# CENG 2034 - Operating Systems

## Week 7 - Week 8: CPU Scheduling

Burak Ekici

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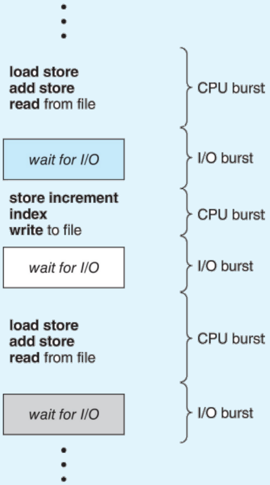
# Outline

1. Basics
2. Scheduling Criteria & Algorithms
3. Thread Scheduling
4. Multiprocessor Scheduling
5. Real-Time CPU Scheduling
6. OS Examples
7. Algorithm Evaluation

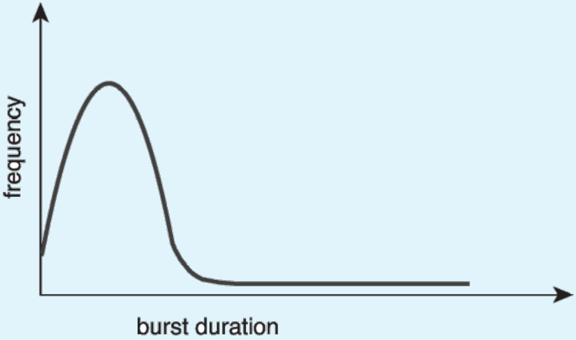
## Basic Concepts

- 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



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- For situations 1 and 4, there is no choice in terms of scheduling. A new process (if one exists in the ready queue) must be selected for execution.
- For situations 2 and 3, however, there is a choice

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- Otherwise, it is preemptive
- Under Nonpreemptive scheduling, once the CPU has been allocated to a process, the process keeps the CPU until it releases it either by terminating or by switching to the waiting state
- Virtually all modern operating systems including Windows, MacOS, Linux, and UNIX use preemptive scheduling algorithms

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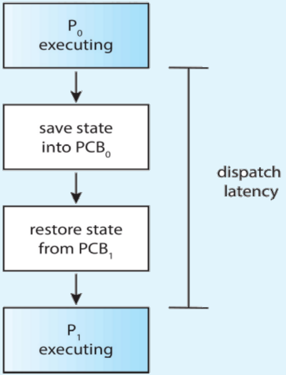
- This issue will be explored in detail in Chapter 6

## Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the CPU 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



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- 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.

## Scheduling Algorithm Optimization Criteria

- Max CPU utilization

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## First-Come, First-Served (FCFS) Scheduling

| Process | Burst Time |
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| $P_1$ | 24 |
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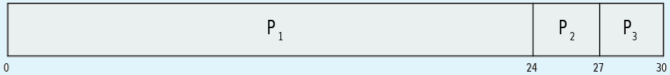

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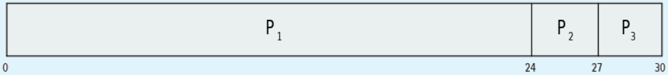


- Waiting time for $P_1 = 0$ $P_2 = 24$ $P_3 = 27$

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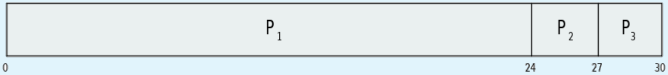


- Waiting time for $P_1 = 0 \quad P_2 = 24 \quad P_3 = 27$
- Average waiting time = $(0 + 24 + 27)/3 = 17$

## First-Come, First-Served (FCFS) Scheduling (cont'd)

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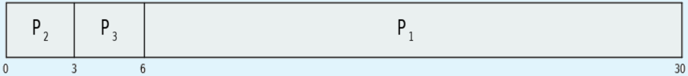


- Waiting time for $P_1 = 6 \quad P_2 = 0 \quad P_3 = 3$
- Average waiting time = $(6 + 0 + 3)/3 = 3$
- Much better than previous case
- Convoy effect - short process behind long process
    - Consider one CPU-bound and many I/O-bound processes

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- How do we determine the length of the next CPU burst?
  - Could ask the user
  - Estimate

## Example (SJF Scheduling)

| Process | Burst Time |
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| $P_1$ | 6 |
| $P_2$ | 8 |
| $P_3$ | 7 |
| $P_4$ | 3 |

