Operating System: Chap5 Process Scheduling

National Tsing Hua University

2022, Fall Semester

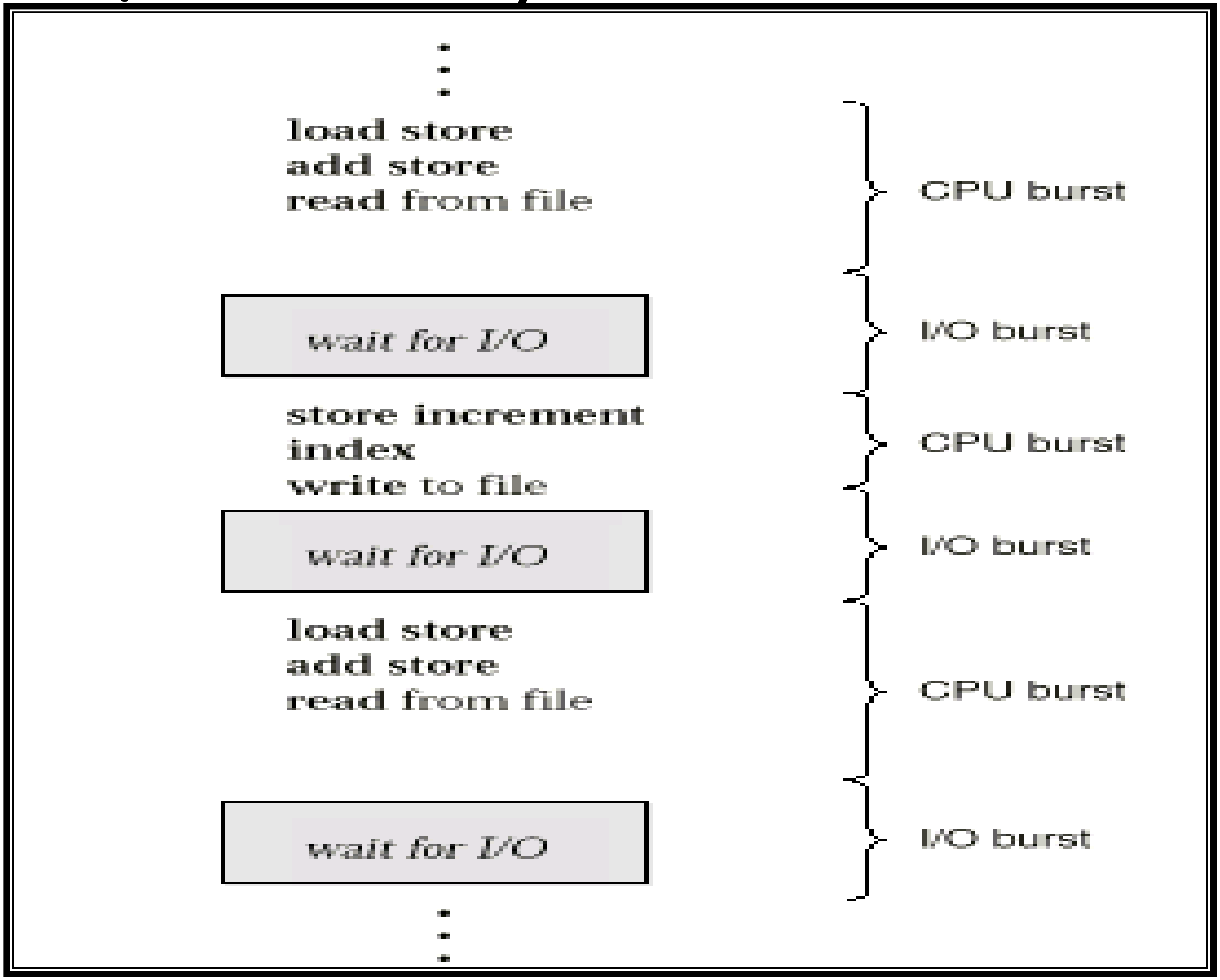
Overview

- Basic Concepts
- Scheduling Algorithms
- Special Scheduling Issues
- Scheduling Case Study

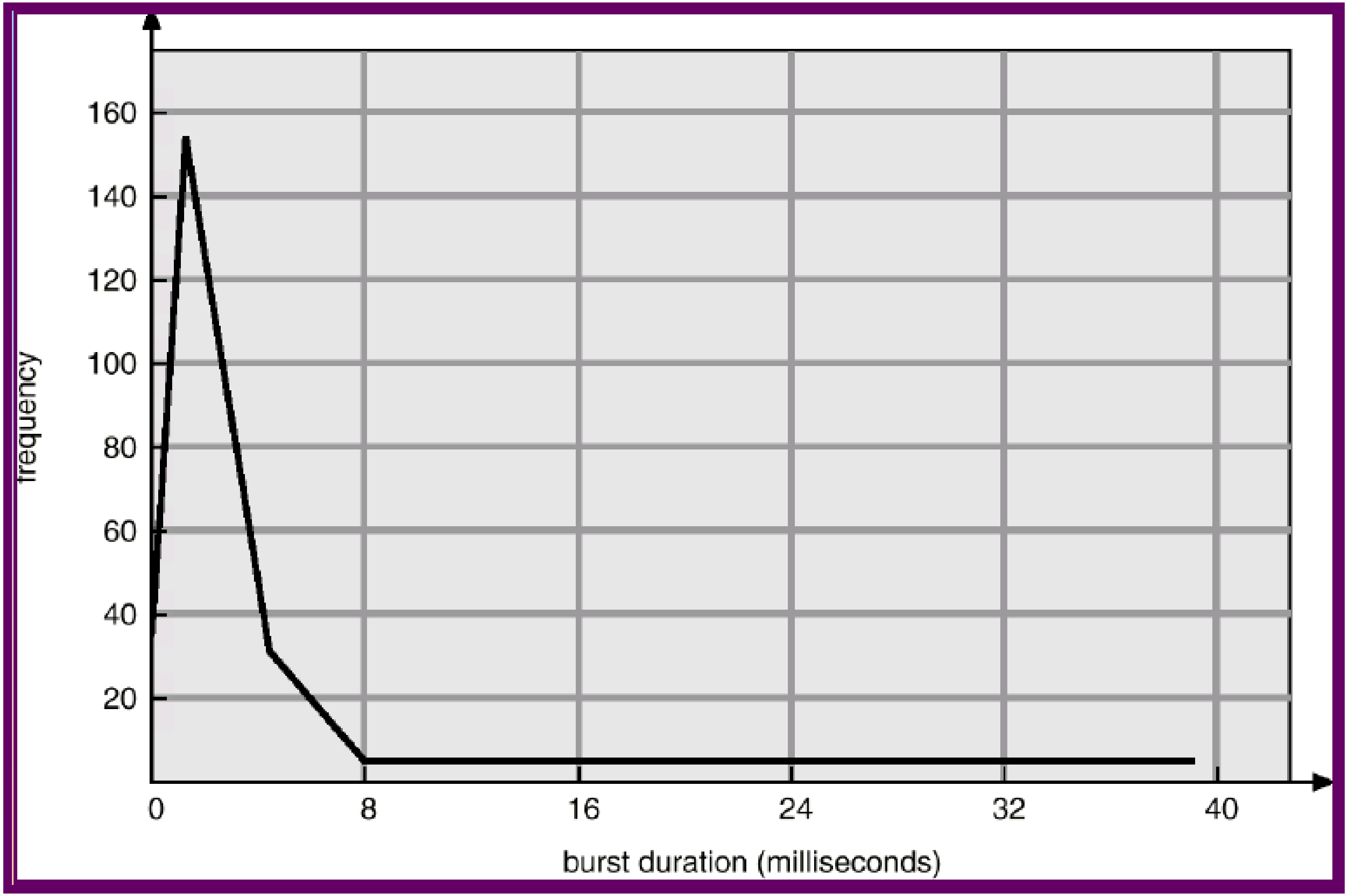
Basic Concepts

- 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
  - A I/O-bound program would typically has many very short CPU bursts
  - A CPU-bound program might have a few long CPU bursts

