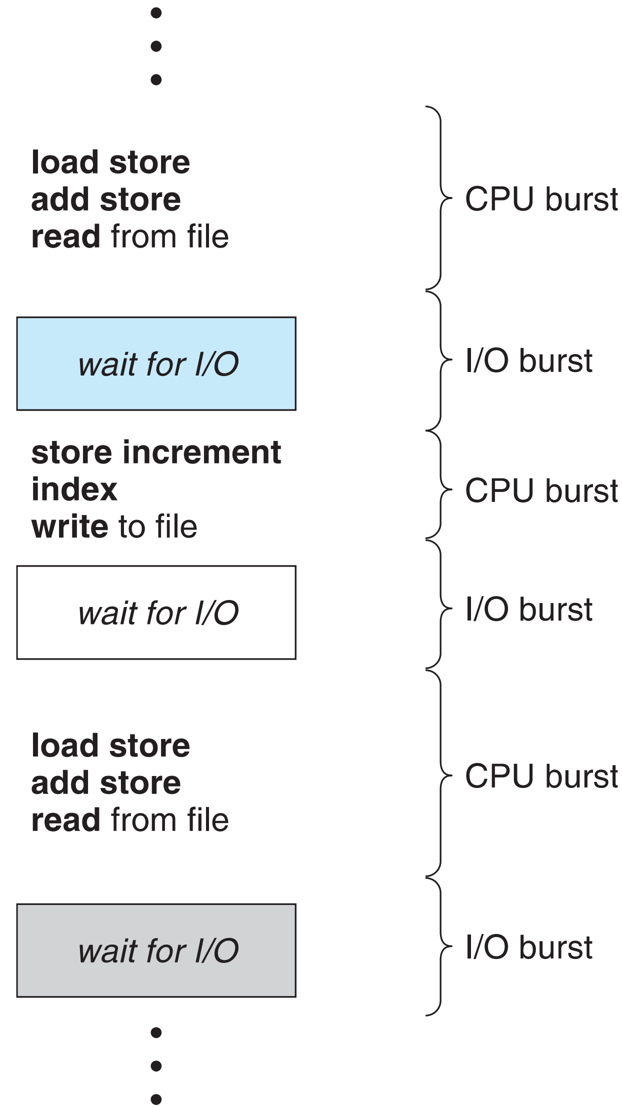
Chapter 5. Process Scheduling

Objectives

- To introduce CPU scheduling, which is the basis for multi-programmed 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

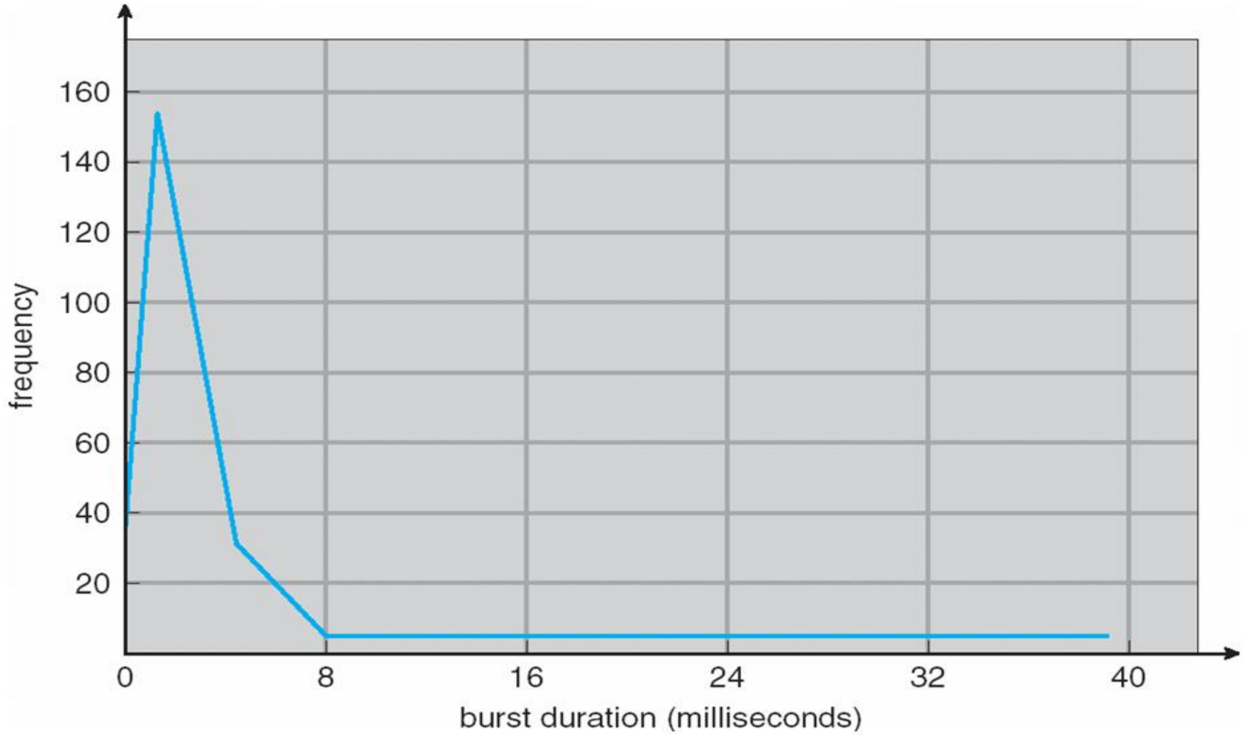
Basic Concepts

- CPU–I/O Burst Cycle
  - Process execution consists of a cycle of CPU execution and I/O waiting
- Process Execution
  - CPU-bound programs tend to have a few very long CPU bursts
  - IO-bound programs tend to have many very short CPU bursts



Histogram of CPU-burst Times

- The distribution can help in selecting an appropriate CPU scheduling algorithms



CPU Scheduler

- Short-term scheduler selects a process among the processes in the ready queue, and allocates the CPU to the selected process
  - 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

Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler
  - switching context
  - switching to user mode
  - jumping to the proper location in the user program to resume that process
- Dispatch latency – the time it takes for the dispatcher to stop one process and start another running

