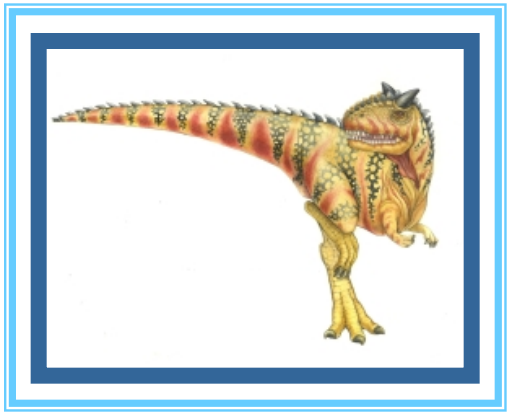
Chapter 6: CPU Scheduling



Chapter 6: CPU Scheduling

- Thread Scheduling
- Multiple-Processor Scheduling
- Operating Systems Examples
- Evaluation Algorithms

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 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, 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");
   }
```

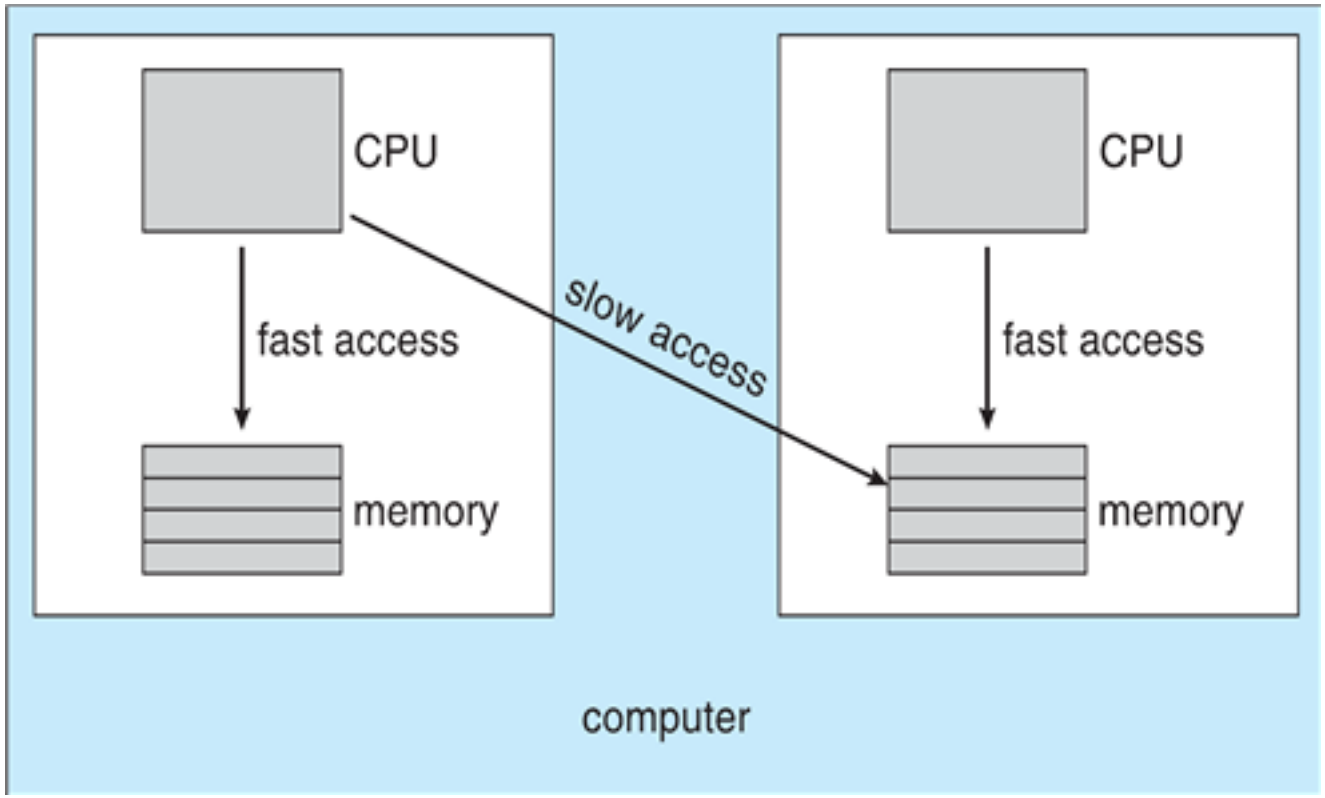
Pthread Scheduling API

```
   /* 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
- **Homogeneous processors** within a multiprocessor system
- **Asymmetric multiprocessing** – only one processor accesses the system data structures
- **Symmetric multiprocessing (SMP)** – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
  - Currently, most common
- **Processor affinity** – process has affinity for processor on which it is currently running
  - **soft affinity**
  - **hard affinity**

