CPU Scheduling

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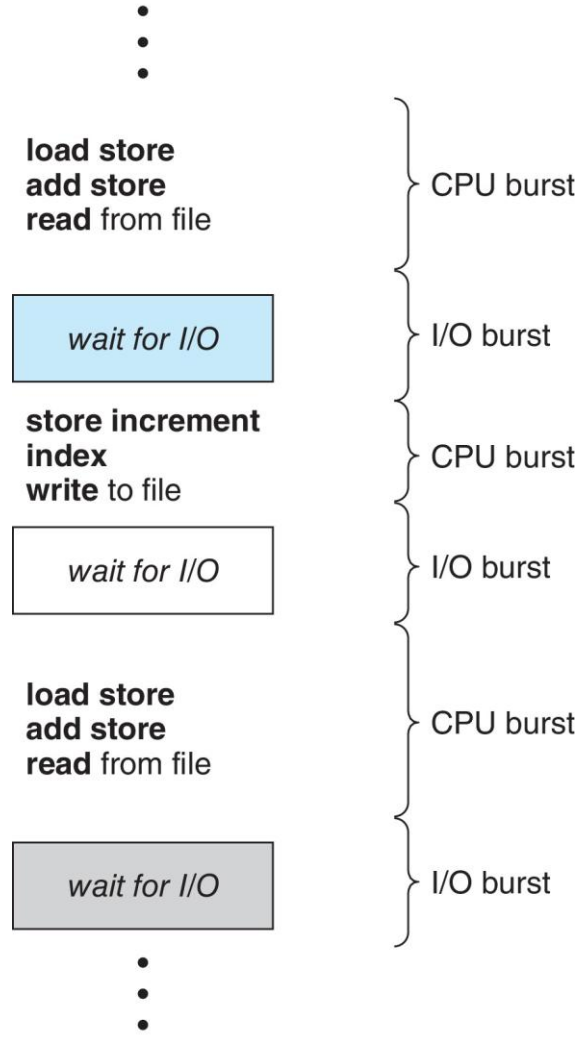
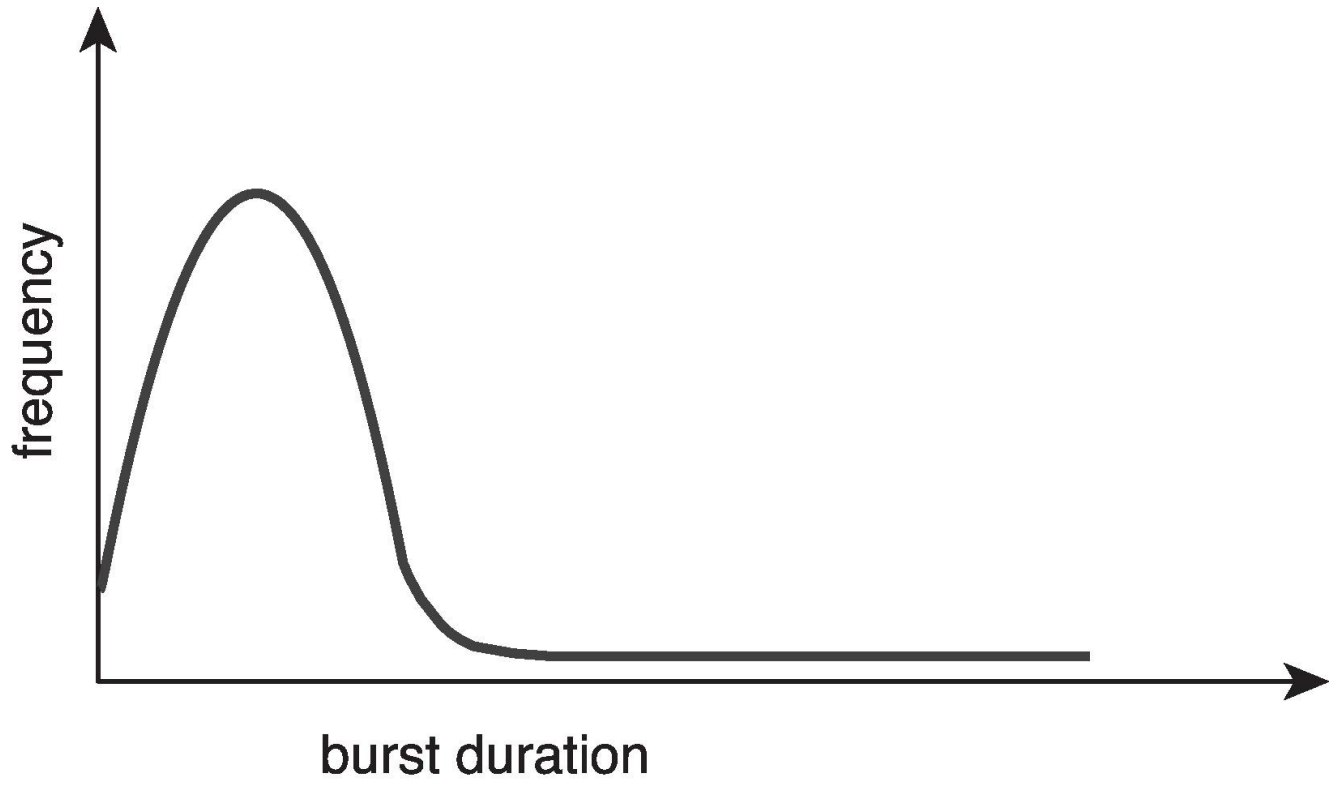
Outline

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

Basic Concepts

- Maximum CPU utilization obtained with multiprogramming
- CPU Burst – 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



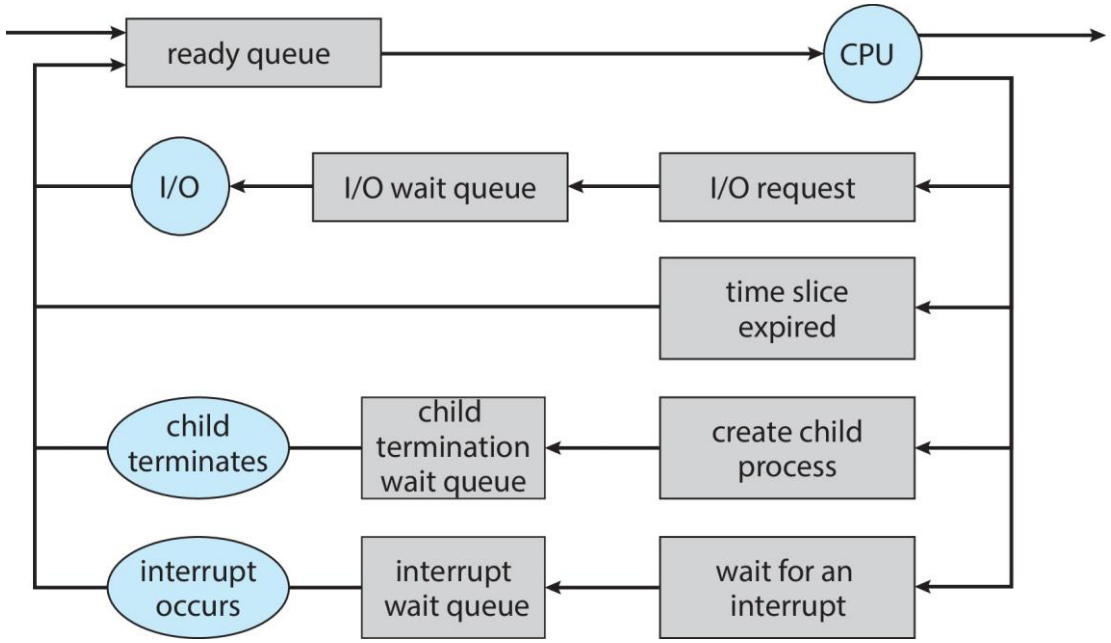


Histogram of CPU-burst Times

CPU Scheduler

- The **CPU scheduler** selects from among the processes in the ready queue and allocates 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
- For situations 1 and 4, there is no choice regarding scheduling for that process. 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.