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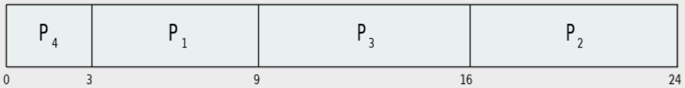
- SJF scheduling chart




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

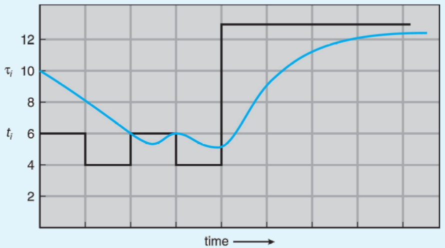
## Determining Length of Next CPU Burst

- 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 $n^{\text{th}}$ CPU burst
  2. $\tau_{n+1}$ = predicted value for the next CPU burst
  3. $\alpha$, $0 \leqslant \alpha \leqslant 1$
  4. Define

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

- Commonly, $\alpha$ set to 1/2

## Prediction of the Length of the Next CPU Burst




| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CPU burst ($t_i$) | | 6 | 4 | 6 | 4 | 13 | 13 | 13 | ... |
| guess ($\tau_i$) | 10 | 8 | 6 | 6 | 5 | 9 | 11 | 12 | ... |

## Example (Exponential Averaging)

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- $\alpha = 1$
  - $\tau_{n+1} = t_n$
  - Only the actual last CPU burst counts
- If we expand the formula for $\tau_{n+1}$, we get:

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

- Since both $\alpha$ and $(1-\alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

## Shortest Remaining Time First Scheduling

- Preemptive version of SJF
- Whenever a new process arrives in the ready queue, the decision on which process to schedule next is redone using the SJF algorithm.
- Is SRT more “optimal” than SJF in terms of the minimum average waiting time for a given set of processes?

## Example (Shortest-remaining-time-first)

- Now we add the concepts of varying arrival times and preemption to the analysis

| Process | Arrival Time | Burst Time |
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| $P_1$ | 0 | 8 |
| $P_2$ | 1 | 4 |
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| $P_4$ | 3 | 5 |

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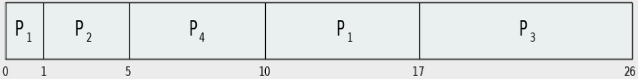

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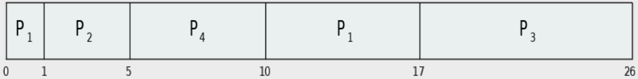


- Waiting time = completion time - execution time - arrival time

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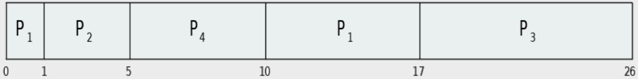


- Waiting time = completion time - execution time - arrival time
- Average waiting time = $[(17-8-0)+(5-4-1)+(26-9-2)+(10-5-3)]/4 = 26/4 = 6.5$

## 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 $(n-1) \times q$ time units
- Timer interrupts every quantum to schedule next process
- Performance $\begin{array}{lll} q \text{ large} & \Rightarrow & \text{FIFO (FCFS)} \\ q \text{ small} & \Rightarrow & \text{RR} \end{array}$
- Note that $q$ must be large with respect to context switch, otherwise overhead is too high

## Example (RR with Time Quantum = 4)

| Process | Burst Time |
|---|---|
| $P_1$ | 24 |
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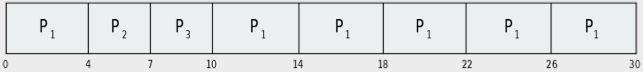
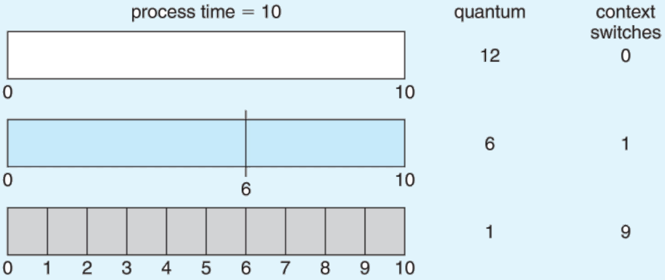



- Typically, higher average turnaround than SJF, but better response
- $q$ should be large compared to context switch time
  - $q$ usually 10 milliseconds to 100 milliseconds,
  - Context switch < 10 microseconds