NUMA and CPU Scheduling



Note that memory-placement algorithms can also consider affinity

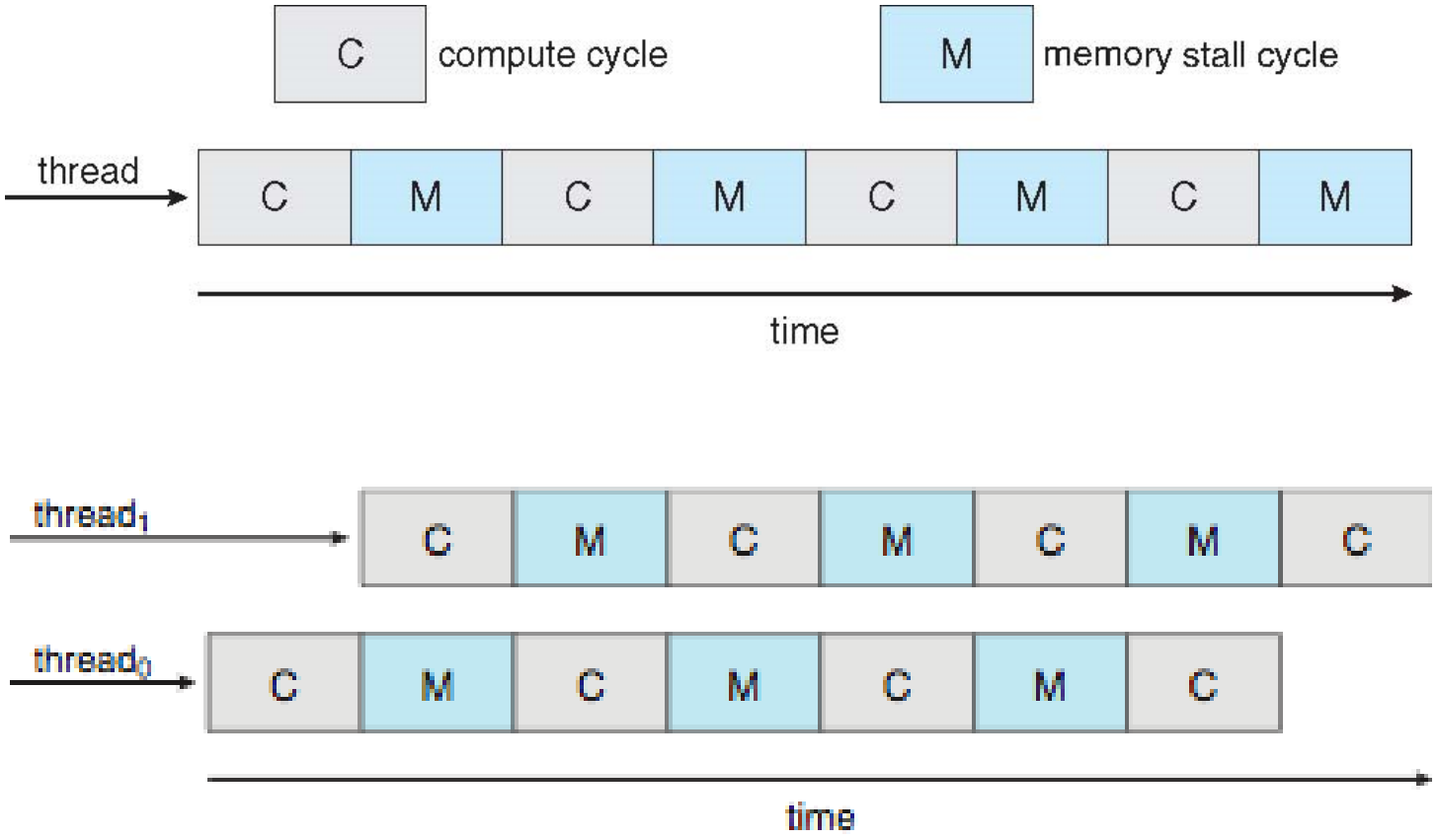
Multiple-Processor Scheduling – Load Balancing

- If SMP, need to keep all CPUs loaded for efficiency
- **Load balancing** attempts to keep workload evenly distributed
- Two general approaches:
  - **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

Multicore Processors

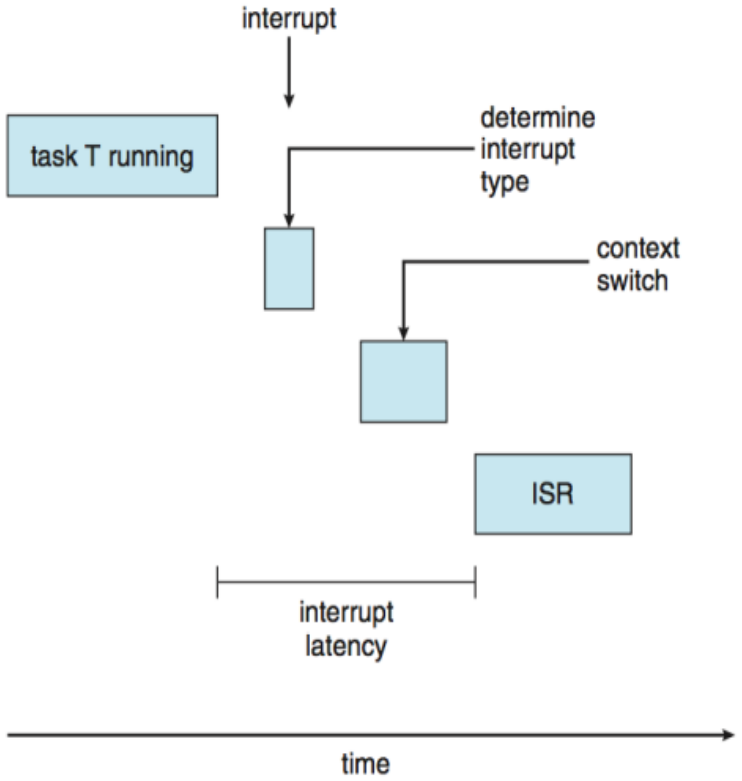
- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

