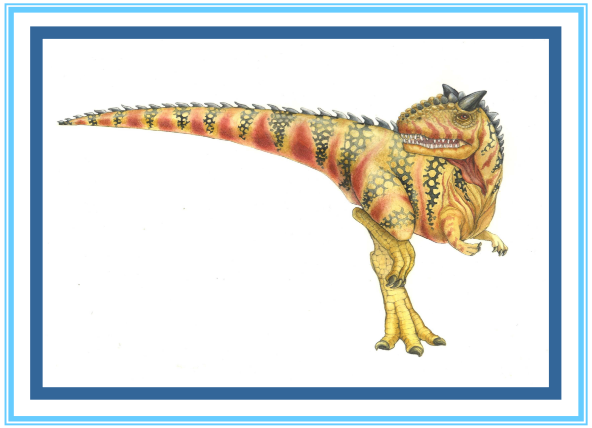
Chapter 5: Process Scheduling



Chapter 5: Process Scheduling

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples
- Algorithm Evaluation

Objectives

To introduce CPU scheduling, which is the basis for multiprogrammed operating systems

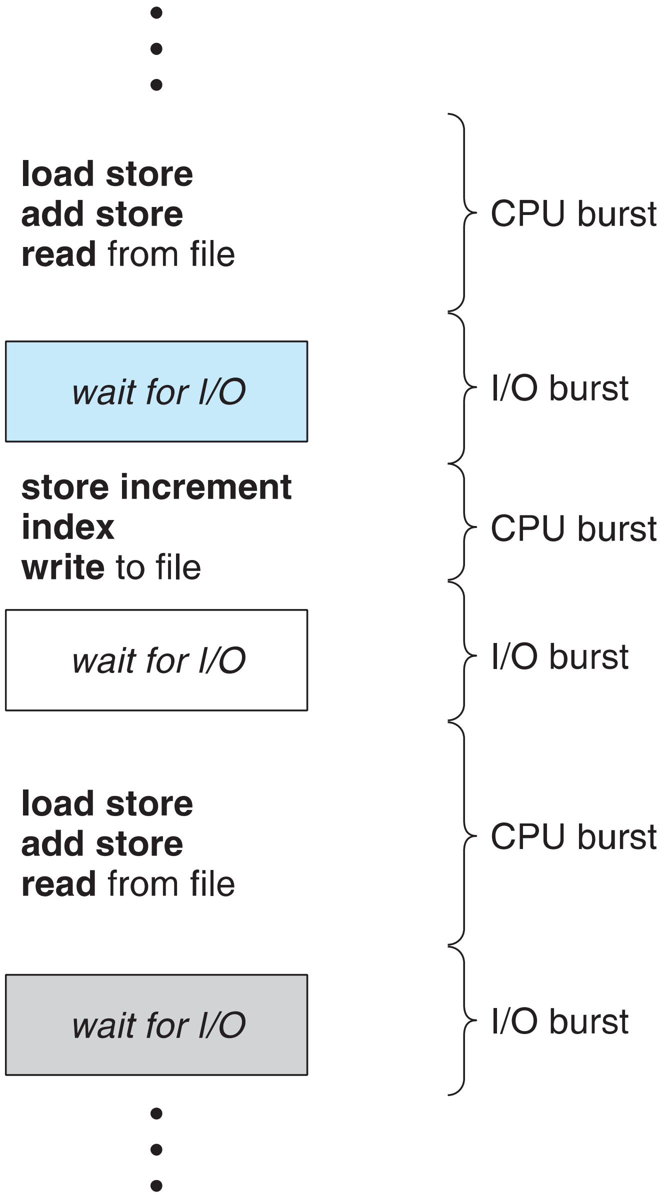
To describe various CPU-scheduling algorithms

To discuss evaluation criteria for selecting a CPU-scheduling algorithm for a particular system

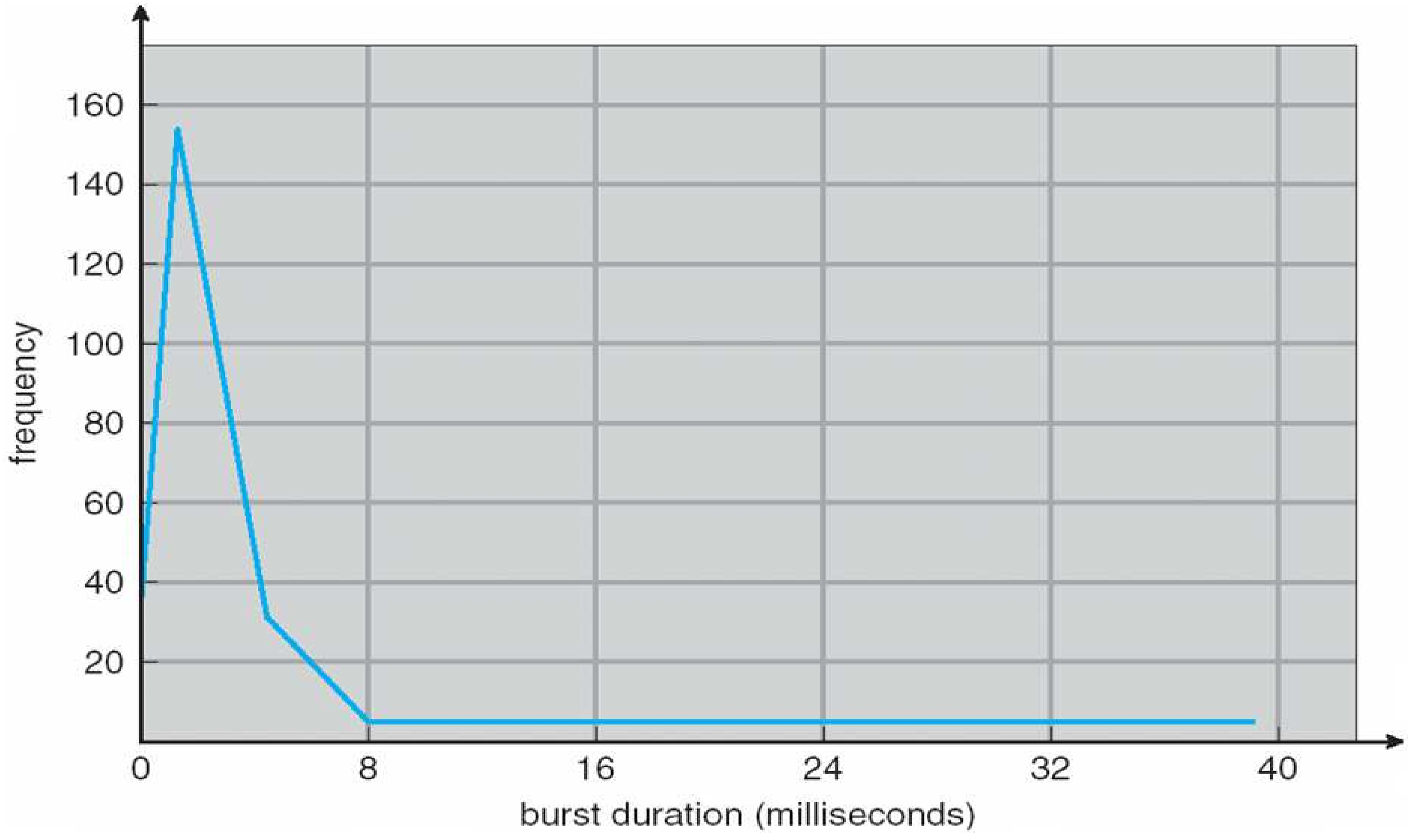
To examine the scheduling algorithms of several operating systems

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



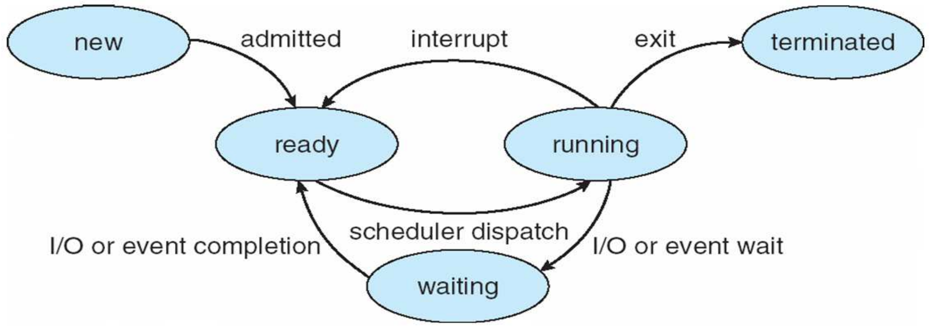
CPU Scheduler

Short-term scheduler selects from among the processes in ready queue, and allocates the CPU 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
   ★ (not always cause scheduling (e.g. if a job is ________))
4. Terminates



Scheduling under 1 and 4 is **nonpreemptive**

All other scheduling is **preemptive**

- Consider access to shared data
- Consider preemption while in kernel mode
- Consider interrupts occurring during crucial OS activities

Dispatcher

Dispatcher module gives control of the CPU to the process selected by the short-term 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 – amount of time to execute a particular process

★(= wait time for memory, in ______ queue, CPU execution, I/O)

Waiting time – amount of time a process has been waiting in the ready queue

★(only the time affected by the _________)

