國立陽明交通大學
NATIONAL YANG MING CHIAO TUNG UNIVERSITY
Institute of Artificial Intelligence Innovation
Department of Computer Science

Operating System

Lecture 05: Process Scheduling

Shuo-Han Chen 陳碩漢
shch@nycu.edu.tw

Wed. 10:10 - 12:00 EC115 +
Fri. 11:10 – 12:00 Online

Course Schedule

W	Date	Lecture	Online	Homework
1	Sept. 4	Lec00: Couse Overview & Historical Prospective		
2	Sept. 11	Lec01: Introduction	V	
3	Sept. 18	Lec02: OS Structure	V	HW01 Due 10/5
4	Sept. 25	Lec03: Processes Concept	X	
5	Oct. 2	Typhoon – No class	V	
6	Oct. 9	Lec07: Memory Management	V	
7	Oct. 16	Lec08: Virtual Memory Management	V	HW02 Due 11/2
8	Oct. 23	Lec04: Multithreaded Programming	V	
9	Oct. 30	Midterm Exam		
10	Nov. 6	Lec05: Process Scheduling	V	Let’s take a breath
11	Nov. 13	Lec06: Process Synchronization & Deadlocks	V	HW03
12	Nov. 20	School Event – No class		
13	Nov. 27	Lec09: File System Interface	V	
14	Dec. 4	Lec10: File System Implementation	V	HW04
15	Dec. 11	Lec11: Mass Storage System & Lec12: IO Systems	V	
16	Dec. 18	School Final Exam		