Multithreaded Multicore System



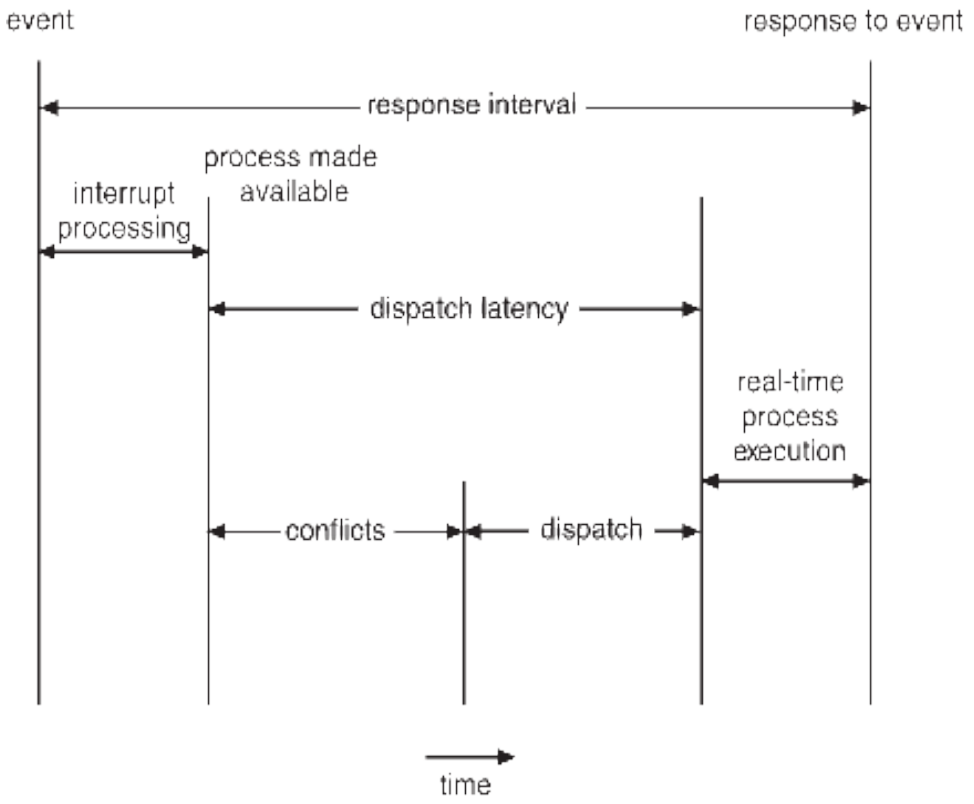
Real-Time CPU Scheduling

- Can present obvious challenges
- **Soft real-time systems** – no guarantee as to when critical real-time process will be scheduled
- **Hard real-time systems** – task must be serviced by its deadline
- 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



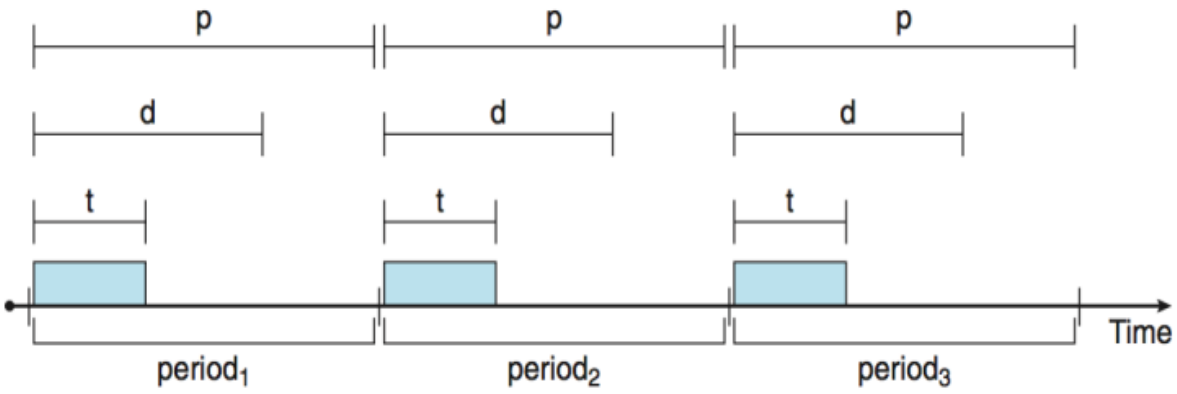
Real-Time CPU Scheduling (Cont.)

