CISC 7310X

C05c: Thread, Multiprocessor, and Real-time Scheduling

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Acknowledgement

- This slides are a revision of the slides by the authors of the textbook

Outline

- Thread Scheduling
- Multi-Processor Scheduling
- Real-Time CPU Scheduling

- Operating Systems Examples
- Algorithm Evaluation

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

Example: 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

- `pthread_attr_getscope`
- `pthread_attr_setscope`

Questions?

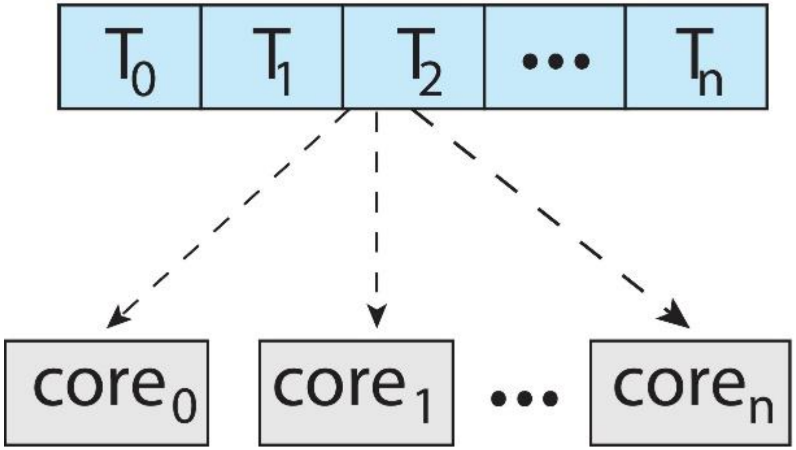
- Thread scheduling
- SCS
- Pthread example

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

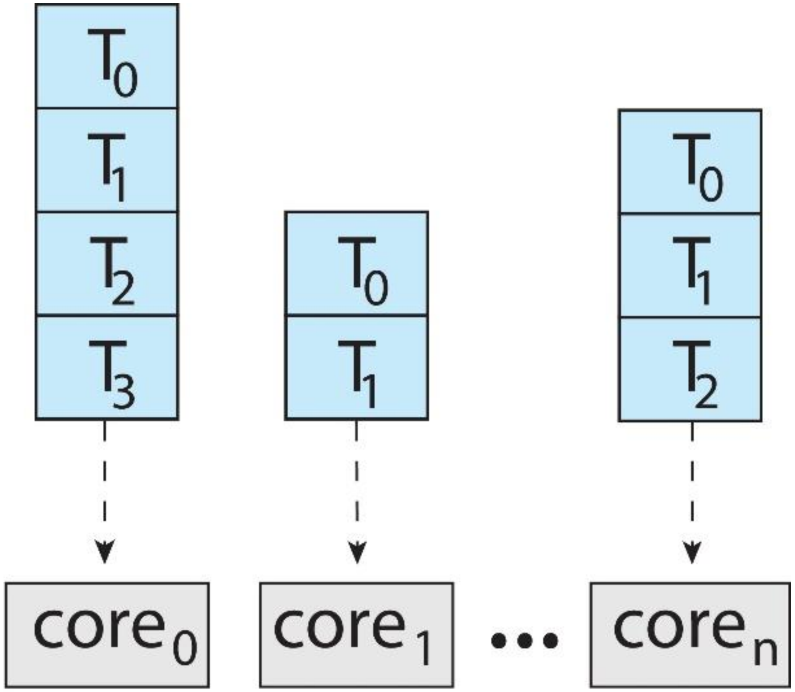
Multiple-Processor Scheduling: SMP

- 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)



common ready queue

(a)

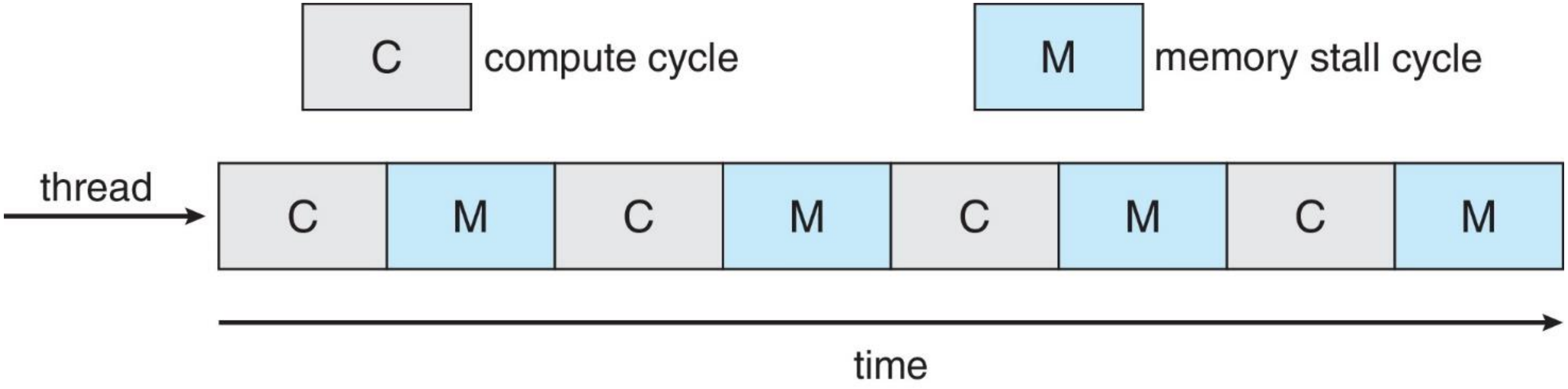


per-core run queues

(b)

Multicore Processors

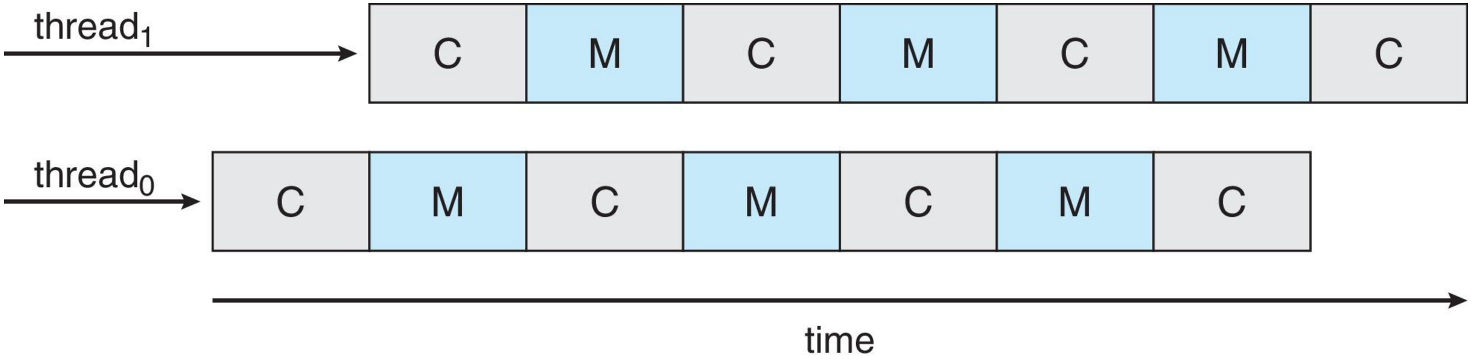
- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens


C
compute cycle
M
memory stall cycle
thread
C
M
C
M
C
M
C
M
time

Multithreaded Multicore System

Each core has > 1 hardware threads.

