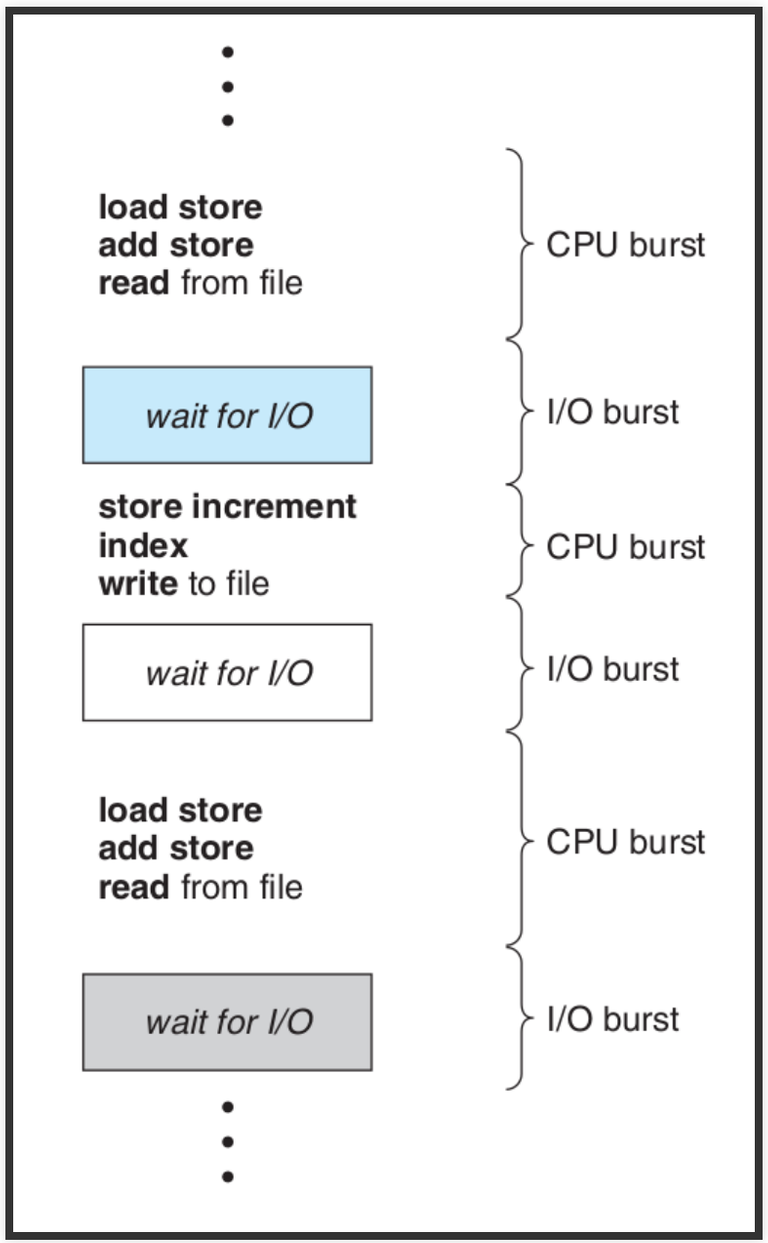
CHAPTER 5 - CPU SCHEDULING

OBJECTIVES

- Introduce CPU scheduling for multiprocessor and multicore systems
- CPU-scheduling algorithms and assessing them
- Evaluation criteria for selecting a CPU-scheduling algorithm for a particular system
- To examine the scheduling algorithms of several operating systems

BASIC CONCEPTS

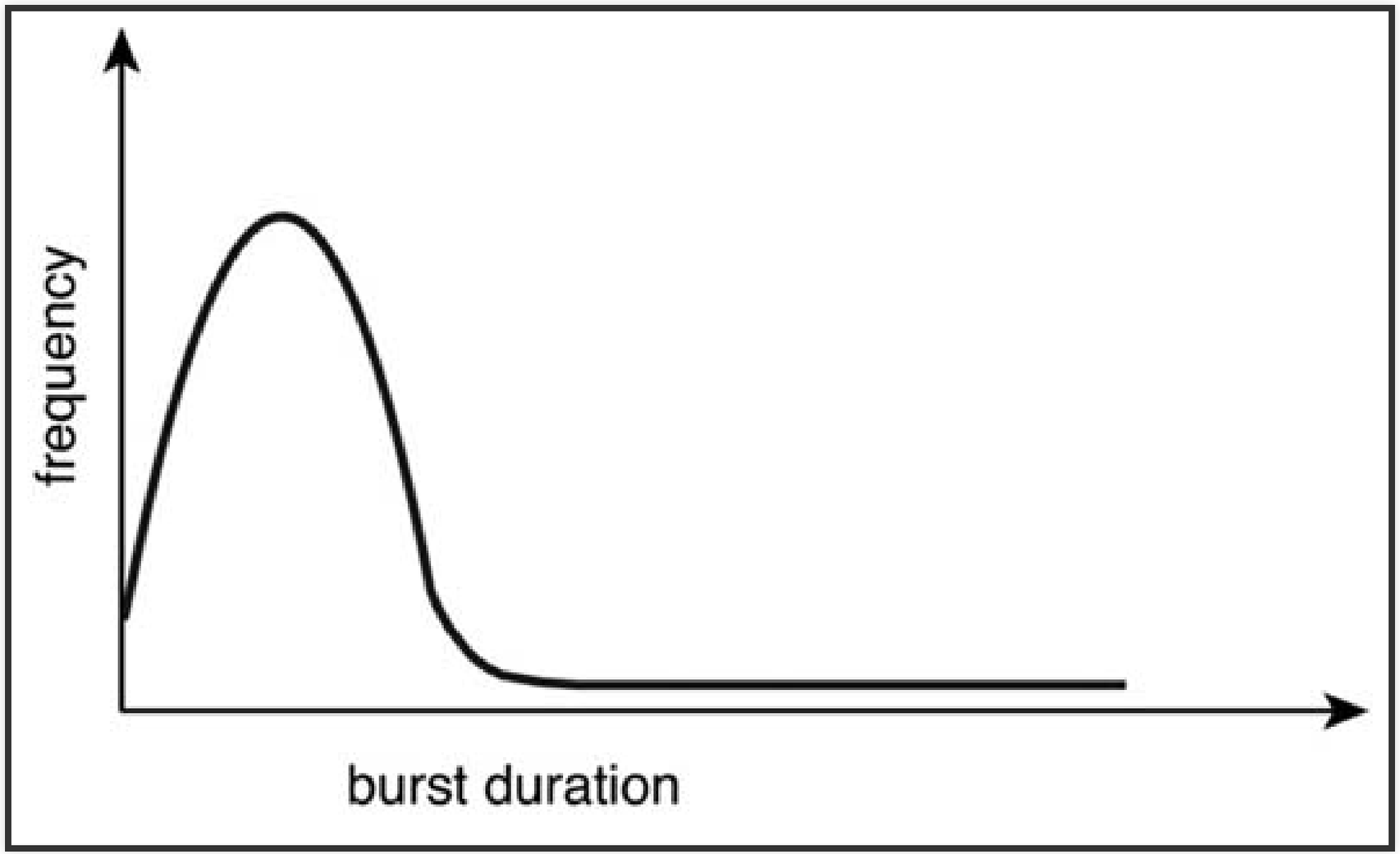
CPU-I/O BURST CYCLE



CPU-I/O BURST CYCLE

- 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 DURATIONS



CPU SCHEDULER

- Scheduler selects from among the processes in ready queue, and allocates the CPU to one of them
  - Queue may be ordered in various ways

PREEMPTIVE SCHEDULING

- 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

CPU SCHEDULER

- Scheduling under 1 and 4 is **nonpreemptive** or **cooperative**
- All other scheduling is preemptive
  - Consider access to shared data
  - Consider preemption while in kernel mode
  - Consider interrupts occurring during crucial OS activities

> **Preemptive** can lead to **race conditions**

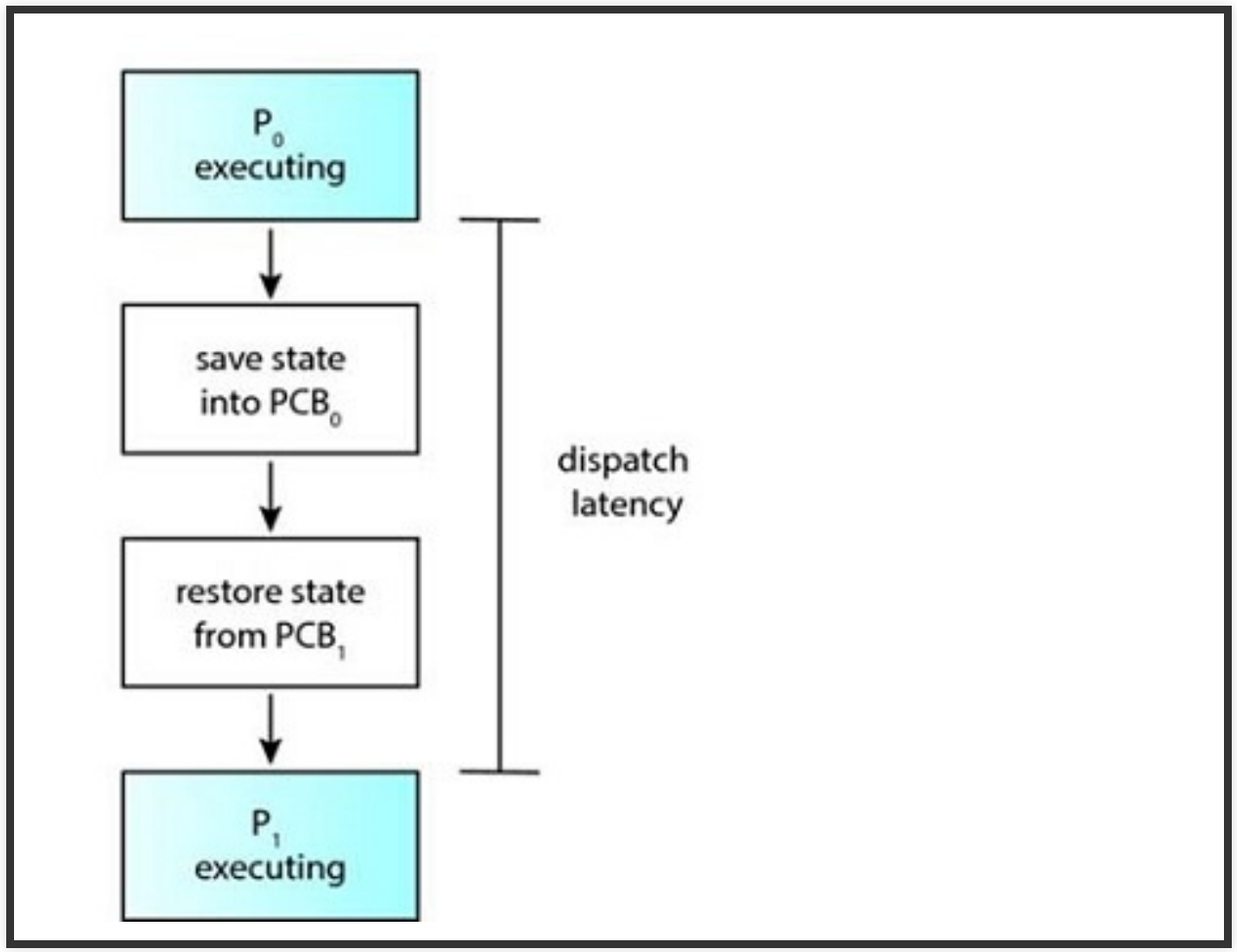
DISPATCHER

Dispatcher module gives control of the CPU to the process selected by the scheduler; this involves:

- switching context
- switching to user mode
- jumping to the proper location in the user program to restart that program

DISPATCHER

Dispatch latency – time it takes for the dispatcher to stop one process and start another running



DISPATCHER

```
~$ vmstat 1 3
```

vmstat reports information about processes, memory, paging, block IO, traps, disks and cpu activity.

```
procs   -----------memory---------- ---swap-- -----io---- -system-- ------cpu-----
 r  b   swpd   free   buff  cache     si   so    bi    bo   in   cs us sy id wa st
 2  0      0 6838372 790652 3562880    0    0    36    28  143   34  2  1 97  0  0
 0  0      0 6838224 790660 3562904    0    0     0    28 1059 3782  1  1 98  0  0
 0  0      0 6838224 790660 3562908    0    0     0     0 1281 4134  1  1 98  0  0
```

DISPATCHER

```
~$ cat /proc/10740/status
```

```
Name:   java
State:  S (sleeping)
...
voluntary_ctxt_switches:        63
nonvoluntary_ctxt_switches:     3
```

SCHEDULING CRITERIA

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
- 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, not output (for time-sharing environment)

SCHEDULING ALGORITHM OPTIMIZATION CRITERIA

- Max CPU utilization
- Max throughput
- Min turnaround time
- Min waiting time
- Min response time