- 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



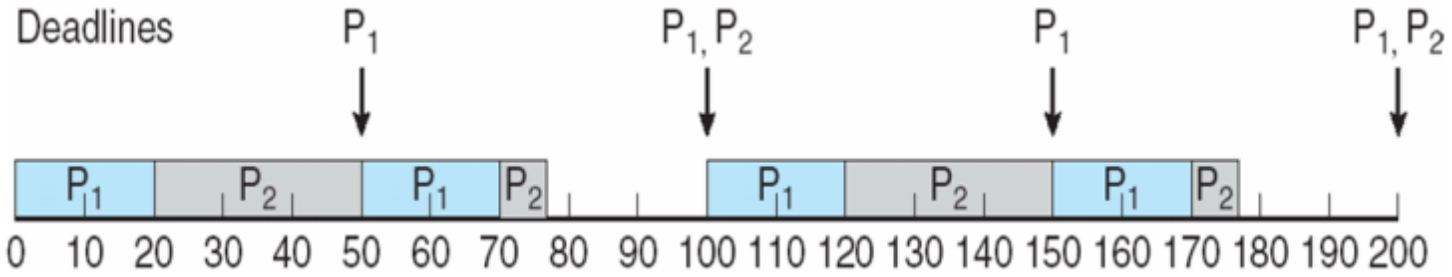
Priority-based Scheduling

- 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*
  - $0 \le t \le d \le p$
  - **Rate** of periodic task is $1/p$

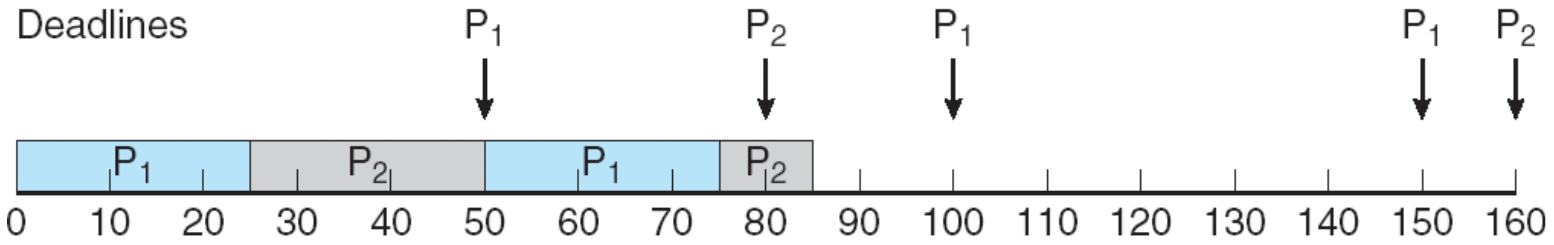


Rate Montonic Scheduling

- 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

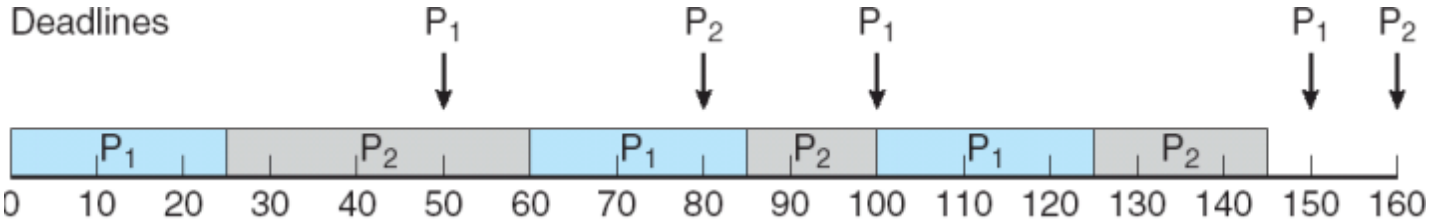


Earliest Deadline First Scheduling (EDF)

- Priorities are assigned according to deadlines:

  the earlier the deadline, the higher the priority;

  the later the deadline, the lower the priority



Virtualization and Scheduling

- Virtualization software schedules multiple guests onto CPU(s)
- Each guest doing its own scheduling
  - Not knowing it doesn't own the CPUs
  - Can result in poor response time
  - Can effect time-of-day clocks in guests
- Can undo good scheduling algorithm efforts of guests