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

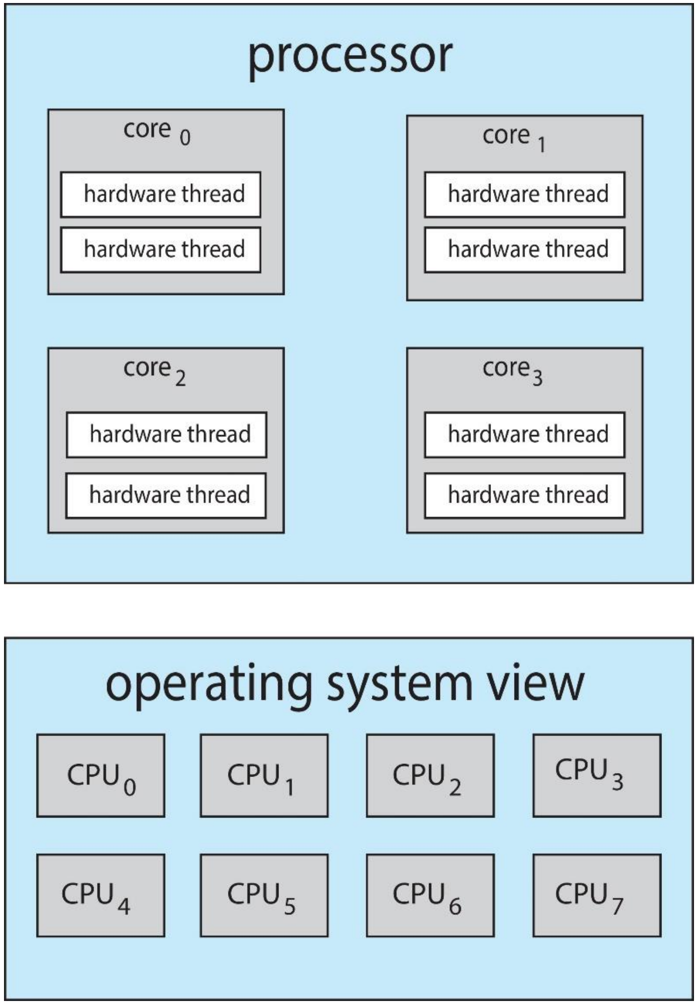


Multithreaded Multicore System

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

Multithreaded Multicore System: Example

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

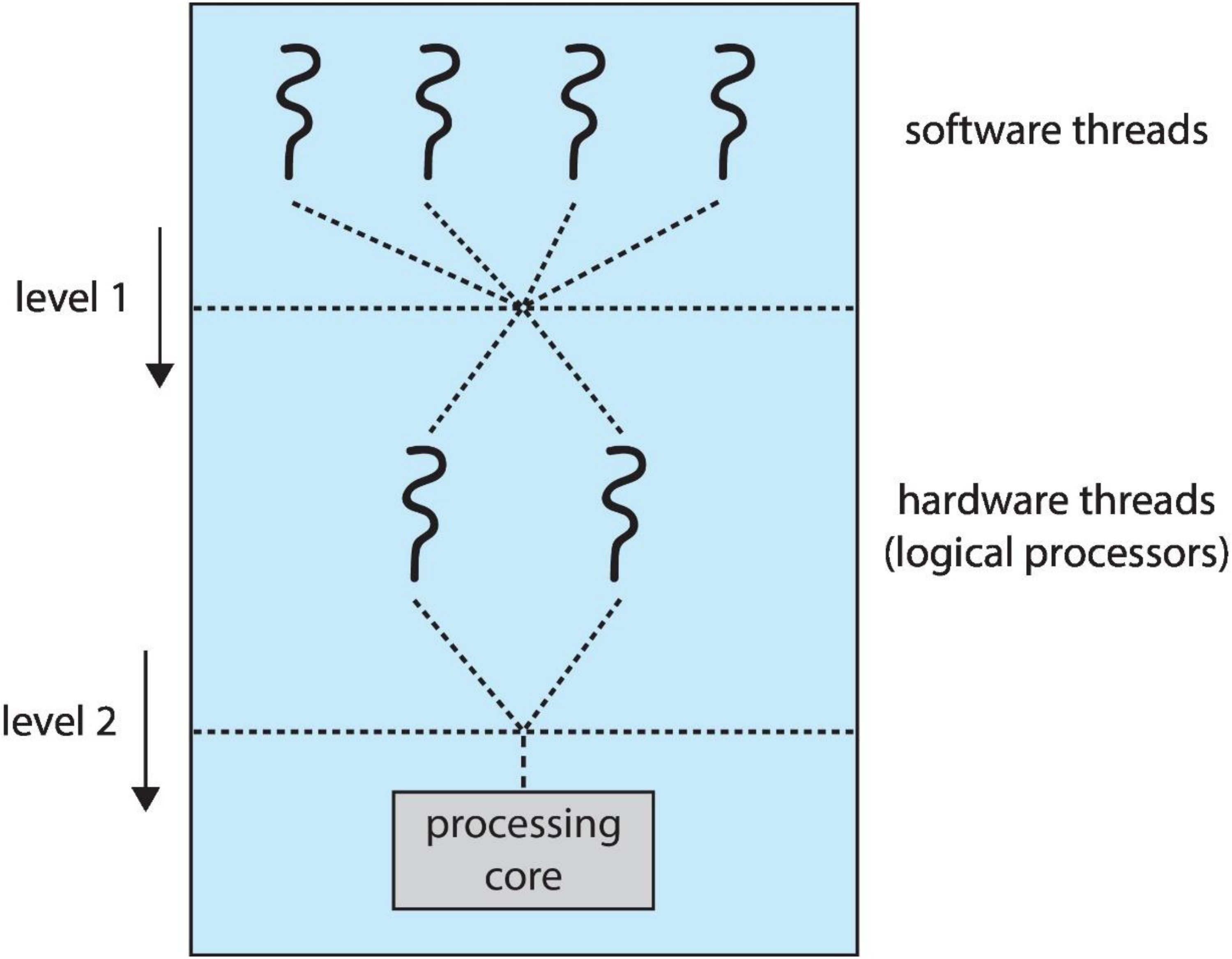


Multithreaded Multicore System: Scheduling

- 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.


software threads
level 1
hardware threads
(logical processors)
level 2
processing
core

