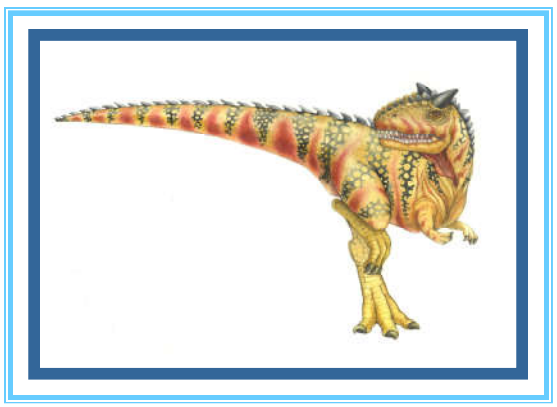
Chapter 5: Process Scheduling



Chapter 5: Process Scheduling

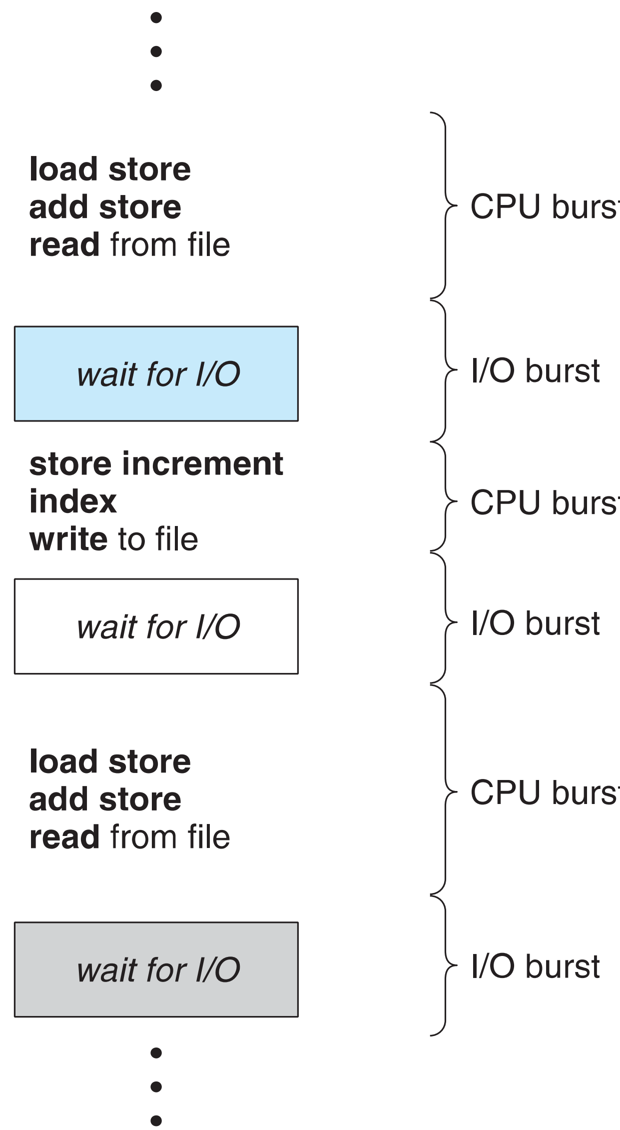
- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples
- Algorithm Evaluation

