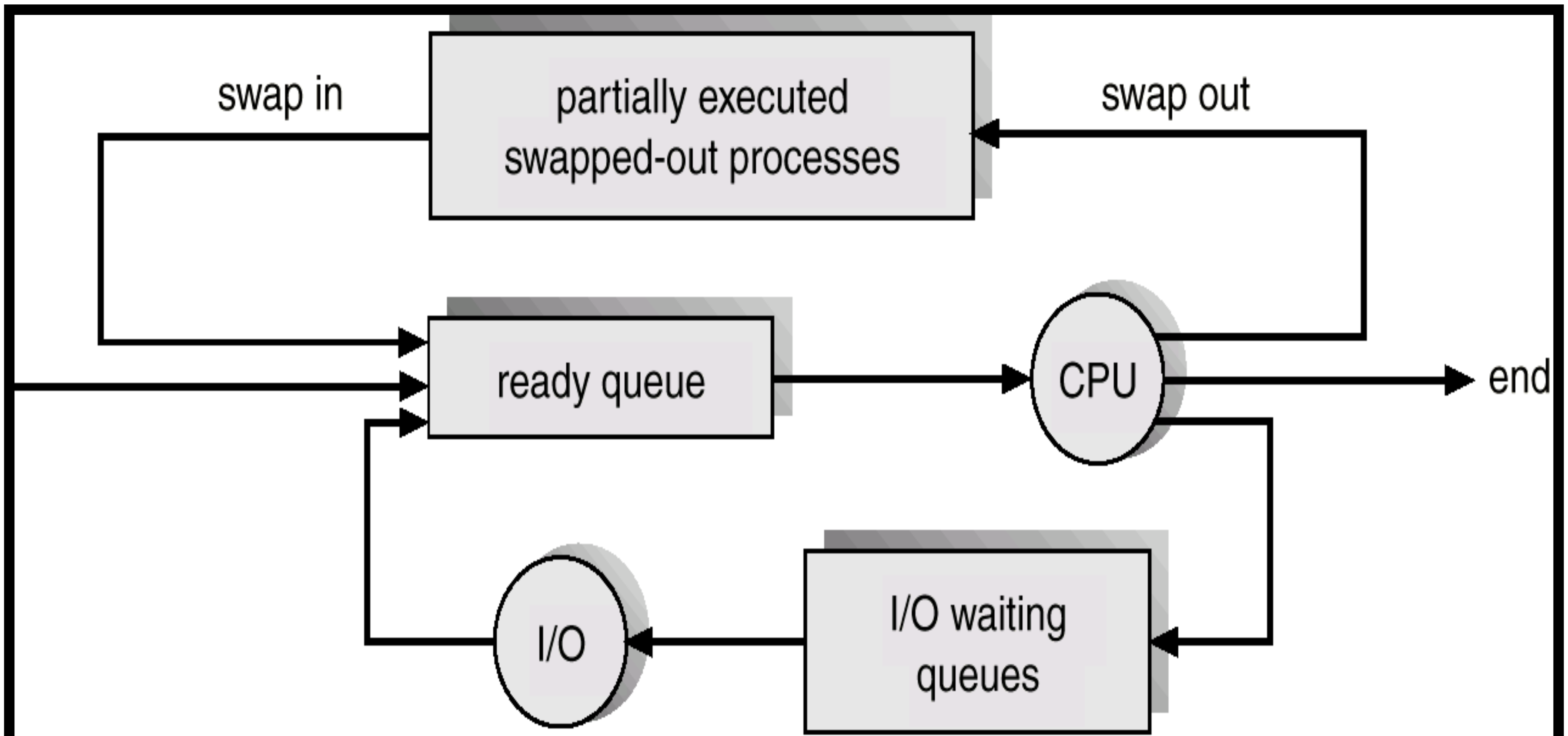
Operating Systems (CSE531)
Lecture # 10

Manish Shrivastava
CVIT, IIIT Hyderabad

Outline

- CPU Scheduling
  - Basic Concepts
  - Scheduling Criteria
  - Scheduling Algorithms
  - Real-Time Scheduling
  - Algorithm Evaluation
  - Process Scheduling Models