## Time Quantum and Context Switch Time



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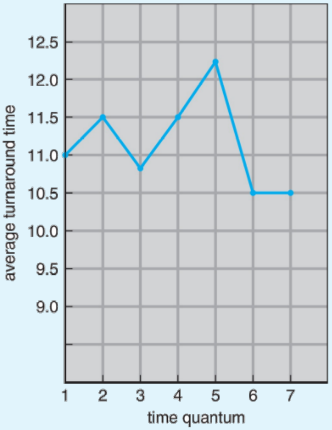


| process | time |
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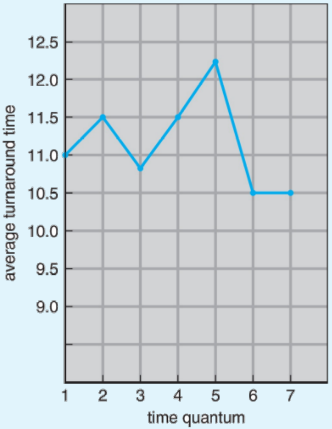
## Turnaround Time Varies With The Time Quantum

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NB: 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

| Process | Burst Time | Priority |
| --- | --- | --- |
| $P_1$ | 10 | 3 |
| $P_2$ | 1 | 1 |
| $P_3$ | 2 | 4 |
| $P_4$ | 1 | 5 |
| $P_5$ | 5 | 2 |

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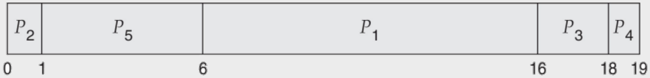
- Priority scheduling Gantt Chart



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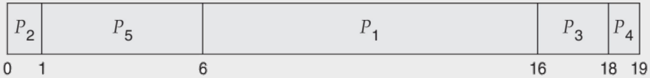


- Average waiting time = 8.2

## 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 |

## Priority Scheduling w/ Round-Robin

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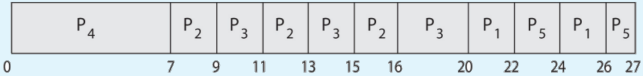
- Gantt Chart with time quantum = 2

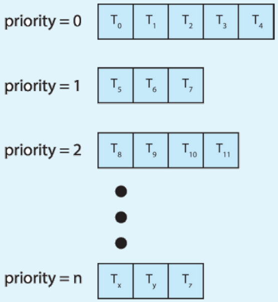


## Multilevel Queue

- The ready queue consists of multiple queues
- Multilevel queue scheduler defined by the following parameters:
  - Number of queues
  - Scheduling algorithms for each queue
  - Method used to determine which queue a process will enter when that process needs service
  - Scheduling among the queues

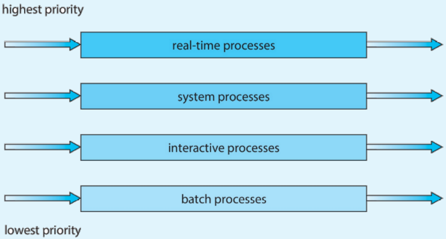
## Multilevel Queue (cont'd)

- With priority scheduling, have separate queues for each priority.
- Schedule the process in the highest-priority queue!



## Multilevel Queue (cont’d)

Prioritization based upon process type



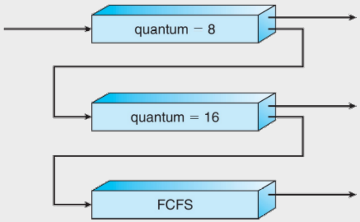
## Multilevel Queue Feedback

Prioritization based upon process type

- A process can move between the various queues.
- 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
- Aging can be implemented using multilevel feedback queue

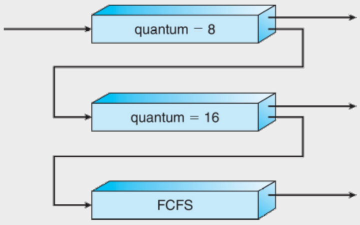
## Example (Multilevel Feedback Queue)

- Three queues:



## Example (Multilevel Feedback Queue)

- Three queues:
  - $Q_0$ – RR with time quantum 8 milliseconds



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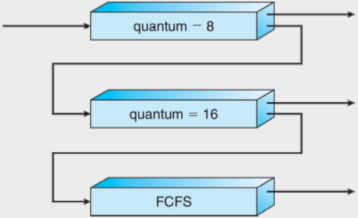

