Operating Systems 2017/2018

Part III – Process Scheduling

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Slides based on the book

'Operating System Concepts, 9th Edition,

Abraham Silberschatz, Peter B. Galvin and Greg Gagne, Wiley'

Chapter 6

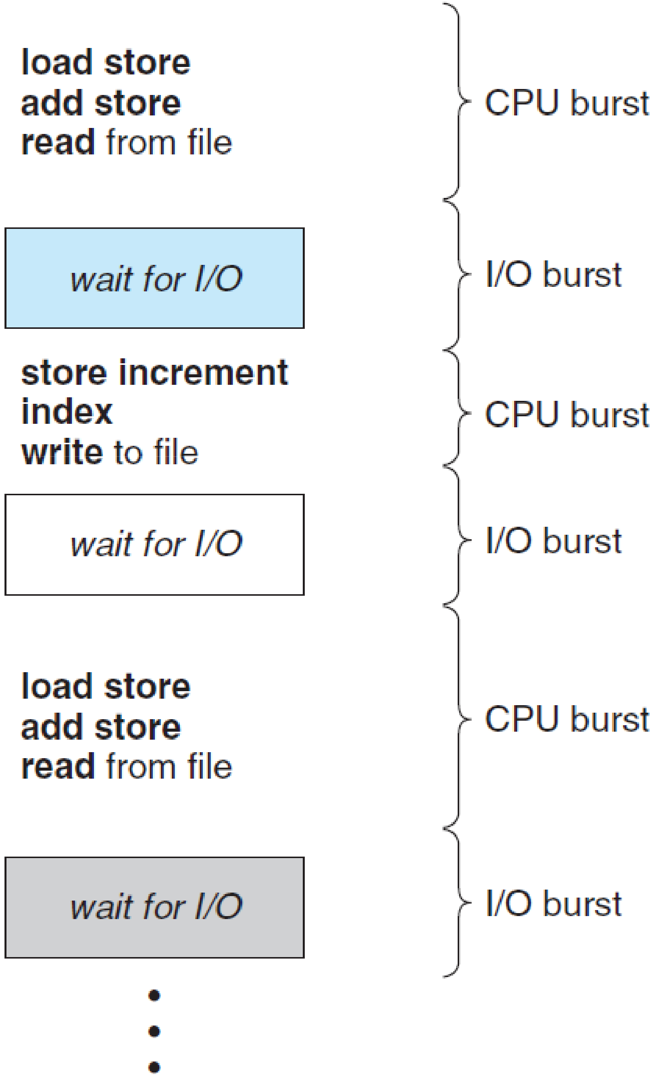
Motivation

- The goal of **multiprogramming** is to have some process running at all times, thus **maximizing CPU utilization**
  - When one process has to wait, the operating system takes that process away from the CPU and gives the CPU to another process

- A fundamental operating system function, which is also the basis of multiprogramming, is thus **process scheduling**
  - By efficiently scheduling the CPU among several processes, the operating system can serve more tasks and make the computer more productive

CPU-I/O Burst Cycle

- Process execution can be seem as a **cycle of CPU execution and I/O wait times**
  - Process execution begins with a CPU burst that is followed by an I/O burst, which is followed by another CPU burst, then another I/O burst, and so on…
  - Eventually, the final CPU burst ends with a system request to terminate execution



Scheduling Decisions

- Scheduling decisions may take place when a process:
  - Switches from running to waiting state (as the result of a I/O request)
  - Switches from waiting to ready (as the result of I/O completion)
  - Switches from running to ready state (as the result of an interrupt)
  - Terminates
- The scheduler selects from among the **processes in the ready queue and allocates the CPU to one of them**
  - When the scheduling decisions takes place only under circumstances 1 and 4, we say that the scheduler is **nonpreemptive (or cooperative)**
  - Otherwise, the scheduler is **preemptive**
- Preemptive scheduling **requires special hardware such as a timer**

Preemptive Scheduling

- Preemptive scheduling can result in **race conditions** (i.e., the output depends on the execution sequence of other uncontrollable events)
  - While one process is updating data, it is preempted so that a second process can run. The second process then tries to read the same data, which can be in an inconsistent state.
  - The processing of a system call may involve changing important kernel data (for instance, I/O queues). If the process is preempted in the middle of these changes and the kernel (or the device driver) needs to read or modify the same structure, then chaos occurs.

- Because interrupts can occur at any time, these sections of code must be guarded from concurrent accesses by several processes and for that **interrupts are disabled at entering such sections and only reenabled at exit**

Scheduling Criteria

- Many criteria have been suggested for comparing scheduling algorithms. Some of the most well-know are:
  - **CPU utilization** – keep the CPU as busy as possible
  - **Throughput** – number of processes that complete execution per time unit
  - **Turnaround/Completion time** – amount of time required to execute a process (interval from the time of submission to the time of completion)
  - **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 a first response (not output) is produced (for time-sharing environments)

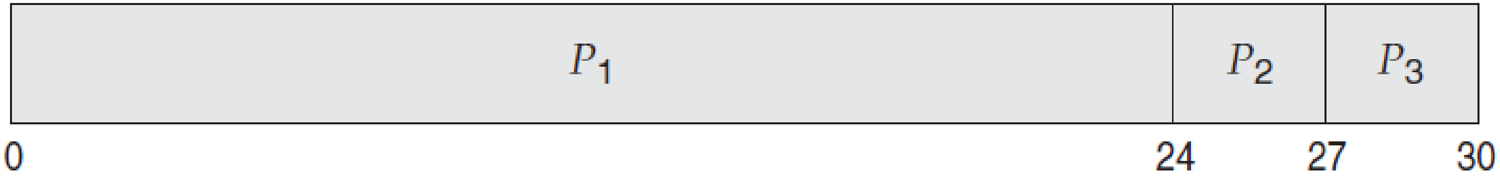
- Optimization criteria:
  - Maximize CPU utilization and throughput
  - Minimize turnaround time, waiting time and response time

First-Come First-Served (FCFS)

- The process that **requests the CPU first is allocated the CPU first**
  - Easily managed with a FIFO queue
  - When a process enters the ready queue, it is linked onto the tail of the queue
  - When the CPU is free, it is allocated to the process at the head of the ready queue (and the process is then removed from the queue)