Scheduling Criteria

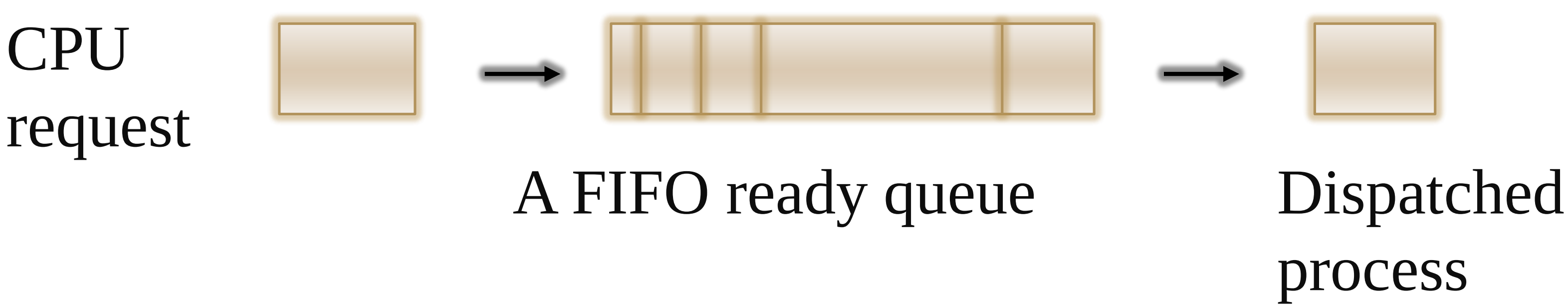
- Why?
  - Different scheduling algorithms may favor one class of processes over another
- Criteria
  - CPU Utilization
  - Throughput
  - Turnaround Time: (Completion Time) – (Start Time)
  - Waiting Time: Waiting in the Ready Queue
  - Response Time: First Response Time

Scheduling Algorithms

- First-Come, First-Served Scheduling (FIFO)
- Shortest-Job-First Scheduling (SJF)
- Priority Scheduling
- Round-Robin Scheduling (RR)
- Multilevel Queue Scheduling
- Multilevel Feedback Queue Scheduling
- Multiple-Processor Scheduling

First-Come, First-Served (FCFS) Scheduling

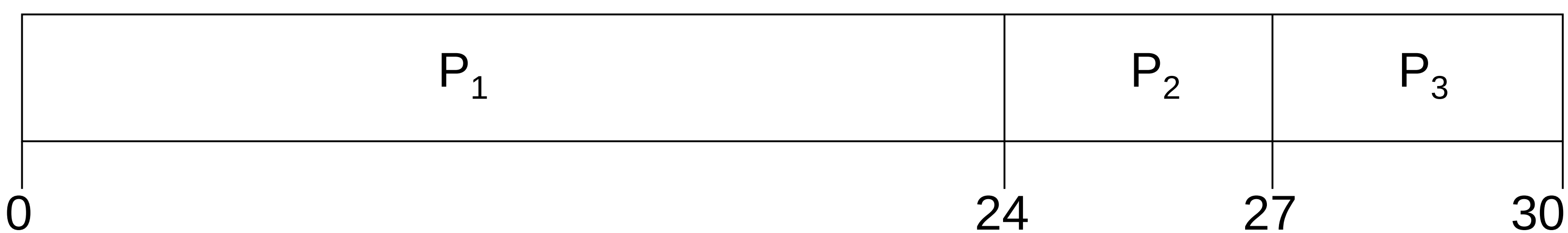
- The process which requests the CPU first is allocated the CPU
- Properties:
  - Non-preemptive scheduling
  - CPU might be hold for an extended period



A Scheduling Example of FCFS (1/2)

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



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

A Scheduling Example of FCFS (2/2)

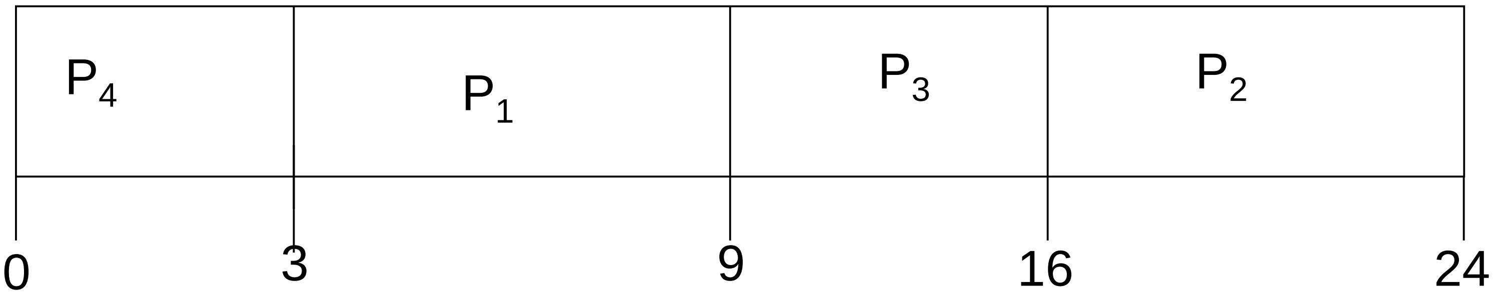
- Suppose that the processes arrive in the order:
  - P2 , P3 , P1
- The Gantt chart for the schedule is:

- Waiting time for $P_1 = 6$; $P_2 = 0$; $P_3 = 3$
- Average waiting time: $(6 + 0 + 3)/3 = 3$
- **Convoy effect** – short processes behind long a process

Shortest-Job-First (SJF) Scheduling

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- SJF scheduling chart



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

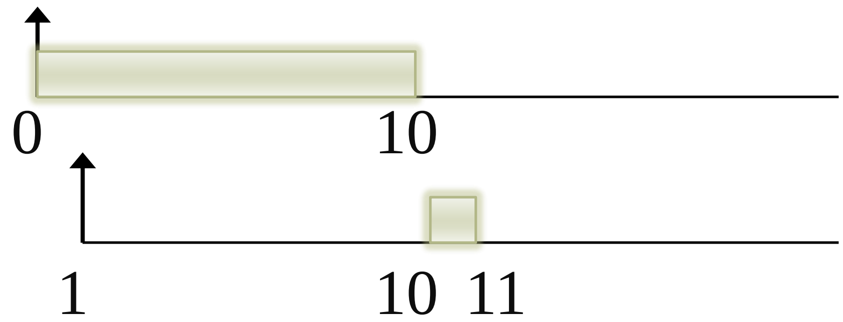
SJF Scheduling Analysis

- Non-preemptive SJF scheduling is optimal when processes are all ready at time 0
  - The minimum average waiting time
- It is difficult to know the length of the next CPU request
  - Prediction of the next CPU burst time 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 : $\tau_{n=1} = \alpha\, t_n + (1-\alpha)\tau_n$

