Chapter 5: CPU Scheduling

Chapter 5: CPU Scheduling

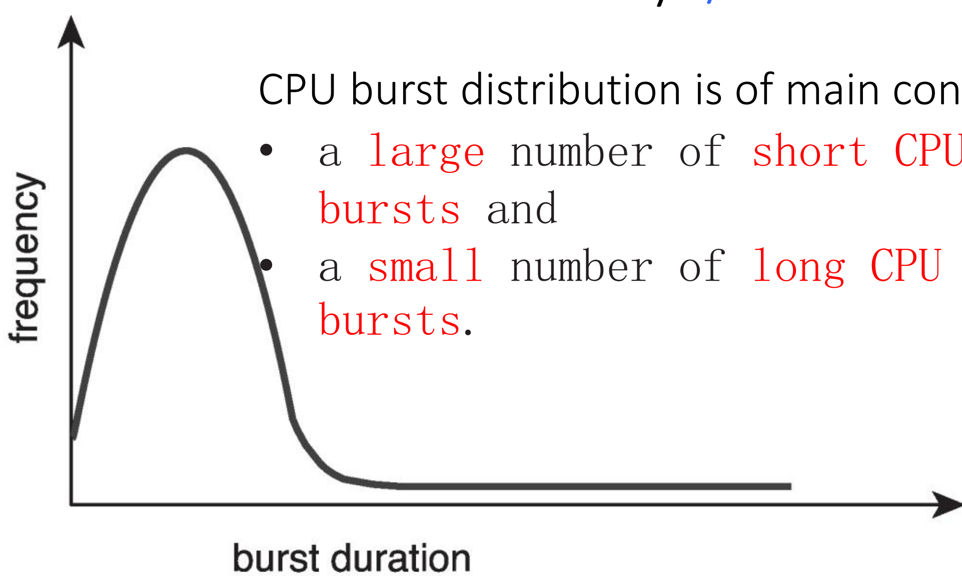
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multi-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples

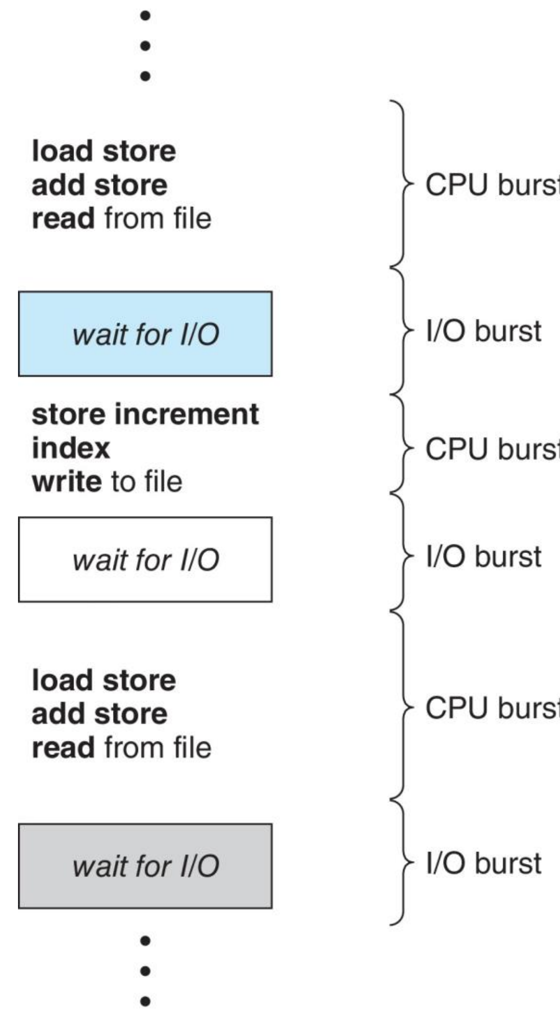
Basic Concepts

- Purpose of multiprogramming: maximum CPU utilization
- 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

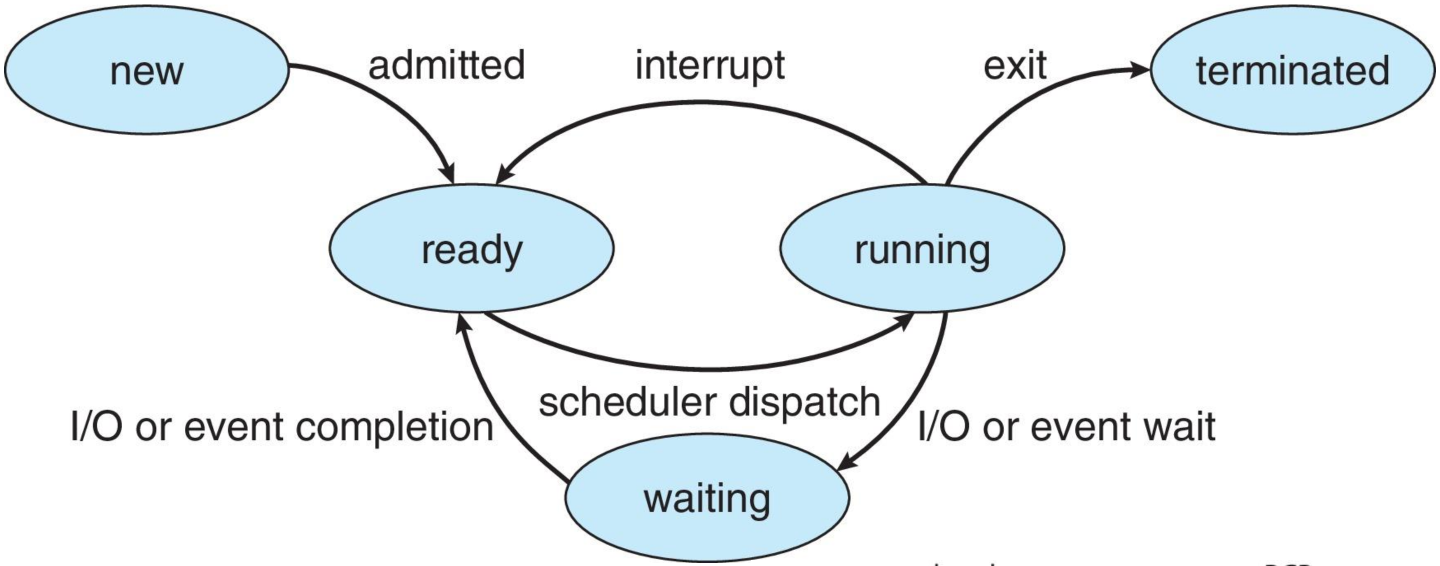
CPU burst distribution is of main concern:

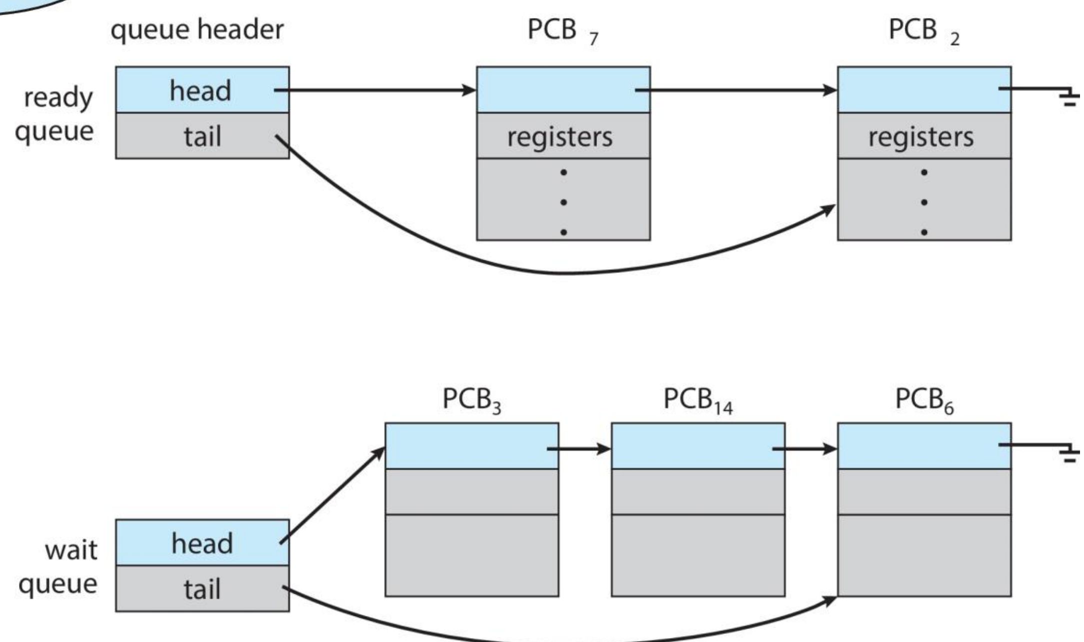
- a large number of short CPU bursts and
- a small number of long CPU bursts.