Multiple-Processor Scheduling - Load Balancing

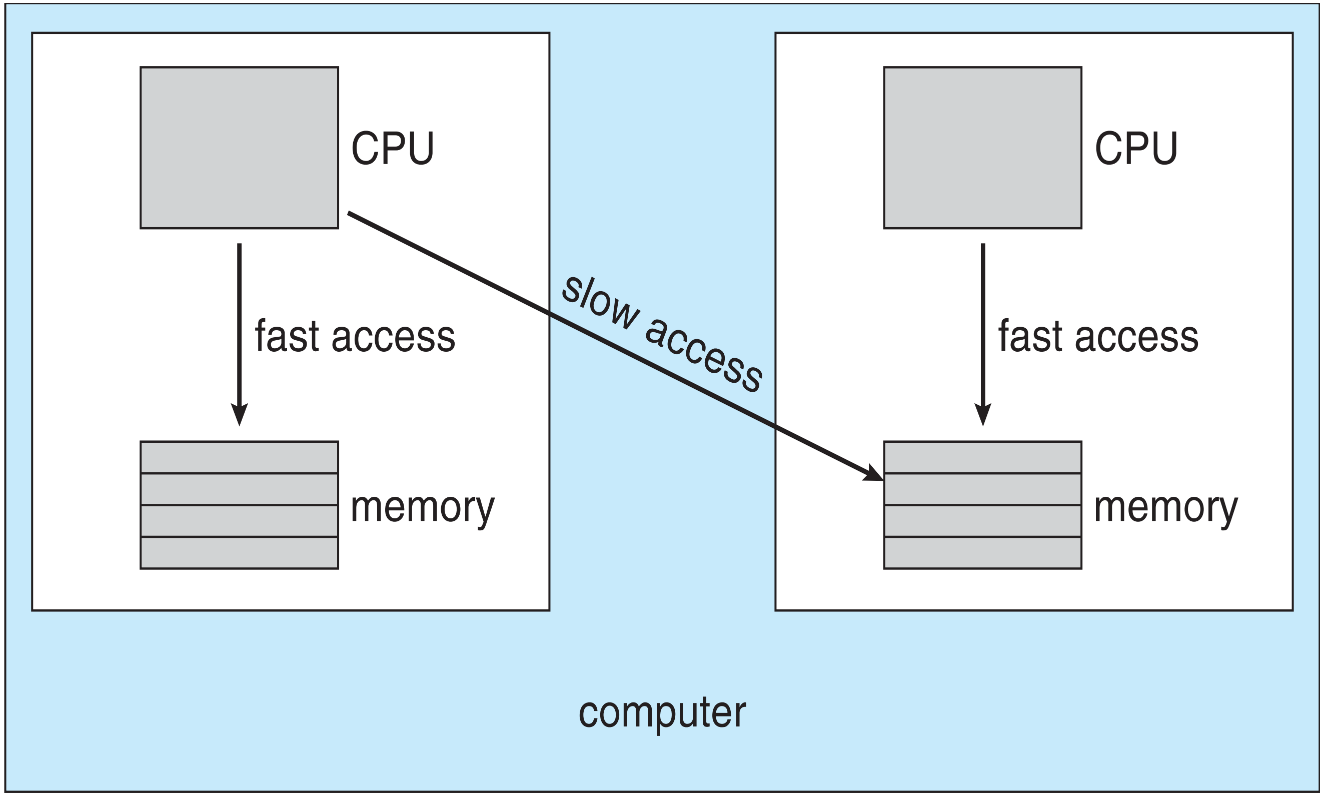
- If SMP, need to keep all CPUs loaded for efficiency
- **Load balancing** attempts to keep workload evenly distributed
- **Push migration** – periodic task checks load on each processor, and if found pushes task from overloaded CPU to other CPUs
- **Pull migration** – idle processors pulls waiting task from busy processor

Multiple-Processor Scheduling – Processor Affinity

- When a thread has been running on one processor, the cache contents of that processor stores the memory accesses by that thread.
- We refer to this as a thread having affinity for a processor (i.e. “processor affinity”)
- Load balancing may affect processor affinity as a thread may be moved from one processor to another to balance loads, yet that thread loses the contents of what it had in the cache of the processor it was moved off of.
- **Soft affinity** – the operating system attempts to keep a thread running on the same processor, but no guarantees.
- **Hard affinity** – allows a process to specify a set of processors it may run on.

NUMA and CPU Scheduling

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


CPU
fast access
memory
slow access
CPU
fast access
memory
computer

Questions?

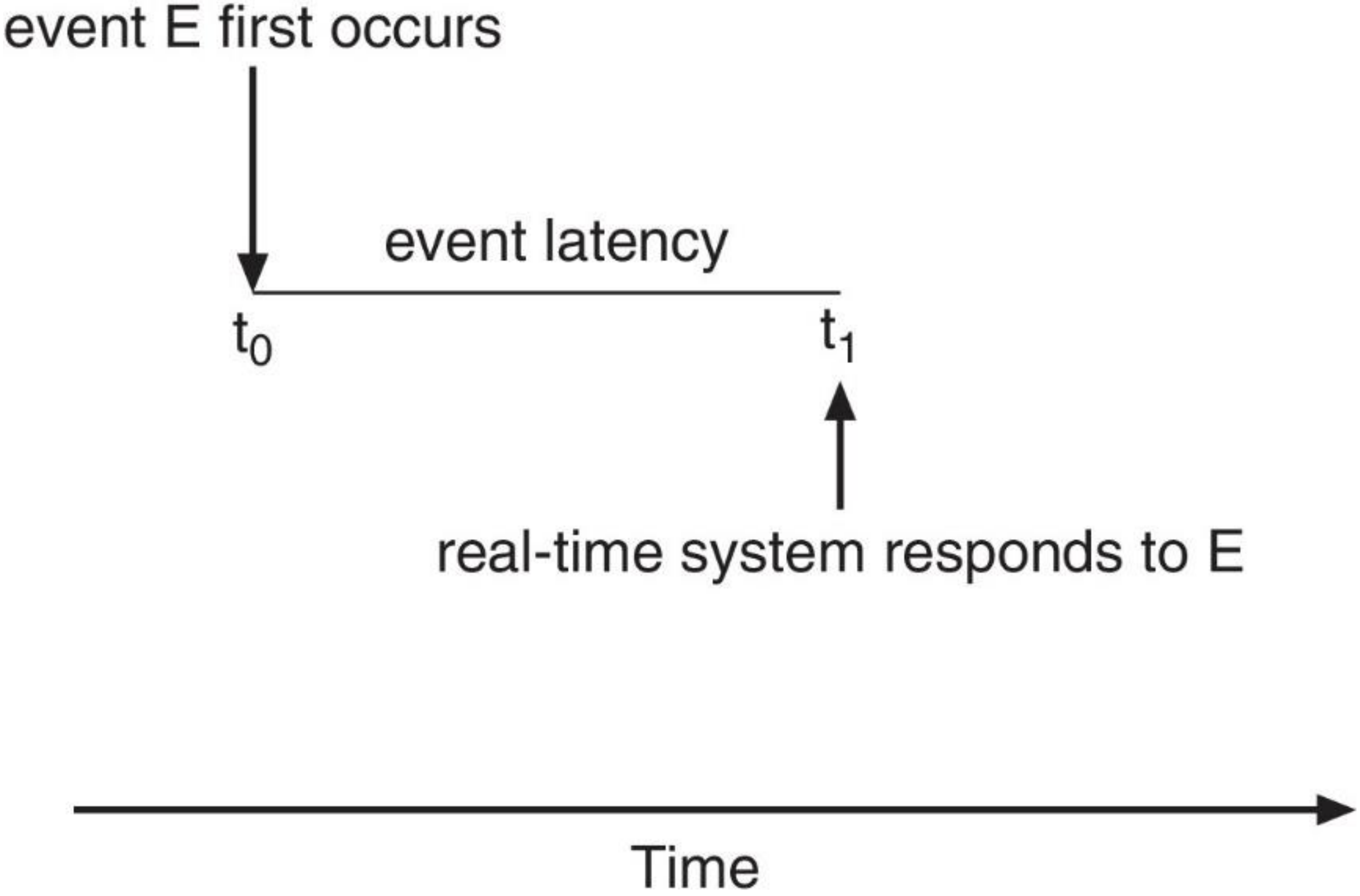
- Multiprocessor scheduling
- Design considerations
  - Multicore vs muiltproccesor
  - SMP
  - NUMA
  - Load balancing
  - CPU Affinity