Scheduling

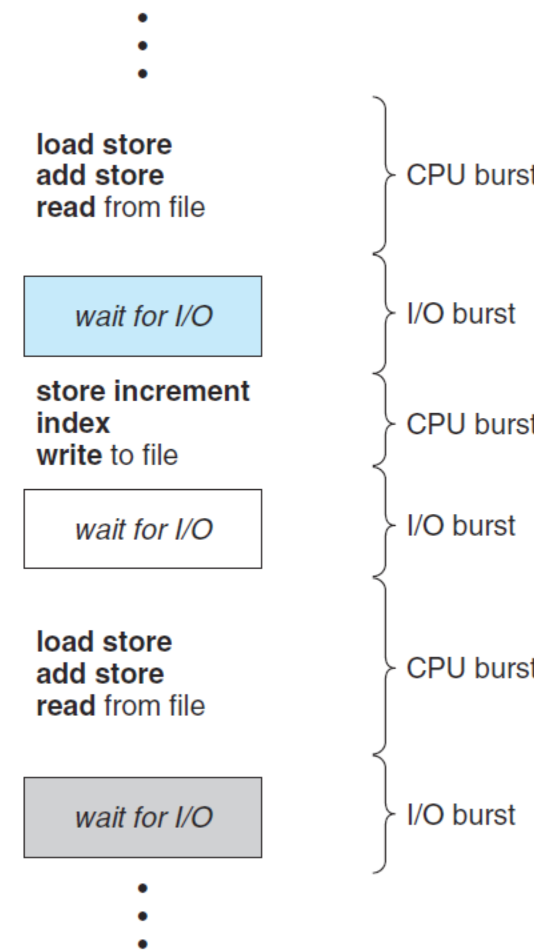

swap in
partially executed
swapped-out processes
swap out
ready queue
CPU
end
I/O
I/O waiting
queues

Basic Concepts

- CPU scheduling is the basis of multi-programmed OS.
- In the uni-processor system only one process runs at a time. Other processes must wait until CPU is free and can be rescheduled.
- Idea: the process is executed until it must wait for completion of I/O request.
- When one process has to wait, OS takes CPU away from that process and gives the CPU to another process.
- All the computer resources are schedules before use.
- 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 distribution