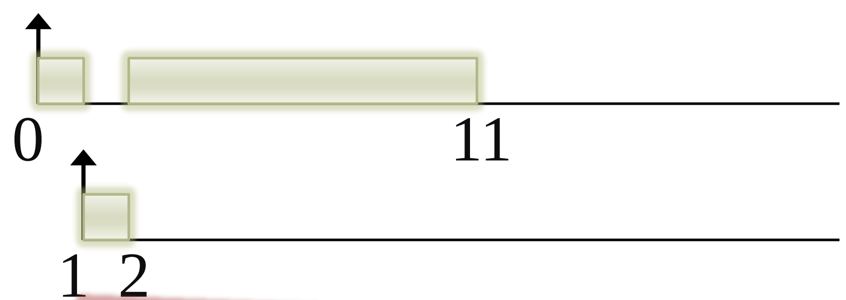
Preemptive SJF Scheduling

- Preemptive or Non-preemptive?
  - Criteria such as AWT (Average Waiting Time)



Non-preemptive
AWT = (0+(10-1))/2
= 9/2 = 4.5

or



Preemptive AWT
= ((2-1)+0) = 0.5

Shortest-Remaining-Time-First Scheduling

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Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority
- Priority Assignment
  - Internally defined – use some measurable quantity, such as the number of open files, $\frac{\text{Average CPU Burst}}{\text{Average I/O Burst}}$
  - Externally defined – set by criteria external to the OS, such as the criticality levels of jobs

A Scheduling Example with Priority Scheduling

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

Gantt Graph

P_2	P_5	P_1	P_3	P_4

0 1 6 16 18 19

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

Issues of Priority Scheduling

- Problem: Starvation – low priority processes may never execute
- Solution: Aging – as time progresses increase the priority of the process
- A Special Case: SJF is priority scheduling where priority is the inverse of predicted next CPU burst time

Round Robin (RR) Scheduling

- Each process gets a small unit of CPU time (time quantum)
- 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
  - 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

A Scheduling Example of RR Scheduling

Process	CPU Burst Time
P1	24
P2	3
P3	3

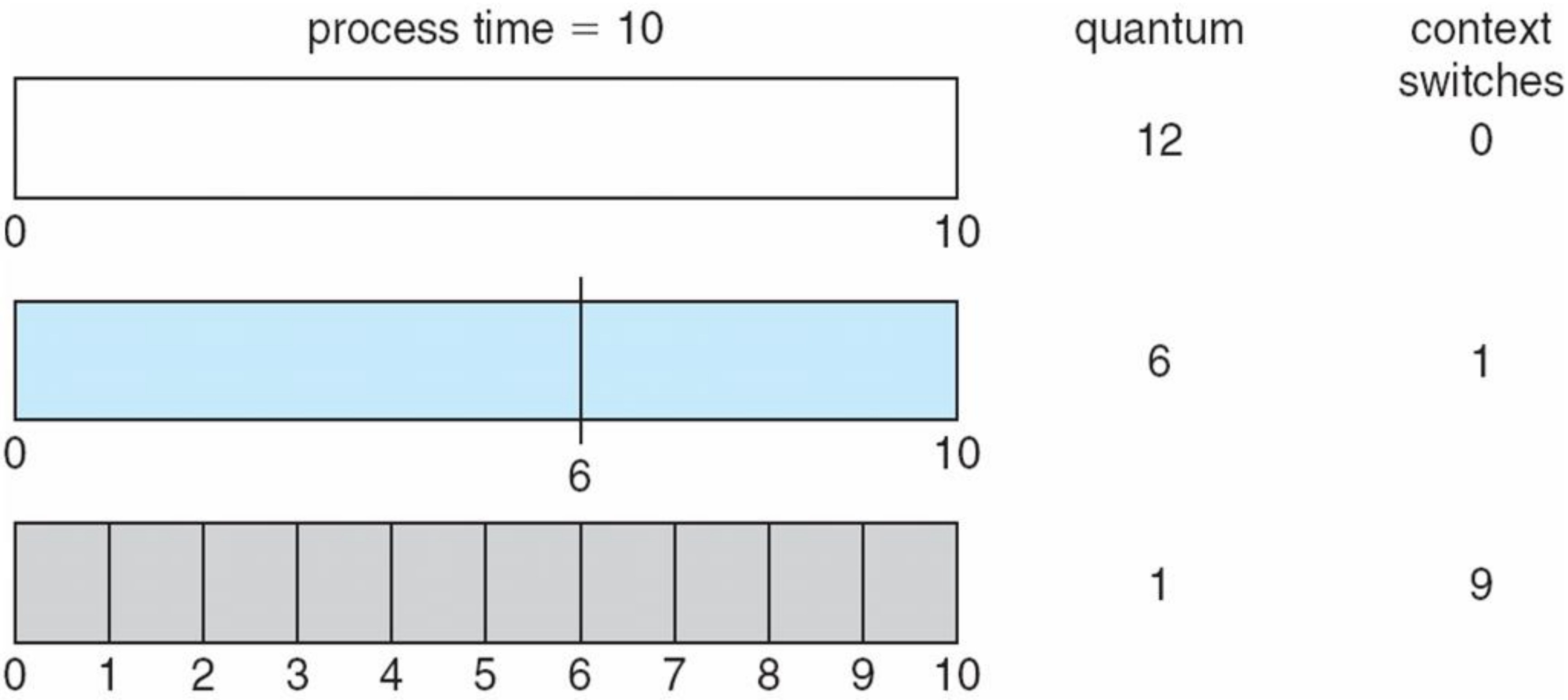
Time slice = 4

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

AWT = ((10-4) + (4-0) + (7-0))/3 = 17/3 = 5.66

Time Quantum and Context Switch



Issues of RR Scheduling

- Time quantum too large $\rightarrow$ FIFO
- Time quantum too small $\rightarrow$ Time quantum must be large with respect to context switch time, otherwise overhead is too high
  - Time quantum usually 10 ms to 100ms
  - Context switch < 10 μs
- A rule of thumb is that 80 percent of the CPU bursts should be shorter than the time quantum