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



event E first occurs

event latency

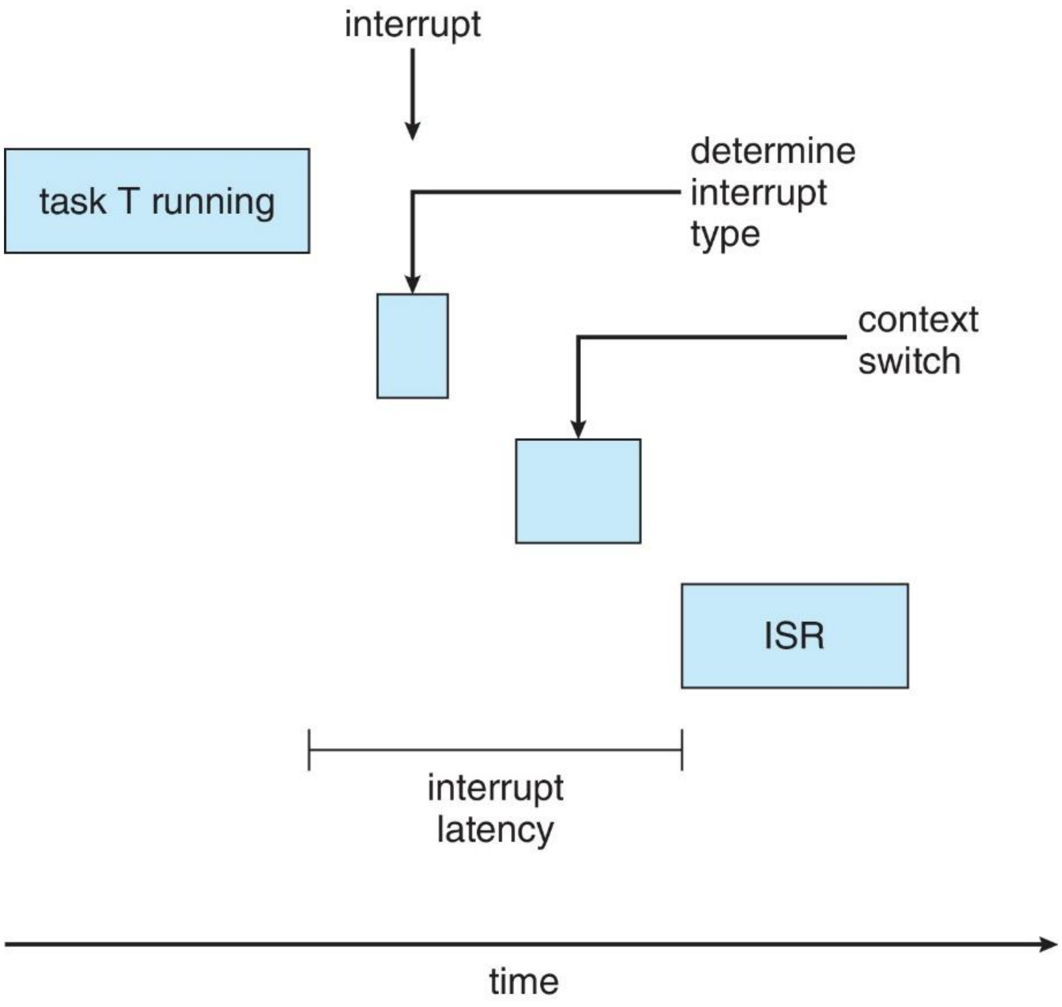
t_0

t_1

real-time system responds to E

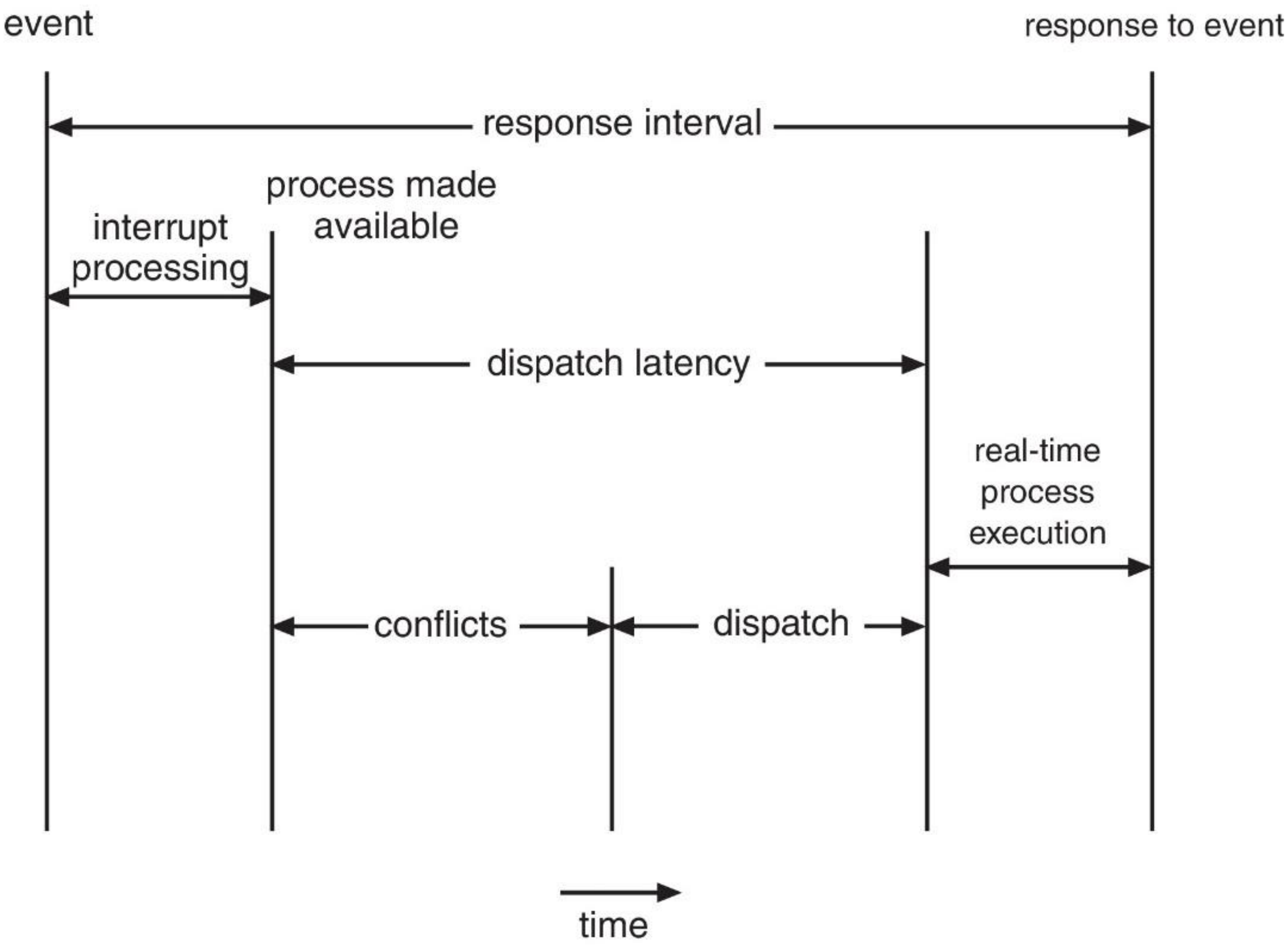
Time

Interrupt Latency



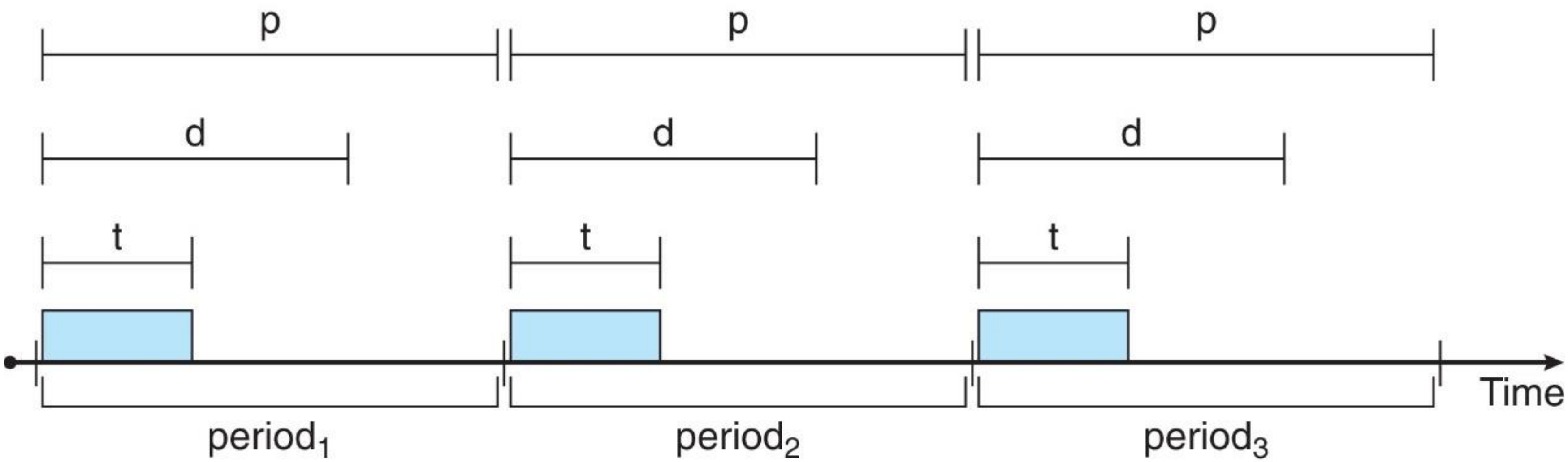
Dispatch Latency

- 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


event
response to event
response interval
process made available
interrupt processing
dispatch latency
real-time process execution
conflicts
dispatch
time

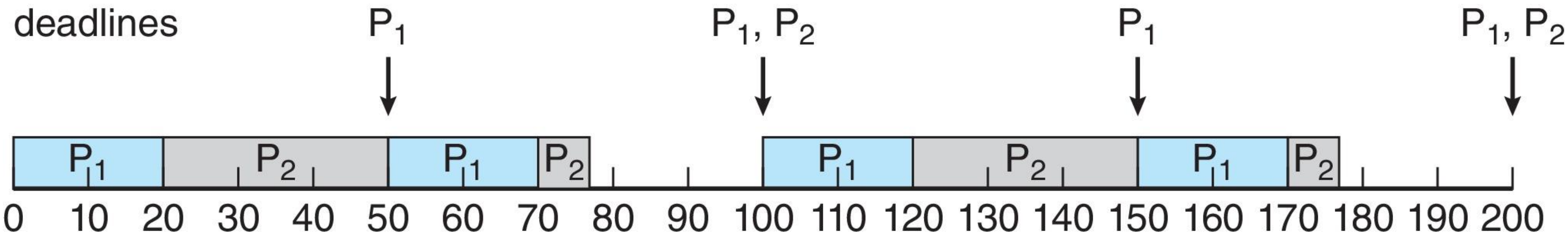
Priority-based Scheduling

- 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 $1/p$


p
p
p
d
d
d
t
t
t
Time
period_1
period_2
period_3

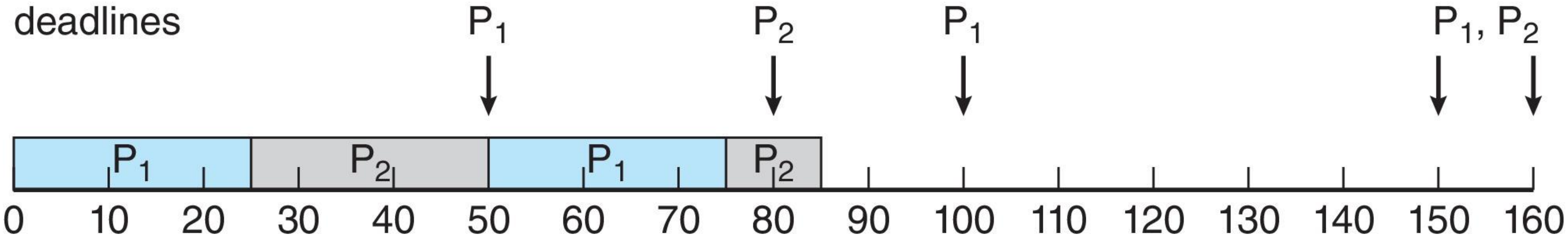
Rate Montonic Scheduling

- A priority is assigned based on the inverse of its period
- Shorter periods = higher priority;
- Longer periods = lower priority