SCHEDULING ALGORITHMS

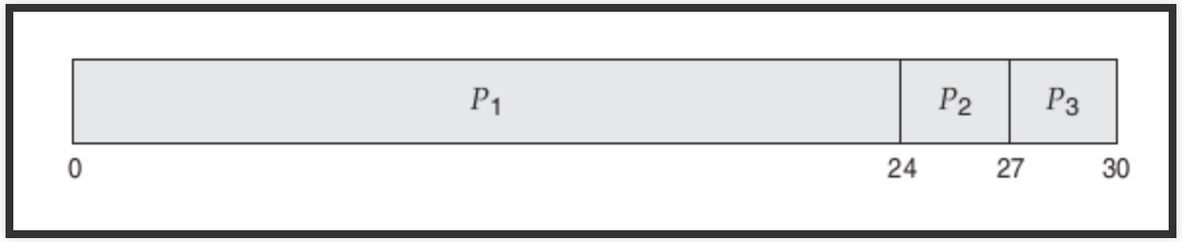
FIRST-COME, FIRST-SERVED (FCFS)

Process	Burst Time
P1	24
P2	3
P3	3

Suppose that the processes arrive in the order: P1 , P2 , P3

FCFS SCHEDULING

The Gantt Chart for the schedule is:



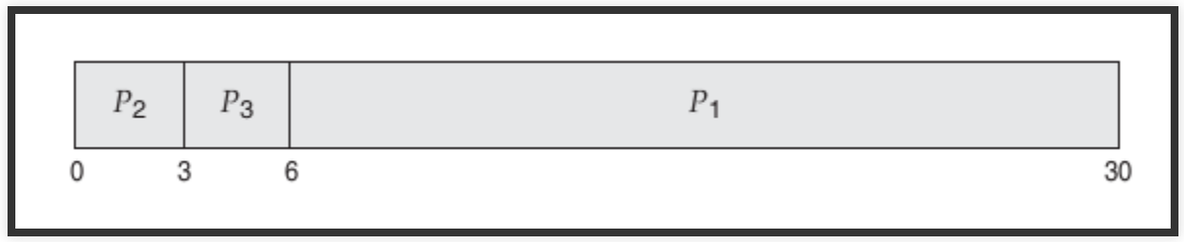
Waiting time for P1 = 0; P2 = 24; P3 = 27

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

FCFS SCHEDULING

Suppose that the processes arrive in the order: P2 , P3 , P1

The Gantt chart for the schedule is:



Waiting time for P1 = 6; P2 = 0; P3 = 3

Average waiting time: (6 + 0 + 3)/3 = 3

FCFS SCHEDULING

- Much better than previous case
- **Convoy effect** - short process behind long process

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

SHORTEST-JOB-FIRST (SJF)

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

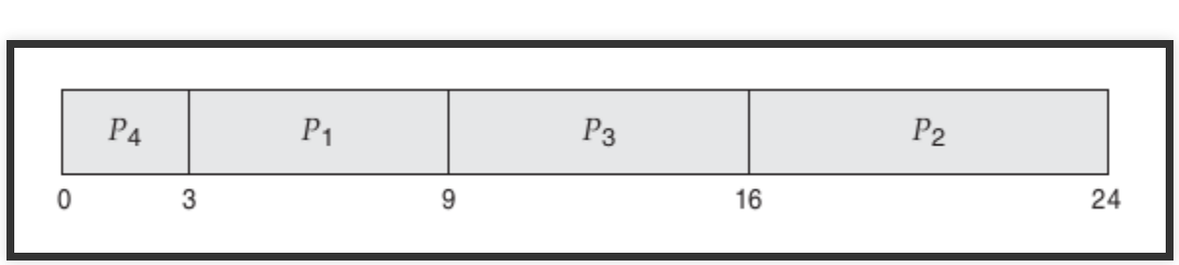
⚠ The difficulty is knowing the length of the next CPU request

EXAMPLE OF SJF

Process	Burst Time
P1	6
P2	8
P3	7
P4	3

EXAMPLE OF SJF

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

DETERMINING LENGTH OF NEXT CPU BURST

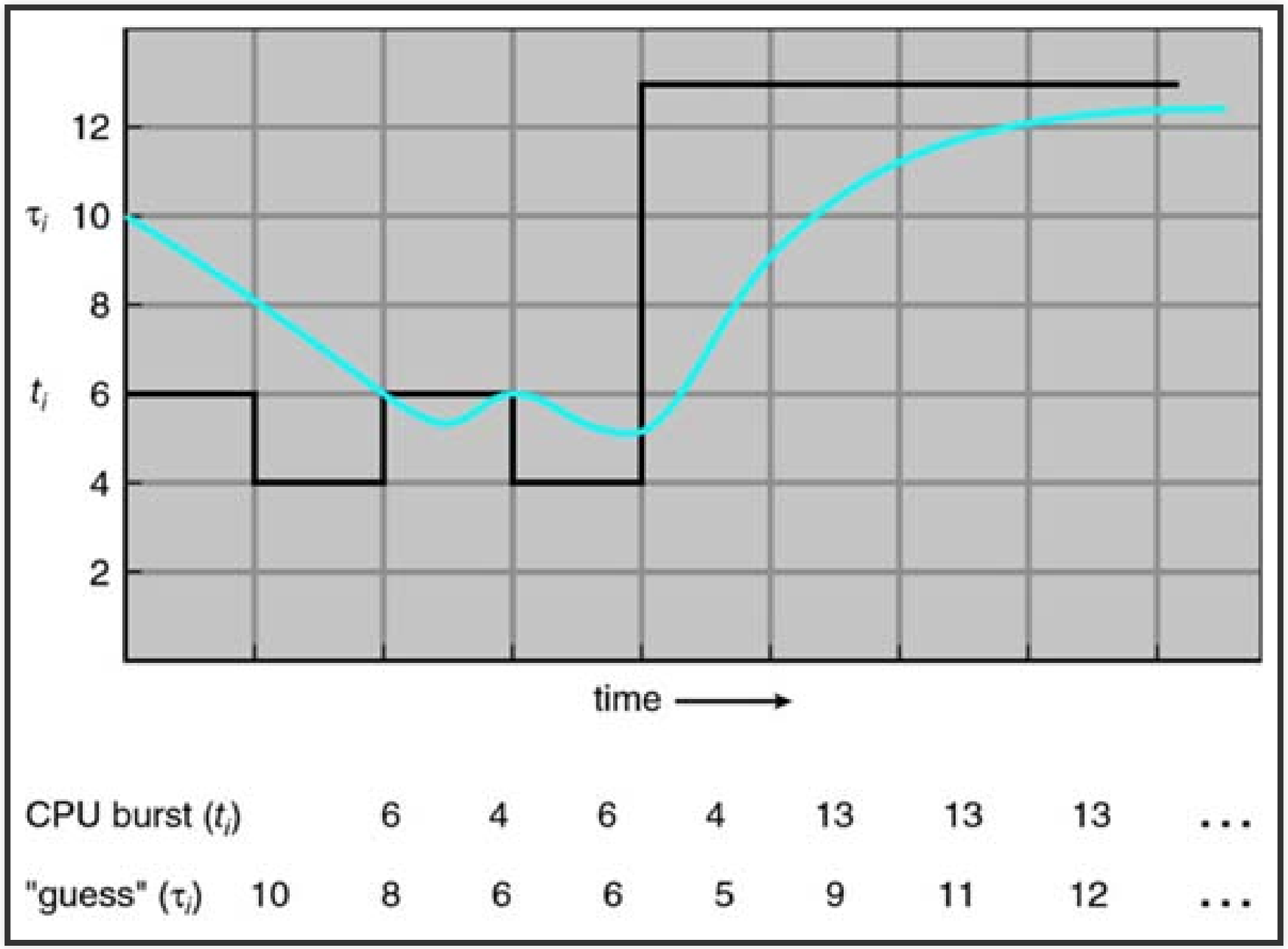
t_n = actual length of n^{th} CPU burst

τ_{n+1} = predicted value for the next CPU burst

α where $0 \leq \alpha \leq 1$

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

PREDICTION OF THE LENGTH OF THE NEXT CPU BURST



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

EXPONENTIAL AVERAGING

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

  $\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\alpha\, t\, n\, -1 + \ldots + (1 - \alpha)^j\, \alpha\, t_{n-j} + \ldots + (1 - \alpha)^{n+1}\, \tau_0$
- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

SHORTEST-REMAINING-TIME-FIRST

The preemptive version of **Shortest Job First** is sometimes called the **Shortest Remaining Time First** algorithm

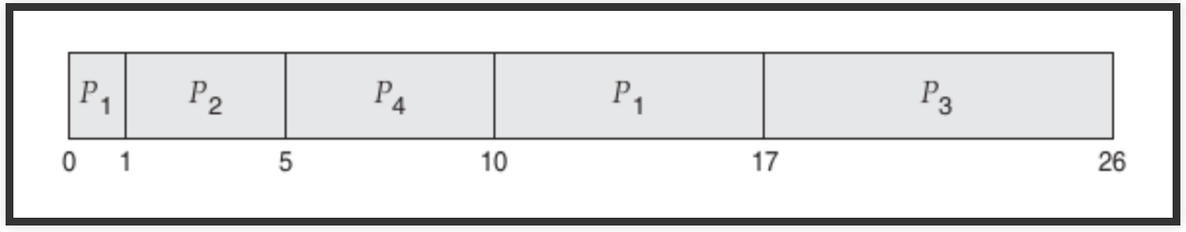
EXAMPLE

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

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
P4	3	5

EXAMPLE

Preemptive SJF Gantt Chart



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

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

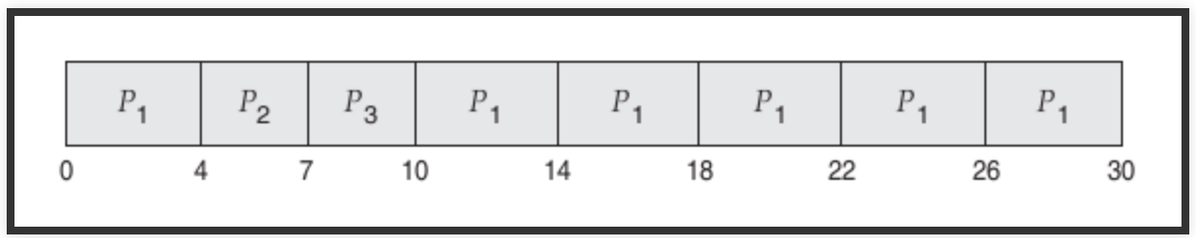
EXAMPLE

Process	Burst Time
P1	24
P2	3
P3	3

EXAMPLE

Time Quantum = 4

The Gantt chart is:



ROUND ROBIN PERFORMANCE

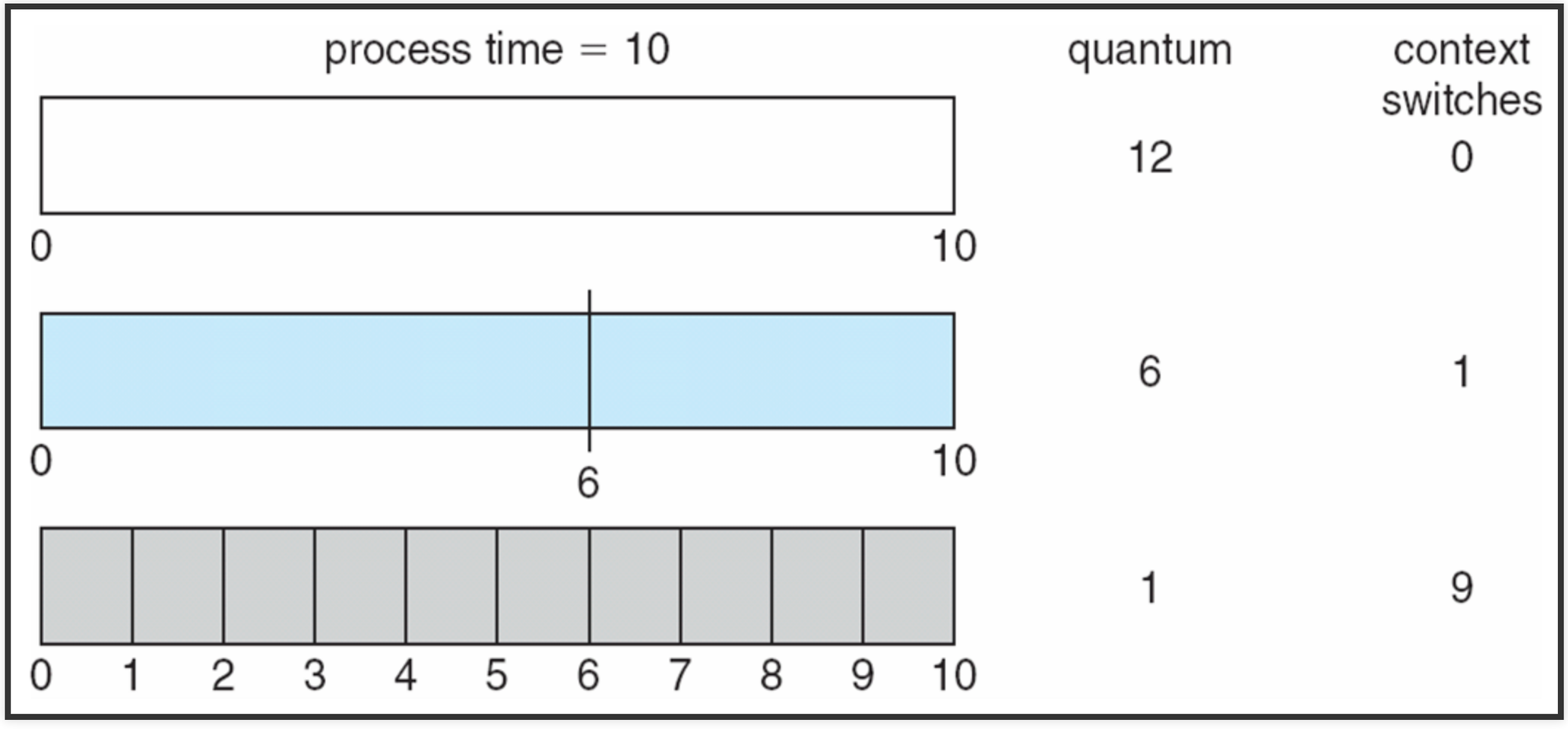
Typically, higher average turnaround than SJF, but better *response*