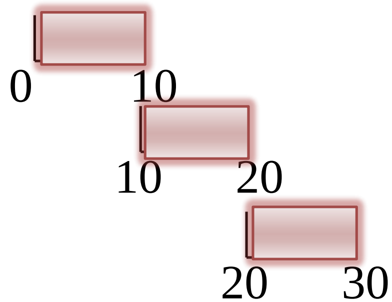
Issues of RR Scheduling — Turnaround Time

process (10ms) quantum = 10 quantum = 1

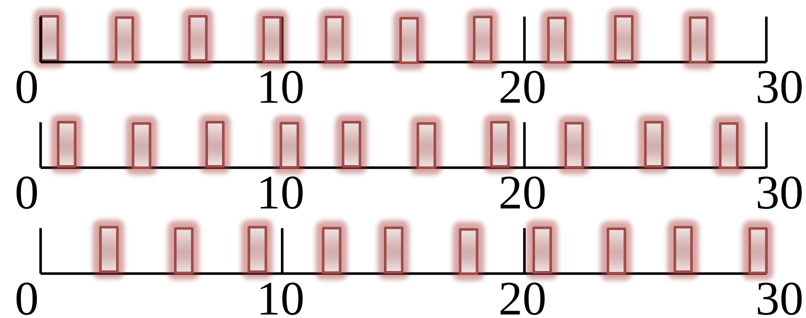
P1

P2

P3



Average Turnaround Time
= (10+20+30)/3 = 20

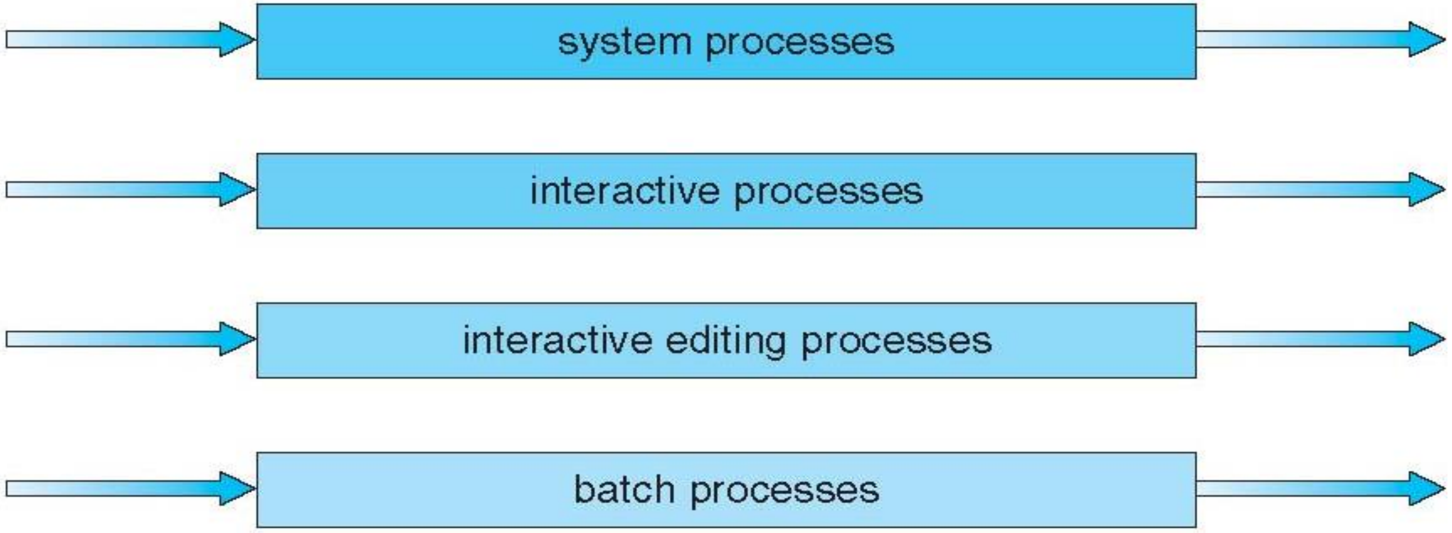


ATT = (28+29+30)/3 = 29

=> 80% CPU Burst < time slice

Multilevel Queue Scheduling

- Partition the ready queue into several separate queues
  - ➔ Processes can be classified into different groups and permanently assigned to one queue



Multilevel Queue Scheduling

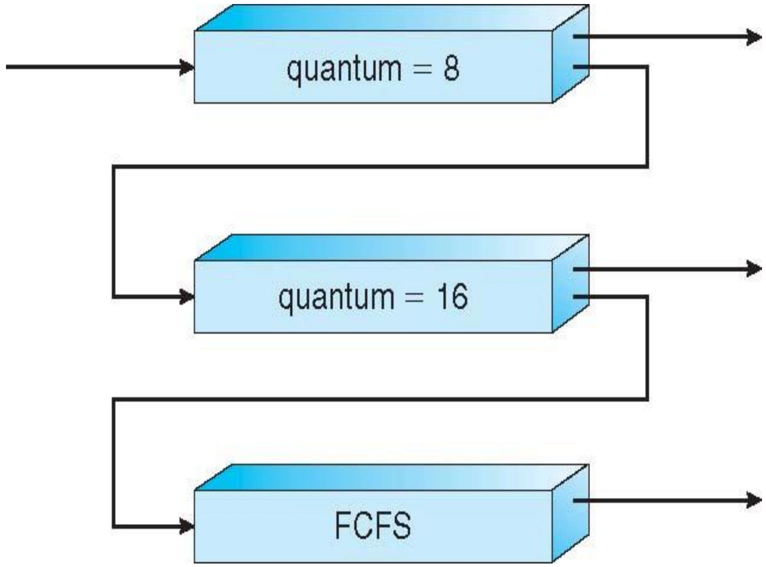
- Intra-queue scheduling
  - Independent choice of scheduling algorithms
    - e. g., foreground – RR, and background – FCFS
- Inter-queue scheduling
  - Fixed-priority preemptive scheduling
    - e.g., foreground queues always have absolute priority over the background queues
  - Time slice between queues
    - e.g., 80% CPU is given to foreground processes, and 20% CPU to background processes

Multilevel Feedback Queue Scheduling

- 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
  - The method to determine which queue a newly ready process will enter

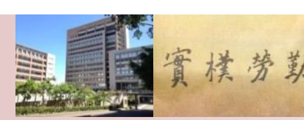
An Example of Multilevel Feedback Queue

- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS
- Scheduling
  - Do jobs in Q_0 first and then Q_1 and then Q_2
  - 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 each job receives 16 additional milliseconds
    - If it still does not complete, it is preempted and moved to queue Q_2



Thread Scheduling

- To run on a CPU, user threads must be mapped to an associated kernel thread
- Local Scheduling
  - Contention Scope: Process-Contention Scope (PCS)
  - How the threads library decides which thread to put onto an available kernel thread
- Global Scheduling
  - Contention Scope: System-Contention Scope (SCS)
  - How the kernel decides which kernel thread to run on CPU next