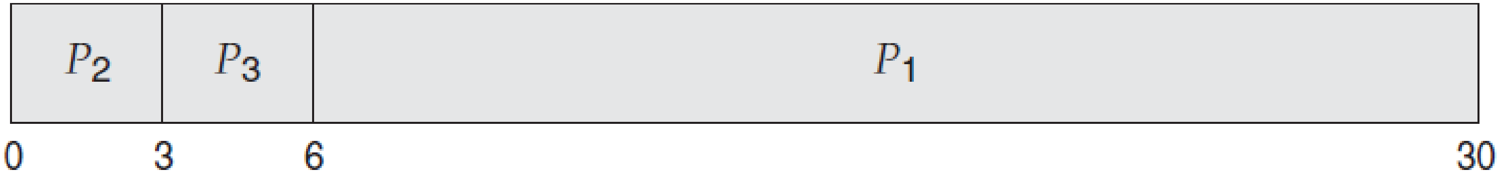
- FCFS is **nonpreemptive**, once the CPU has been allocated to a process, that process keeps the CPU until it either terminates or requests I/O
  - The **average turnaround and waiting time is often quite long**
  - **Troublesome for time-sharing systems**, where it is important that each user get a share of the CPU at regular intervals (it would be disastrous to allow one process to keep the CPU for an extended period)

First-Come First-Served (FCFS)



Process	Burst Time
P_1	24
P_2	3
P_3	3

- FCFS average waiting time
  - (0 + 24 + 27) / 3 = 51 / 3 = 17



Process	Burst Time
P_2	3
P_3	3
P_1	24

- FCFS average waiting time
  - (0 + 3 + 6) / 3 = 9 / 3 = 3

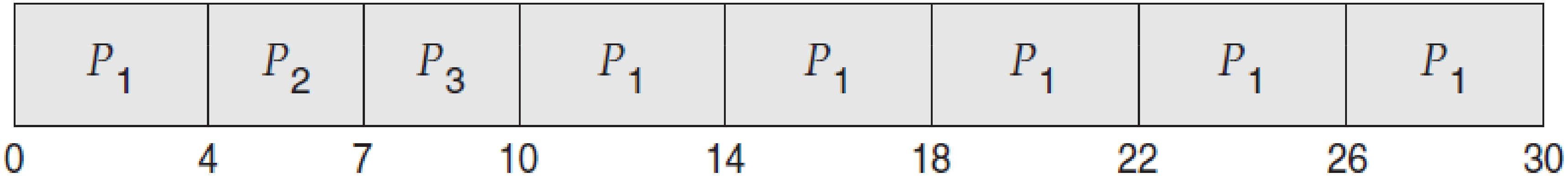
Round Robin (RR)

- Kind of **FCFS with preemption** specially designed for time-sharing systems:
  - Each process gets a **time quantum** or **time slice** (small unit of CPU time)
  - Timer interrupts every quantum to schedule next process, the current process is preempted and added to the end of the ready queue (ready queue works like a circular queue)

- If the time quantum is Q and there are N processes in the ready queue, 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 $(N\text{-}1)^*Q$ time units)
  - Q large $\Rightarrow$ same as FCFS
  - Q small $\Rightarrow$ increases number of context switches, overhead can be too high