CPU – I/O Burst Cycle

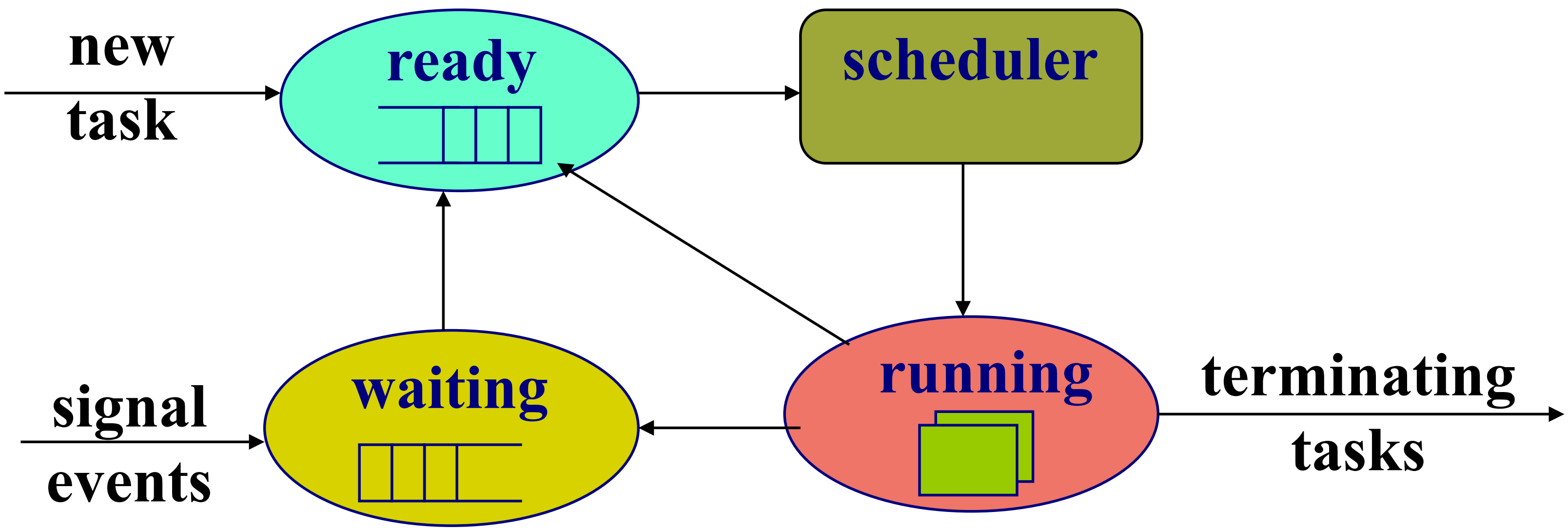


Histogram of CPU-Burst Times



CPU Scheduler

- Selects from ready queue to execute (i.e. allocates a CPU for the selected process)



Preemptive vs. Non-preemptive

- 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
- **Non-preemptive** scheduling:
  - Scheduling under 1 and 4 (no choice in terms of scheduling)
  - The process keeps the CPU until it is terminated or switched to the waiting state
  - E.g., Window 3.x
- **Preemptive** scheduling:
  - Scheduling under all cases
  - E.g., Windows 95 and subsequent versions, Mac OS X

Preemptive Issues

- Inconsistent state of shared data
  - Require **process synchronization** (Chap6)
  - incurs a cost associated with access to shared data
- Affect the design of **OS kernel**
  - 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 (disable interrupt)

Dispatcher

- Dispatcher module gives control of the CPU to the process selected by scheduler
  - switching context
  - jumping to the proper location in the selected program
- Dispatch latency – time it takes for the dispatcher to stop one process and start another running
  - Scheduling time
  - Interrupt re-enabling time
  - Context switch time

Scheduling Algorithms

Scheduling Criteria

- **CPU utilization**
  - theoretically: 0%~100%
  - real systems: 40% (light)~90% (heavy)
- **Throughput**
  - number of completed **processes** per time unit
- **Turnaround time**
  - submission ~ completion
- **Waiting time**
  - total waiting time in the **ready queue**
- **Response time**
  - submission ~ the **first response** is produced

Algorithms

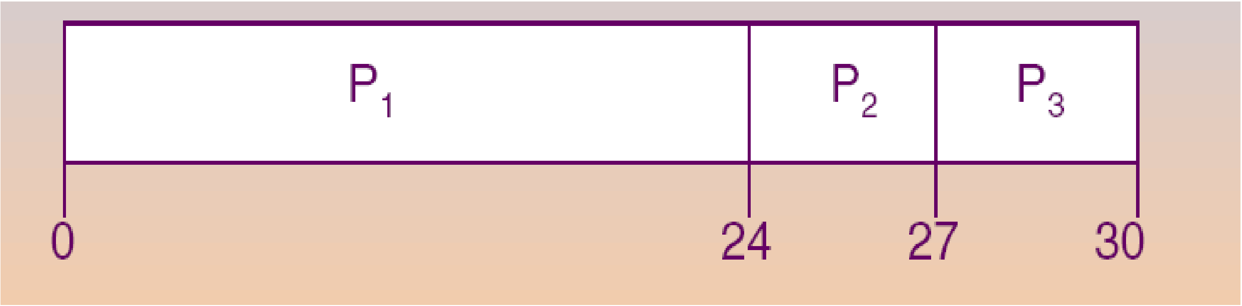
- First-Come, First-Served (FCFS) scheduling
- Shortest-Job-First (SJF) scheduling
- Priority scheduling
- Round-Robin scheduling
- Multilevel queue scheduling
- Multilevel feedback queue scheduling

FCFS Scheduling

- Process (Burst Time) in arriving order:

  P1 (24), P2 (3), P3 (3)

- The Gantt Chart of the schedule



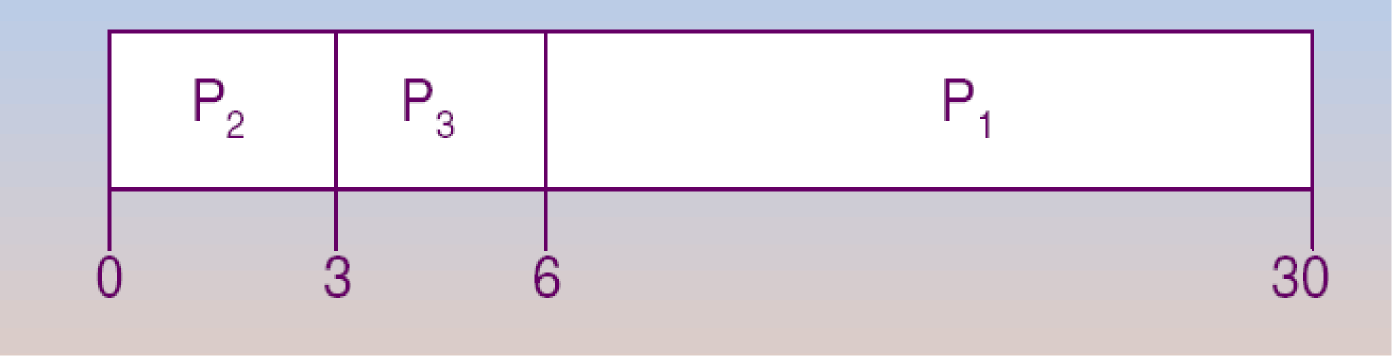
- Waiting time: P1 = 0, P2 = 24, P3 = 27
- **Average Waiting Time** (AWT): (0+24+27) / 3 = 17
- **Convoy effect**: short processes behind a long process

FCFS Scheduling

- Process (Burst Time) in arriving order:

  P2 (3),   P3 (3),   P1 (24)

- The Gantt Chart of the schedule



- Waiting time: P1 = 6, P2 = 0, P3 = 3
- Average Waiting Time (AWT): (6+0+3) / 3 = 3

Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its next CPU burst
- A process with shortest burst length gets the CPU first
- SJF provides the minimum average waiting time (optimal!)
- Two schemes
  - **Non-preemptive** – once CPU given to a process, it cannot be preempted until its completion
  - **Preemptive** – if a new process arrives with shorter burst length, preemption happens

Non-Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Ready queue: t=0

P1 (7)

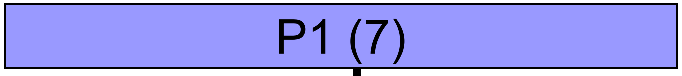
Schedule

0

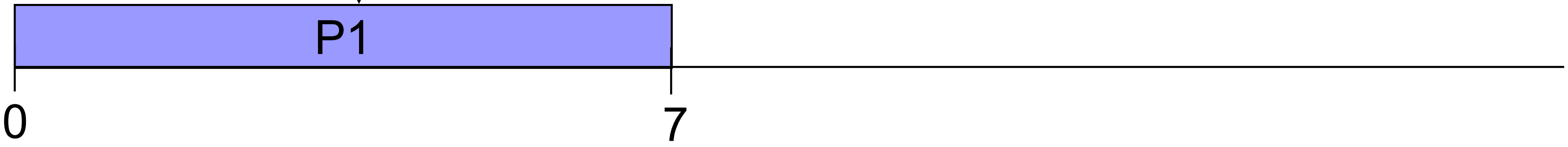
Non-Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Ready queue: t=0