Multiple-Processor Scheduling

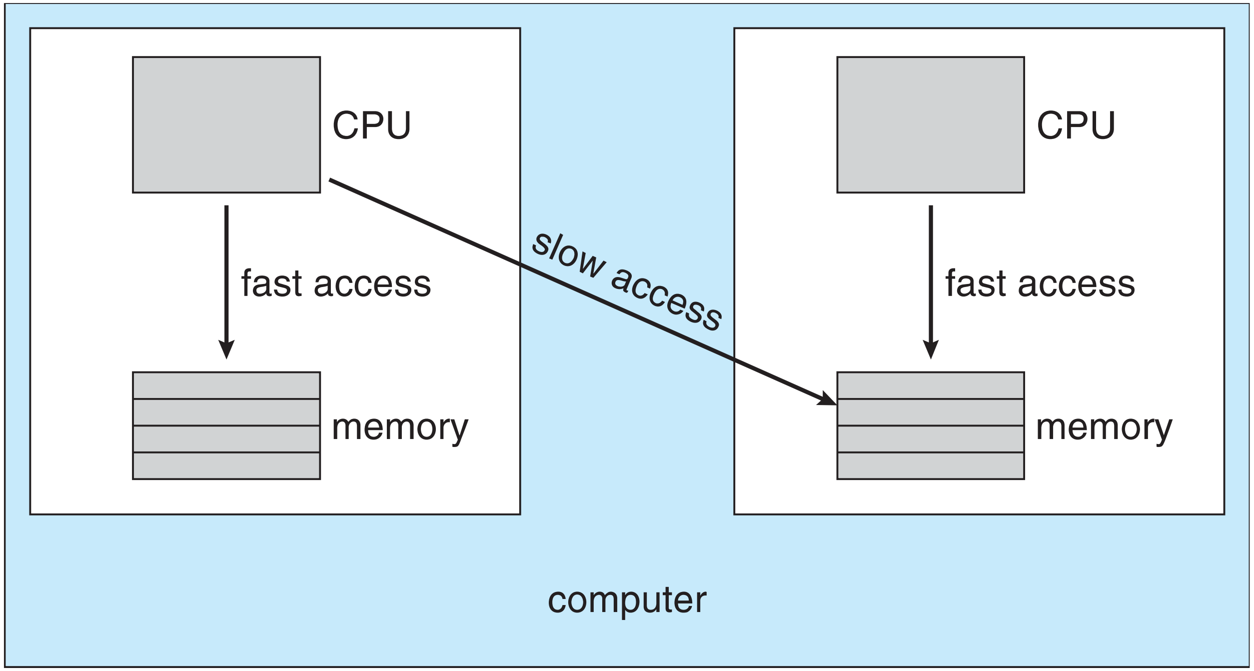
- CPU scheduling in a system with multiple CPUs
- A Homogeneous System
  - Processors are identical in terms of their functionality
- A Heterogeneous System
  - Programs must be compiled for instructions on proper processors

Homogeneous Processors

- **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 processor has its own private queue of ready processes

Multiple-Processor Scheduling—Processor Affinity

- A process might prefer to run on specific processors
  - Hard affinity: `sched_setaffinity()`
  - Soft affinity: non-uniform memory access



Multiple-Processor Scheduling—Load Balancing

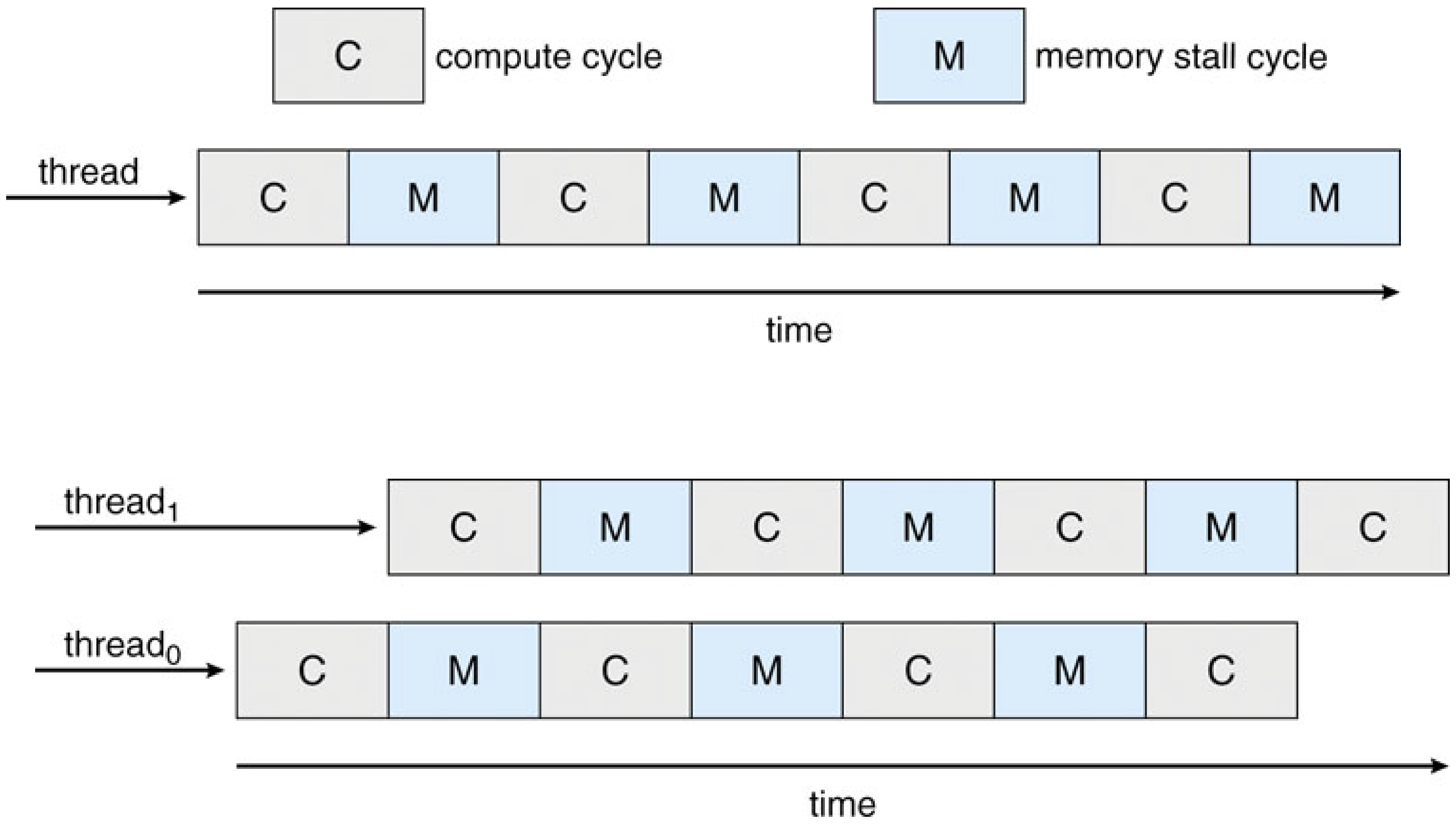
- Attempt to keep the workload evenly distributed across all processors in an SMP system
- Push migration
  - A specific task periodically checks the load on each processor and evenly distributes the load by moving processes from overloaded to idle or less-busy processors
- Pull migration
  - An idle processor pulls a waiting task from a busy processor