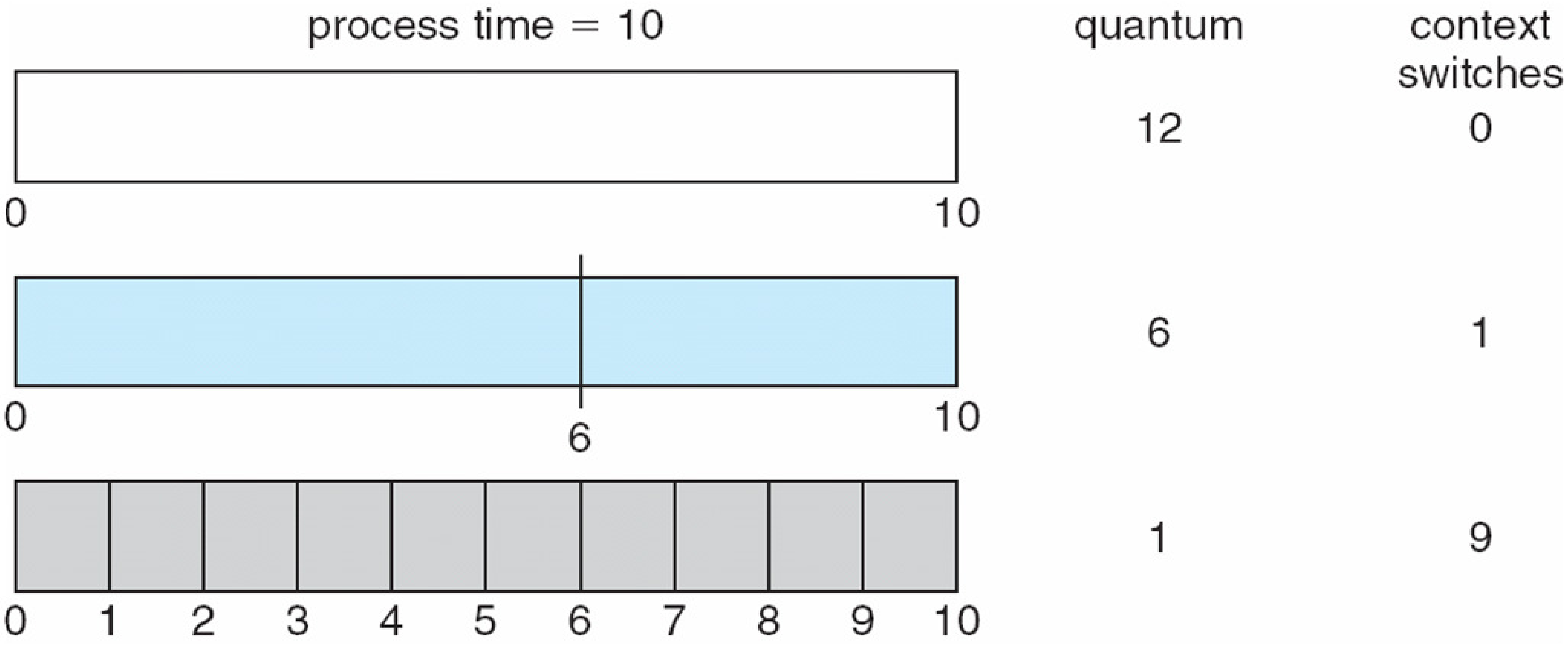
Round Robin (RR) with Time Quantum 4

Process	Burst Time
P_1	24
P_2	3
P_3	3



- RR (time quantum 4) average waiting time
  - (6 + 4 + 7) / 3 = 17 / 3 = 5.66

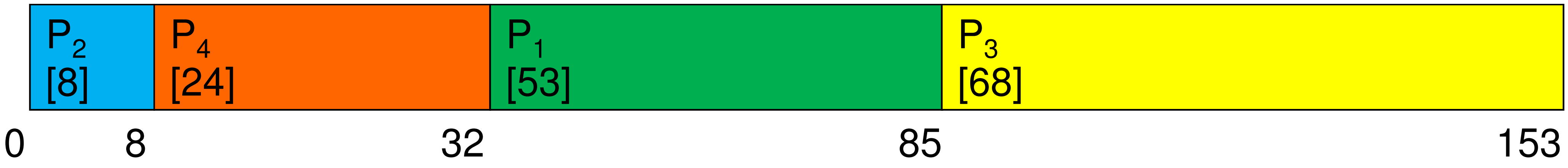
Time Quantum x Context Switch Time



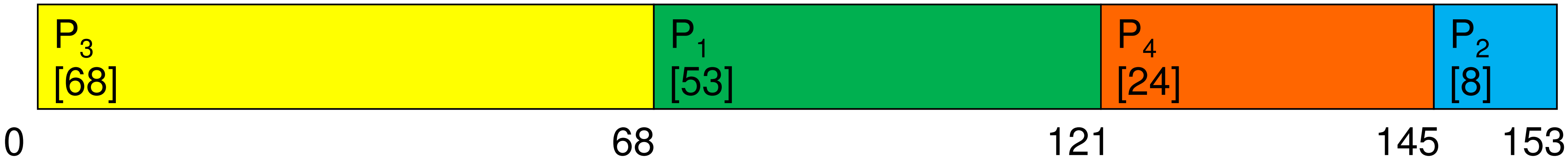
- Context switch time should be a small fraction of the time quantum:
  - The time required for a context switch is typically less than 10 microseconds
  - Most modern systems have time quantum ranging from 10-100 milliseconds

FCFS x RR

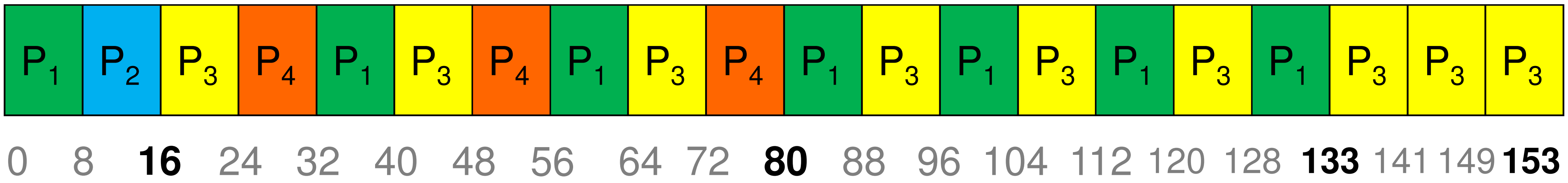
Best FCFS



Worst FCFS



Best RR – Time Quantum 8



FCFS x RR

	Quantum	P_1	P_2	P_3	P_4	Average
Average Waiting Time	Best FCFS	32	0	85	8	31¼
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	61¼
	Q = 8	80	8	85	56	**57¼**
	Q = 10	82	10	85	68	61¼
	Q = 20	72	20	85	88	66¼
	Worst FCFS	68	145	0	121	83½
Average Completion Time	Best FCFS	85	8	153	32	69½
	Q = 1	137	30	153	81	100½
	Q = 5	135	28	153	82	99½
	Q = 8	133	16	153	80	**95½**
	Q = 10	135	18	153	92	99½
	Q = 20	125	28	153	112	104½
	Worst FCFS	121	153	68	145	121¾

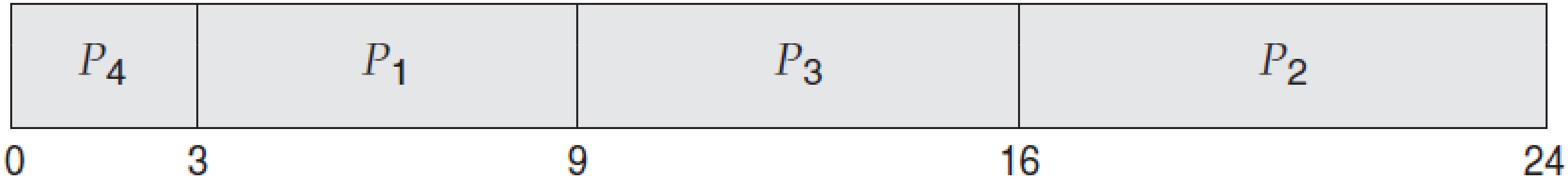
Shortest-Job-First (SJF)

- Associate each process with the length of its next CPU burst and use these lengths to **schedule the process with the shortest CPU burst**
  - If the next CPU bursts of two processes are the same, FCFS scheduling is used to break the tie
  - Also called **shortest-time-to-completion-first (STCF)** but a more appropriate name would be **shortest-next-CPU-burst** since scheduling depends on the length of the next CPU burst of a process, rather than its total length

- **SJF is optimal** because it always gives the minimum average waiting time for a given set of processes
  - Moving a short process before a long one decreases the waiting time of the short process more than it increases the waiting time of the long process
  - The **difficulty is knowing the length of the next CPU burst**

Shortest-Job-First (SJF)

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3



- SJF average waiting time
  - (0 + 3 + 9 + 16) / 4 = 28 / 4 = 7
- FCFS average waiting time
  - (0 + 6 + 14 + 21) / 4 = 41 / 4 = 10.25

Predicting Next CPU Burst Length

- We may not know the length of the next CPU burst, but we may be able to predict its value using the length of the previous CPU bursts
- Generally predicted as an **exponential average** of the measured lengths of previous CPU bursts with the formula:

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

where

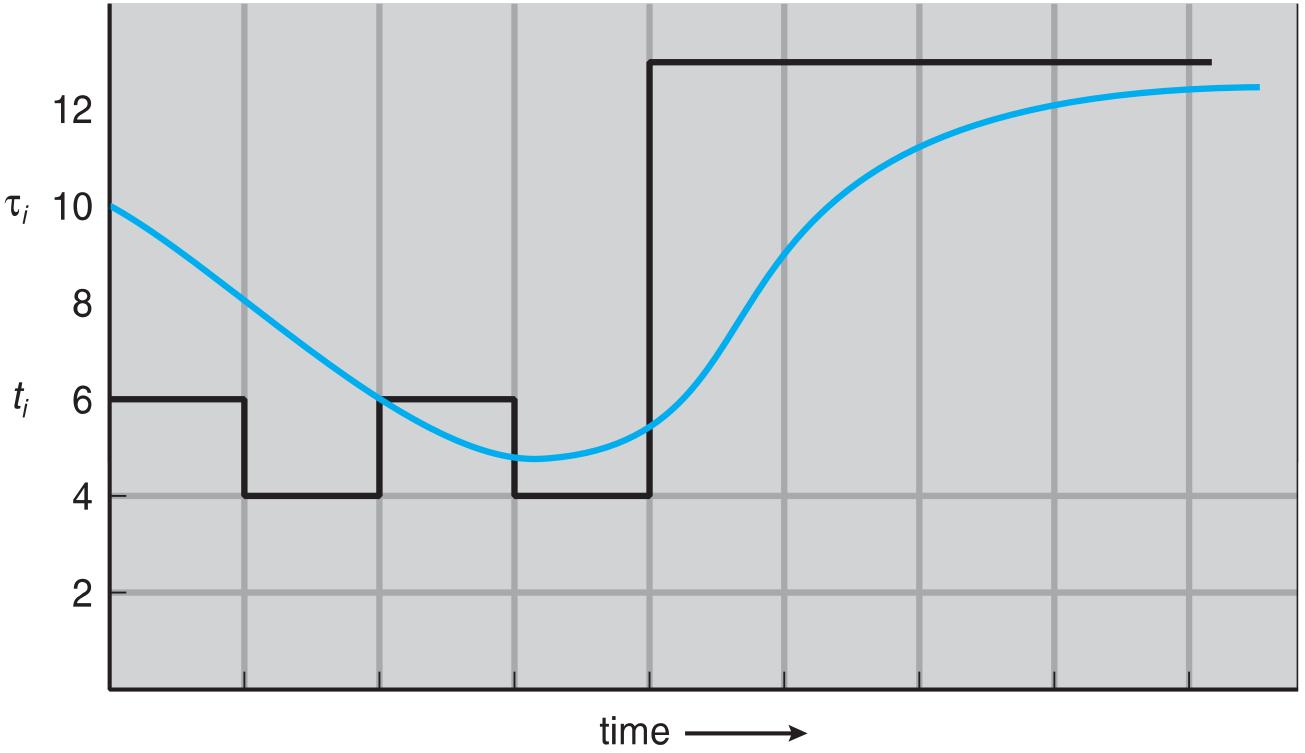
$\tau_{n+1} =$ predicted value for the next CPU burst

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

$0 \le \alpha \le 1$, commonly $\alpha = 1/2$

- Considering $\alpha = 1/2$ we thus have $\tau_{n+1} = (t_n + \tau_n)/2$

Predicting Next CPU Burst Length



CPU burst (t_i) 6 4 6 4 13 13 13 …

"guess" (τ_i) 10 8 6 6 5 9 11 12 …

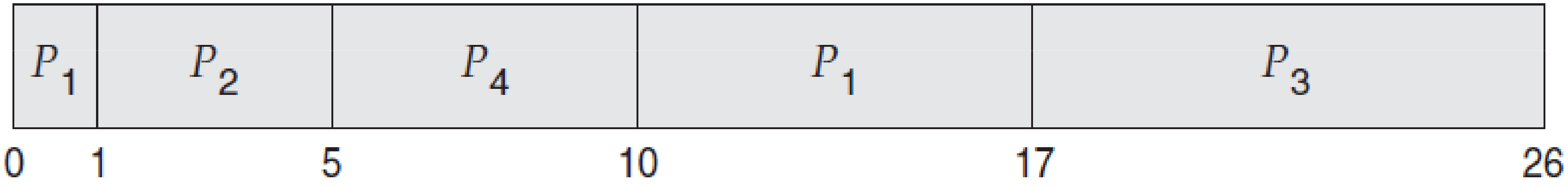
$$\tau_{n+1} = (t_n + \tau_n)/2$$

Shortest-Remaining-Time-First (SRTF)

- SJF scheduling can be **either nonpreemptive or preemptive**
  - Preemptive SJF is usually called SRFT scheduling
- The choice of being preemptive or not occurs when a new process arrives at the ready queue and the next CPU burst of the newly arrived process may be shorter than what is left of the currently executing process
  - **SJF (nonpreemptive)** scheduling will allow the currently running process to finish its CPU burst
  - **SRTF (preemptive)** scheduling will preempt the currently executing process and schedule the newly arrived process

Shortest-Remaining-Time-First (SRTF)

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

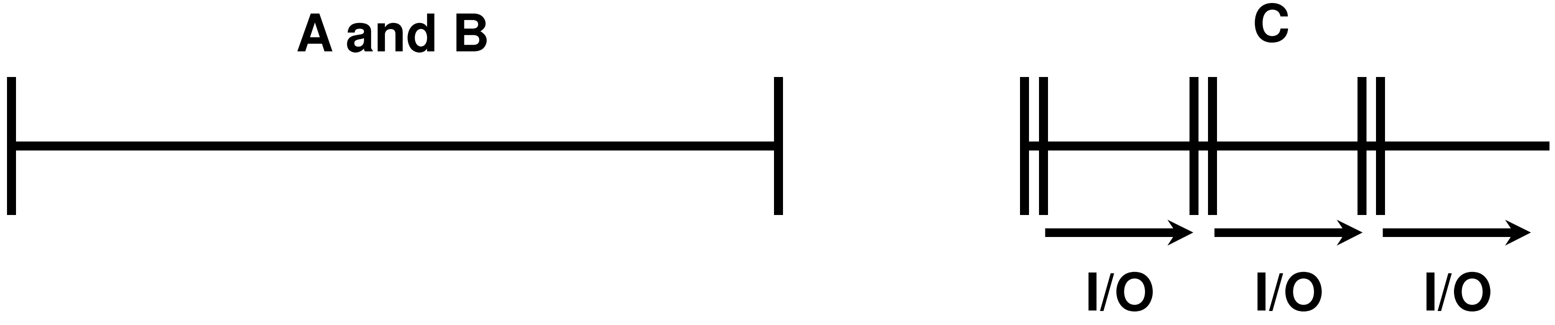


- SRTF (preemptive) average waiting time
  - [(17-8-0) + (5-4-1) + (26-9-2) + (10-5-3)] / 4 = 26 / 4 = 6.5
- SJF (nonpreemptive) average waiting time
  - [0 + (8-1) + (12-3) + (17-2)] / 4 = 31 / 4 = 7.75