Operating System Examples

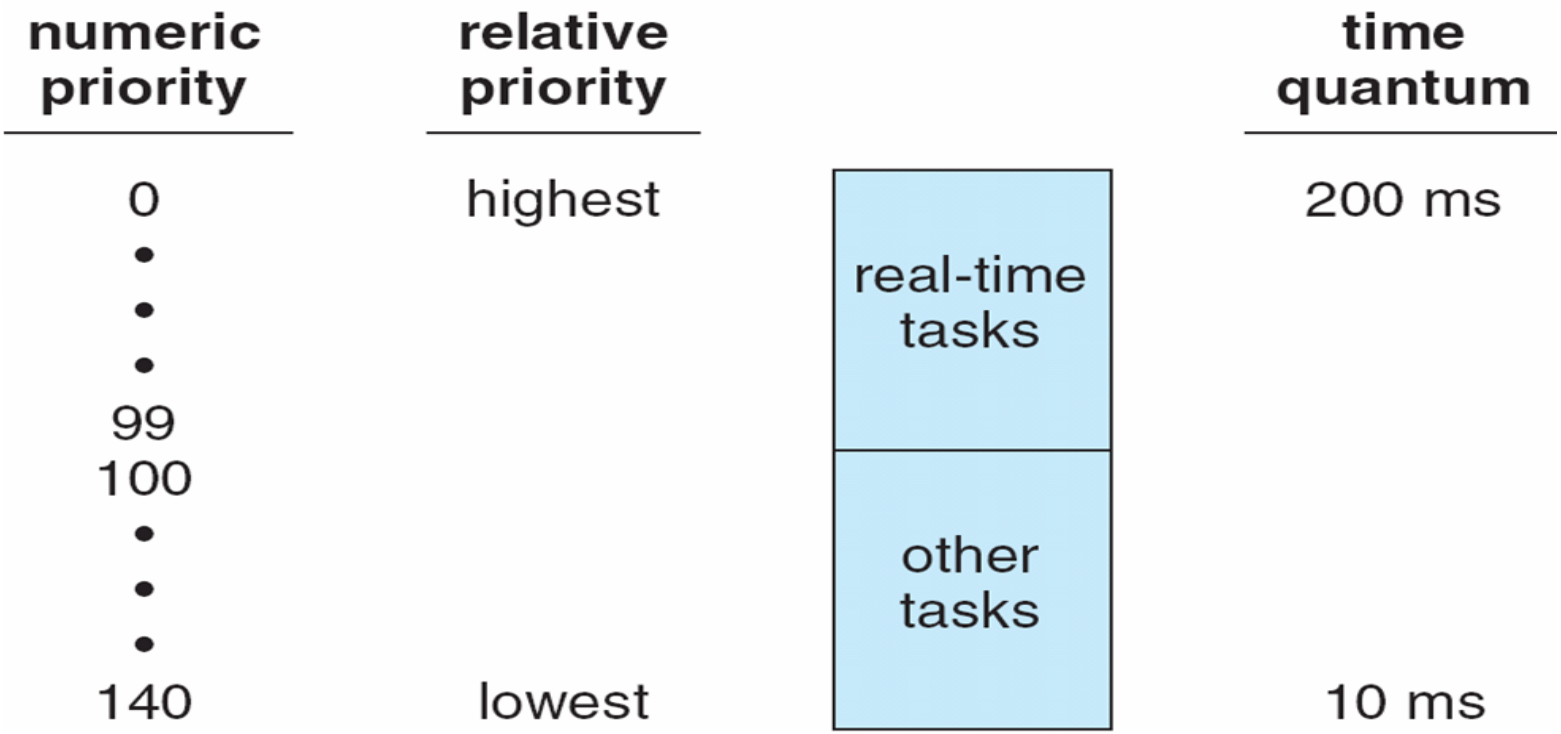
- Linux scheduling
- Windows scheduling
- Solaris scheduling

Linux Scheduling

- 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

Linux Scheduling (Cont.)

- Priority and time-slice length



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 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

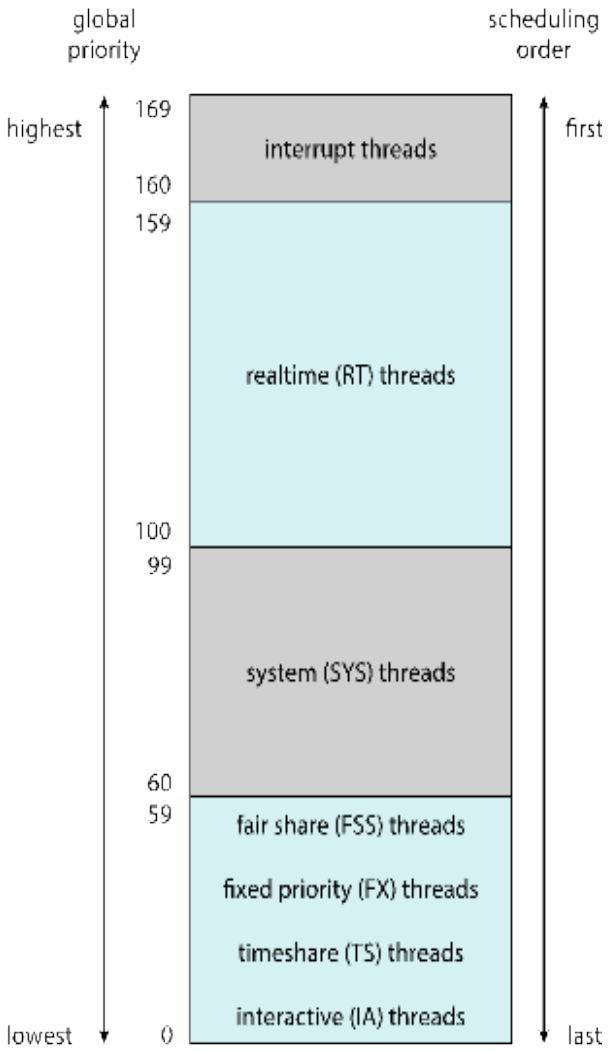
Solaris

- 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

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

Quiz

1. Assume that an operating system maps user-level threads to the kernel using the many-to-many model and that the mapping is done through the use of LWPs. Furthermore, the system allows program developers to create real-time threads. Is it necessary to bind a real-time thread to an LWP?