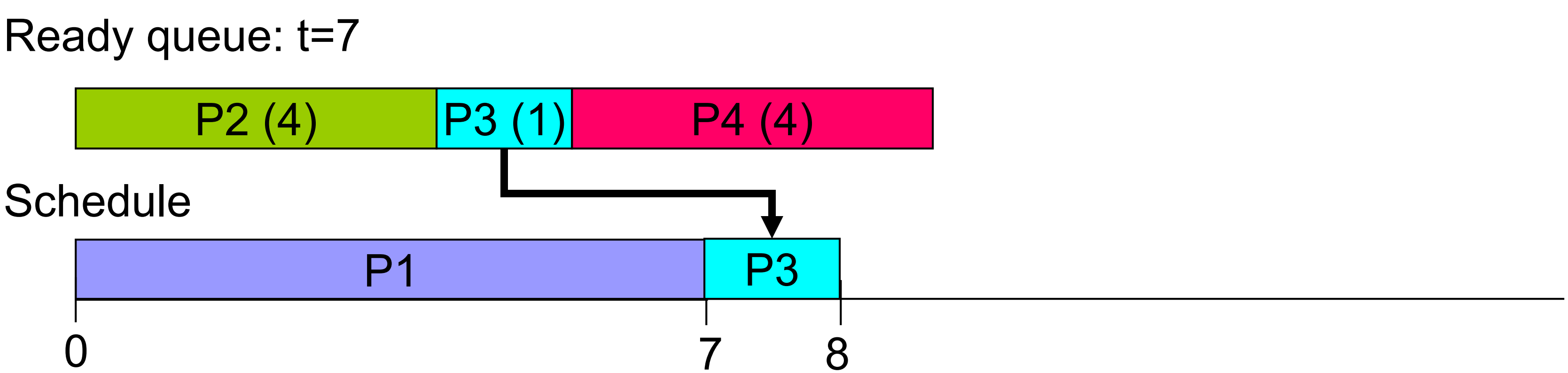


Schedule



Non-Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

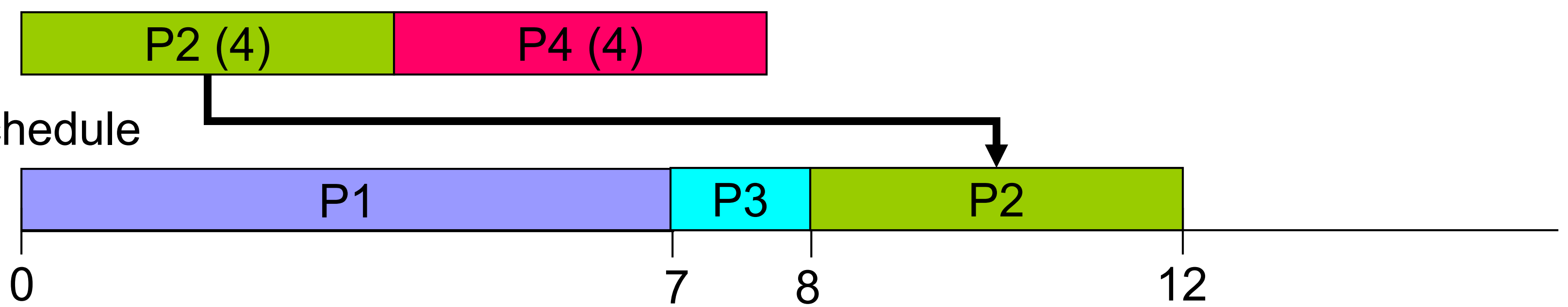


Non-Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Ready queue: t=8

Schedule

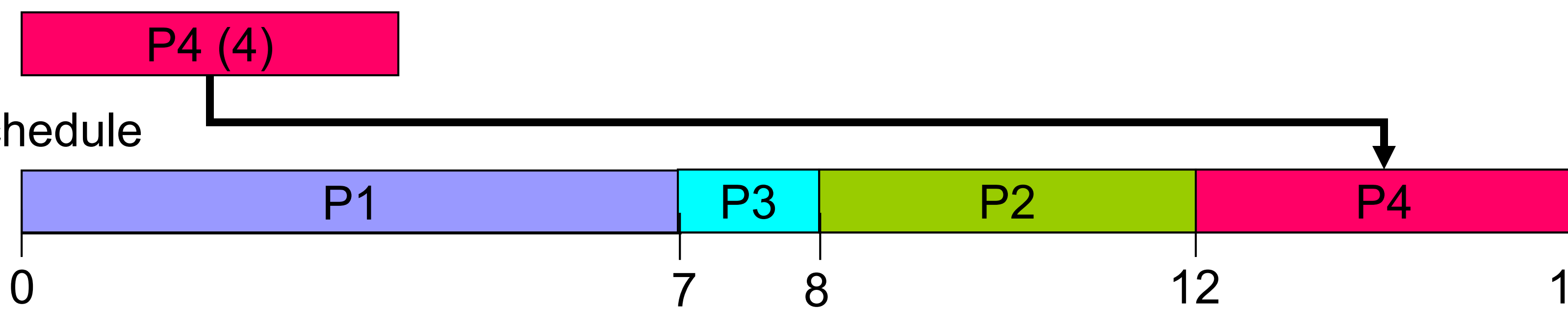


Non-Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Ready queue: t=12

Schedule



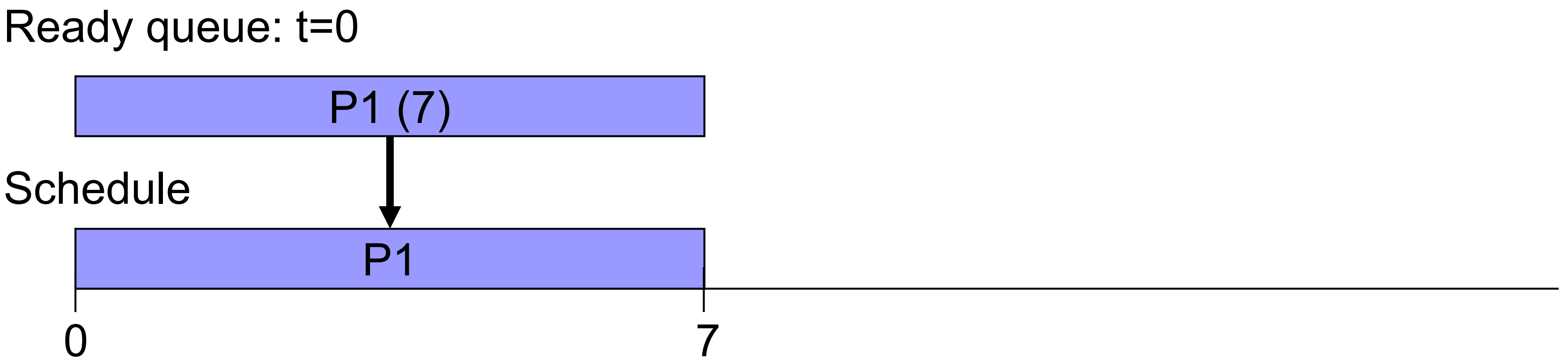
Wait time = completion time – arrival time – run time (burst time)