Representation of Process Scheduling



Preemptive and Nonpreemptive Scheduling

- When scheduling takes place only under circumstances 1 and 4, the scheduling scheme is **non-preemptive**.
- Otherwise, it is **preemptive**.
- Under non-preemptive 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.

Preemptive Scheduling and Race Conditions

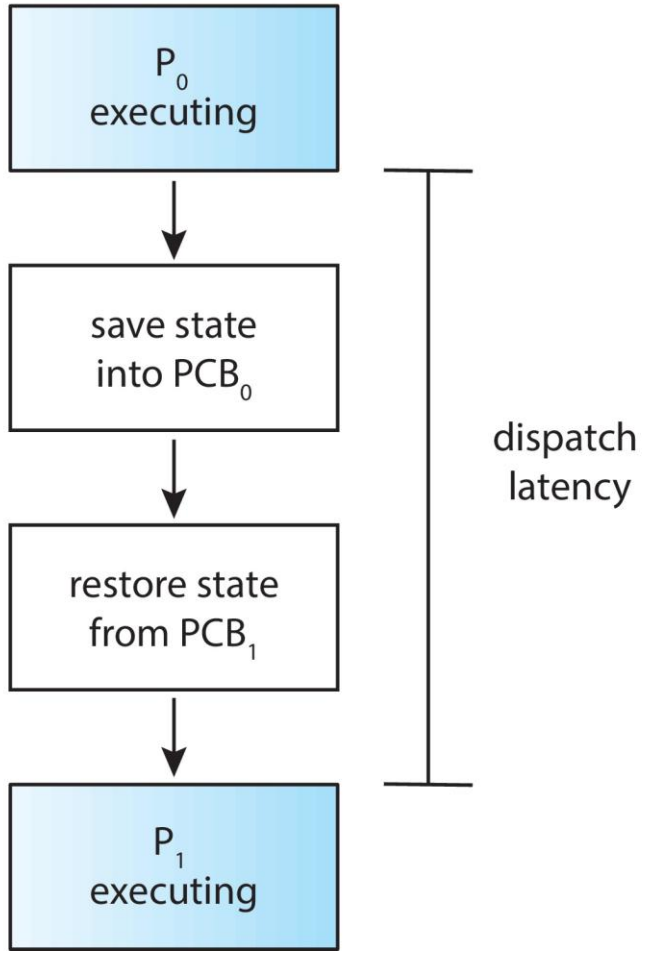
- Preemptive scheduling can result in race conditions when data are shared among several processes.

> **Consider the case of two processes that share data. While one process is updating the data, it is preempted so that the second process can run. The second process then tries to read the data, which are in an inconsistent state.**

- Commands of interest in Linux:
  - `vmstat 1 10`
  - `cat /proc/2166/status`

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



Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes that complete their execution per time unit
- **Turnaround time** – the amount of time to execute a particular process (waiting time + CPU time + I/O time)
- **Waiting time** – the amount of time a process has been waiting in the ready queue
- **Response time** – the time it takes from when a request was submitted until the first response is produced.

First- Come, First-Served (FCFS) Scheduling (AKA FIFO)

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 the previous case
- **Convoy effect** - short process behind long process
  - Consider one CPU-bound and many I/O-bound processes

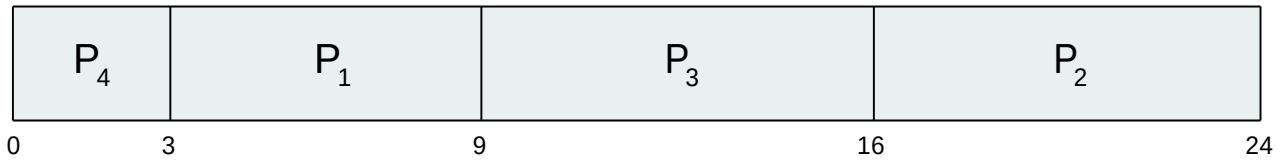
Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its **next CPU burst**
  - Use these lengths to schedule the process in the shortest time
- SJF is optimal – gives minimum average waiting time for a given set of processes
- How do we determine the length of the next CPU burst?
  - Could ask the user
  - Estimate

Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- SJF scheduling chart



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

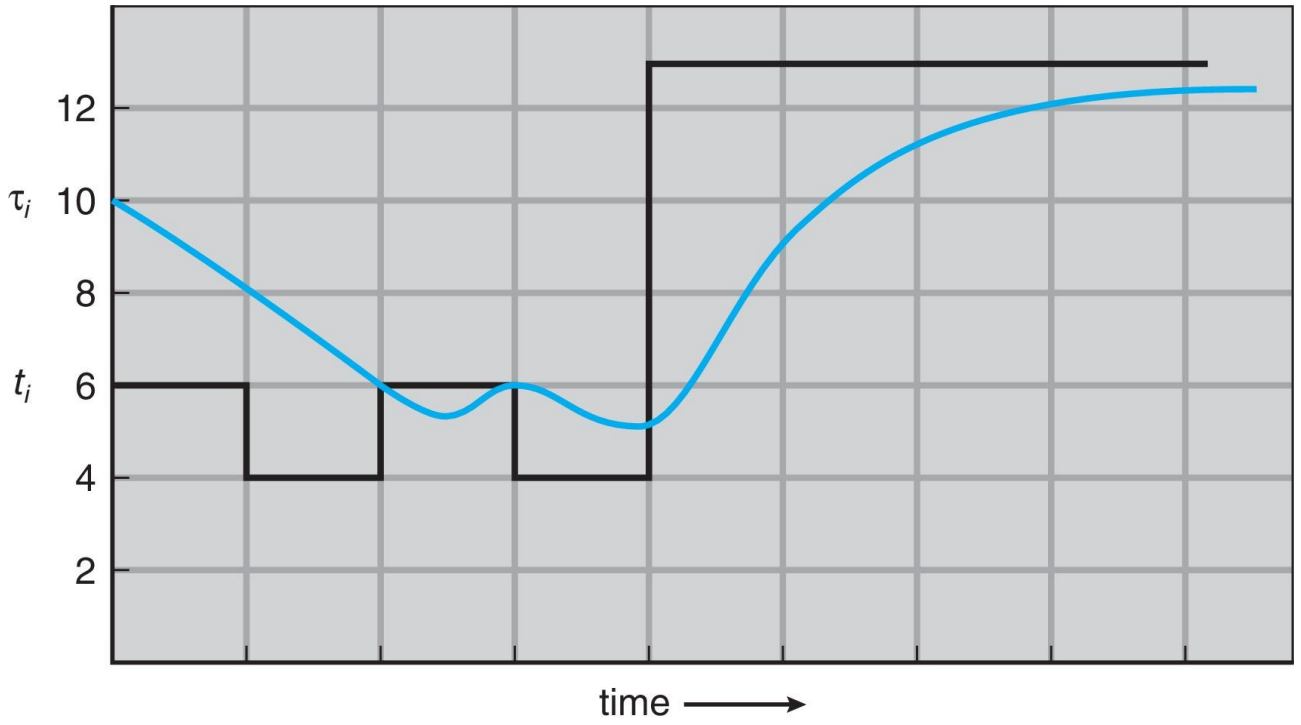
Determining Length of Next CPU Burst

- Can only estimate the length – should be similar to the previous one
  - Then pick the process with the 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. τ_{n+1} = predicted value for the next CPU burst
3. α, $0 \leq \alpha \leq 1$
4. Define:

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

- Commonly, α set to ½



CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Prediction of the Length of the Next CPU Burst

Examples of Exponential Averaging

- α =0
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- α =1
  - $\tau_{n+1} = \alpha\, t_n$
  - Only the actual last CPU burst counts