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)

Scheduling Algorithm Optimization Criteria

Max CPU utilization

Max throughput

Min turnaround time

Min waiting time

Min response time

★(Usually optimize _______ value)

★(Sometimes optimize min or max is more important, (ex) min the max response time, min the variance in response time for _________ sys)

Process	Burst Time
P_1	24
P_2	3 ★(They all arrive at time 0)
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

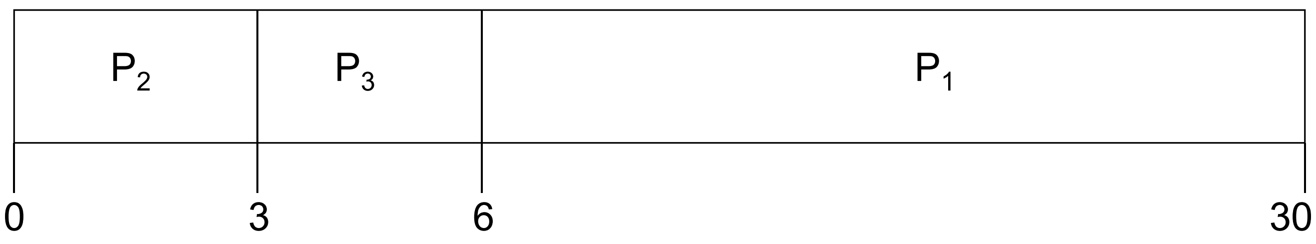
Average waiting time: (0 + 24 + 27)/3 = 17

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 previous case

Convoy effect - short process behind long process

Consider one CPU-bound and many I/O-bound processes

(as they move around the ready queue and device queue, short processes are always blocked by the _____ one)

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

Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

SJF scheduling chart

P_4	P_1	P_3	P_2	
0	3	9	16	24

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

★ (3-0) (16-0) (9-0) (0-0)

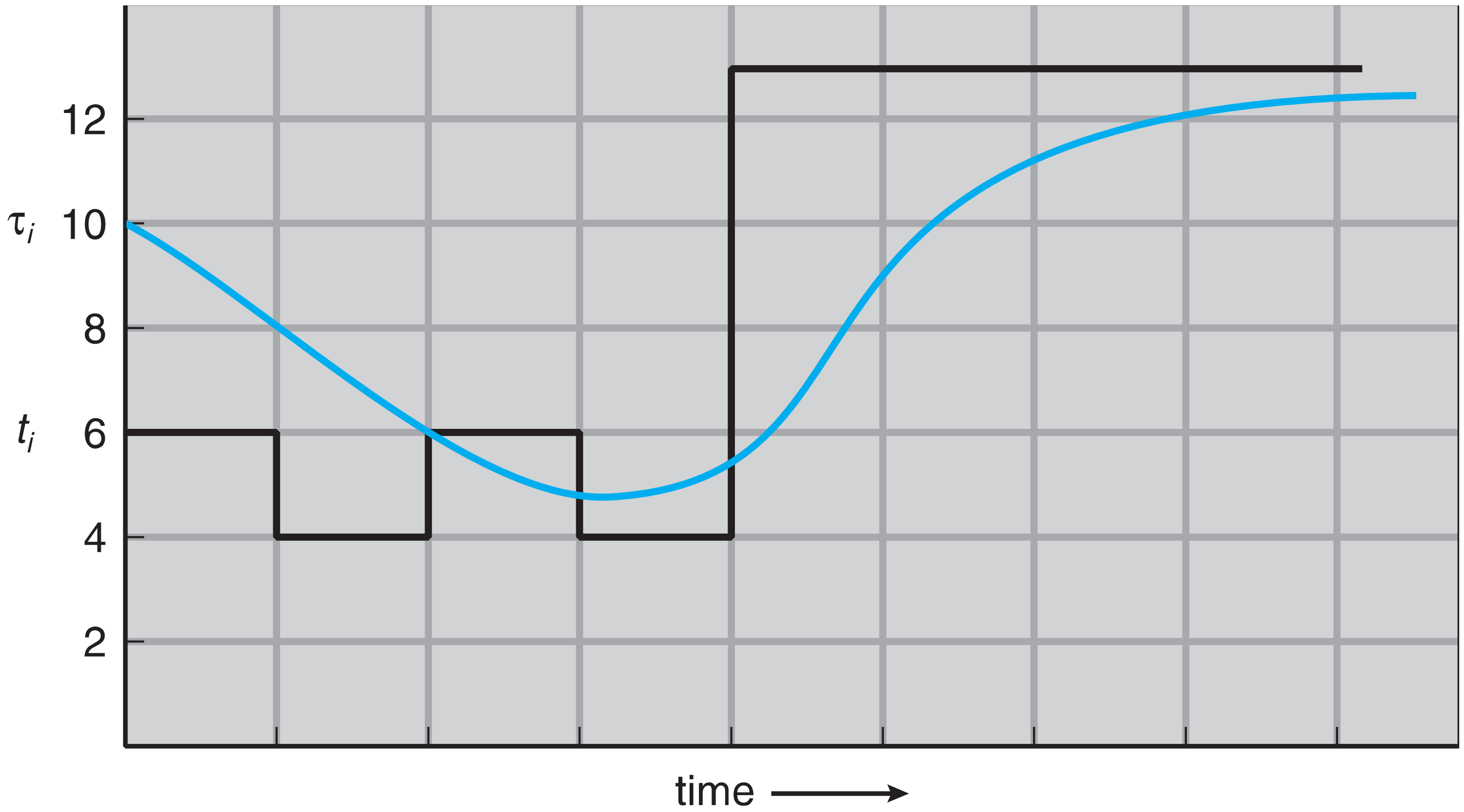
Determining Length of Next CPU Burst

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

- Commonly, α set to ½
- Preemptive version called **shortest-remaining-time-first**

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	...

($\alpha = 0.5$)

Examples of Exponential Averaging

$\alpha = 0$

$\tau_{n+1} = \tau_n$

Recent history does not count

$\alpha = 1$

$\tau_{n+1} = \alpha\, t_n$

Only the actual last CPU burst counts

If we expand the formula, we get:

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

★
$$\begin{aligned}
\tau_{n+1} &= \alpha\, t_n + (1-\alpha)\tau_n \\
&= \alpha\, t_n + (1-\alpha)(\alpha t_{n-1} + (1-\alpha)\tau_{n-1}) \\
&= \alpha\, t_n + (1-\alpha)\alpha t_{n-1} + (1-\alpha)^2 \tau_{n-1} \\
&= \alpha\, t_n + (1-\alpha)\alpha t_{n-1} + (1-\alpha)^2 (\alpha t_{n-2} + (1-\alpha)\tau_{n-2}) \\
&= \alpha\, t_n + (1-\alpha)\alpha t_{n-1} + (1-\alpha)^2 \alpha t_{n-2} + (1-\alpha)^3 \tau_{n-2} \\
&= \ldots
\end{aligned}$$

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

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 Gantt Chart

P_1	P_2	P_4	P_1	P_3

0 1 5 10 17 26

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

★ (P_1(rem) = 7 > 4; ________)

(at t=2; P_2(rem) = 3 < __; no preempt)

(at t=3; P_2(rem) = 2 < 5; ____________)

(P_4 (rem)=5 < P_1 (rem) __ and P_3 (rem) __)

(P_1 (rem)=7 < ___(rem) 9)

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

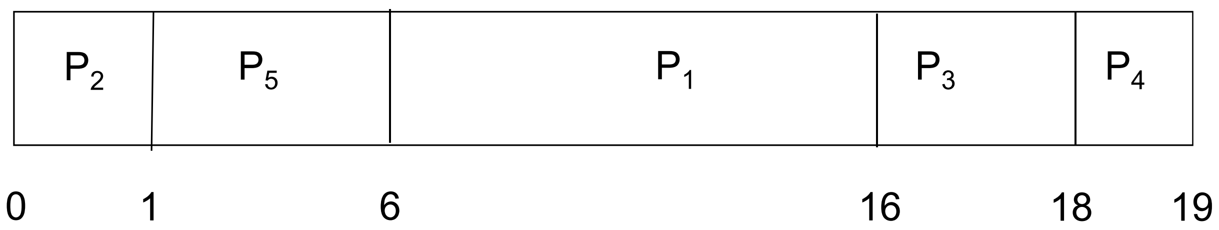
Problem ≡ **Starvation** – low priority processes may never execute

Solution ≡ **Aging** – as time progresses increase the priority of the process

Example 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 msec * ((6–0)+(__ –0)+(16– __)+(___ –0)+(1–0))=41/5=8.2)

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
- *q* small $\Rightarrow$ *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:

P_1	P_2	P_3	P_1	P_1	P_1	P_1	P_1

0 4 7 10 14 18 22 26 30 ★

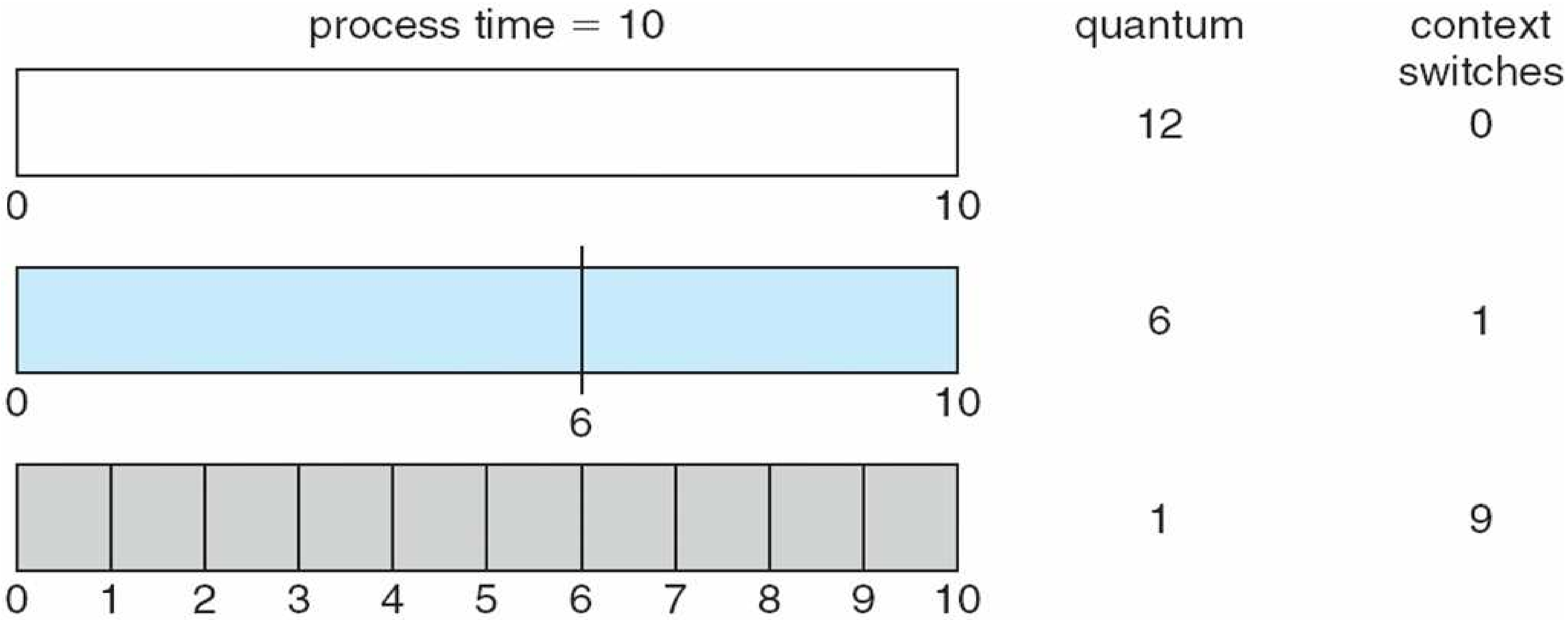
Typically, higher average turnaround than SJF, but better ***response***

q should be large compared to context switch time

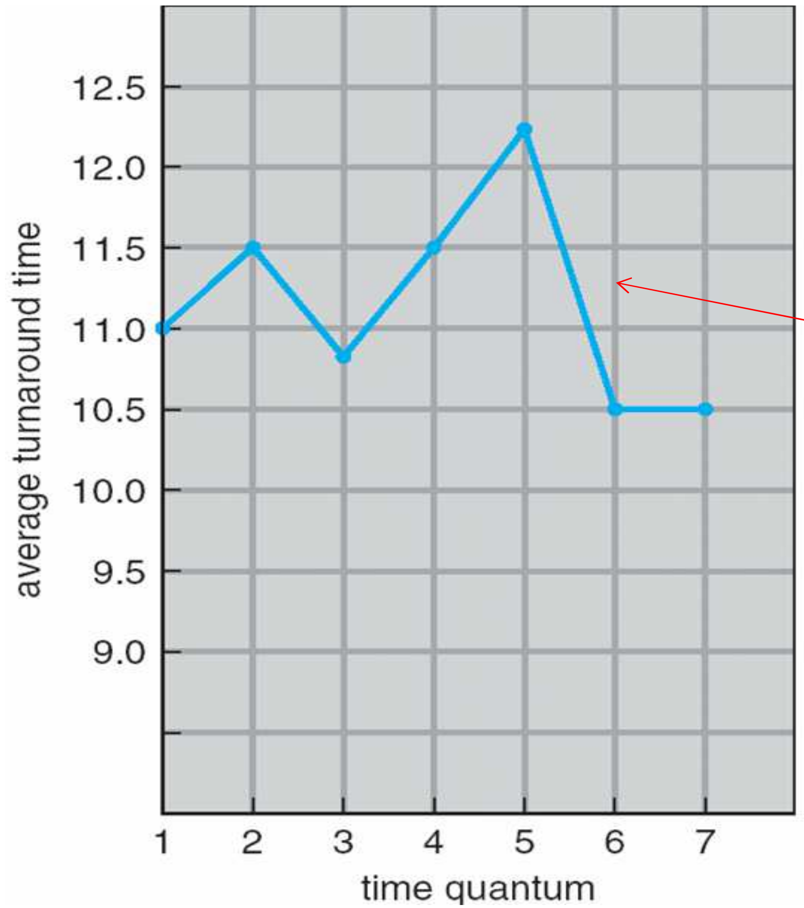
q usually 10ms to 100ms, context switch < 10 usec

(The sum must be 30 regardless of __________)
(Turnaround = (30+7+ __)/3=15.6)
(Response = (4+7+ __)/3=7)

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

★(turnaround time does not necessary
_________ as quantum increases)

80% of CPU bursts should
be shorter than q

★(q=1; 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
1 2 3 4 1 2 4 1 2 4 1 4 1 4 1 4 4 = (15+9 +3+ __)/4=44/4=11)
★(q=7; 1 2 3 4 = (6+ __ +10+17)/4=42/4=10.5;
considering context switching overhead, q=7 case of only __ switching will allow much smaller turnaround time)

Multilevel Queue

★(For separating proc having different ____-burst characteristics)

Ready queue is partitioned into separate queues, eg:

- **foreground** (interactive) *(also I/O bound proc)
- **background** (batch)

Process permanently in a given queue

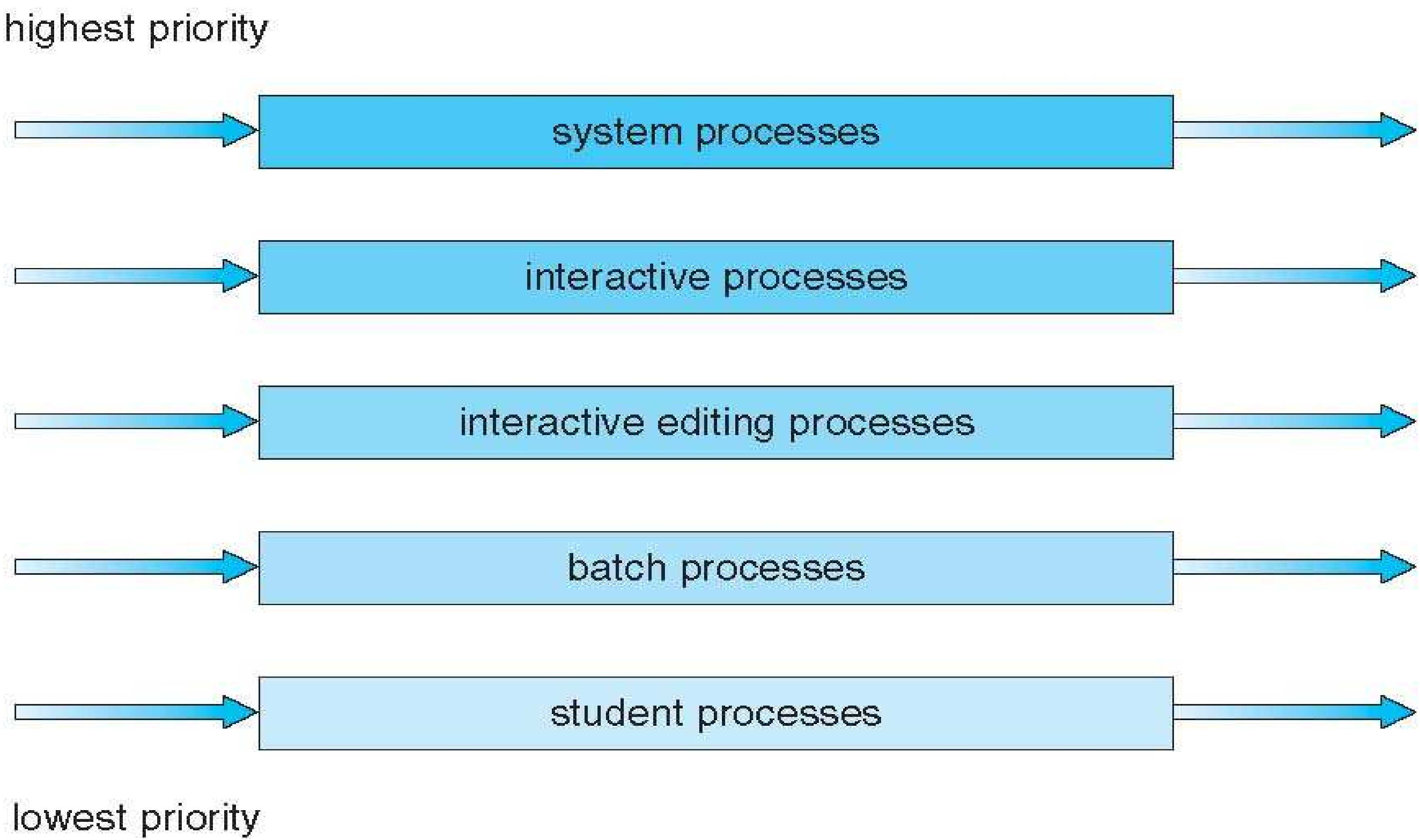
Each queue has its own scheduling algorithm:

- foreground – RR
- background – FCFS

Scheduling must be done between the queues:

- Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation. *(Solaris 2)
- Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; i.e., 80% to foreground in RR
- 20% to background in FCFS

Multilevel Queue Scheduling



Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way
- 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

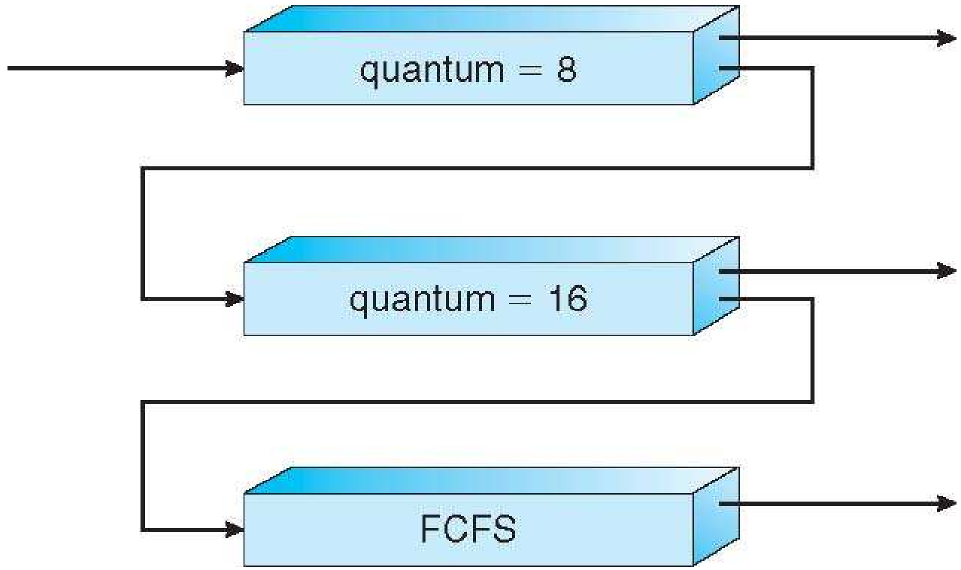
Example of Multilevel Feedback Queue

Three queues:

- Q_0 – RR with time quantum 8 milliseconds
- Q_1 – RR time quantum 16 milliseconds
- Q_2 – FCFS

Scheduling

- A new 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



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 * (used for one-to-____ model of XP, Solaris, Linux)

Pthread Scheduling

- API allows specifying either PCS or SCS during thread creation
  - PTHREAD_SCOPE_PROCESS schedules threads using PCS scheduling
  - PTHREAD_SCOPE_SYSTEM schedules threads using SCS scheduling
- Can be limited by OS – Linux and Mac OS X only allow PTHREAD_SCOPE_SYSTEM

Pthread Scheduling API

```
#include <pthread.h>
#include <stdio.h>
#define NUM THREADS 5
int main(int argc, char *argv[]) {
   int i, scope;
   pthread t tid[NUM THREADS];
   pthread attr t attr;
   /* get the default attributes */
   pthread attr init(&attr);
   /* first inquire on the current scope */
   if (pthread attr getscope(&attr, &scope) != 0)
      fprintf(stderr, "Unable to get scheduling scope\n");
   else {
      if (scope == PTHREAD SCOPE PROCESS)
         printf("PTHREAD SCOPE PROCESS");
      else if (scope == PTHREAD SCOPE SYSTEM)
         printf("PTHREAD SCOPE SYSTEM");
      else
         fprintf(stderr, "Illegal scope value.\n");
   }
```

Pthread Scheduling API

```
   /* set the scheduling algorithm to PCS or SCS */
   pthread attr setscope(&attr, PTHREAD SCOPE SYSTEM);
   /* create the threads */
   for (i = 0; i < NUM THREADS; i++)
      pthread create(&tid[i],&attr,runner,NULL);
   /* now join on each thread */
   for (i = 0; i < NUM THREADS; i++)
      pthread join(tid[i], NULL);
}
/* Each thread will begin control in this function */
void *runner(void *param)
{
   /* do some work ... */
   pthread exit(0);
}
```

Multiple-Processor Scheduling

CPU scheduling more complex when multiple CPUs are available

Homogeneous processors within a multiprocessor

Asymmetric multiprocessing – only one processor accesses the system data structures, alleviating the need for data sharing

Symmetric multiprocessing (**SMP**) – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes

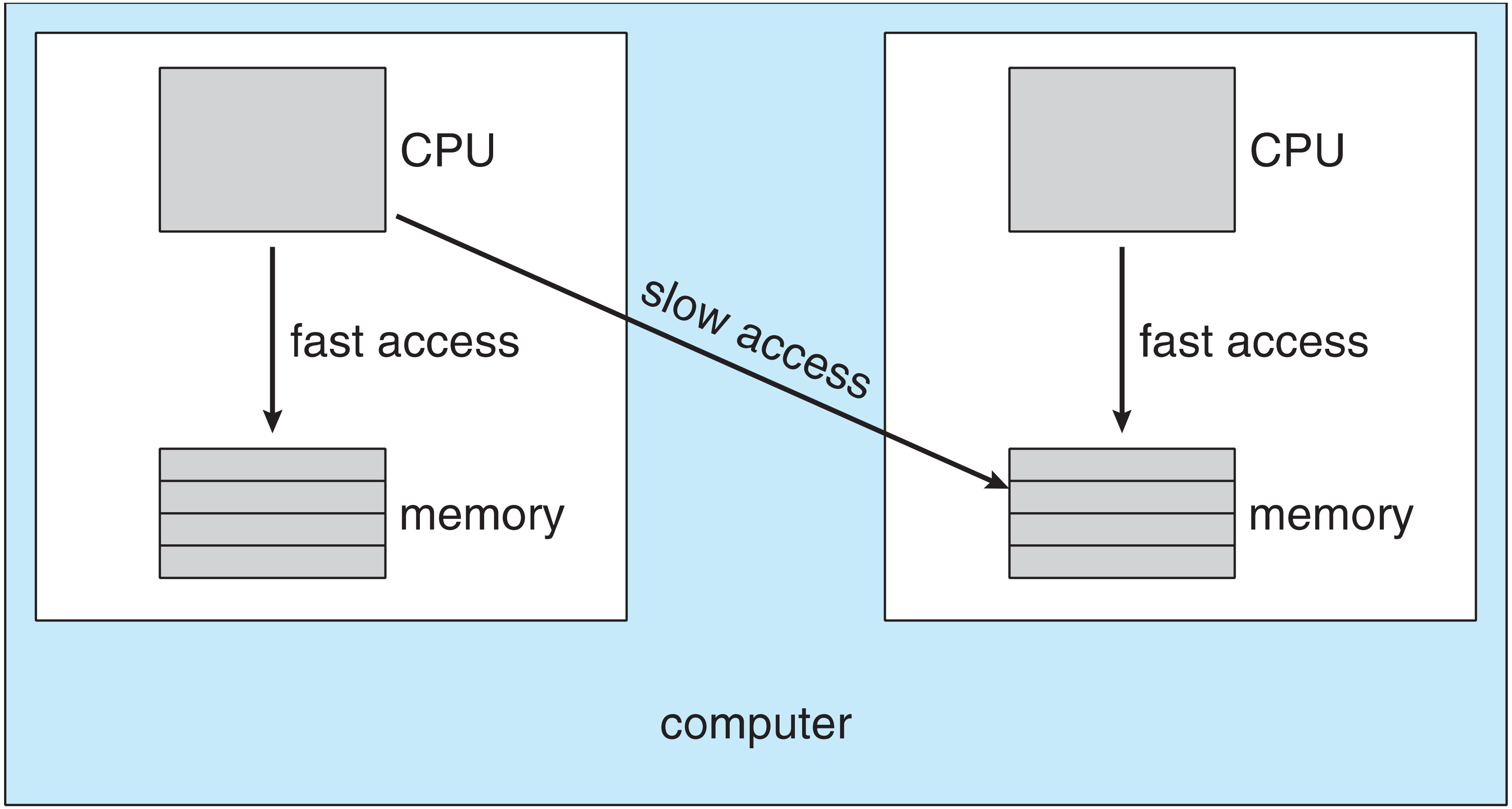
- Currently, most common

* (limit a proc to stay in a specific processor to avoid cache __________ problem)

Processor affinity – process has affinity for processor on which it is currently running

- **soft affinity** * (allow proc to ______)
- **hard affinity** * (Linux)
- Variations including **processor sets** * (Solaris)