Objectives

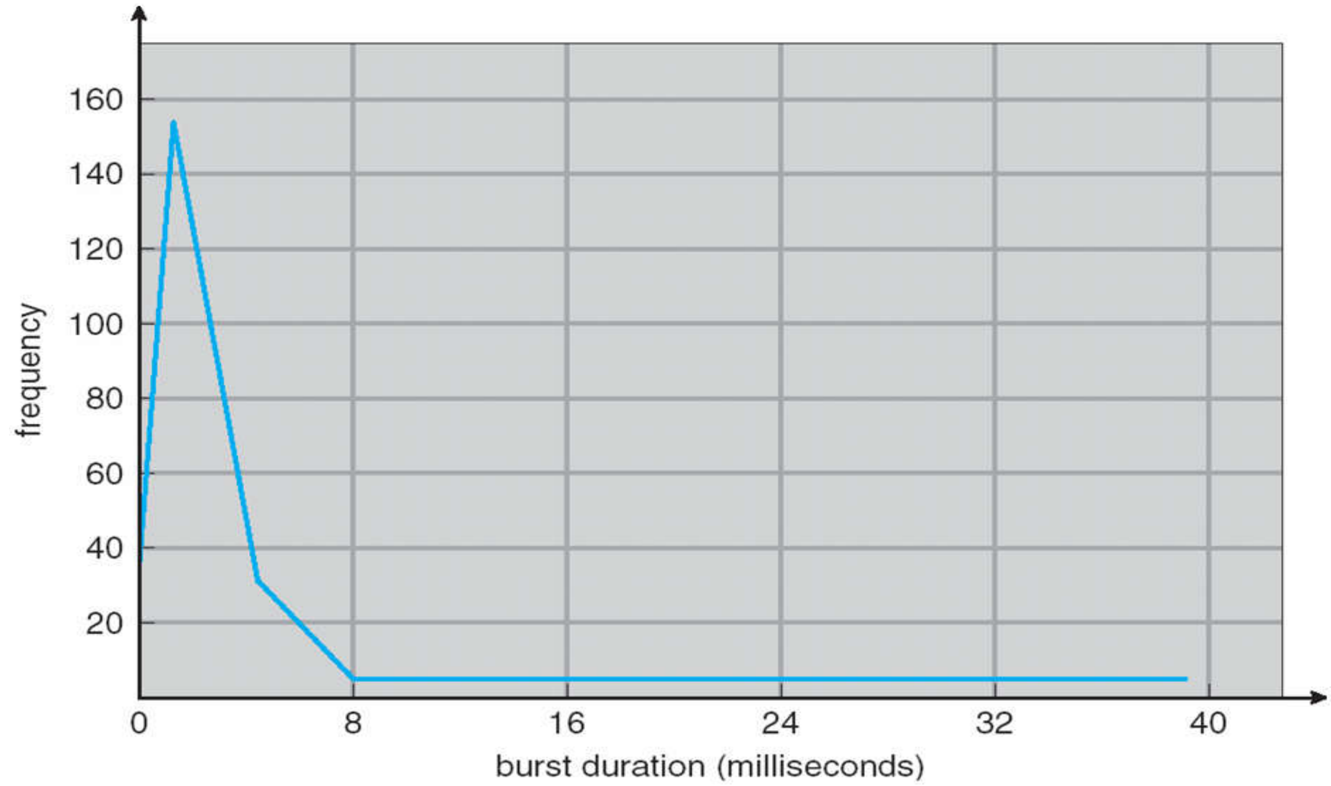
- To introduce CPU scheduling, which is the basis for multiprogrammed operating systems
- To describe various CPU-scheduling algorithms
- To discuss evaluation criteria for selecting a CPU-scheduling algorithm for a particular system
- To examine the scheduling algorithms of several operating systems

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
  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
- **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

First-Come, First-Served (FCFS) Scheduling

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:

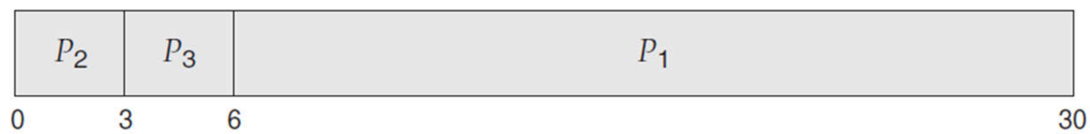
- Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
- Average waiting time: (0 + 24 + 27)/3 = 17
- **Convoy effect** - short process behind long process
  - Consider one CPU-bound and many I/O-bound processes

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

Shortest-Job-First (SJF) Scheduling

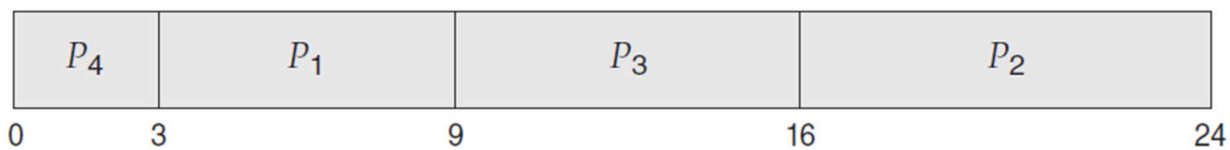
- Associate with each process the length of its next CPU burst
  - Use these lengths to schedule the process with the shortest time

- 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 predict the next CPU burst based on previous ones.

Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- SJF scheduling chart



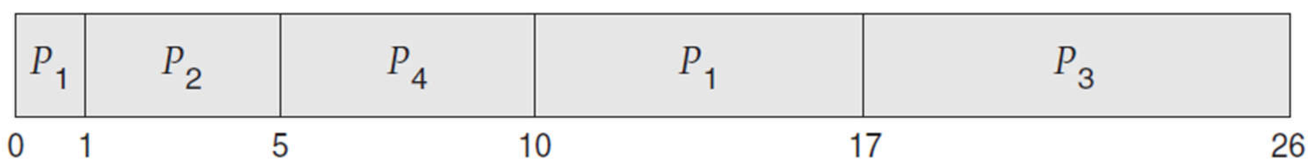
- Average waiting time = (3 + 16 + 9 + 0) / 4 = 7

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



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

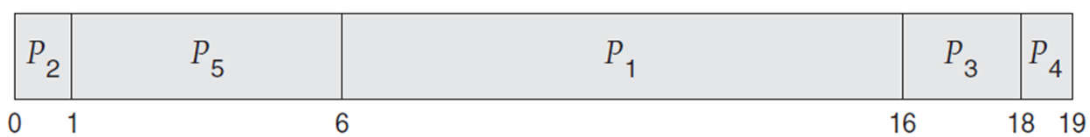
Priority Scheduling

- 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

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

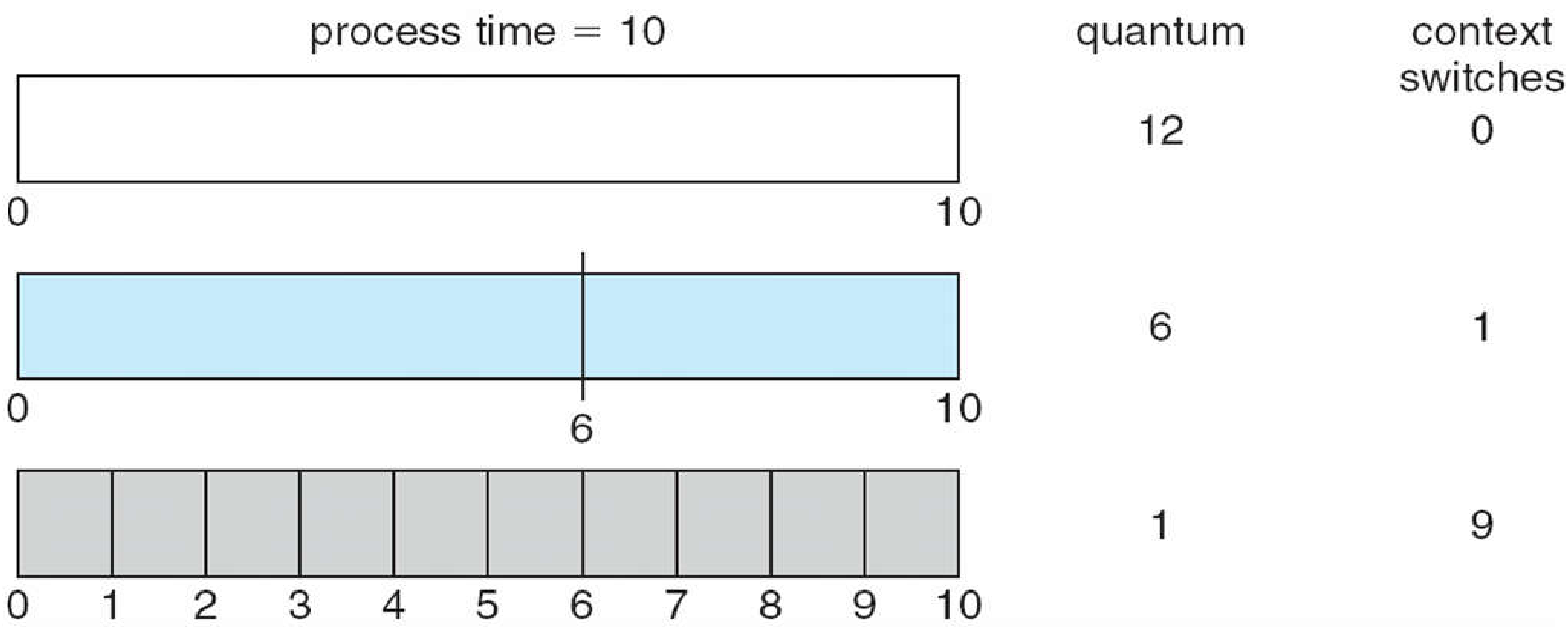
Process	Burst Time
P_1	24
P_2	3
P_3	3

- The Gantt chart is:

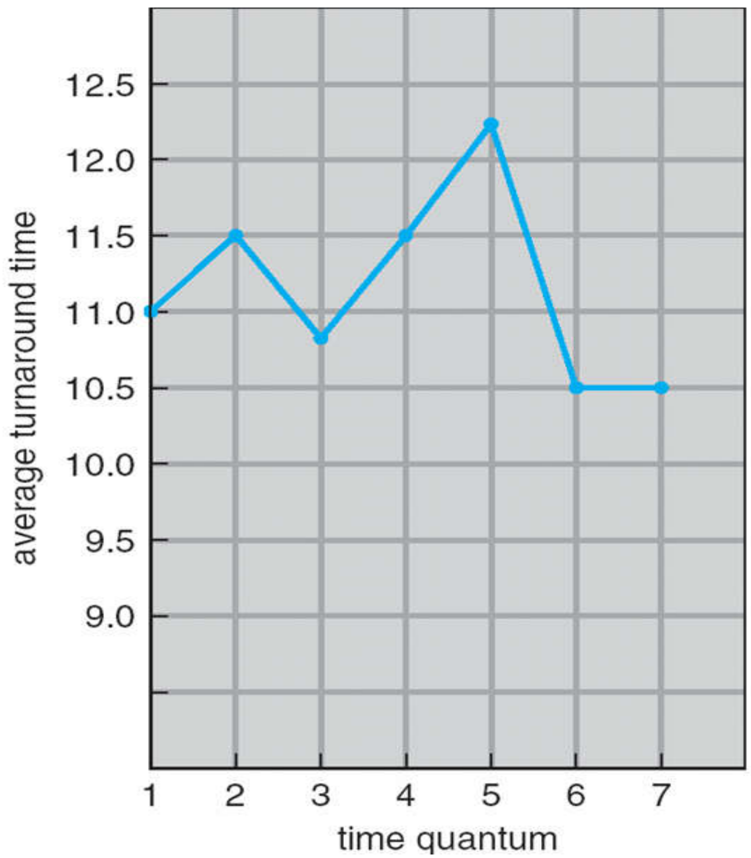
P_1	P_2	P_3	P_1	P_1	P_1	P_1	P_1
0–4	4–7	7–10	10–14	14–18	18–22	22–26	26–30