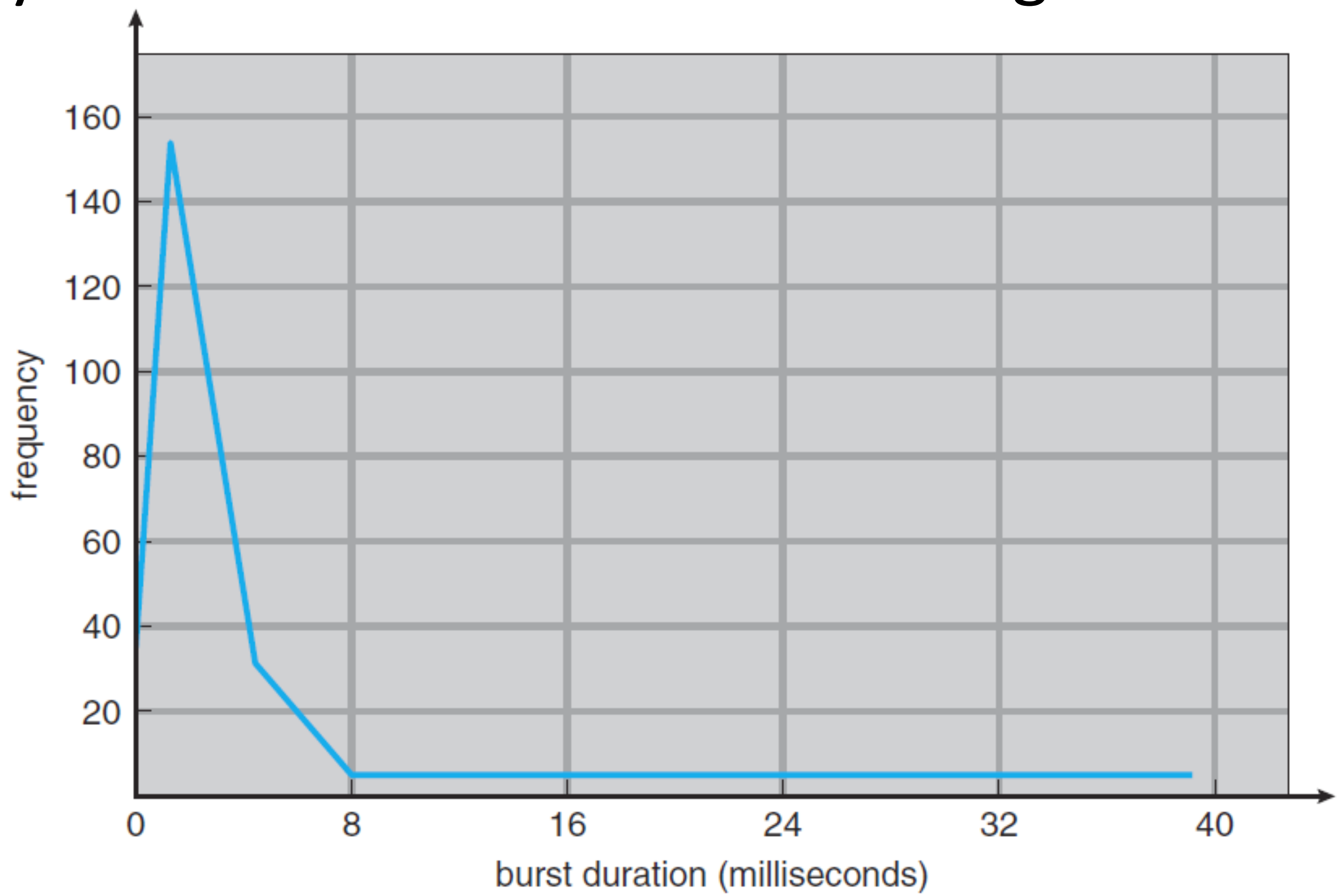
Observed Property

- Process execution consists of a cycle of execution and I/O wait.
- CPU–I/O Burst Cycle – Process execution consists of a *cycle* of CPU execution and I/O wait.
- Process execution starts with CPU-burst. That is followed by I/O burst.
- The execution ends with CPU burst.
- CPU burst distribution



Histogram of CPU-burst Times

- Many short CPU bursts and a few long CPU bursts.



CPU and I/O bound processes

- An I/O bound program would have many short CPU bursts.
- A CPU bound program would have long CPU bursts.

CPU Scheduler

- Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them.
- Short-term scheduler
- CPU scheduling decisions may take place when a process:
    1. Switches from running to waiting state (due to I/O).
    2. Switches from running to ready state (due to interrupt)
    3. Switches from waiting to ready. (Completion of I/O)
    4. Terminates.
- Scheduling under 1 and 4 is *non-preemptive*.
    - Once a CPU has been allocated to a process, the process keeps the CPU until it releases the CPU either by terminating or by switching to the waiting state.
        - WINDOWS 3.1 and MAC
- All other scheduling is *preemptive.*
    - The process can be preempted and another process can be run.
        - UNIX
        - Difficult to implement.

Preemptive Scheduling

- It incurs cost to access shared data
- Affects the design of OS
  - Interrupts occur at arbitrary time, changing of data modified by kernel
- Section of code modified by interrupts should be guarded
- But, all modern OSs are preemptive scheduling due to performance advantages as compared to non-preemptive scheduling

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

- Scheduling algorithm favors one process to another.
- User oriented criteria
  - **Turnaround time** – amount of time to execute a particular process
    - The interval from the time of submission of a process to the time of completion.
    - The sum of periods spent in waiting to get into memory, waiting in the ready queue, executing on CPU and doing I/O
  - **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)
  - **Deadlines**: When the process completion deadlines can be specified, the scheduling discipline should subordinate their goals to that of maximizing the percentage of deadlines met.