q large → FIFO

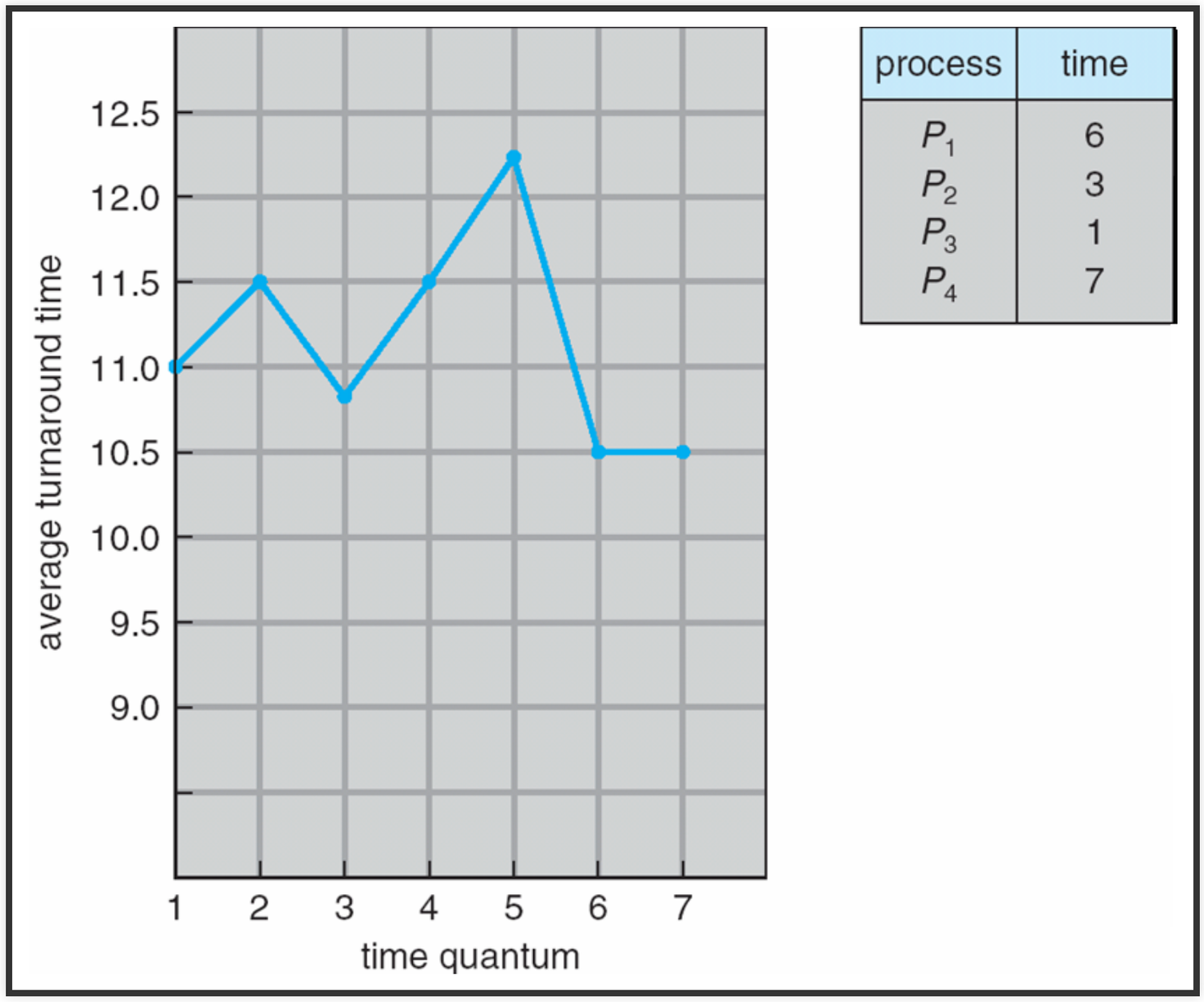
q small → q must be large with respect to context switch, otherwise overhead is too high

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

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

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

PRIORITY SCHEDULING

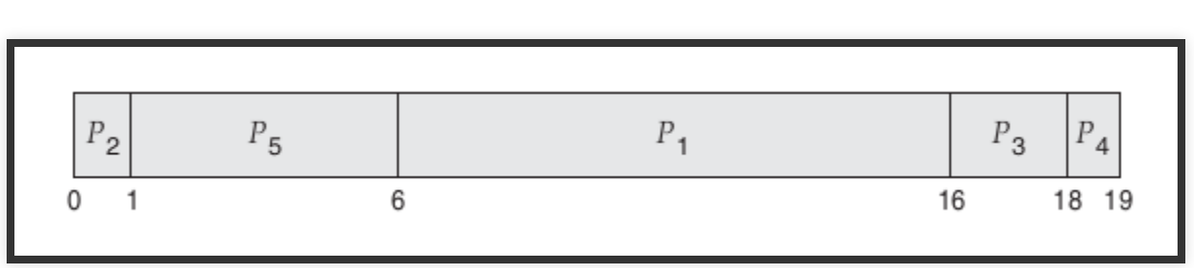
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time
  - **Problem** → **Starvation** – low priority processes may never execute
  - **Solution** → **Aging** – as time progresses increase the priority of the process

EXAMPLE

Process	Burst Time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

EXAMPLE

Priority scheduling Gantt Chart



Average waiting time = 8.2 msec

MULTILEVEL QUEUE

Ready queue is partitioned into separate queues, eg:

- foreground (interactive)
- background (batch)

Process permanently in a given queue

MULTILEVEL QUEUE

Each queue has its own scheduling algorithm:

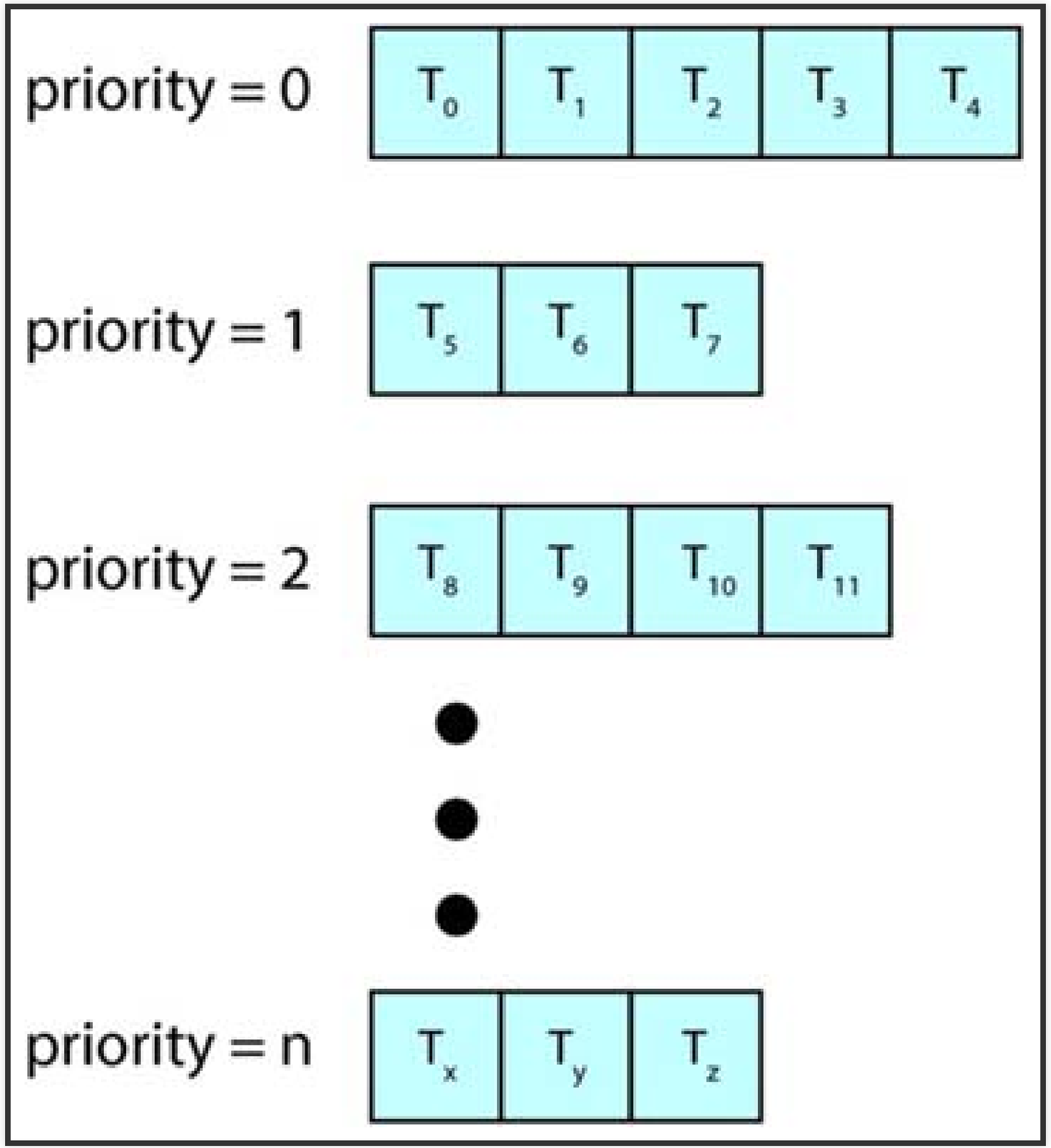
- foreground – RR
- background – FCFS

MULTILEVEL QUEUE

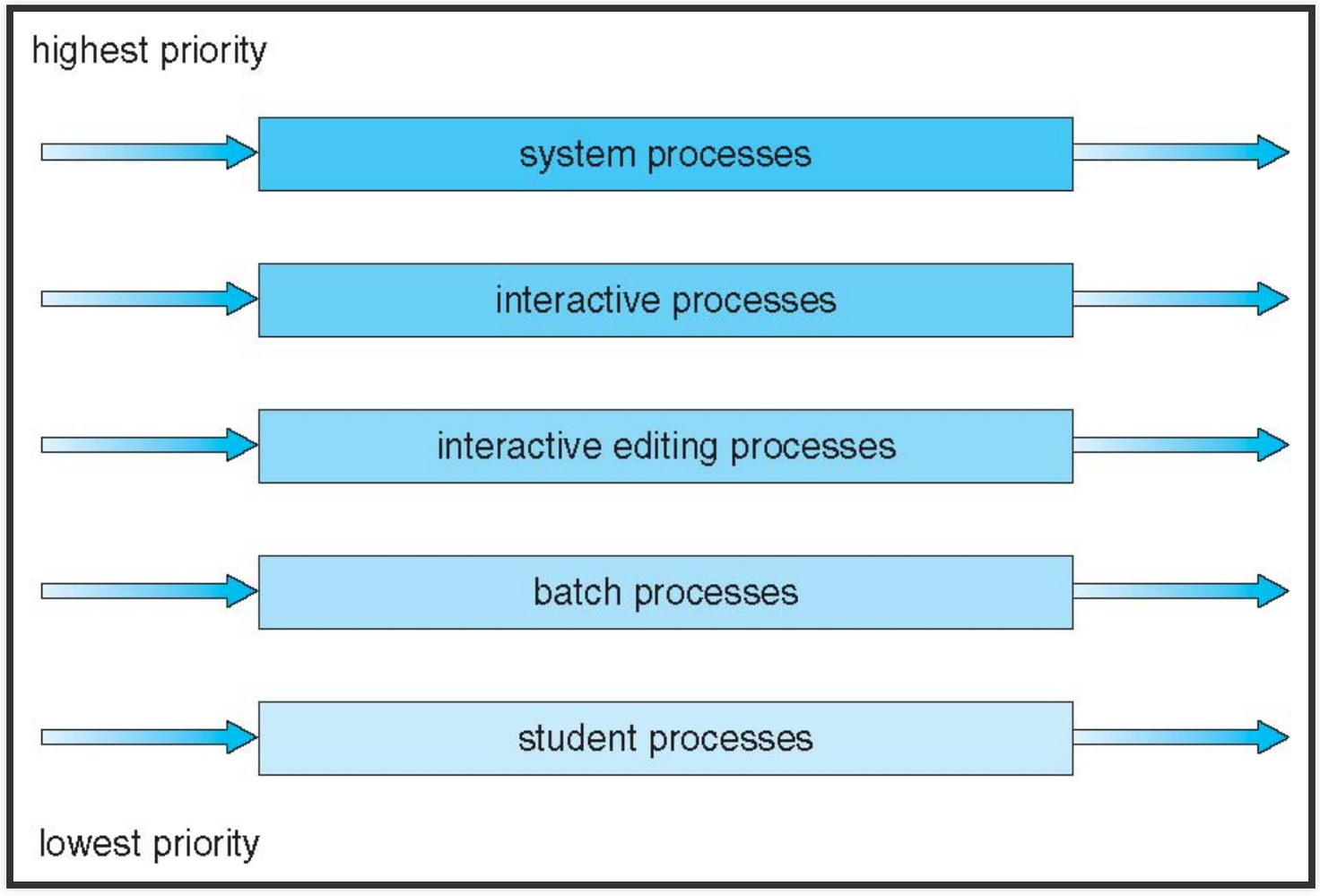
Scheduling must be done between the queues:

- Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation.
- 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


priority = 0
T0
T1
T2
T3
T4
priority = 1
T5
T6
T7
priority = 2
T8
T9
T10
T11
priority = n
Tx
Ty
Tz

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:

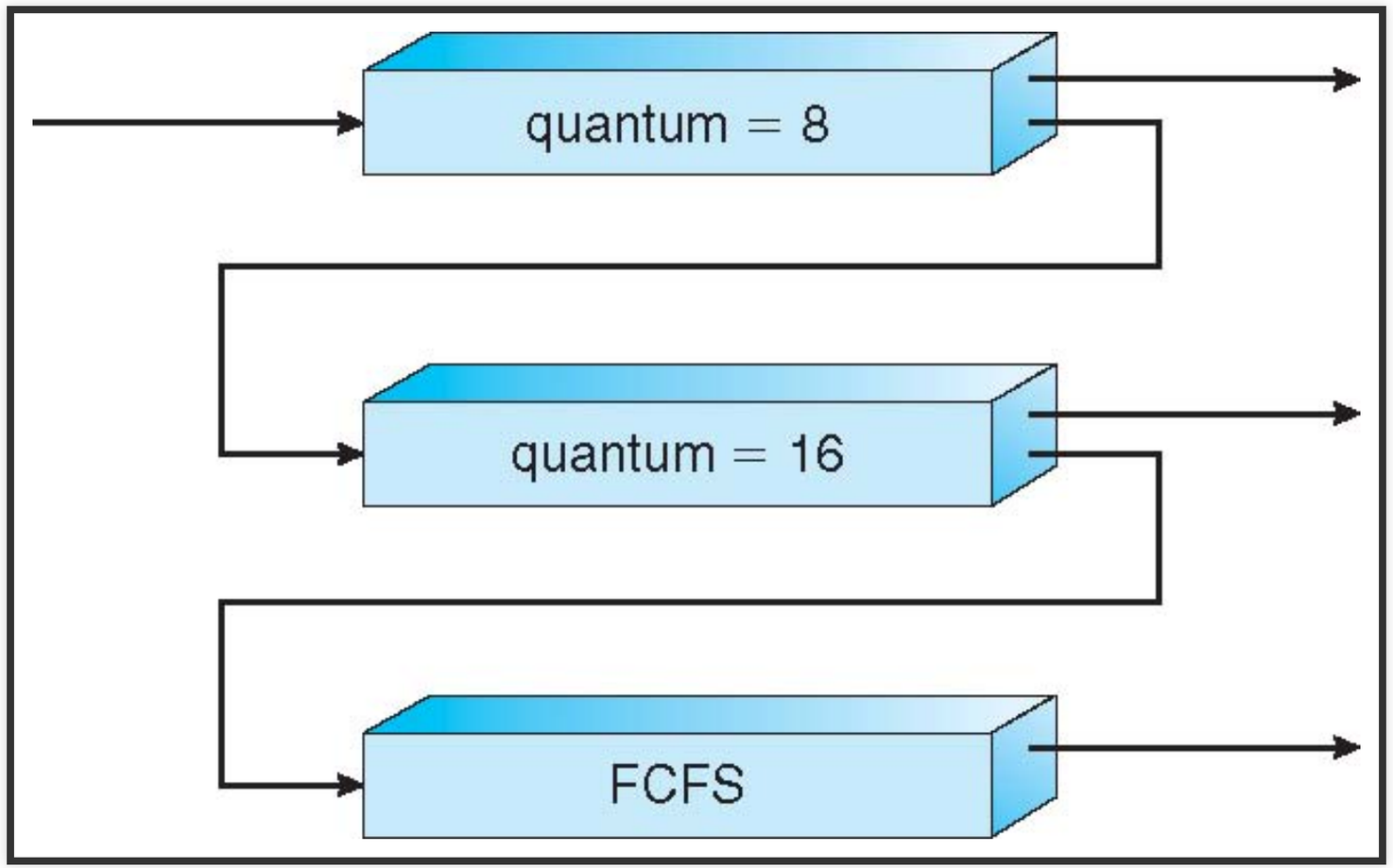
- number of queues
- scheduling algorithms for each queue
- method used to determine when to upgrade a process
- method used to determine when to demote a process
- method used to determine which queue a process will enter when that process needs service

EXAMPLE

Three queues:

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

EXAMPLE



EXAMPLE

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

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

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

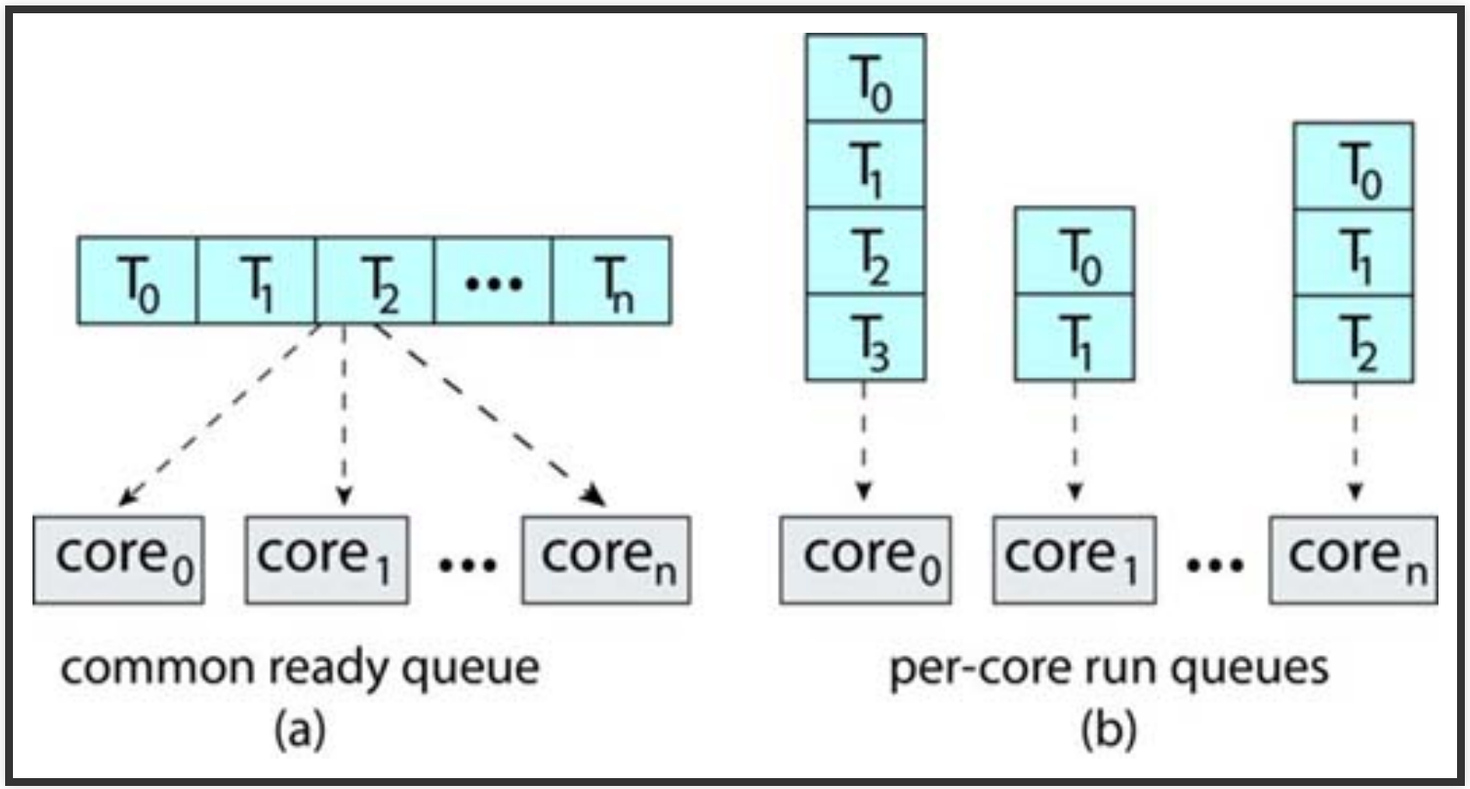
```c
#include <pthread.h>
#include <stdio.h>

#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");
        }
    }
    /* 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);
```

MULTIPLE-PROCESSOR SCHEDULING

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

ORGANIZATION OF READY QUEUES



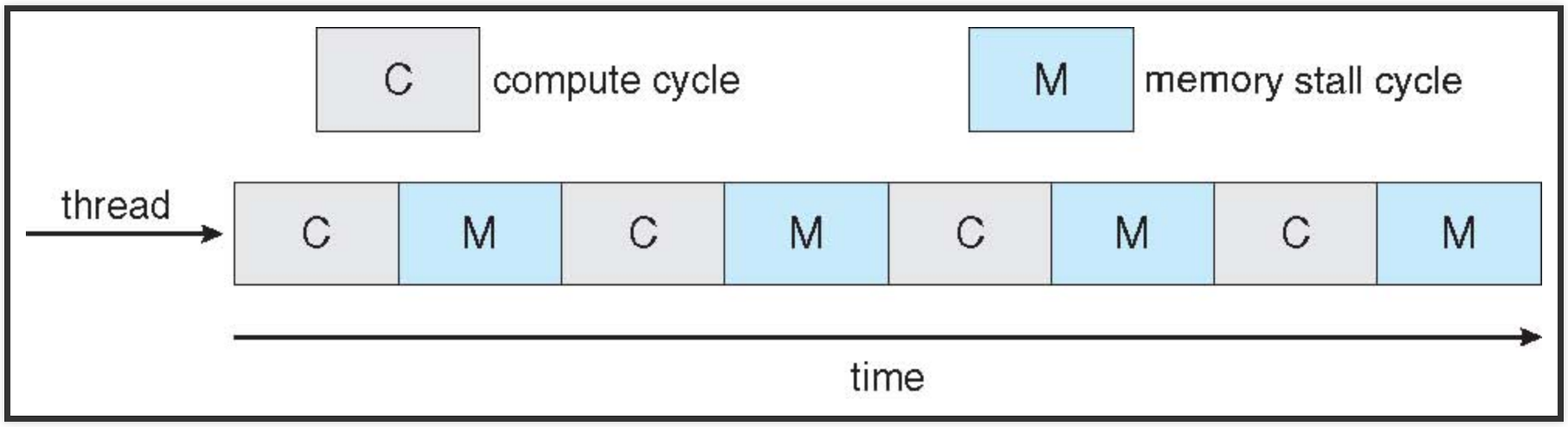
MULTICORE PROCESSORS

Recent trend to place multiple processor cores on same physical chip

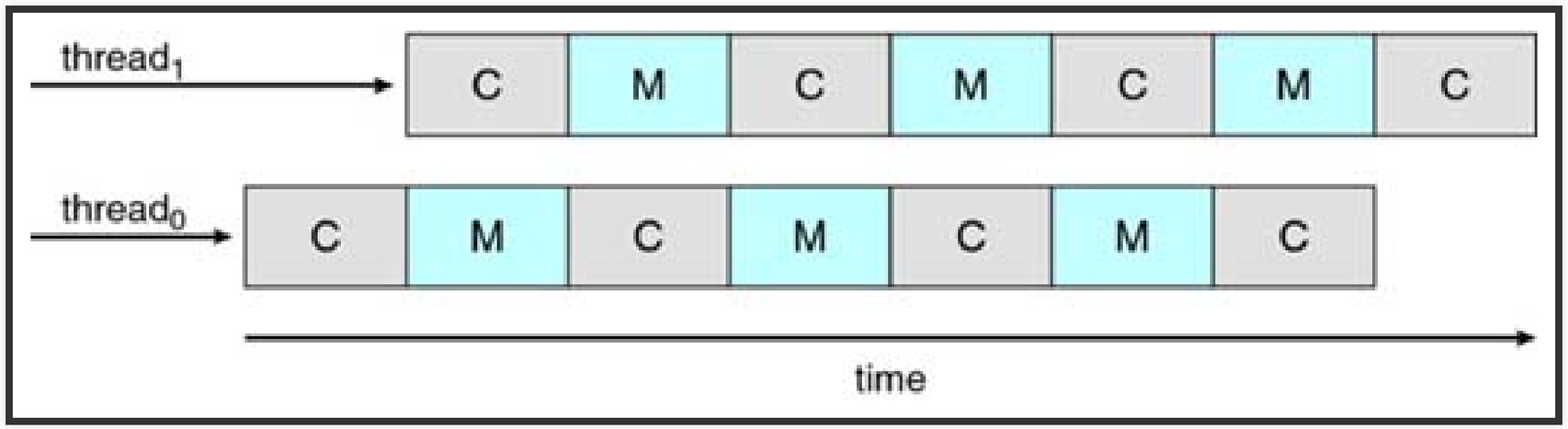
- Faster and consumes less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

MEMORY STALL

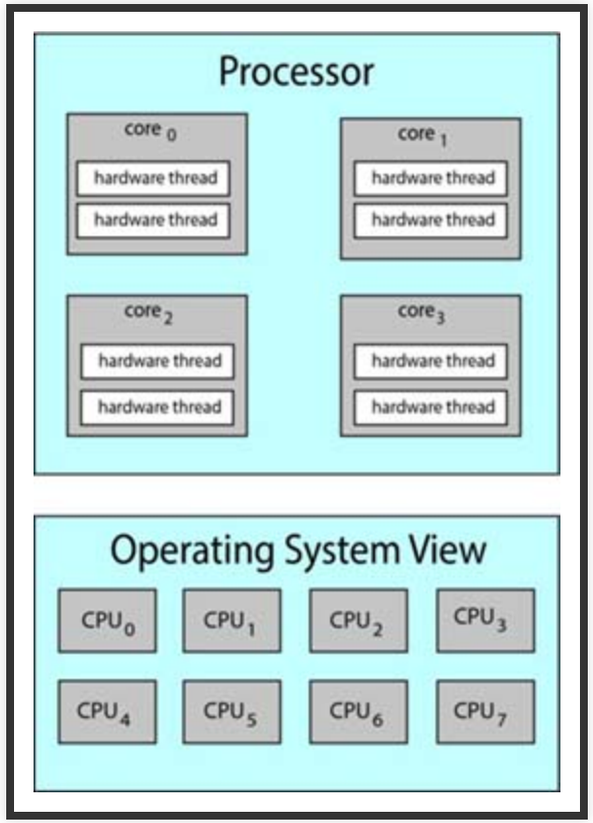
Memory Stall - due to cache miss etc.