- 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

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



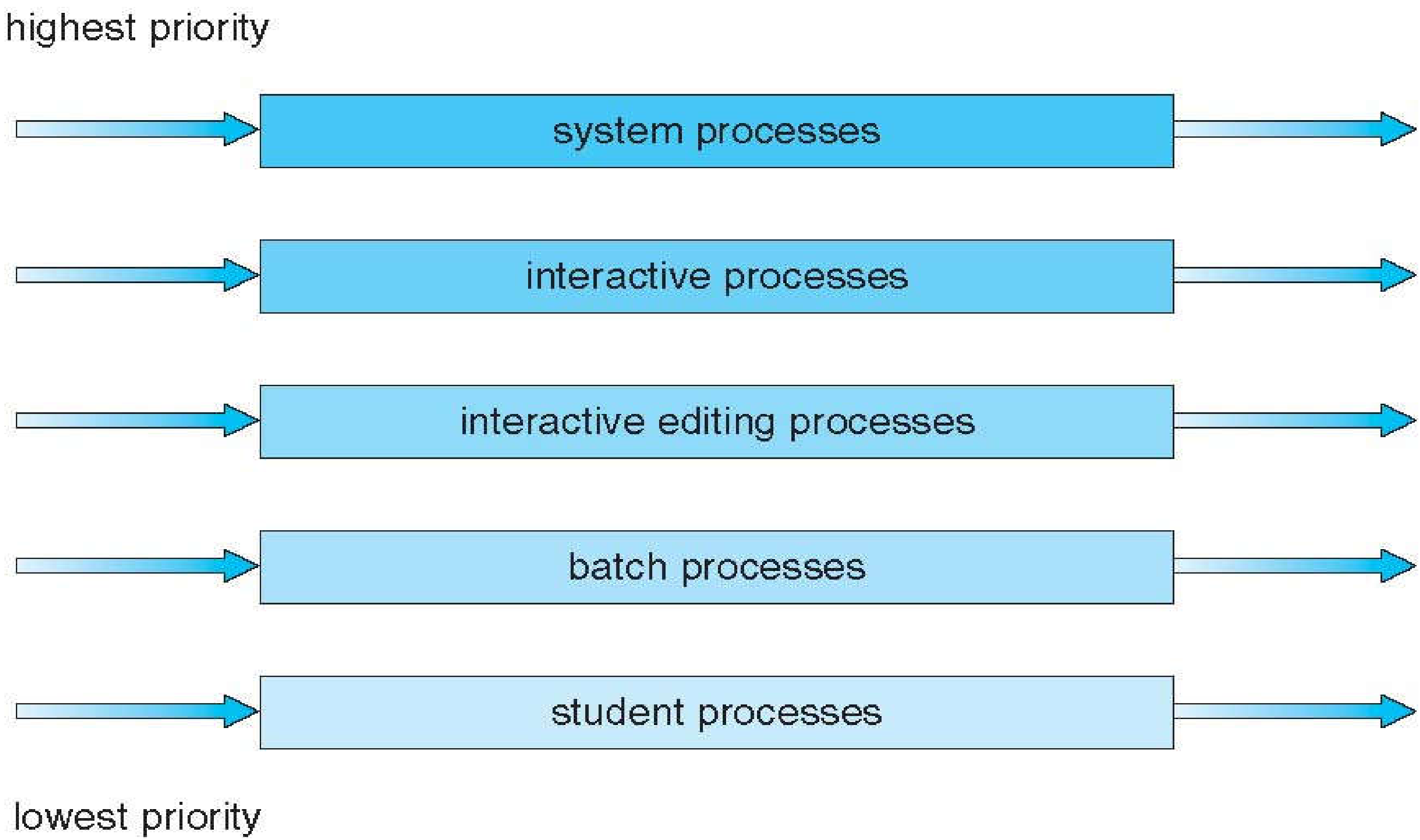
process	time
P_1	6
P_2	3
P_3	1
P_4	7

80% of CPU bursts should be shorter than q

Multilevel Queue

- Ready queue is partitioned into separate queues, eg:
  - **foreground** (interactive)
  - **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.
  - 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



Thread Scheduling

- **Process-contention scope (PCS)** – scheduling among threads belonging to the same process
- **System-contention scope (SCS)** – scheduling among all threads in the system
- Systems using one-to-one model (e.g. Windows, Linux) uses only SCS.