AWT = [(7-0-7)+(12-2-4)+(8-4-1)+(16-5-4)]/4 = (0+6+3+7)/4 = 4

Response Time: P1=0, P2=6, P3=3, P4=7

Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

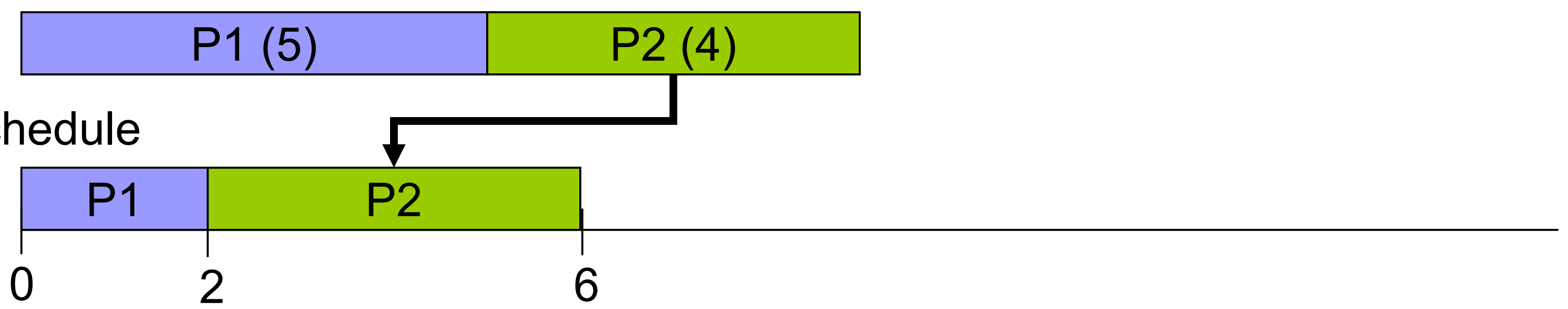


Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

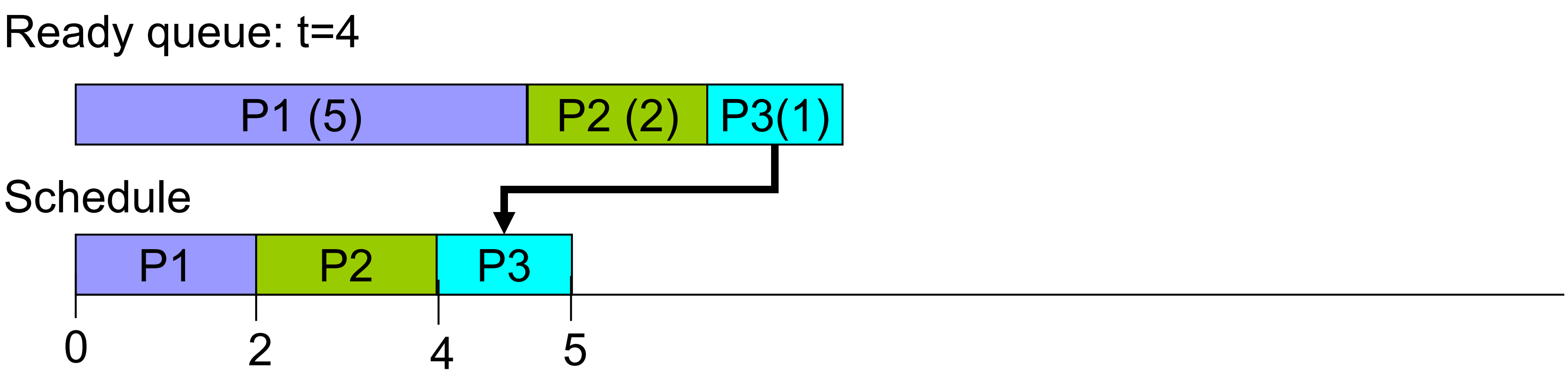
Ready queue: t=2

Schedule



Preemptive SJF Example

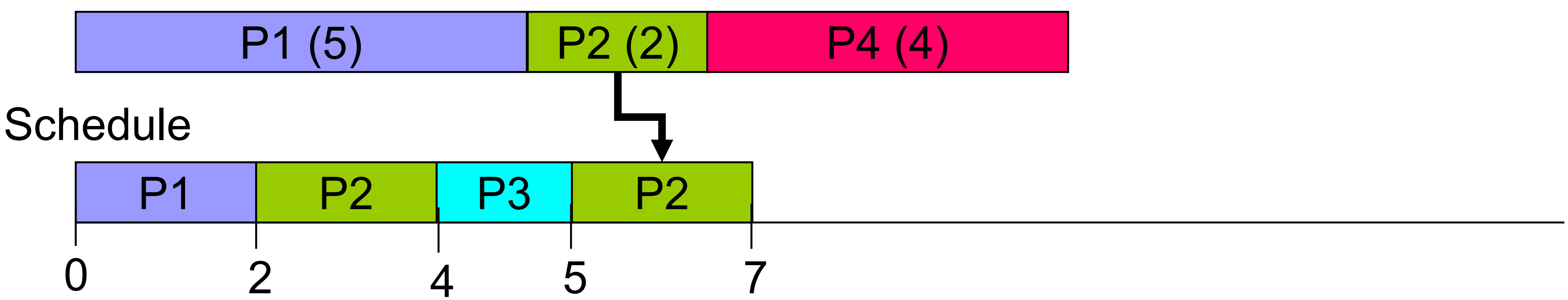
Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4



Preemptive SJF Example

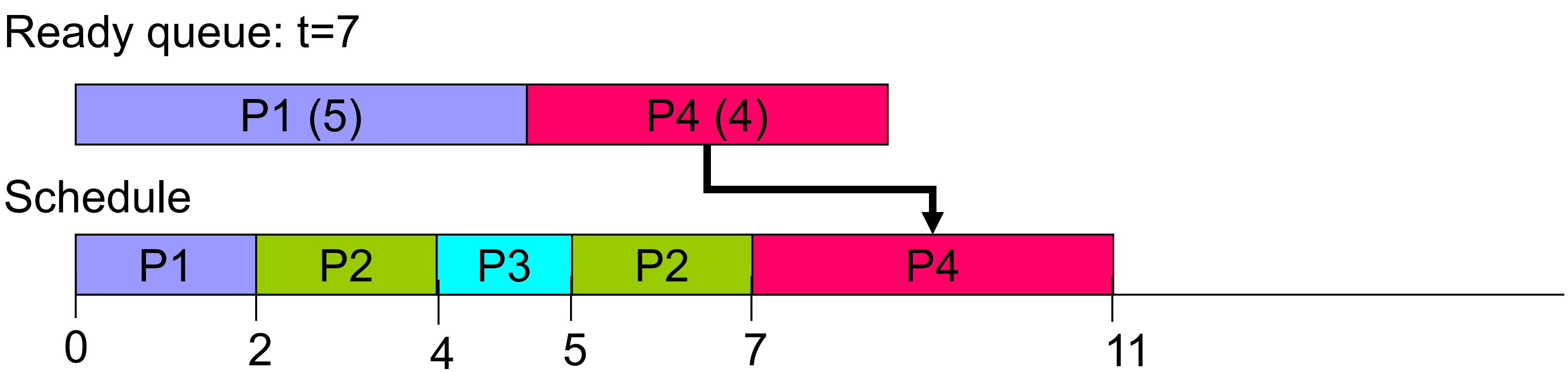
Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Ready queue: t=5



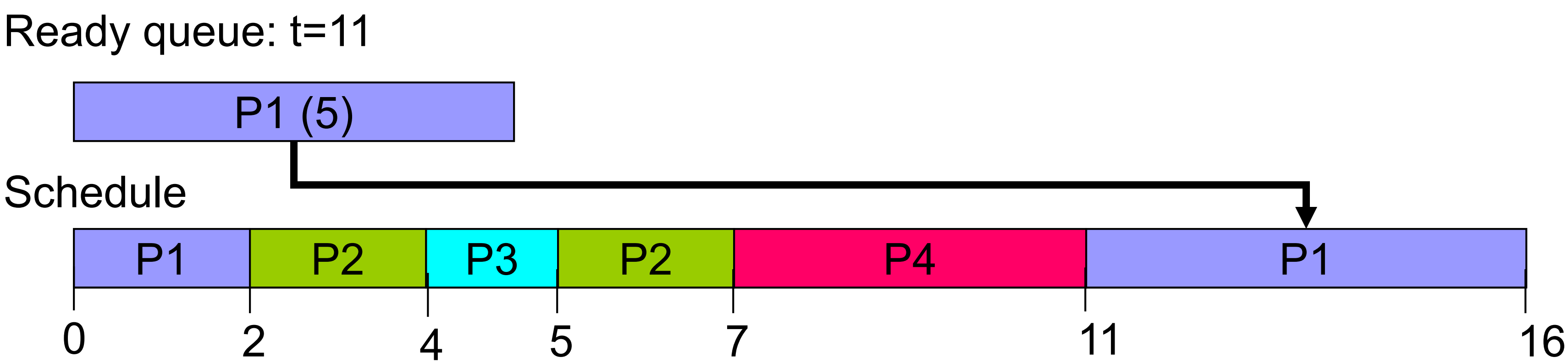
Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4



Preemptive SJF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4



Wait time = completion time – arrival time – run time (burst time)

AWT = [(16-0-7)+(7-2-4)+(5-4-1)+(11-5-4)]/4 = (9+1+0+2)/4 = 3

Response Time: P1=0, P2=0, P3=0, P4=2

Approximate Shortest-Job-First (SJF)

- SJF difficulty: no way to know length of the next CPU burst
- **Approximate SJF**: the next burst can be predicted as an **exponential average** of the measured length of previous CPU bursts