Shortest Remaining Time First Scheduling

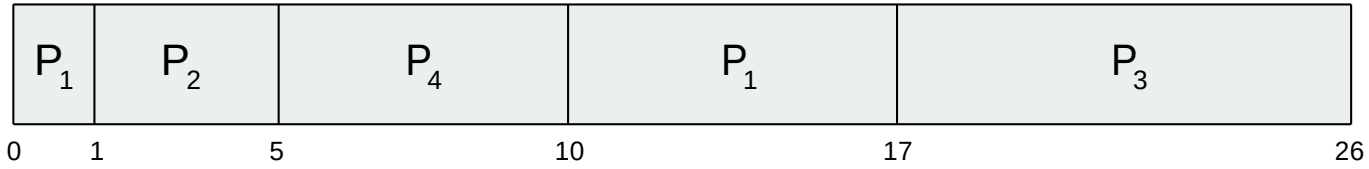
- Preemptive version of SJF
- Whenever a new process arrives in the ready queue, the decision on which process to schedule next is redone using the SJF algorithm.
- **Is SRT more “optimal” than SJF in terms of the minimum average waiting time for a given set of processes?**

Example of Shortest-remaining-time-first

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

Process i	*Arrival* Time T	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

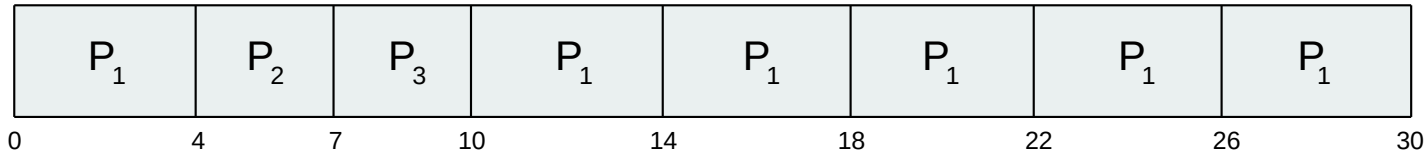
Round Robin (RR)

- 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 (FCFS)
  - q small $\Rightarrow$ RR
- Note that q must be large with respect to context switch, otherwise overhead is too high

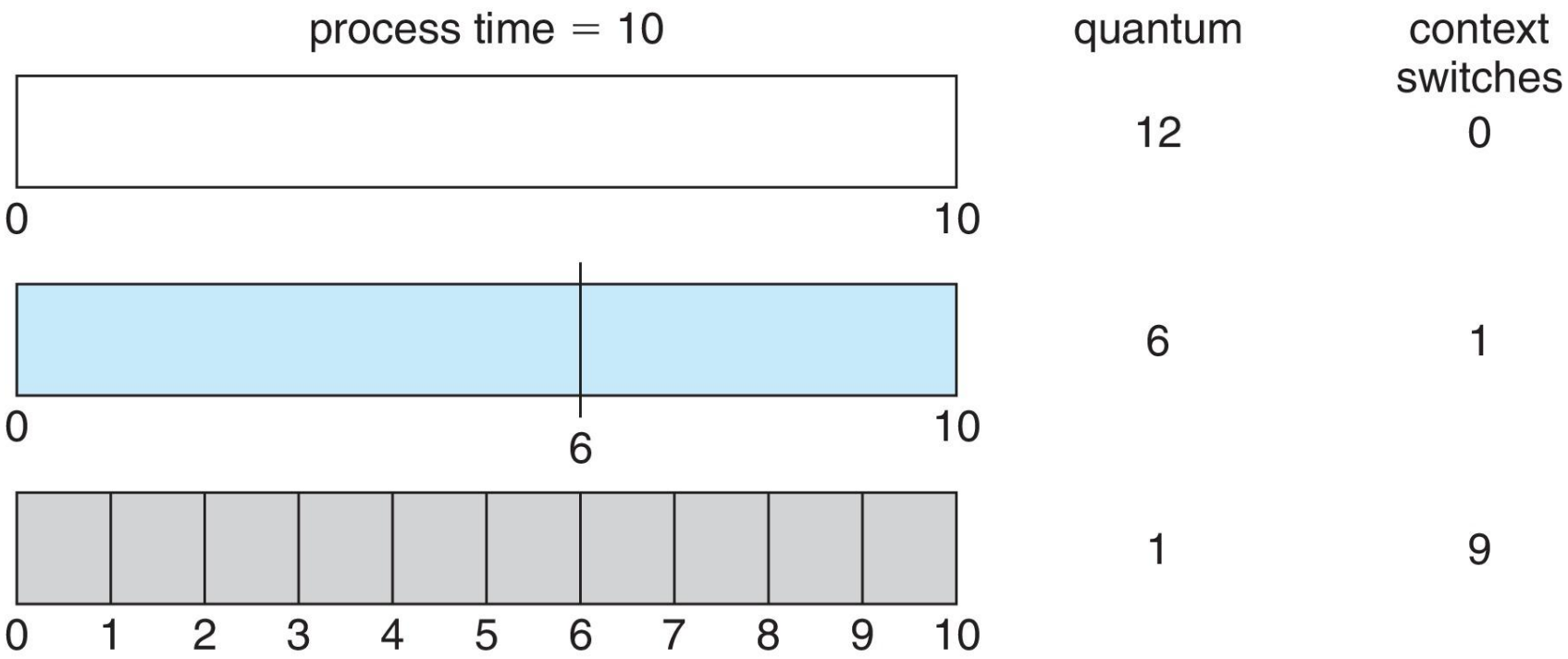
Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

- The Gantt chart is:

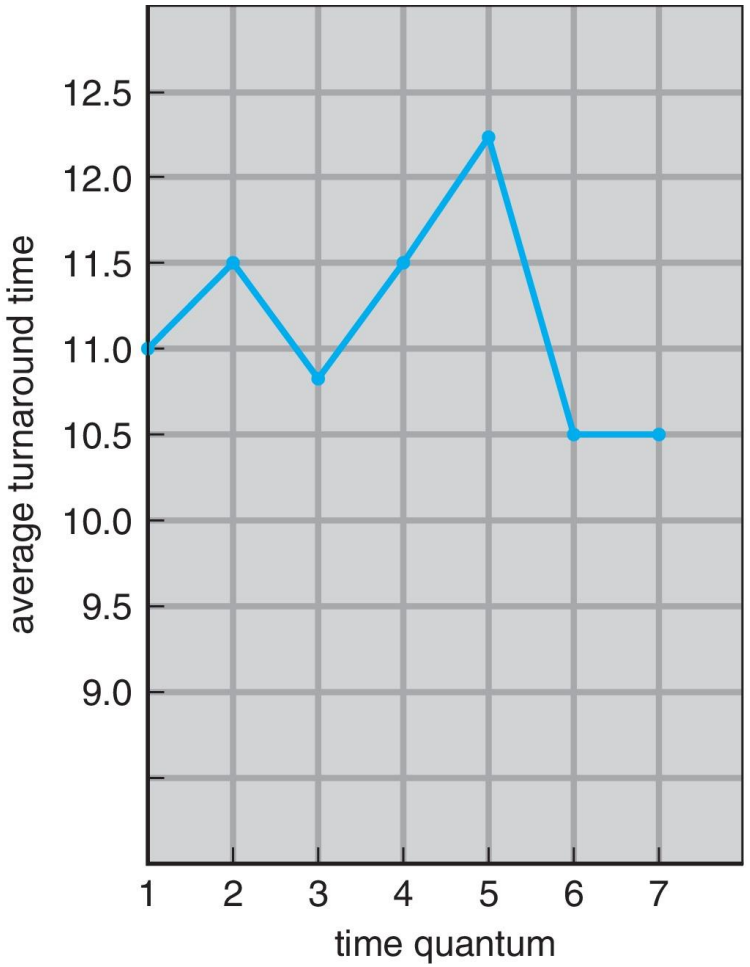


- Typically, **higher average turnaround** than SJF, but better ***response***
- q should be large compared to context switch time
  - q usually 10 milliseconds to 100 milliseconds,
  - Context switch < 10 microseconds



The performance of the RR algorithm depends heavily on the size of the time quantum.