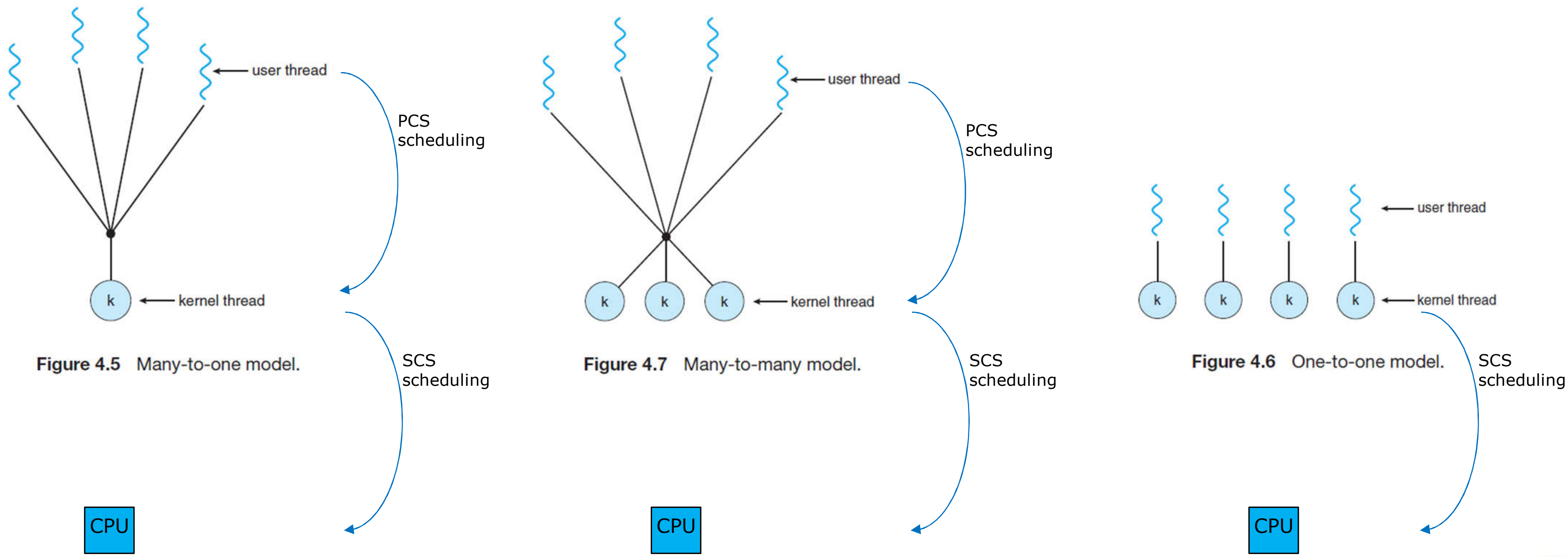


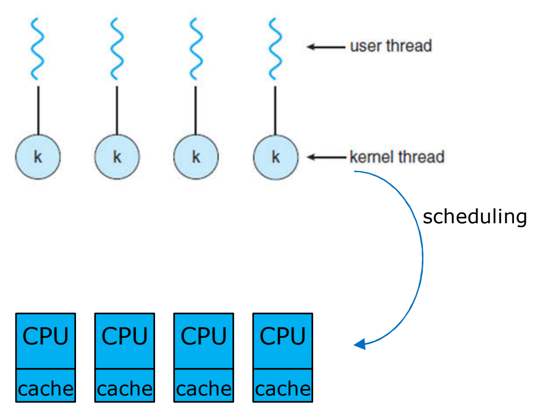
Figure 4.5 Many-to-one model.

Figure 4.7 Many-to-many model.

Figure 4.6 One-to-one model.

Multiple-Processor Scheduling

- With multi-core/multi-processor, parallel computing and load sharing become possible.
- Each processor has its own private queue of ready processes.
- Processor Affinity
  - Keep each process/thread running on the same processor.
  - To benefit from cache memory.
- Load balancing
  - Keep workload evenly distributed across all processors.
  - To benefit from multiple-processor.
  - Migrate processes from overloaded processors to less-busy processors.
- Load balancing often counteracts the benefits of process affinity.



DEMONSTRATION

```
To see every process on the system using standard syntax:
   ps -e
   ps -ef
   ps -eF
   ps -ely

To see every process on the system using BSD syntax:
   ps ax
   ps axu

To print a process tree:
   ps -ejH
   ps axjf

To get info about threads:
   ps -eLf
   ps axms
```

```
pom@X280:/mnt/c/Users/Pom$ ps axu
USER       PID %CPU %MEM    VSZ   RSS TTY      STAT START   TIME COMMAND
root         1  0.0  0.0   1744   432 ?        Sl   Feb17   0:00 /init
root       111  0.0  0.0   1764     0 ?        Ss   Feb17   0:00 /init
root       112  0.0  0.0   1764   116 ?        S    Feb17   0:00 /init
root       113  0.0  0.5 1088556 10428 pts/0   Ssl+ Feb17   0:21 /mnt/wsl/docker-desktop/docker-desktop-proxy --distro-name Ubuntu-20.04
root       119  0.0  0.0   1764     4 ?        S    Feb17   0:00 /init
pom        120  0.0  0.7 763732 14736 pts/1    Ssl+ Feb17   0:36 docker serve --address unix:///home/pom/.docker/run/docker-cli-api.sock
root       146  0.0  0.0   1764    40 ?        Ss   17:24   0:00 /init
root       147  0.0  0.0   1764    64 ?        S    17:24   0:00 /init
pom        148  0.0  0.2  10188  5300 pts/2    Ss   17:24   0:00 -bash
pom        389  0.0  0.1  10604  3300 pts/2    R+   18:11   0:00 ps axu
```

```
pom@X280:/mnt/c/Users/Pom$ ps axjf
 PPID   PID  PGID   SID TTY      TPGID STAT   UID   TIME COMMAND
    0     1     0     0 ?           -1 Sl       0   0:00 /init
    1   111   111   111 ?           -1 Ss       0   0:00 /init
  111   112   111   111 ?           -1 S        0   0:00  \_ /init
  112   113   113   113 pts/0      113 Ssl+     0   0:21  |   \_ /mnt/wsl/docker-desktop/docker-desktop-proxy --distro-name Ubuntu-20.04
  111   119   111   111 ?           -1 S        0   0:00  \_ /init
  119   120   120   120 pts/1      120 Ssl+  1000   0:36      \_ docker serve --address unix:///home/pom/.docker/run/docker-cli-api.sock
    1   146   146   146 ?           -1 Ss       0   0:00 /init
  146   147   146   146 ?           -1 S        0   0:00  \_ /init
  147   148   148   148 pts/2      397 Ss    1000   0:00      \_ -bash
  148   397   397   148 pts/2      397 R+    1000   0:00          \_ ps axjf
```