MULTITHREADED MULTICORE SYSTEM



CHIP MULTITHREADING

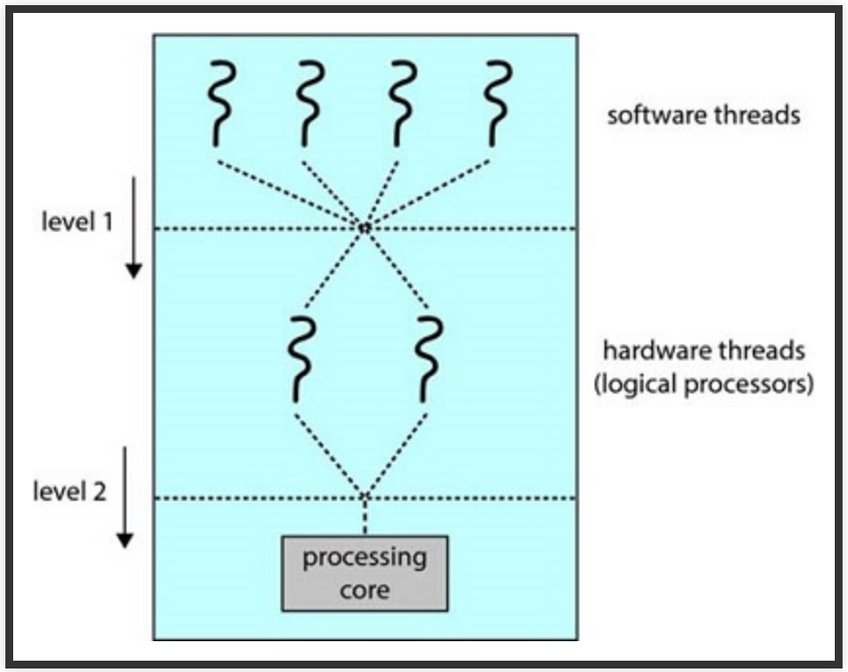


MULTITHREADED MULTICORE SYSTEM

Two ways to multithread a processing core

- Coarse grained - run until long-latency event occurs → flush pipeline (expensive)
- Fine grained - Switch at fx. instruction level

TWO LEVELS OF SCHEDULING



LOAD BALANCING

If SMP, need to keep all CPUs loaded for efficiency

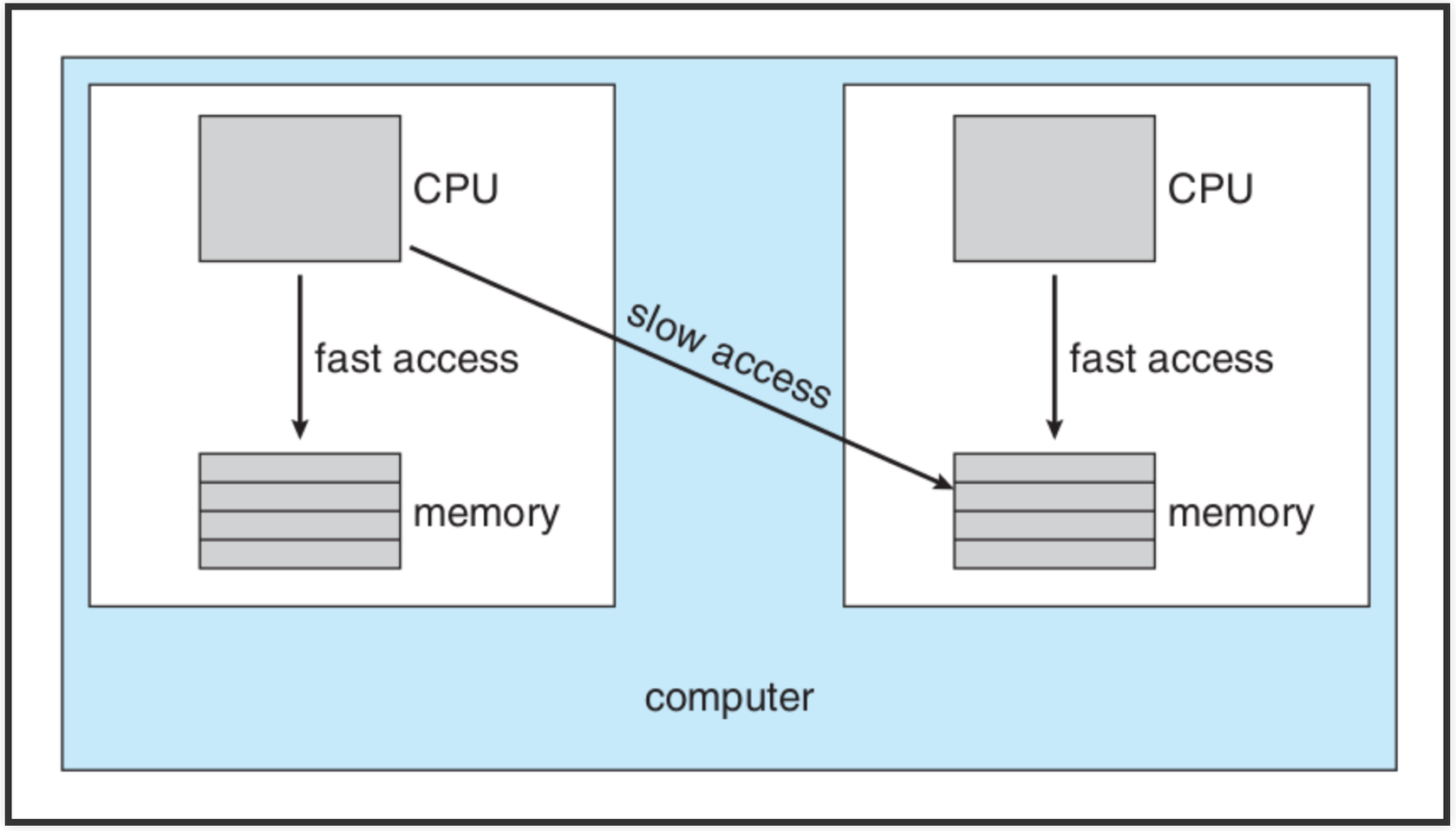
Load balancing attempts to keep workload evenly distributed

- **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

PROCESSOR AFFINITY

- Processor affinity – process has affinity for processor on which it is currently running
- soft affinity - tries but no guarantee
- hard affinity - guarantees a subset of processors
- Variations including processor sets

NUMA AND CPU SCHEDULING



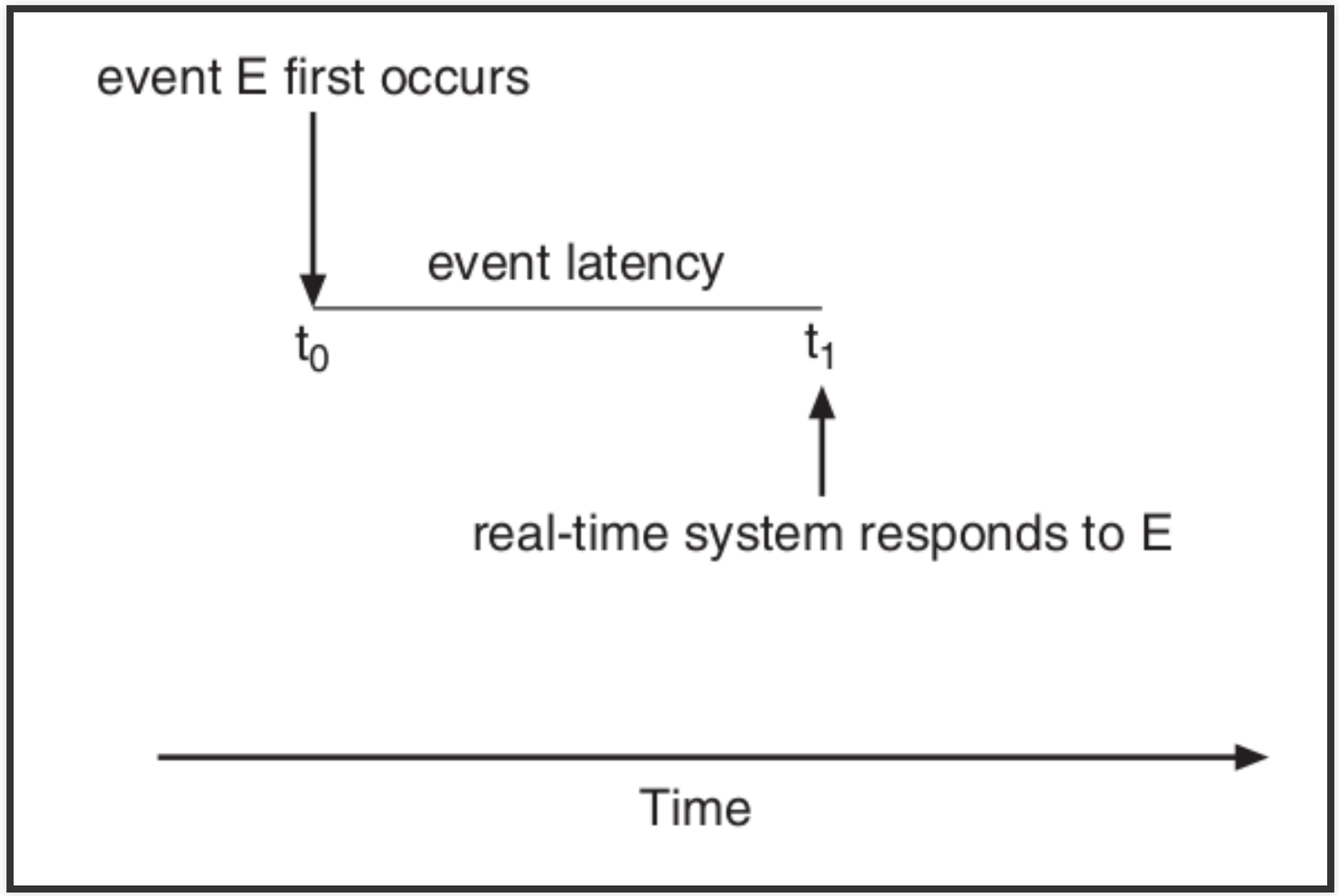
REAL-TIME CPU SCHEDULING

REAL-TIME CPU SCHEDULING

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

EVENT LATENCY



Event Latency: The amount of time that elapses from when an event occurs to when it is serviced