Time Quantum and Context Switch Time



process	time
P_1	6
P_2	3
P_3	1
P_4	7

- 80% of CPU bursts should be shorter than TQ

Turnaround Time Varies With The Time Quantum

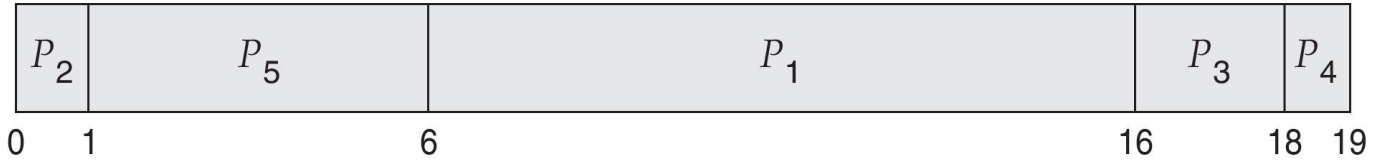
Priority Scheduling

- 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 a priority scheduling where priority is the inverse of the 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



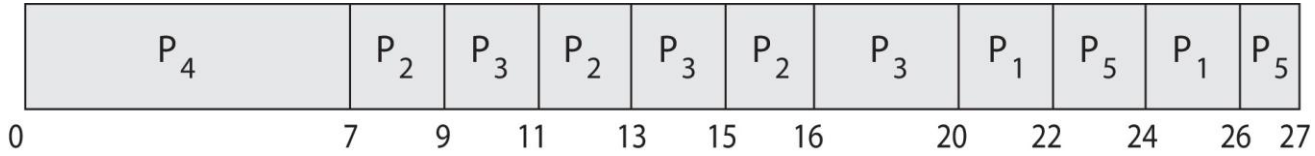
- Average waiting time = 8.2

Priority Scheduling w/ Round-Robin

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

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

- Gantt Chart with time quantum = 2

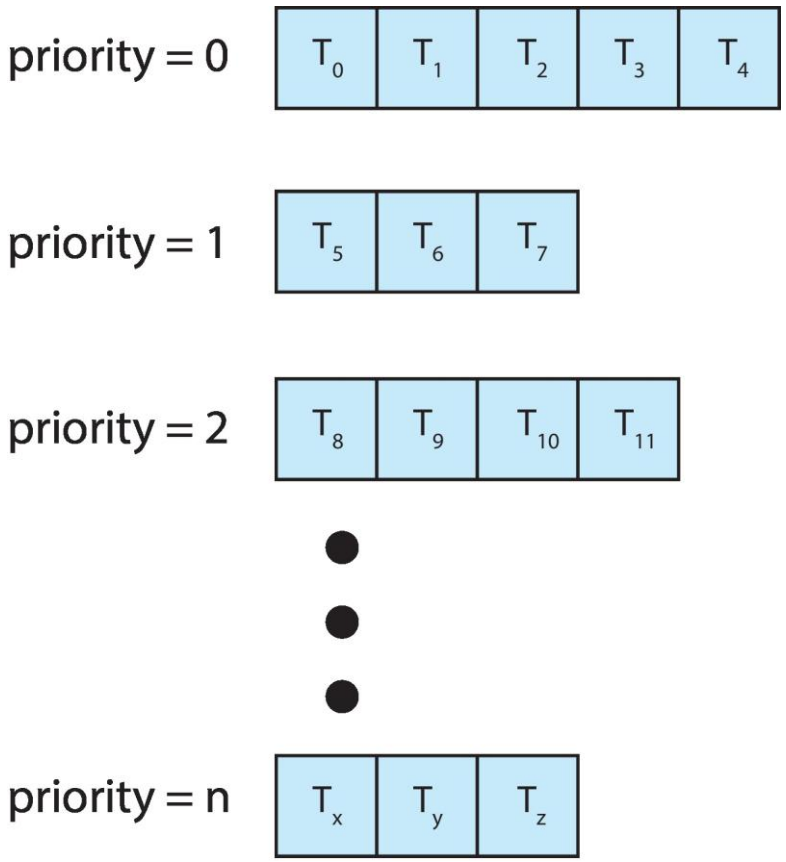


Multilevel Queue

- 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

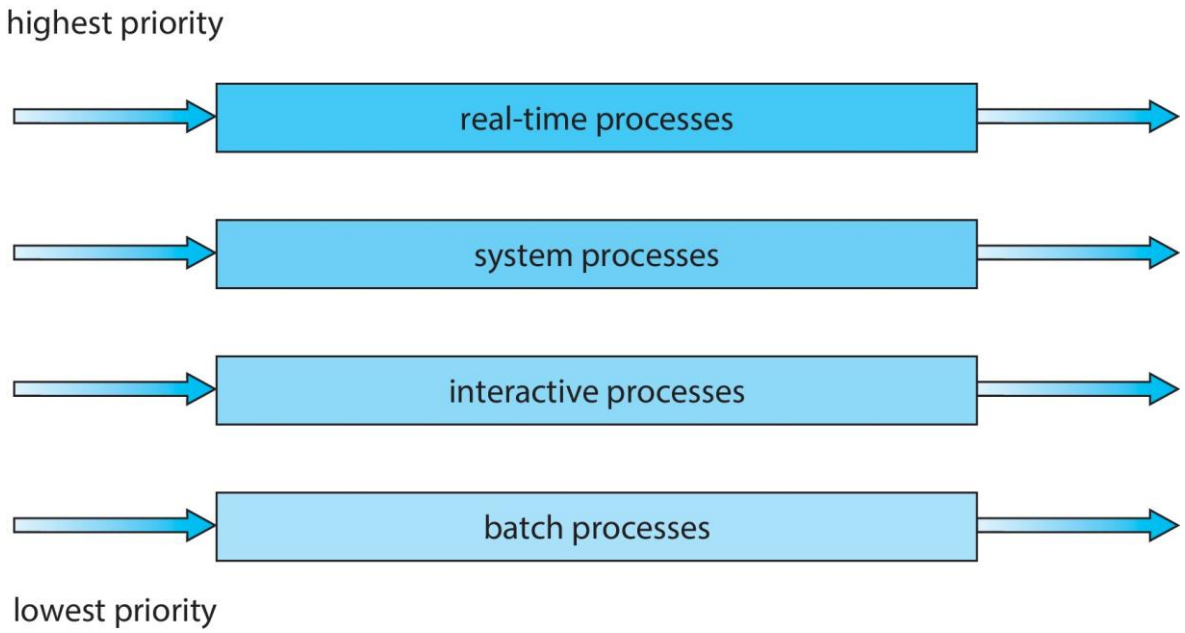
Multilevel Queue

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



Multilevel Queue

Prioritization based upon process type



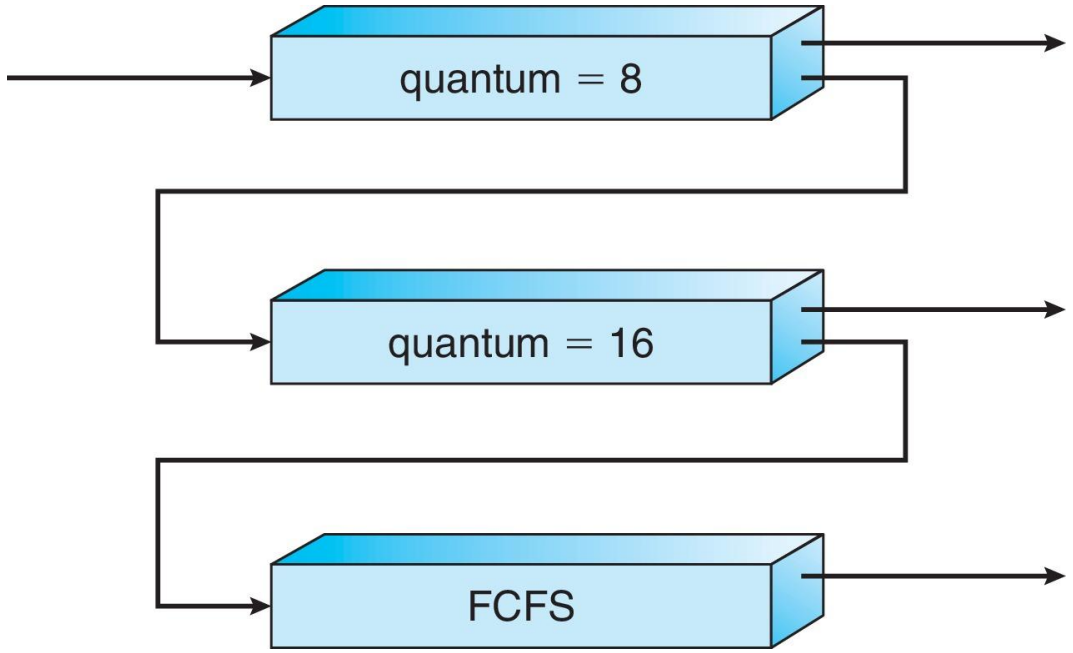
Multilevel Feedback Queue

- A process can move between the various queues.
- 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 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 process enters queue Q_0 which is served in RR
  - When it gains CPU, the process receives 8 milliseconds
  - If it does not finish in 8 milliseconds, the process is moved to queue Q_1
- At Q_1 job is again served in RR 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 are 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