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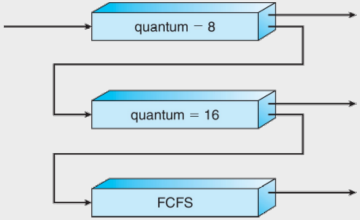

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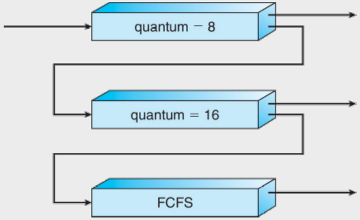

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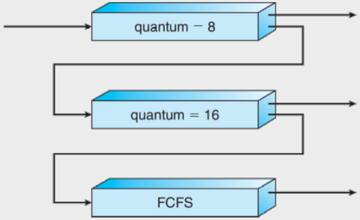

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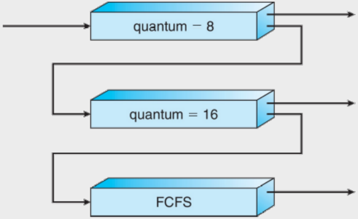

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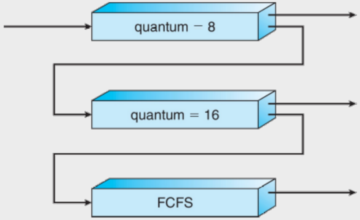

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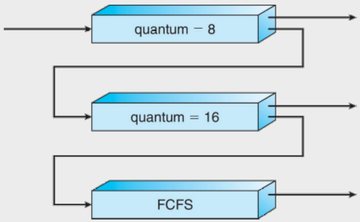

# Outline

## Thread Scheduling

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- 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

```c
#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 (cont'd)