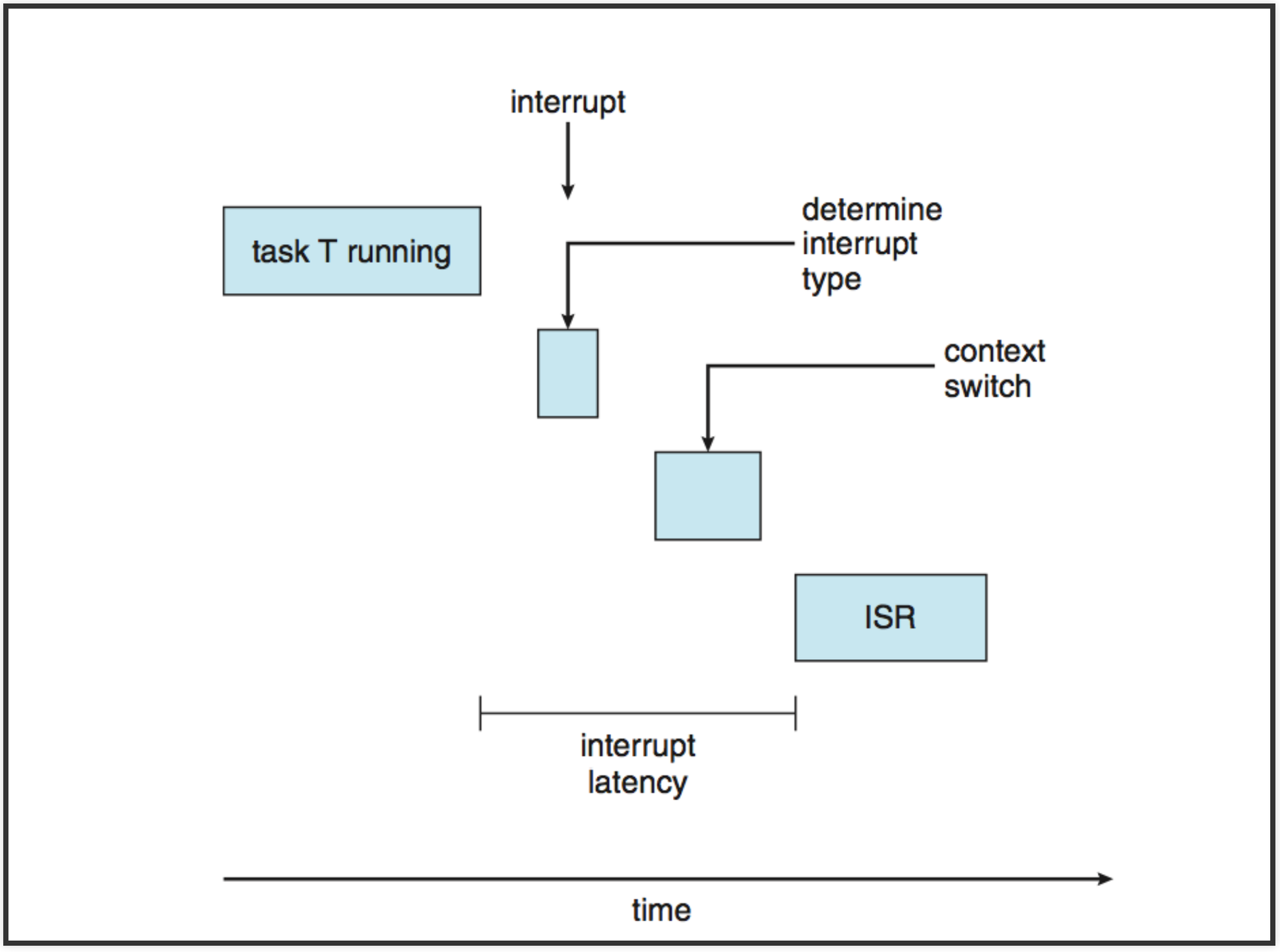
LATENCIES

Two types of latencies affect performance

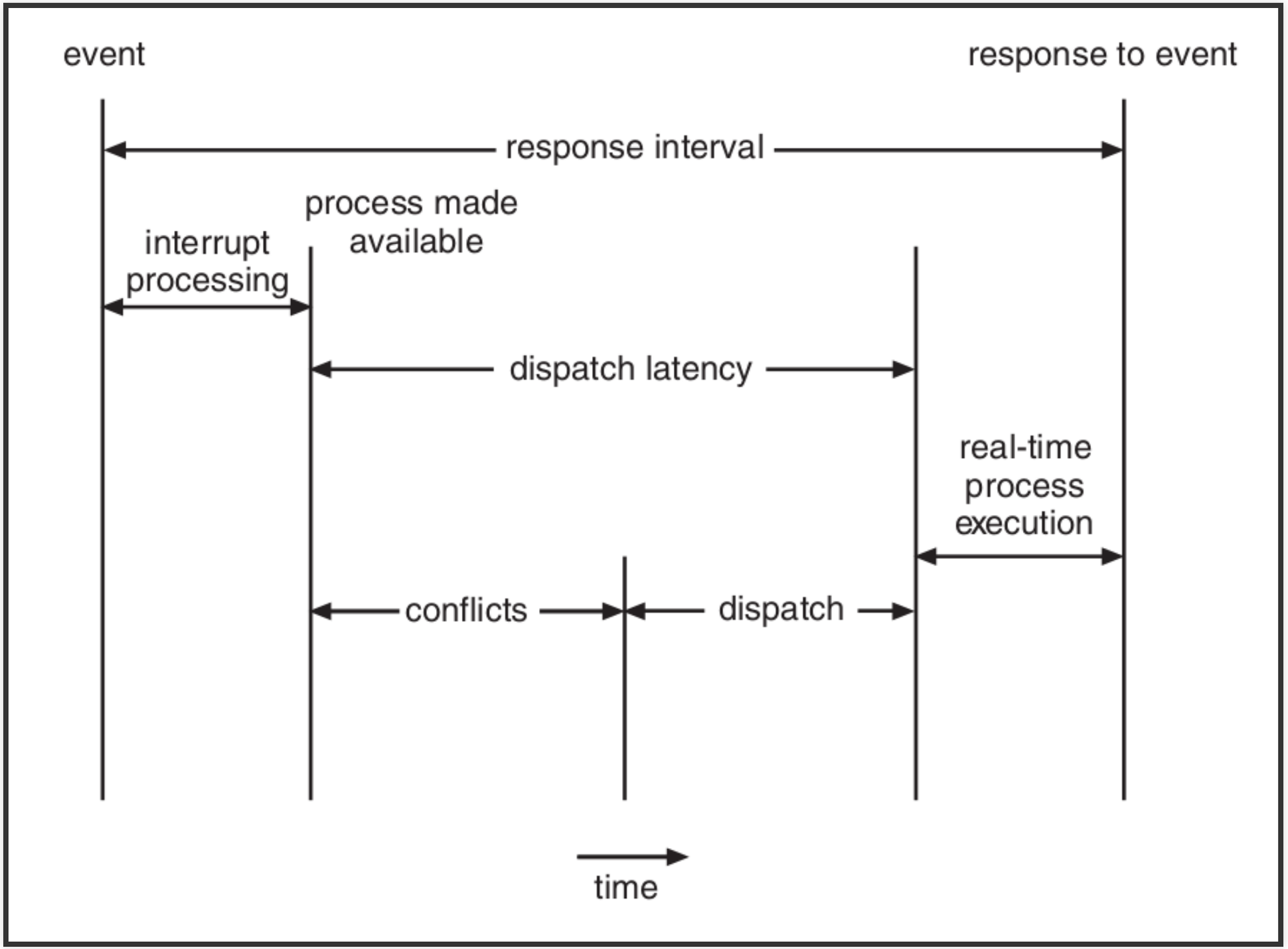
Interrupt latency – time from arrival of interrupt to start of routine that services interrupt

Dispatch latency – time for schedule to take current process off CPU and switch to another

INTERRUPT LATENCY


interrupt
task T running
determine
interrupt
type
context
switch
ISR
interrupt
latency
time

DISPATCH LATENCY

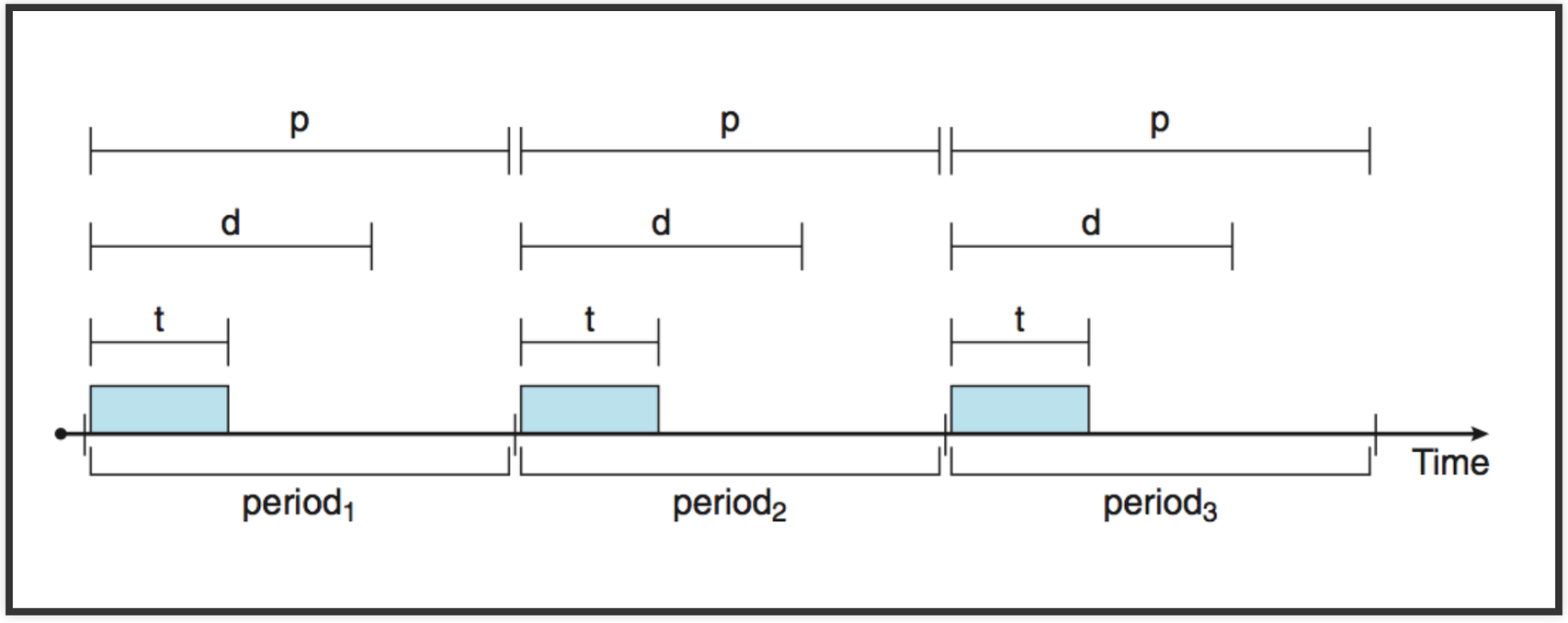

event
response to event
response interval
process made available
interrupt processing
dispatch latency
real-time process execution
conflicts
dispatch
time

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

PRIORITY-BASED SCHEDULING

- 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


p
p
p
d
d
d
t
t
t
Time
period1
period2
period3

ADMISSION CONTROL

Process have to announce its deadline requirements.

Scheduler does one of two things

1. Accepts and guarantees
2. Rejects the request as impossible

RATE MONOTONIC SCHEDULING

A priority is assigned based on the inverse of its period

- Shorter periods = higher priority;
- Longer periods = lower priority

If a lower-priority process is running and a higher-priority process becomes available to run, it will preempt the lower-priority process.

Assign higher priority to tasks that require the CPU more often

EXAMPLE

Process	Period	Processing time
P1	50	20
P2	100	35

EXAMPLE

Is it possible?

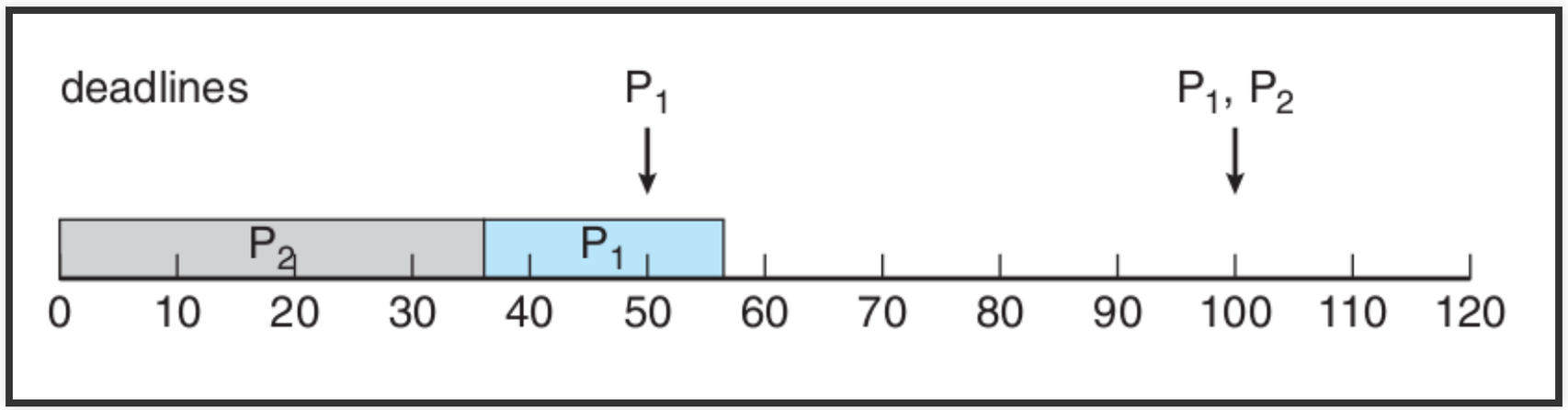
CPU utilization: Ratio of burst to period

- P1: 20/50 = 0.40 = 40%
- P2: 35/100 = 0.35 = 35%

Total: 75%

EXAMPLE

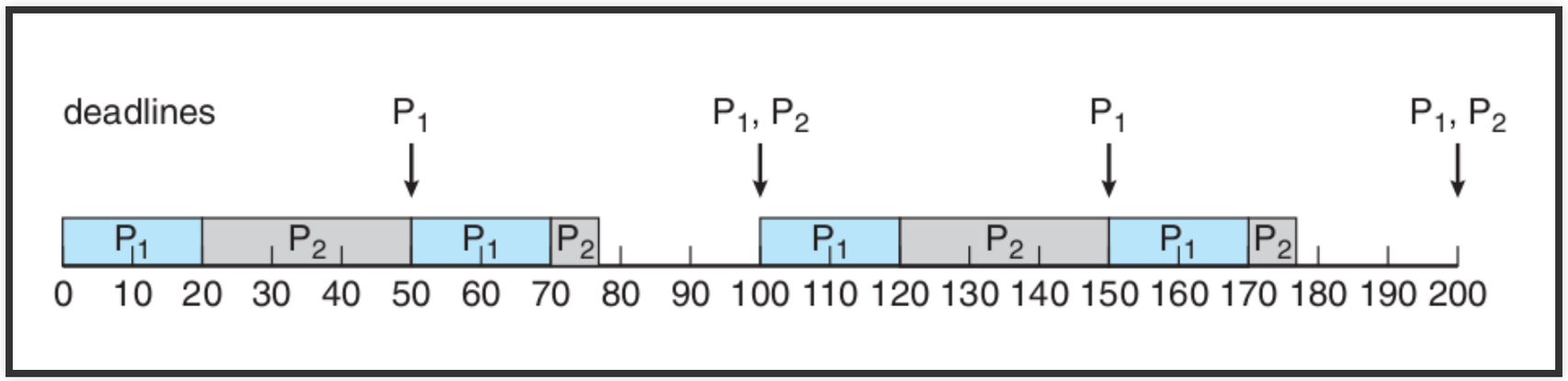
Suppose we assign P2 a higher priority than P1



P1 misses deadline! Lets try with Rate Monotonic Scheduling

EXAMPLE

P1 is assigned a higher priority than P2, because of shorter period.