- Information about process is kept in /proc/<pid>

```
pom@X280:/mnt/c/Users/Pom$ ls /proc
1    146        bus        crypto       filesystems  kallsyms     kpagecount  misc          partitions    swaps        uptime
111  147        cgroups    devices      fs           kcore        kpageflags  modules       sched_debug   sys          version
112  148        cmdline    diskstats    interrupts   key-users    loadavg     mounts        schedstat     sysvipc      vmallocinfo
113  401        config.gz  dma          iomem        keys         locks       mtrr          self          thread-self  vmstat
119  acpi       consoles   driver       ioports      kmsg         mdstat      net           softirqs      timer_list   zoneinfo
120  buddyinfo  cpuinfo    execdomains  irq          kpagecgroup  meminfo     pagetypeinfo  stat          tty
```

```
pom@X280:/mnt/c/Users/Pom$ ls /proc/148
arch_status  cmdline          environ  io         mountinfo   oom_adj        projid_map  smaps         status         uid_map
attr         comm             exe      limits     mounts      oom_score      root        smaps_rollup  syscall        wchan
auxv         coredump_filter  fd       map_files  mountstats  oom_score_adj  sched       stack         task
cgroup       cpuset           fdinfo   maps       net         pagemap        schedstat   stat          timers
clear_refs   cwd              gid_map  mem        ns          personality    setgroups   statm         timerslack_ns
```

Context Switches

Run “top” command in one console.

```
pom@X280:/mnt/c/Users/Pom$ top -d 1
```

Update every 1 second

```
top - 18:50:33 up 4 days, 12:32,  0 users,  load average: 0.24, 0.28, 0.31
Tasks:  13 total,   1 running,  12 sleeping,   0 stopped,   0 zombie
%Cpu(s):  1.0 us,  2.0 sy,  0.0 ni, 96.5 id,  0.0 wa,  0.0 hi,  0.5 si,  0.0 st
MiB Mem :   1916.6 total,    104.7 free,   1230.5 used,    581.4 buff/cache
MiB Swap:   1024.0 total,    229.8 free,    794.2 used.    366.1 avail Mem

  PID USER      PR  NI    VIRT    RES    SHR S  %CPU  %MEM     TIME+ COMMAND
    1 root      20   0    1744    432    396 S   0.0   0.0   0:00.02 init
  111 root      20   0    1764      0      0 S   0.0   0.0   0:00.00 init
  112 root      20   0    1764    116    116 S   0.0   0.0   0:00.02 init
  113 root      20   0 1088556  11988   3644 S   0.0   0.6   0:21.43 docker-desktop-
  119 root      20   0    1764      4      0 S   0.0   0.0   0:00.00 init
  120 pom       20   0  763732  14736      0 S   0.0   0.8   0:36.52 docker
  146 root      20   0    1764     40      0 S   0.0   0.0   0:00.00 init
  147 root      20   0    1764     64      0 S   0.0   0.0   0:00.39 init
  148 pom       20   0   10188   5300   3464 S   0.0   0.3   0:00.57 bash
  437 root      20   0    1764     40      0 S   0.0   0.0   0:00.00 init
  438 root      20   0    1764     64      0 S   0.0   0.0   0:00.02 init
  439 pom       20   0   10056   5148   3408 S   0.0   0.3   0:00.11 bash
  485 pom       20   0   10860   3720   3216 R   0.0   0.2   0:00.10 top
```