```
   /* 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);
}
```

# Outline

## 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 (cont'd)

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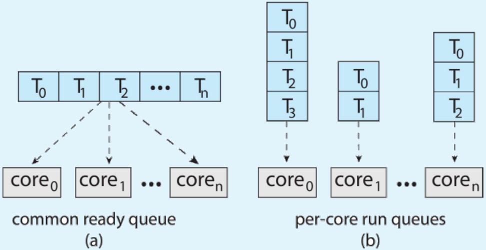
- Each processor may have its own private queue of threads (b)



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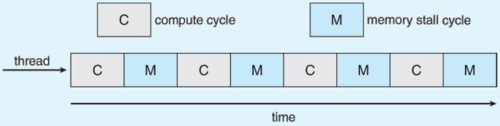

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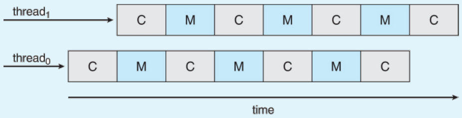
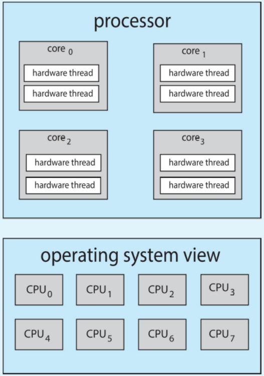


## Multithreaded Multicore System (cont'd)

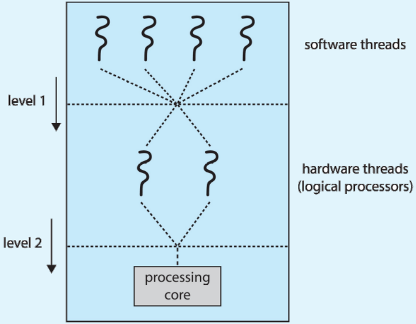
- Chip-multithreading (CMT) assigns each core multiple hardware threads – Intel refers to this as hyperthreading
- On a quad-core system with 2 hardware threads per core, the operating system sees 8 logical processors



## Multithreaded Multicore System (cont'd)

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



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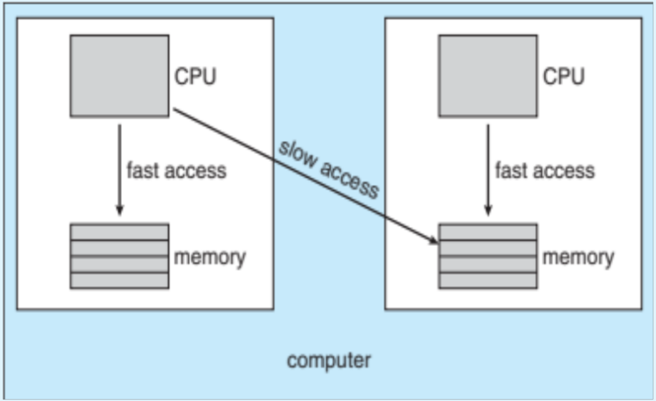
- Hard affinity – allows a process to specify a set of processors it may run on

## NUMA and CPU Scheduling

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



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- Hard real-time systems – task must be serviced by its deadline

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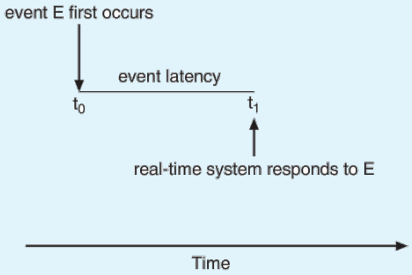

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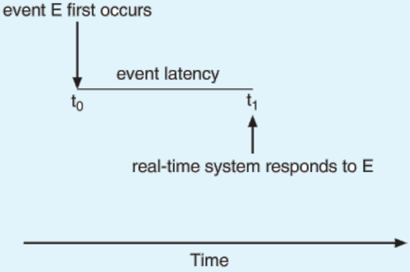

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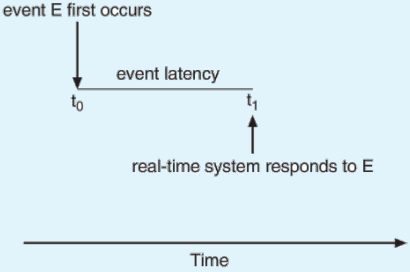

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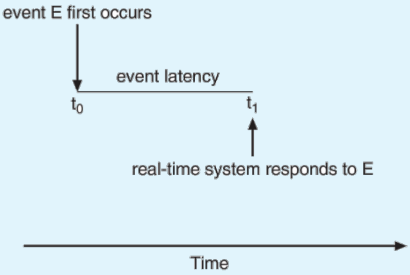

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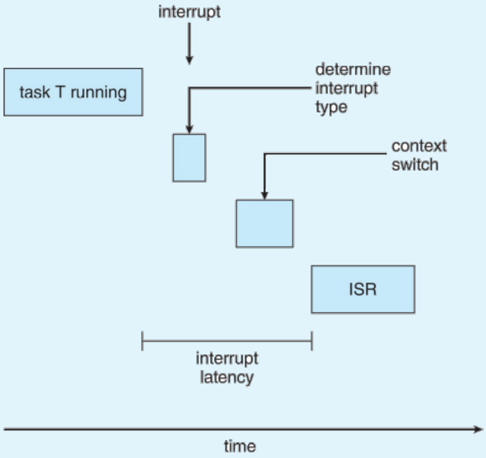

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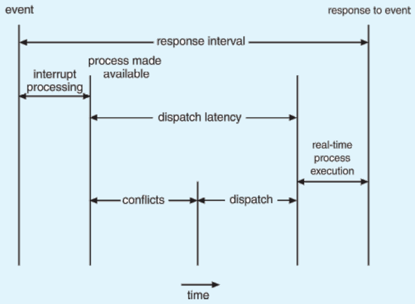

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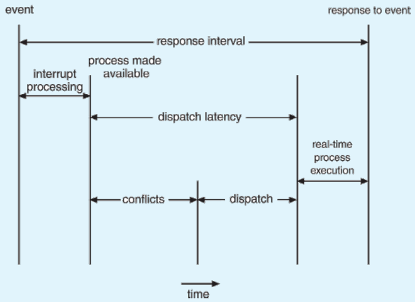

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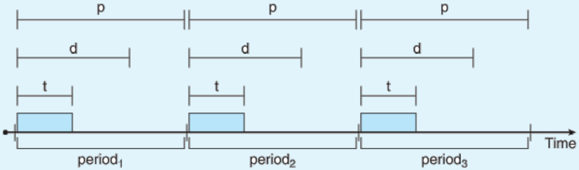

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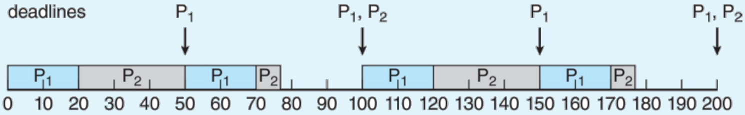

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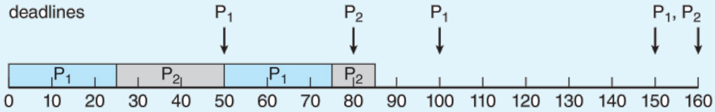

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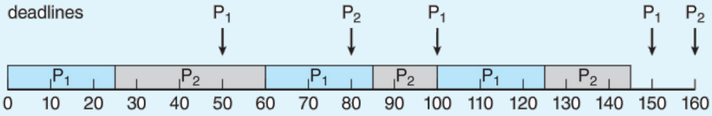

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  1. `SCHED_FIFO` - threads are scheduled using a FCFS strategy with a FIFO queue. There is no time-slicing for threads of equal priority
  2. `SCHED_RR` - similar to `SCHED_FIFO` except time-slicing occurs for threads of equal priority
- Defines two functions for getting and setting scheduling policy:
  1. `pthread_attr_getsched_policy(pthread_attr_t *attr, int *policy)`

## POSIX Real-Time Scheduling

- The POSIX.1b standard
- API provides functions for managing real-time threads
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  2. `pthread_attr_setsched_policy(pthread_attr_t *attr, int policy)`

## POSIX Real-Time Scheduling API