Process State Transition





CPU Scheduler

- The CPU scheduler (CPU 调度程序) selects a process from the processes in ready queue, and allocates the CPU to it
  - Ready queue may be ordered in various ways
- CPU scheduling decisions may take place when a process
  1. switches from running to waiting state (non-preemptive 自愿离开CPU)
     - Example: the process does an I/O system call.
  2. switches from running to ready state (preemptive 强占)
     - Example: there is a clock interrupt.
  3. switches from waiting to ready (preemptive)
     - Example: there is a hard disk controller interrupt because the I/O is finished.
  4. terminates (non-preemptive 自愿离开CPU)

CPU Scheduler

- Scheduling under 1 and 4 is non-preemptive (非强占的, decided by the process itself)
- All other scheduling is pre-emptive (强占的，decided by the hardware and kernel)
- Preemptive scheduling can result in race conditions（will introduced in chapter 6）when data are shared among several processes
- Some considerations in pre-emptive scheduling
  1. Access to shared data
  2. Preemption issue while CPU is in kernel mode
  3. How to handle interrupts during crucial OS activities

Preemptive vs. Nonpreemptive Scheduling

- When a process is pre-empted,
  - It is moved from its current processor
  - However, it still remains in memory and in ready queue
- Why preemptive scheduling is used？
  - Improve response times
  - Create interactive environments (real-time)
- Non-preemptive scheduling
  - Process runs until completion or until they yield control of a processor
  - Disadvantage
    - Unimportant processes can block important ones indefinitely

Scheduling Criteria

maximize

- CPU utilization – keep the CPU as busy as possible
- Throughput – number of processes that complete their execution per time unit
  - Increase throughput as high as possible

minimize

- 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)
- Waiting time – total amount of time a process has been waiting in the ready queue
- Turnaround time – amount of time to execute a particular process (from start to end of process, including waiting time)
  - Turnaround time = Waiting time + time for all CPU bursts

How to calculate these criteria?

Scheduling Algorithms

1. First-Come, First-Served (FCFS)
2. Shortest-Job-First (SJF)
3. Priority Scheduling (PS)
4. Round-Robin (RR)
5. Multilevel Queue Scheduling (MQS)
6. Multilevel Feedback Queue Scheduling (MFQS)

First- Come, First-Served (FCFS) Scheduling

- Suppose that the processes arrive in the ready queue at time t = 0 in the following order: P_1 , P_2 , P_3
- Burst time for each process is

Process	Burst Time
P_1	24
P_2	3
P_3	3

The Gantt Chart for the schedule is:

- Waiting time: $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
- Average waiting time: (0 + 24 + 27) / 3 = 17
- Average turnaround time = (24+27+30)/3 = 27

FCFS Scheduling (Cont.)

- Suppose the order is changed to this:

$$P_2 , P_3 , P_1$$

- The Gantt chart for the schedule is then:

- Waiting time: $P_1 = 6; P_2 = 0, P_3 = 3$
- Average waiting time: (6 + 0 + 3) / 3 = 3
- Average turnaround time = (30+3+6)/3 = 13
- Much better than previous case
- Convoy effect(护送效应)[1] - short process behind long process
  - Consider one CPU-bound (long CPU burst, short I/O burst) and many I/O-bound (long I/O burst, short CPU burst) processes

[1]This effect results in lower CPU and device utilization than might be possible if the shorter processes were allowed to go first.

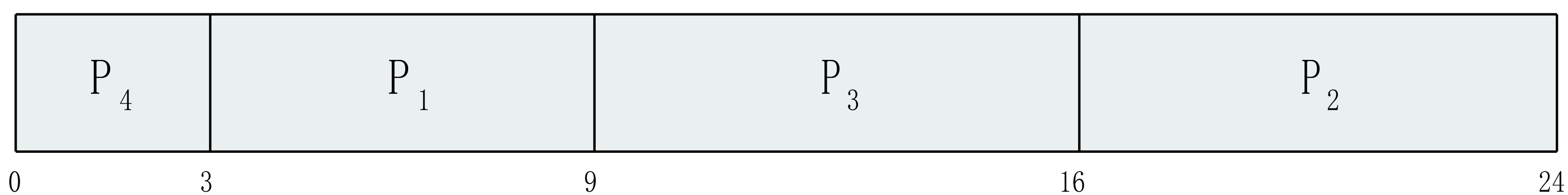
Shortest-Job-First (SJF) Scheduling

- 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

Shortest-Job-First (SJF) Scheduling

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- SJF scheduling chart



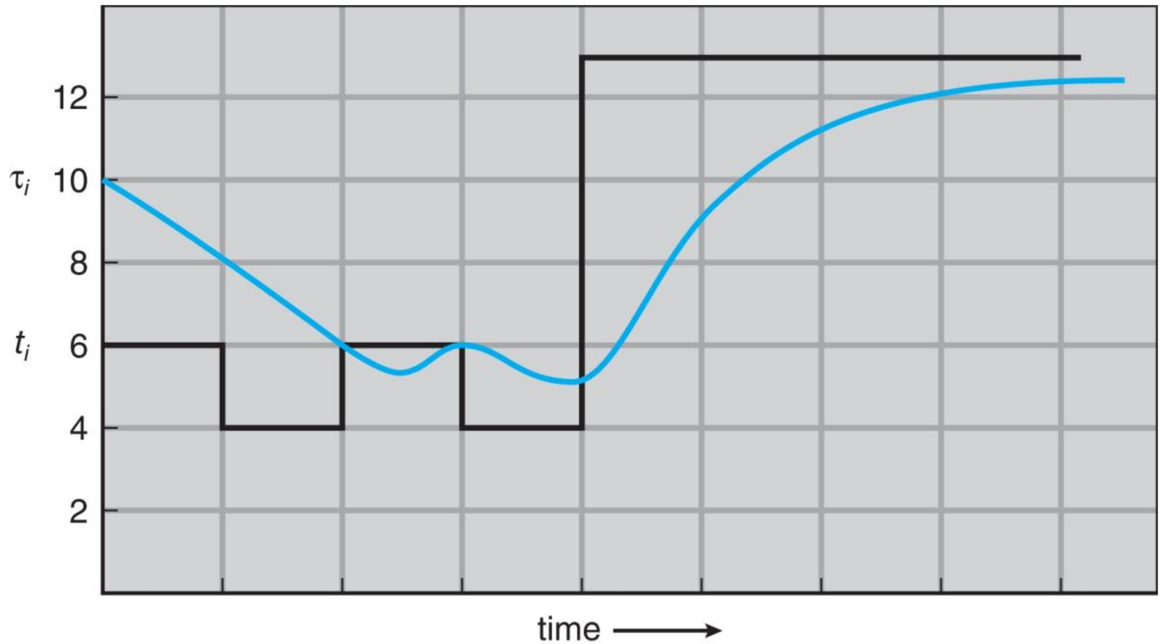
- Average waiting time = (3 + 16 + 9 + 0) / 4 = 7
- Average turnaround time = (9+24+16+3)/4 = 13

Determining Length of Next CPU Burst

- Actually the length of next CPU burst can only be estimated
  - Next burst length should be similar to the previous one (use the past to predict the future).
  - Then pick process with shortest predicted next CPU burst
- Use the length of previous CPU bursts, with exponential averaging

1. $t_n =$ actual length of n^{th} CPU burst
2. $\tau_{n+1} =$ predicted value for the next CPU burst
3. $\alpha, 0 \le \alpha \le 1$ (commonly, α set to ½)
4. Define: $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n$

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	…

$$\tau_{n+1} = \alpha\, t_n + (1-\alpha)\tau_n = \frac{1}{2}(t_n + \tau_n)$$

(Assume α set to ½)

Examples of Exponential Averaging

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

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n = \ldots = \tau_0$
  - History does not count: always use the same guess regardless of what the process actually does.
- $\alpha = 1$
  - $\tau_{n+1} = t_n$
  - Only the actual last CPU burst counts
- In general, if we expand the formula, we get:

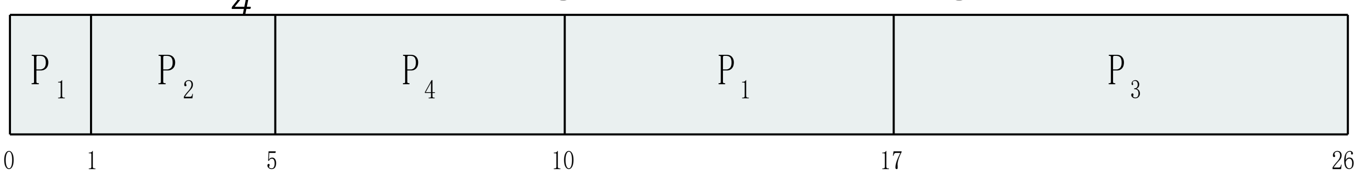
$$\begin{aligned}\tau_{n+1} &= \alpha\, t_n + (1-\alpha)\alpha\, t_{n-1} + \ldots \\ &\quad + (1-\alpha)^j \alpha\, t_{n-j} + \ldots \\ &\quad + (1-\alpha)^{n+1} \tau_0\end{aligned}$$

- 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

- The preemptive version of SJF is also called 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



Gantt Chart

(P1:7)

(P1:7, p3: 9)

- Average waiting time = [(10-1)+(1-1)+(17-2)+(5-3)] / 4 = 26 / 4 = 6.5
- Average turnaround time = ((17-0)+(5-1)+(26-2)+(10-3))/4 = 13

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

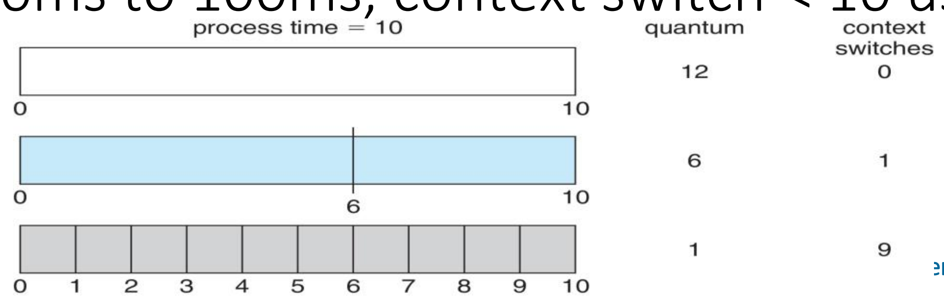
- *Preemptive* SJF (shortest-remaining-time-first) Gantt Chart

Question： how if time for P4 is 1

- Average waiting time = ???
- Average turnaround time = ???

Round Robin (RR)

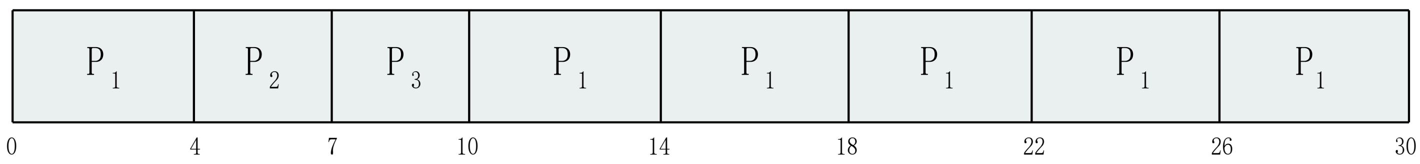
- Each process gets a small unit of CPU time (time quantum 定额 *q*), usually 10-100 milliseconds.
- After *q* has elapsed, the process is preempted by a clock interrupt and added to the end of the ready queue.
  - Timer interrupts every quantum *q* to schedule next process
- If there are *n* processes in the ready queue and the time quantum is *q*. No process waits more than (*n*-1)**q*.
- Performance
  - *q* too large ⇒ FCFS
  - *q too* small ⇒ too much time is spent on context switch
    - *q* should be large compared to context switch time
    - *q* usually 10ms to 100ms, context switch < 10 usec (微秒)



Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

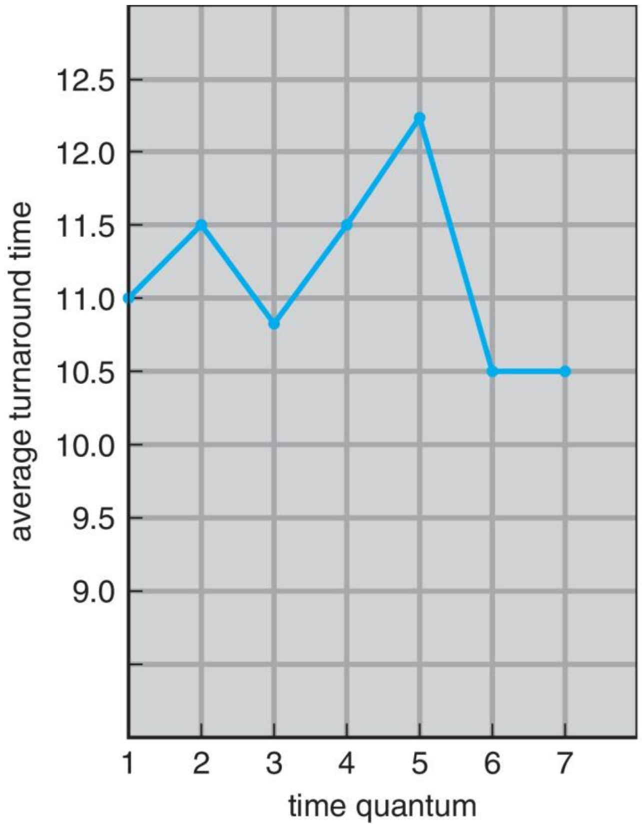
- The Gantt chart is:



- Typically, higher average turnaround than SJF, but better *response*
- Average waiting time = (6+4+7)/3 = 5.67
- Average turnaround time = (30+7+10)/3 = 15.7

Question： how if time for q is 25?

Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

General rule: 80% of CPU bursts should be shorter than q, that way most processes can finish their current CPU burst without being interrupted.

q=6, Average turnaround time = (6+9+10+17)/4 = 10.5

q=7, Average turnaround time = (6+9+10+17)/4 = 10.5

Priority Scheduling

- A priority number (integer) may be associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer ≡ highest priority)
  - Two policies
    - Preemptive
      - the current process is pre-empted immediately by high priority process
    - Non-preemptive
      - the current process finishes its burst first, then scheduler chooses the process with highest priority
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time

Priority Scheduling

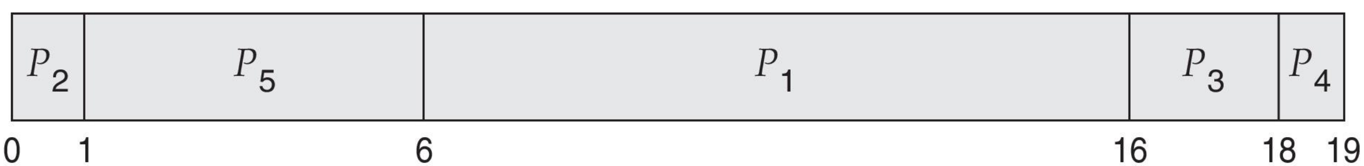
- Problem
  - Starvation: low priority processes may never execute
- Solution
  - Aging: as time progresses increase the priority of the process

Example of Priority Scheduling

smallest integer ≡ highest priority

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 (not preemptive) Gantt Chart

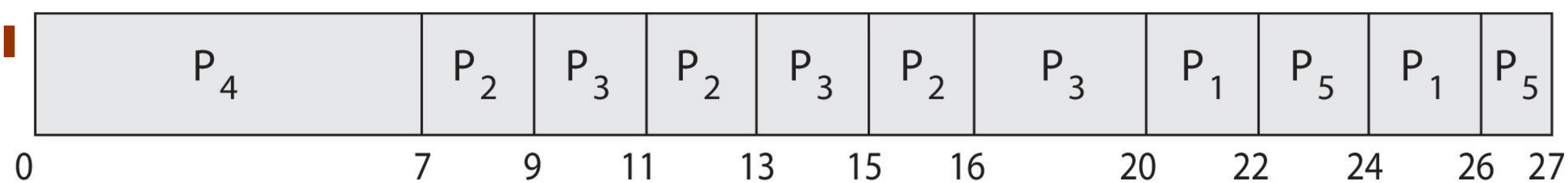


- Average waiting time = (6+0+16+18+1)/5 = 8.2

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** (in this example, assume q=2)