Multiple-Processor Scheduling

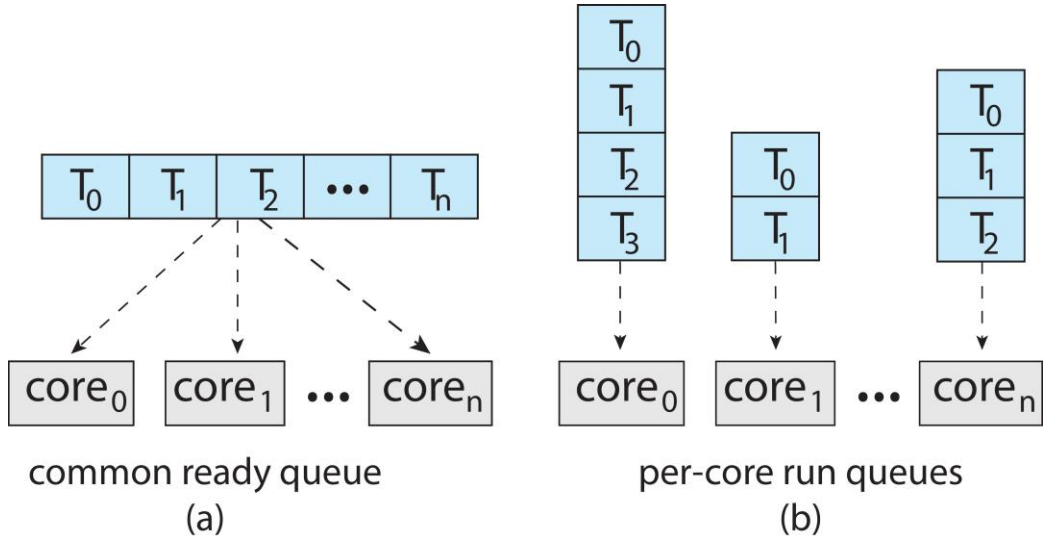
- CPU scheduling is more complex when multiple CPUs are available
- Multiprocess may be any one of the following architectures:
  - Multicore CPUs
  - Multithreaded cores
  - NUMA systems

Multiple-Processor Scheduling

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

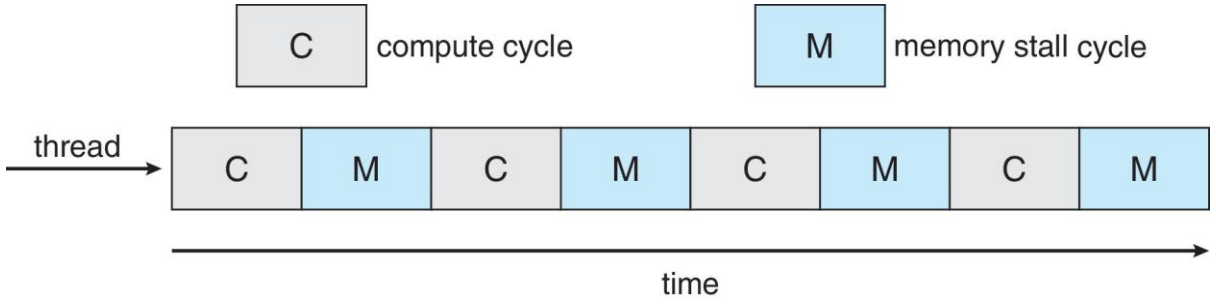
All threads may be in a common ready queue (a)

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



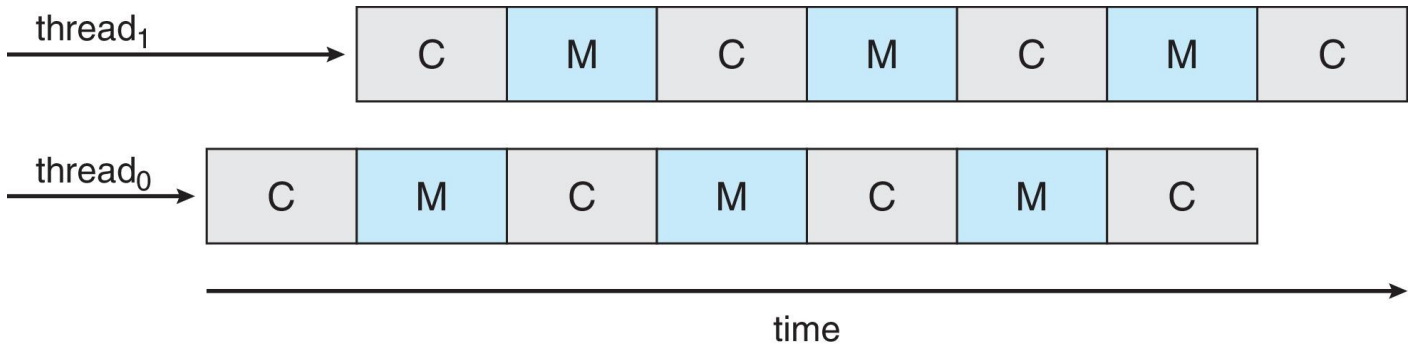
Multicore Processors

- 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 retrieval happens



Multithreaded Multicore System

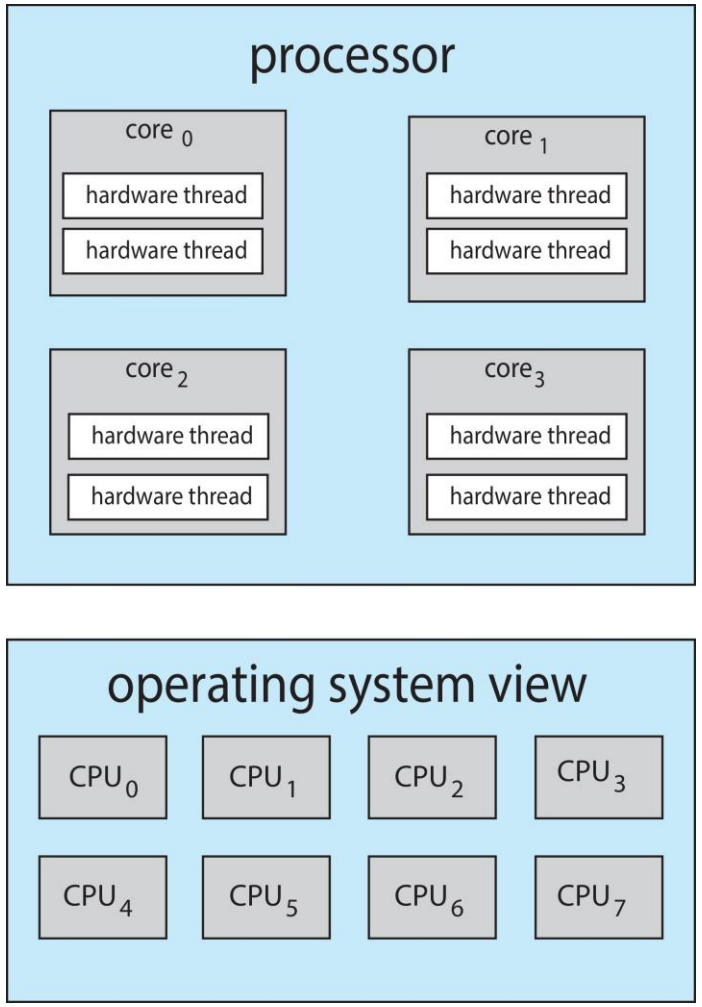
- Each core has > 1 hardware threads.
- If one thread has a memory stall, switch to another thread!