```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'd)

```
   /* 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);
}
```

# Outline

## 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
  - Two scheduling classes included, others can be added: default and real-time

## Linux Scheduling in Version 2.6.23 + (cont's)

- 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

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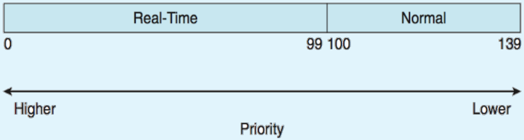
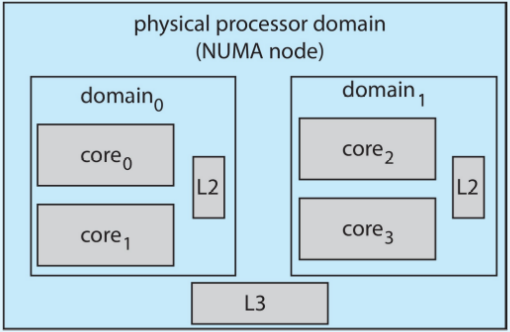


## Linux Scheduling (cont'd)

- 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.



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- 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 |

# Outline

## 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 |

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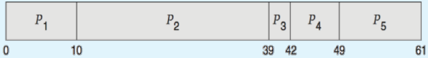

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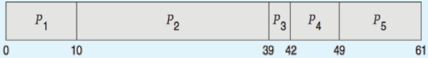


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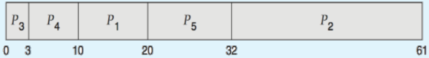

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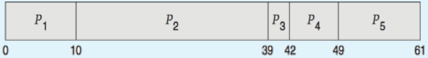


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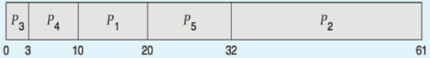
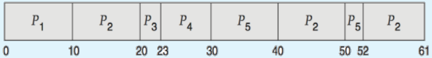



  - RR is 23ms:



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

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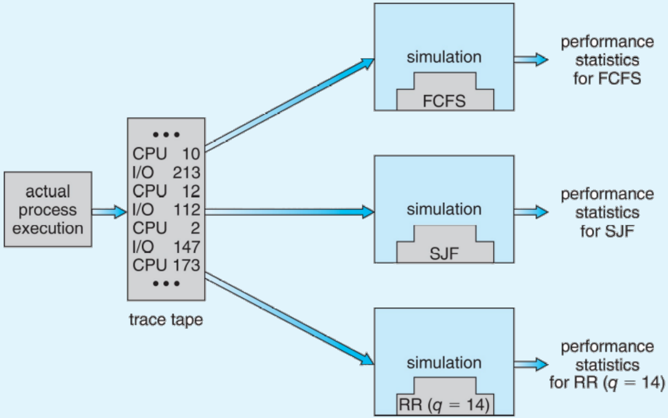
## Evaluation of CPU Schedulers by Simulation



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Thanks! & Questions?