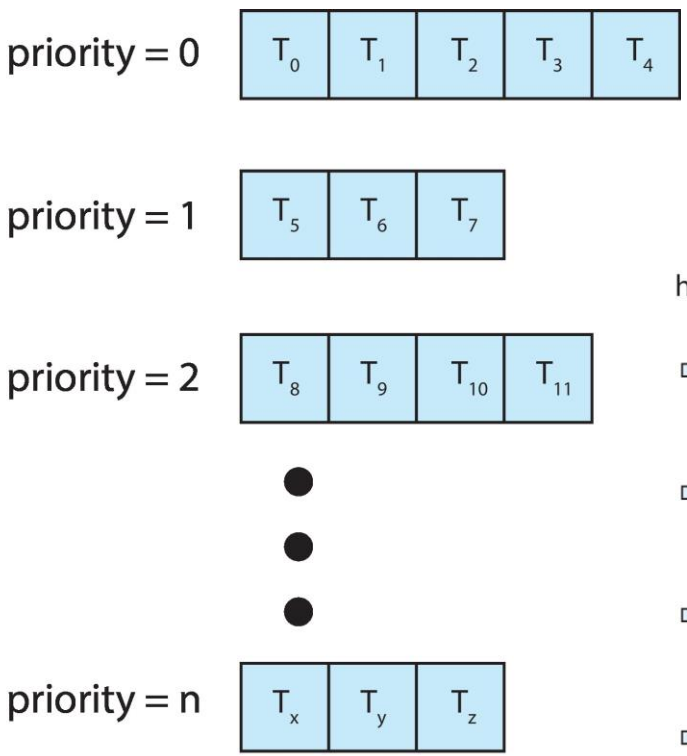
Average waiting time = (22+11+12+0+24)/5 = 13.8

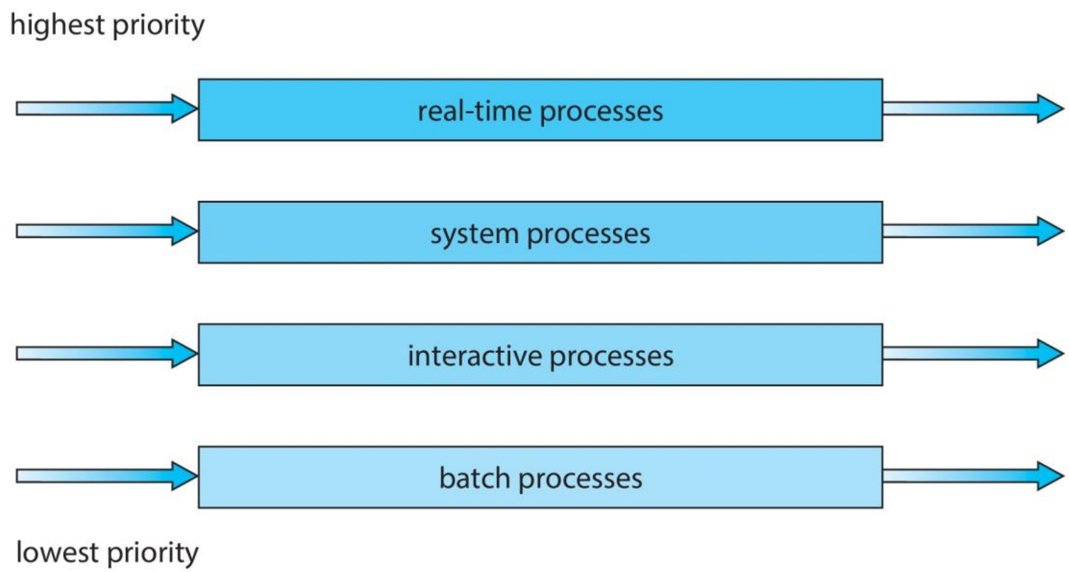
Multilevel Queue

- Ready queue is partitioned into separate queues, e.g.:
  - foreground (interactive 交互processes)
  - background (batch 批处理 processes)
- Process permanently in a given queue (stay in that queue)
- Each queue has its own scheduling algorithm:
  - foreground – RR
  - background – FCFS
- Scheduling must be done between the queues:
  - Fixed priority scheduling
    - Each queue has a given priority
      - High priority queue is served before low priority queue
      - Possibility of starvation
  - Time slice
    - Each queue gets a certain amount of CPU time

Multilevel Queue

- With priority scheduling, for each priority, there is a separate queue
- Schedule the process in the highest-priority queue!





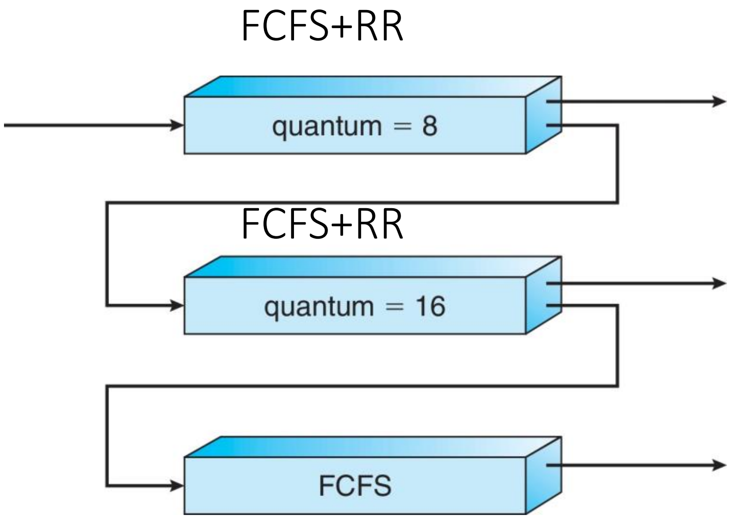
Prioritization based upon **process type**

Multilevel Feedback Queue

- A process can move between the various queues;
  - aging can be considered in this way (prevent starvation)
  - advantage: prevent starvation
- The multilevel feedback queue scheduler
  - the most general CPU scheduling algorithm
  - defined by the following parameters:
    1. number of queues
    2. scheduling algorithms for each queue
    3. Policies on moving process between queues
       1. when to upgrade a process
       2. when to demote (降级) a process
       3. which queue a process will enter when that process needs service

Example of Multilevel Feedback Queue

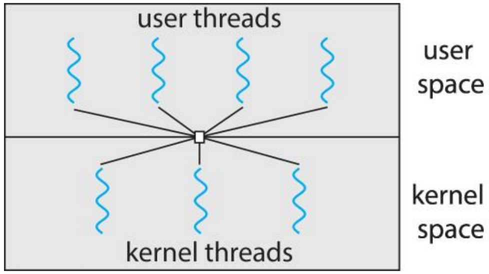
- Three queues:
  1. Q_0 – RR with time quantum 8 milliseconds
  2. Q_1 – RR with time quantum 16 milliseconds
  3. Q_2 – FCFS



- 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 where it runs until completion but with a low priority