Multicore Processors

- Multicore Processor: A physical chip with multiple processor cores.
- Scheduling Issues:
  - Memory Stall
    - Coarse-Grained Multithreading
      - Thread execution until a long latency
    - Fine-Grained Multithreading
      - Better architecture design for switching

→ Multiple Hardware Threads

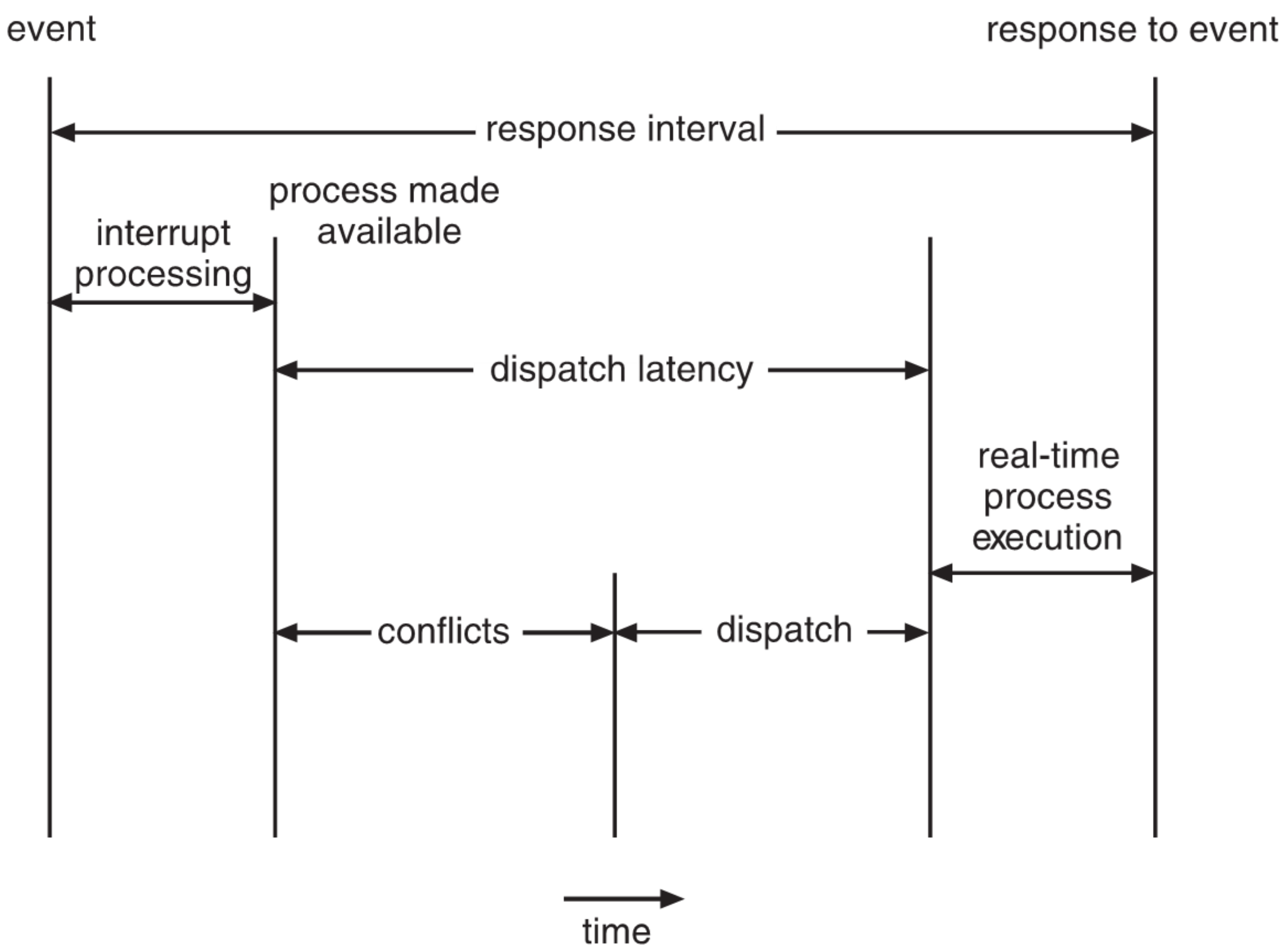
Multithreaded Multicore (Hyper-Threading) System



Real-Time Scheduling (1/2)

- Each task (process) has to be completed before its **deadline**
- **Soft real-time systems** – try to serve a real-time task by its deadline
- **Hard real-time systems** – a real-time task must be served by its deadline
- Two types of latencies affect performance
  1. Interrupt latency – time from arrival of interrupt to start of routine that serves the interrupt
  2. Dispatch latency – time for schedule to take current process off CPU and switch to another

Real-Time Scheduling (2/2)



Operating System Examples – Linux in Version 2.6.23 + (1/3)

- Completely Fair Scheduler (CFS)
  - CFS scheduler maintains per task **virtual run time** in variable **`vruntime`**
  - Associated with decay factor based on priority of task:
    - lower priority ➔ 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
- Nice Value
  - From -20 to +19
  - Lower value is higher priority