Multithreaded Multicore System

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

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

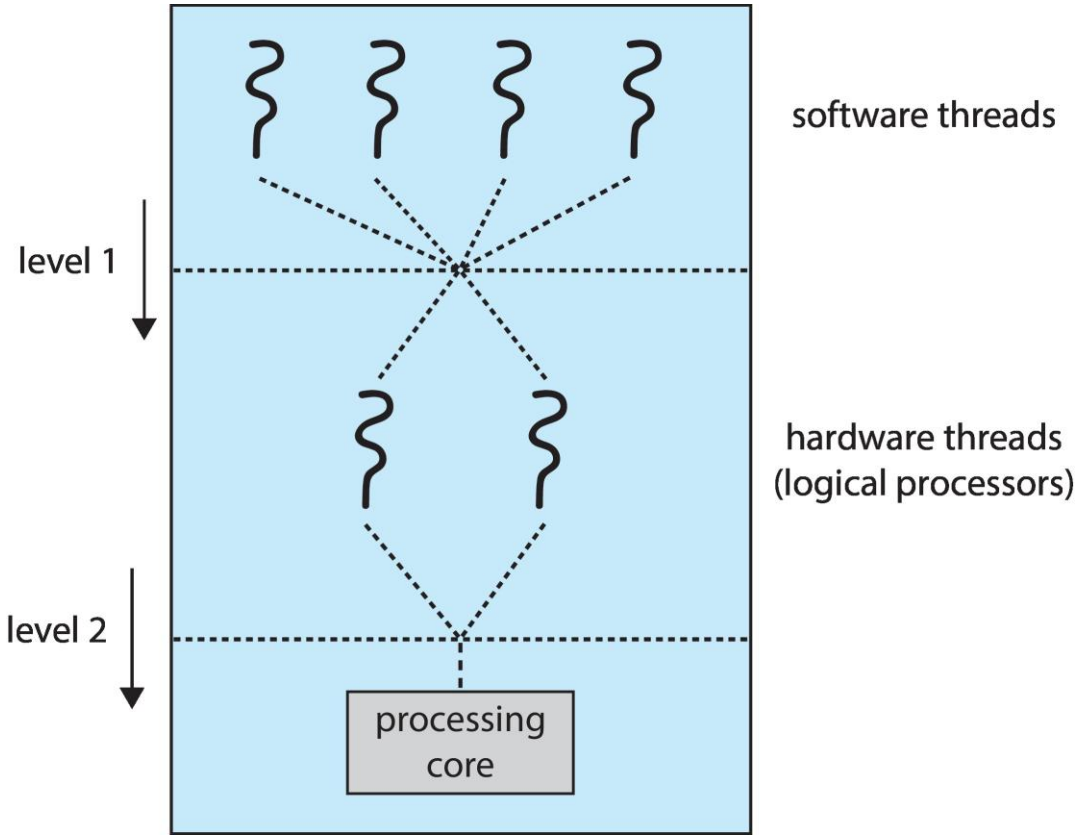


Multithreaded Multicore System

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, needs to keep all CPUs loaded for efficiency
- **Load balancing** attempts to keep the 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 pull 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 store the memory accessed by that thread.

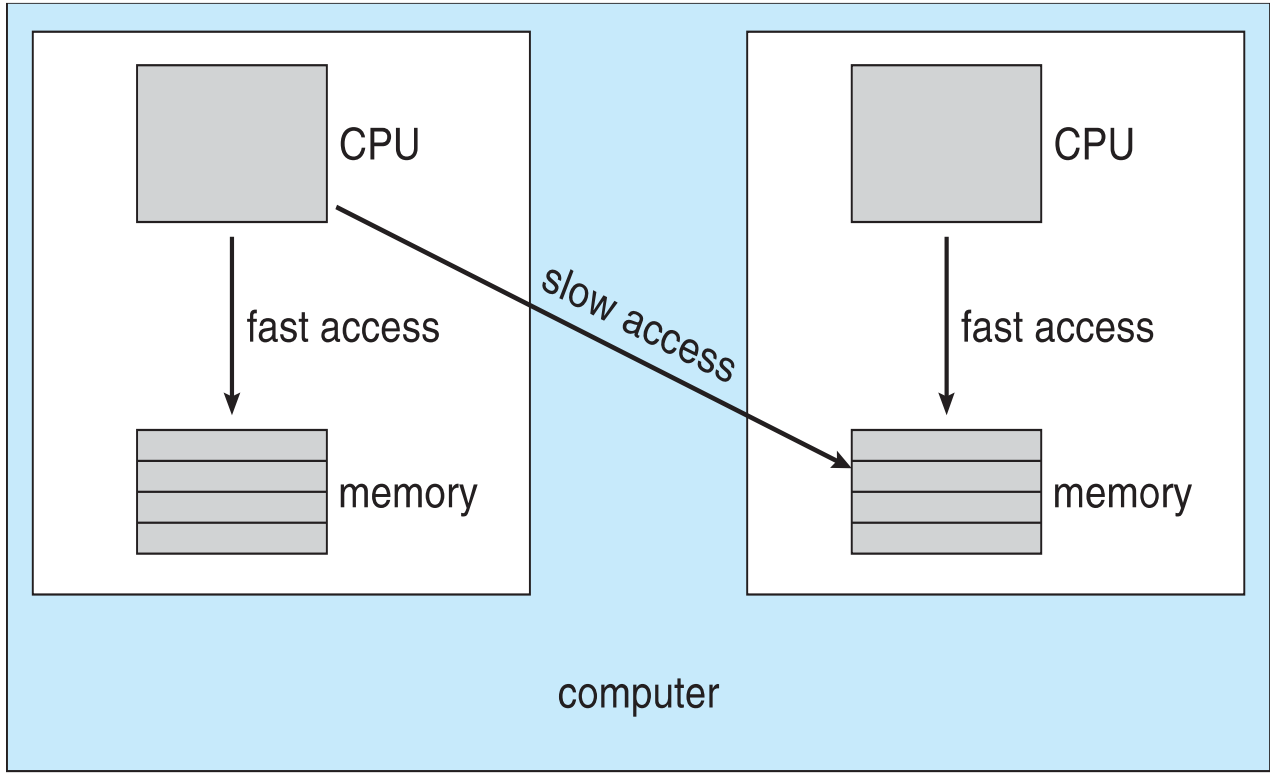
We refer to this as a thread having affinity for a processor (i.e., “processor affinity”)

Load balancing may affect processor affinity. 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. (e.g. Linux)