NUMA and CPU Scheduling



Note that memory-placement algorithms can also consider affinity

Multiple-Processor Scheduling – Load Balancing

If SMP, need to keep all CPUs loaded for efficiency

Load balancing attempts to keep workload evenly distributed * (not necessary for the sys of a _______ ready queue)

Push migration – periodic task checks load on each processor, and if found pushes task from overloaded CPU to other CPUs

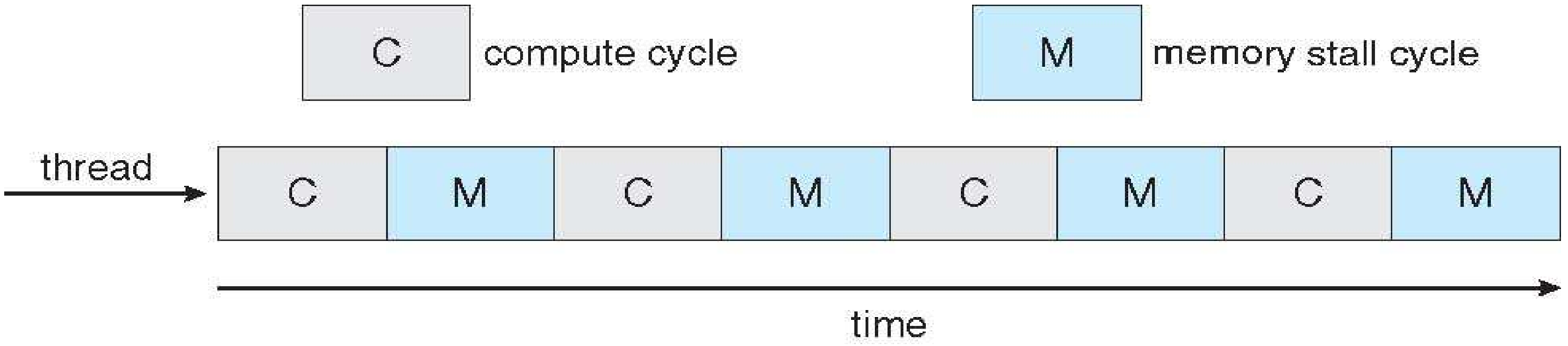
Pull migration – idle processors pulls waiting task from busy processor

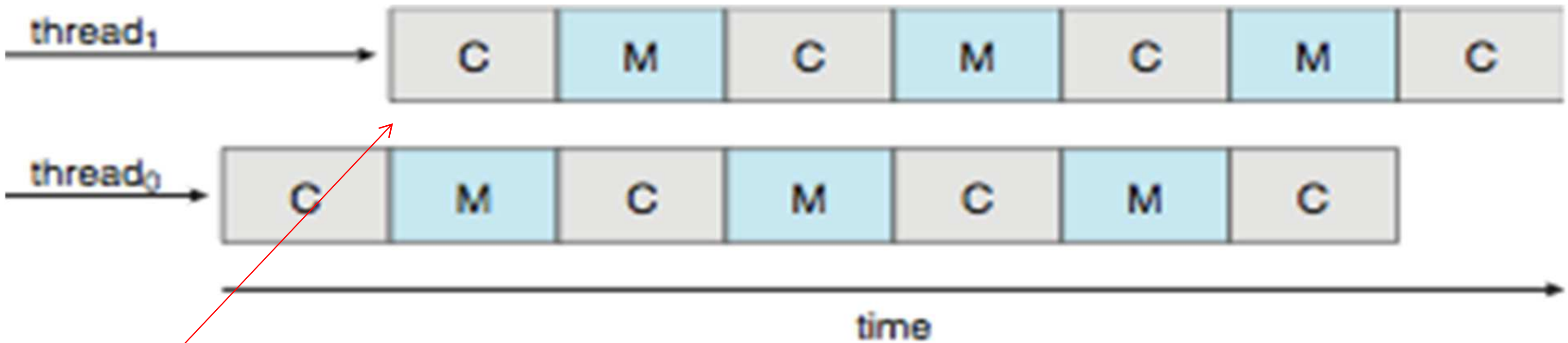
* (both are implemented together in Linux and FreeBSD)
* (Linux runs load balancing algo every 200 msec(____ migration) or whenever the run queue is empty(____ migration))
* (Load balancing counteracts with processor _______)

Multicore Processors

- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens * (CPU loses __% of time due to mem stall (caused by cache ____))

Multithreaded Multicore System





* (dual core sys with dual-thr looks like to have __ logical processors)

* (_______-grained multithreading: a thr executes until a long-latency event like mem stall, and then thr ________ occurs which takes time)
* (_____-grained (or interleaved) multithreading: switches between thr at a much finer level of granularity (typically _____); includes logic for thr switching which allows low _____ of switching)

Real-Time CPU Scheduling

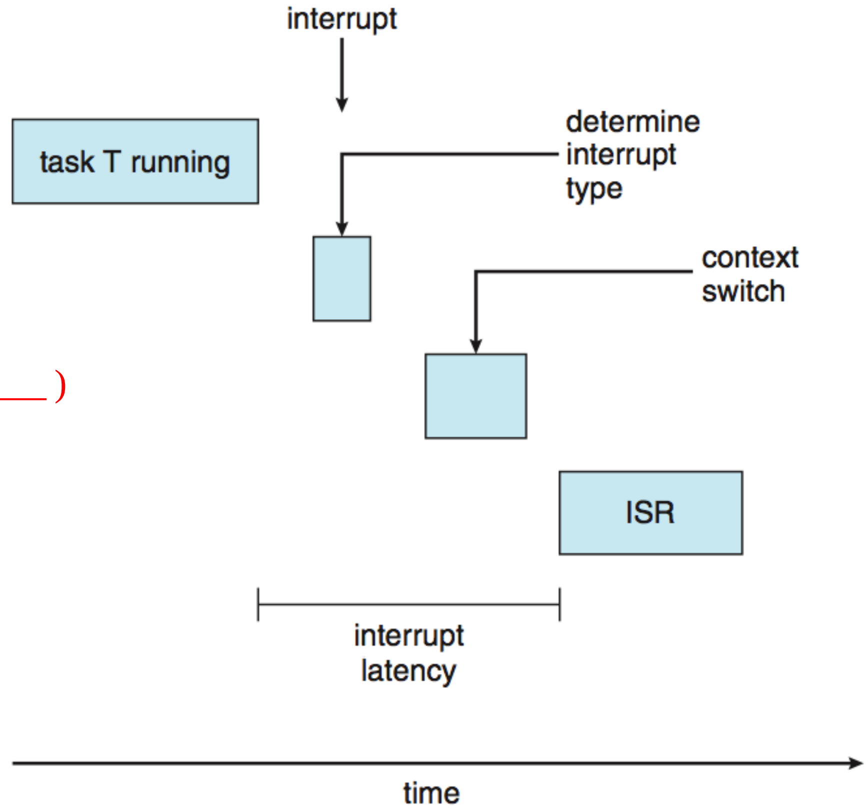
Can present obvious challenges

Soft real-time systems – no guarantee as to when critical real-time process will be scheduled

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

Two types of latencies affect performance

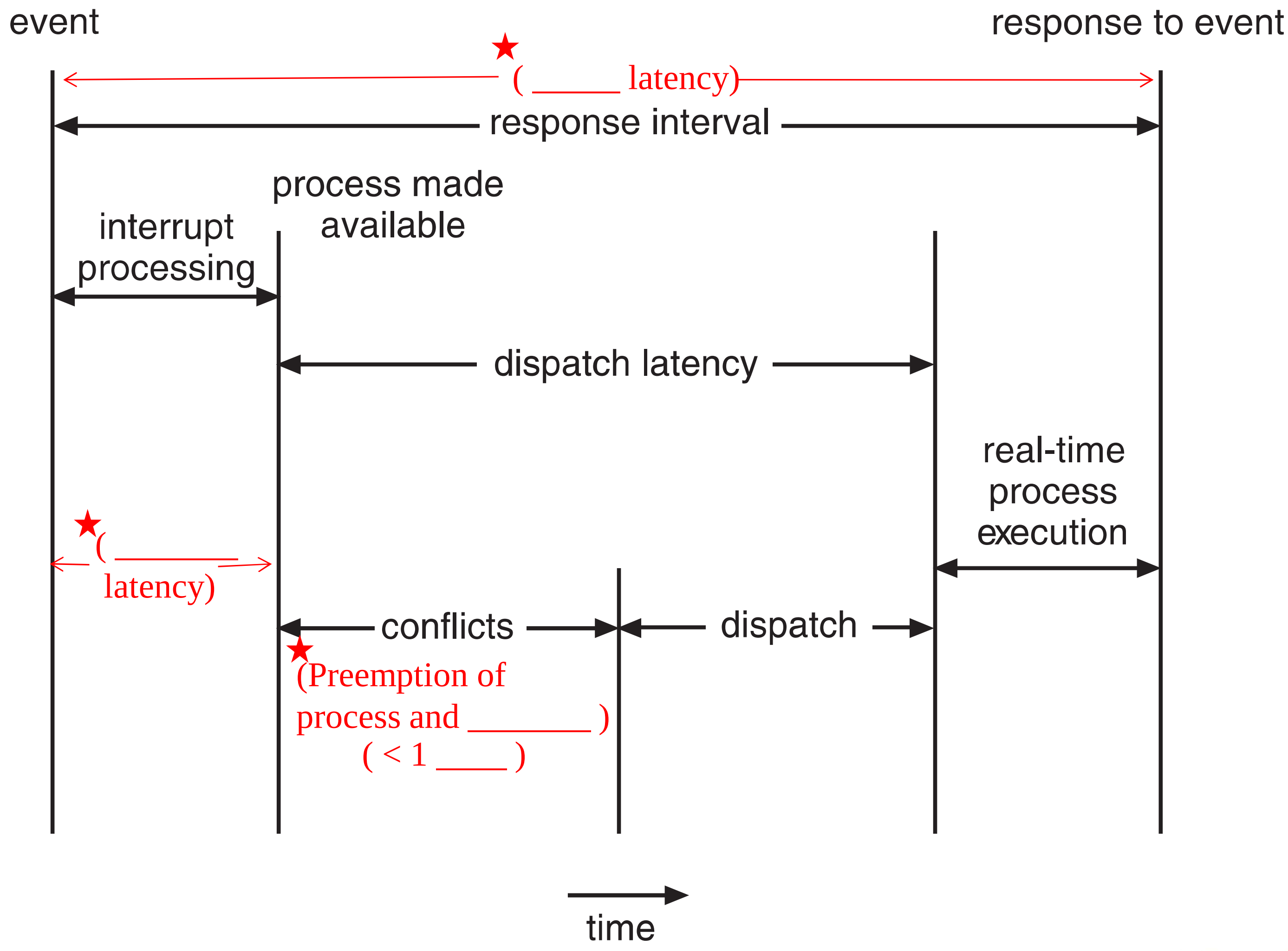
1. Interrupt latency – time from arrival of interrupt to start of routine that services interrupt*(For RT, this must not be minized but _________)
2. Dispatch latency – time for schedule to take current process off CPU and switch to another