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

new one

history

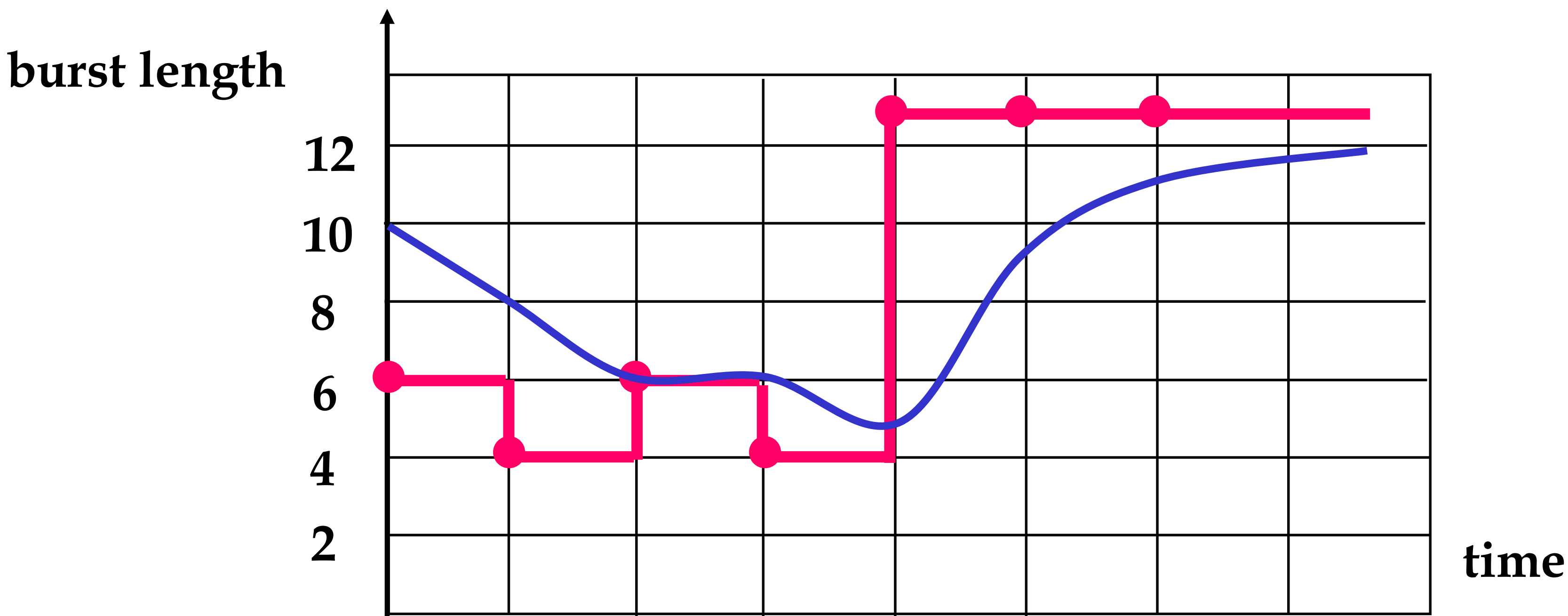
Commonly,

$\alpha = 1/2$

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

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

Exponential predication of next CPU burst



	$t0$	$t1$	$t2$	$t3$	$t4$	$t5$	$t6$
CPU burst t_n	6	4	6	4	13	13	13
guess τ_n	10	8	6	6	5	9	11

Priority Scheduling

- A priority number is associated with each process
- The CPU is allocated to the highest priority process
  - Preemptive
  - Non-preemptive
- SJF is a priority scheduling where priority is the predicted next CPU burst time
- Problem: starvation (low priority processes never execute)
  - e.g. IBM 7094 shutdown at 1973, a 1967-process never run)
- Solution: aging (as time progresses increase the priority of processes)
  - e.g. increase priority by 1 every 15 minutes

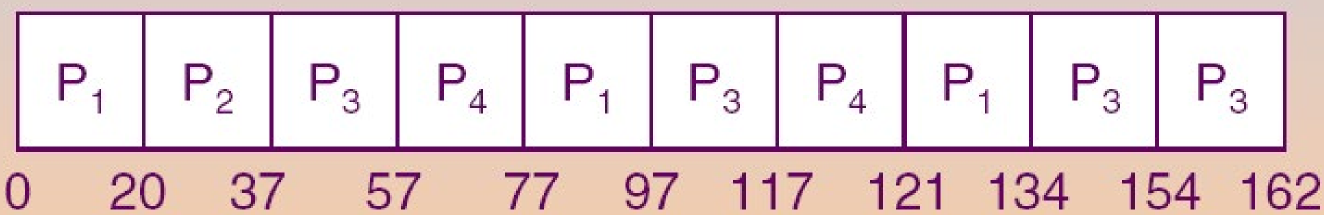
Round-Robin (RR) Scheduling

- Each process gets a small unit of CPU time (*time quantum*), usually 10~100 ms
- After TQ elapsed, process is preempted and added to the end of the ready queue
- Performance
  - TQ large → FIFO (FCFS)
  - TQ small → (context switch) overhead increases

RR Scheduling (TQ = 20)

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

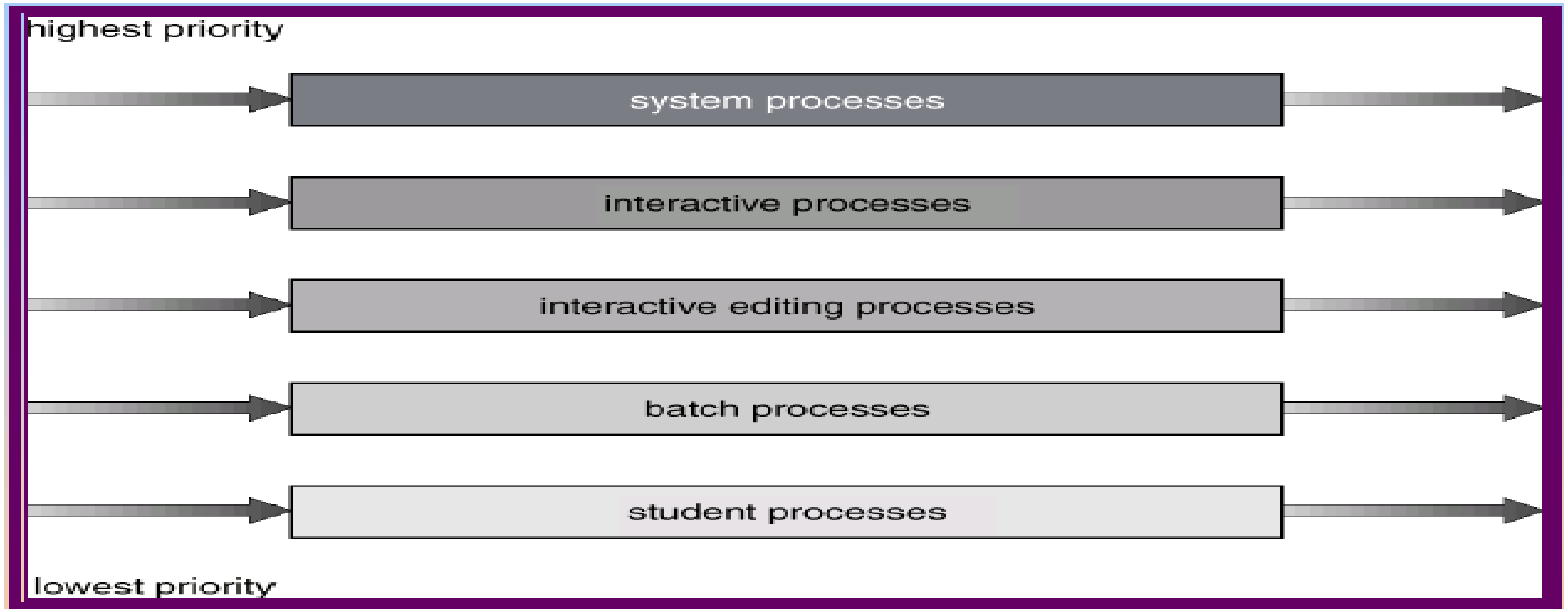
- The Gantt chart is:



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

Multilevel Queue Scheduling

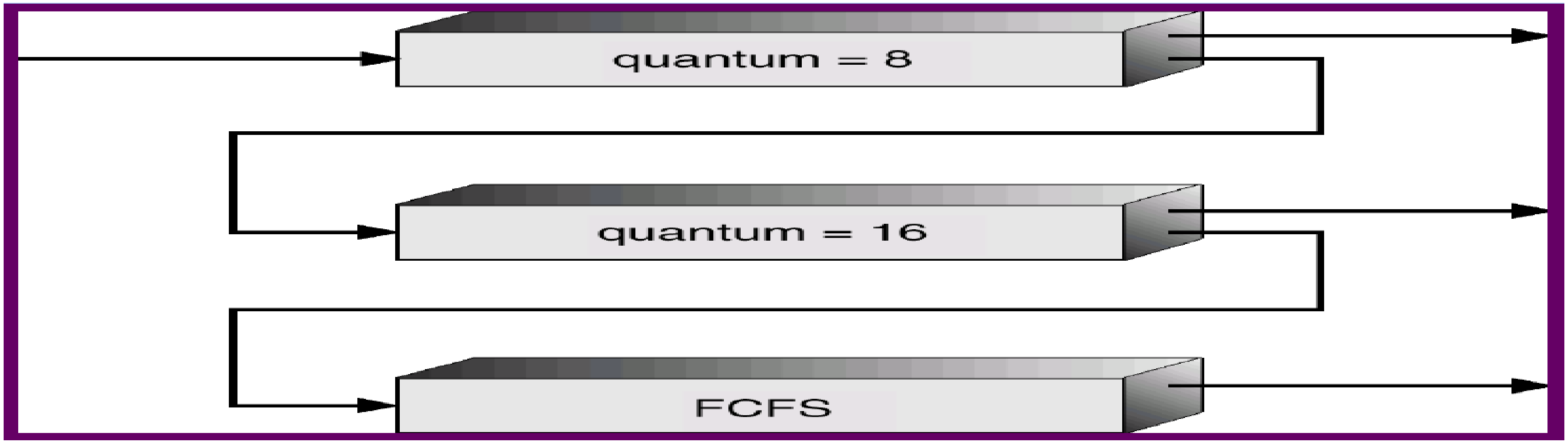
- Ready queue is partitioned into separate queues
- Each queue has its own scheduling algorithm
- Scheduling must be done between queues
  - Fixed priority scheduling: possibility of starvation
  - Time slice – each queue gets a certain amount of CPU time (e.g. 80%, 20%)