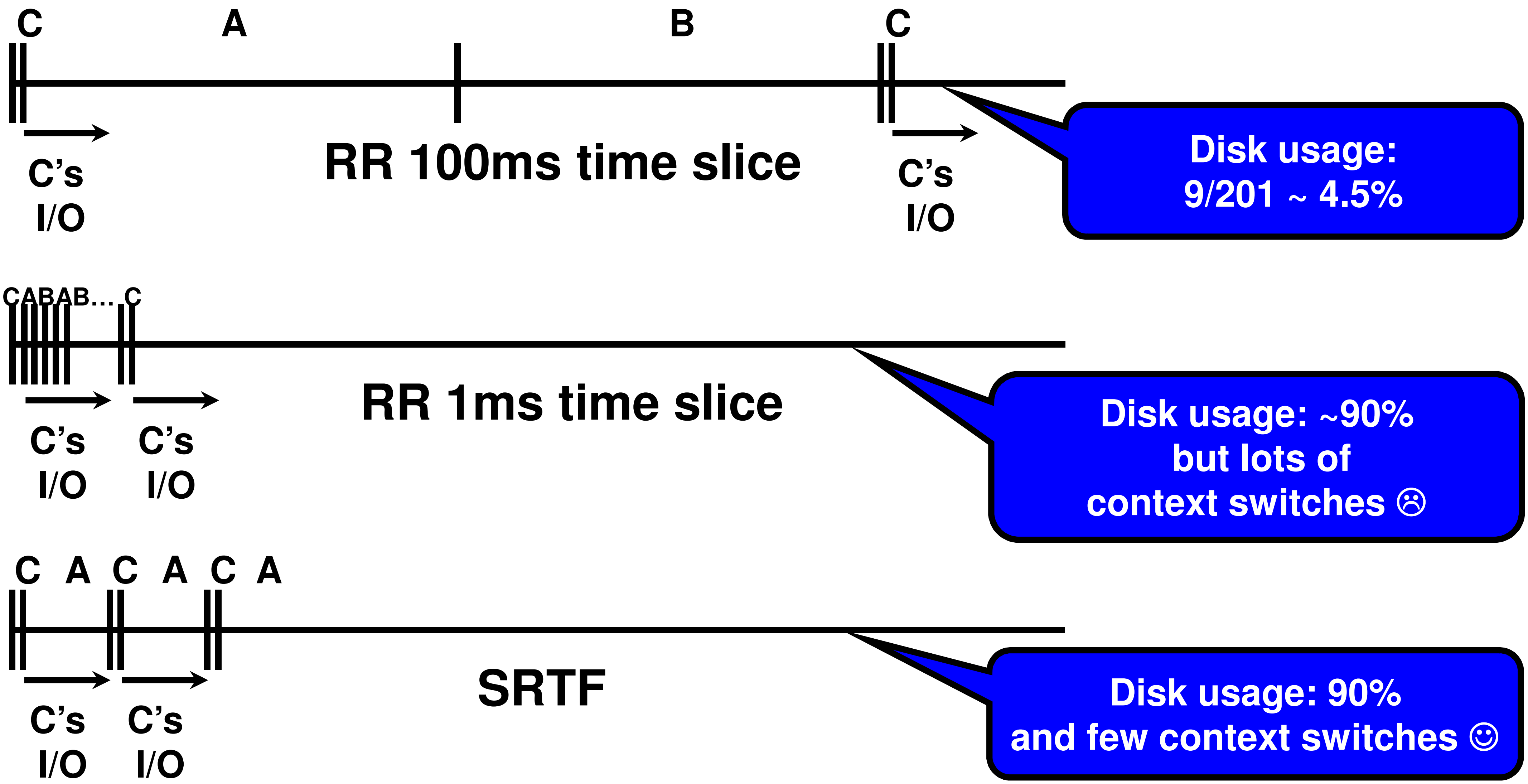
RR x SRTF

- Consider three processes:
  - Processes A and B: CPU-bound, each run for a hour
  - Process C: I/O-bound, loop 1ms CPU, 9ms disk I/O

- If only one at a time:
  - Processes A or B use 100% of the CPU
  - Process C uses 10% of the CPU (90% accessing the disk)



RR x SRTF



C A B C

C's I/O

RR 100ms time slice

C's I/O

Disk usage:
9/201 ~ 4.5%

CABAB… C

C's I/O C's I/O

RR 1ms time slice

Disk usage: ~90%
but lots of
context switches ☹

C A C A C A

C's I/O C's I/O

SRTF

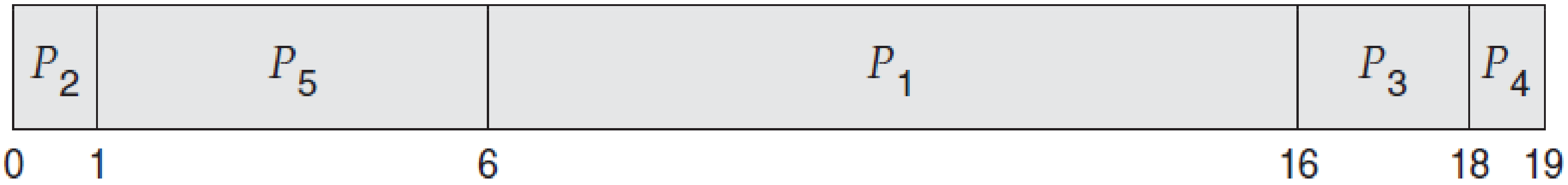
Disk usage: 90%
and few context switches ☺

