Chapter 5: CPU Scheduling

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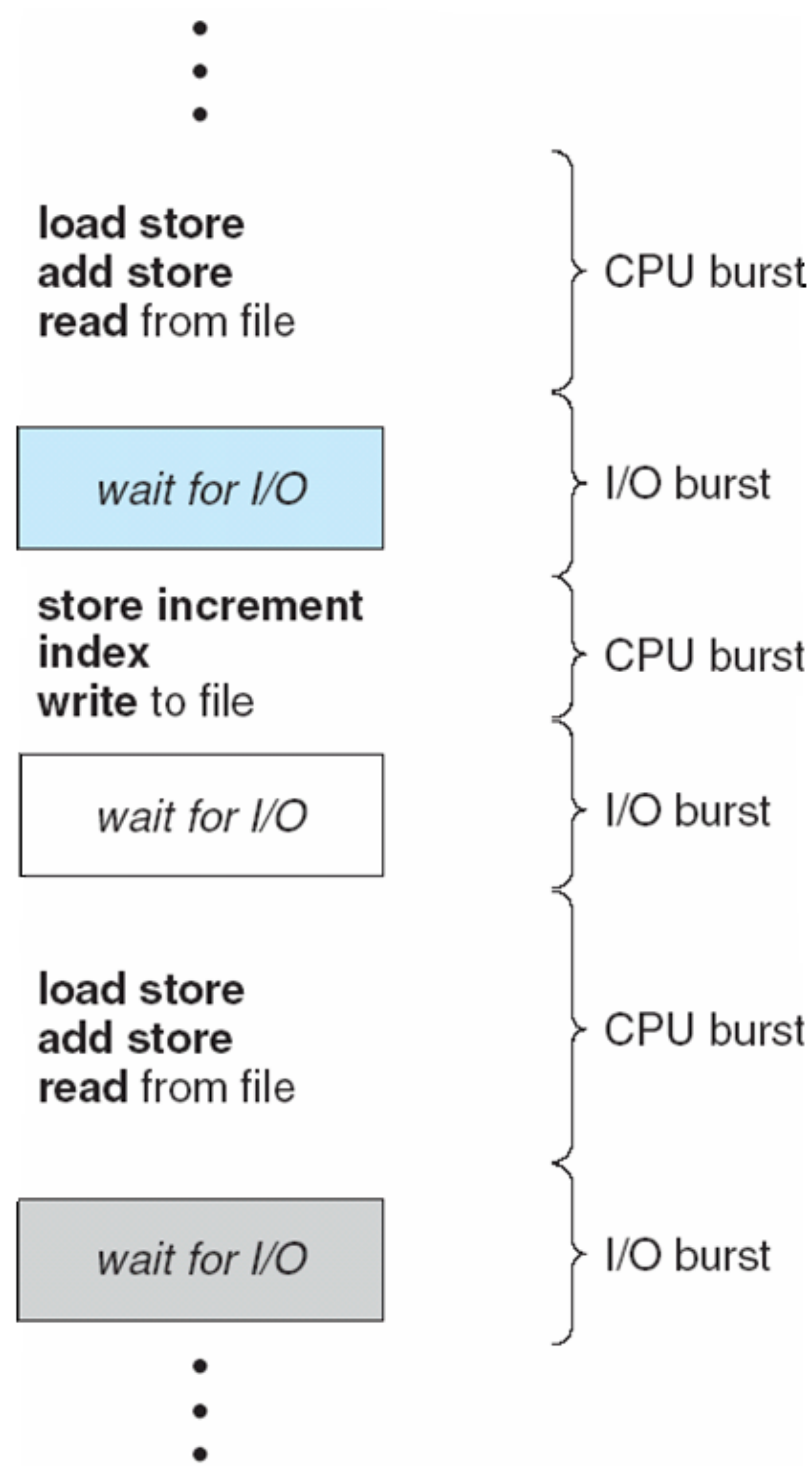
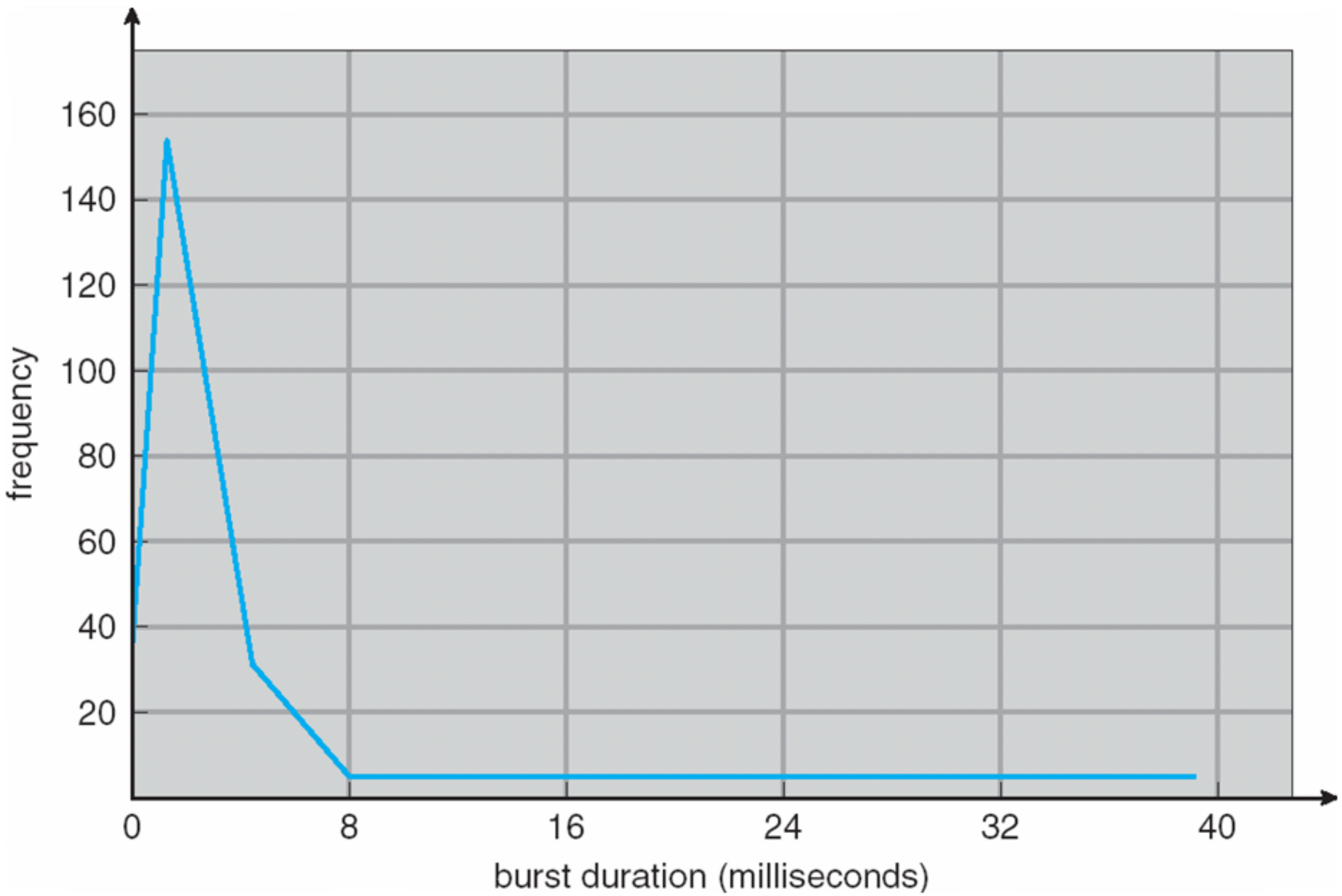
Basic Concepts

- Process execution consists of a cycle of CPU execution and I/O wait
  - **CPU burst** and **I/O burst** alternate
  - CPU burst distribution varies greatly from process to process, and from computer to computer, but follows similar curves
- Maximum CPU utilization obtained with **multiprogramming**
  - CPU scheduler selects another process when current one is in I/O burst

Alternating Sequence of CPU and I/O Bursts



Histogram of CPU-burst Distribution



CPU Scheduler

- CPU scheduler selects from among the processes in **ready queue**, and allocates the CPU to one of them
- CPU scheduling decisions may take place when a process:
    - switches from **running to waiting state** (e.g., wait for I/O)
    - switches from **running to ready state** (e.g., when an interrupt occurs)
    - switches from **waiting to ready** (e.g., at completion of I/O)
    - **terminates**
- Scheduling under condition**1 and 4 only** is **nonpreemptive**
    - once the CPU has been allocated to a process, the process keeps it until terminates or waiting for I/O
    - also called **cooperative scheduling**
- **Preemptive scheduling** schedules process ***also*** in condition **2 and 3**
    - preemptive scheduling needs hardware support such as a timer
    - synchronization primitives are necessary

Kernel Preemption

- Preemption also affects the OS kernel design
  - kernel states will be inconsistent if preempted when updating shared data
  - i.e., kernel is serving a system call when an interrupt happens
- Two solutions:
  - waiting either the system call to complete or I/O block
    - kernel is **nonpreemptive** (still a preemptive scheduling for processes!)
  - disable kernel preemption when updating shared data
    - recent Linux kernel takes this approach:
      - Linux supports SMP
      - shared data are protected by kernel synchronization
      - disable kernel preemption when in kernel synchronization
      - turned a non-preemptive SMP kernel into a **preemptive** kernel

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 restart that program
- **Dispatch latency** : the time it takes for the dispatcher to stop one process and start another running

Scheduling Criteria

- **CPU utilization** : percentage of CPU being busy
- **Throughput**: # of processes that complete execution per time unit
- **Turnaround time**: the time to execute a particular process
  - from the time of *submission* to the time of *completion*
- **Waiting time**: the total time spent waiting in the *ready queue*
- **Response time**: the time it takes from when a request was submitted until the first response is produced
  - the time it takes to *start responding*

Scheduling Algorithm Optimization Criteria

- Generally, **maximize** CPU utilization and throughput, and **minimize** turnaround time, waiting time, and response time
- Different systems optimize different values
  - in most cases, optimize **average** value
  - under some circumstances, optimizes **minimum** or **maximum** value
    - e.g., real-time systems
  - for interactive systems, minimize **variance** in the response time

Scheduling Algorithms

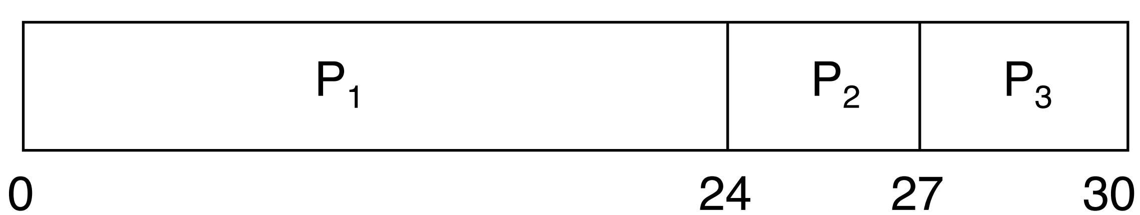
- First-come, first-served scheduling
- Shortest-job-first scheduling
- Priority scheduling
- Round-robin scheduling
- Multilevel queue scheduling
- Multilevel feedback queue scheduling

First-Come, First-Served (FCFS) Scheduling

- Example processes:

Process	Burst Time
P_1	24
P_2	3
P_3	3

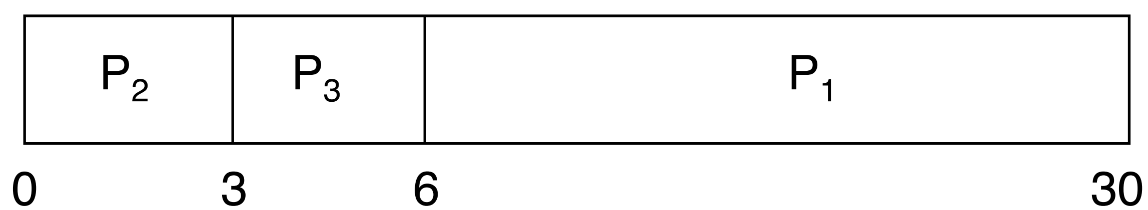
- Suppose that the processes arrive in the order: P_1 , P_2 , P_3
- the Gantt Chart for the FCFS schedule is:



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

FCFS Scheduling

- Suppose that the processes arrive in the order: P_2 , P_3 , P_1
  - the Gantt chart for the FCFS schedule is:



- Waiting time for $P_1 = 6$; $P_2 = 0$; $P_3 = 3$, average waiting time: $(6 + 0 + 3)/3 = 3$
- **Convoy effect**: all other processes waiting until the running CPU-bound process is done
  - considering one CPU-bound process and many I/O-bound processes
- FCFS is **non-preemptive**

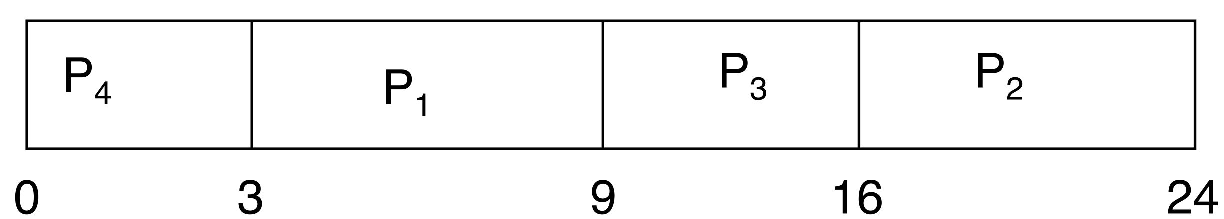
Shortest-Job-First Scheduling

- Associate with each process: the length of its next CPU burst
  - the process with the **smallest next CPU burst** is scheduled to run next
- SJF is **provably optimal**: it gives **minimum average waiting** time for a given set of processes
  - moving a short process before a long one decreases the overall waiting time
  - the difficulty is to know the length of the next CPU request
    - long-term scheduler can use the **user-provided processing time estimate**
    - short-term scheduler needs to **approximate** SFJ scheduling
- SJF can be **preemptive** or **nonpreemptive**
  - preemptive version is called **shortest-remaining-time-first**

Example of SJF

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

Predicting Length of Next CPU Burst

- We may not know length of next CPU burst for sure, but can **predict** it
  - assuming it is related to the previous CPU burst
- Predict length of the next CPU bursts w/ **exponential averaging**

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

t_n : *measured* length of n^{th} CPU burst

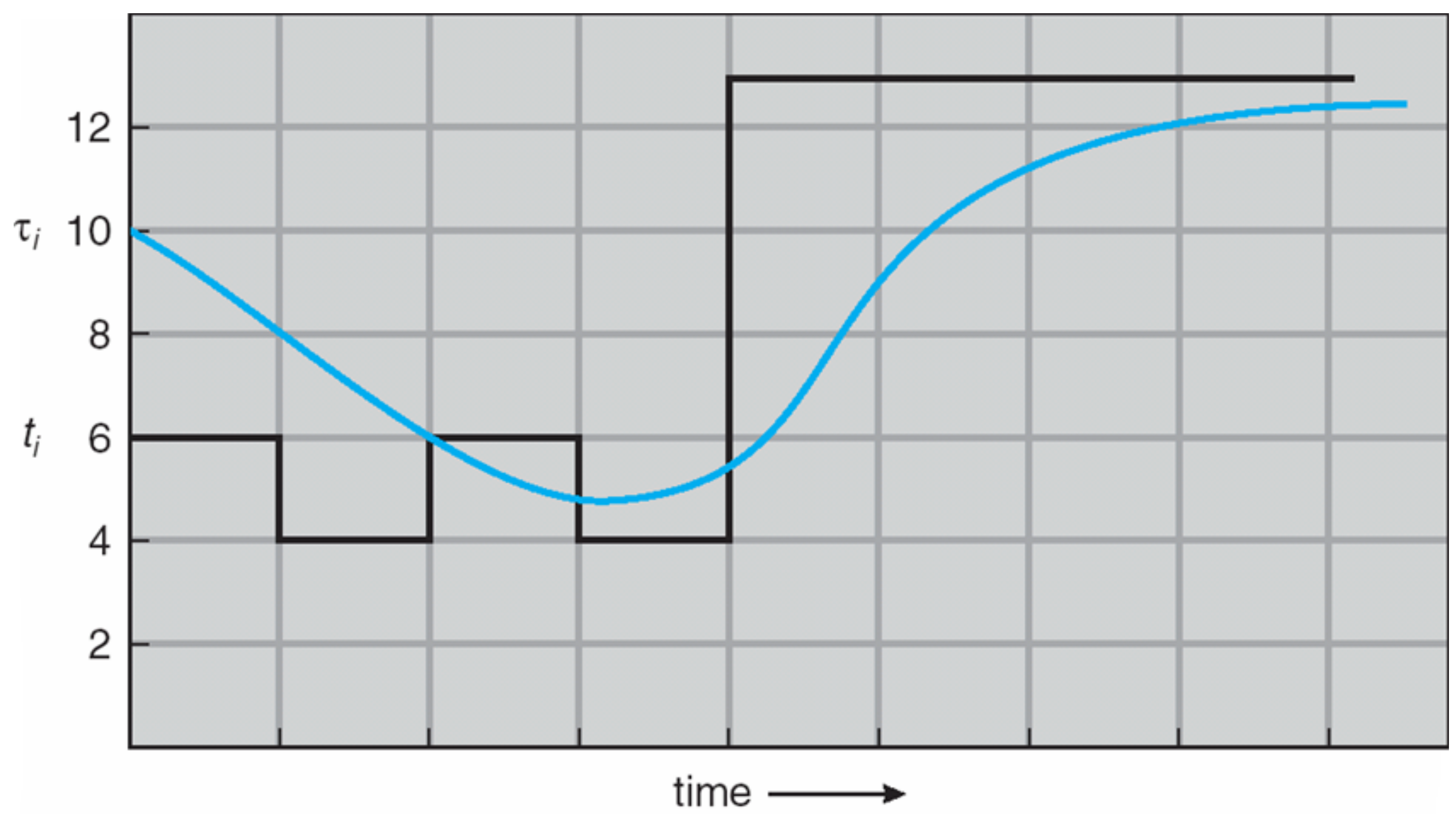
τ_{n+1} : predicted length of the next CPU burst

$0 \le \alpha \le 1$ (normally set to $\frac{1}{2}$)

  - α determines how the history will affect prediction
    - α=0 ➙ $\tau_{n+1} = \tau_n$ ➙ recent history does not count
    - α=1 ➙ $\tau_{n+1} = \alpha t_n$ ➙ only the actual last CPU burst counts
  - older history carries less weight in the prediction

$$\tau_{n+1} = \alpha\, t_n + (1-\alpha)\,\alpha t_{n-1} + \ldots + (1-\alpha)^j \alpha t_{n-j} + \ldots + (1-\alpha)^{n+1}\, \tau_0$$

Prediction Length of 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	…

Shortest-Remaining-Time-First

- SJF can be **preemptive**: **reschedule when a process arrives**

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

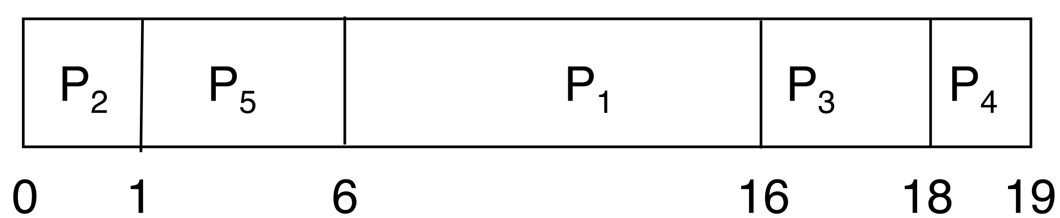
Priority Scheduling

- Priority scheduling selects the ready process with **highest priority**
  - a priority number is associated with each process, smaller integer, higher priority
  - the CPU is allocated to the process with the highest priority
  - SJF is special case of priority scheduling
    - priority is the inverse of predicted next CPU burst time
- Priority scheduling can be **preemptive** or **nonpreemptive**, similar to SJF
- **Starvation** is a problem: **low priority processes may never execute**
  - **Solution: aging — gradually increase priority of processes that wait for a long time**

Example of Priority Scheduling

ProcessA	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



- Average waiting time = 8.2 msec

Round Robin (RR)

- Round-robin scheduling selects process in a **round-robin** fashion
  - each process gets a small unit of CPU time (time quantum, q)
    - q is too large ➙ FIFO, q is too small ➙ context switch overhead is high
    - a time quantum is generally 10 to 100 milliseconds
  - process used its quantum is **preempted** and put to **tail of the ready queue**
    - a **timer** interrupts every quantum to schedule next process
- Each process gets 1/n of the CPU time if there are n processes
  - no process waits more than (n-1)q time units
- Turnaround time is not necessary decrease if we increase the quantum

Example of Round-Robin

Process	Burst Time
P1	24
P2	3
P3	3

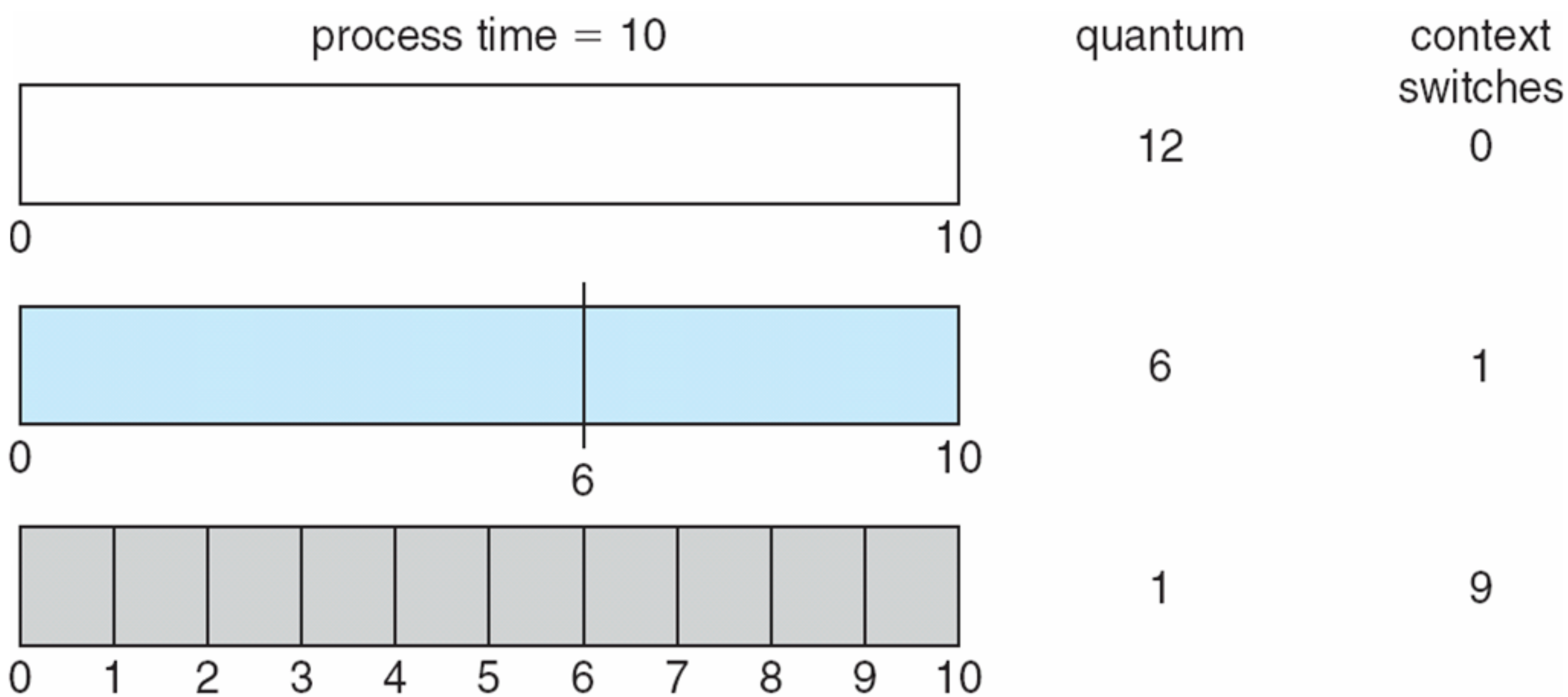
- The Gantt chart is (q = 4):

P_1	P_2	P_3	P_1	P_1	P_1	P_1	P_1

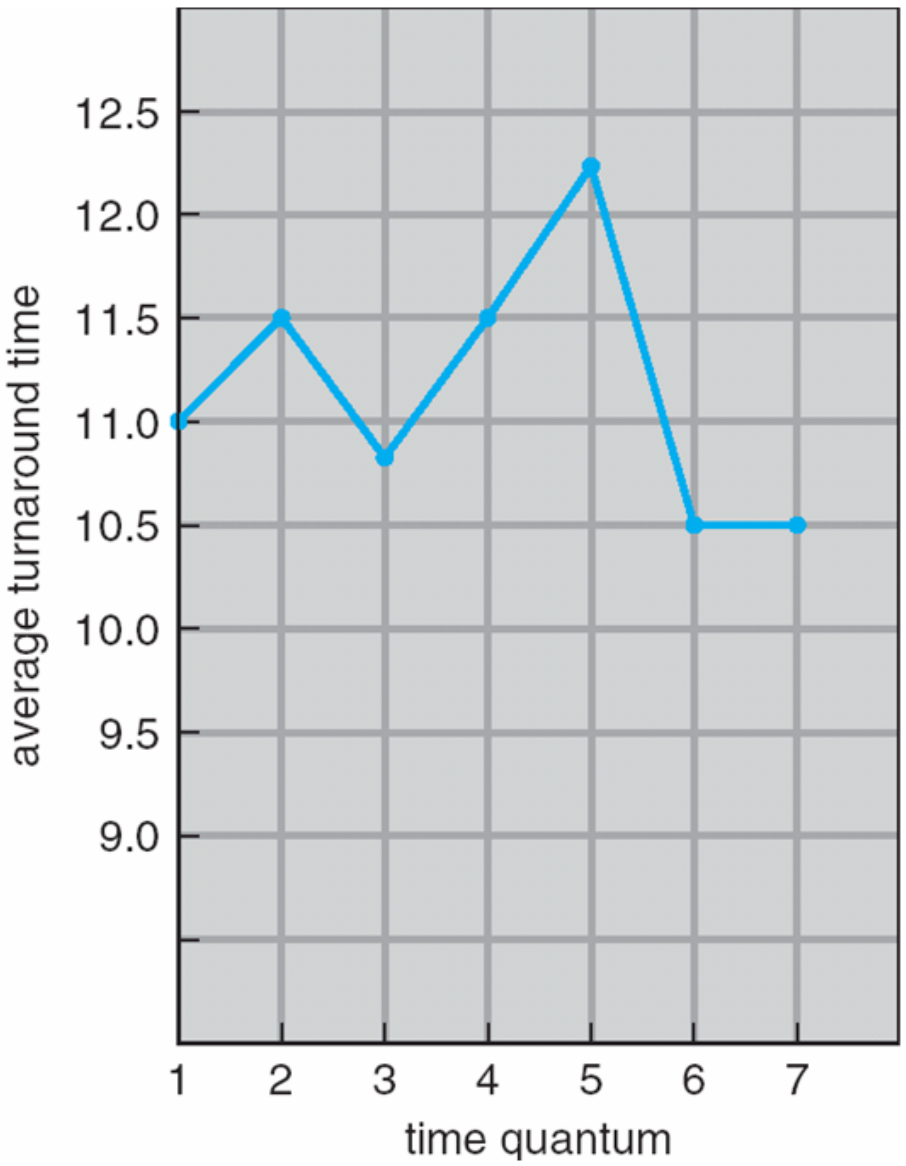
0 4 7 10 14 18 22 26 30

- Wait time for **P_1 is 6**, P_2 is 4, P_3 is 7, average is 5.66

Time Quantum and Context Switch



Turnaround Time Varies With Quantum

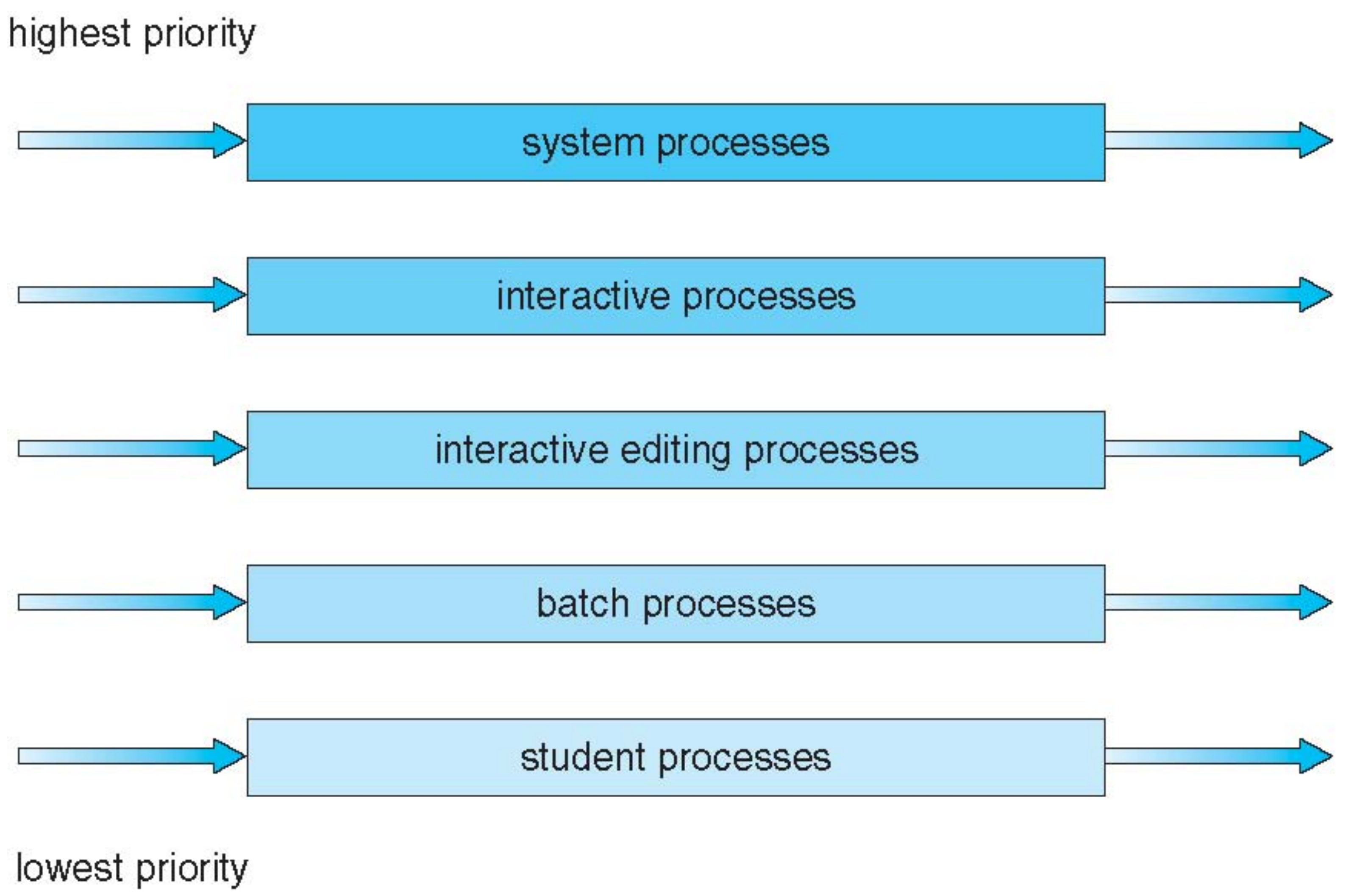


process	time
P_1	6
P_2	3
P_3	1
P_4	7

Multilevel Queue

- Multilevel queue scheduling
  - ready queue is partitioned into **separate queues**
    - e.g., foreground (interactive) and background (batch) processes
  - processes are **permanently** assigned to a given queue
  - each queue has **its own scheduling** algorithm
    - e.g., interactive: RR, batch: FCFS
- Scheduling must be done **among** the queues
  - **fixed priority scheduling**
    - possibility of **starvation**
  - **time slice**: each queue gets a certain amount of CPU time which it can schedule amongst its processes
    - e.g., 80% to foreground in RR, 20% to background in FCFS

Multilevel Queue Scheduling



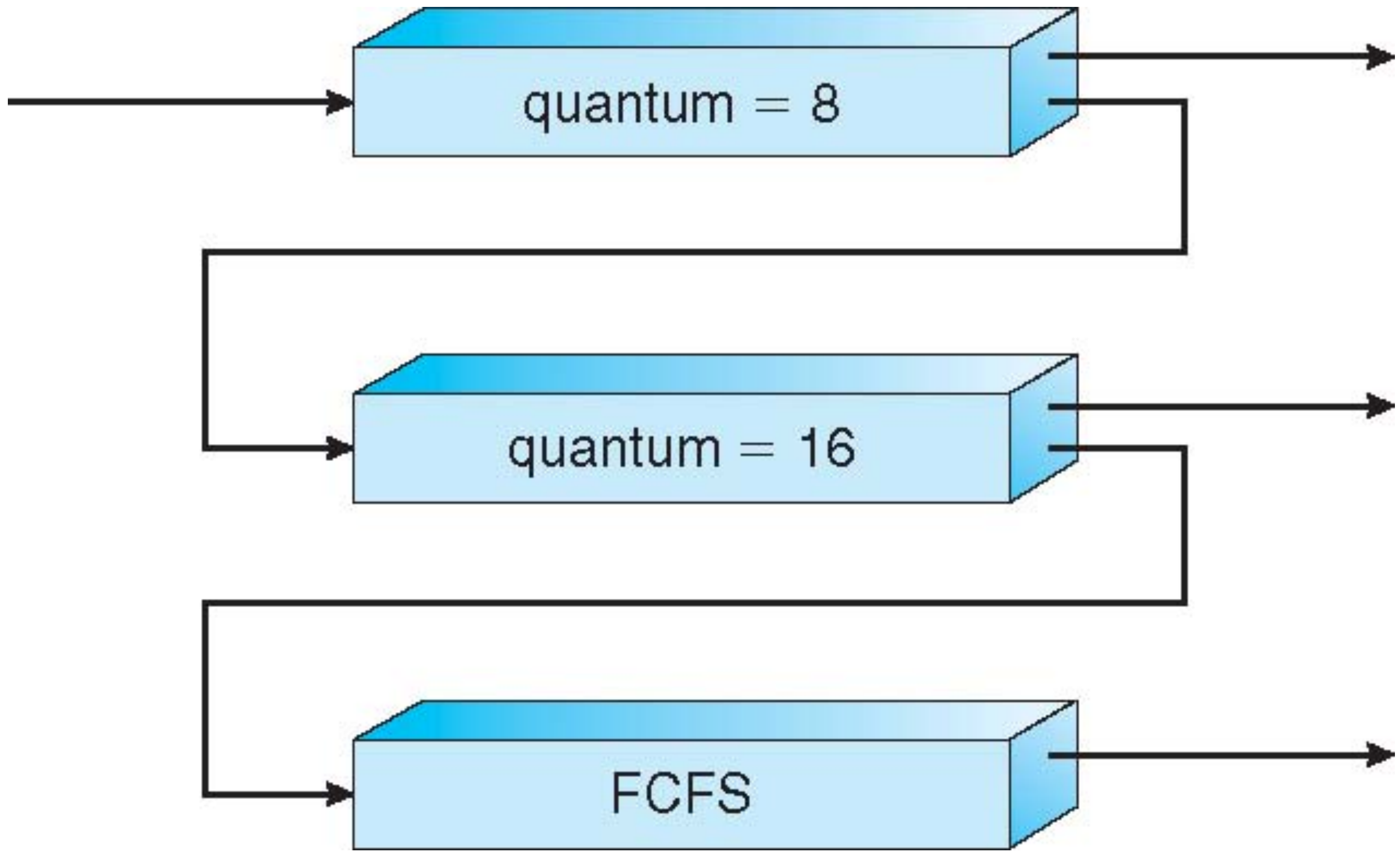
Multilevel Feedback Queue

- Multilevel **feedback** queue scheduling uses multilevel queues
  - a process can **move between the various queues**
    - it tries to infer the **type of the processes** (interactive? batch?)
    - aging can be implemented this way
  - the goal is to give **interactive** and **I/O intensive** process **high priority**
- MLFQ schedulers are defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine when to assign a process a higher priority
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when it needs service
- MLFQ is the **most general** CPU-scheduling algorithm

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
- A new job enters queue Q_0 which is served FCFS
  - when it gains CPU, the job receives 8 milliseconds
  - if it does not finish in 8 milliseconds, the job is moved to queue Q_1
- In Q_1, the job is again served FCFS and receives 16 milliseconds
  - if it still does not complete, it is preempted and moved to queue Q_2

Multilevel Feedback Queues



Thread Scheduling

- OS kernel schedules kernel threads
  - **system-contention scope**: competition among all threads in system
  - kernel does not aware user threads
- Thread library schedule user threads onto LWPs
  - used in many-to-one and many-to-many threading model
  - **process-contention scope**: scheduling competition within the process
  - PCS usually is based on priority set by the user
  - user thread scheduled to a LWP do not necessarily running on a CPU
    - OS kernel needs to schedule the kernel thread for LWP to a CPU

Pthread Scheduling

- API allows specifying either PCS or SCS during thread creation
    - pthread_attr_set/getscope is the API
        - PTHREAD_SCOPE_PROCESS: schedules threads using PCS scheduling
        - PTHREAD_SCOPE_SYSTEM: schedules threads using SCS scheduling
- Which scope is available can be limited by OS
    - e.g., Linux and Mac OS X only allow PTHREAD_SCOPE_SYSTEM

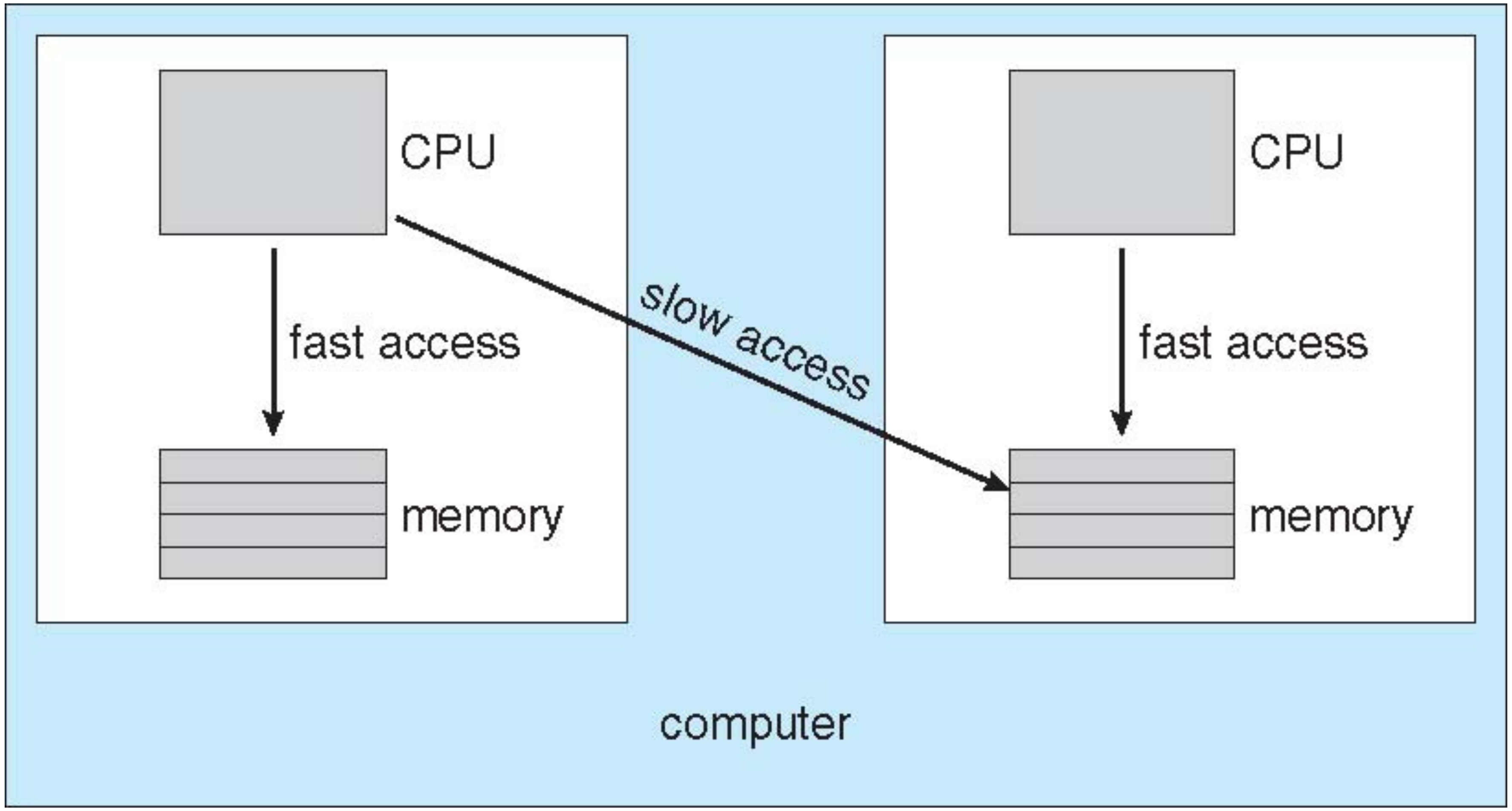
Pthread Scheduling API

```
#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);
      /* now join on each thread */
   for (i = 0; i < NUM THREADS; i++)
      pthread_join(tid[i], NULL);
}
```

Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
  - assume processors are **identical** (homogeneous) in functionality
- Approaches to multiple-processor scheduling
  - **asymmetric multiprocessing**:
    - only one processor makes scheduling decisions, I/O processing, and other activity
    - other processors act as dummy processing units
  - **symmetric multiprocessing** (SMP): each processor is self-scheduling
    - scheduling data structure are shared, needs to be synchronized
    - used by common operating systems
- **Processor affinity**
  - migrating process is expensive to invalidate and repopulate cache
  - solution: **let a process has an affinity for the processor currently running**
    - soft affinity and hard affinity

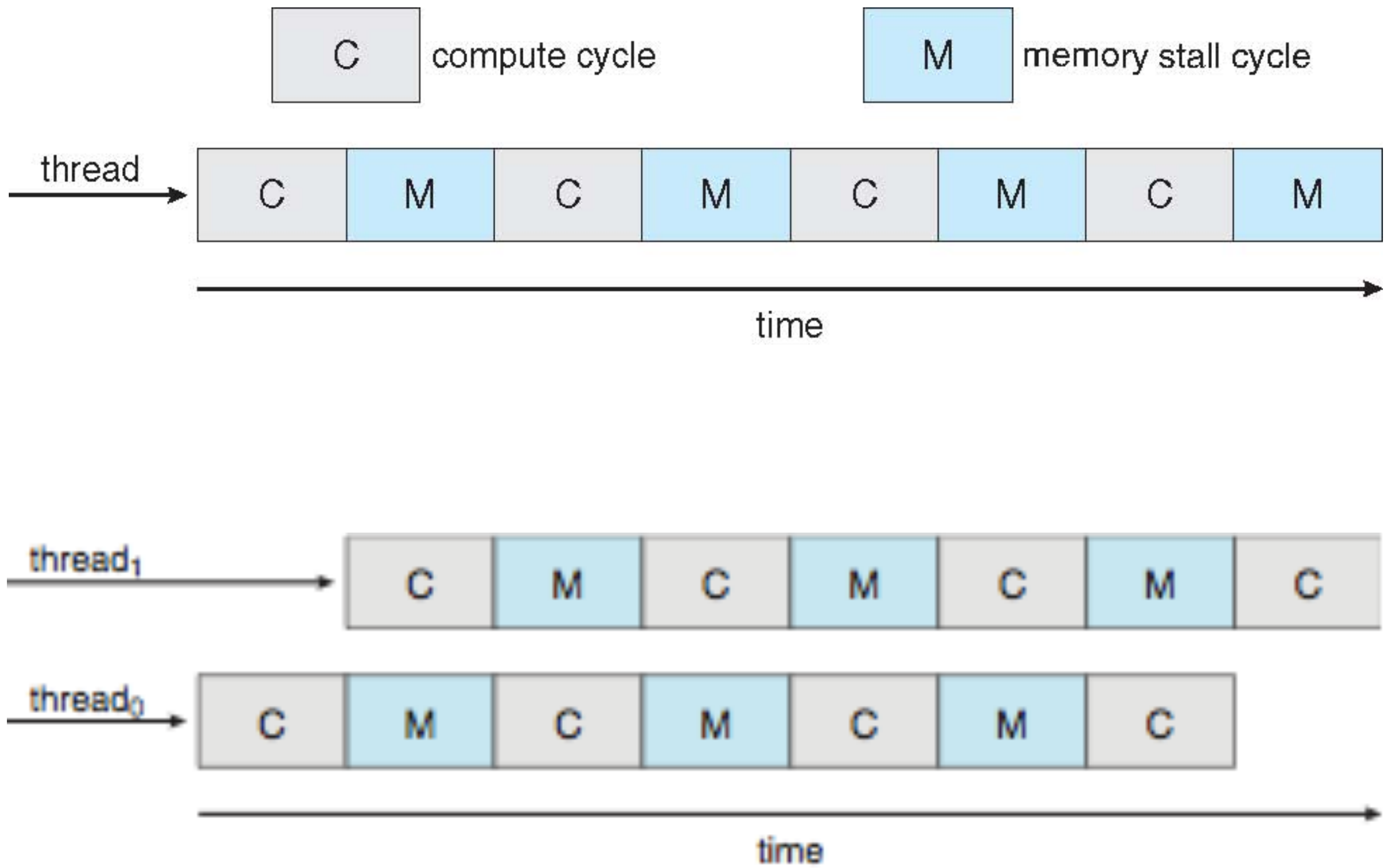
NUMA and CPU Scheduling



Multicore Processors

- Multicore processor has multiple processor cores on same chip
  - previous multi-processor systems have processors connected through bus
- Multicore processor may complicate scheduling due to memory stall
  - **memory stall**: when access memory, a process spends a significant amount of time waiting for the data to become available
- Solution: **multithreaded CPU core**
  - **share the execute unit**, but **duplicate architecture states** (e.g., registers) for each CPU thread
    - e.g., Intel Hyper-Threading technology
  - one thread can execute while the other in memory stall

Multithreaded Multicore System



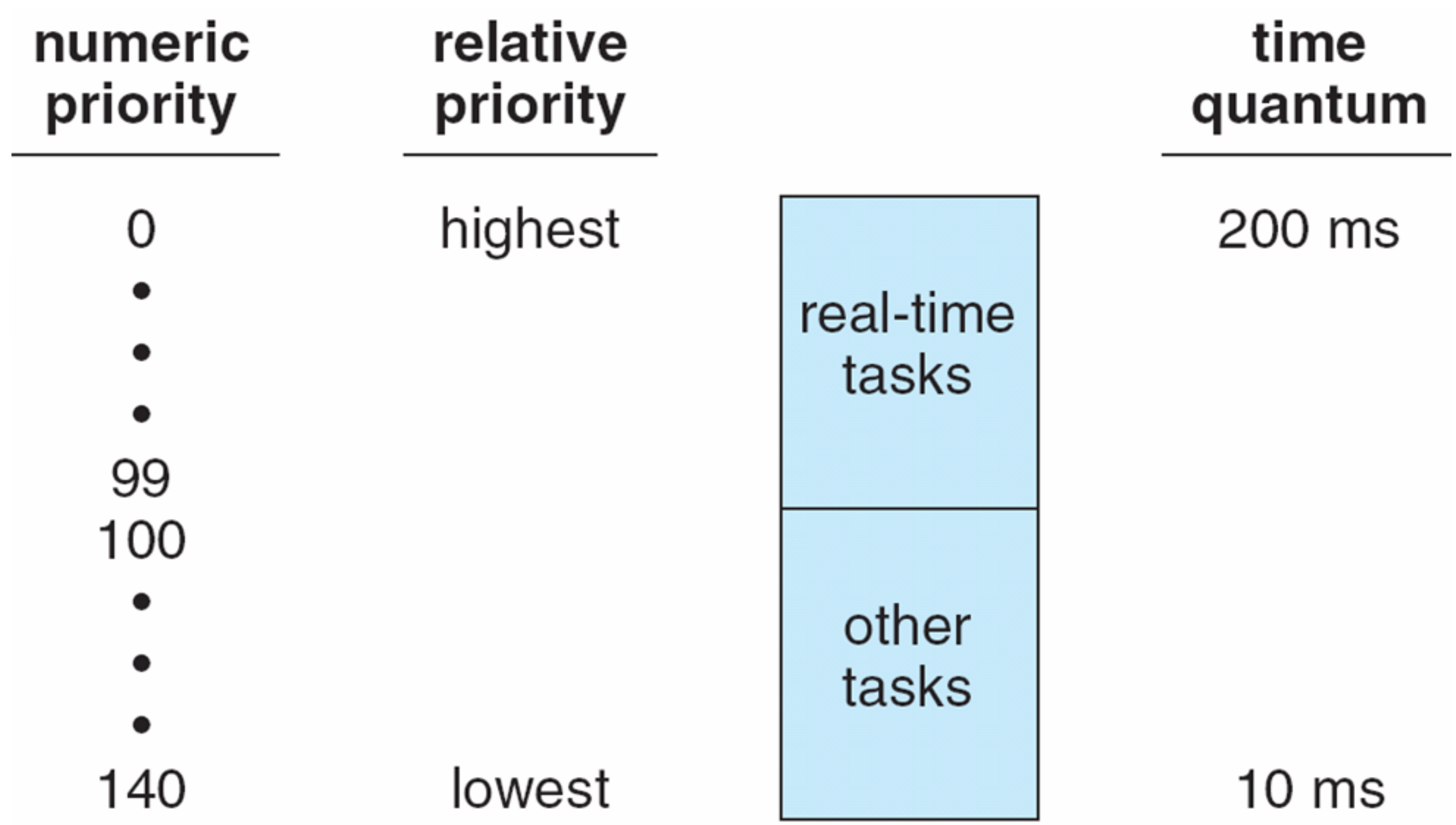
Virtualization and Scheduling

- Virtualization may undo good scheduling efforts in the host or guests
  - Host kernel schedules multiple guests onto CPU(s)
    - in some cases, the host isn’t aware of guests, views them as processes
  - each guest does its own scheduling
    - not knowing it is running on a virtual processor
  - it can result in poor response time and performance

Linux Scheduling

- Linux kernel scheduler runs in constant time (aka. **O(1) scheduler**)
- Linux scheduler is preemptive, priority based
  - two priority ranges: real-time range: 0~99, nice value: 100 ~ 140
    - real-time tasks have static priorities
    - priority for other tasks is dynamic +/-5, determined by interactivity
  - these ranges are mapped into global priority; lower values, higher priority
  - higher priority gets longer quantum
  - tasks are run-able as long as there is time left in its time slice (active)
  - if no time left (expired), it is not run-able until all other tasks use their slices
    - priority is recalculated when task expired

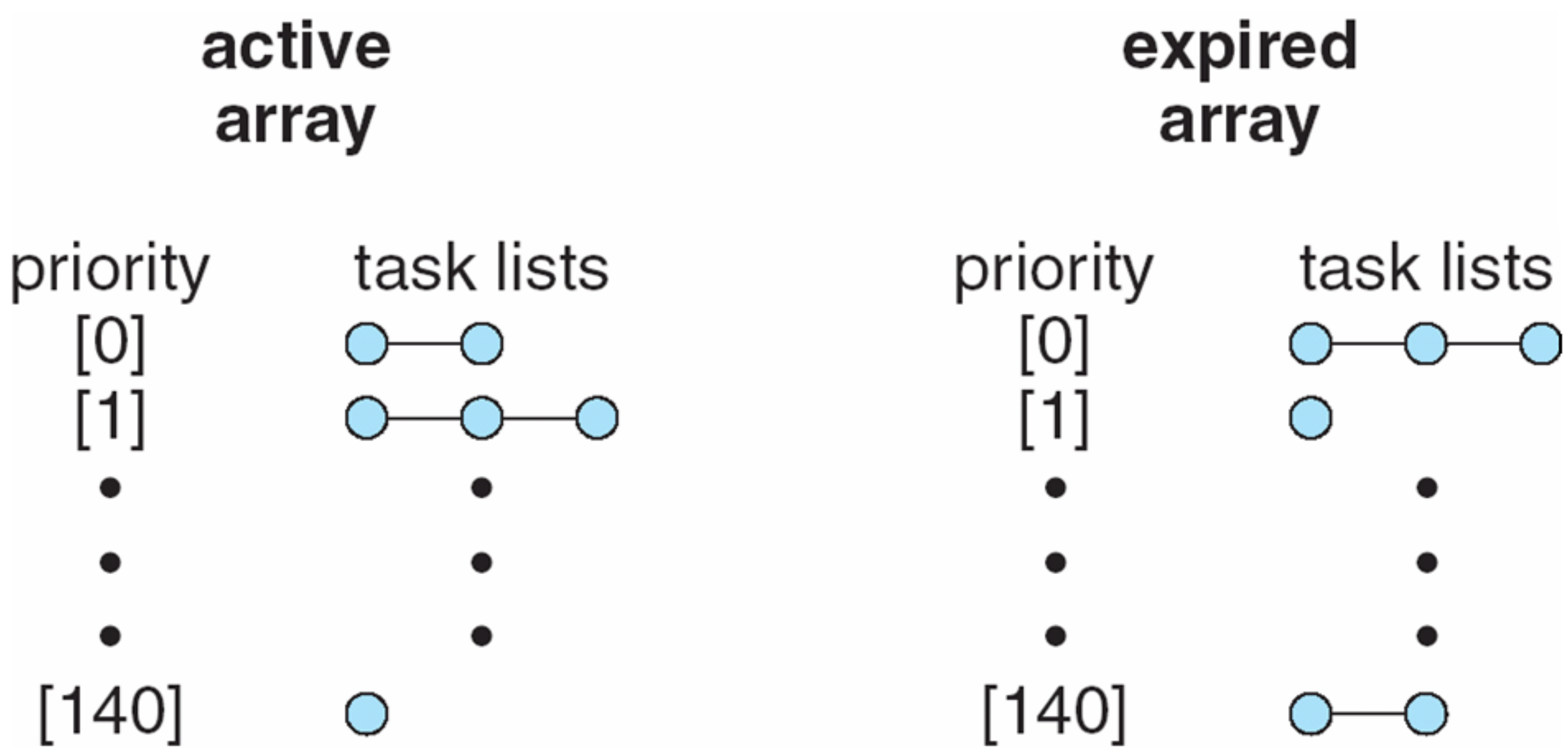
Priorities and Time-slice length



Linux Scheduling

- Kernel maintains a **per-CPU** runqueue for all the runnable tasks
  - each processor schedules itself independently
  - each runqueue has two priority arrays: active, expired
  - tasks in these two arrays are indexed by priority
    - always select the first process with the highest priority
  - when active array is empty, two arrays are exchanged

List of Runnable Tasks



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