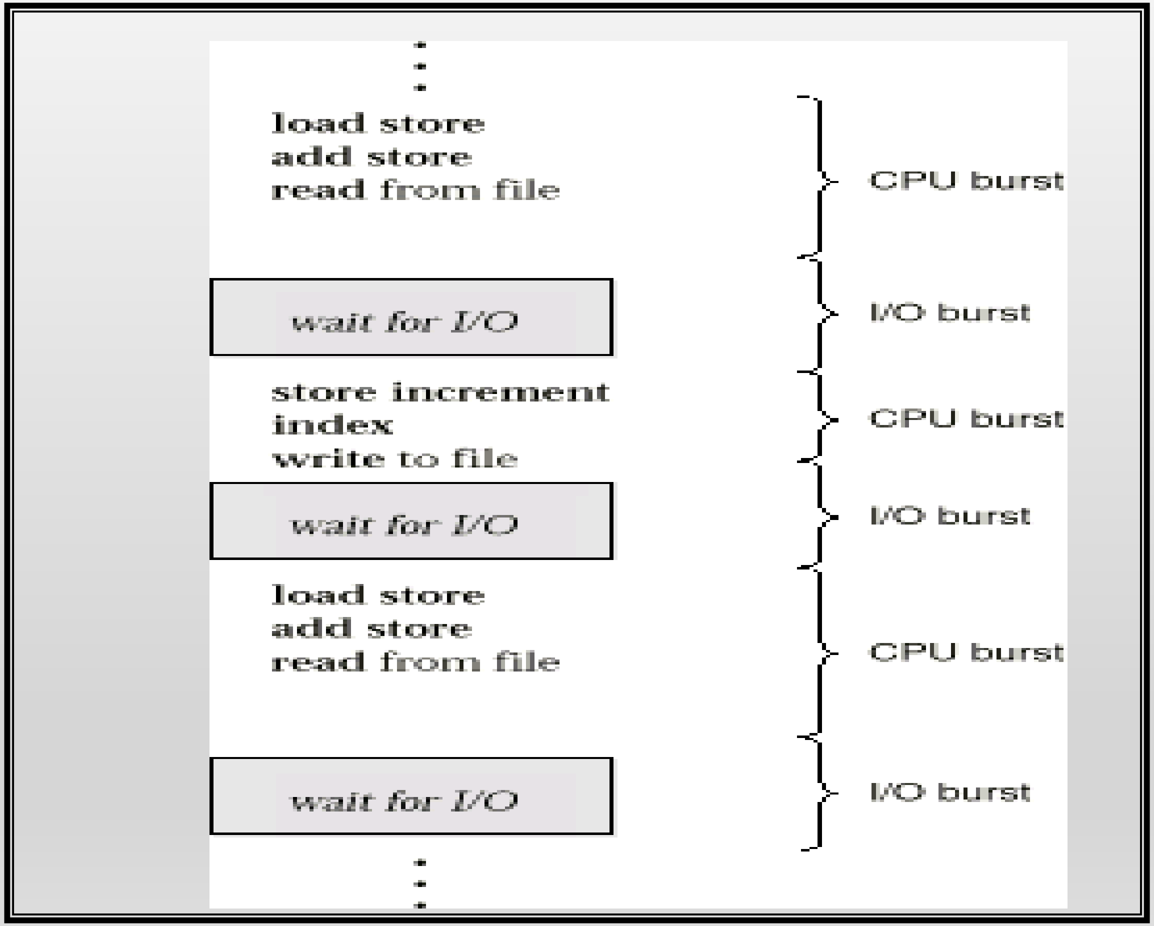
Overview

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

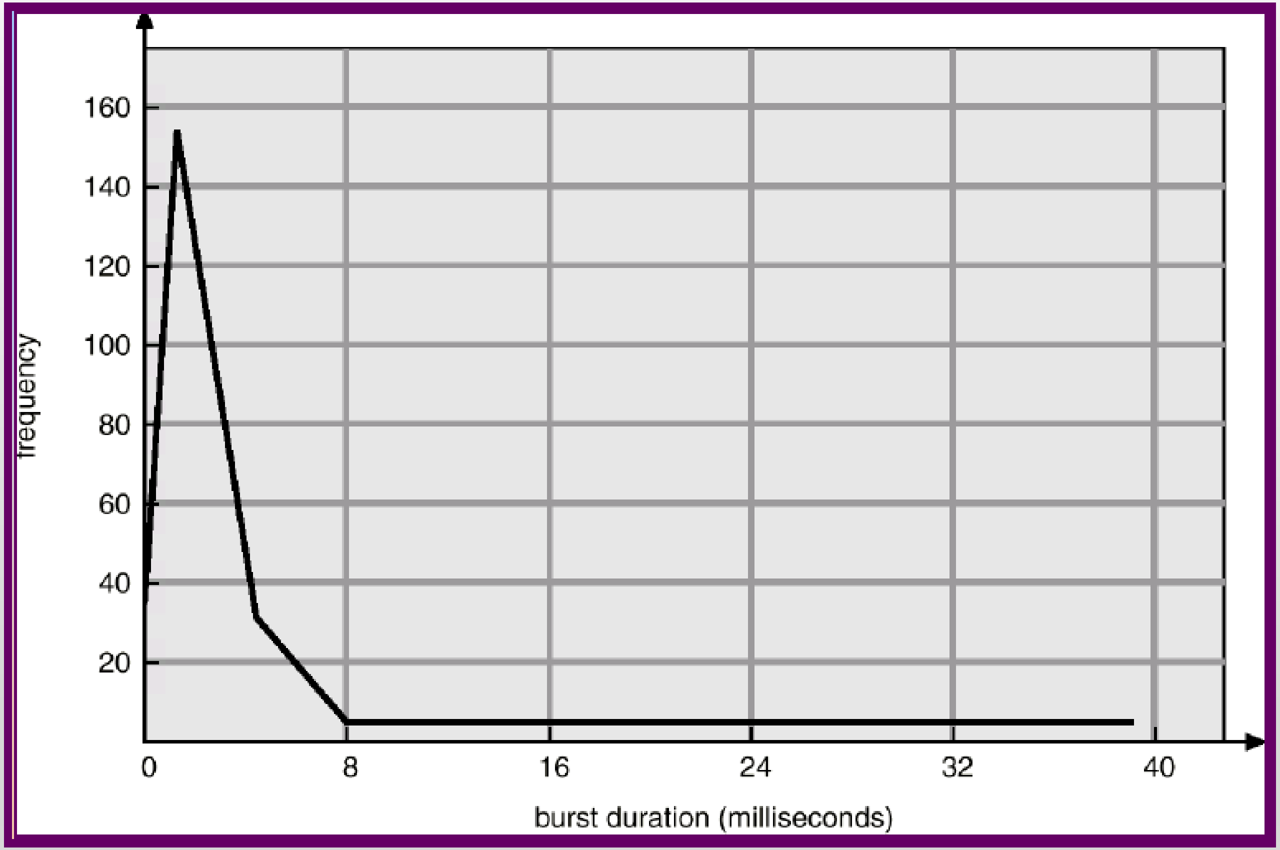
Basic Concepts

- 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

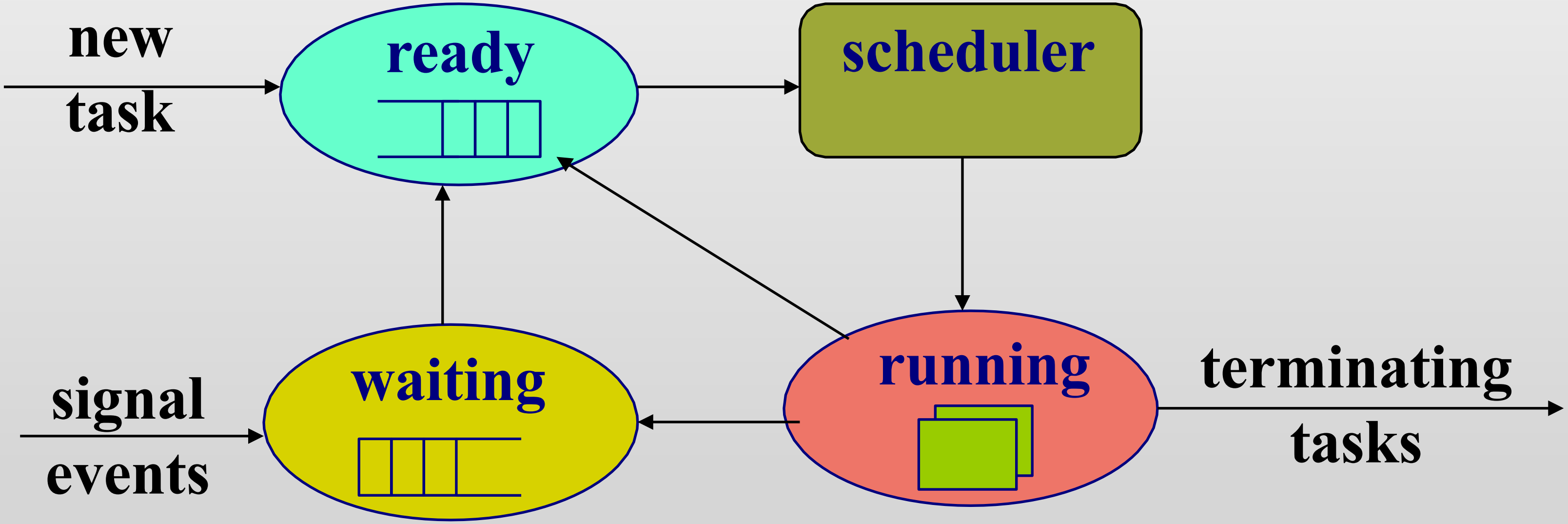


Histogram of CPU-Burst Times



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:
  - Switches from running to waiting state
  - Switches from running to ready state
  - Switches from waiting to ready
  - 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 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

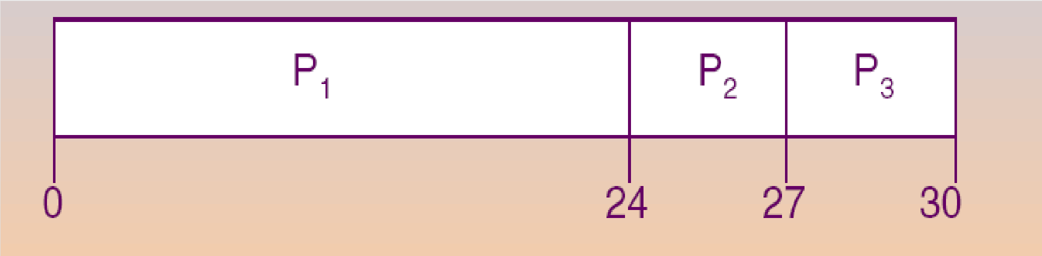
- First-Come, First-Served (FCFS) scheduling
- Shortest-Job-First (SJF) scheduling
- Priority scheduling
- Round-Robin scheduling
- Multilevel queue scheduling
- Multilevel feedback queue scheduling

FCFS Scheduling

- Process (Burst Time) in arriving order:

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

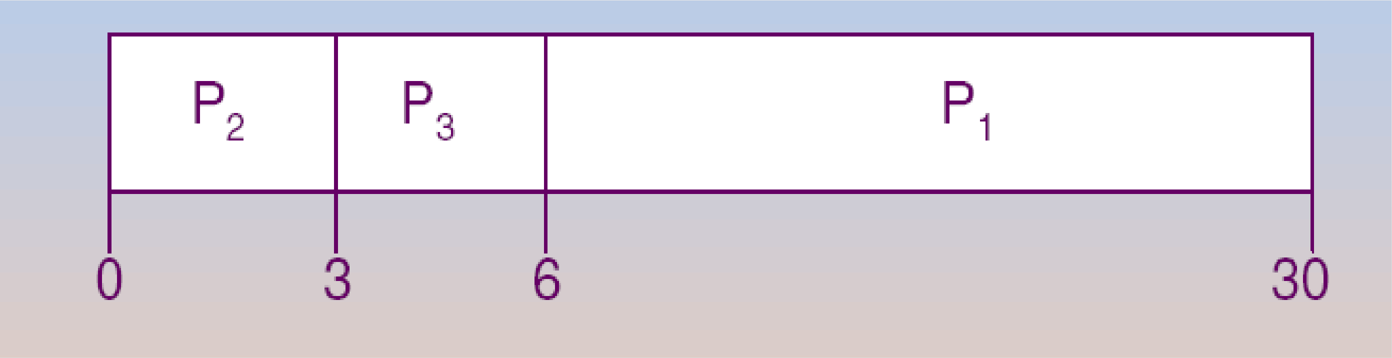
- The Gantt Chart of the schedule



- 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

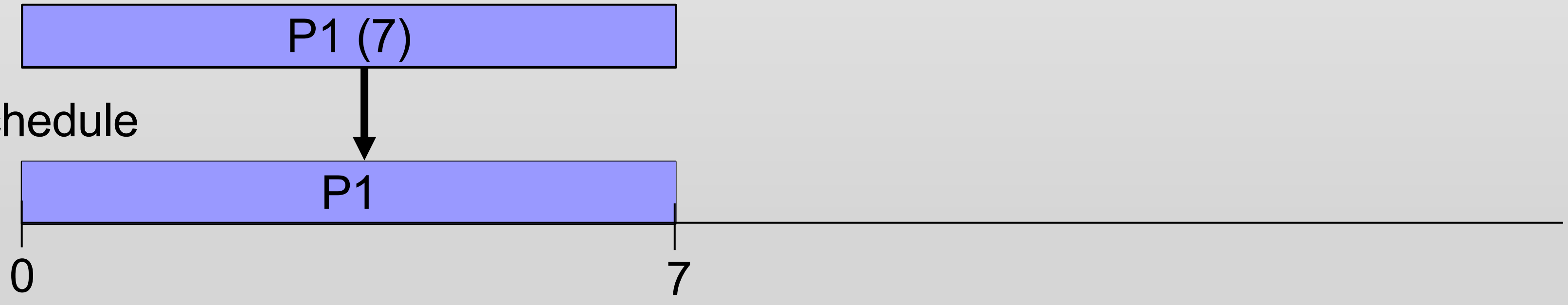
0

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

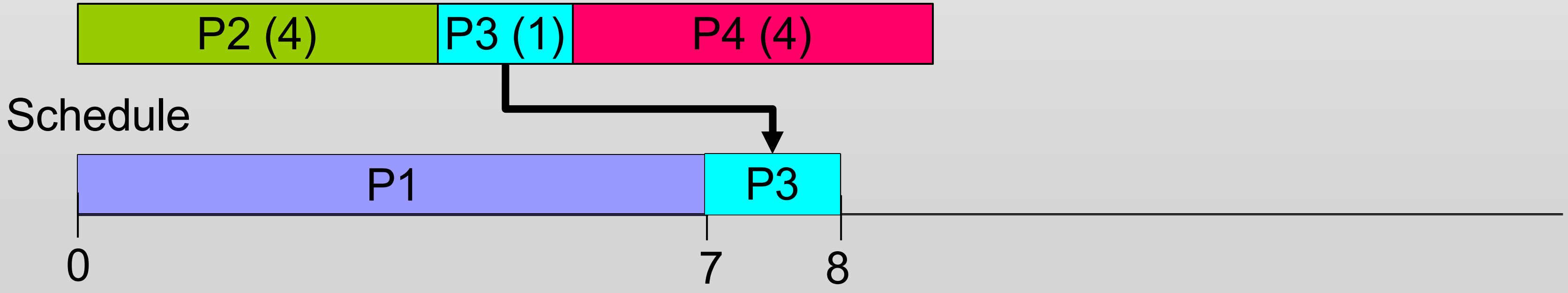
Schedule



Non-Preemptive SJF Example

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

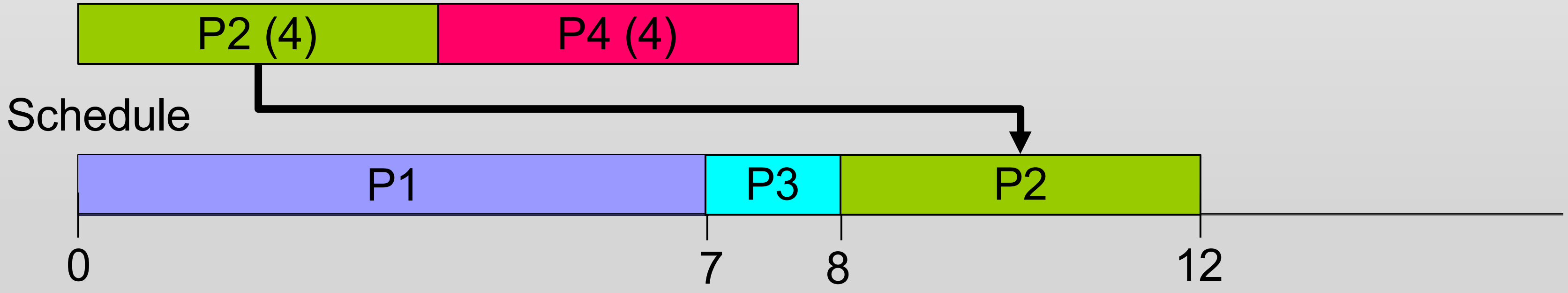
Ready queue: t=7



Non-Preemptive SJF Example

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

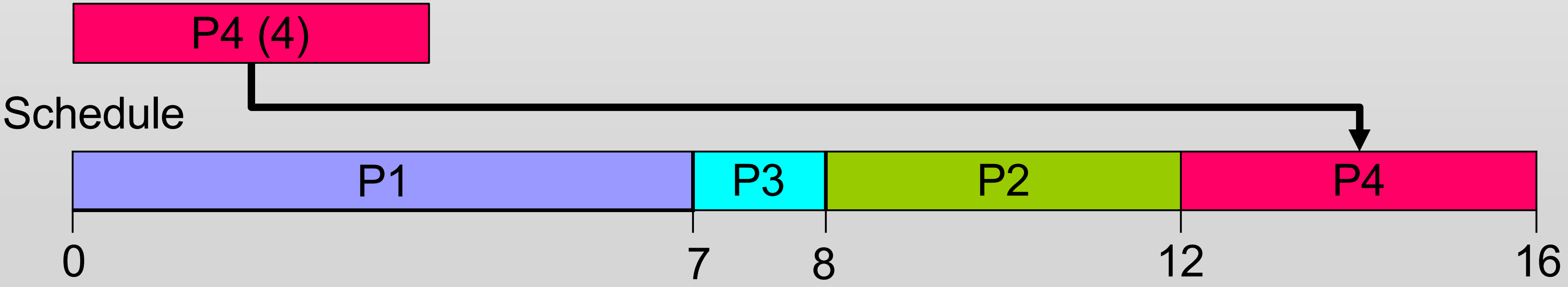
Ready queue: t=8



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

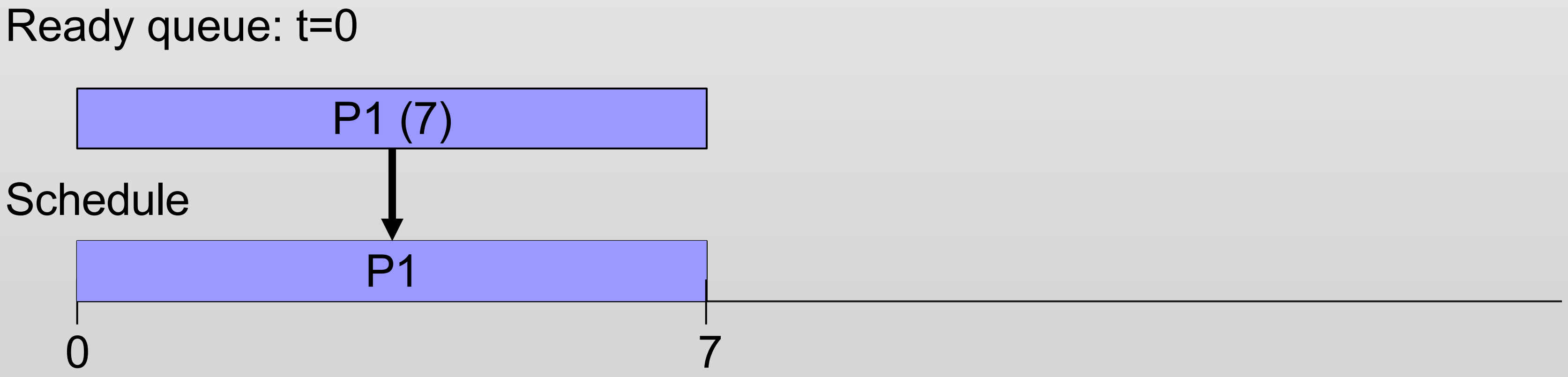


Wait time = completion time – arrival time – run time (burst time) AWT = [(7-0-7)+(12-2-4)+(8-4-1)+(16-5-4)]/4 = (0+6+3+7)/4 = 4