Priority Scheduling

- Priority scheduling associates a **priority number** with each process and the **CPU is allocated to the process with the highest priority**
  - Equal-priority processes are scheduled in FCFS order
  - SJF and SRTF can be seen as priority algorithms
- Priority scheduling can be either:
  - **Preemptive**, preempts the CPU if the priority of the newly arrived process is higher than the priority of the currently running process
  - **Nonpreemptive**, allows the currently running process to finish its CPU burst
- A major problem is **indefinite blocking or starvation**
  - Low priority processes may never execute and wait indefinitely
  - A common solution is **aging**, which involves **gradually increasing the priority of processes that wait in the system for a long time**

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 average waiting time
  - (0 + 1 + 6 + 16 + 18) / 5 = 41 / 5 = 8.2

FCFS x RR x SJF & SRTF: Pros and Cons

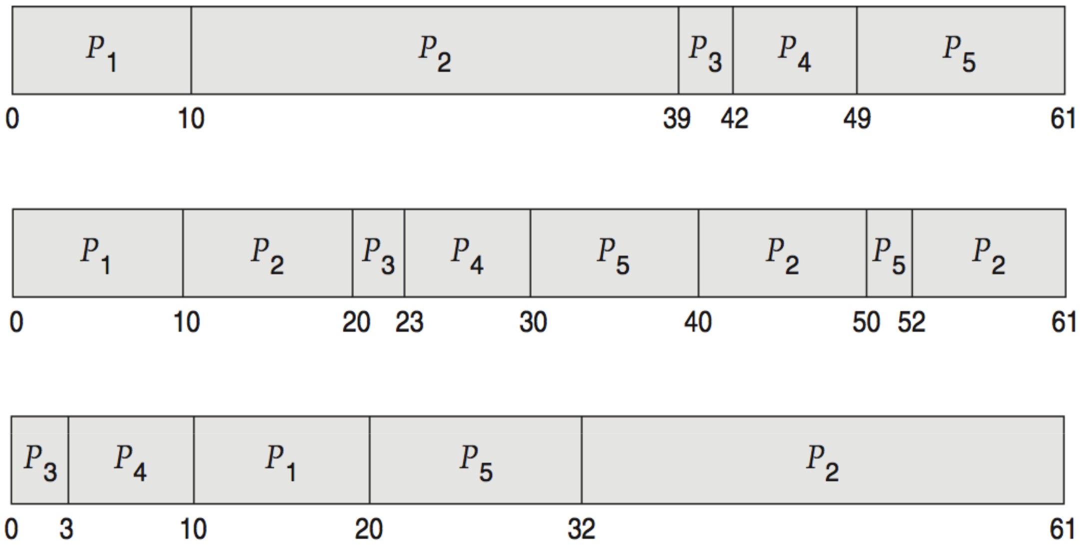
- FCFS
  - (+) Simple
  - (–) Short jobs get stuck behind long ones

- RR
  - (+) Better for short jobs
  - (–) Context switching time adds up for long jobs

- SJF & SRTF
  - (+) Optimal average waiting time
  - (+) Big effect on short jobs
  - (–) Hard to predict future
  - (–) Starvation