Real-Time CPU Scheduling (Cont.)

Conflict phase of dispatch latency:

1. Preemption of any process running in kernel mode
2. Release by low-priority process of resources needed by high-priority processes



Priority-based Scheduling

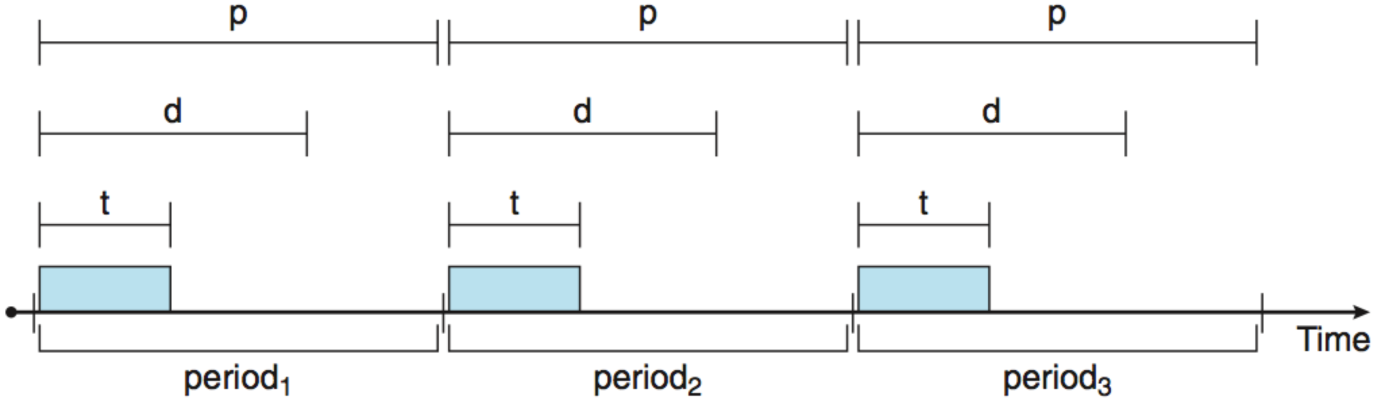
For real-time scheduling, scheduler must support preemptive, priority-based scheduling

- But only guarantees soft real-time

For hard real-time must also provide ability to meet deadlines

Processes have new characteristics: **periodic** ones require CPU at constant intervals

- Has processing time *t*, deadline *d*, period *p*
- $0 \leq t \leq d \leq p$
- **Rate** of periodic task is $1/p$



★ (________ control algo is used to decide if a RT proc can meet its deadline. Then accept it.)

Virtualization and Scheduling

Virtualization software schedules multiple guests onto CPU(s)

Each guest doing its own scheduling

- Not knowing it doesn't own the CPUs
- Can result in poor response time
- Can effect time-of-day clocks in guests

Can undo good scheduling algorithm efforts of guests

Rate Monotonic Scheduling

A priority is assigned based on the inverse of its period

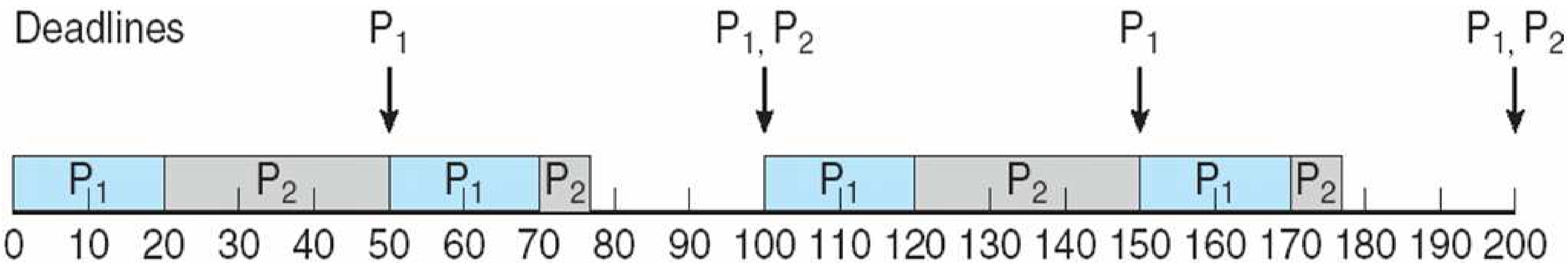
Shorter periods = higher priority;

Longer periods = lower priority

P_1 is assigned a higher priority than P_2.

*(P_1: period 50; processing time 20) * (P_2: period 100; processing time 35)

*(Schedulability? 20/50 + __ /100 = 0.4 + 0.35 = 0.75, so ___)



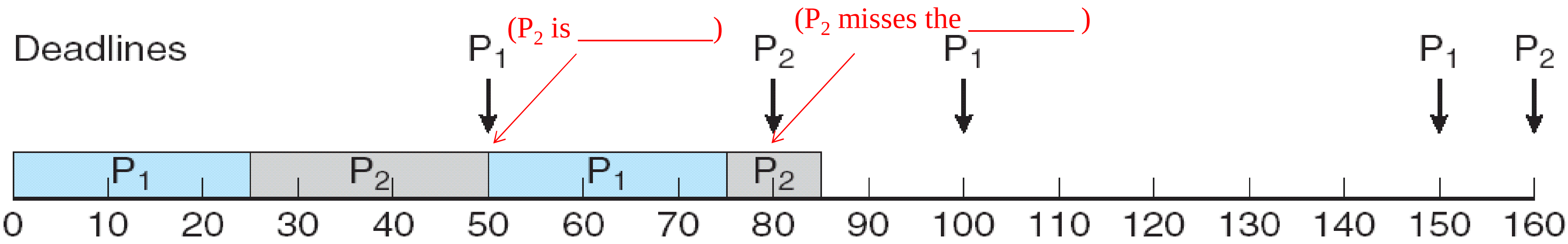
*(Rate monotonic is _______ : if a set of proc cannot be scheduled by this algo, it can't be scheduled by any other algo assigning static priority)

Missed Deadlines with Rate Monotonic Scheduling

*(P_1: period 50; processing time 25)

*(P_2: period 80; processing time 35)

*(Schedulability? 25/50 + 35/ __ = 0.94, seems ___)



* (Rate monotonic does not maximize CPU __________)

*(Worst-case CPU utilization for scheduling N processes: $N(2^{1/N} - 1)$;
if $N = 1$, then ___%; $N = \infty$, then __ %)

Earliest Deadline First Scheduling (EDF)

* (dynamically)

Priorities are assigned according to deadlines:

*(When a proc becomes ________, it announces its deadline)

the earlier the deadline, the higher the priority;

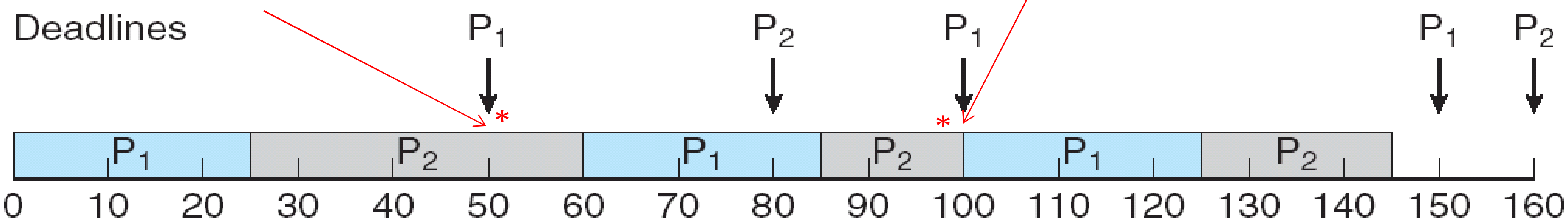
the later the deadline, the lower the priority