- P_1 is assigned a higher priority than P_2.



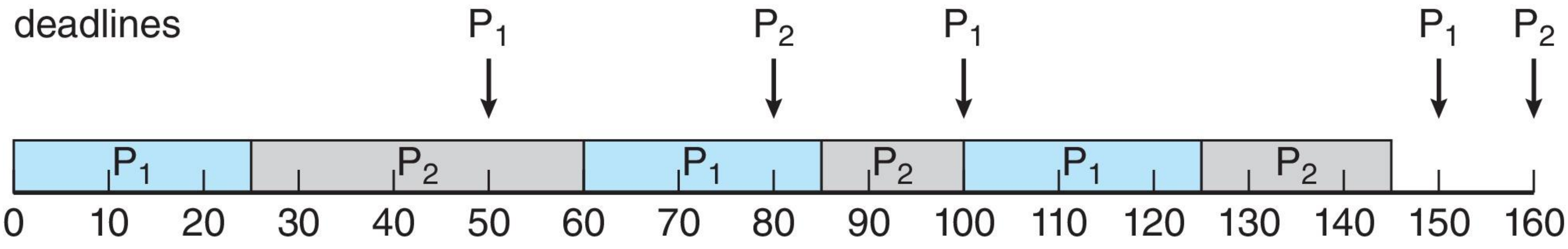
Missed Deadlines with Rate Monotonic Scheduling

- Process P2 misses finishing its deadline at time 80



Earliest Deadline First Scheduling (EDF)

- Priorities are assigned according to deadlines:
  - the earlier the deadline, the higher the priority;
  - the later the deadline, the lower the priority



Proportional Share Scheduling

- T shares are allocated among all processes in the system
- An application receives N shares where $N < T$
- This ensures each application will receive $\mathbf{N} / T$ of the total processor time

Example: POSIX Real-Time Scheduling

- The POSIX.1b standard
- API provides functions for managing real-time threads
- Defines two scheduling classes for real-time threads:

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

- Defines two functions for getting and setting scheduling policy:

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

POSIX Real-Time Scheduling API

- pthread_attr_getschedpolicy
- pthread_attr_setschedpolicy

Questions

- Real-time scheduling
- Scheduling algorithms
- Example API

Operating System Examples

- Linux scheduling
- Windows scheduling
- Solaris scheduling

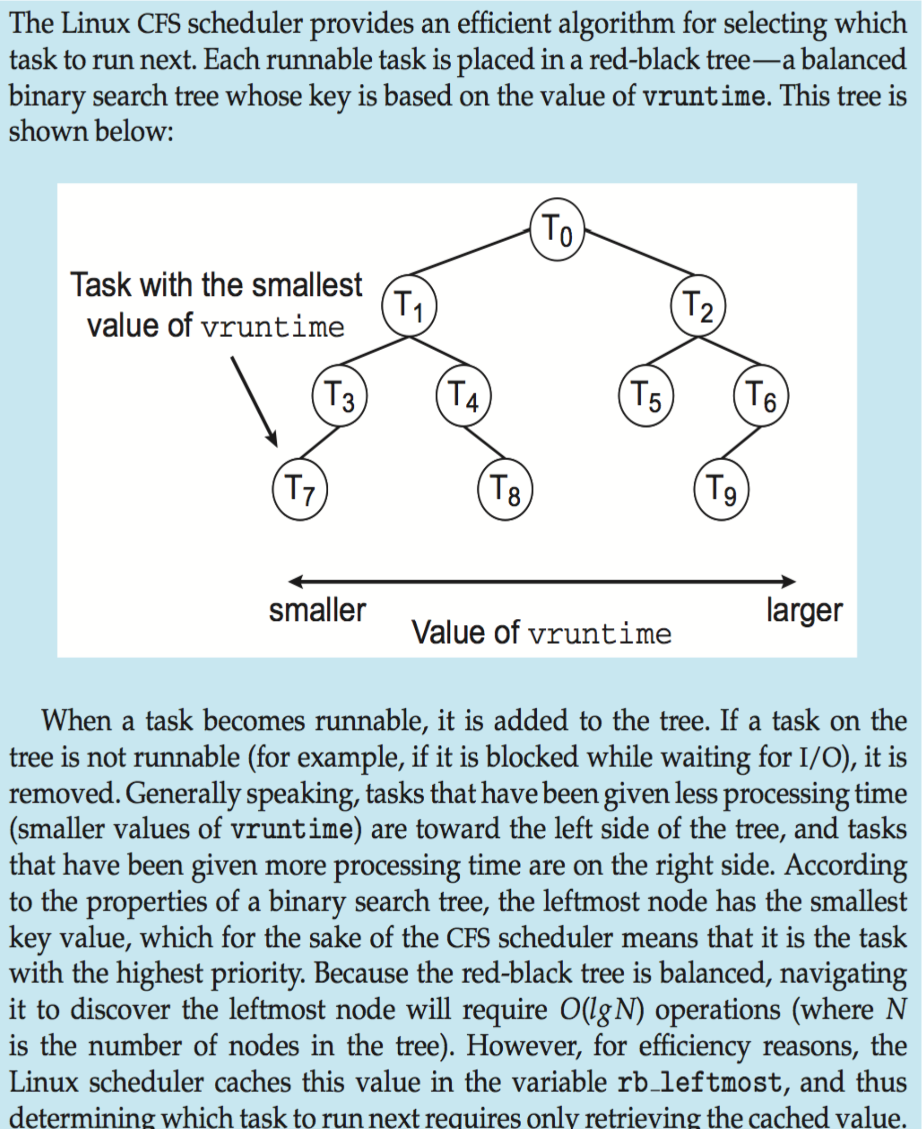
Linux Scheduling Through Version 2.5

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

Linux Scheduling in Version 2.6.23 +

- ***Completely Fair Scheduler*** (CFS)
- **Scheduling classes**
  - Each has specific priority
  - Scheduler picks highest priority task in highest scheduling class
  - Rather than quantum based on fixed time allotments, based on proportion of CPU time
  - 2 scheduling classes included, others can be added
    1. default
    2. real-time
- Quantum calculated based on **nice value** from -20 to +19
  - Lower value is higher priority
  - Calculates **target latency** – interval of time during which task should run at least once
  - Target latency can increase if say number of active tasks increases
- CFS scheduler maintains per task **virtual run time** in variable **`vruntime`**
  - Associated with decay factor based on priority of task – lower priority is higher decay rate
  - Normal default priority yields virtual run time = actual run time
- To decide next task to run, scheduler picks task with lowest virtual run time

CFS Performance

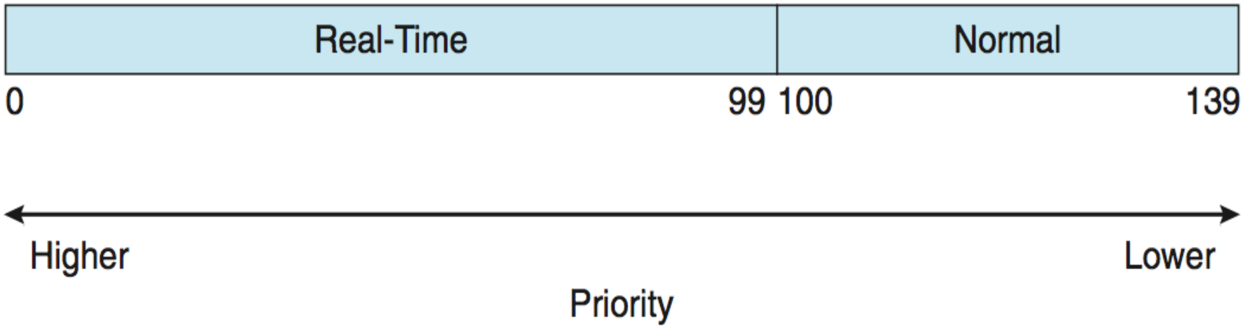


The Linux CFS scheduler provides an efficient algorithm for selecting which task to run next. Each runnable task is placed in a red-black tree—a balanced binary search tree whose key is based on the value of `vruntime`. This tree is shown below:

When a task becomes runnable, it is added to the tree. If a task on the tree is not runnable (for example, if it is blocked while waiting for I/O), it is removed. Generally speaking, tasks that have been given less processing time (smaller values of `vruntime`) are toward the left side of the tree, and tasks that have been given more processing time are on the right side. According to the properties of a binary search tree, the leftmost node has the smallest key value, which for the sake of the CFS scheduler means that it is the task with the highest priority. Because the red-black tree is balanced, navigating it to discover the leftmost node will require $O(lg N)$ operations (where N is the number of nodes in the tree). However, for efficiency reasons, the Linux scheduler caches this value in the variable `rb_leftmost`, and thus determining which task to run next requires only retrieving the cached value.

Linux Scheduling (Cont.)

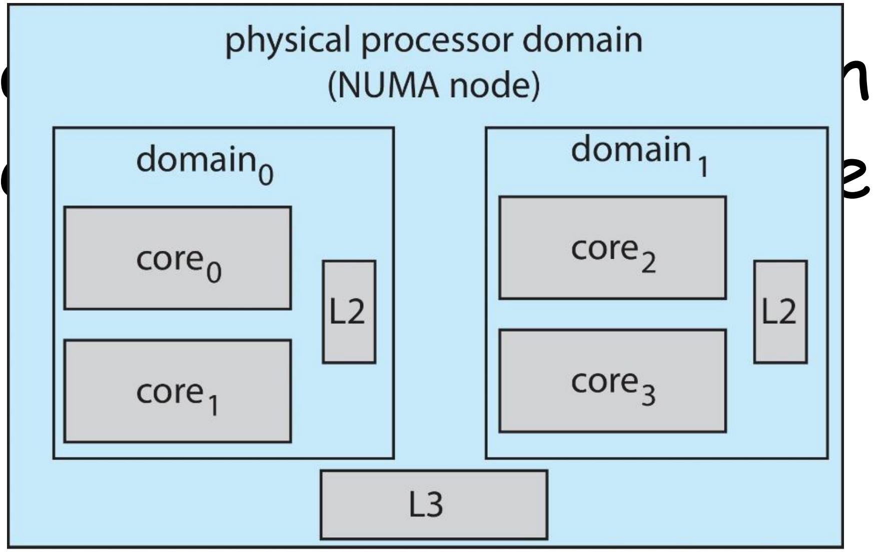
- Real-time scheduling according to POSIX.1b
  - Real-time tasks have static priorities
- Real-time plus normal map into global priority scheme



- Nic
  10
- Nic

Linux Scheduling (Cont.)