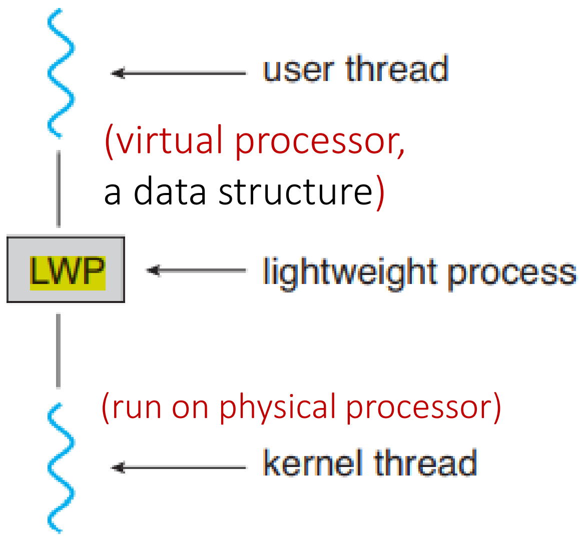
Thread Scheduling

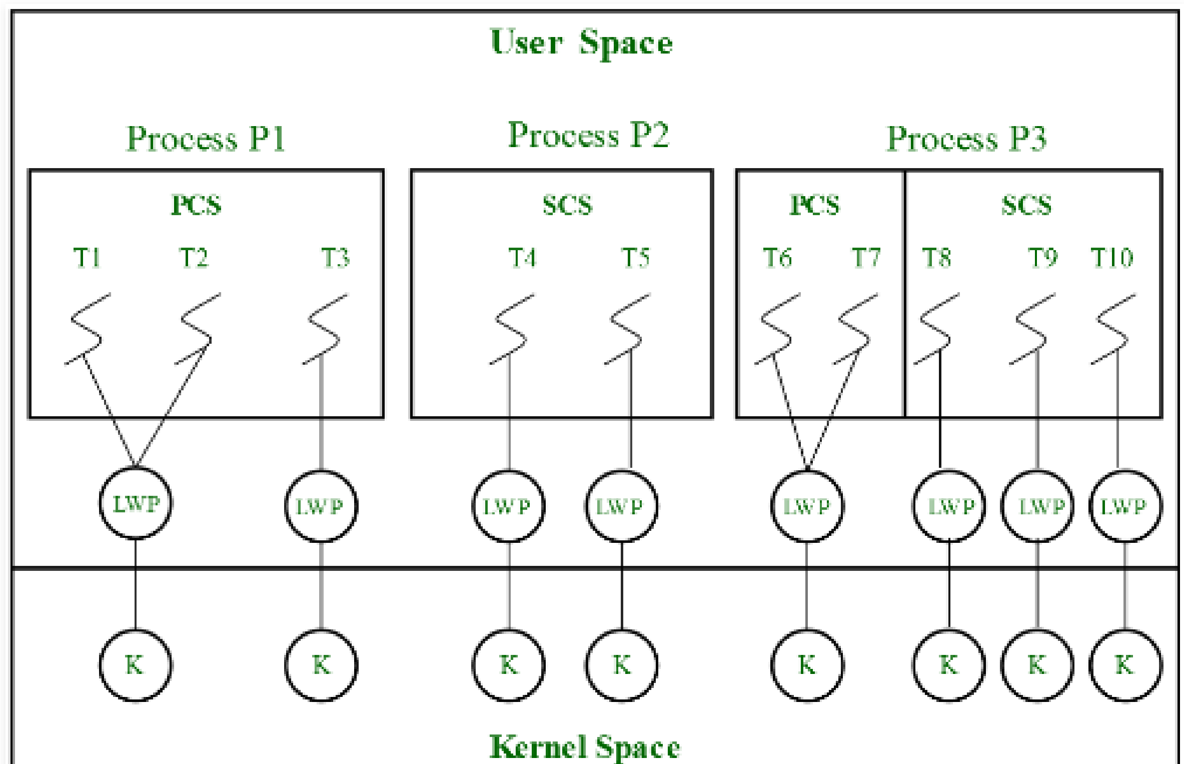
- Distinguish between user-level and kernel-level threads
- When threads are supported by kernel,
  - threads are scheduled, not processes



- Many-to-one and many-to-many models,
  - thread library schedules user-level threads to run on kernel threads (LWP: light-weight process)
    - process-contention scope (PCS)
    - competition is between user-level threads within the same process
  - Typically priority is set by programmer
- Kernel threads are scheduled by Kernel onto available CPU
  - system-contention scope (SCS)
  - competition is among all kernel-level threads from all processes in the system

Thread Scheduling



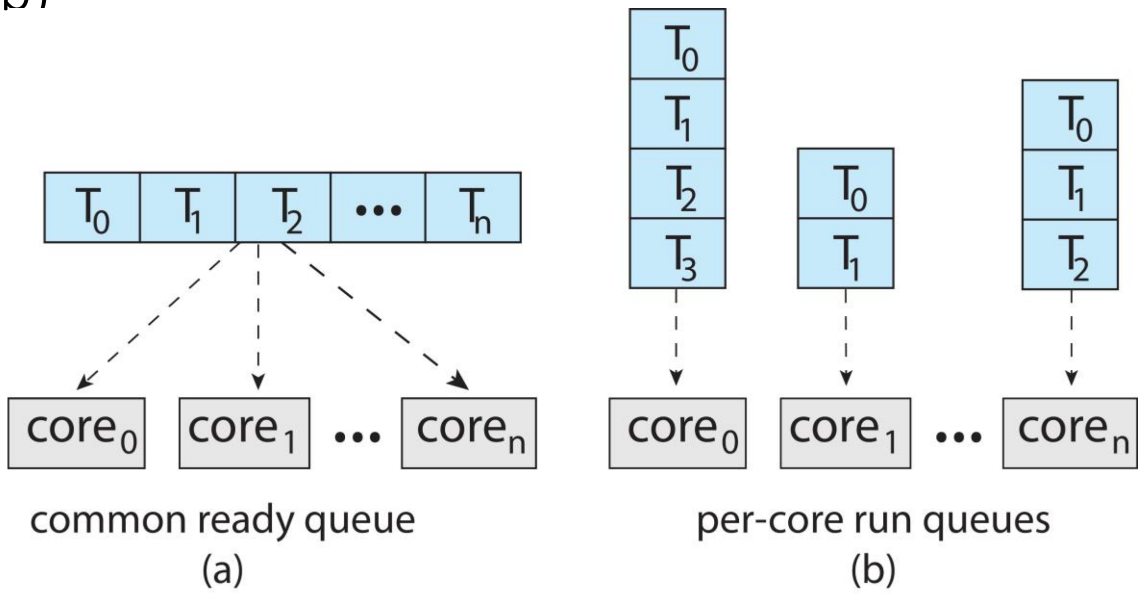


Multiple-Processor Scheduling

- CPU scheduling is more complex when multiple CPUs are available
- Traditionally, Multiprocessor means multiple processors
- The term Multiprocessor now applies to the following system architectures:
  - Multicore CPUs
  - Multithreaded cores
  - NUMA systems

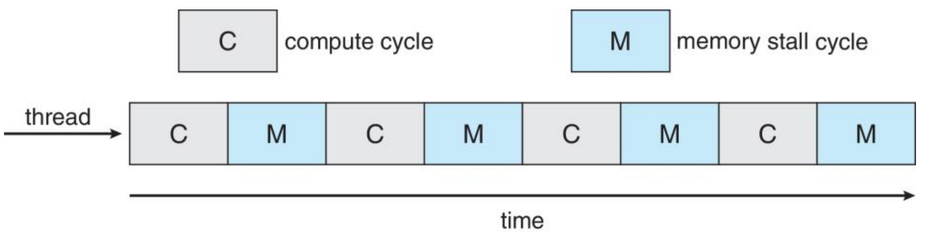
Multiple-Processor Scheduling

- **Symmetric multiprocessing (SMP)** is where each processor is self scheduling
  - Two possible strategies
    1. All threads may be in a common ready queue (a)
    2. Each processor may have its own private queue of threads (b)

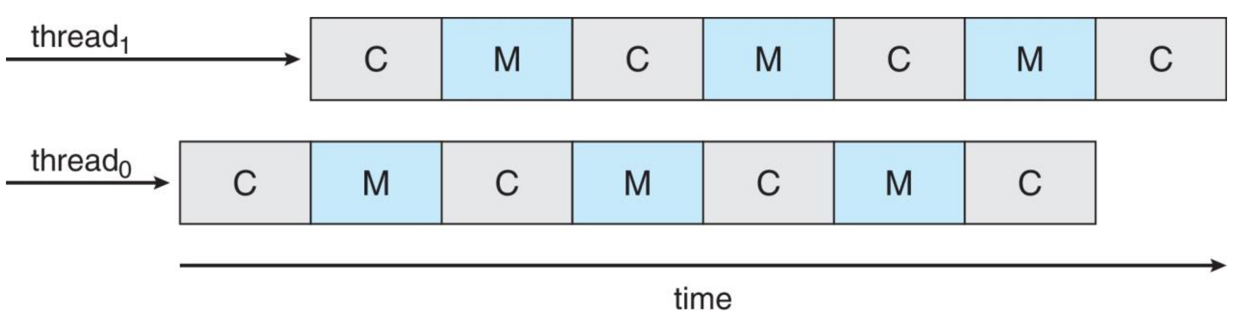


Multicore Processors

- Recent trend: multiple processor cores are on same physical chip
  - Faster and consumes less power
- Multiple threads per core also growing
  - memory stall (延迟) : An event that occurs when a thread is on CPU and accesses memory content that is not in the CPU's cache. The thread's execution stalls while the memory content is retrieved and fetched

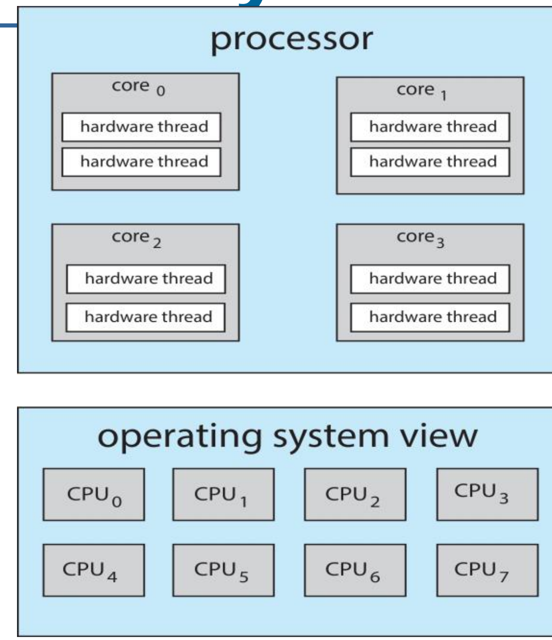


  - Solution :
    - Each core has more than one hardware threads. If one thread has a memory stall, switch to another thread!