Multilevel Feedback Queue Scheduling

- **Processes can move between queues** according to the **runtime behavior**(i.e. feedback) of process
- Higher level queue must be executed first
  - aging can be implemented to avoid starvation
- Example:: separate processes according to the characteristic of their CPU burst to **mimic SJF** and reduce **average wait time**
  - I/O-bound and interactive processes in higher priority queue → short CPU burst
  - CPU-bound processes in lower priority queue→ long CPU burst

Multilevel Feedback Queue Example



- A new job enters Q_0. Algorithm: RR. If it does not finish in 8 ms CPU time, job is moved to Q_1
- At Q_1 is again served RR and receives 16 ms TQ. If it still does not finish in 16 ms, it is preempted and moved to Q_2
- Q_i only gets executed if $Q_0 \sim Q_{i-1}$ is empty

Multilevel Feedback Queue

- In general, multilevel feedback queue scheduler is defined by the following parameters:
  - Number of queues
  - Scheduling algorithm for each queue
  - Method used to determine when to upgrade a process
  - Method used to determine when to demote a process

Evaluation Methods

- Deterministic modeling – takes a particular predetermined workload and defines the performance of each algorithm for that workload
  - Cannot be generalized
- Queueing model – mathematical analysis
- Simulation – random-number generator or trace tapes for workload generation
- Implementation – the only completely accurate way for algorithm evaluation

Review Slides (I)

- Preemptive scheduling vs Non-preemptive scheduling?
- Issues of preemptive scheduling
- Turnaround time? Waiting time? Response time? Throughput?
- Scheduling algorithms
  - FCFS
  - Preemptive SJF, Nonpreemptive SJF
  - Priority scheduling
  - RR
  - Multilevel queue
  - Multilevel feedback queue

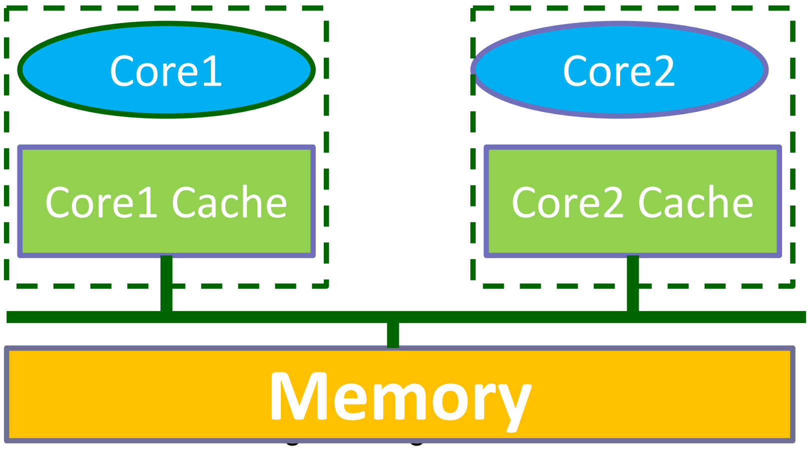
Multi-Processor Scheduling
Multi-Core Processor Scheduling
Real-Time Scheduling

Multi-Processor Scheduling

- **Asymmetric multiprocessing**:
  - all system activities are handled by a processor (alleviating the need for data sharing)
  - the others only execute user code (allocated by the master)
  - far simple than **SMP**
- **Symmetric multiprocessing (SMP):**
  - each processor is self-scheduling
  - all processes in common ready queue, or each has its own private queue of ready processes
  - need synchronization mechanism

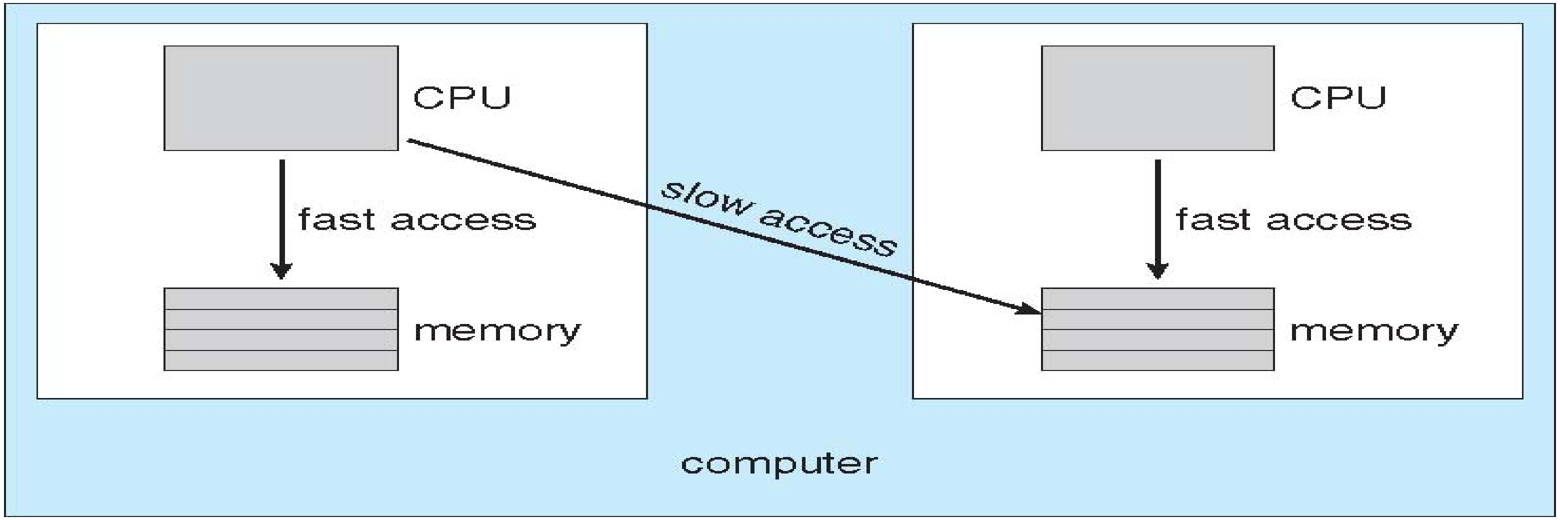
Processor affinity

- **Processor affinity:** a process has an affinity for the processor on which it is currently running
  - A process populates its recent used data in cache memory of its running processor
  - Cache invalidation and repopulation has high cost
- Solution
  - **soft affinity**:
    - possible to migrate between processors
  - **hard affinity**:
    - not to migrate to other processor



NUMA and CPU Scheduling

- **NUMA** (non-uniform memory access):
  - Occurs in systems containing combined CPU and memory boards
  - CPU scheduler and memory-placement works together
  - A process (assigned affinity to a CPU) can be allocated memory on the board where that CPU resides