P2 is preempted, but deadlines hold

RATE MONOTONIC SCHEDULING

- Is considered optimal in if a set of processes cannot be scheduled with it, it cannot with any other that assigns static priorities

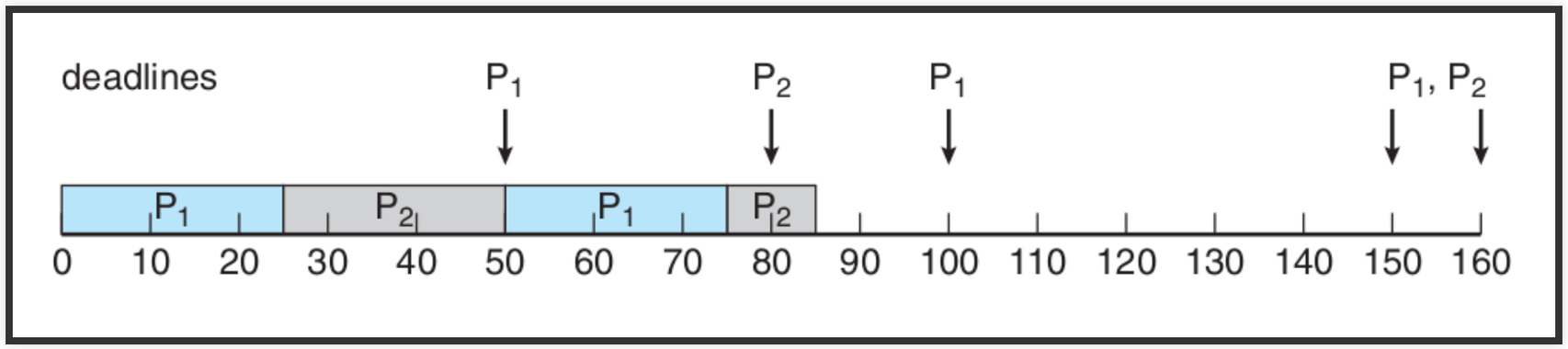
But it does not guarantee optimal utilization!

EXAMPLE

Process	Period	Processing time
P1	50	20
P2	80	35

EXAMPLE

Total utilization = (20/50) + (35/80) = 94%



Deadlines missed for P2

EARLIEST DEADLINE FIRST SCHEDULING (EDF)

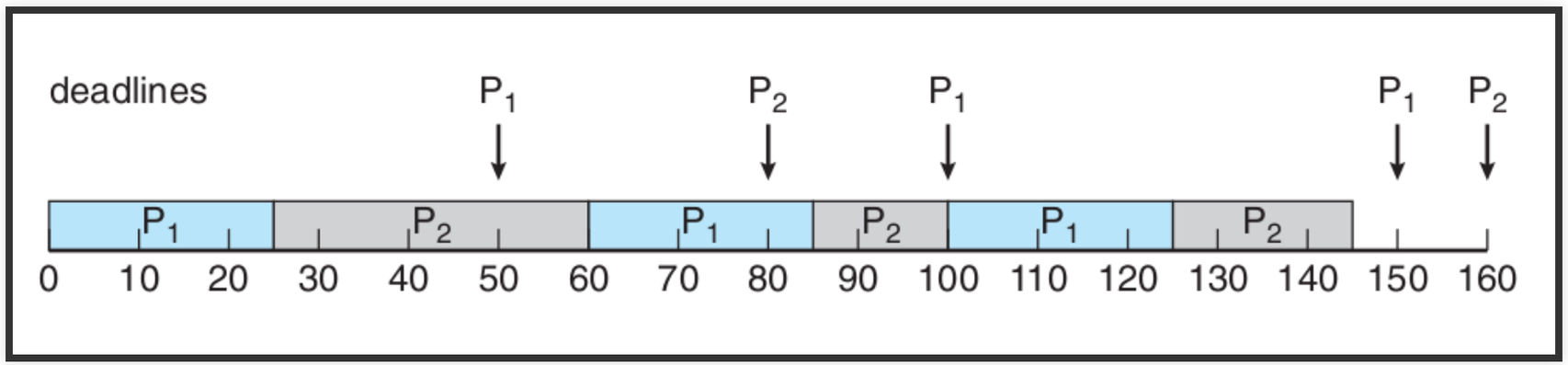
- Priorities are assigned according to deadlines:
  - the earlier the deadline, the higher the priority
  - the later the deadline, the lower the priority

Priorities are *dynamic*

EXAMPLE

Process	Period	Processing time
P1	50	20
P2	80	35

EXAMPLE


deadlines
P1
P2
P1
P1
P2
P1
P2
P1
P2
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

EARLIEST DEADLINE FIRST SCHEDULING (EDF)

- Does not require processes to be periodic nor use constant CPU time per burst
- Requirement: Announce deadline when it becomes runnable
- Theoretical optimal - all reach deadline and CPU utilization 100%
- Practice: Impossible due to context switching and interrupt handling

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

Admission control checks if enough shares are available

PROPORTIONAL SHARE SCHEDULING

Example - 100 total shares (T):

- **A** gets 50 shares
- **B** gets 15 shares
- **C** gets 20 shares

If **D** arrives and requests 30 shares, it is not allowed

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

POSIX REAL-TIME SCHEDULING

- Defines two functions for getting and setting scheduling policy:

```
pthread_attr_getsched_policy(pthread attr t *attr, int *policy)
pthread_attr_setsched_policy(pthread attr t *attr, int policy)
```

POSIX REAL-TIME SCHEDULING

```c
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

void *runner(void *param);

// gcc -pthread file.c
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");
        }
    }
    /* set the scheduling policy - FIFO, RR, or OTHER */
    if (pthread_attr_setschedpolicy(&attr, SCHED_FIFO) != 0) {
```

OPERATING-SYSTEM EXAMPLES

LINUX SCHEDULING < = 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

LINUX SCHEDULING <= VERSION 2.5

- 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

LINUX SCHEDULING <= VERSION 2.5

- 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 > 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