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

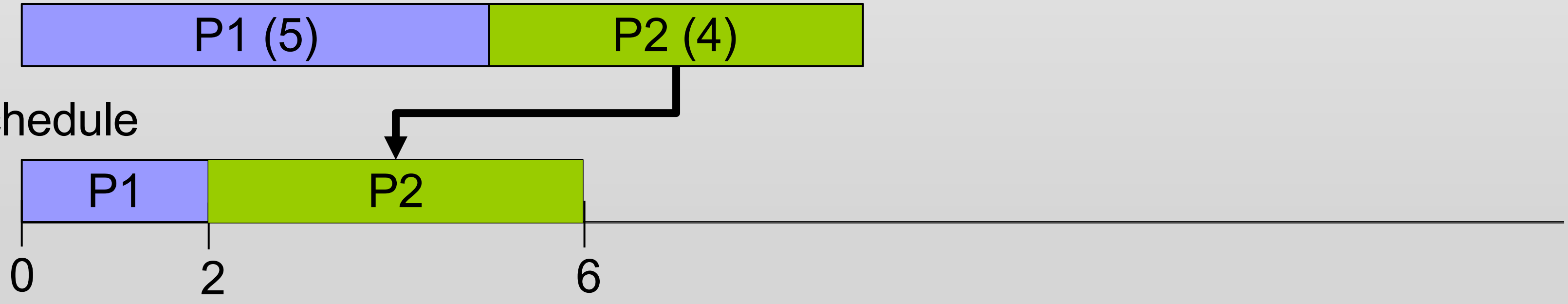


Preemptive SJF Example

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

Ready queue: t=2

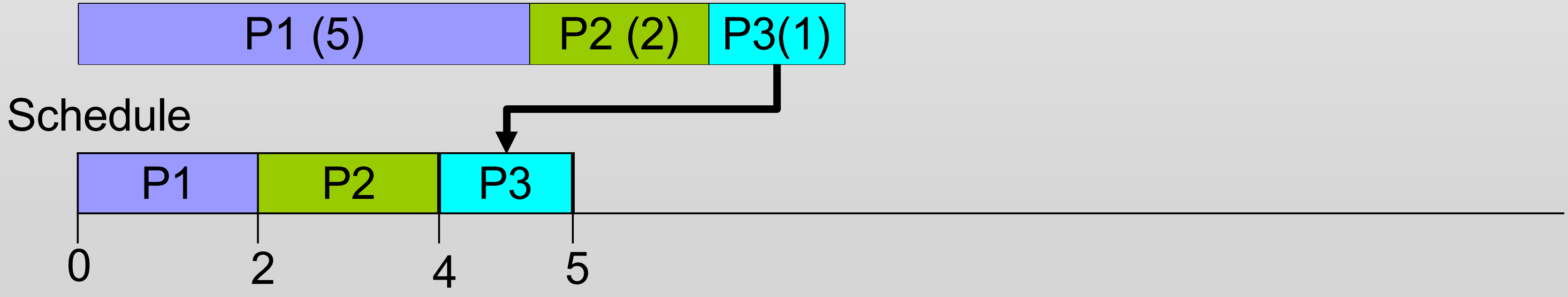
Schedule



Preemptive SJF Example

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

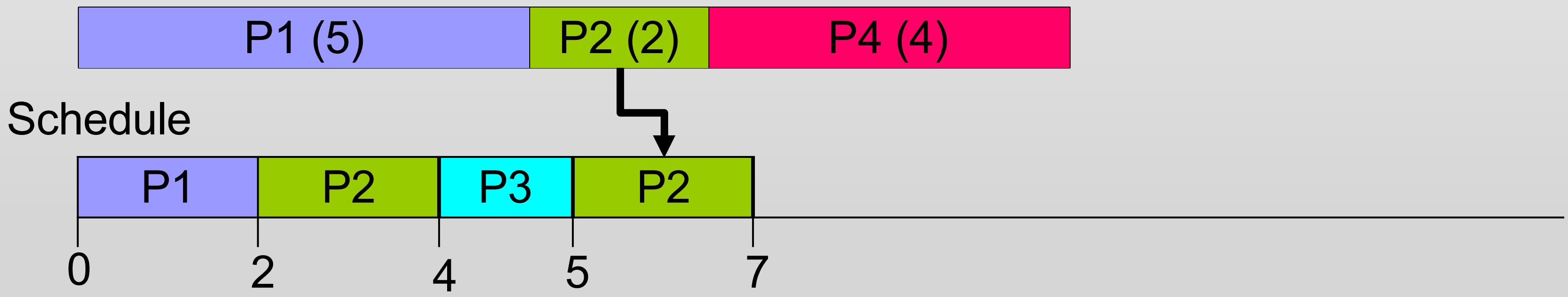
Ready queue: t=4



Preemptive SJF Example

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

Ready queue: t=5

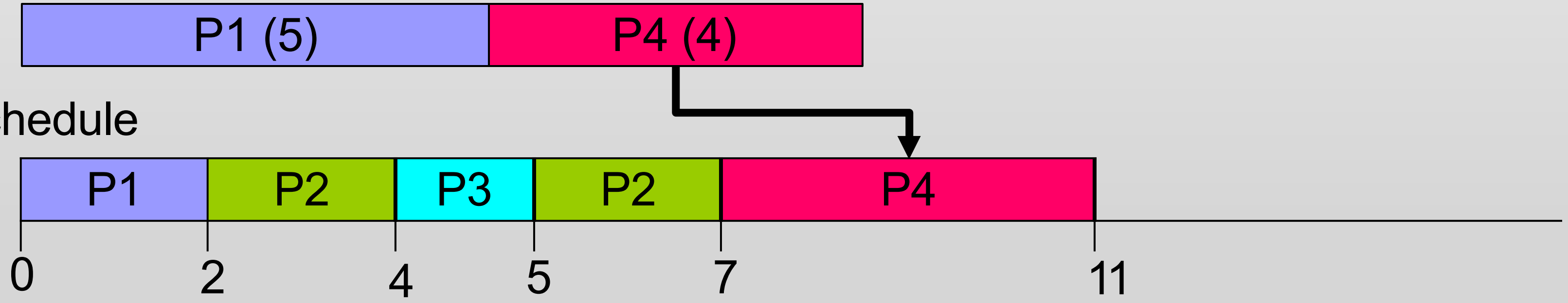


Preemptive SJF Example

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

Ready queue: t=7

Schedule