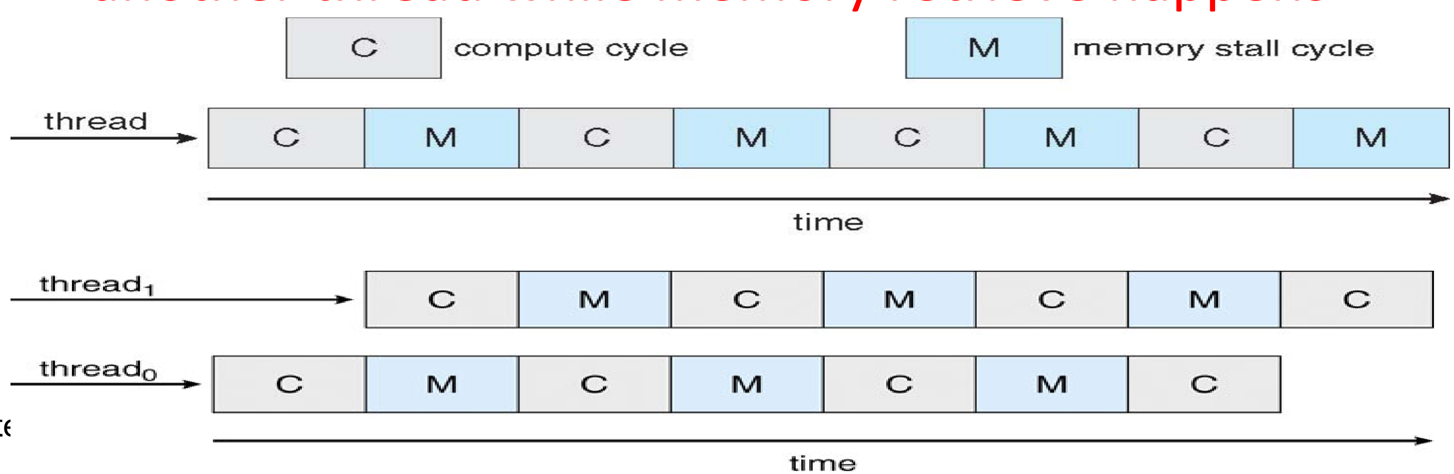


Load-balancing

- Keep the workload evenly distributed across all processors
  - Only necessary on systems where each processor has its own private queue of eligible processes to execute
- Two strategies:
  - **Push migration**: move (push) processes from overloaded to idle or less-busy processor
  - **Pull migration**: idle processor pulls a waiting task from a busy processor
  - Often implemented in parallel
- Load balancing often counteracts the benefits of processor affinity

Multi-core Processor Scheduling

- **Multi-core Processor:**
  - Faster and consume less power
  - memory stall: When access memory, it spends a significant amount of time waiting for the data become available. (e.g. cache miss)
- **Multi-threaded multi-core systems**:
  - Two (or more) hardware threads are assigned to each core (i.e. Intel Hyper-threading)
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens



Multi-core Processor Scheduling

- Two ways to multithread a processor:
  - **coarse-grained**: switch to another thread **when a memory stall occurs**. The cost is high as the instruction pipeline must be flushed.
  - **fine-grained** (interleaved): switch between threads at the **boundary of an instruction cycle**. The architecture design includes logic for thread switching – cost is low.
- Scheduling for Multi-threaded multi-core systems
  - 1st level: Choose which software thread to run on each hardware thread (logical processor)
  - 2nd level: How each core decides which hardware thread to run

Real-Time Scheduling

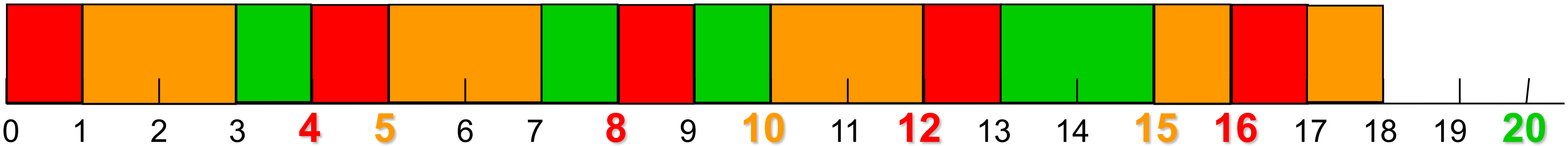
- Real-time does not mean speed, but *keeping deadlines*
- Soft real-time requirements:
  - Missing the deadline is unwanted, but is not immediately critical
  - Examples: multimedia streaming
- Hard real-time requirements:
  - Missing the deadline results in *a fundamental failure*
  - Examples: nuclear power plant controller

Real-Time Scheduling Algorithms

- FCFS scheduling algorithm – Non-RTS
  - T1 = (0, 4, 10) == (Ready, Execution, Period)
  - T2 = (1, 2, 4)
- Rate-Monotonic (RM) algorithm
  - Shorter period → higher priority
  - Fixed-priority RTS scheduling algorithm
- Earliest-Deadline-First (EDF) algorithm
  - Earlier deadline → higher priority
  - Dynamic priority algorithm

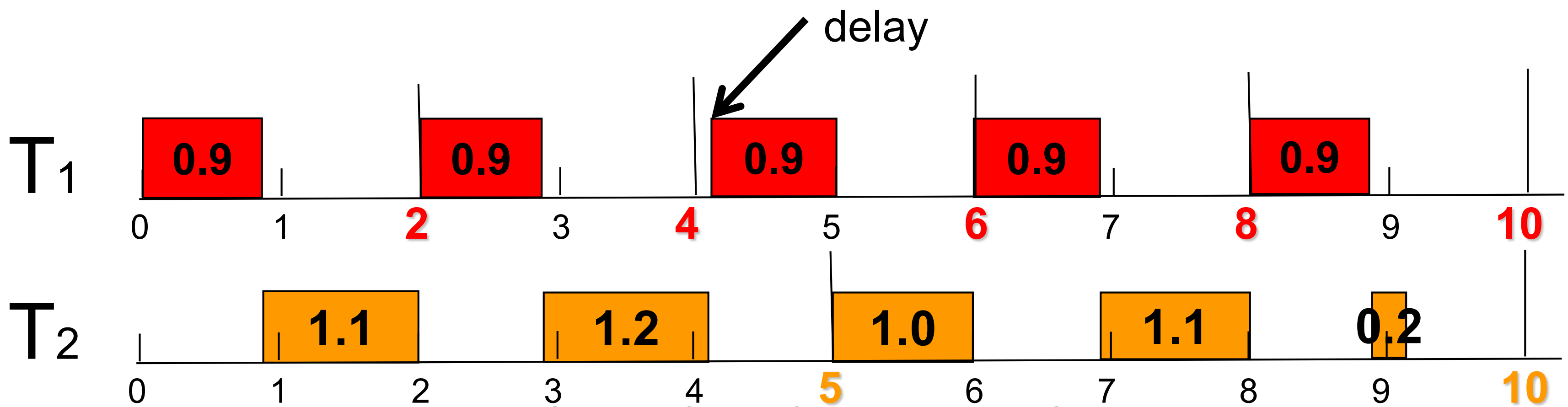
Rate-Monotonic (RM) Scheduling

- Fixed-priority schedule.
  - All jobs of the same task have same priority.
  - The task's priority is fixed.
- The shorter period, the higher priority.
- Ex: ***T_1=(4,1)***, ***T_2=(5,2)***, ***T_3=(20,5)*** (Period, Execution)
  - ∵period: $4 < 5 < 20$
  - ∴priority: $T_1 > T_2 > T_3$



Early Deadline First (EDF) Scheduler

- Dynamic-priority scheduler
  - Task's priority is not fixed
  - Task's priority is determined by deadline.
- Ex: $T_1=(2,0.9)$, $T_2=(5,2.3)$
  - time: 8.9



Review Slides (II)

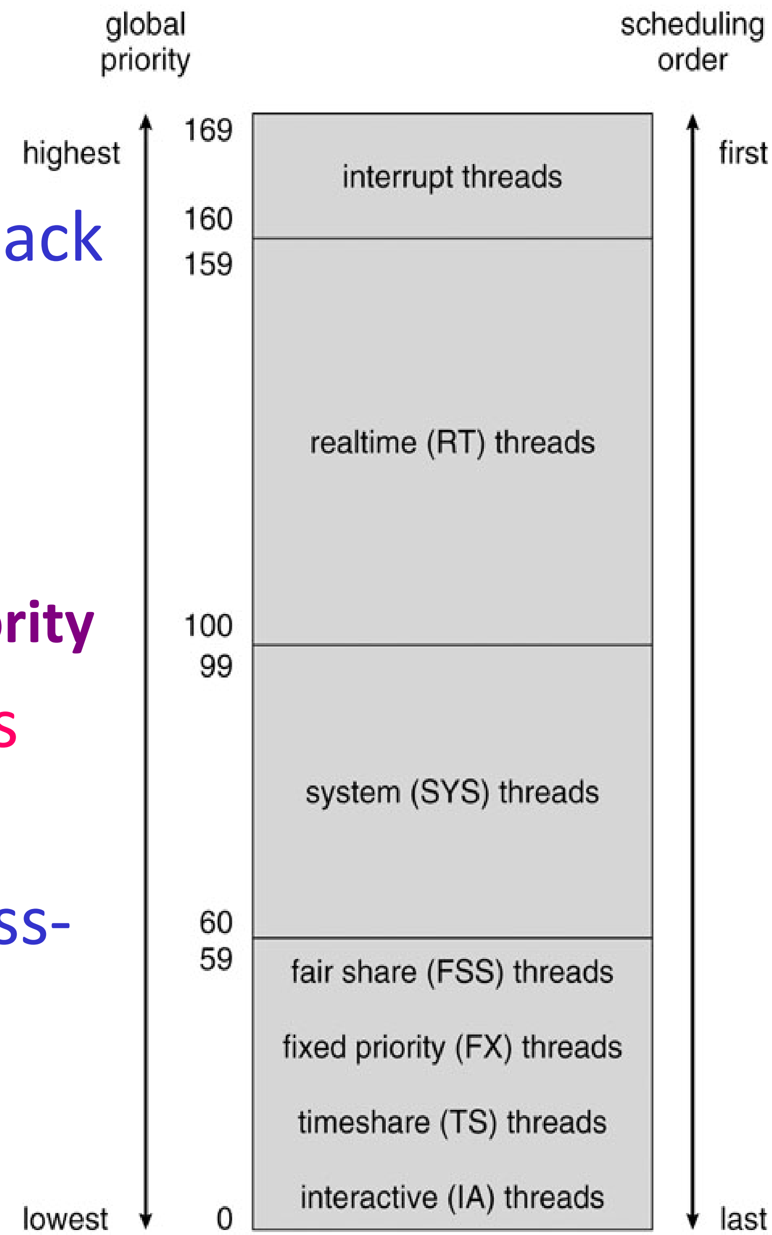
- What is processor affinity?
- Real-time scheduler
  - Rate-Monotonic
  - Earliest deadline first