* (P_1: period 50; processing time 25)

*(P_2: period 80; processing time 35)

(__________ of P_2 since P_1 deadline(150) is earlier than P_2(160))

(_____________ of P_2 since P_1 deadline(100) is later than P_2(80))



*(EDF does not require proc to be _______, require _________ CPU burst time)

*(EDF is theoretically ________ in meeting the deadlines and maximizing CPU utilization)

*(Context switch and int handling overhead disallow 100% CPU _________)

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 ***N*** / *T* of the total processor time

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

```
#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 ... */
    pthread exit(0);
 }
```

Operating System Examples

- Linux scheduling
- Windows scheduling
- Solaris scheduling

Linux Scheduling Through Version 2.5

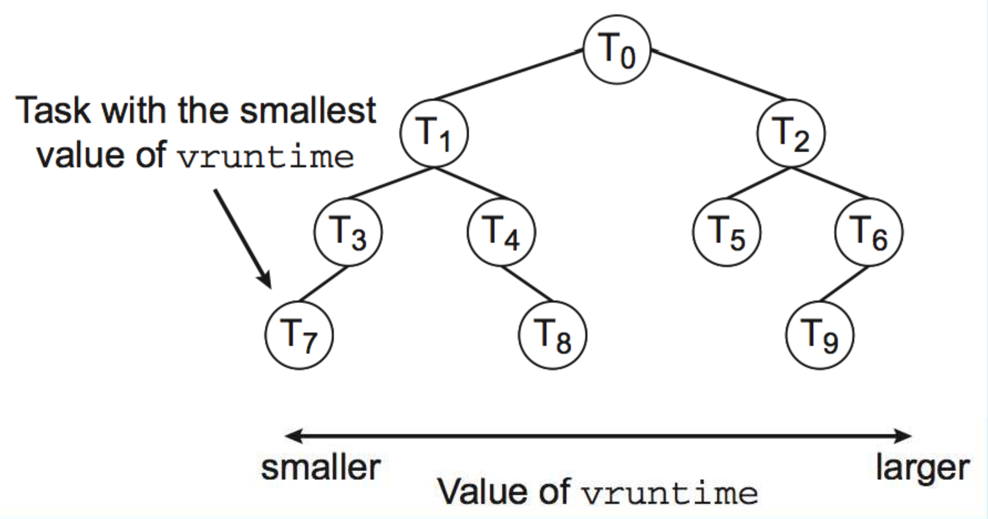
- Prior to kernel version 2.5, ran variation of standard UNIX scheduling algorithm (no SMP-based)
- Version 2.5 moved to constant order *O*(1) scheduling time
  - Preemptive, priority based
  - Two priority ranges: time-sharing and real-time
  - **Real-time** range from 0 to 99 and **nice** value from 100 to 140* (for normal nonRT)
  - 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 * (Default is _)
  - Lower value is higher priority
  - Calculates **target latency** – interval of time during which task should run at least once *(every ________)
  - Target latency can increase if say number of active tasks increases *(beyond a certain ________)
- 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
  - *(For high priority, virtual run time _ actual run time; low priority, virtual _ actual)
- 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.)

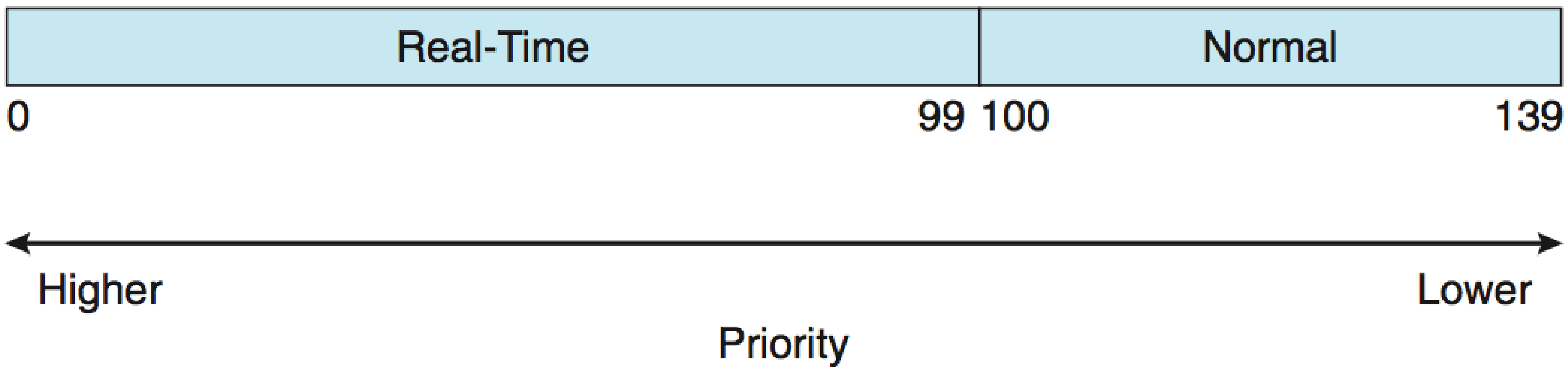
Real-time scheduling according to POSIX.1b

- Real-time tasks have static priorities

Real-time plus normal map into global priority scheme

Nice value of -20 maps to global priority 100

Nice value of +19 maps to priority 139



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
- 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

*(______ classes)

*(relative priority in each ______)

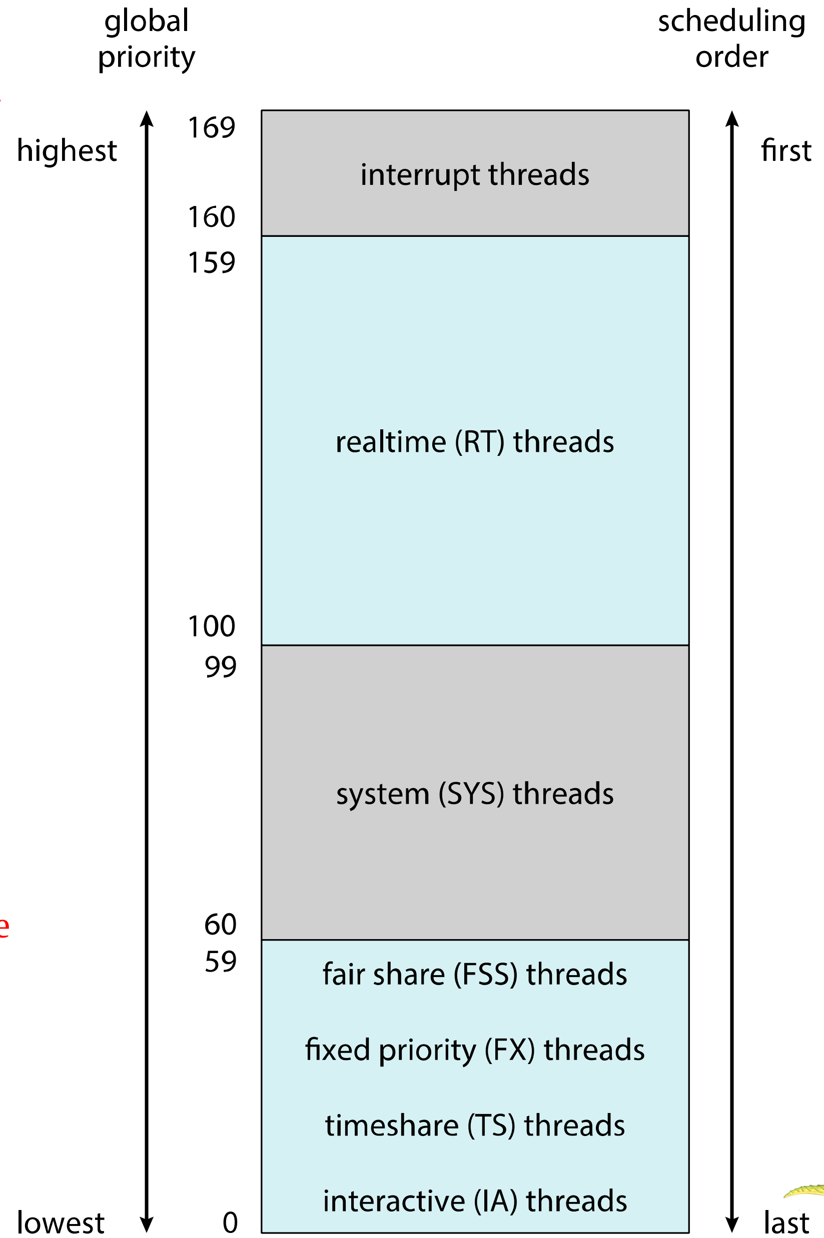
	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

Solaris

- Priority-based scheduling *
- Six classes available
  - Time sharing (default) (TS)*(default _____)
  - 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

* (Higher priority, _______ time slice)

* (Interactive thr given _______ priority than CPU-bound thr; for good __________ time for interactive thr and good __________ for CPU-bound thr)