Run these commands in another console.

```
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/485/status
Mon Feb 21 18:49:48 +07 2022
voluntary_ctxt_switches:        90
nonvoluntary_ctxt_switches:     1
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/485/status
Mon Feb 21 18:49:54 +07 2022
voluntary_ctxt_switches:        97
nonvoluntary_ctxt_switches:     1
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/485/status
Mon Feb 21 18:50:02 +07 2022
voluntary_ctxt_switches:        104
nonvoluntary_ctxt_switches:     1
```

This output shows the number of context switches over the lifetime of the process. Notice the distinction between *voluntary* and *nonvoluntary* context switches. A voluntary context switch occurs when a process has given up control of the CPU because it requires a resource that is currently unavailable (such as blocking for I/O.) A nonvoluntary context switch occurs when the CPU has been taken away from a process, such as when its time slice has expired or it has been preempted by a higher-priority process.

```
pom@X280:/mnt/c/Users/Pom$ top -d 0.01
```

Update every 10 msec

```
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/656/status
Mon Feb 21 19:40:54 +07 2022
voluntary_ctxt_switches:        3784
nonvoluntary_ctxt_switches:     742
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/656/status
Mon Feb 21 19:41:03 +07 2022
voluntary_ctxt_switches:        4681
nonvoluntary_ctxt_switches:     849
pom@X280:/mnt/c/Users/Pom$
```

Nonvoluntary context switch about every 100 msec.

```
pom@X280:~/OS$ cat infinite.c
void main()
{
        for (;;)
            ;
}
```

```
pom@X280:~/OS$ ./infinite
```

```
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/730/status
Mon Feb 21 20:34:18 +07 2022
voluntary_ctxt_switches:        0
nonvoluntary_ctxt_switches:     1585
pom@X280:/mnt/c/Users/Pom$ date; grep ctxt /proc/730/status
Mon Feb 21 20:34:28 +07 2022
voluntary_ctxt_switches:        0
nonvoluntary_ctxt_switches:     1926
```

Nonvoluntary context switch about every 30 msec.

Nice (set priority of process)

```
NICE(1)                                  User Commands                                  NICE(1)

NAME
       nice - run a program with modified scheduling priority

SYNOPSIS
       nice [OPTION] [COMMAND [ARG]...]

DESCRIPTION
       Run  COMMAND with an adjusted niceness, which affects process scheduling.  With no COMMAND, print the current niceness.
       Niceness values range from -20 (most favorable to the process) to 19 (least favorable to the process).

       Mandatory arguments to long options are mandatory for short options too.

       -n, --adjustment=N
              add integer N to the niceness (default 10)
```

```
pom@X280:~/OS$ cat multiply.c
int main(void) {
    int total = 1;
      for (int j =1; j <=50000 ; j++)
        for (int k =1; k <=50000 ; k++)
          total *= j*k;

}
```

```
pom@X280:~/OS$ cat multiply.sh
time ./multiply &
time nice -n 1 ./multiply &
time nice -n 2 ./multiply &
time nice -n 3 ./multiply &
```

```
pom@X280:~/OS$ ./multiply.sh
pom@X280:~/OS$
real    0m14.801s
user    0m8.918s
sys     0m0.041s

real    0m19.142s
user    0m9.243s
sys     0m0.067s

real    0m21.373s
user    0m9.237s
sys     0m0.059s

real    0m22.535s
user    0m8.989s
sys     0m0.086s
```

```
top - 23:29:09 up 4 days, 17:11,  0 users,  load average: 0.92, 0.53, 0.47
Tasks:  21 total,   5 running,  16 sleeping,   0 stopped,   0 zombie
%Cpu(s):  97.8/2.2   100[||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
MiB Mem :   1916.6 total,     73.2 free,   1250.4 used,    593.0 buff/cache
MiB Swap:   1024.0 total,    290.5 free,    733.5 used.    407.4 avail Mem

  PID USER      PR  NI    VIRT    RES    SHR S  %CPU  %MEM     TIME+ COMMAND
  860 pom       20   0    2360    580    516 R  62.5   0.0   0:05.47 multiply
  864 pom       21   1    2360    576    512 R  49.2   0.0   0:04.28 multiply
  863 pom       22   2    2360    584    520 R  38.9   0.0   0:03.52 multiply
  865 pom       23   3    2360    516    452 R  30.6   0.0   0:02.76 multiply
```