2. The traditional UNIX scheduler enforces an inverse relationship between priority numbers and priorities: the higher the number, the lower the priority. The scheduler recalculates process priorities once per second using the following function: Priority = (recent CPU usage / 2) + base, where base = 60 and *recent CPU usage* refers to a value indicating how often a process has used the CPU since priorities were last recalculated. Assume that recent CPU usage for process *P*1 is 40, for process *P*2 is 18, and for process *P*3 is 10. What will be the new priorities for these three processes when priorities are recalculated? Based on this information, does the traditional UNIX scheduler raise or lower the relative priority of a CPU-bound process?

Algorithm Evaluation

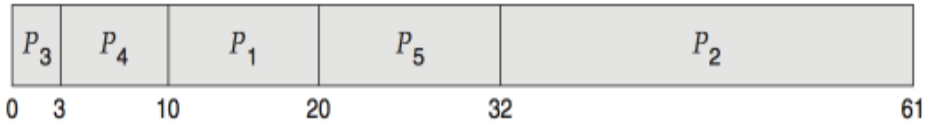
- How to select CPU-scheduling algorithm for an OS?
- Determine criteria, then evaluate algorithms
- **Deterministic modeling**
  - Type of **analytic evaluation**
  - Takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Consider 5 processes arriving at time 0:

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

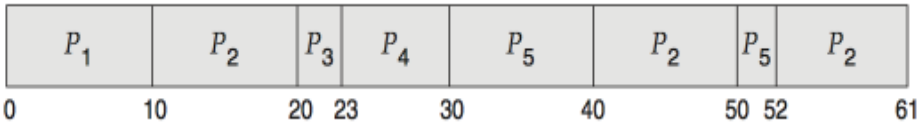
Deterministic Evaluation

- For each algorithm, calculate minimum average waiting time
- Simple and fast, but requires exact numbers for input, applies only to those inputs
  - FCFS 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 its mean
  - Computes average throughput, utilization, waiting time, etc.
- Computer system described as network of servers, each with queue of waiting processes
  - Knowing arrival 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:

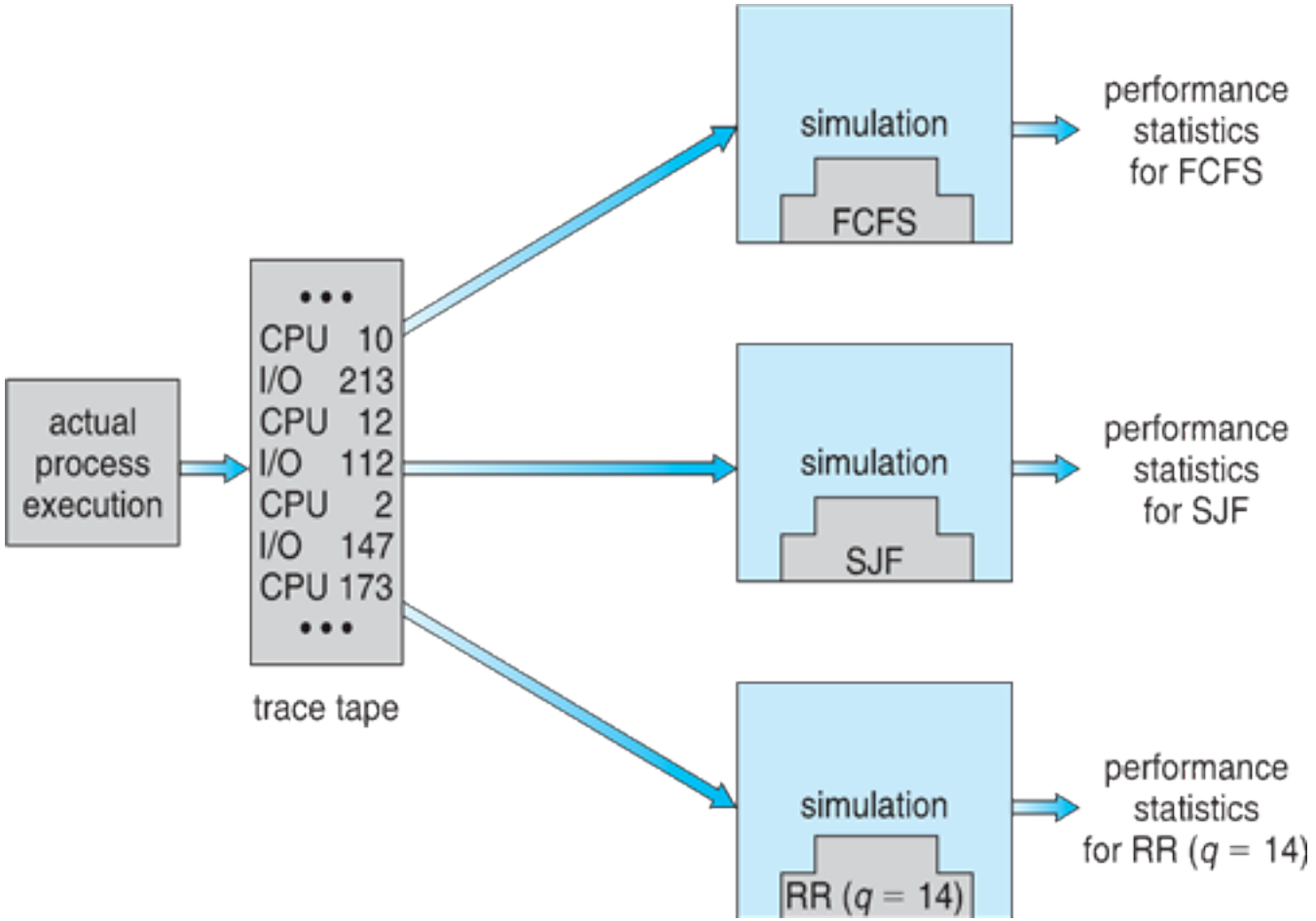
  $n = \lambda \times W$

  - 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 (Arrival and service distribution are often defined in mathematically tractable-but unrealistic-ways)
- **Simulations** more accurate
  - Programmed model of computer system
  - Software data structures represent the major component of the 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

Questions

1. Distinguish between PCS and SCS scheduling
2. Describe four criteria to be used in selecting a CPU scheduling algorithm

Review for the midterm 1

Operating Systems

- What is Operating System?
- Client –server and peer-to-peer computing
- Dual mode operation, timer
- Operating system structures

Processes

- Process states
- Process creations
- Interprocess communication
  - Reasons
  - Shared-memory system
  - Message passing system

Threads

- Benefits of multithreaded programing
- User-level threads
- Kernel-level threads
- Multithreading models
- Threading issues

Process Synchronization

- Requirements of solution to the critical-section
- Peterson's solution
- Semaphores
- The bounded-buffer problem

Review for the midterm 1

Scheduling

- Scheduling Criteria
- CPU scheduling algorithms
  - FCFS, SJF, SRTF, Priority, Round-Robin
- Scheduling in the threading system
- Algorithm evaluation
  - Deterministic modeling
  - Queueing modeling
  - Simulations
  - Implementation

Problem 1

- A producer and a consumer threads are sharing a buffer as shown below. The buffer is initialized with “blank” characters in each position. Semaphores X, Y, and Z are used to protect the buffer and are initializing properly. After the threads have been running for a while, the buffer appears as shown below and the threads are executing at the location shown by the arrows below. If the last character placed in the buffer was ‘8’ and the value of semaphore Y is 5, answer the question below.

2	a	8	d	f	1	9	s	m	c	w	7	b

Consumer

```
Repeat
        do other calculation
        P(X)
        P(Z)
        Read item from buffer
        V(Z)
        Do other calculation  <-----
        V(Y)
Until false
```

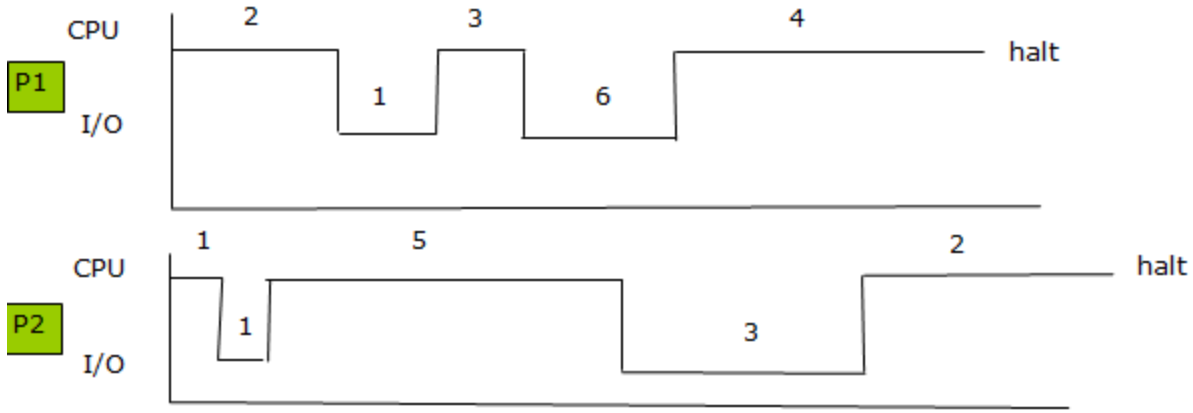
Producer

```
Repeat
        do other calculation  <-----
        P(Y)
        P(Z)
        Place item in buffer
        V(Z)
        Do other calculation
        V(X)
Until false
```