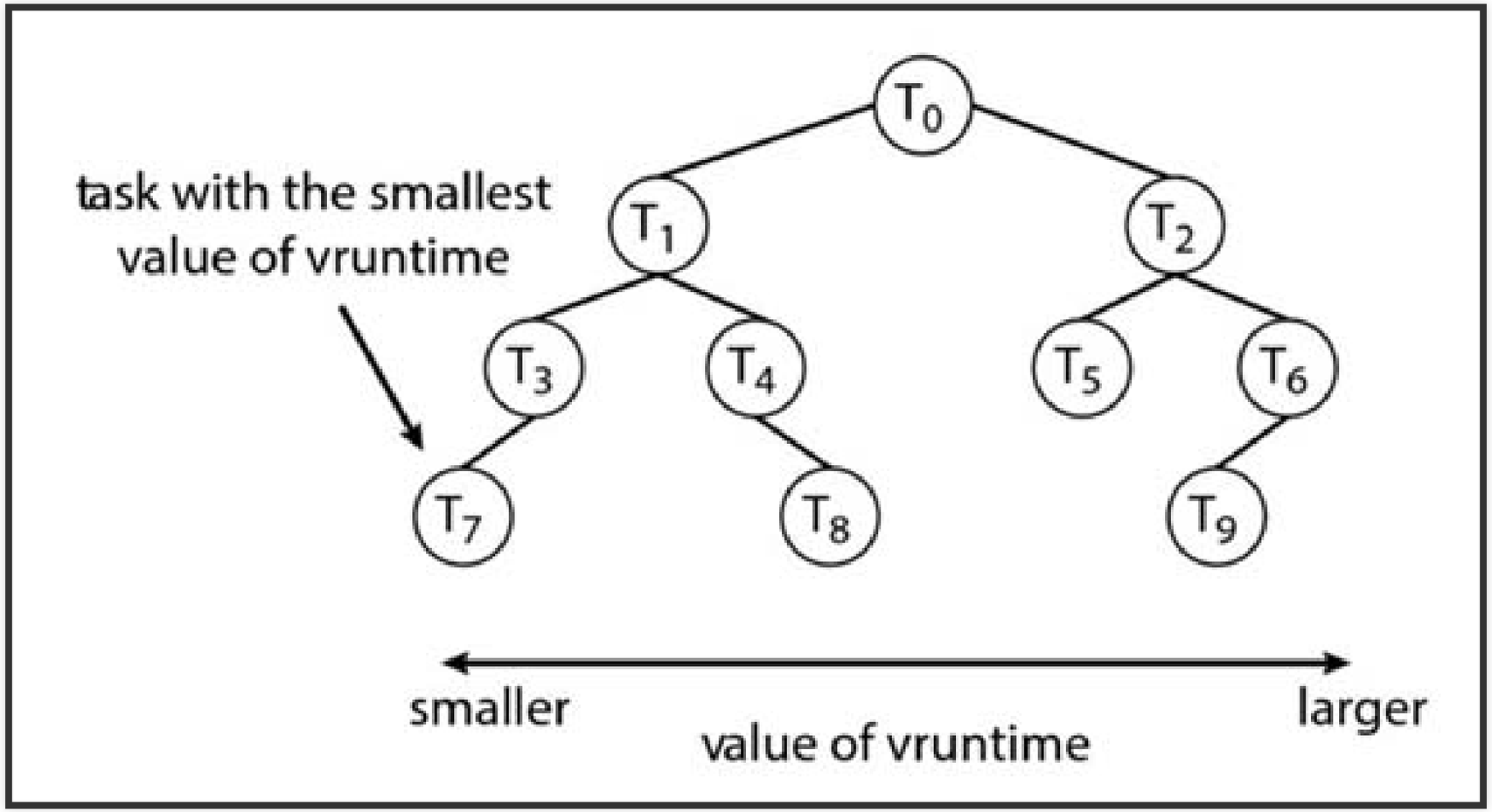
LINUX SCHEDULING IN > 2.6.23

- 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

LINUX SCHEDULING IN > 2.6.23

- 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

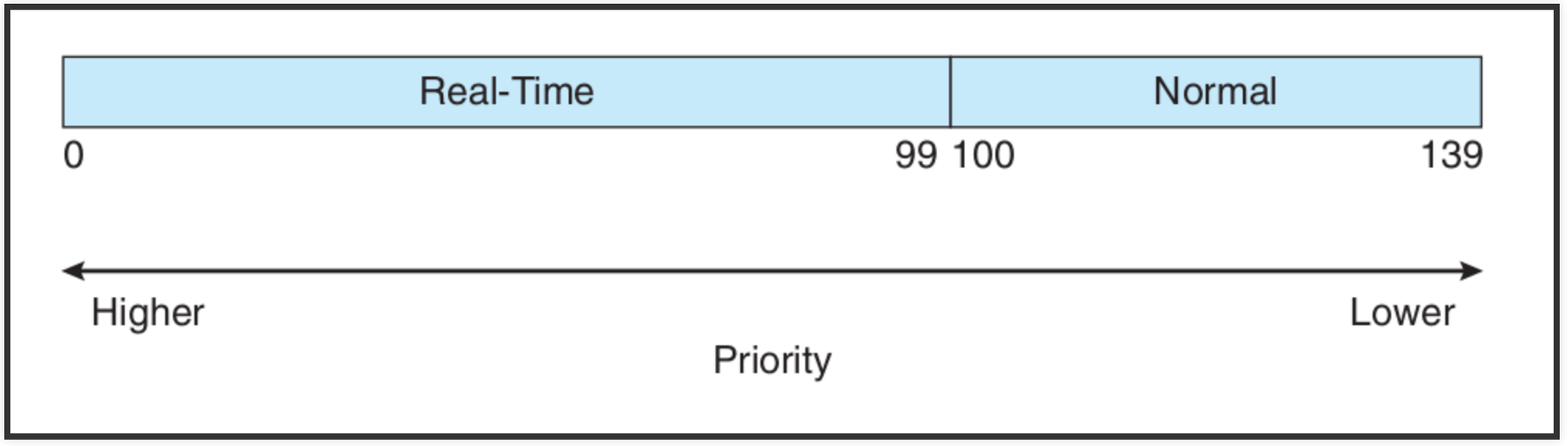
CFS PERFORMANCE



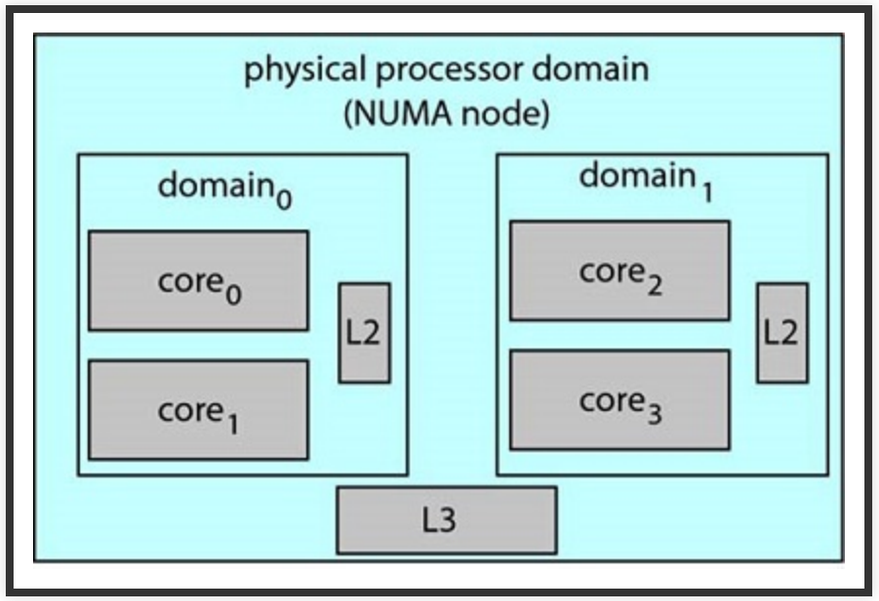
LINUX SCHEDULING

- 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

LINUX SCHEDULING



LINUX SCHEDULING



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

WINDOWS SCHEDULING

- 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

WINDOWS PRIORITY CLASSES

- 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

WINDOWS PRIORITY CLASSES

- 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)

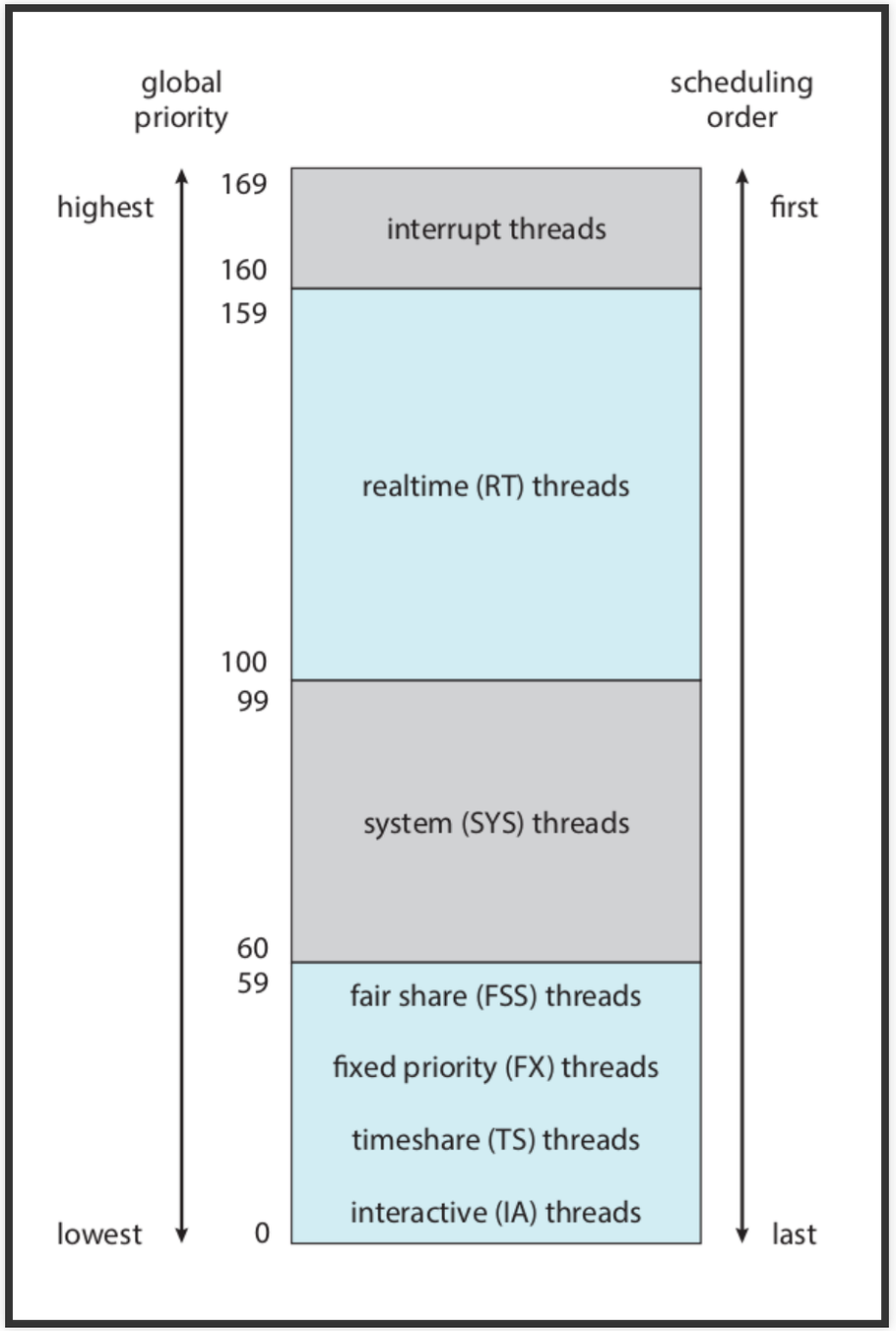
SOLARIS

- 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


global
priority
scheduling
order
highest
first
169
160
159
100
99
60
59
0
interrupt threads
realtime (RT) threads
system (SYS) threads
fair share (FSS) threads
fixed priority (FX) threads
timeshare (TS) threads
interactive (IA) threads
lowest
last

SOLARIS SCHEDULING

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

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

EXAMPLE

Process	Burst Time
P1	10
P2	29
P3	3
P4	7
P5	12

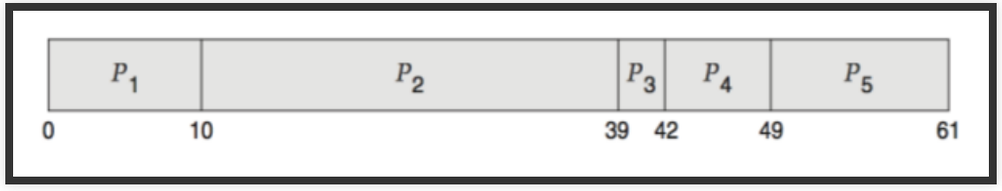
DETERMINISTIC EVALUATION

For each algorithm, calculate minimum average waiting time

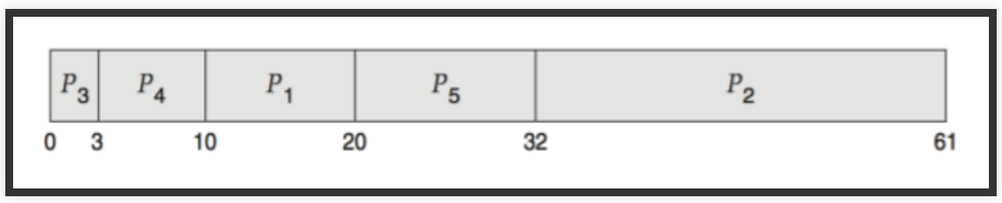
Simple and fast, but requires exact numbers for input, applies only to those inputs

DETERMINISTIC EVALUATION

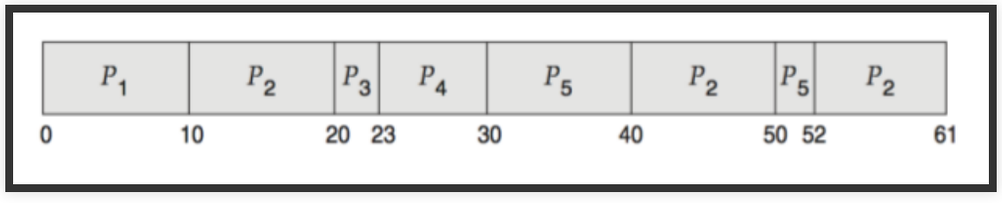
FCFS: 28 ms



Non-preemptive SJF: 13ms



RR: 23ms



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

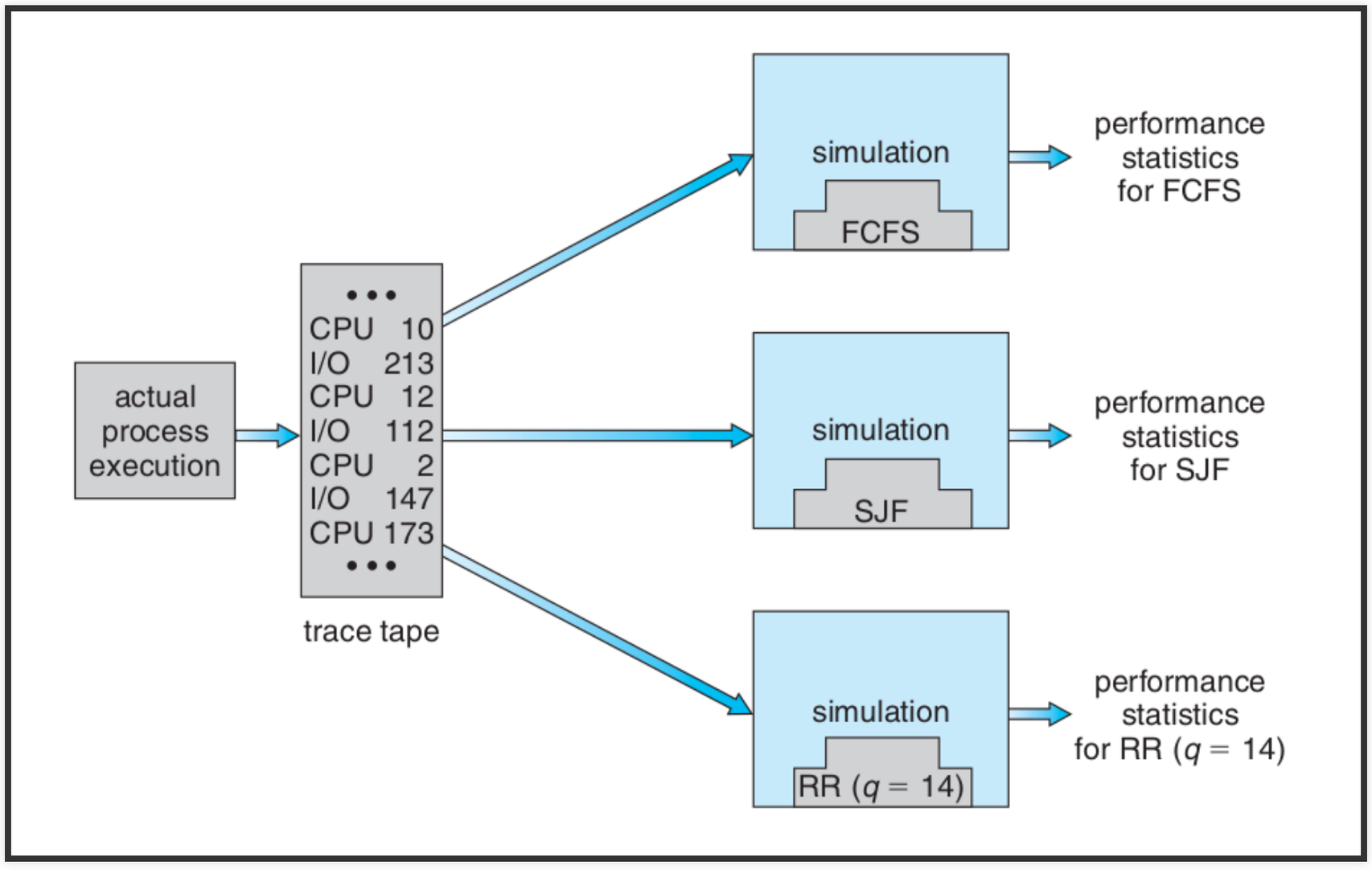
LITTLE'S FORMULA

- 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 = λ x 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 prob.
    - 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

QUESTIONS

BONUS

Exam question number 3: **Process Scheduling**