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



NUMA and CPU Scheduling

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**

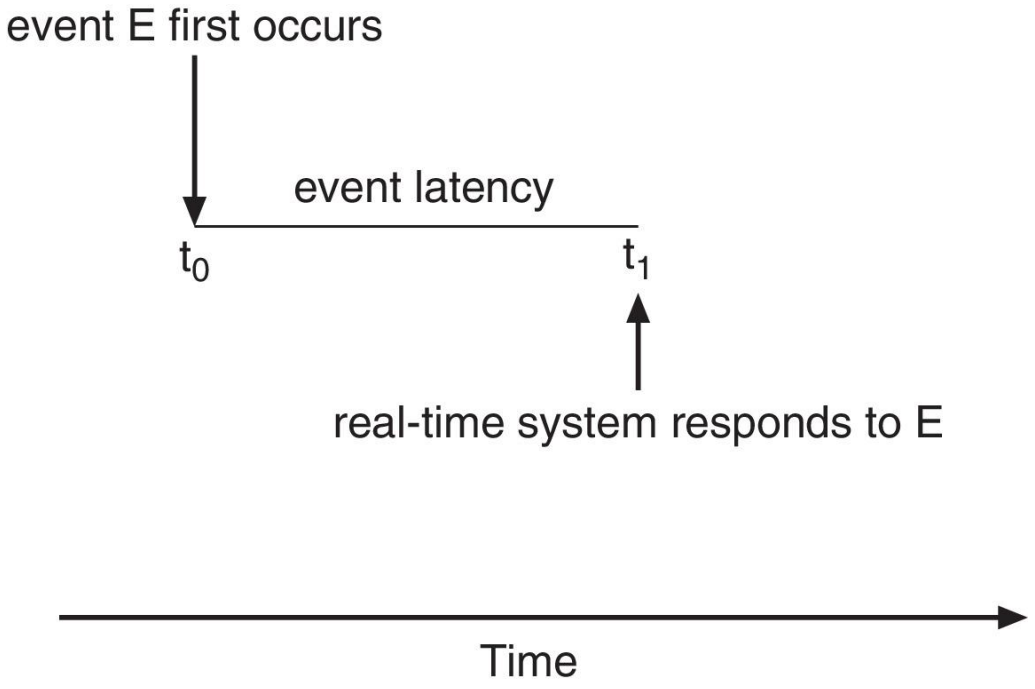
Real-Time CPU Scheduling

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

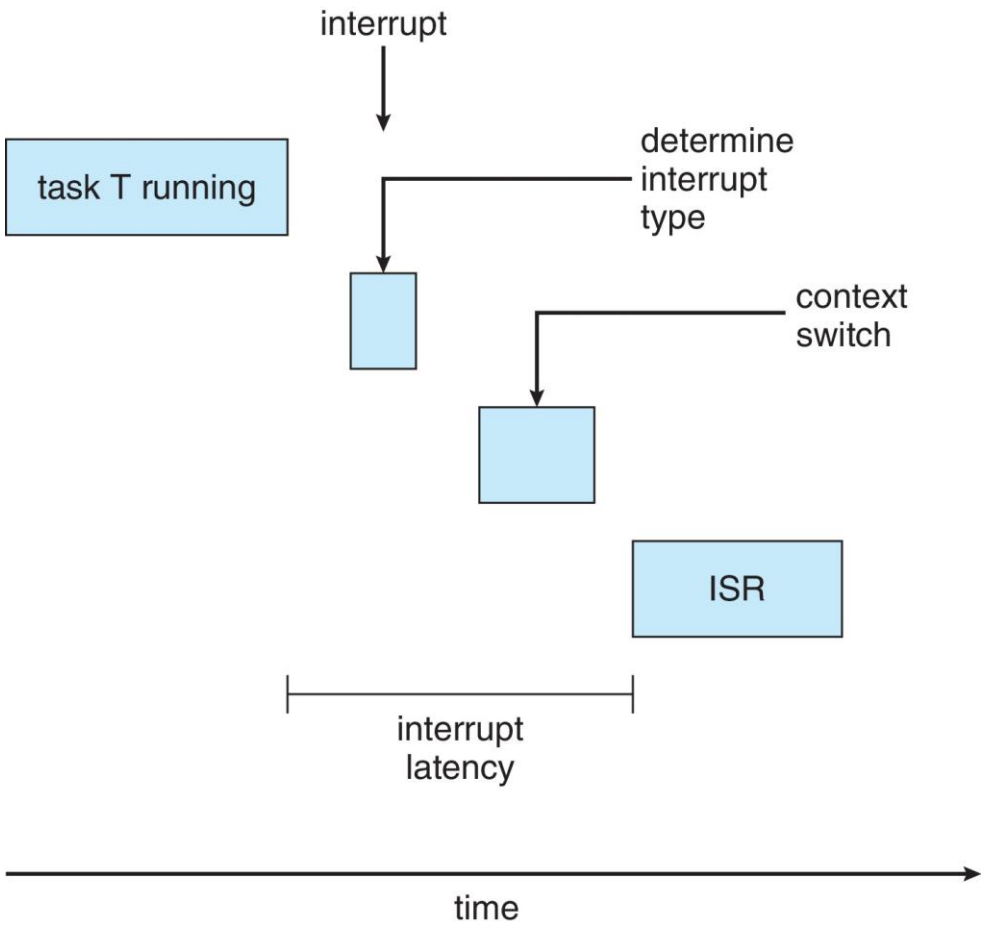
Two types of latencies affect performance

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



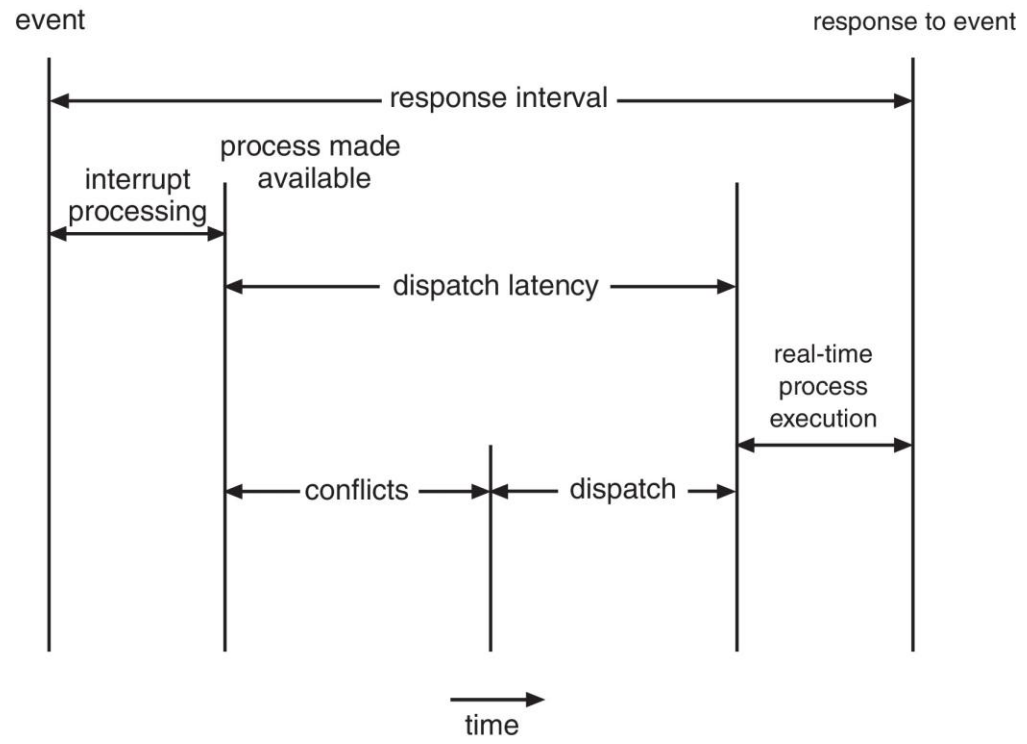
Interrupt Latency



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

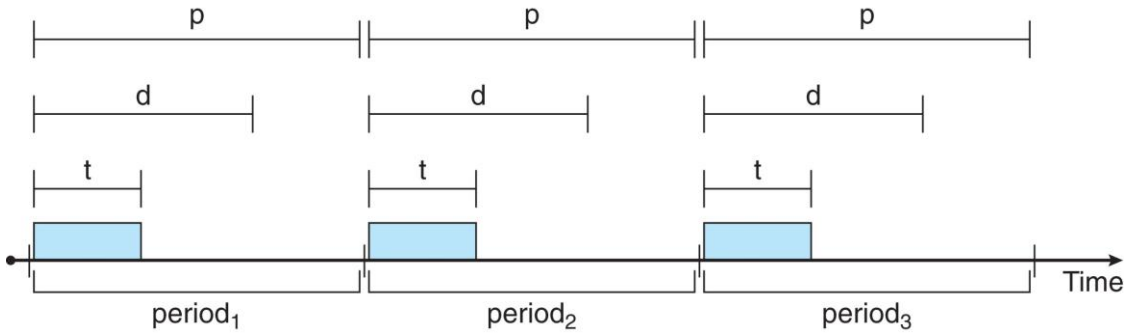
For real-time scheduling, scheduler must support preemptive, priority-based scheduling

- 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 $1/p$



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)`

Linux Scheduling Through Version 2.5

- Before kernel version 2.5, ran a 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 (CFS)
    - real-time

Linux Scheduling in Version 2.6.23 + (Cont.)