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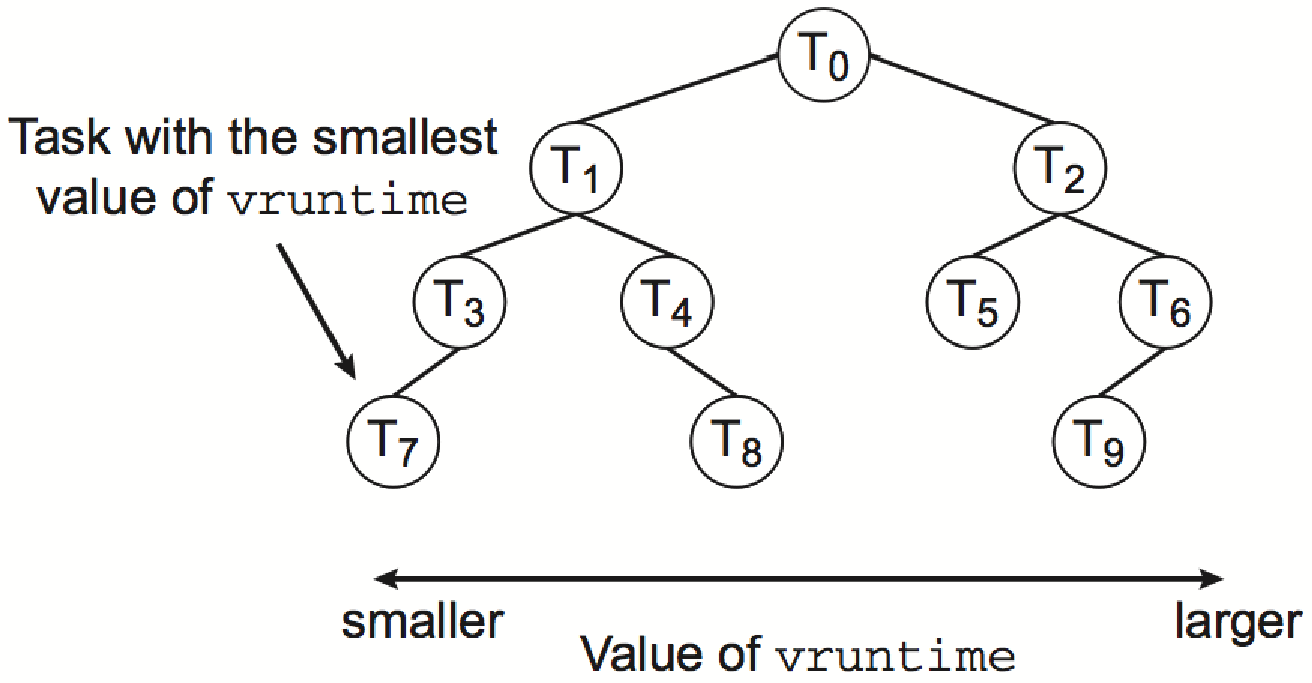
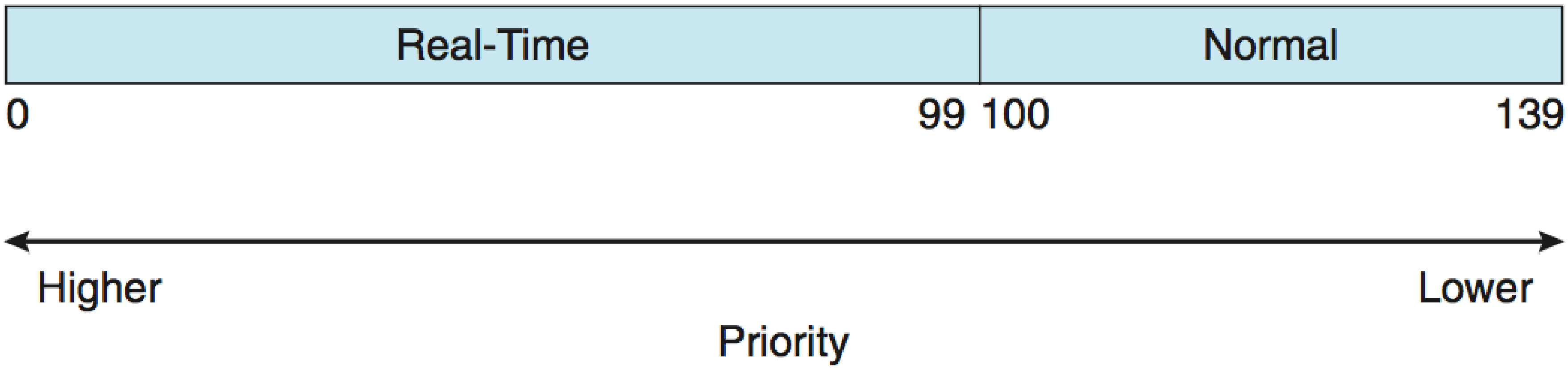
Operating System Examples – Linux in Version 2.6.23 + (2/3)

- A red-back tree is used to maintain the virtual run times of tasks



Operating System Examples – Linux in Version 2.6.23 + (3/3)

- Real-time scheduling according to POSIX
  - 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



Operating System Examples – Windows Scheduling (1/3)

A Typical Class

Base Priority

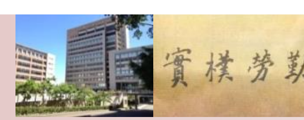
	Real-time	High	Above normal	Normal	Below normal	Idle priority
Time-critical	31	15	15	15	15	15
Highest	26	15	12	10	8	6
Above normal	25	14	11	9	7	5
Normal	24	13	10	8	6	4
Below normal	23	12	9	7	5	3
Lowest	22	11	8	6	4	2
Idle	16	1	1	1	1	1

Real-Time Class

Variable Class (1..15)

Operating System Examples – Windows Scheduling (2/3)

- Priority-Based Preemptive Scheduling
  - Priority Range: from 0 to 31
    - Variable class uses 1-15
    - Real-time class uses 16-31
  - Dispatcher: A process runs until
    - It is preempted by a higher-priority process
    - It terminates
    - Its time quantum ends
    - It calls a blocking system call
  - Idle thread
- A Queue per Priority Level



Operating System Examples – Windows Scheduling (3/3)

- Each thread has a base priority that represents a value in the priority range of its class
- Priority Changing
  - Increased after some waiting
    - Different amount for different I/O devices
  - Decreased after some computation
    - The priority is never lowered below the base priority
- Favor foreground processes
  - Each foreground task is given more time quantum (typically 3 times longer)

Scheduling Algorithm Evaluation

- A General Procedure
  - Select criteria that may include several measures, e.g., maximize CPU utilization while confining the maximum response time to 1 second
  - Evaluate various algorithms
- Evaluation Methods:
  - Deterministic modeling
  - Queuing models
  - Simulation
  - Implementation

Deterministic Modeling

- A Typical Type of Analytic Evaluation
  - Take a particular predetermined workload and defines the performance of each algorithm for that workload
- Properties
  - Simple and fast
  - Through excessive executions of a number of examples, trends might be identified
  - But it needs exact numbers for inputs, and its answers only apply to those cases
    - Being too specific and requires too exact knowledge to be useful