Operating System Examples

- Solaris
- Windows
- Linux

Solaris Scheduler

- Priority-based multilevel feedback queue scheduling
- Six classes of scheduling:
  - **real-time, system, time sharing, interactive, fair share, fixed priority**
- Each class has its own priorities and scheduling algorithm
- The scheduler converts the class-specific priorities into global priorities



Solaris Scheduler Example (**time sharing, interactive**)

- Inverse relationship between priorities and time slices: the **higher** the priority, the **smaller** the time slice
  - Time quantum expired: the new priority of a thread that has used its entire time quantum without blocking
  - Return from sleep: the new priority of a thread that is returning from sleeping (I/O wait)

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

Higher priority

New priority

Windows XP Scheduler

- Similar to Solaris: Multilevel feedback queue
- Scheduling: from the highest priority queue to lowest priority queue (priority level: 0 ~ 31)
  - The highest-priority thread always run
  - Round-robin in each priority queue
- Priority changes dynamically except for Real-Time class

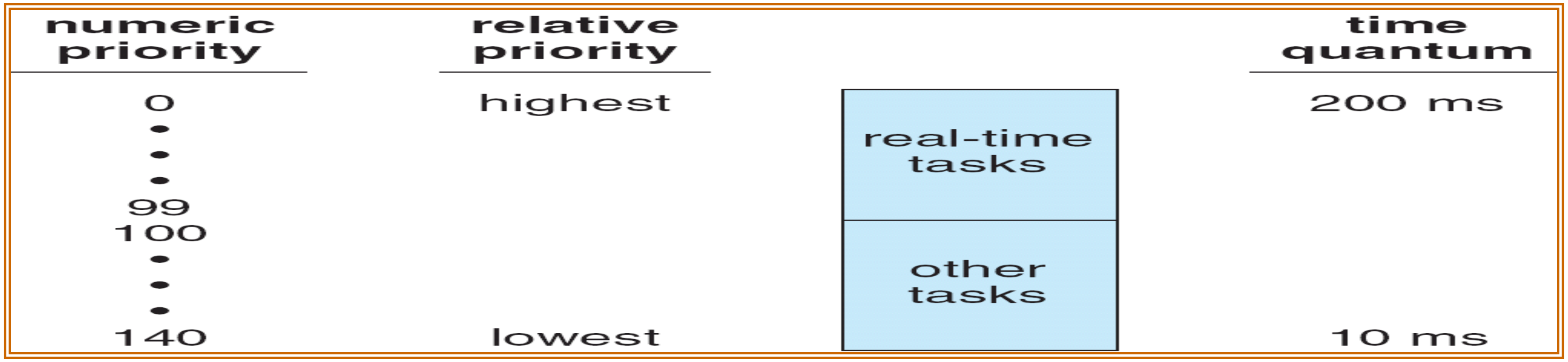
Higher priority

class / relative	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**

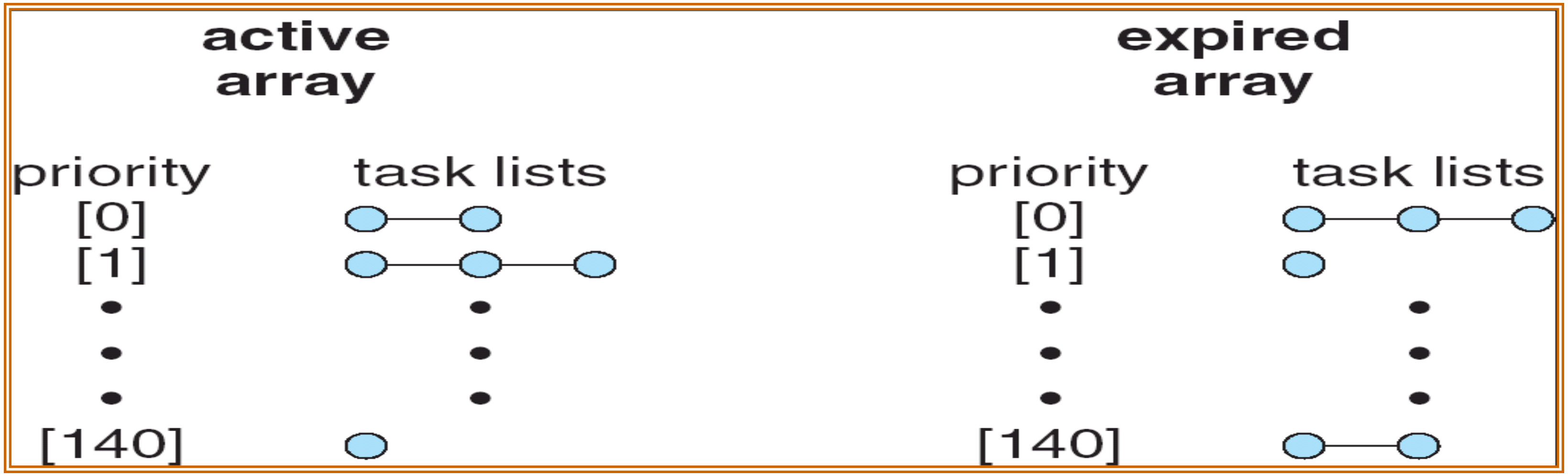
Linux Scheduler

- Preemptive priority based scheduling
  - But allows only **user mode** processes to be preempted
  - Two separate process priority ranges
  - Lower values indicate higher priorities
  - **Higher priority with longer time quantum**
- Real-time tasks: (priority range 0~99)
  - static priorities
- Other tasks: (priority range 100~140)
  - dynamic priorities based on task interactivity



Linux Scheduler

- Scheduling algorithm
  - A runnable task is eligible for execution as long as it has remaining time quantum
  - When a task exhausted its time quantum, it is considered expired and not eligible for execution
  - New priority and time quantum is given after all tasks are expired



Textbook Questions

- 5.3: Consider a system running ten I/O-bound task and one CPU-bound task. Assume that the I/O-bound tasks issue an I/O operation once for every millisecond of CPU computing and that each I/O operation takes 10 milliseconds to complete. Also assume that the context-switching overhead is 0.1 millisecond and that all processes are long-running tasks. Describe the CPU utilization for a round-robin scheduler when:
  a. The time quantum is 1 millisecond
  b. The time quantum is 10 milliseconds
- 5.4: What advantage is there in having different time-quantum sizes at different levels of a multilevel queueing system?
- 5.7: Explain the differences in how much the following scheduling the algorithms descriminate in favor of short processes: a. FCFS; b. RR; c. Multilevel feedback queues.
- 5.9: Which of the following scheduling algorithms could result in starvation? a. First-come, first-served b. Shortest job first c. Round robin d. Priority.

Textbook Questions

- 5.13: Consider the following set of processes, with the length of the CPU burst given in milliseconds:

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

The processes are assumed to have arrived in the order P1, P2, P3, P4, P5, all at time 0.

a. Draw four Gantt charts that illustrate the execution of these processes using the following scheduling algorithms: FCFS, SJF, nonpreemptive priority (a larger priority number implies a higher priority), and RR (quantum = 2)

b. What is the turnaround time of each process for each of the scheduling algorithms in part a?

c. What is the waiting time of each process for each of these scheduling algorithms?

d. Which of the algorithms results in the minimum average waiting time (over all processes)?