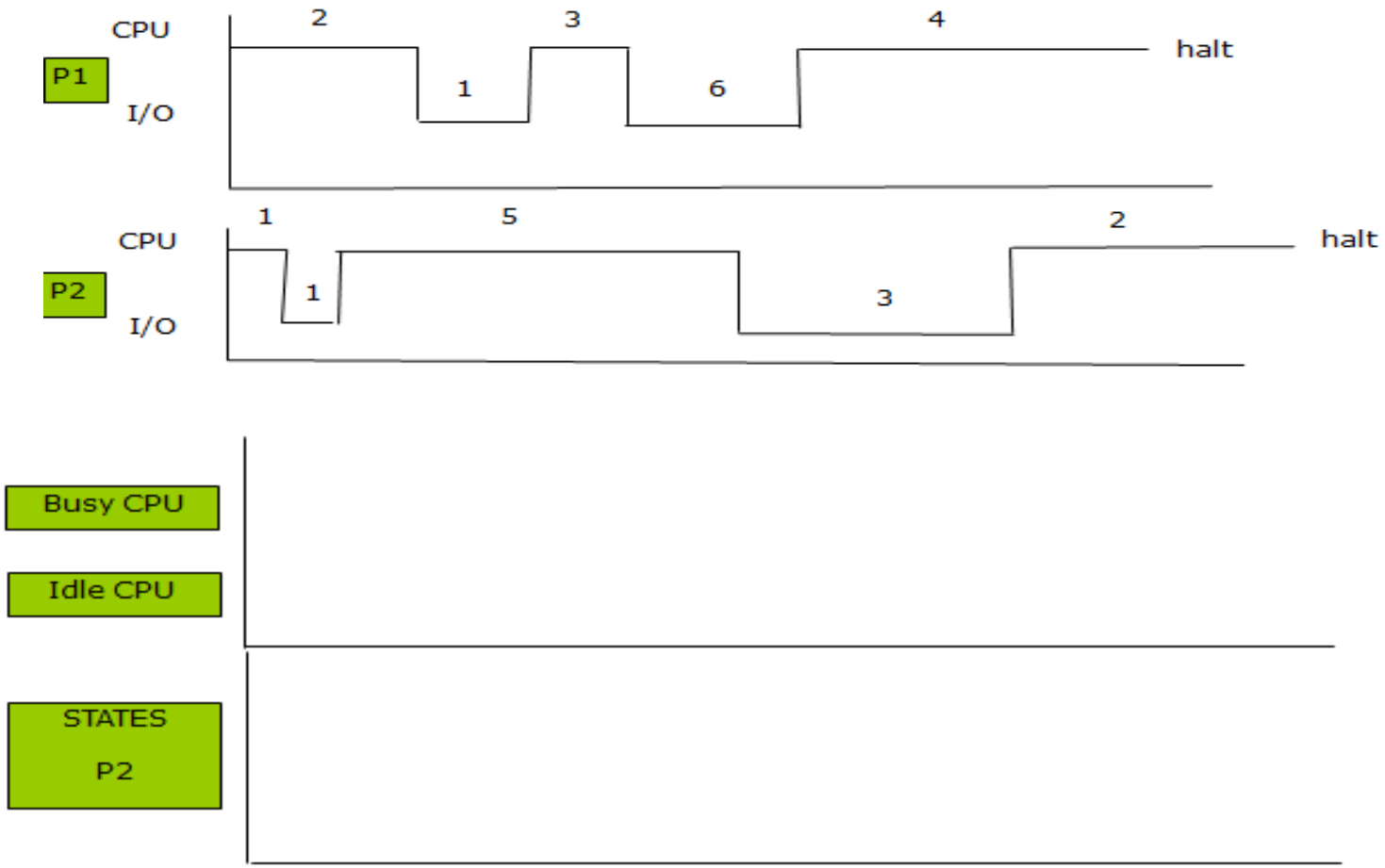
- What was the value of semaphore X when it was initialized? _____0_____
- What is the value of semaphore X now? _____7_____
- What is the value of the consumer buffer index now? _____9_____
- What is the value of the producer buffer index now? _____3_____
- Which was the last character read by the consumer? _____m_____
- Which specific character that are still in the buffer HAVE BEEN READ by the consumer _____df19sm___
- **Note. Initialization: X (full)= 0, Y(empty)=13, Z(mutex) = 1**

Questions

- **The CPU and I/O times for 2 processes are shown below. Assume that PI gets to the ready queue just before P2 and the scheduling algorithm used by the OS is Round Robin with a time slice of 3 time units. Assume that the I/Os for the processes are different so that there is no I/O queue. Assume also that an interrupt from a completed I/O for process "X" will place process "X" in the ready queue BEHIND the process that was just interrupted.**
- Using the first empty graph, describe how the CPU will be assigned to each process and for how long.
- Use the second empty graph to show ALL the states that P1 goes through and the amount of time it has remained in that state until it has halted.



Questions


CPU
P1
I/O
2
1
3
6
4
halt
CPU
P2
I/O
1
1
5
3
2
halt
Busy CPU
Idle CPU
STATES
P2

End of Chapter 6