- Linux supports load balancing, but is also NUMA-aware.
- **Scheduling domain** is a set of CPU cores that can be balanced against one another.
- Domains ney share (i.e. cach ep threads from mig



Windows Scheduling

- Windows uses priority-based preemptive scheduling
- Highest-priority thread runs next
- **Dispatcher** is scheduler
- Thread runs until (1) blocks, (2) uses time slice, (3) preempted by higher-priority thread
- Real-time threads can preempt non-real-time
- 32-level priority scheme
- **Variable class** is 1-15, **real-time class** is 16-31
- Priority 0 is memory-management thread
- Queue for each priority
- If no run-able thread, runs **idle thread**

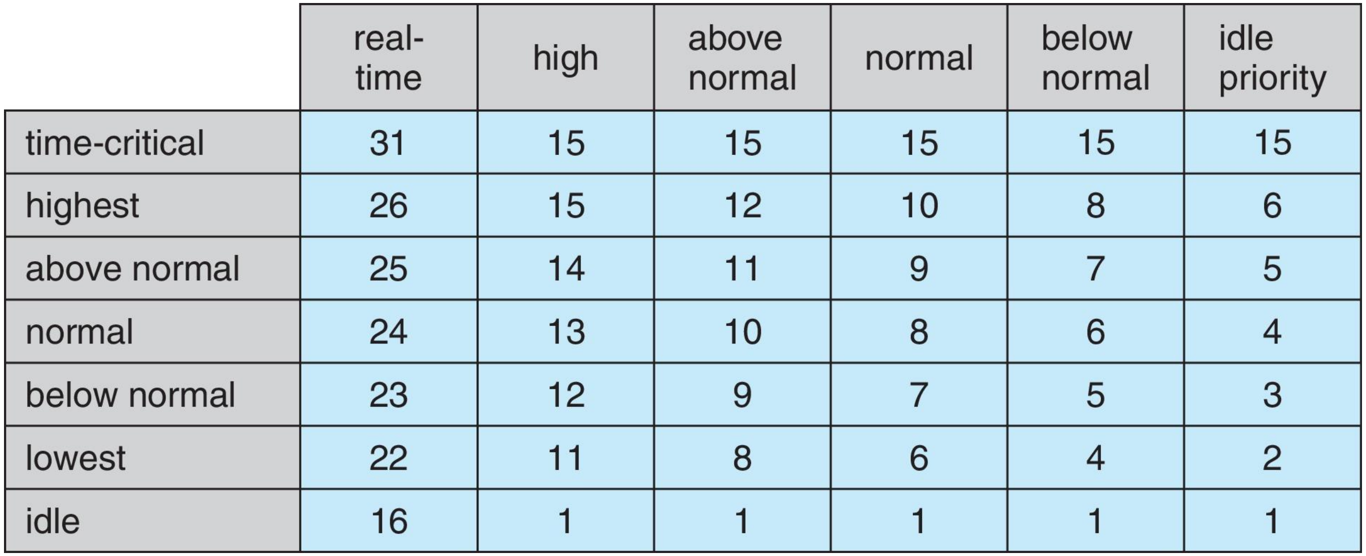
Windows Priority Classes

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

Windows Priority Classes (Cont.)

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

Windows Priorities

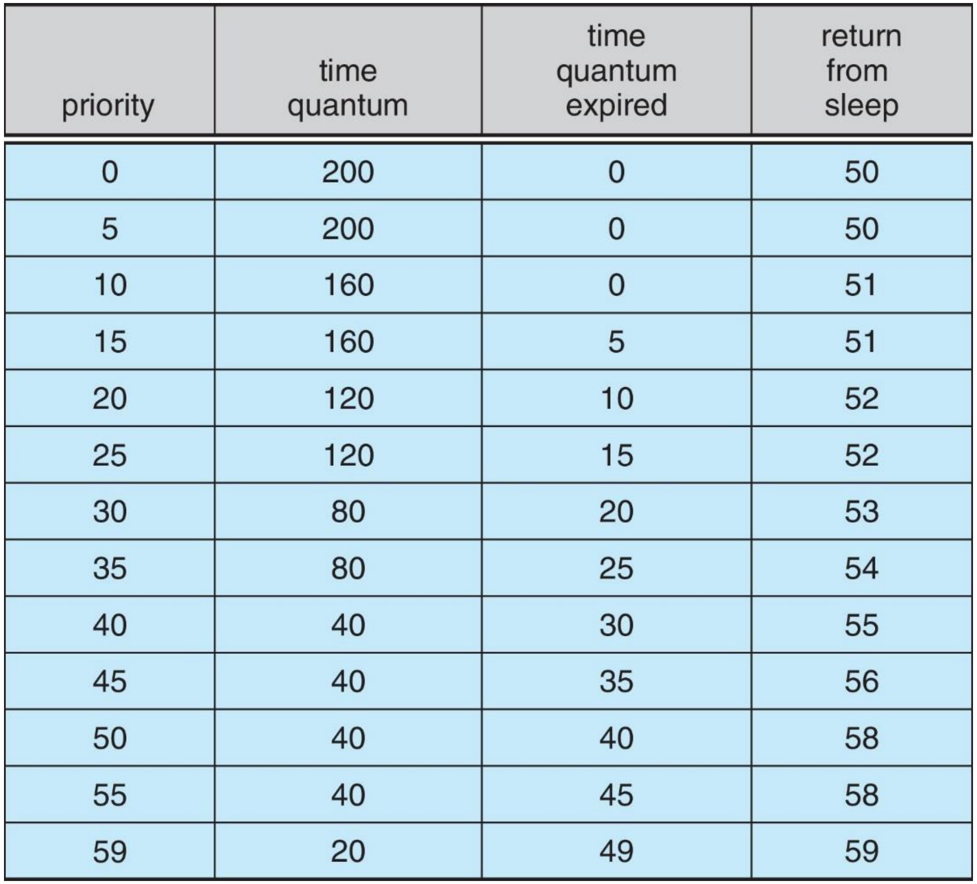


	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

Solaris

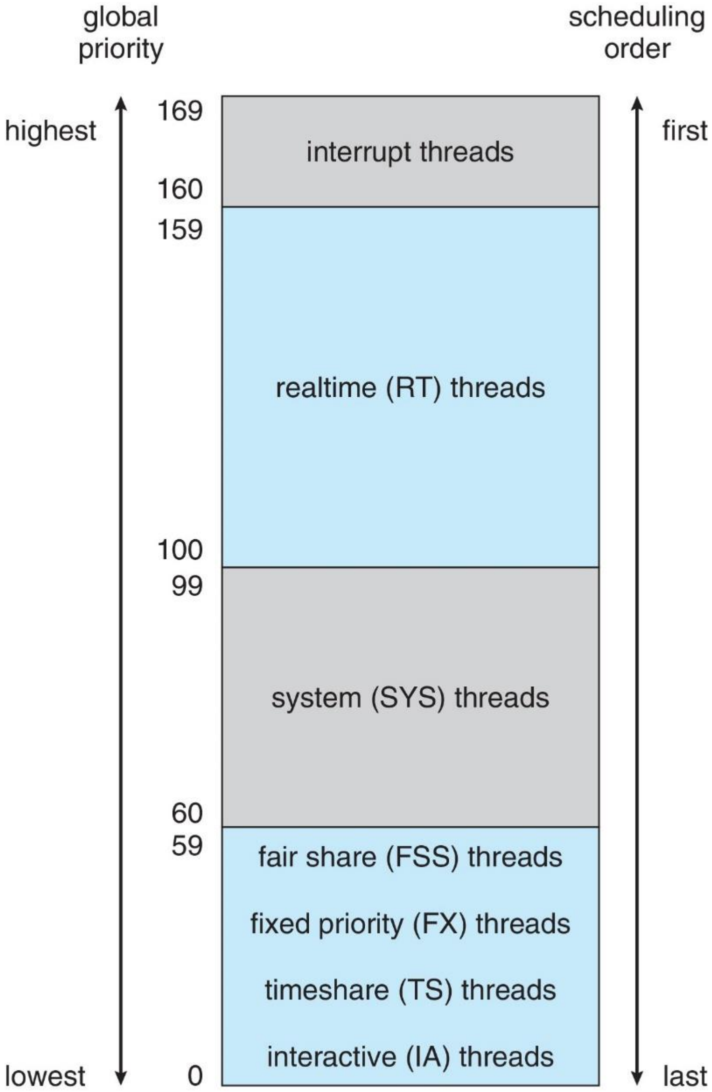
- Priority-based scheduling
- Six classes available
    - Time sharing (default) (TS)
    - Interactive (IA)
    - Real time (RT)
    - System (SYS)
    - Fair Share (FSS)
    - Fixed priority (FP)
- Given thread can be in one class at a time
- Each class has its own scheduling algorithm
- Time sharing is multi-level feedback queue
    - Loadable table configurable by sysadmin

Solaris Dispatch Table



priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Solaris Scheduling

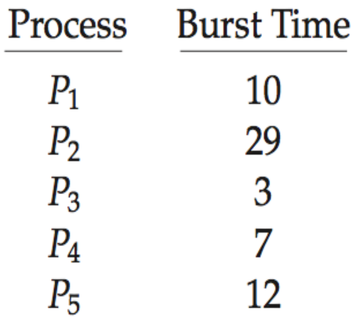


Solaris Scheduling (Cont.)