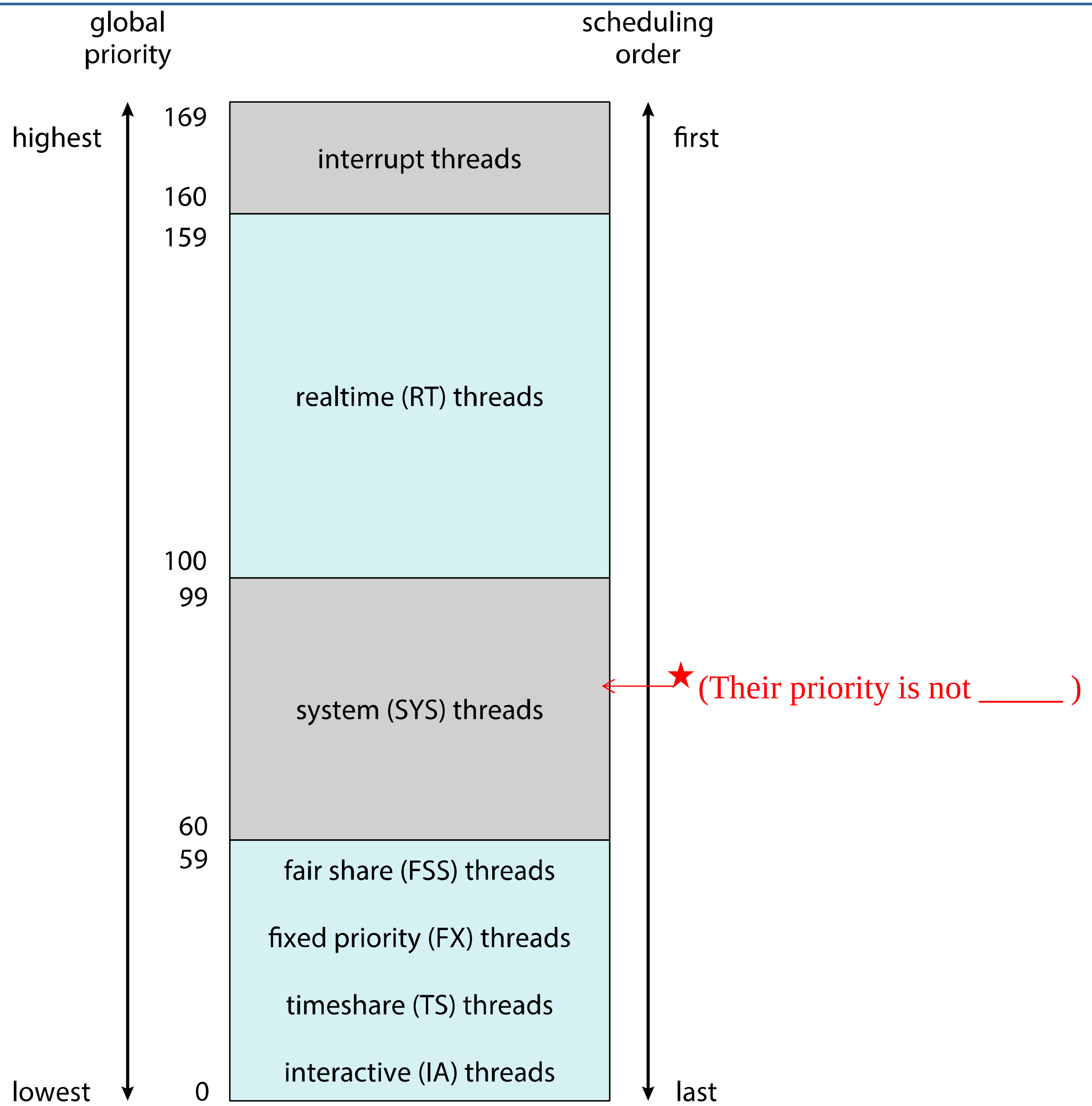


Solaris Dispatch Table ★ (For time-sharing and ________ thr)

priority	time quantum ★(msec)	time quantum expired ★(without ________)	return from sleep ★
0	200	0★ (New ________)	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

(50 ~ 59 to allow ______ response time for interactive thr)

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 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

* (sum 61)

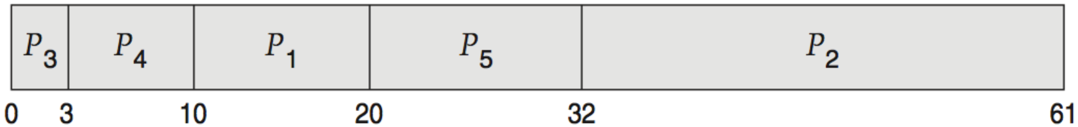
Deterministic Evaluation

For each algorithm, calculate minimum average waiting time

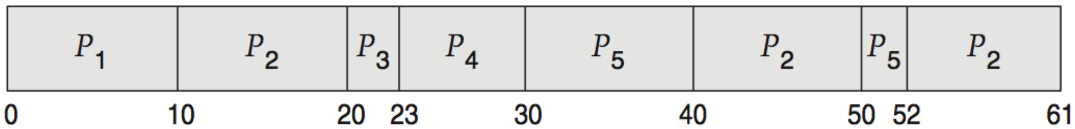
Simple and fast, but requires exact numbers for input, applies only to those inputs

FCS is 28ms:

Non-preemptive SJF is 13ms:



RR is 23ms:



* (What is q?)

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
$n = \lambda \times W$

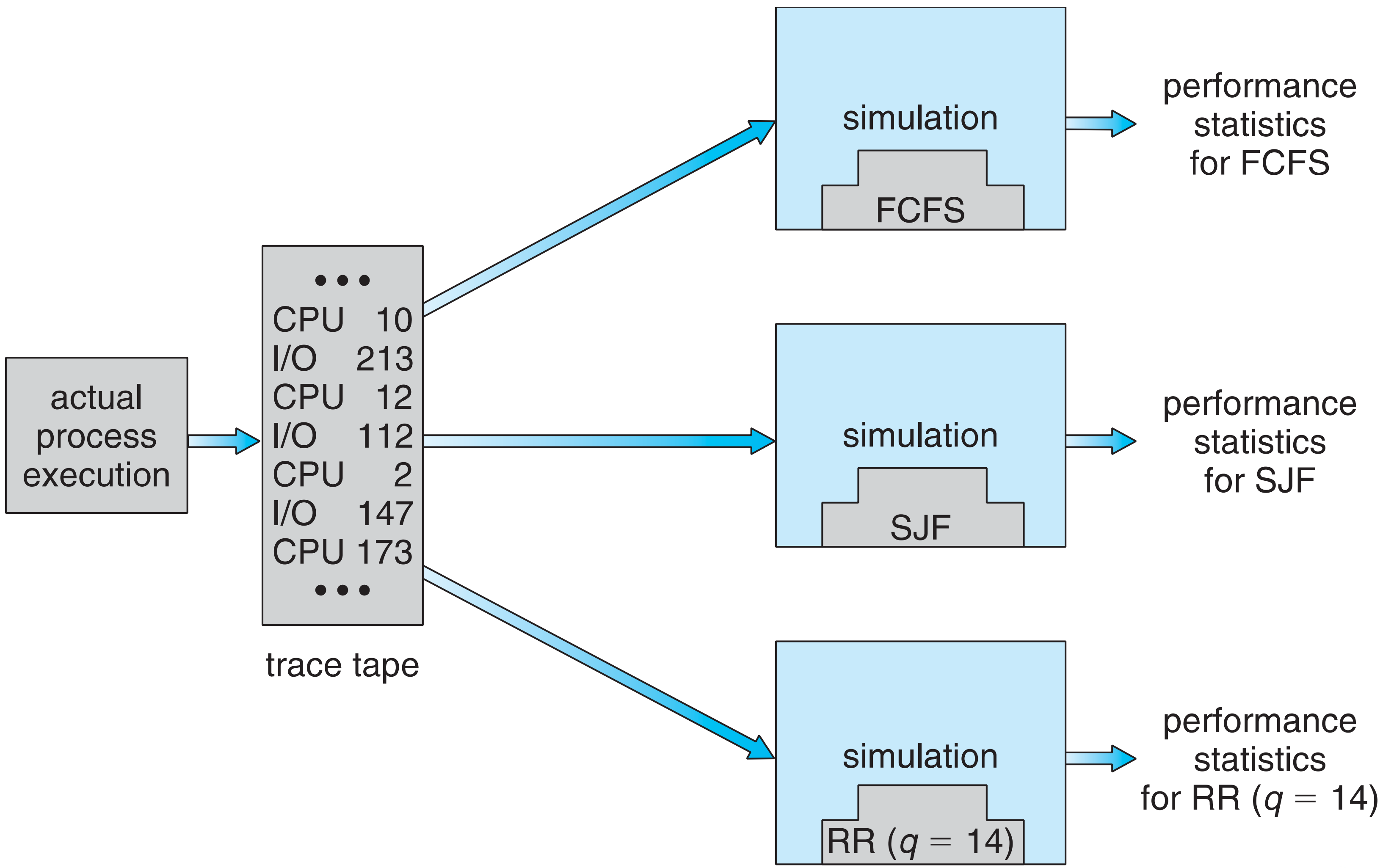
Valid for any scheduling algorithm and arrival distribution

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