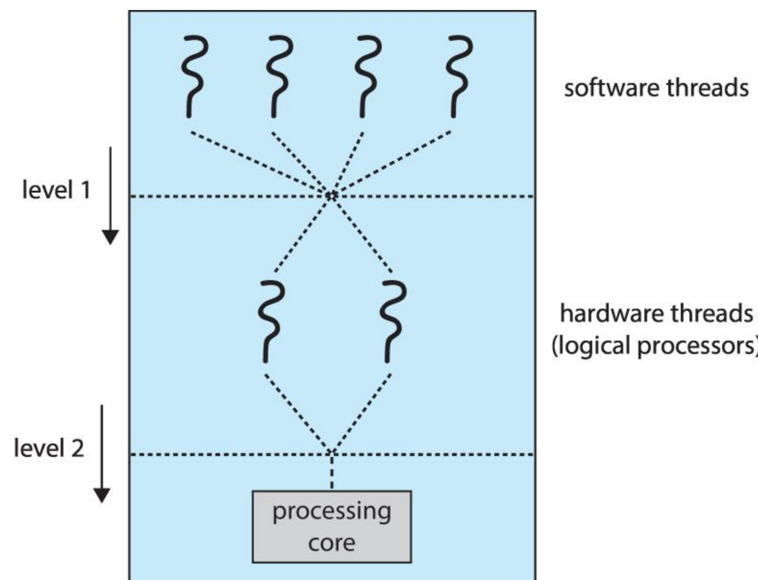


Multithreaded Multicore System

- Chip-multithreading (CMT) assigns each core multiple hardware threads. (Intel refers to this as hyperthreading.)
- On a quad-core system (4核) with 2 hardware threads per core, the operating system sees 8 logical processors.



- Two levels of scheduling:
  1. The operating system deciding which software thread to run on a logical CPU
  2. Each core decides which hardware thread to run on the physical core.



Multiple-Processor Scheduling – Load Balancing

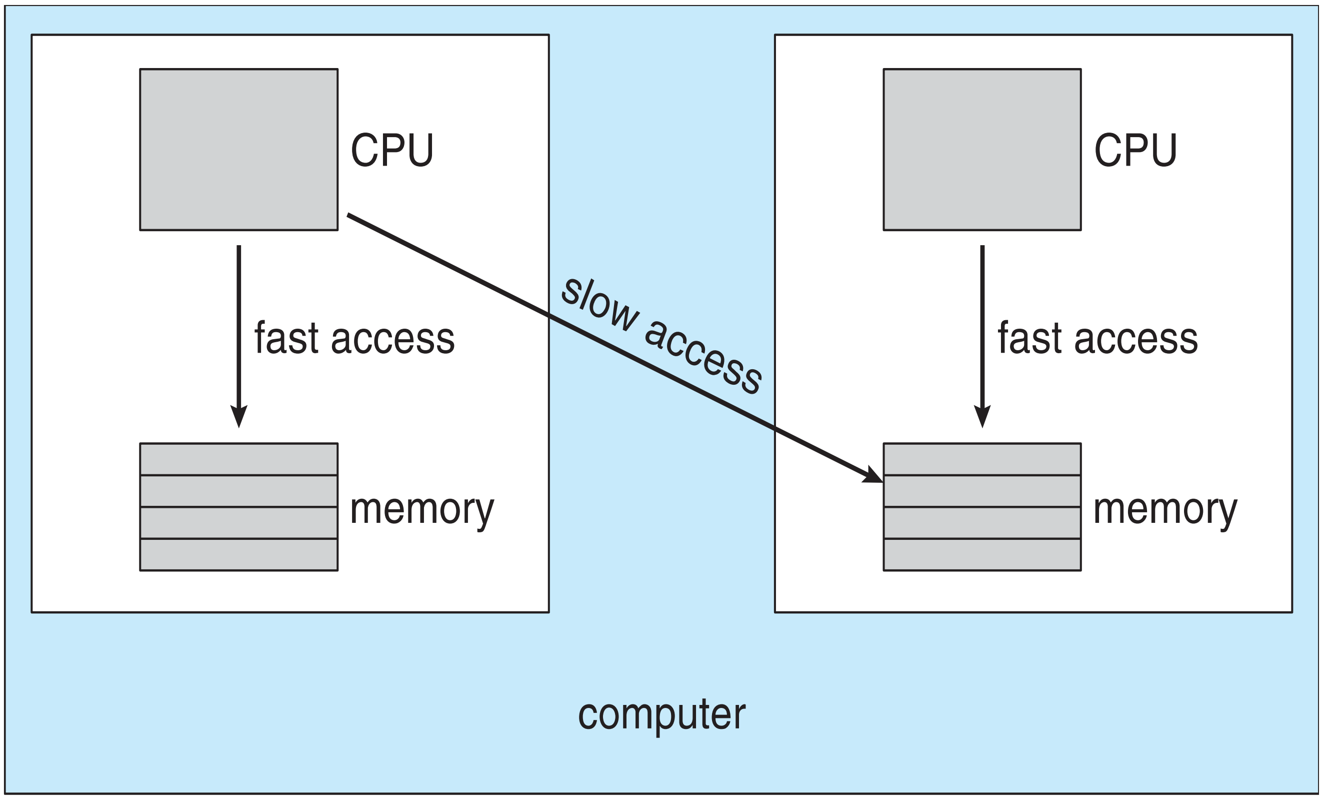
- If SMP, need to keep all CPUs loaded for efficiency
- Load balancing attempts to keep workload evenly distributed
  - Push migration – periodic task checks load on each processor, and pushes tasks from overloaded CPU to other less loaded CPUs
  - Pull migration – idle CPUs pulls waiting tasks from busy CPU
- Push and pull migration need not be mutually exclusive
  - They are **often implemented in parallel** on load-balancing systems.

Multiple-Processor Scheduling – Processor Affinity

- Processor affinity
  - When a thread has been running on one processor, the cache contents of that processor stores the memory accesses by that thread, i.e., a thread has affinity for a processor
- Load balancing may affect processor affinity
  - a thread may be moved from one processor to another to balance loads,
  - that thread loses the contents of what it had in the cache of the processor it was moved off
- 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.
  - The kernel then never moves the process to other CPUs, even if the current CPUs have high loads.

NUMA and CPU Scheduling

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



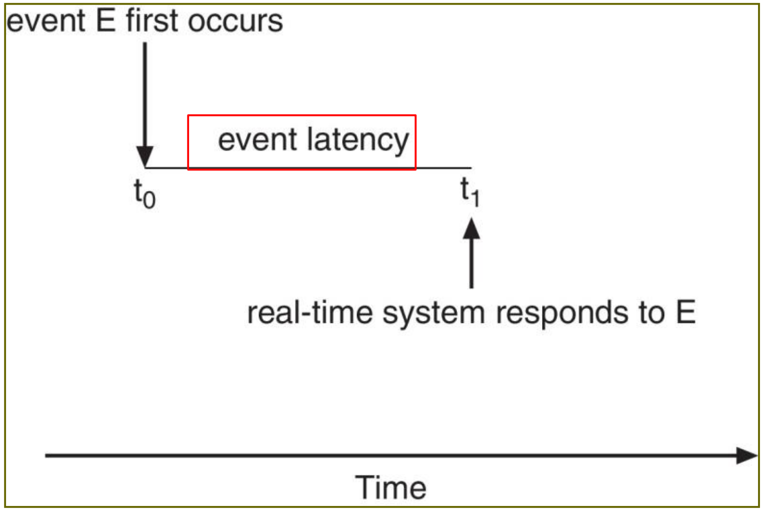
Non-uniform memory access (NUMA) is a computer memory design used in multiprocessing, where the memory access time depends on the memory location relative to the processor. Under NUMA, a processor can access its own local memory faster than non-local memory (memory local to another processor or memory shared between processors).