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

Algorithm Evaluation

- How to select CPU-scheduling algorithm for an OS?
- Determine criteria, then evaluate algorithms
- **Deterministic modeling**
  - Type of **analytic evaluation**
  - Takes redetermined workload and defin ance of each algorithm for that w
- Conside s arriving at time 0:

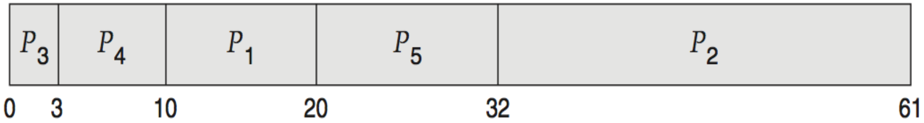


Process	Burst Time
P_1	10
P_2	29
P_3	3
P_4	7
P_5	12

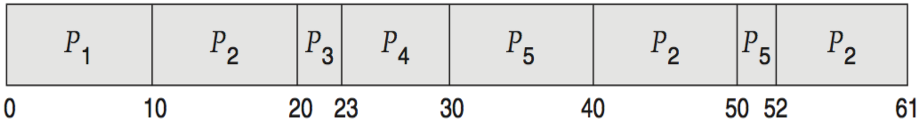
Deterministic Evaluation

- For each algorithm, calculate minimum average waiting time
- Simple and fast, but requires exact numbers for input, applies only to those inputs
  - FCS is 28ms:

  - Nc



  - RR



Queueing Models

- Describes the arrival of processes, and CPU and I/O bursts probabilistically
    - Commonly exponential, and described by mean
    - Computes average throughput, utilization, waiting time, etc
- Computer system described as network of servers, each with queue of waiting processes
    - Knowing arrival rates and service rates
    - Computes utilization, average queue length, average wait time, etc

Little's Formula

- *n* = average queue length
- *W* = average waiting time in queue
- λ = average arrival rate into queue
- Little's law – in steady state, processes leaving queue must equal processes arriving, thus:

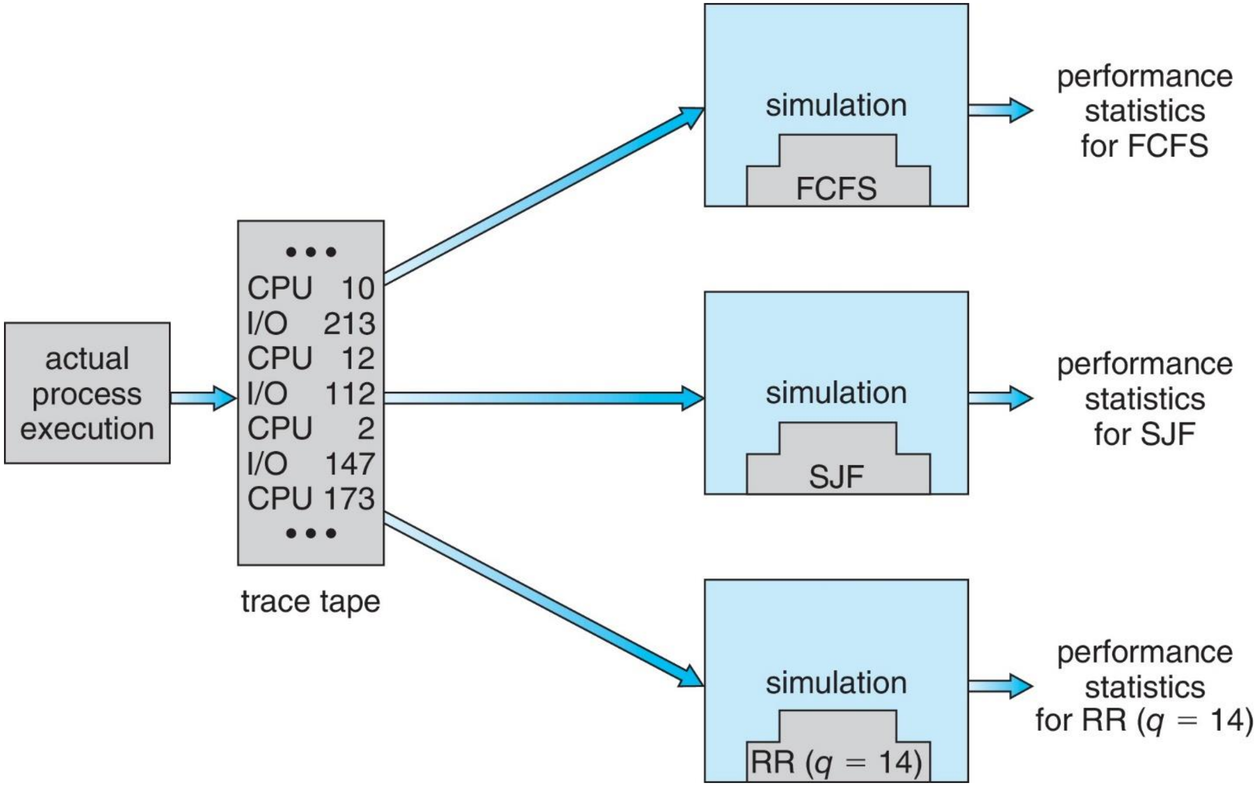
  $n = \lambda \times W$

  - Valid for any scheduling algorithm and arrival distribution
- For example, if on average 7 processes arrive per second, and normally 14 processes in queue, then average wait time per process = 2 seconds

Simulations

- Queueing models limited
- **Simulations** more accurate
  - Programmed model of computer system
  - Clock is a variable
  - Gather statistics indicating algorithm performance
  - Data to drive simulation gathered via
    - Random number generator according to probabilities
    - Distributions defined mathematically or empirically
    - Trace tapes record sequences of real events in real systems

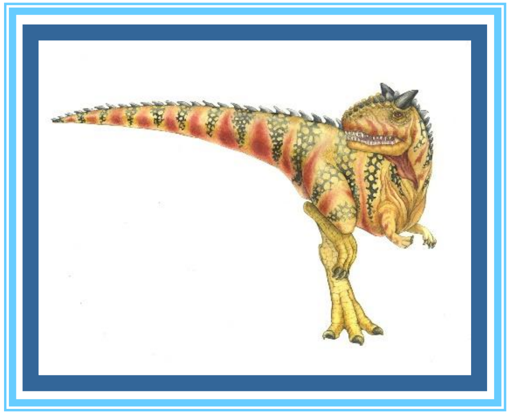
Evaluation of CPU Schedulers by Simulation



Implementation

- Even simulations have limited accuracy
- Just implement new scheduler and test in real systems
    - High cost, high risk
    - Environments vary
- Most flexible schedulers can be modified per-site or per-system
- Or APIs to modify priorities
- But again environments vary

End of Chapter 5



Objectives

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