Quantum calculated based on **nice value** from -20 to +19

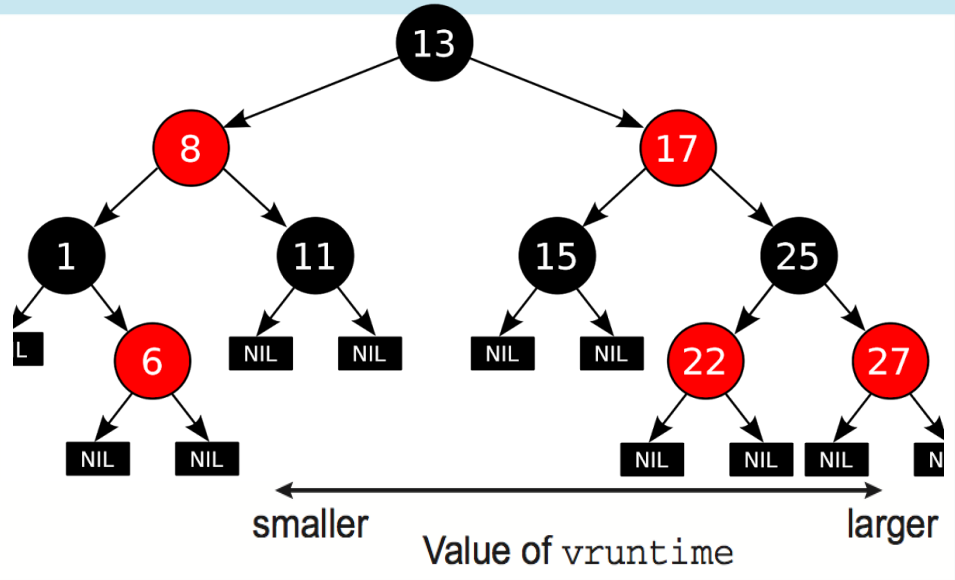
- Lower value is higher priority
- Calculates **target latency** – interval of time during which task should run at least once
- Target latency can increase if say number of active tasks increases

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

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:

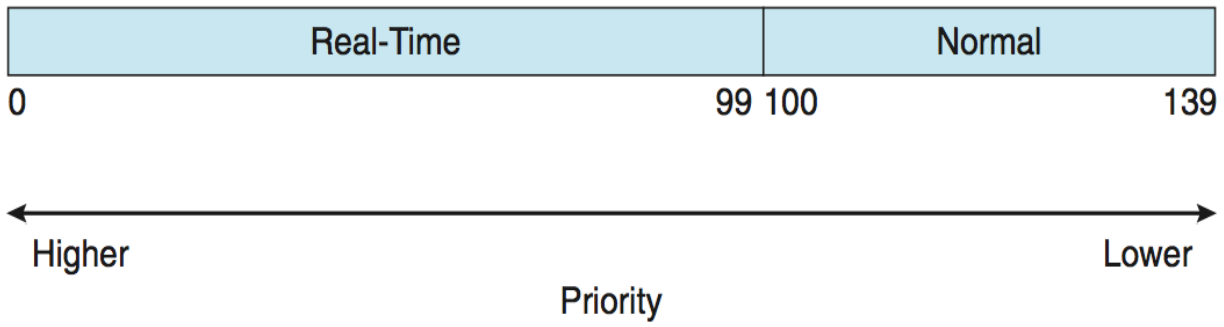


When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable (for example, if it is blocked while waiting for I/O), it is removed. Generally speaking, tasks that have been given less processing time (smaller values of `vruntime`) are toward the left side of the tree, and 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.

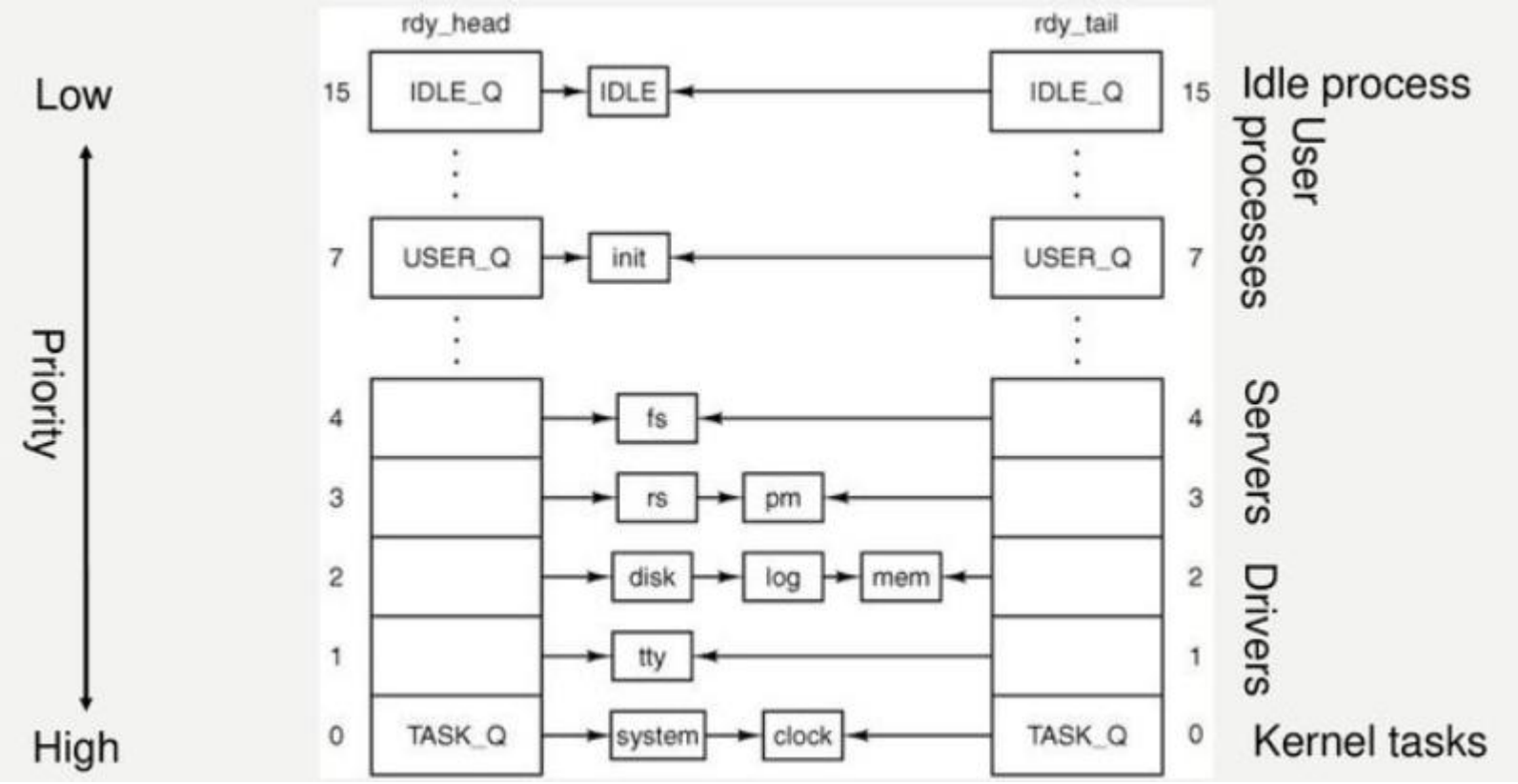
CFS Performance

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



Scheduling in Minix



Thank you

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