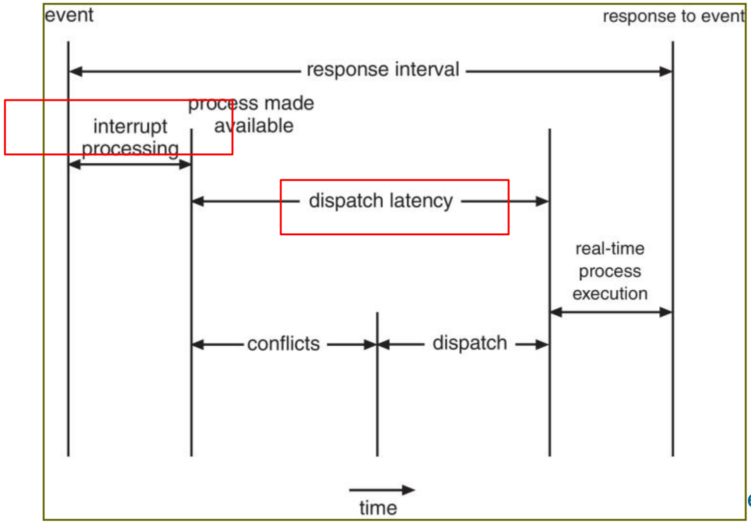
Real-Time CPU Scheduling

- Real-time CPU scheduling presents obvious challenges
  - Soft real-time systems
    - Critical real-time tasks have the highest priority, but no guarantee as to when tasks will be scheduled (best try only)
  - Hard real-time systems
    - a task must be serviced by its deadline (guarantee)

Real-Time CPU Scheduling

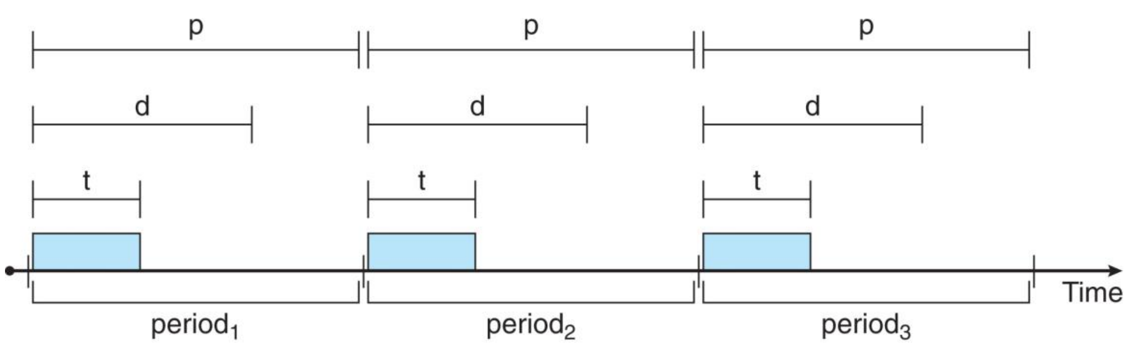
- Event latency – the amount of time that elapses from when an event occurs to when it is serviced.
- Two types of latencies affect performance
  1. Interrupt latency – time from arrival of interrupt to start of kernel interrupt service routine (ISR) that services interrupt
  2. Dispatch latency(调度延迟) – time for scheduler to take current process off CPU and switch to another





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: periodically 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 Monotonic Scheduling

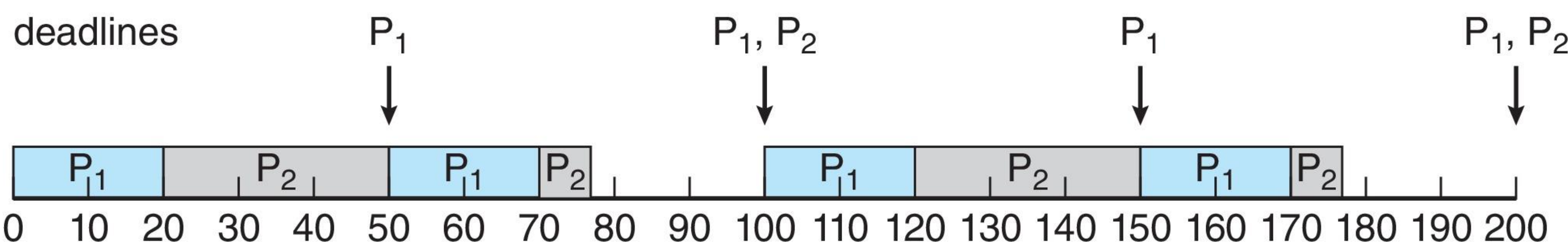
- A priority is assigned based on the inverse of its period

  Shorter periods = higher priority

  Longer periods = lower priority

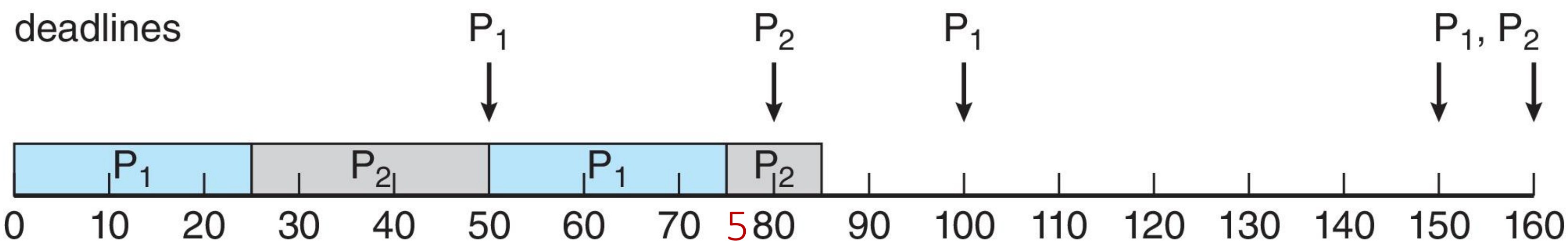
- In the following example, P_1 is assigned a higher priority than P_2.
  - P_1 needs to run for 20 ms every **50** ms. t = 20, d = p = 50
  - P_2 needs to run for 35 ms every **100** ms. t = 35, d = p = 100

  Assume deadline d = p



Missed Deadlines with Rate Monotonic Scheduling

- Example:
  - P_1 needs to run for 25 ms every 50 ms. t = 25, d = p = 50
  - P_2 needs to run for 35 ms every 80 ms. t = 35, d = p = 80

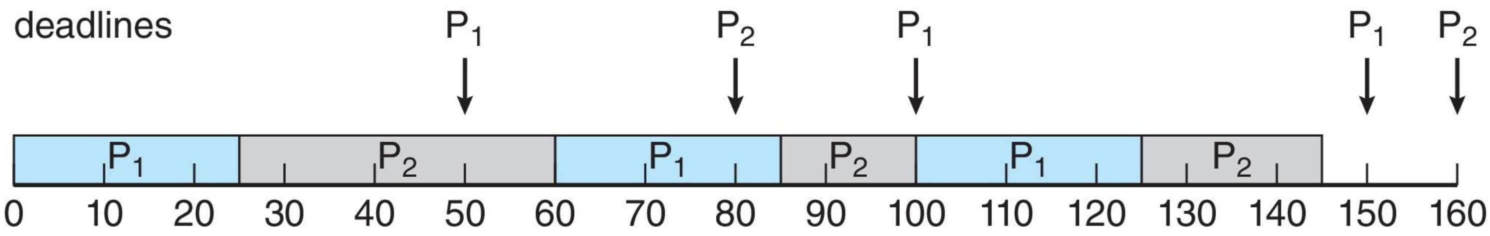


P2:25 P2:needs 10

- Process P_2 misses its deadline at time 80 ms.
- Observation: if P_2 is allowed to run from 25 to 60 and P_1 then runs from 60 to 85 then both processes can meet their deadline.
- So the problem is not a lack of CPU time, the problem is that rate monotonic scheduling is not a very good algorithm.

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.



- Example:
  - P_1 needs to run for 25 ms every 50 ms.
  - P_2 needs to run for 35 ms every 80 ms.
- This is the scheduling algorithm many students use when they have multiple deadlines for different homework assignments!

Proportional Share Scheduling

- *T* shares are allocated among all processes in the system
  - Example: $T = 20$, therefore there are 20 shares, where one share represents 5% of the CPU time
- An application receives *N* shares where $N < T$
  - This ensures each application will receive $\boldsymbol{N} / T$ of the total processor time
  - Example: an application receives $N = 5$ shares
    - the application then has 5 / 20 = 25% of the CPU time.
    - This percentage of CPU time is available to the application whether the application uses it or not.