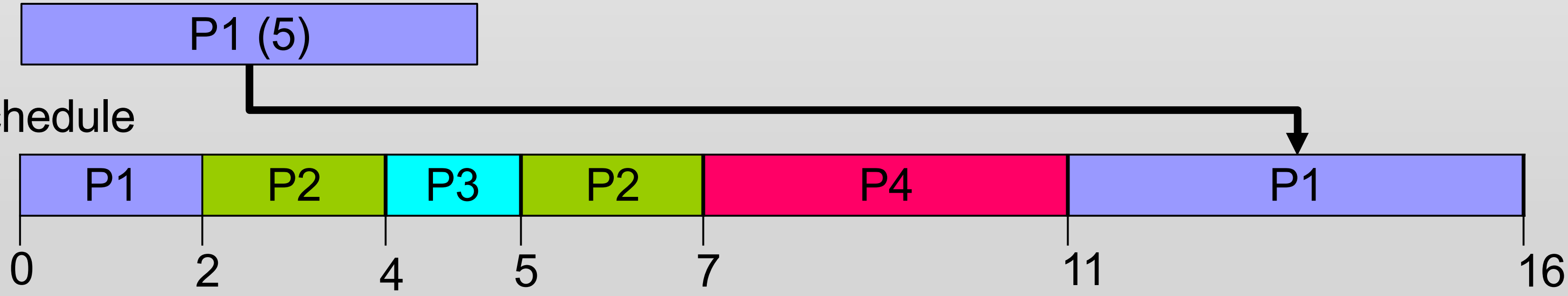


Preemptive SJF Example

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

Ready queue: t=11

Schedule



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

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

history

new one

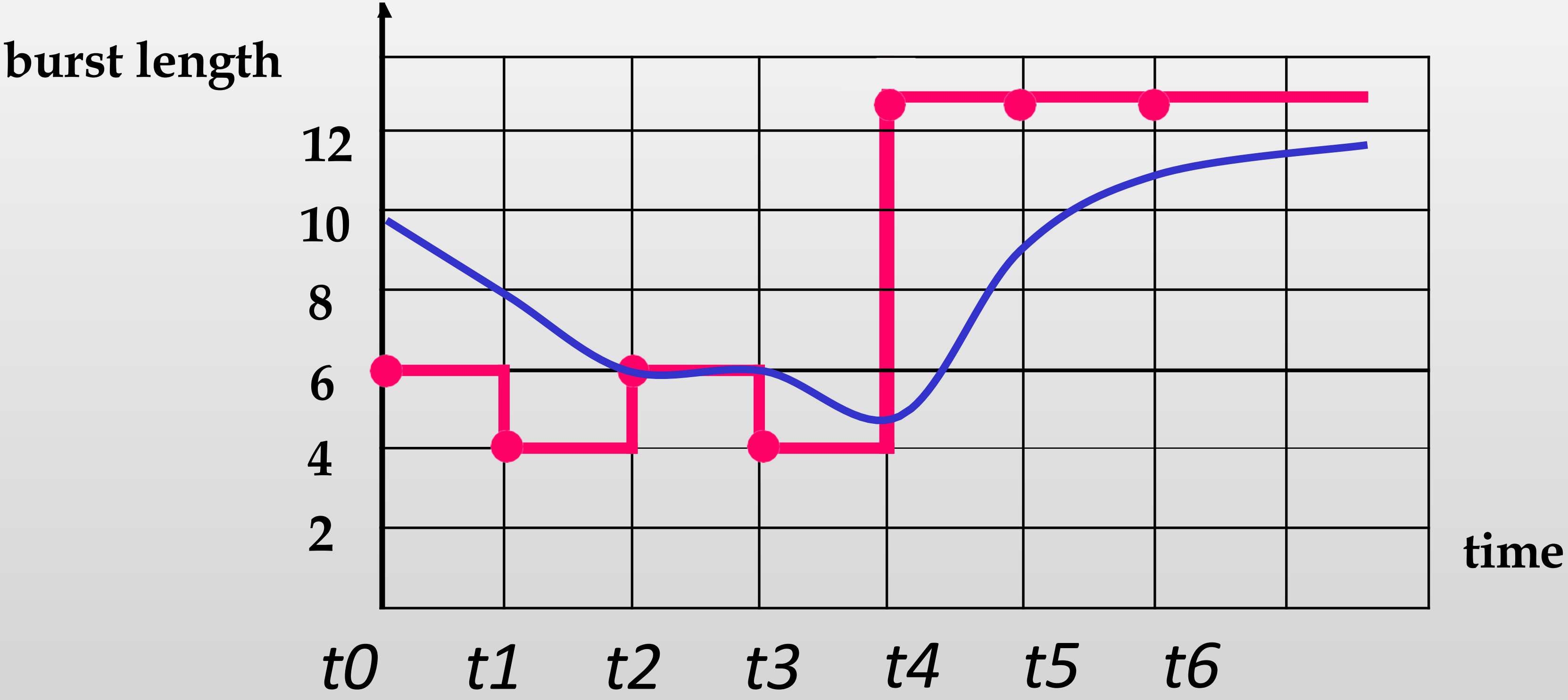
Commonly,

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

$\alpha = 1/2$

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

Exponential predication of next CPU burst



CPU burst t_n 6 4 6 4 13 13 13

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
    - 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

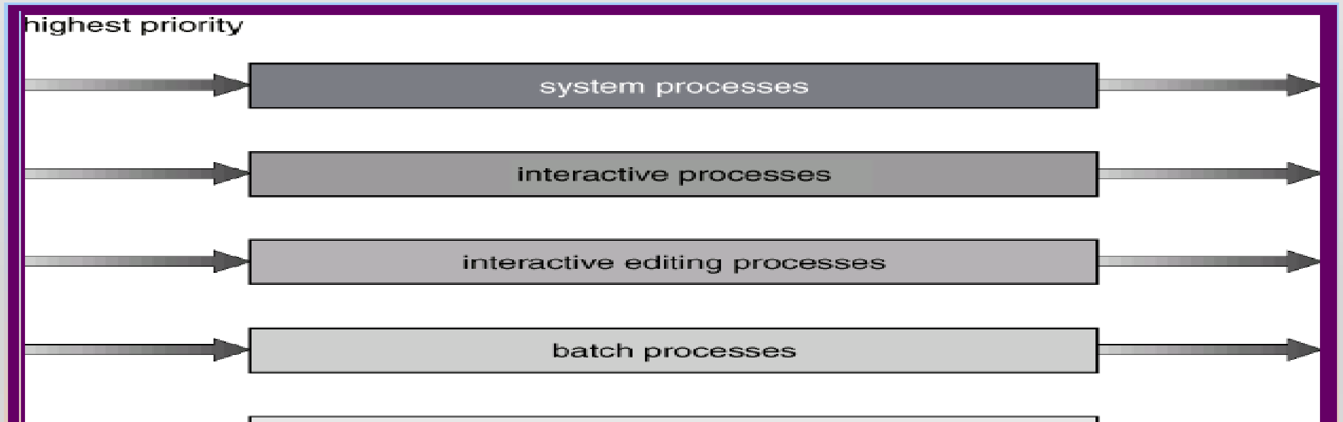
- The Gantt chart is:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

0 20 37 57 77 97 117 121 134 154 162

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%)

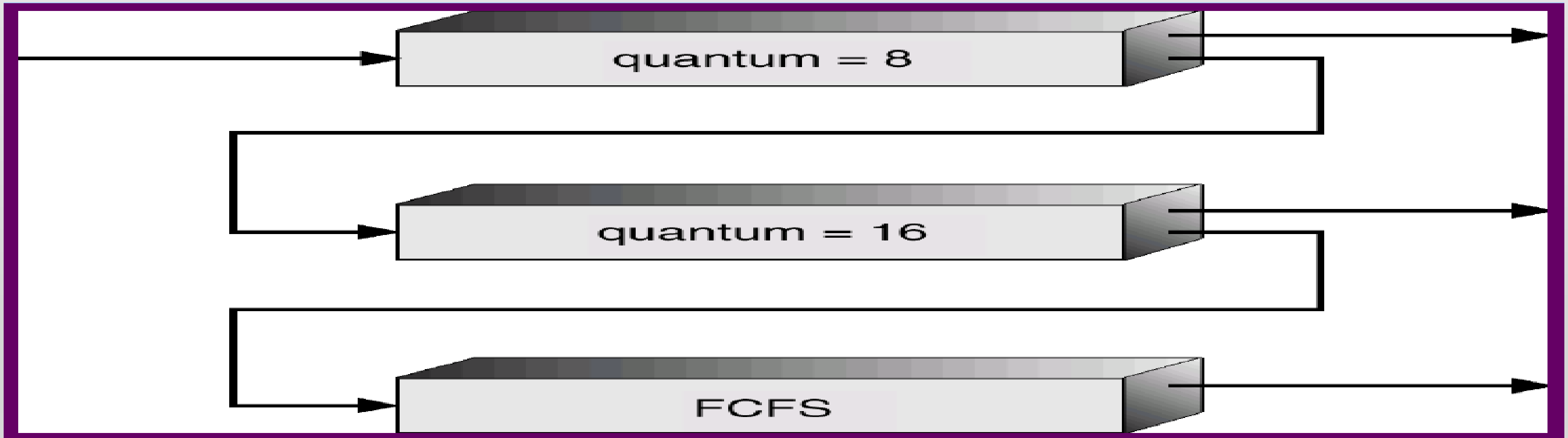


Multilevel Feedback Queue Scheduling

- A process can move between the various queues; aging can be implemented
- Idea: separate processes according to the characteristic of their CPU burst
  - 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 Q0. Algorithm: FCFS. If it does not finish in 8 ms CPU time, job is moved to Q1
- At Q1 is again served FCFS and receives 16 ms TQ. If it still does not finish in 16 ms, it is preempted and moved to Q2
- Qi only gets executed if Q0 ~Qi-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

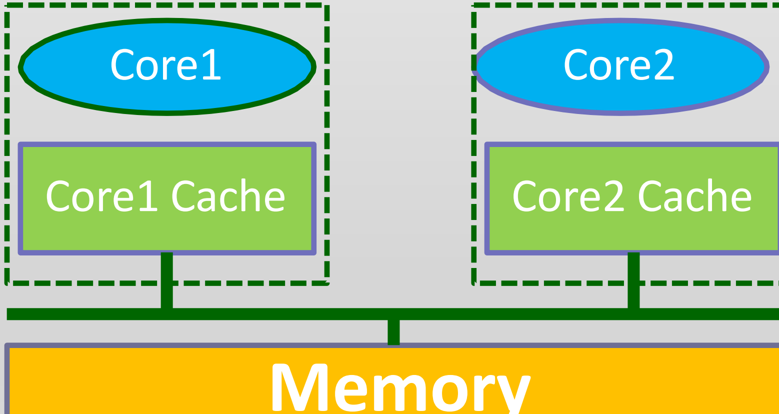
- Multi-Processor Scheduling
- Multi-Core Processor Scheduling
- Real-Time Scheduling

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

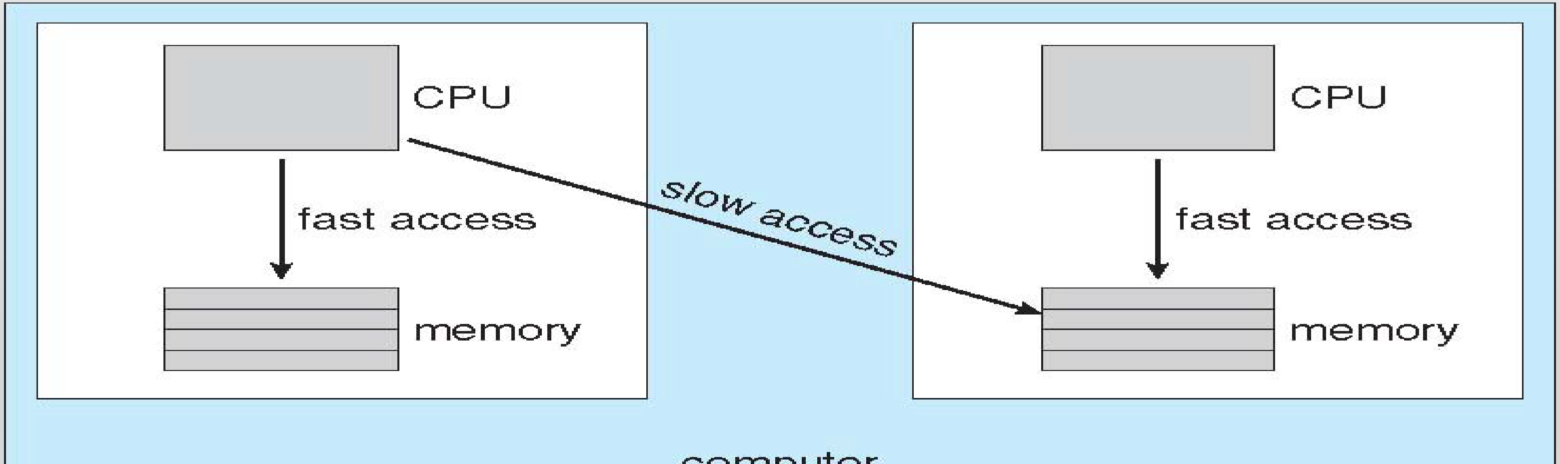
Processor affinity

- 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

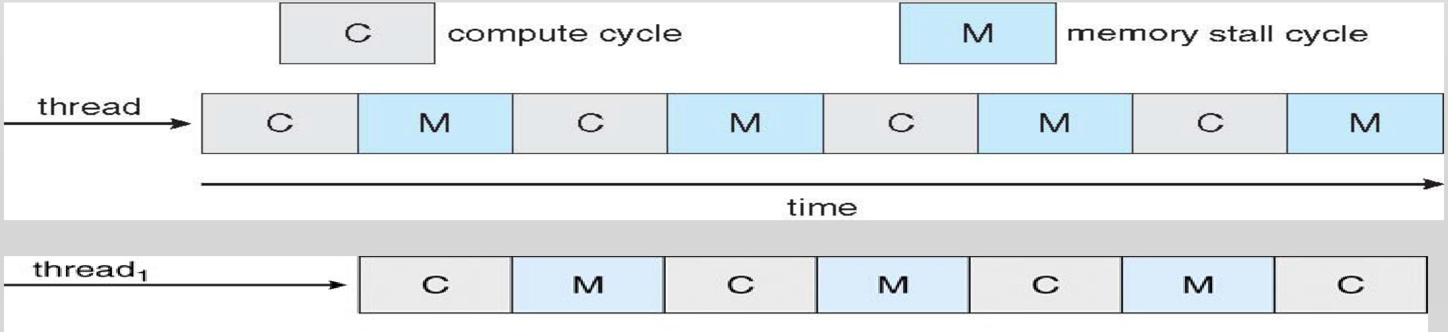


Load-balancing

- 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

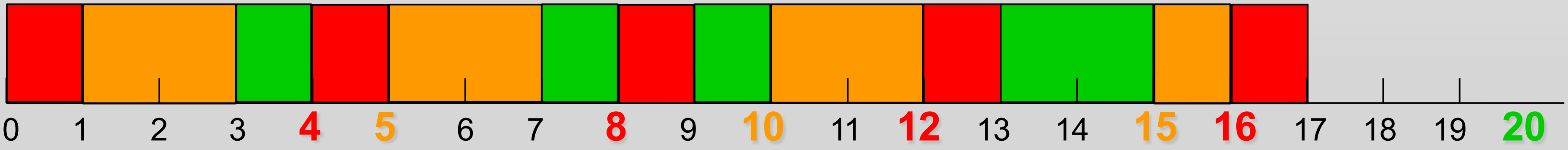
- Real-time does not mean speed, but *keeping deadlines*
- Soft real-time requirements:
  - Missing the deadline is unwanted, but is not immediately critical
  - Examples: multimedia streaming
- Hard real-time requirements:
  - Missing the deadline results in *a fundamental failure*
  - Examples: nuclear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

Real-Time Scheduling Algorithms

- FCFS scheduling algorithm – Non-RTS
  - T1 = (0, 4, 10) == (Ready, Execution, Deadline)
  - 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

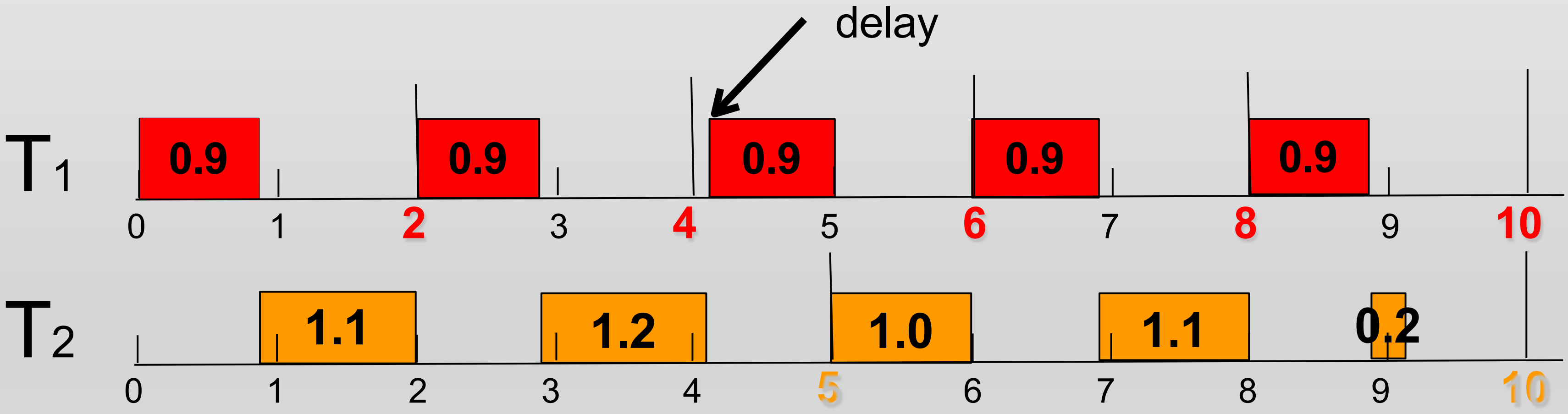
Rate-Monotonic (RM) Scheduling

- 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: T1=(4,1), T2=(5,2), T3=(20,5) (Period, Execution)
    - ∵period: 4 < 5 < 20
    - ∴priority: T1 > T2 > T3



Early Deadline First (EDF) Scheduler

- Dynamic-priority scheduler
  - Task's priority is not fixed
  - Task's priority is determined by deadline.
- Ex: T1=(2,0.9), T2=(5,2.3)
  - time: ?



Review Slides (II)

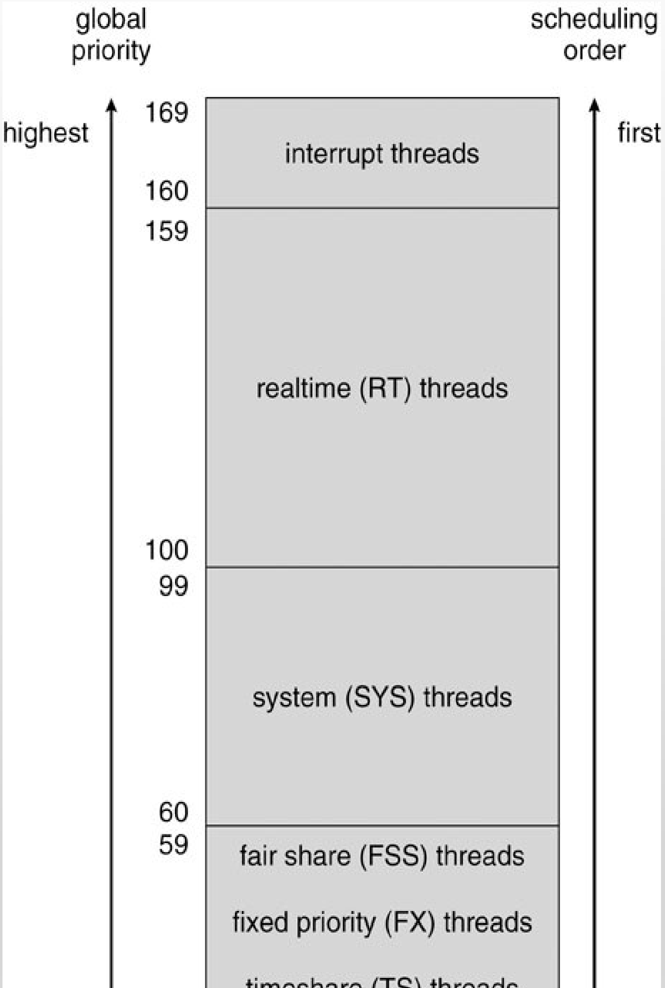
- What is processor affinity?
- Real-time scheduler
  - Rate-Monotonic
  - Earliest deadline first

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

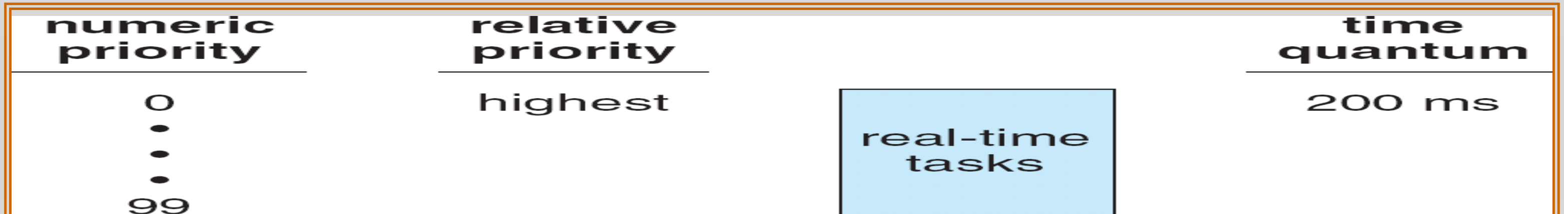
Windows XP Scheduler

- 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

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

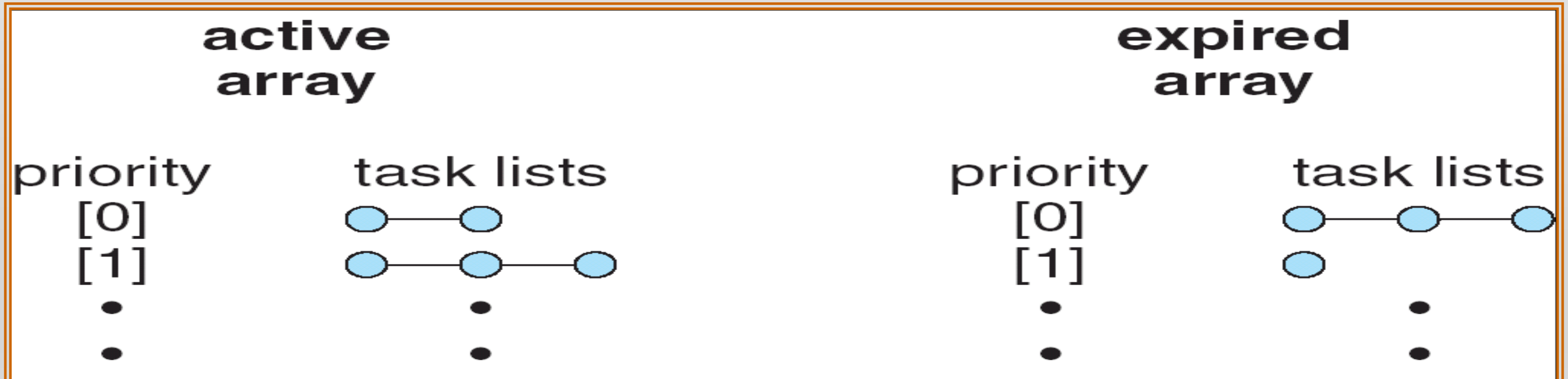
Linux Scheduler

- 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 a task is expired



Q & A

Thank you for your attention