FCFS X RR x SJF: One Last Example

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

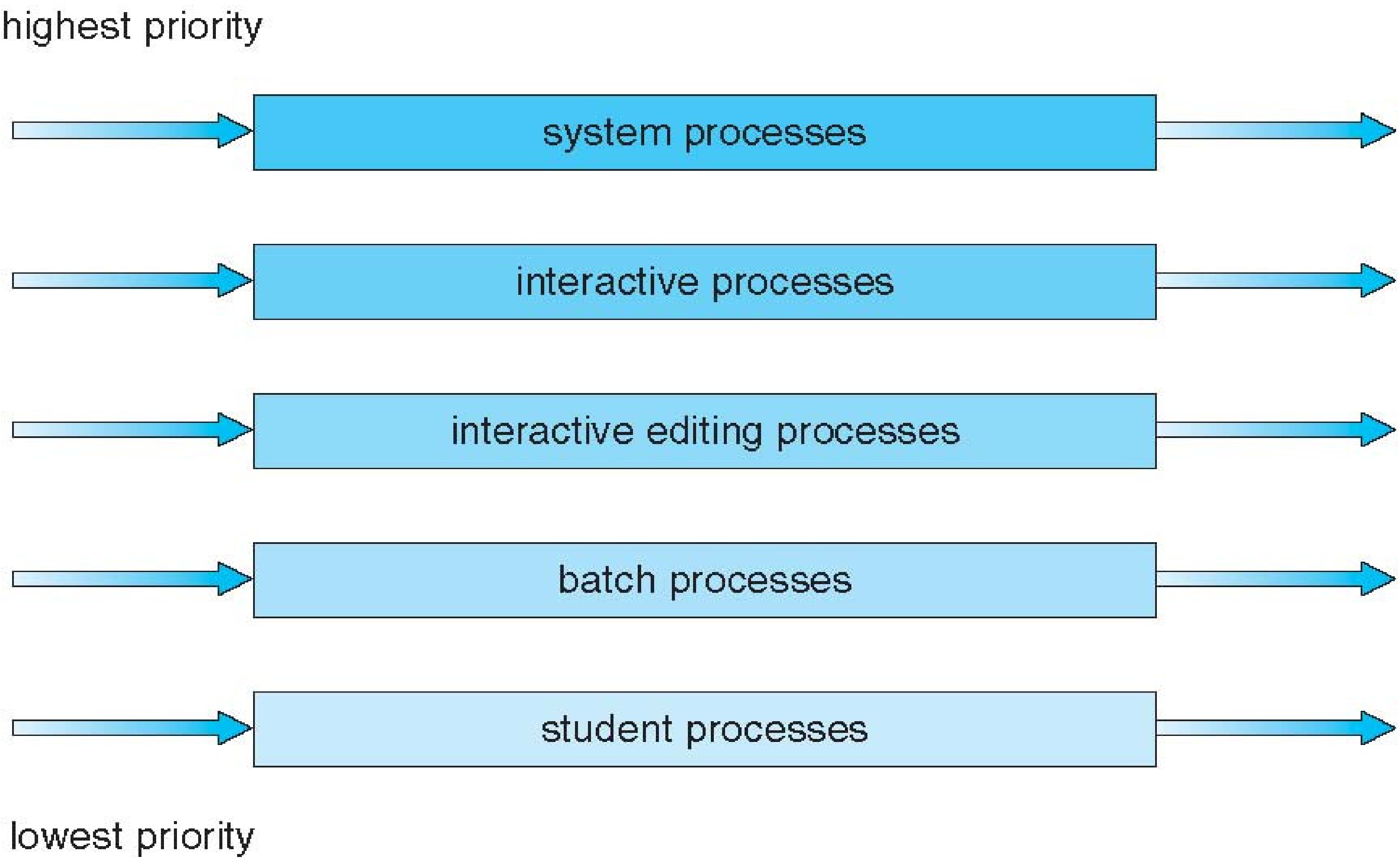


- FCFS average waiting time
  - (0 + 10 + 39 + 42 + 49) / 5 = 28
- RR (time quantum 10) average waiting time
  - [0 + (61-29) + 20 + 23 + (52-12)] / 5 = 115 / 5 = 23
- SJF (nonpreemptive) average waiting time
  - (0 + 3 + 10 + 20 + 32) / 5 = 65 / 5 = 13

Multilevel Queue (MLQ)

- MLQ scheduling **partitions the ready queue into several separate queues**
  - The processes are **permanently assigned to one queue**, generally based on some property of the process, such as memory size, process priority, …
  - **Each queue has its own scheduling algorithm** (one queue might be scheduled using RR while other is scheduled by FCFS)
- In addition, there must be **scheduling among the queues**:
  - **Fixed priority scheduling** – each queue has absolute priority over lower-priority queues (**preemptive scheduling with possibility of starvation**)
  - **Time slice** – each queue gets a certain amount of CPU time which is then schedule amongst its processes (for example, 80% to the queue using RR and 20% to the queue using FCFS)

Multilevel Queue (MLQ)



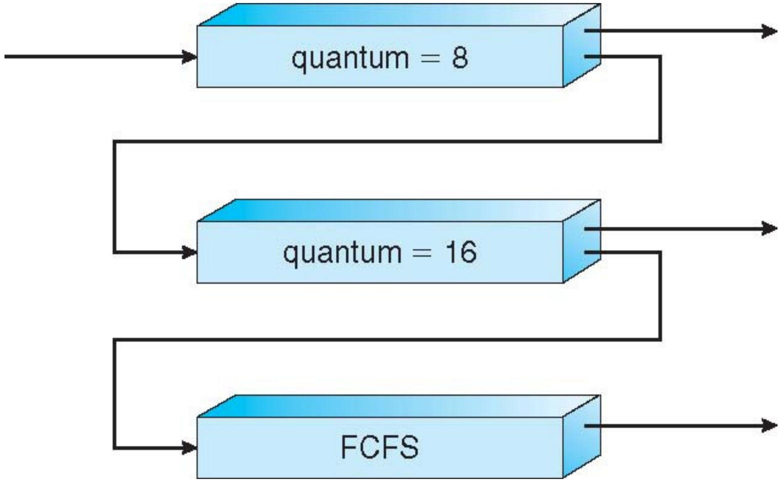
Multilevel Feedback Queue (MLFQ)

- Both setups for MLQ (fixed priority and time slice) have **low scheduling overhead, but are inflexible**

- MLFQ scheduling is more flexible as it **allows processes to move between queues**
  - Processes that use too much CPU time are moved to lower-priority queues
  - I/O-bound and interactive processes stay in the higher-priority queues
  - **Implement the concept of aging** by moving a process that waits too long in a lower-priority queue to a higher-priority queue, thus **preventing starvation**

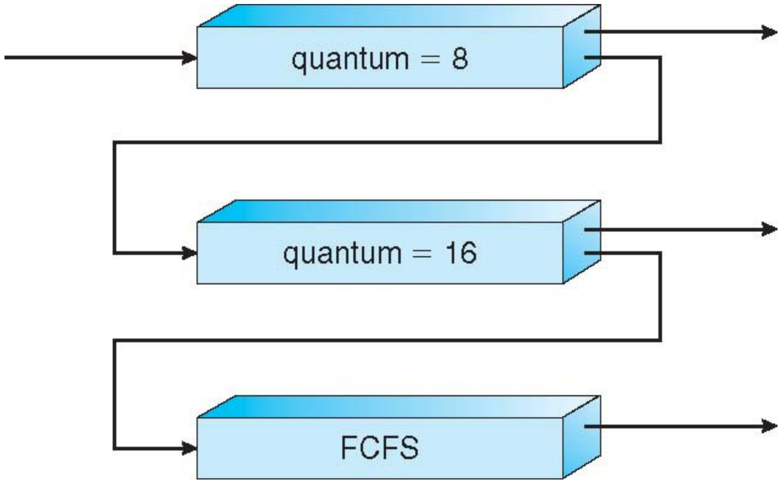
- BSD UNIX derivatives, Solaris, Windows NT and subsequent Windows operating systems use a form of MLFQ as their base scheduler

Multilevel Feedback Queue (MLFQ)



- Consider three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR with time quantum 16 milliseconds
  - Q_2 – FCFS
- Possible scheduling algorithm (I):
  - New processes enter the ready queue at the tail of Q_0
  - A process in the head of Q_0 is given a time quantum of 8ms, in the head of Q_1 is given a time quantum of 16ms, and in the head of Q_2 runs in an FCFS basis
  - Processes in Q_1 only run when Q_0 is empty and processes in Q_2 only run when both Q_0 and Q_1 are empty, but if a queue is not run for a certain amount of time, processes are moved to the next higher level (or topmost) queue
  - A process entering a higher level queue will preempt any process running in a lower level queue

Multilevel Feedback Queue (MLFQ)



- Consider three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR with time quantum 16 milliseconds
  - Q_2 – FCFS
- Possible scheduling algorithm (II):
  - If a process completes within its time quantum, it leaves the system
  - If a process uses all the time quantum, it is preempted and moved to the next lower level queue (thus penalizing CPU-bound processes)
  - If a process blocks for I/O, it leaves the current queue and when the process becomes ready again it is inserted at the tail of the same queue
  - Alternatively, once a process uses its total time quantum at a given level (regardless of how many times it has blocked for I/O), it is preempted and moved to the next lower level queue (thus preventing gaming the scheduler)