POSIX Real-Time Scheduling API

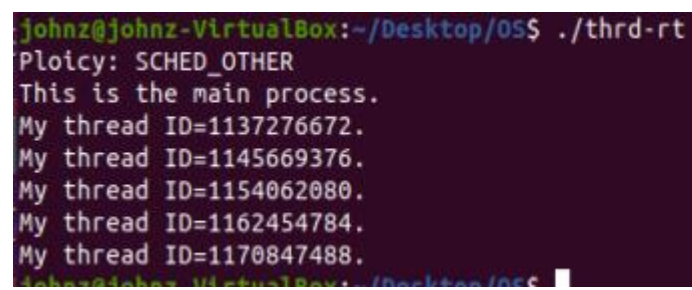
thrd-rt.c

```
#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 ... */
  printf("my thread ID=%u\n", *(unsigned int*)param);
   pthread_exit(0);
}
```

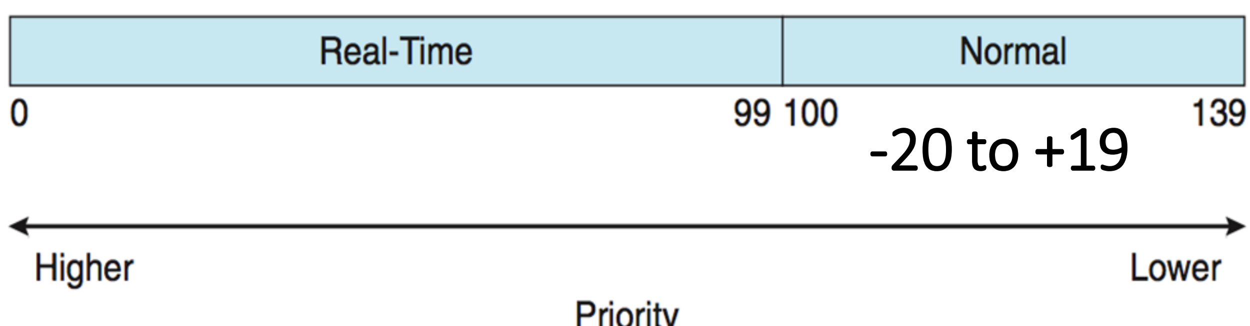


Operating System Examples

- Linux scheduling
- Windows scheduling

Linux Scheduling

- Scheduling classes
  - 2 scheduling classes are included, others can be added
    1. default
    2. real-time
  - Each process/task has specific priority
- Real-time scheduling according to POSIX.1b
  - Real-time tasks have static priorities
- Real-time plus normal tasks map into global priority scheme
  - Nice value of -20 maps to global priority 100
  - Nice value of +19 maps to priority 139



Linux Scheduling

- Completely Fair Scheduler (CFS)
  - Scheduler picks highest priority task in highest scheduling class
    - Quantum is not fixed
    - Calculated based on nice value from -20 to +19
      - Lower value is higher priority
- CFS 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 (Nice value: 0) yields virtual run time = actual run time
  - To decide next task to run, scheduler picks task with lowest virtual run time

Linux Scheduling

	High-priority Nice value -10	Normal-priority Nice value 0	Low-priority Nice value 10
Run-time	200 ms	200 ms	200 ms
vruntime	150 ms (decay factor: 0.75)	200 ms (decay factor: 1)	250 ms (decay factor: 1.25)

Next time:
Pick this one

Operating System Examples

- Windows scheduling
- Windows uses priority-based preemptive scheduling
  - Highest-priority thread runs next
    - 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
  - There is a queue for each priority
  - If no run-able thread, runs idle thread

Windows Priorities

The Windows API identifies the following six priority classes to which a process can belong:

real-time class

Variable class

	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

A thread within a given priority class also has a relative priority.

Variable: meaning that the priority of a thread belonging to one of these classes can change.

End of Chapter 5

Appendices

- The appendix parts are for students who are interested in knowing more about the thread programming that use Process Scope and System Scope, and algorithm evaluation.

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

thrd-demo2.c

gcc –o thrd-demo2 thrd-demo2.c -lpthread

pthread_t => unsigned int

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5
void *runner(void *param);
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("Scope: PTHREAD_SCOPE_PROCESS");
    else if (scope == PTHREAD_SCOPE_SYSTEM)
      printf("Scope: PTHREAD_SCOPE_SYSTEM");
    else
      fprintf(stderr, "Illegal scope value.\n");
  }
```

Pthread Scheduling API Cont.

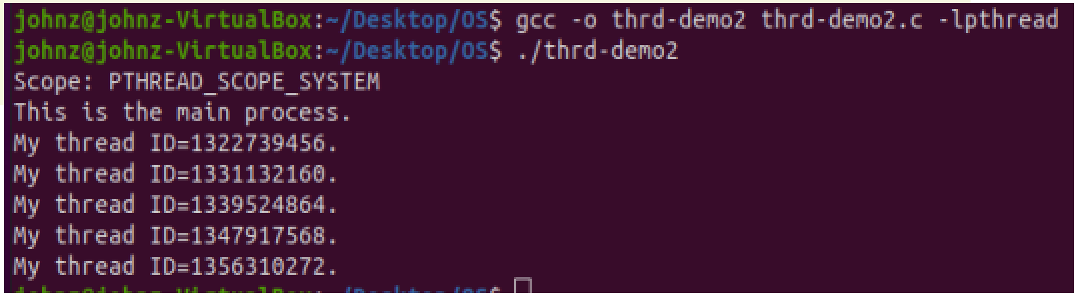
thrd-demo2.c

```
  /* set the scheduling algorithm to PCS or SCS */
  //pthread_attr_setscope(&attr, scope);

  /* create the threads */
  for (i = 0; i < NUM_THREADS; i++)
    pthread_create(&tid[i],&attr,runner,&tid[i]);

  printf("This is the main process\n");

  /* 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 ... */
  printf("my thread ID=%d\n", *(int*)param);
  pthread_exit(0);
}
```



Algorithm Evaluation

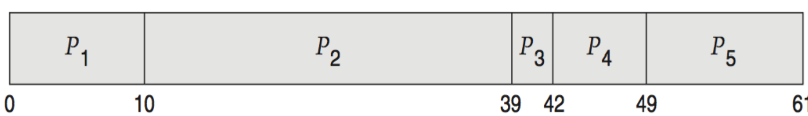
- How to select CPU-scheduling algorithm for an OS?
  1. Determine criteria
     - What is the computer used for?
  2. Evaluate algorithms
     - Find which algorithm is the best one for that kind of usage.
- Three ways to evaluate an algorithm
  1. Deterministic modeling
  2. Queueing Models
  3. Simulations

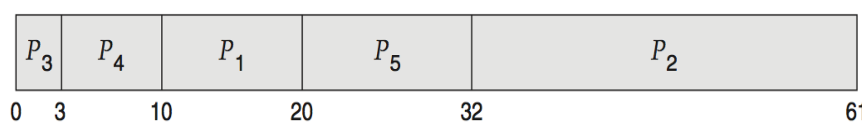
Deterministic modeling

- Deterministic modeling
  - Type of analytic evaluation
  - Takes a particular predetermined workload and defines the performance of each algorithm for that workload

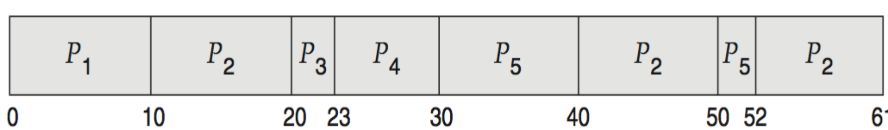
Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

- Consider 5 processes arriving at time 0
  - For each algorithm, calculate minimum average waiting time
    - Simple and ... rs for input, applies only
  - FCFS is 28ms:





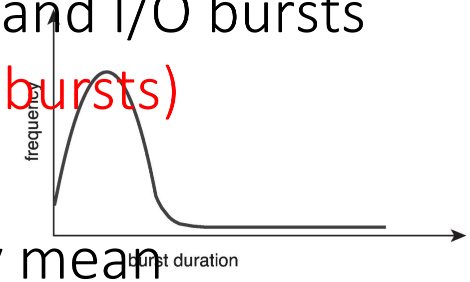
  - Non-preem



  - RR is 23ms:

Queueing Models

- Describes the arrival of processes, and CPU and I/O bursts probabilistically (distribution of arrivals and bursts)



  - Commonly exponential, and described by mean
  - Computes average throughput, utilization, waiting time, etc. according to the distribution of arrival times and CPU bursts
- Computer system is 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.
- Queueing models has limitation
  - because the behavior of real computers does not follow any simple ideal probability distribution

Simulations

- Compared with Queueing models, **Simulations** are more accurate
  - Running simulations involves programming a model of the computer system
    - The simulator has a variable representing a clock
    - As this variable's value is increased, the simulator modifies the system state to reflect the activities of the devices, the processes, and the scheduler
  - Gather statistics from real computers usage indicating algorithm performance
  - Data to drive simulation can be generated in several ways
    - Uses a random-number generator that is programmed to generate processes, CPU burst times, arrivals, departures, and so on, according to probability distributions (i.e., distribution-driven, most common method)
      - distributions are defined mathematically or empirically

Implementation

- Even simulations have limited accuracy
  - because trace tape used in simulation might be different from the way you use your computer
- The only completely accurate ways is
  - Just implement new scheduler and test in real systems
    - High cost, high risk, but best results
    - Environments vary
- More approaches
  - Use most flexible schedulers that can be modified or tuned per-site or per-system
  - Use APIs to modify priorities of process or thread
- However, environments can still vary