Deterministic Modeling

process	CPU Burst time
P1	10
P2	29
P3	3
P4	7
P5	12

FCFS

P1	P2	P3	P4	P5

0 10 39 42 49 61

Average Waiting Time (AWT)=(0+10+39+42+49)/5=28

Nonpreemptive Shortest Job First

P3	P4	P1	P5	P2

0 3 10 20 32 61

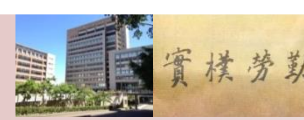
AWT=(10+32+0+3+20)/5=13

Round Robin (quantum =10)

P1	P2	P3	P4	P5	P2	P5	P2

0 10 2023 30 40 5052 61

AWT=(0+(10+20+2)+20+23+(30+10))/5=23



Queuing Models

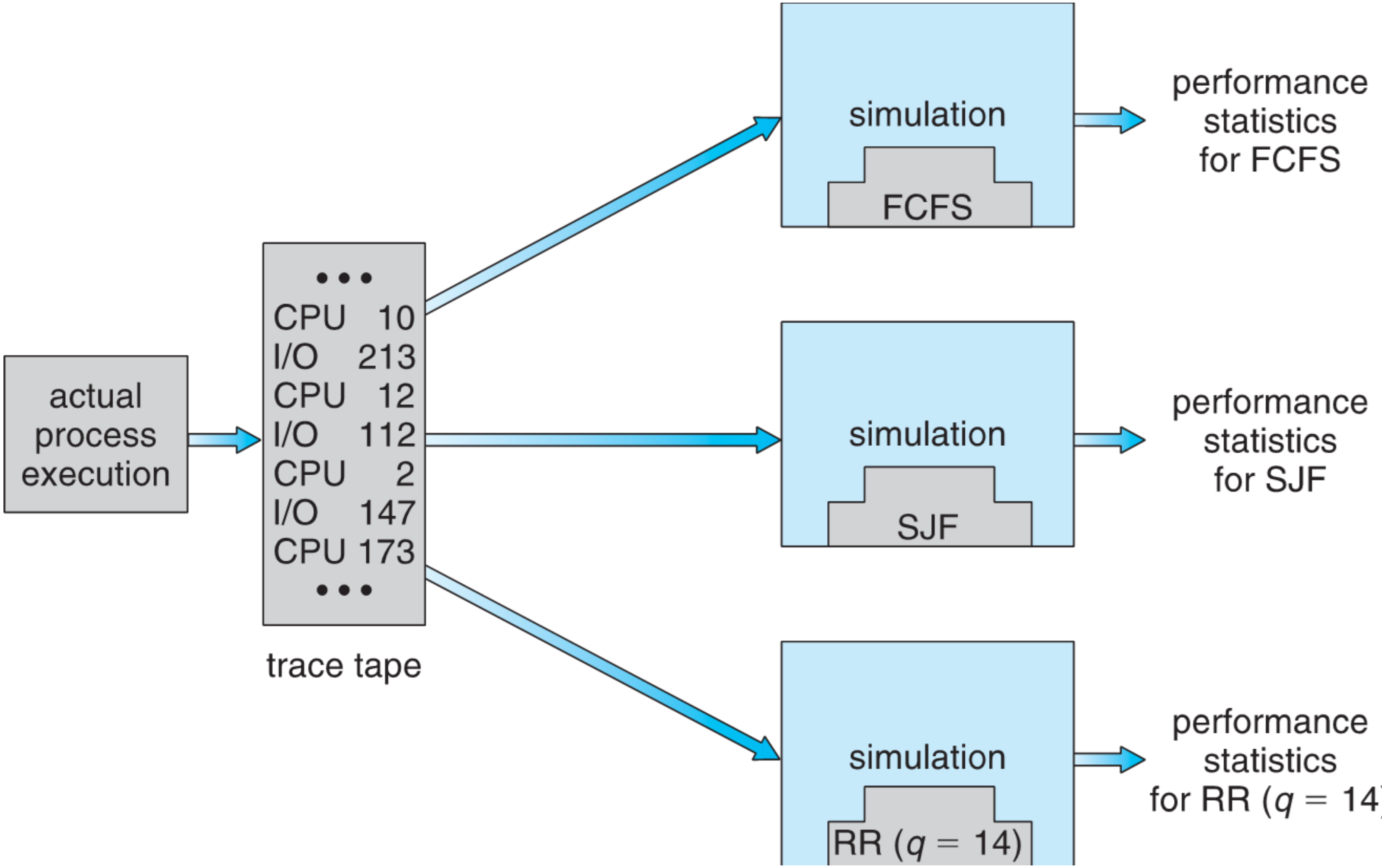
- Motivation:
  - Workloads vary, and there is no static set of processes
- Models (~ Queuing-Network Analysis)
  - Workload:
    - Arrival rate: the distribution of times when processes arrive
    - The distributions of CPU & I/O bursts
  - Service rate

Simulation (1/2)

- Motivation:
  - Get a more accurate evaluation
- Procedures:
  - Program a model of the computer system
  - Drive the simulation with various data sets
    - Randomly generated according to some probability distributions

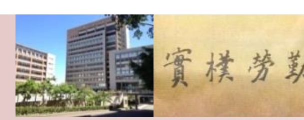
      ➔ Inaccuracy occurs because of only the occurrence frequency of events. Miss the order & the relationships of events.
    - Trace tapes: monitor the real system & record the sequence of actual events.

Simulation (2/2)



Implementation

- Motivation:
  - Get more accurate results than a simulation
- Procedure:
  - Code scheduling algorithms
  - Put them in the OS
  - Evaluate the real behaviors
- Difficulties:
  - Cost in coding algorithms and modifying the OS
  - Reaction of users to a constantly changing the OS
  - The environment in which algorithms are used will change



Quiz

(40%) 考慮在時間點0的時候已經就緒的五個工作，到達的順序為P1, P2, P3, P4, P5。使用兩個排程演算法FCFS (First-Come, First-Served)以及SJF (Shortest-Job-First) 來排程。(1)請畫下兩個排程演算法的排程圖，(2)請分別算出兩個排程演算法中每個工作的等待時間，若無算式一率不給分(算式可以只是簡單的加減法運算)。

Process	Burst Time
P_1	10 ms
P_2	1 ms
P_3	2 ms
P_4	6 ms
P_5	3 ms

- 其他考題：
  - FIFO, Preemptive and Nonpreemptive SJF, RR
  - Turnaround Time, Waiting Time, Response Time: