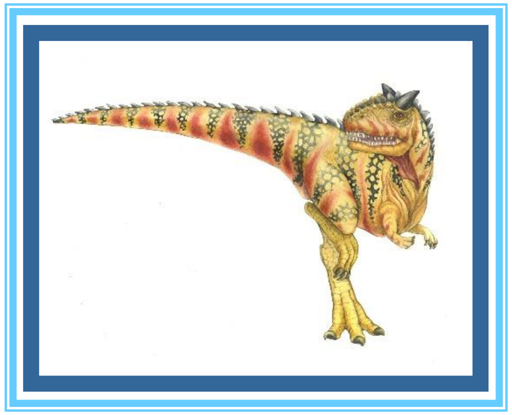
Chapter 5: CPU Scheduling



Chapter 5: CPU Scheduling

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

Objectives

- Describe various CPU scheduling algorithms
- Assess CPU scheduling algorithms based on scheduling criteria
- Explain the issues related to multiprocessor and multicore scheduling
- Describe various real-time scheduling algorithms
- Describe the scheduling algorithms used in the Windows, Linux, and Solaris operating systems
- Apply modeling and simulations to evaluate CPU scheduling algorithms

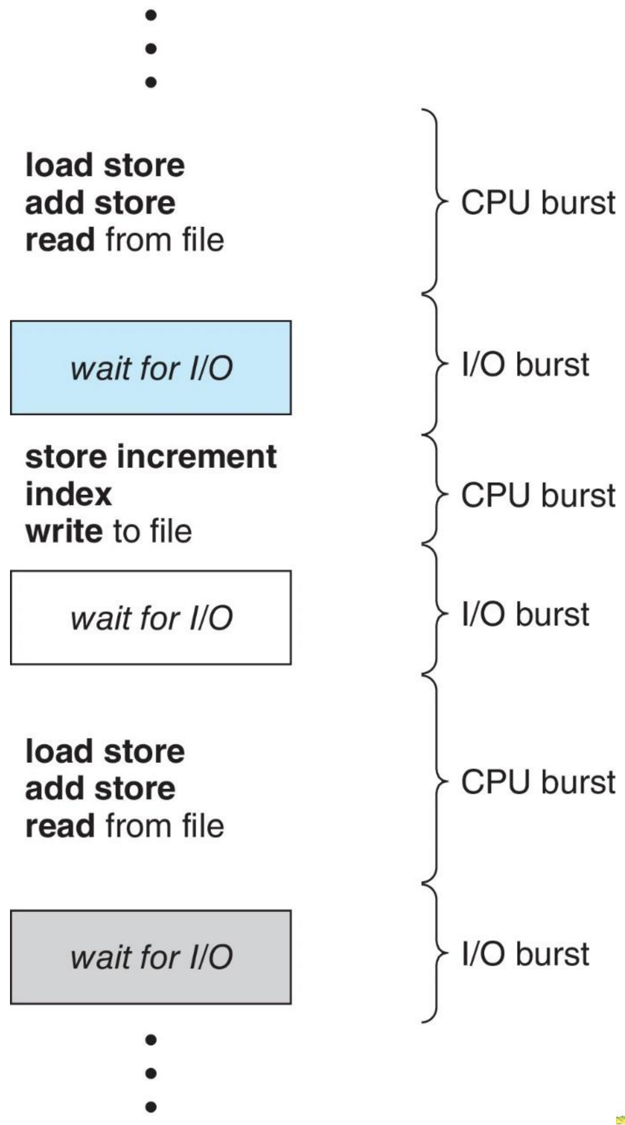
Basic Concepts

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**

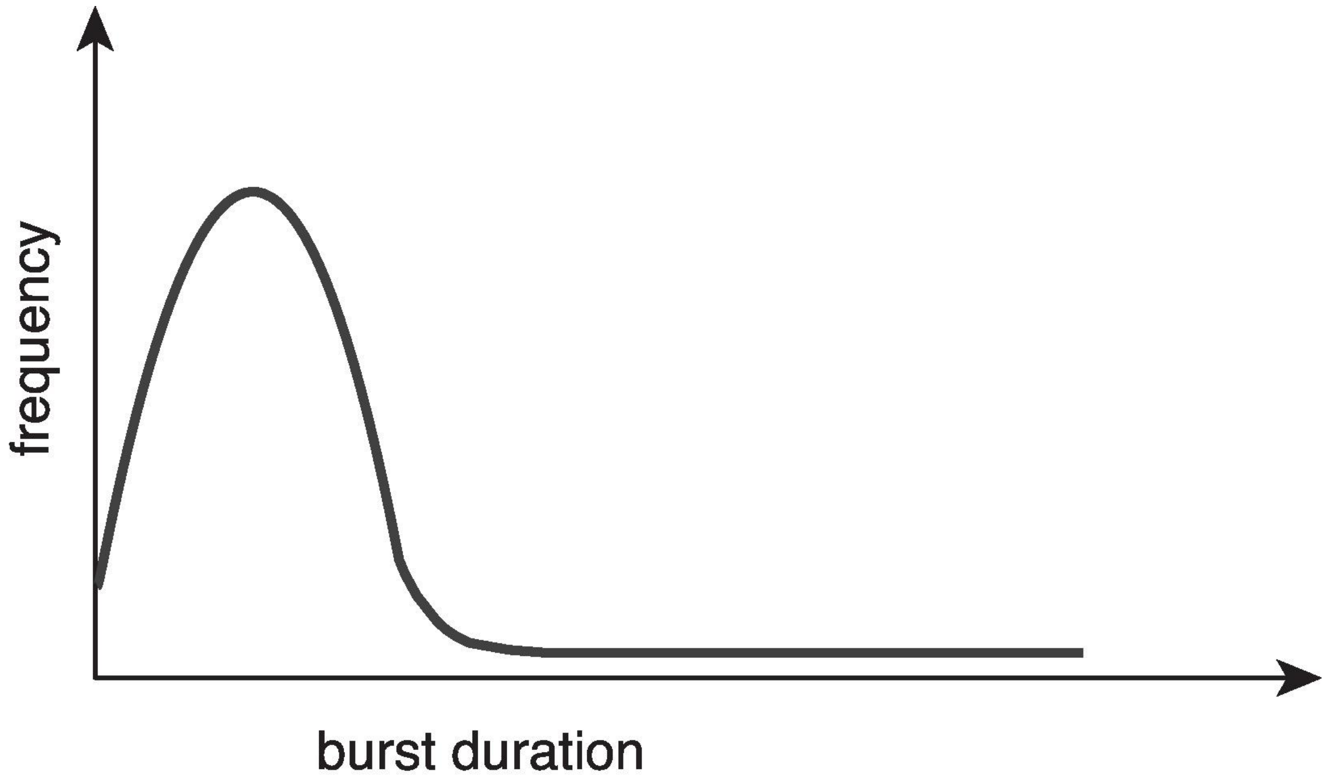
CPU burst distribution is of main concern



Histogram of CPU-burst Times

Large number of short bursts

Small number of longer bursts



CPU Scheduler

The **CPU scheduler** selects from among the processes in ready queue, and allocates the a CPU core to one of them

- Queue may be ordered in various ways

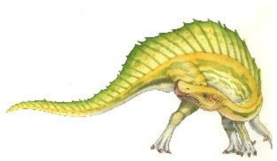
CPU scheduling decisions may take place when a process:

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

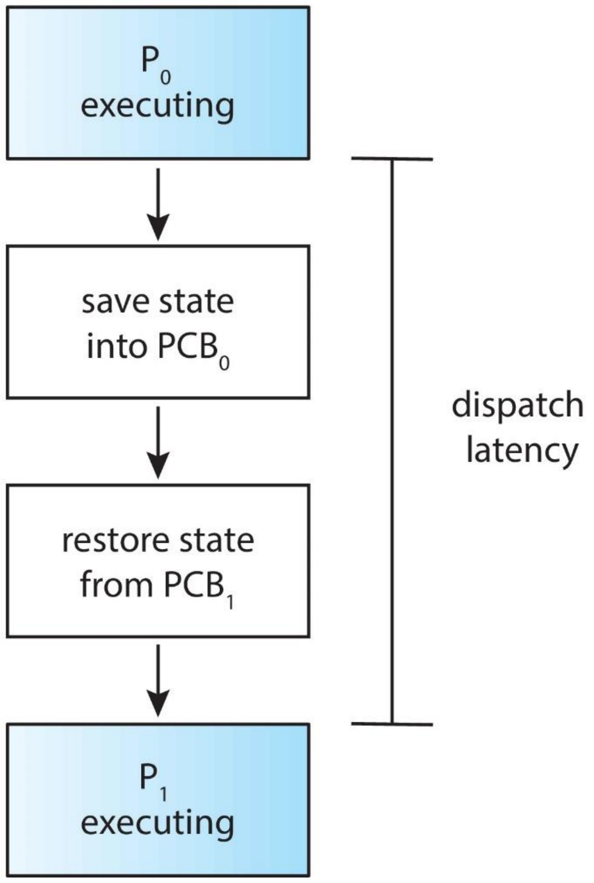


Dispatcher

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

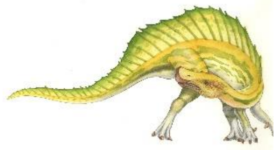
CPU utilization – keep the CPU as busy as possible

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, not output (for time-sharing environment)



Scheduling Algorithm Optimization Criteria

Max CPU utilization

Max throughput

Min turnaround time

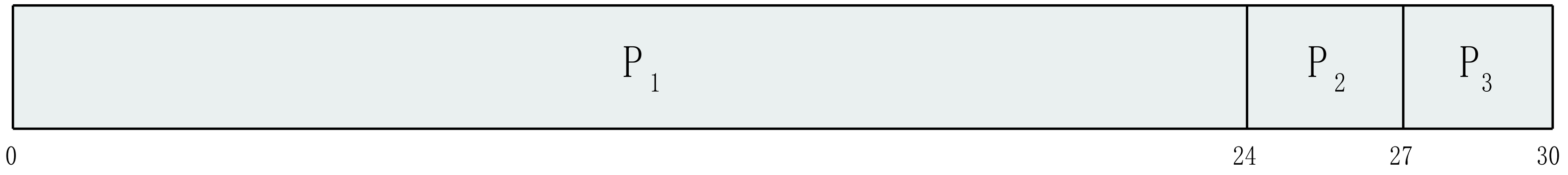
Min waiting time

Min response time

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:



Waiting time for P_1 = 0; P_2 = 24; P_3 = 27

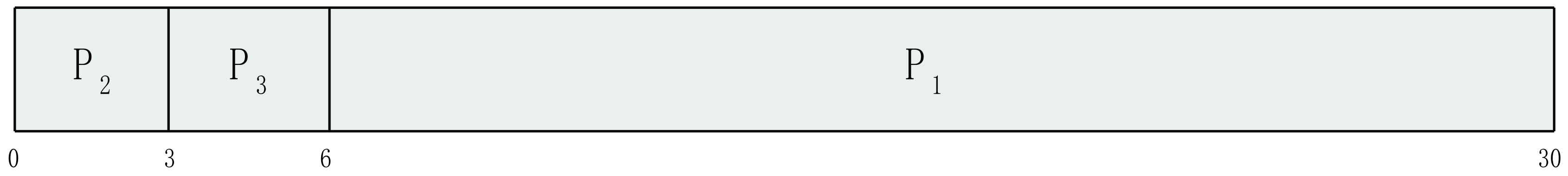
Average waiting time: (0 + 24 + 27)/3 = 17

FCFS Scheduling (Cont.)

Suppose that the processes arrive in the order:

$$P_2 , P_3 , P_1$$

The Gantt chart for the schedule is:



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

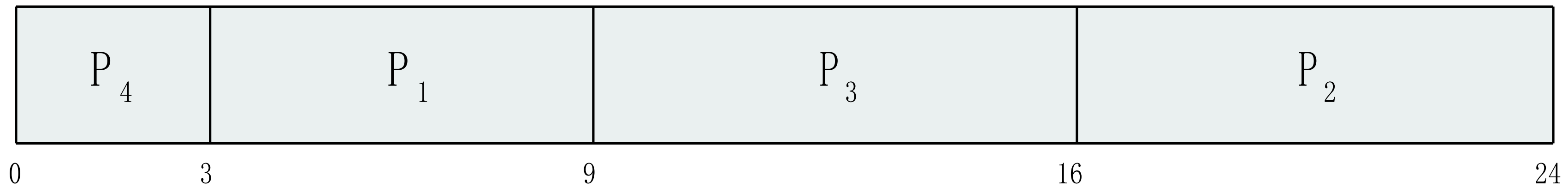
Shortest-Job-First (SJF) Scheduling

- 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	Arrival Time	Burst Time
P_1	0.0	6
P_2	2.0	8
P_3	4.0	7
P_4	5.0	3

SJF scheduling chart



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

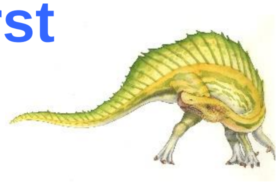
Then pick process with shortest predicted next CPU burst

Can be done by using the length of previous CPU bursts, using exponential averaging

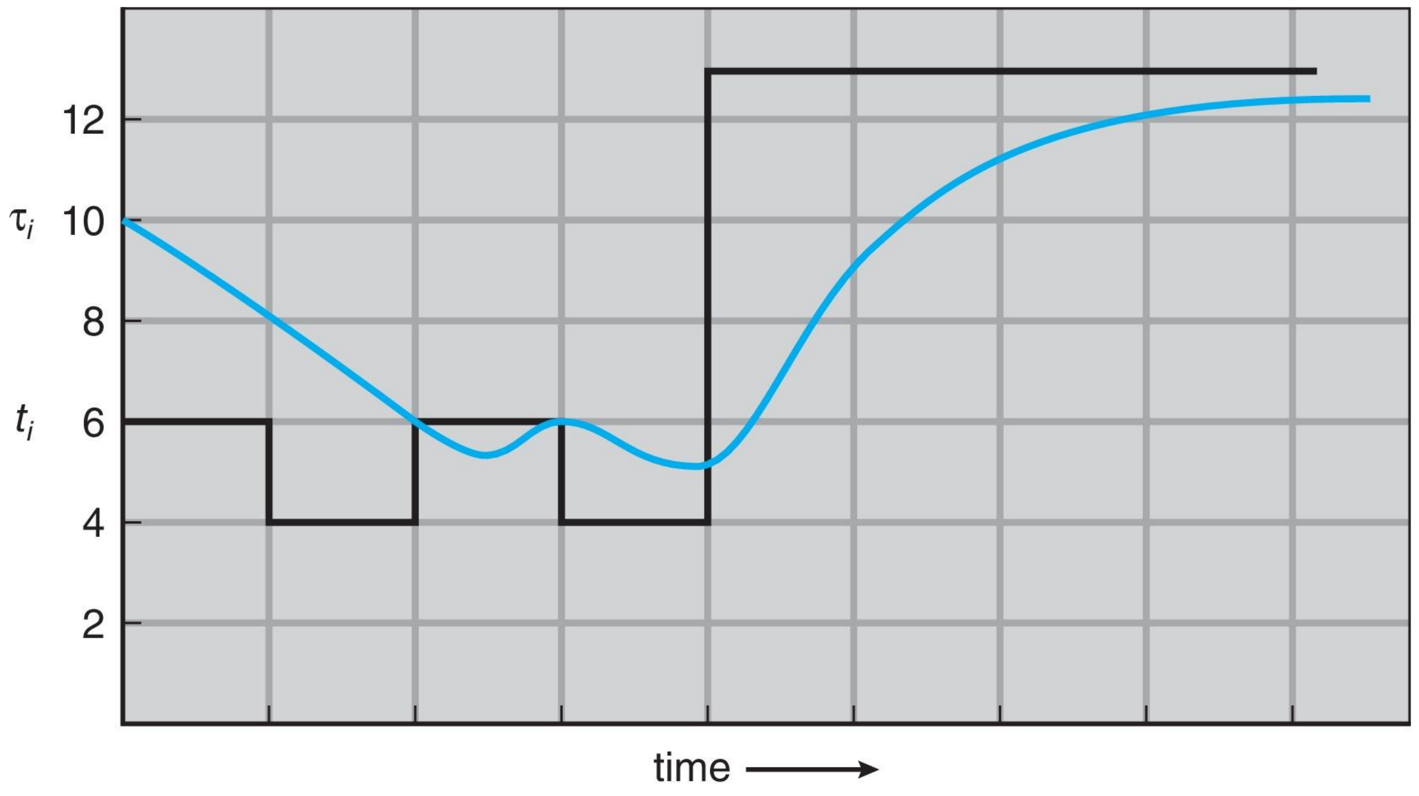
1. $t_n =$ actual length of n^{th} CPU burst
2. $\tau_{n+1} =$ predicted value for the next CPU burst
3. $\alpha, 0 \leq \alpha \leq 1$
4. Define : $\tau_{n=1} = \alpha\, t_n + (1-\alpha)\tau_n .$

Commonly, α set to ½

Preemptive version called **shortest-remaining-time-first**



Prediction of the Length of the 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	...

Examples of Exponential Averaging

$\alpha = 0$

$\tau_{n+1} = \tau_n$

Recent history does not count

$\alpha = 1$

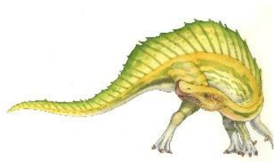
$\tau_{n+1} = \alpha t_n$

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

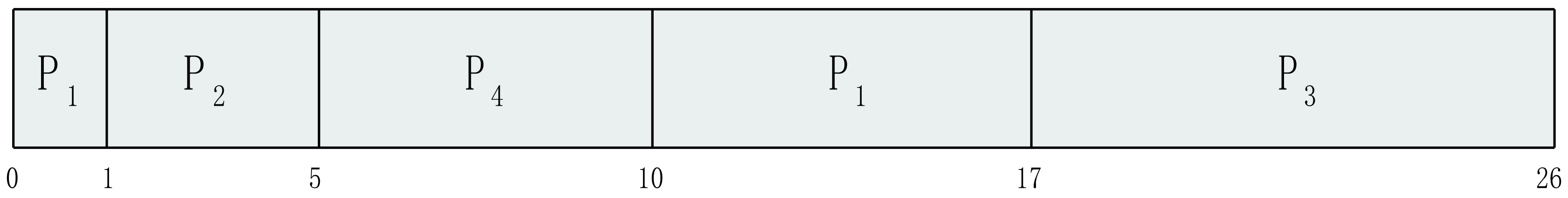


Example of Shortest-remaining-time-first

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



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

Round Robin (RR)

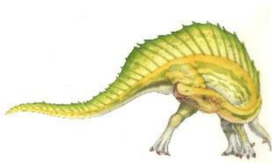
Each process gets a small unit of CPU time (**time quantum** *q*), usually 10-100 milliseconds. After this time has elapsed, the process is preempted and added to the end of the ready queue.

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

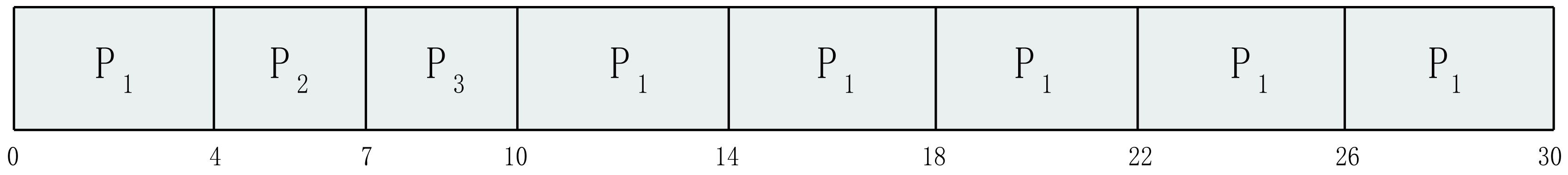
- *q* large $\Rightarrow$ FIFO
- *q* small $\Rightarrow$ *q* must be large with respect to context switch, otherwise overhead is too high



Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

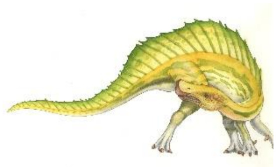
The Gantt chart is:



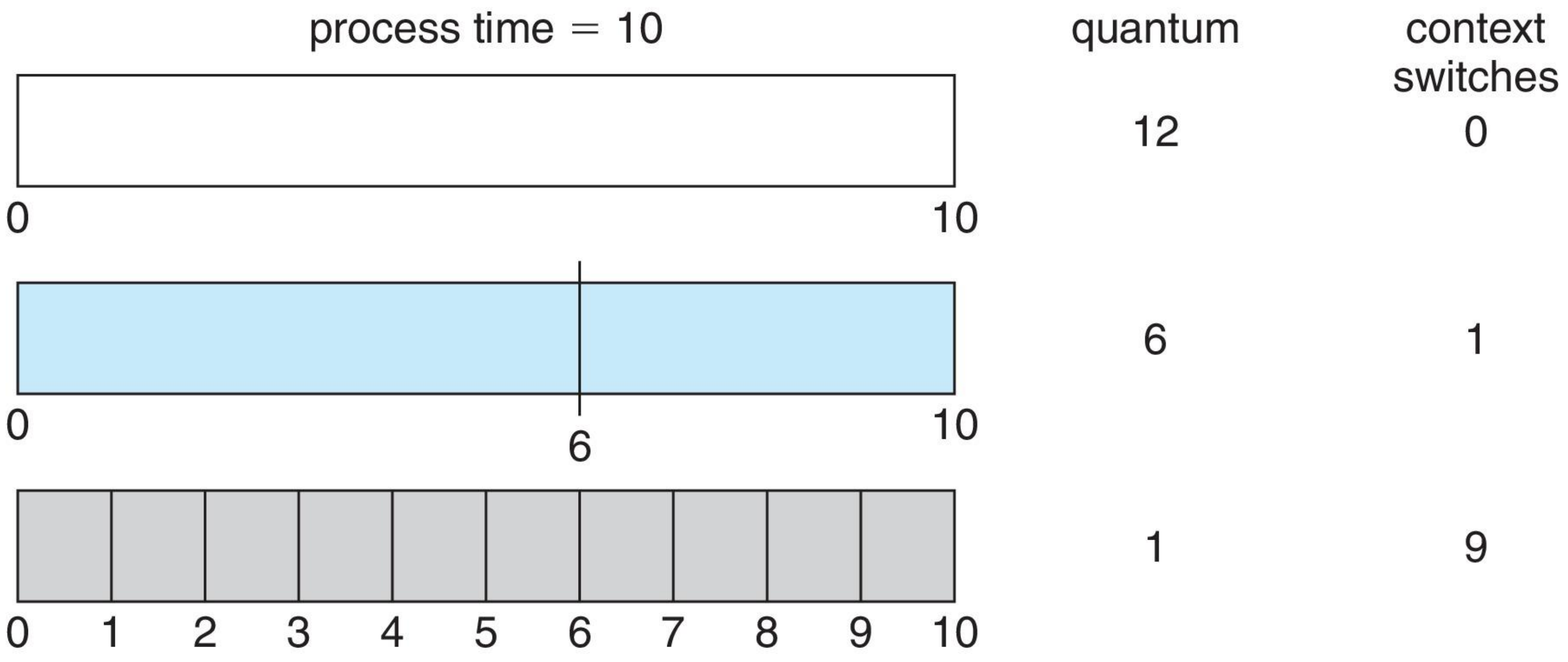
Typically, higher average turnaround than SJF, but better ***response***

q should be large compared to context switch time

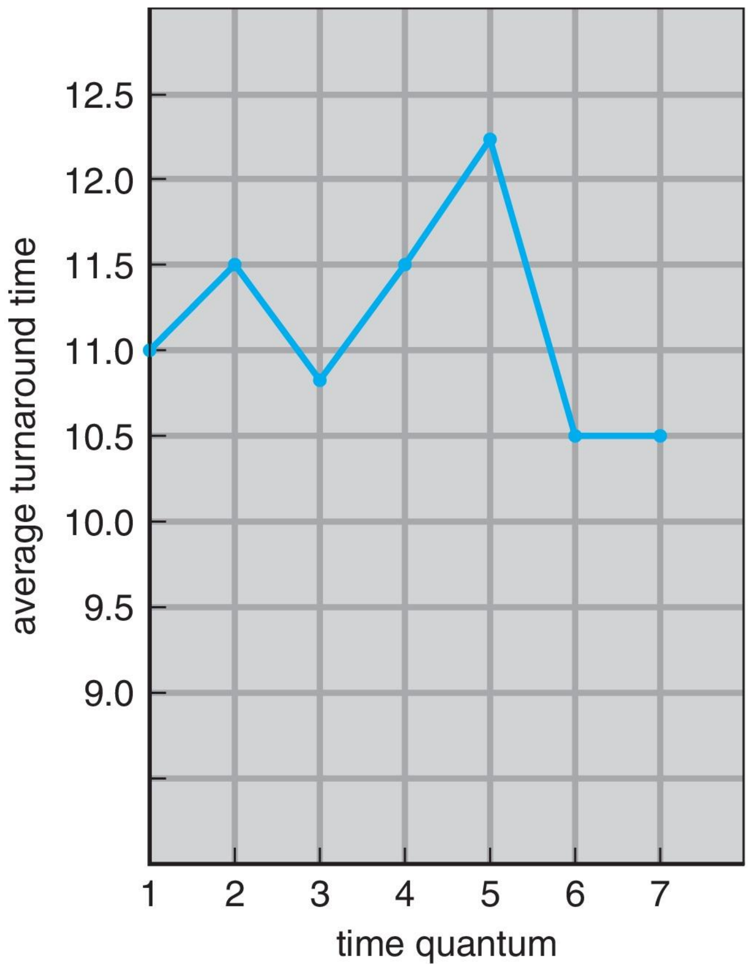
q usually 10ms to 100ms, context switch < 10 usec



Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

80% of CPU bursts should be shorter than q

Priority Scheduling

A priority number (integer) is associated with each process

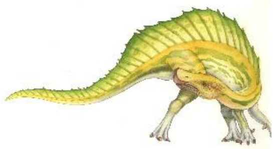
The CPU is allocated to the process with the highest priority (smallest integer ≡ highest priority)

- Preemptive
- Nonpreemptive

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

Problem ≡ **Starvation** – low priority processes may never execute

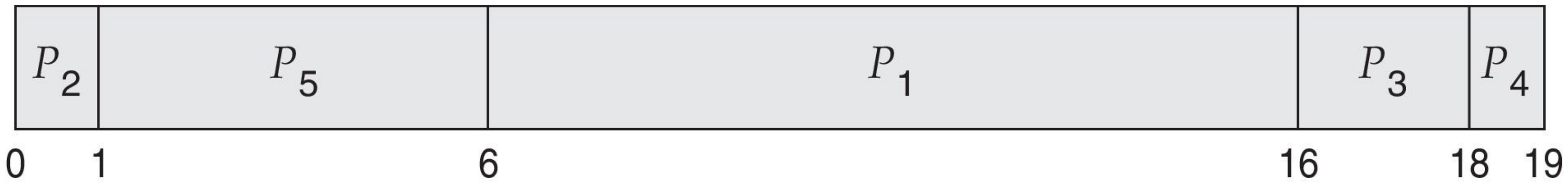
Solution ≡ **Aging** – as time progresses increase the priority of the process



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



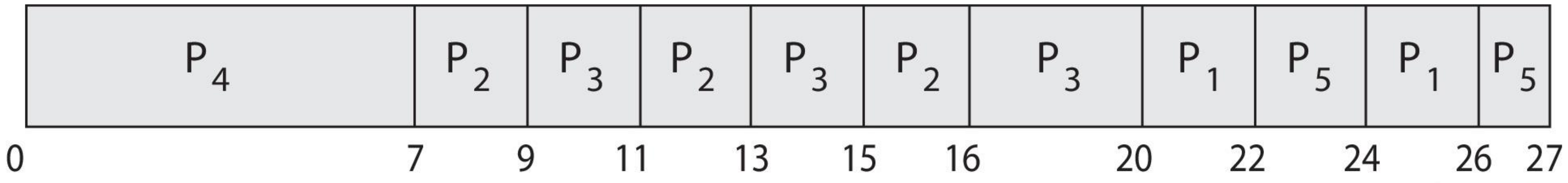
Average waiting time = 8.2 msec

Priority Scheduling w/ Round-Robin

Process	Burst Time	Priority
P_1	4	3
P_2	5	2
P_3	8	2
P_4	7	1
P_5	3	3

- Run the process with the highest priority. Processes with the same priority run round-robin

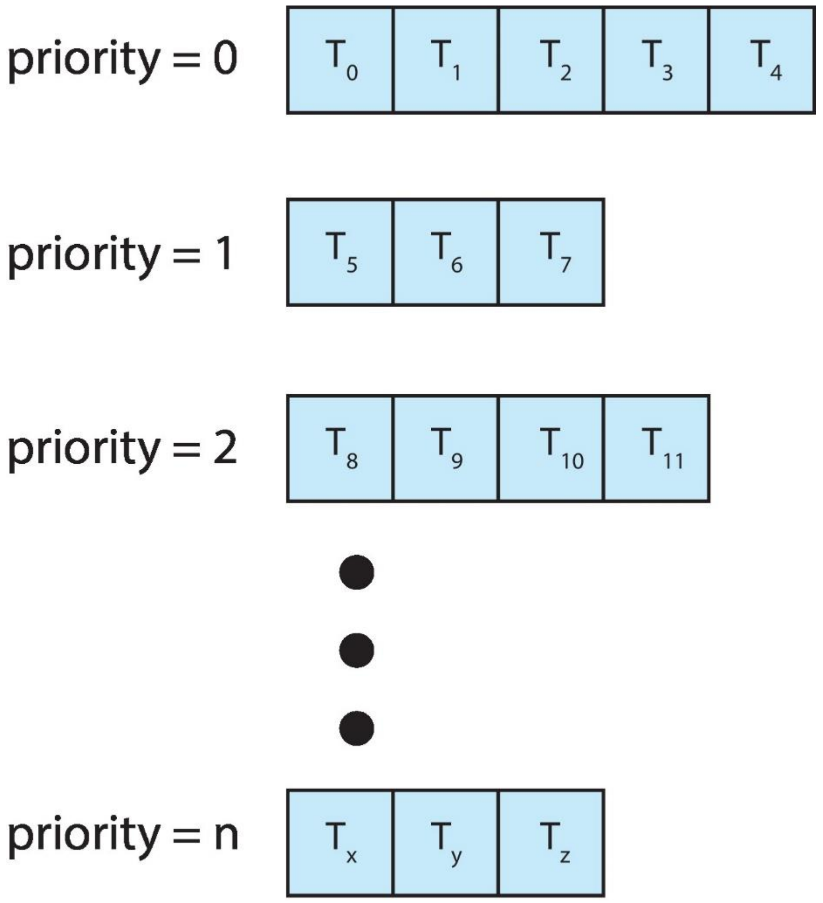
Gantt Chart with 2ms time quantum



Multilevel Queue

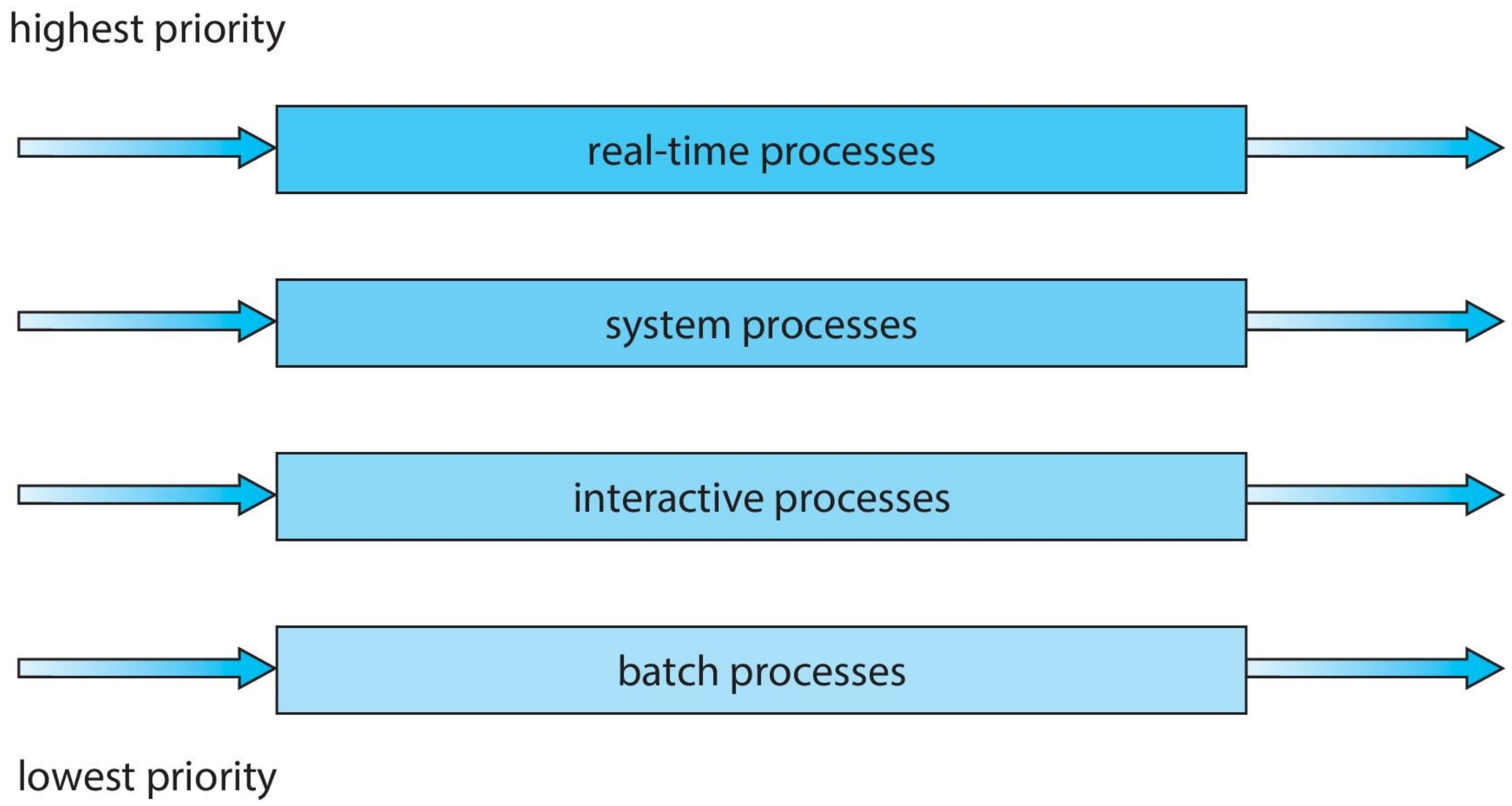
With priority scheduling, have separate queues for each priority.

Schedule the process in the highest-priority queue!



Multilevel Queue

Prioritization based upon process type



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
  - 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

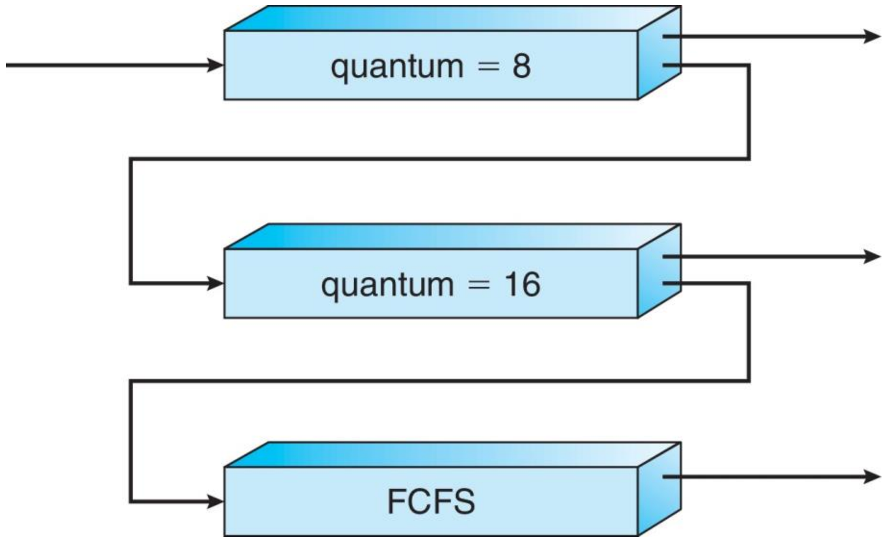
Example of Multilevel Feedback Queue

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

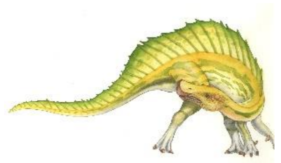
Distinction between user-level and kernel-level threads

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

- 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

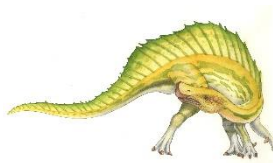


Pthread Scheduling

API allows specifying either PCS or SCS during thread creation

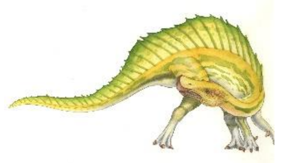
- PTHREAD_SCOPE_PROCESS schedules threads using PCS scheduling
- PTHREAD_SCOPE_SYSTEM schedules threads using SCS scheduling

Can be limited by OS – Linux and macOS 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, scope;
   pthread_t tid[NUM THREADS];
   pthread_attr_t attr;
   /* get the default attributes */
   pthread_attr_init(&attr);
   /* first inquire on the current scope */
   if (pthread_attr_getscope(&attr, &scope) != 0)
      fprintf(stderr, "Unable to get scheduling scope\n");
   else {
      if (scope == PTHREAD_SCOPE_PROCESS)
         printf("PTHREAD_SCOPE_PROCESS");
      else if (scope == PTHREAD_SCOPE_SYSTEM)
         printf("PTHREAD_SCOPE_SYSTEM");
      else
         fprintf(stderr, "Illegal scope value.\n");
   }
```



Pthread Scheduling API

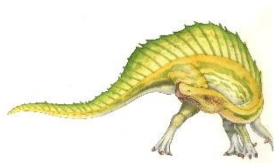
```
   /* set the scheduling algorithm to PCS or SCS */
   pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM);
   /* create the threads */
   for (i = 0; i < NUM_THREADS; i++)
      pthread_create(&tid[i],&attr,runner,NULL);
   /* now join on each thread */
   for (i = 0; i < NUM_THREADS; i++)
      pthread_join(tid[i], NULL);
}
/* Each thread will begin control in this function */
void *runner(void *param)
{
   /* do some work ... */
   pthread_exit(0);
}
```

Multiple-Processor Scheduling

CPU scheduling more complex when multiple CPUs are available

Multiprocess may be any one of the following architectures:

- Multicore CPUs
- Multithreaded cores
- NUMA systems
- Heterogeneous multiprocessing

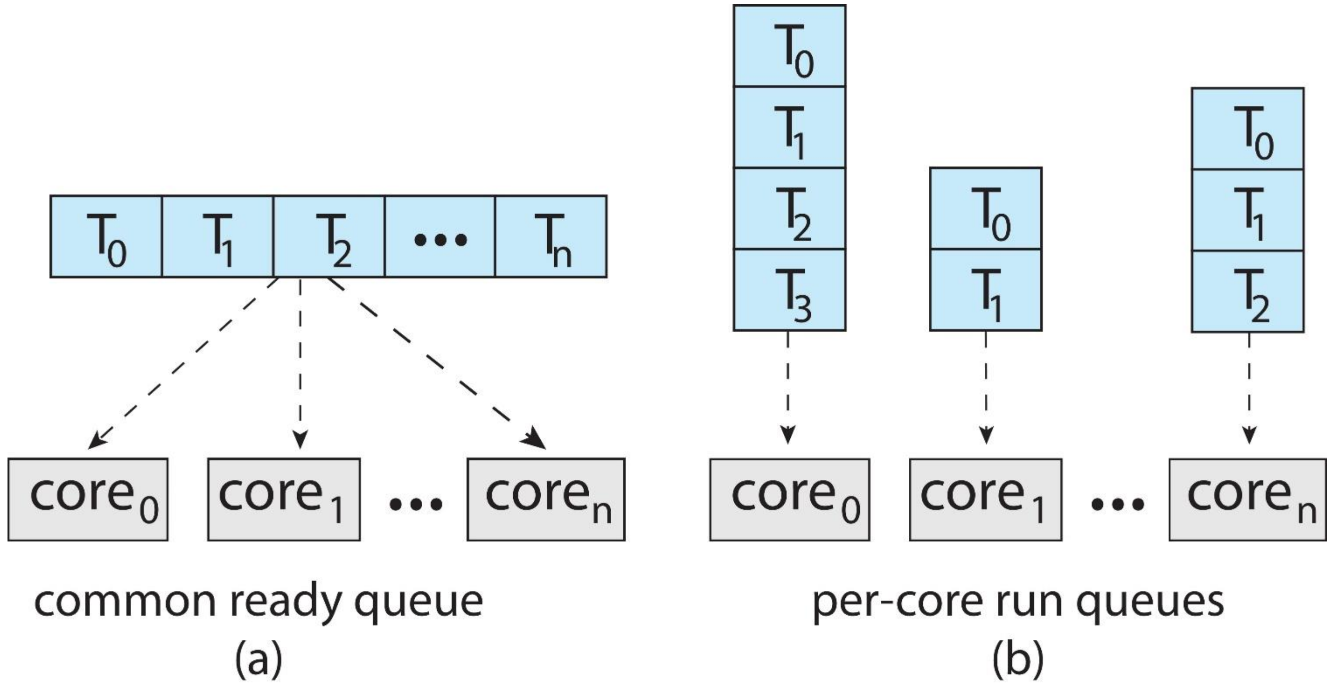


Multiple-Processor Scheduling

Symmetric multiprocessing (SMP) is where each processor is self scheduling.

All threads may be in a common ready queue (a)

Each processor may have its own private queue of threads (b)



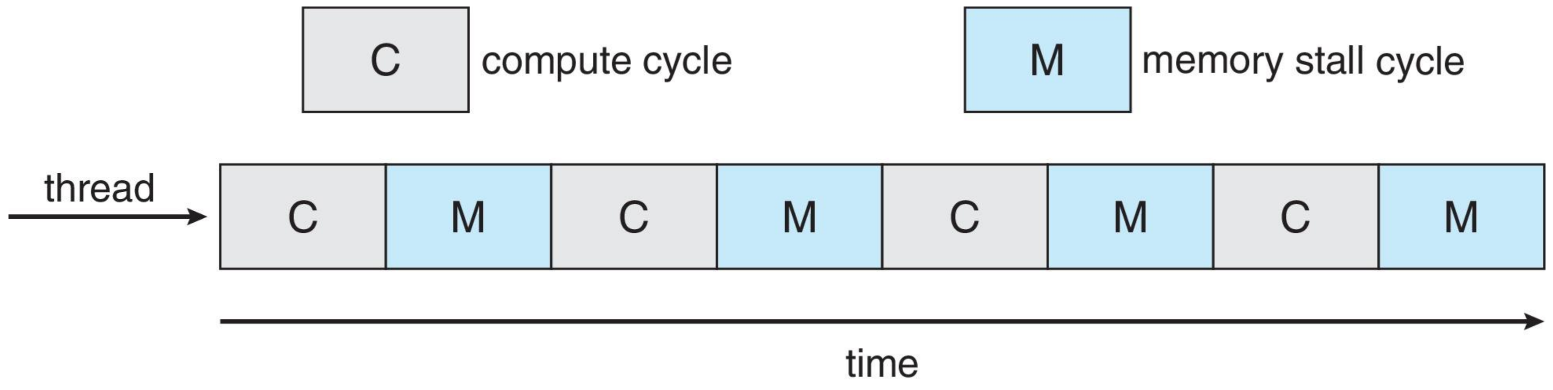
Multicore Processors

Recent trend to place multiple processor cores on same physical chip

Faster and consumes less power

Multiple threads per core also growing

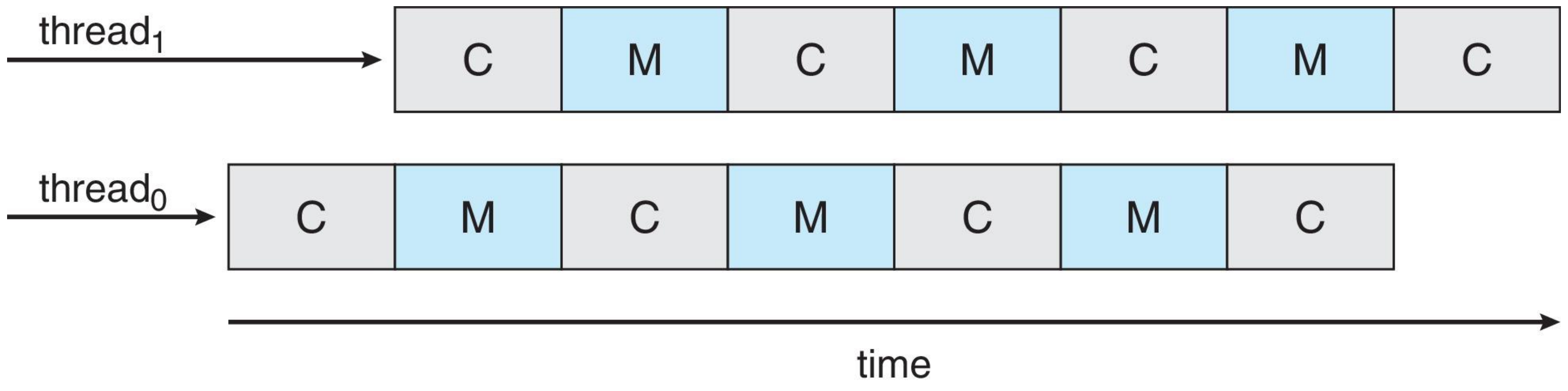
- Takes advantage of memory stall to make progress on another thread while memory retrieve happens



Multithreaded Multicore System

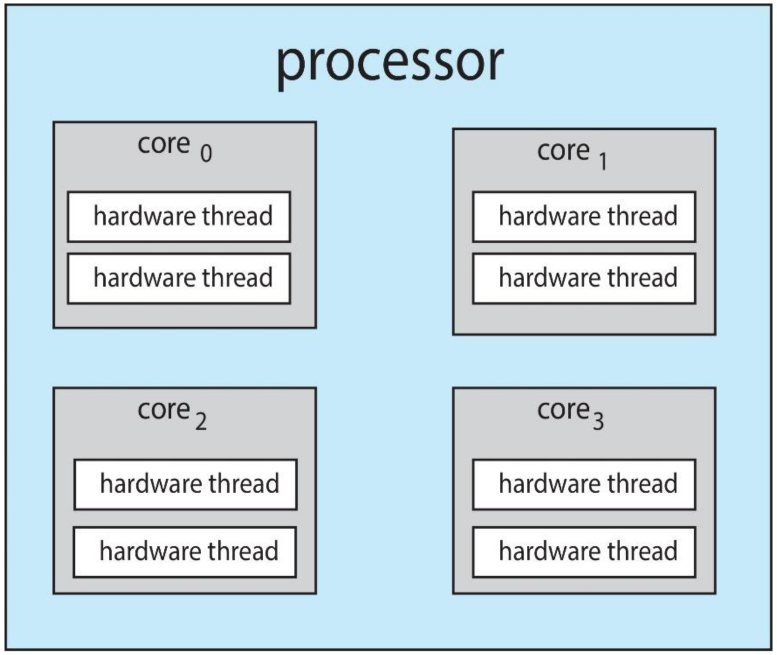
Each core has > 1 hardware threads.

If one thread has a memory stall, switch to another thread!

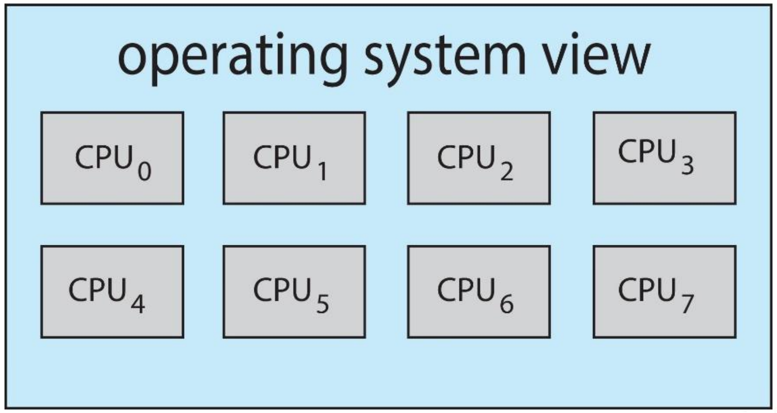


Multithreaded Multicore System

Chip-multithreading (CMT) assigns each core multiple hardware threads. (Intel refers to this as **hyperthreading**.)



On a quad-core system with 2 hardware threads per core, the operating system sees 8 logical processors.

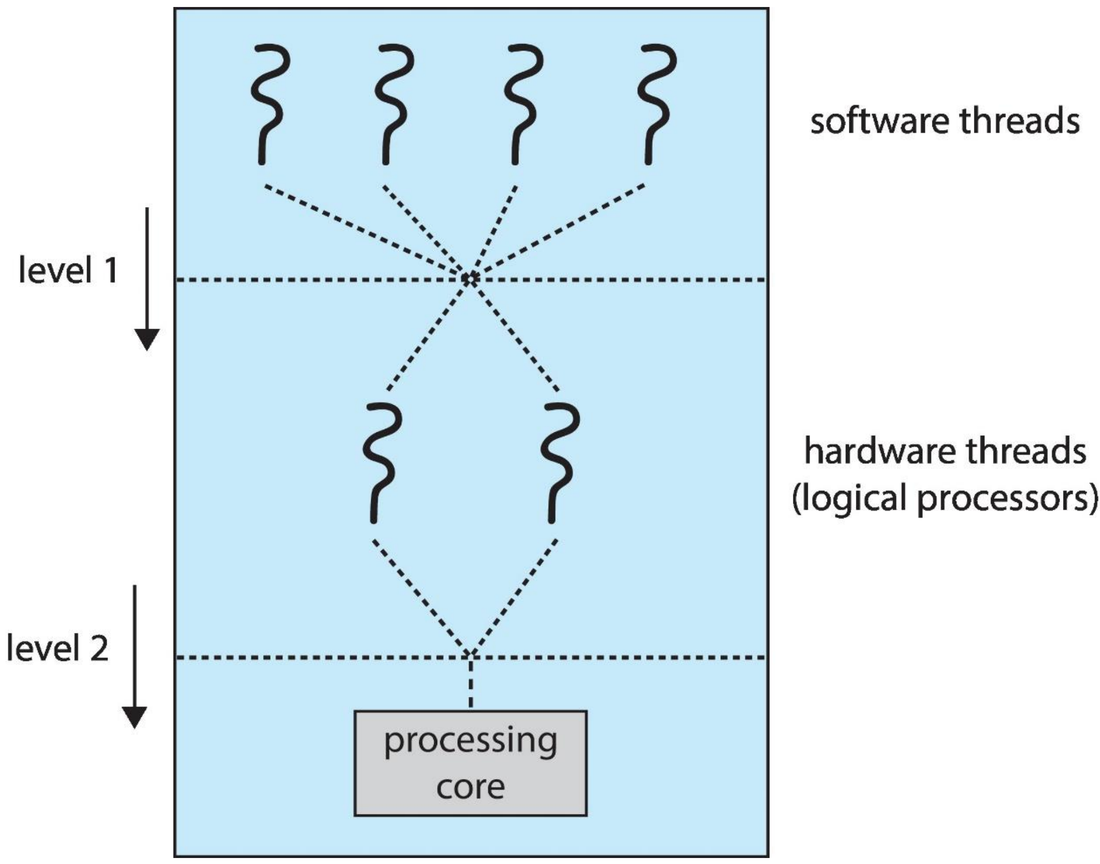


Multithreaded Multicore System

Two levels of scheduling:

1. The operating system deciding which software thread to run on a logical CPU

2. How each core decides which hardware thread to run on the physical core.



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

Multiple-Processor Scheduling – Processor Affinity

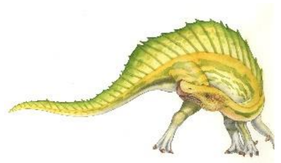
When a thread has been running on one processor, the cache contents of that processor stores the memory accesses by that thread.

We refer to this as a thread having affinity for a processor (i.e. “processor affinity”)

Load balancing may affect processor affinity as a thread may be moved from one processor to another to balance loads, yet that thread loses the contents of what it had in the cache of the processor it was moved off of.

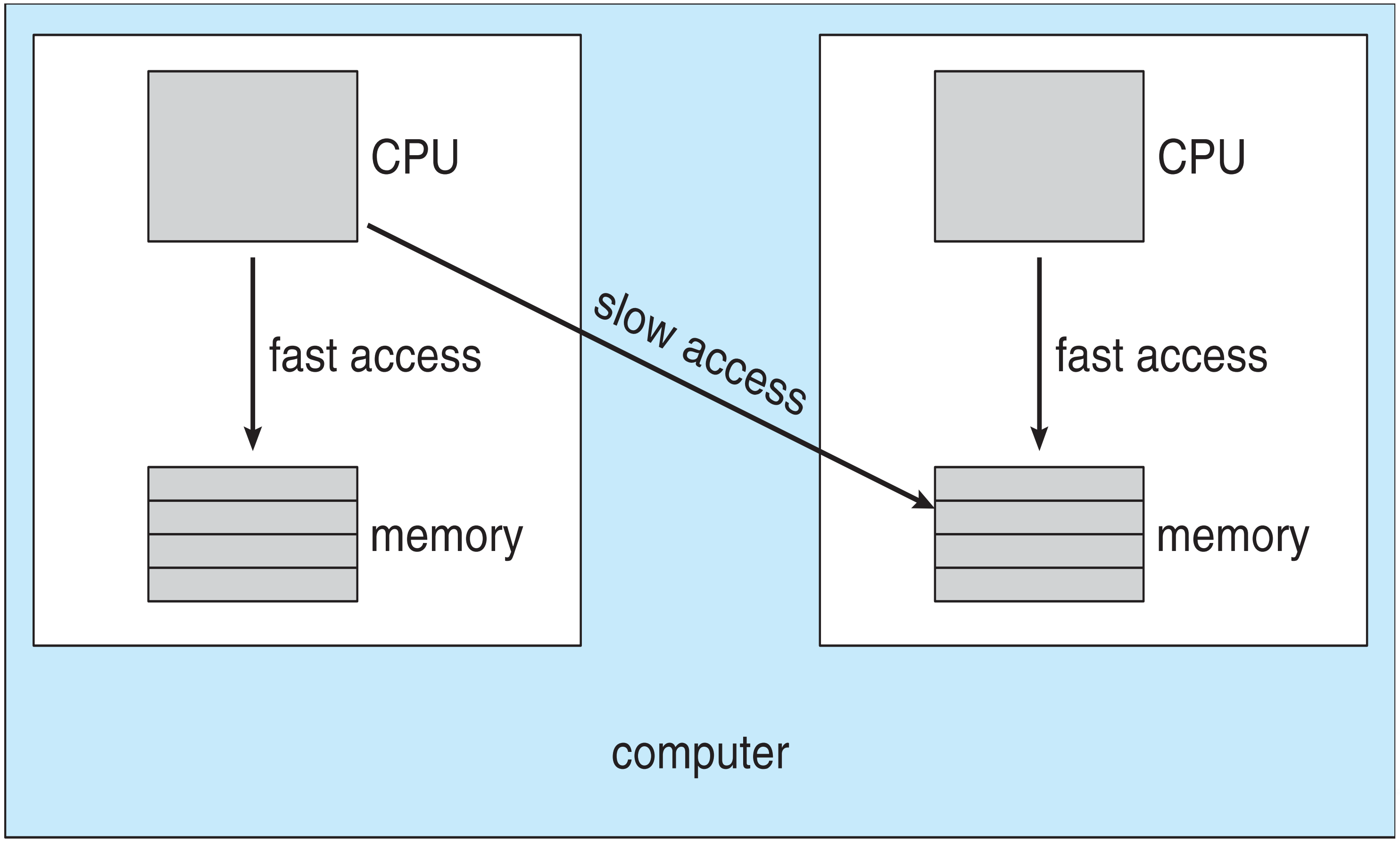
Soft affinity – the operating system attempts to keep a thread running on the same processor, but no guarantees.

Hard affinity – allows a process to specify a set of processors it may run on.



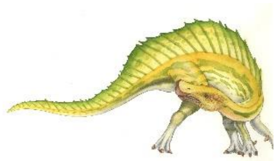
NUMA and CPU Scheduling

If the operating system is **NUMA-aware**, it will assign memory closes to the CPU the thread is running on.



Real-Time CPU Scheduling

- Can present obvious challenges
- **Soft real-time systems** – Critical real-time tasks have the highest priority, but no guarantee as to when tasks will be scheduled
- **Hard real-time systems** – task must be serviced by its deadline

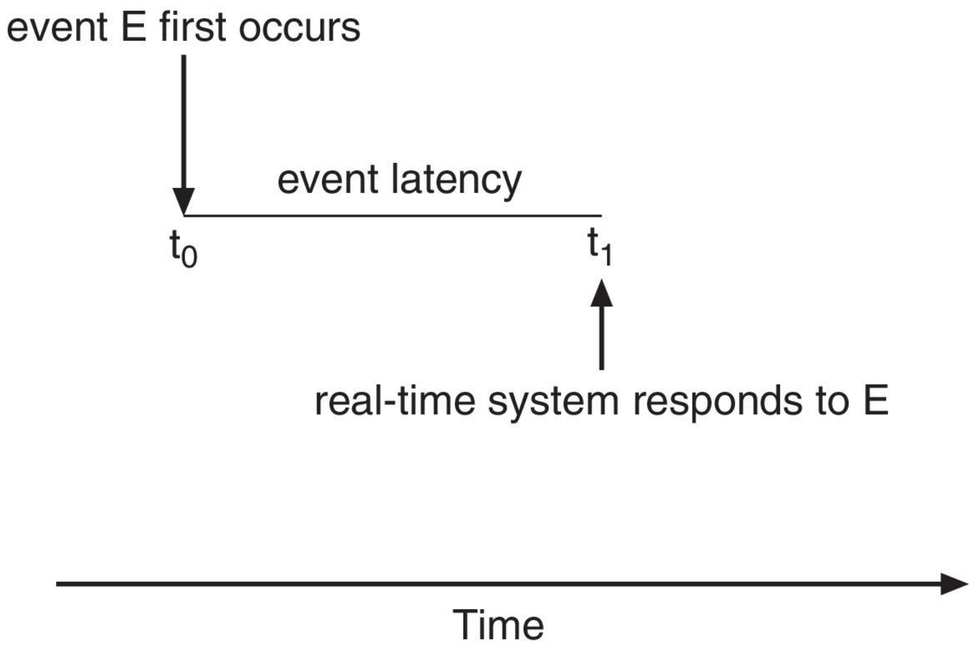


Real-Time CPU Scheduling

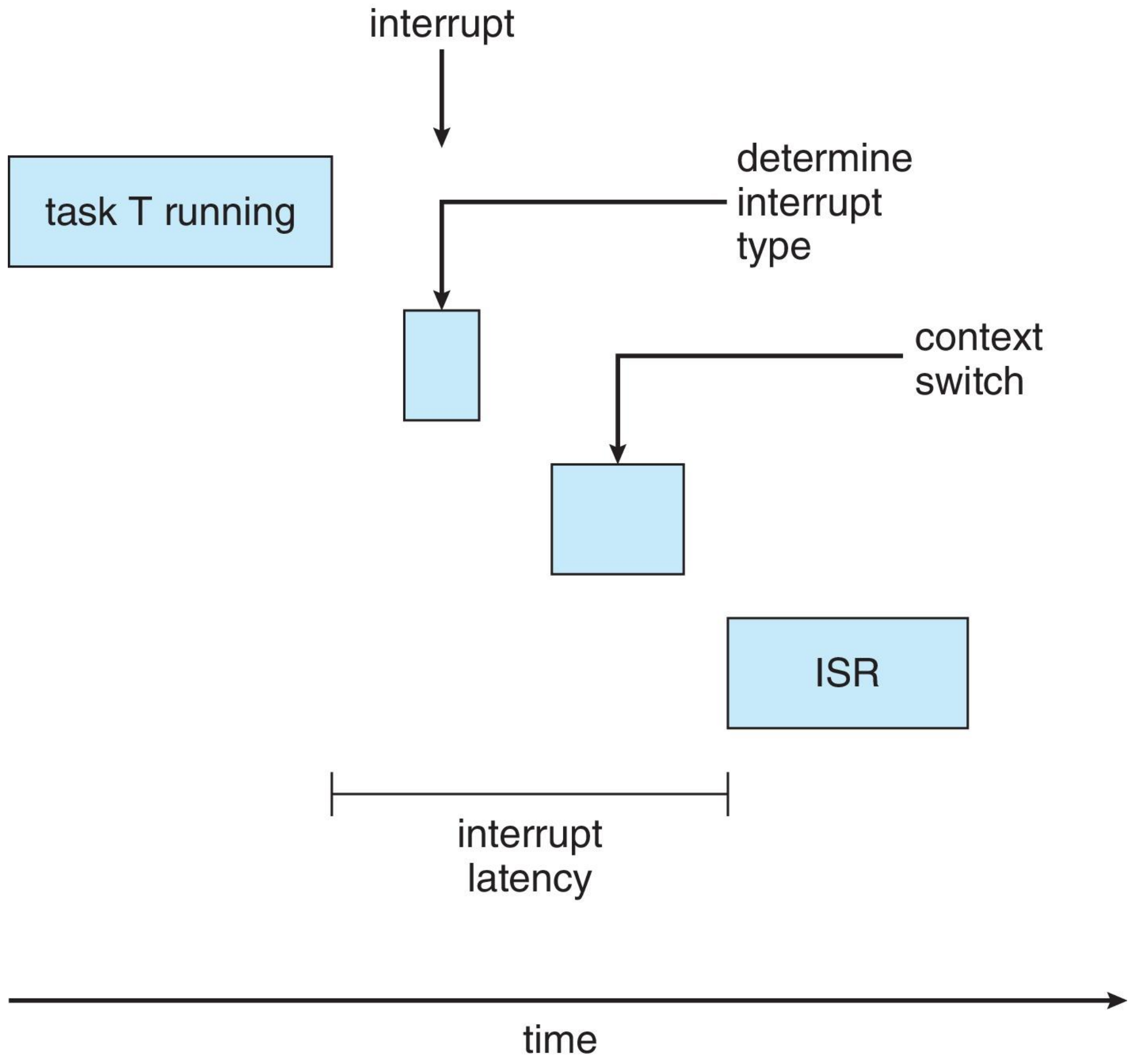
Event latency – the amount of time that elapses from when an event occurs to when it is serviced.

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



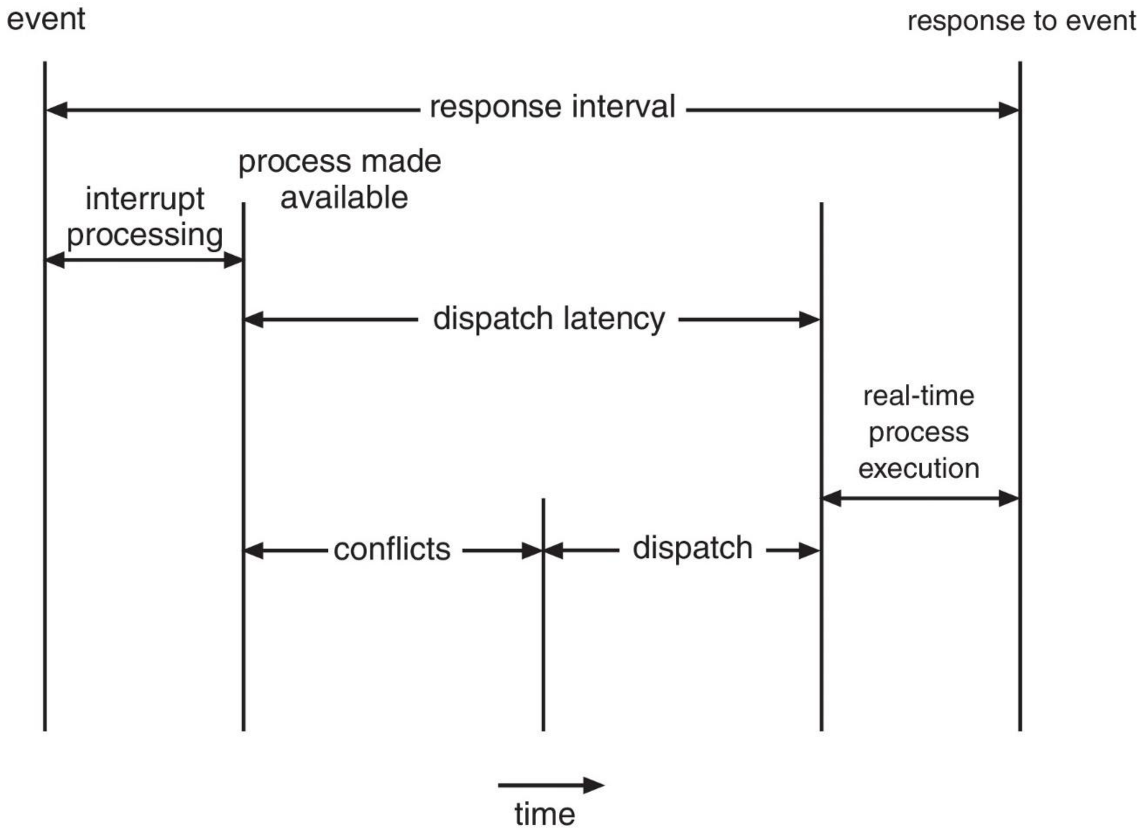
Interrupt Latency



Dispatch Latency

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



Priority-based Scheduling

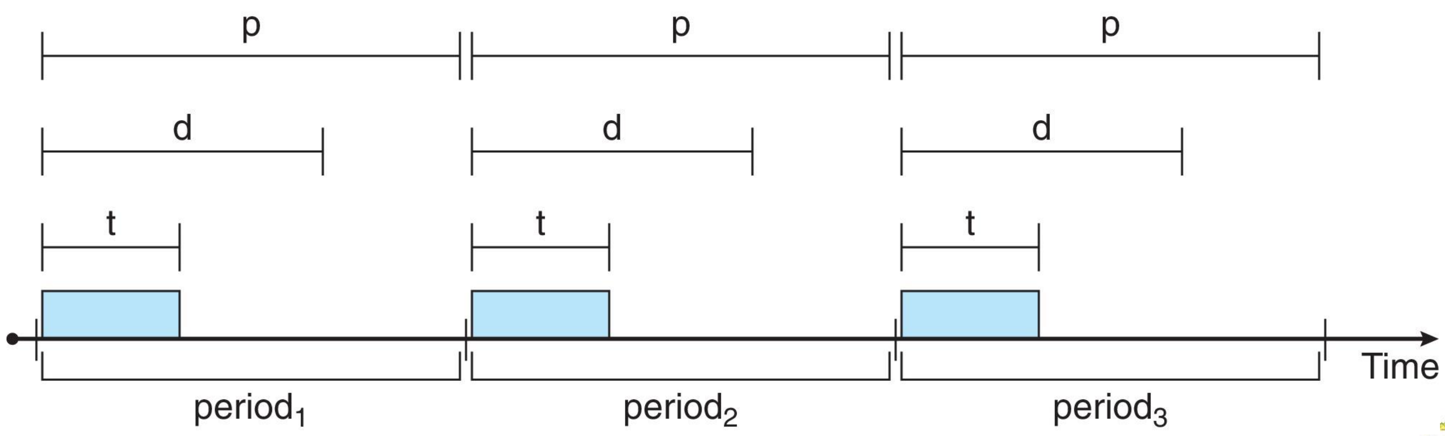
For real-time scheduling, scheduler must support preemptive, priority-based scheduling

- 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*



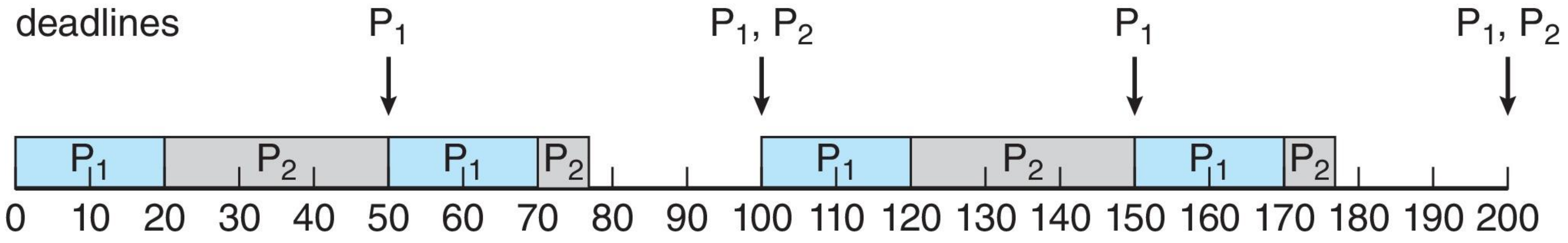
Rate Montonic Scheduling

A priority is assigned based on the inverse of its period

Shorter periods = higher priority;

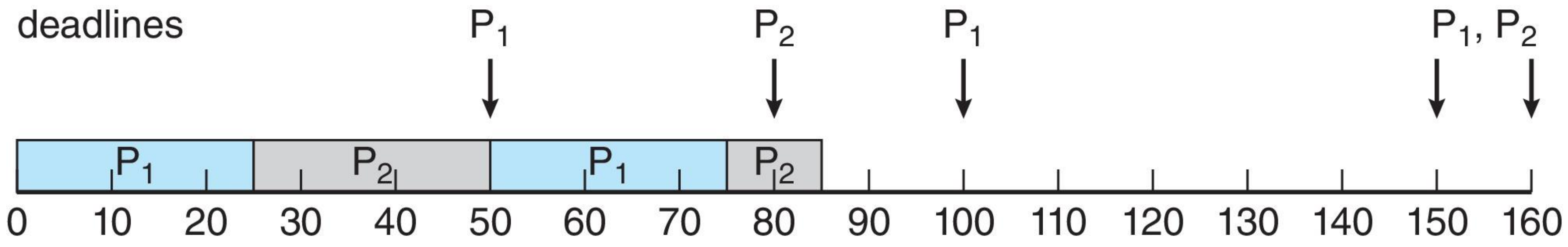
Longer periods = lower priority

P_1 is assigned a higher priority than P_2.



Missed Deadlines with Rate Monotonic Scheduling

Process P2 misses finishing its deadline at time 80

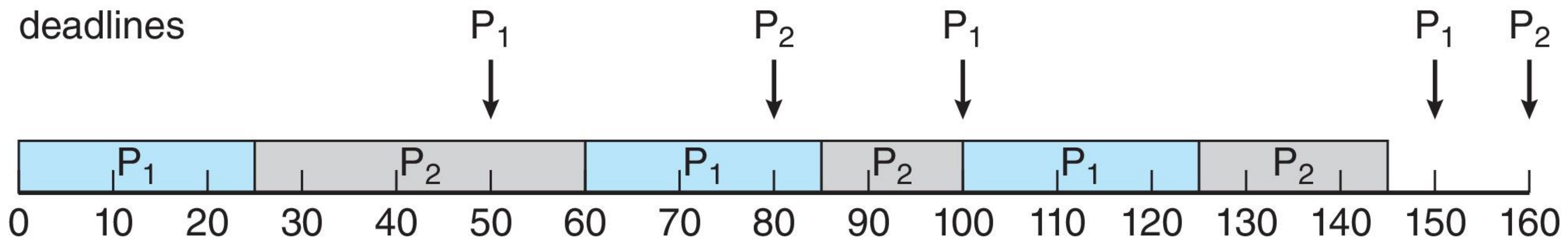


Earliest Deadline First Scheduling (EDF)

Priorities are assigned according to deadlines:

the earlier the deadline, the higher the priority;

the later the deadline, the lower the priority

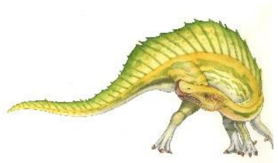


Proportional Share Scheduling

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



POSIX Real-Time Scheduling

The POSIX.1b standard

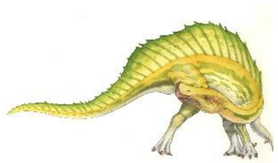
API provides functions for managing real-time threads

Defines two scheduling classes for real-time threads:

1. SCHED_FIFO - threads are scheduled using a FCFS strategy with a FIFO queue. There is no time-slicing for threads of equal priority
2. SCHED_RR - similar to SCHED_FIFO except time-slicing occurs for threads of equal priority

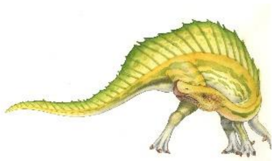
Defines two functions for getting and setting scheduling policy:

1. **`pthread_attr_getsched_policy(pthread_attr_t *attr, int *policy)`**
2. **`pthread_attr_setsched_policy(pthread_attr_t *attr, int policy)`**



POSIX Real-Time Scheduling API

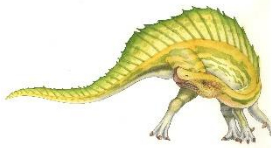
```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5
int main(int argc, char *argv[])
{
   int i, policy;
   pthread_t_tid[NUM_THREADS];
   pthread_attr_t attr;
   /* get the default attributes */
   pthread_attr_init(&attr);
   /* get the current scheduling policy */
   if (pthread_attr_getschedpolicy(&attr, &policy) != 0)
      fprintf(stderr, "Unable to get policy.\n");
   else {
      if (policy == SCHED_OTHER) printf("SCHED_OTHER\n");
      else if (policy == SCHED_RR) printf("SCHED_RR\n");
      else if (policy == SCHED_FIFO) printf("SCHED_FIFO\n");
   }
```



POSIX Real-Time Scheduling API (Cont.)

```
   /* set the scheduling policy - FIFO, RR, or OTHER */
   if (pthread_attr_setschedpolicy(&attr, SCHED_FIFO) != 0)
      fprintf(stderr, "Unable to set policy.\n");
   /* 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);
}

/* Each thread will begin control in this function */
void *runner(void *param)
{
   /* do some work ... */
   pthread_exit(0);
}
```

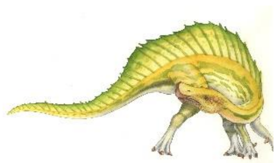


Operating System Examples

Linux scheduling

Windows scheduling

Solaris scheduling



Linux Scheduling Through Version 2.5

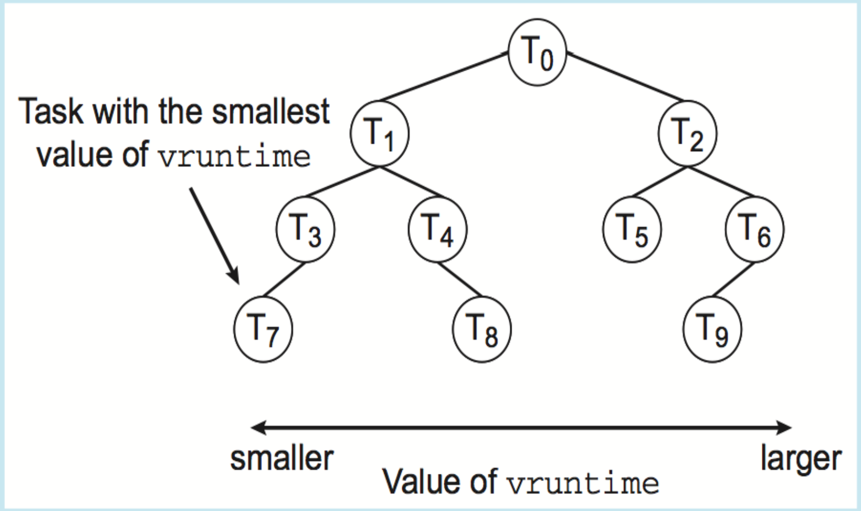
- Prior to kernel version 2.5, ran variation of standard UNIX scheduling algorithm
- Version 2.5 moved to constant order *O*(1) scheduling time
  - Preemptive, priority based
  - Two priority ranges: time-sharing and real-time
  - **Real-time** range from 0 to 99 and **nice** value from 100 to 140
  - Map into global priority with numerically lower values indicating higher priority
  - Higher priority gets larger q
  - Task run-able as long as time left in time slice (**active**)
  - If no time left (**expired**), not run-able until all other tasks use their slices
  - All run-able tasks tracked in per-CPU **runqueue** data structure
    - Two priority arrays (active, expired)
    - Tasks indexed by priority
    - When no more active, arrays are exchanged
  - Worked well, but poor response times for interactive processes

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

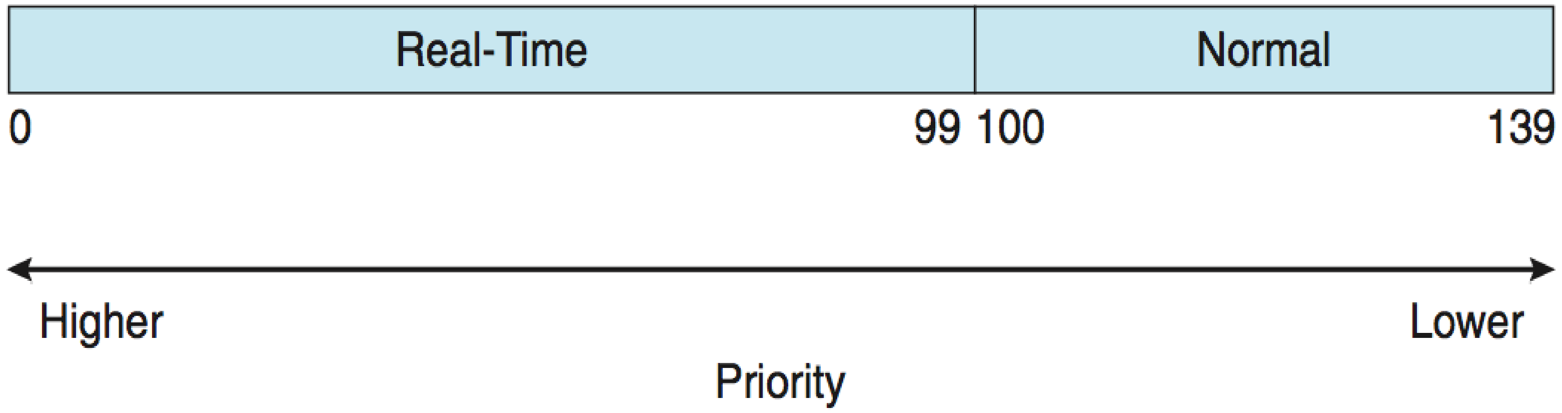
The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Each runnable task is placed in a red-black tree—a balanced binary search tree whose key is based on the value of `vruntime`. This tree is shown below:



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

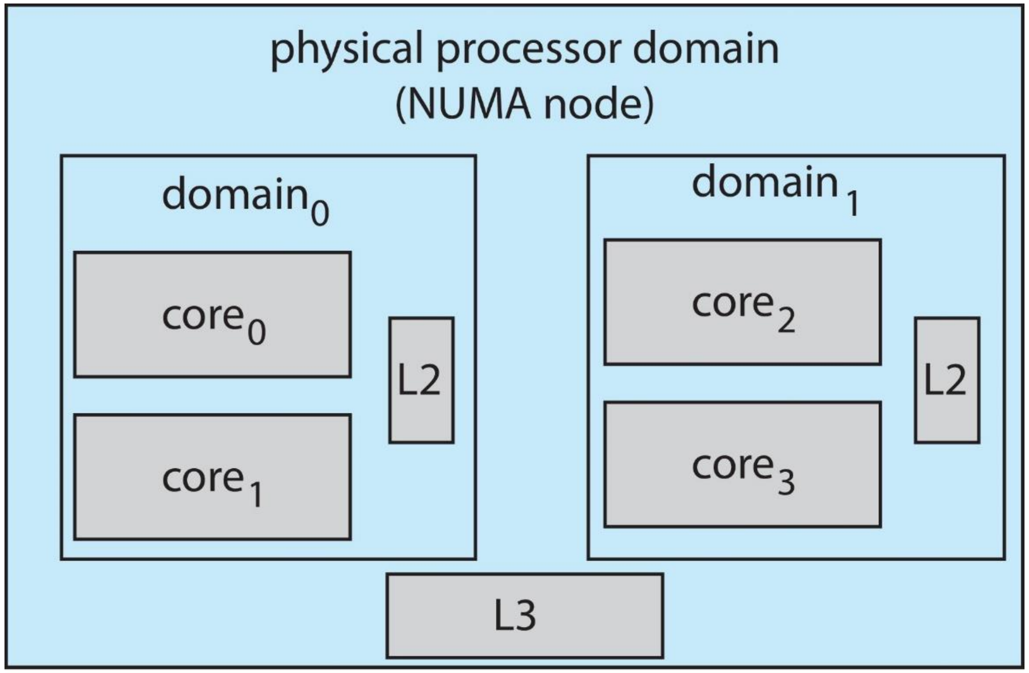


Linux Scheduling (Cont.)

Linux supports load balancing, but is also NUMA-aware.

Scheduling domain is a set of CPU cores that can be balanced against one another.

Domains are organized by what they share (i.e. cache memory.) Goal is to keep threads from migrating between domains.



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

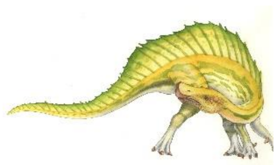
32-level priority scheme

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**

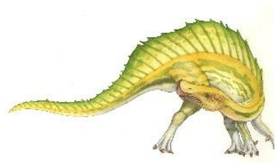


Windows Priority Classes

- Win32 API identifies several priority classes to which a process can belong
  - REALTIME_PRIORITY_CLASS, HIGH_PRIORITY_CLASS, ABOVE_NORMAL_PRIORITY_CLASS,NORMAL_PRIORITY_CLASS, BELOW_NORMAL_PRIORITY_CLASS, IDLE_PRIORITY_CLASS
  - All are variable except REALTIME
- A thread within a given priority class has a relative priority
  - TIME_CRITICAL, HIGHEST, ABOVE_NORMAL, NORMAL, BELOW_NORMAL, LOWEST, IDLE
- Priority class and relative priority combine to give numeric priority
- Base priority is NORMAL within the class
- If quantum expires, priority lowered, but never below base

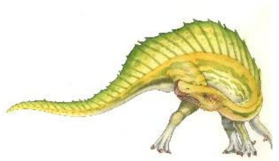
Windows Priority Classes (Cont.)

- If wait occurs, priority boosted depending on what was waited for
- Foreground window given 3x priority boost
- Windows 7 added **user-mode scheduling** (**UMS**)
  - Applications create and manage threads independent of kernel
  - For large number of threads, much more efficient
  - UMS schedulers come from programming language libraries like C++ **Concurrent Runtime** (ConcRT) framework



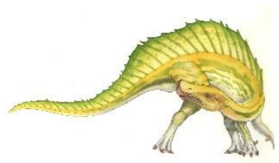
Windows Priorities

	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



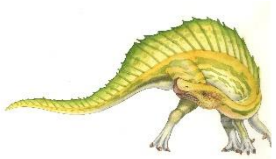
Solaris

- 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

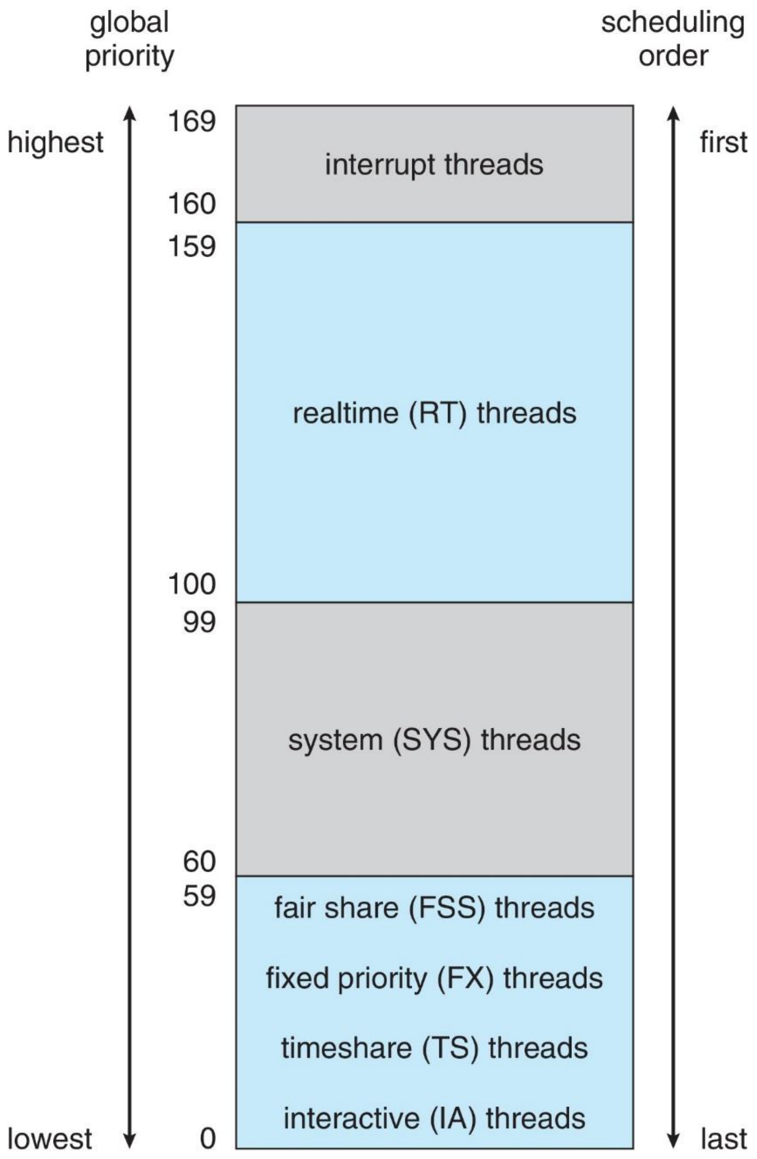


Solaris Dispatch Table

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

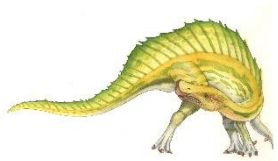


Solaris Scheduling



Solaris Scheduling (Cont.)

- Scheduler converts class-specific priorities into a per-thread global priority
  - Thread with highest priority runs next
  - Runs until (1) blocks, (2) uses time slice, (3) preempted by higher-priority thread
  - Multiple threads at same priority selected via RR



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:

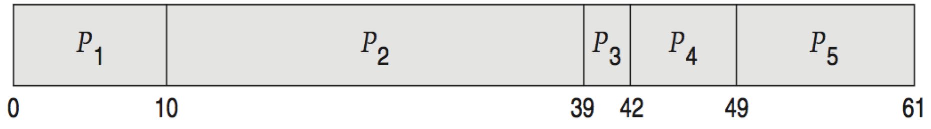
Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

Deterministic Evaluation

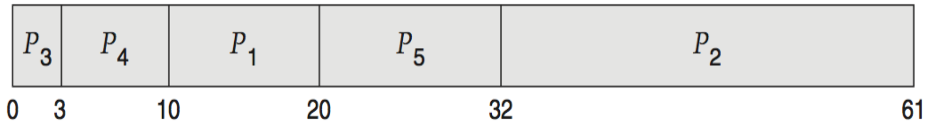
For each algorithm, calculate minimum average waiting time

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

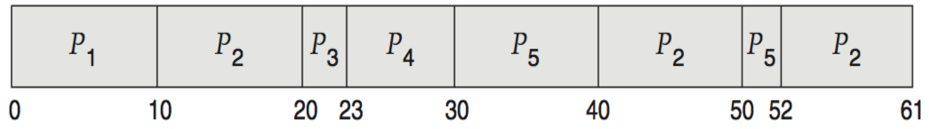
FCS is 28ms:



Non-preemptive SFJ is 13ms:



RR is 23ms:



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:

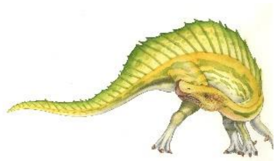
$$n = \lambda \times W$$

Valid for any scheduling algorithm and arrival distribution

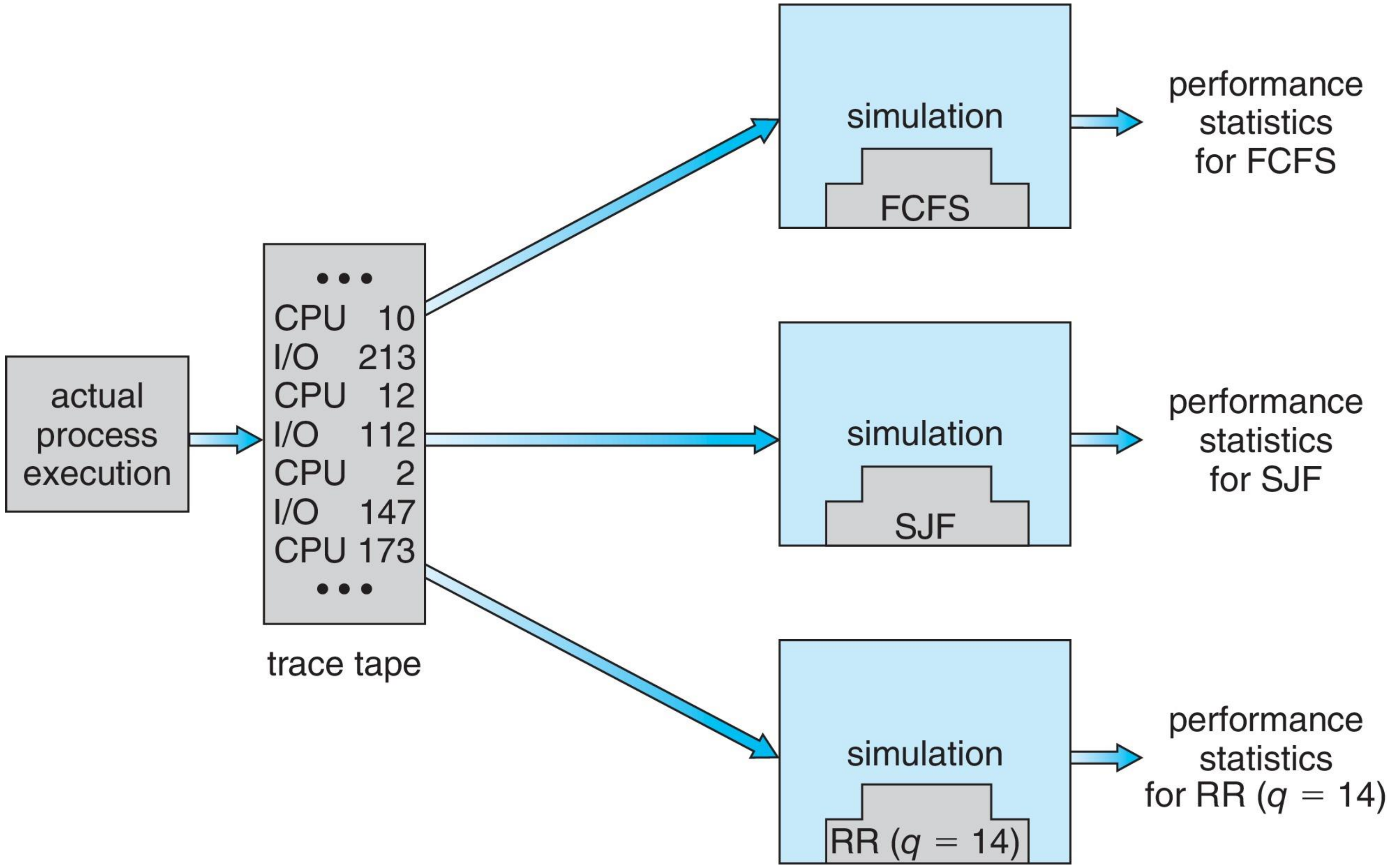
For example, if on average 7 processes arrive per second, and normally 14 processes in queue, then average wait time per process = 2 seconds

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



Evaluation of CPU Schedulers by Simulation



Implementation

Even simulations have limited accuracy

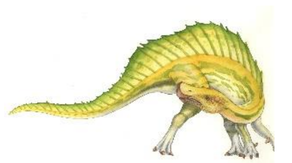
Just implement new scheduler and test in real systems

- 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



End of Chapter 5