MLQ x MLFQ

- MLQ scheduling involves defining 4 parameters:
  - Number of queues
  - Scheduling algorithm for each queue
  - Scheduling algorithm among the queues (fixed priority or time slice)
  - Method to determine which queue a process will be assigned to

- MLFQ scheduling involves defining 5 parameters:
  - Number of queues
  - Scheduling algorithm for each queue
  - Method to determine which queue a process will initially enter
  - Method to determine when to upgrade a process to a higher-priority queue
  - Method to determine when to demote a process to a lower-priority queue

MLQ x MLFQ: Pros and Cons

- MLQ
  - (+) Low scheduling overhead
  - (–) Fixed priority scheduling is unfair, inflexible and can lead to starvation
  - (–) Time slice can hurt the average waiting time

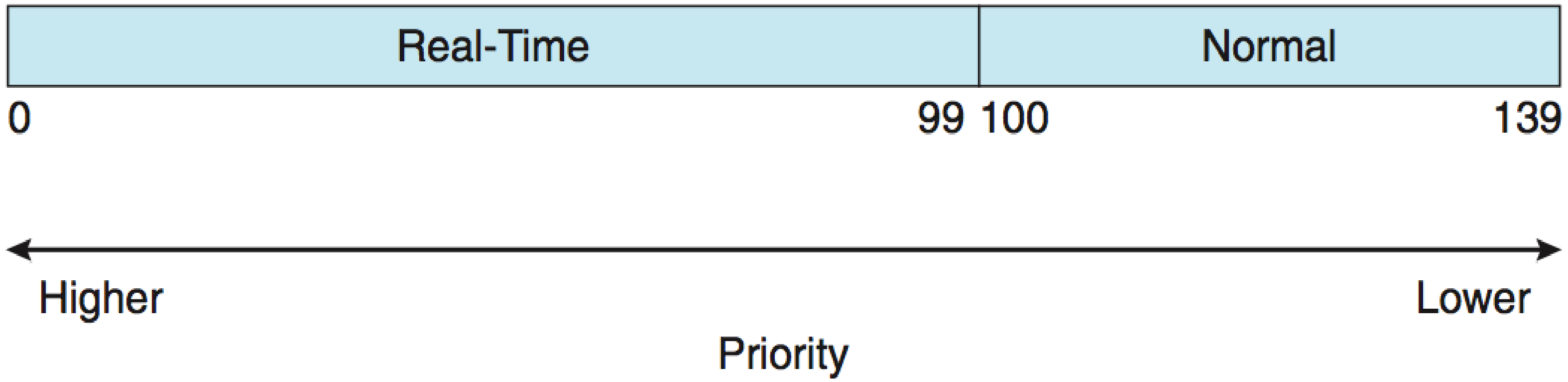
- MLFQ
  - (+) Excellent overall performance for short-running I/O bound processes and fair enough for long-running CPU-bound processes
  - (+) Results approximate SRTF
  - (+) Avoids starvation
  - (–) Requires some means by which to tune/select values for all 5 parameters

Completely Fair Scheduler (CFS)

- CFS is the scheduling algorithm adopted by the Linux kernel since release 2.6.23
- CFS tries to **divide CPU time fairly among all tasks** (processes or threads) **by taking into account their priorities and CPU usage history**
- CFS is based on **scheduling classes** where each class has a specific **priority range**
  - Scheduler picks the highest priority task from the highest priority class
  - Lower-priority tasks are preempted when higher-priority tasks are ready to run
- Typically, standard Linux kernels implement two scheduling classes:
  - **Real-time class**
  - **Normal (default) class**

Completely Fair Scheduler (CFS)

- The real-time class plus the normal class map into a global priority range:
  - **Real-time tasks** are assigned **static priorities** within the range [0,99]
  - **Normal tasks** have **nice values** and are assigned **dynamic priorities** within the range [100,139] based on their nice values
  - Nice values range from [-20,+19] and map to priorities [100,139] (the default nice value is 0)
  - A lower/higher nice value means higher/lower priority (the idea is that if a task increases its nice value, it is being nice to the other tasks in the system)



Completely Fair Scheduler (CFS)

- Real-time tasks are scheduled by priority and before tasks in other classes
- Normal tasks are scheduled accordingly to the **lowest virtual runtime value**
  - CFS maintains a per task virtual runtime value which **measures CPU time by associating a decay factor based on the nice value of the task**
  - Nice values of 0 yields a virtual runtime identical to the real runtime (if a task runs for 100 milliseconds, its virtual runtime will also be 100 milliseconds)
  - Lower-priority tasks have higher factors of decay, where higher-priority tasks have lower factors of delay (if a task runs for 100 milliseconds, its virtual runtime will be proportionally higher/lower than 100 milliseconds accordingly to its lower/higher-priority)
  - When a new task is created, it is assigned a virtual runtime equal to the current minimum virtual runtime

Completely Fair Scheduler (CFS)

- With CFS, tasks have **no fixed time slices** but rather **run until they are no longer the most unfairly treated task**

- CFS identifies a **target latency**, which is an interval of time during which every runnable task should run at least once
  - Target latency has default and minimum values but can increase if the number of active tasks in the system grows beyond a certain threshold

- Tasks get **proportions of CPU time** from the target latency value **accordingly to their relative priorities**

- When a task is awakened, the difference from its virtual runtime to the current minimum virtual runtime cannot exceed the target latency, otherwise its virtual runtime is adjusted to such limit
  - This prevents a task that has waiting too long from monopolizing the CPU

Completely Fair Scheduler (CFS)

- Consider the following scenario:
  - A target latency of 10ms and a decay factor of 2x
  - Process P_0 with virtual runtime 100ms and nice value 0 (min proportion: 2ms)
  - Process P_1 with virtual runtime 101ms and nice value -1 (min proportion: 4ms)
  - Process P_2 with virtual runtime 97ms and nice value -1 (min proportion: 4ms)

CFS x Virtual Runtimes	P_0	P_1	P_2
Initial virtual runtimes	100	101	97
Schedule P_2 for 6ms			100
Schedule P_0 for 2ms (I/O system call after 1ms)	101		
Schedule P_2 for 4ms	🟥		102
Schedule P_1 for 4ms	🟥	103	
Schedule P_2 for 4ms (hardware interrupt after 2ms)			103
Schedule P_0 for 2ms	103		