Scheduling Criteria

- System oriented criteria
  - **Throughput** – # of processes that complete their execution per time unit
  - **CPU utilization** – keep the CPU as busy as possible; percentage of time the processor is busy.
    - It may range from 0 to 100 percent.
    - In a real system, it should range from 40 percent (lightly loaded) to 90 percent (heavily loaded)
  - **Waiting time:** It is the sum of the periods spent waiting in the ready queue.
- System oriented: other
  - **Fairness**: In the absence of guidance from user or other system supplied guidance, processes should be treated the same, and no process should suffer starvation.
  - **Enforcing priorities:** When processes are assigned priorities, the scheduling policy should favor higher priority processes.
  - **Balancing resources:** The scheduling policy should keep the resources of the system busy. Processes that underutilize the stressed resources should be favored which involves long term scheduling.

Optimization Criteria

- Maximize
  - CPU utilization
  - Throughput
- Minimize
  - Turnaround time
  - Waiting time
  - Response time

Scheduling Algorithms

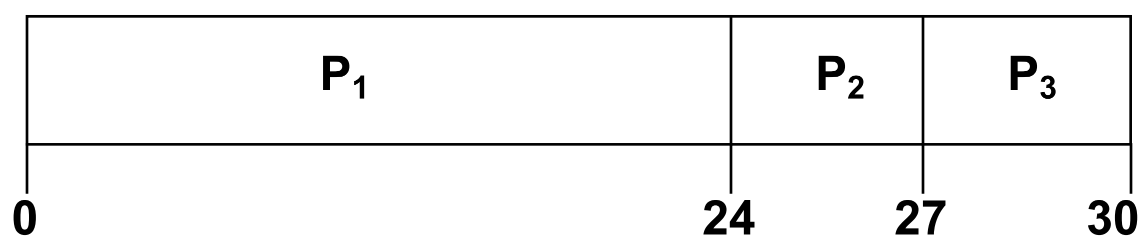
- First Come First Served (FCFS)
- Shortest Job First (SJF)
- Priority
- Round Robin
- Multilevel
- Multilevel Feedback

First Come First Served (FCFS) Scheduling

- The process that requests CPU first is allocated the CPU first.

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:



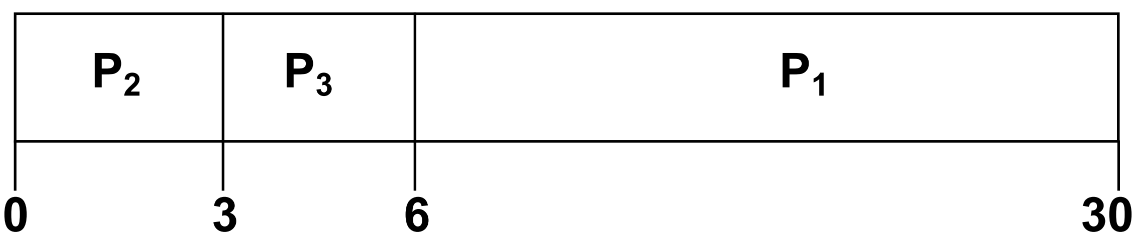
- Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
- Average waiting time: $(0 + 24 + 27)/3 = 17$

First Come First Served (FCFS) Scheduling

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.
- *Dynamic environment*
  - *Convoy effect:* short process behind long process

First Come First Served (FCFS) Scheduling

- Scenarios
  - One CPU bound process and many I/O bound process
  - CPU bound process will hold the CPU for a long time
  - All I/O processes are in ready queue
    - The I/O devices are idle
- FCFS algorithm is non-preemptive
- Positive Points
  - code is simple to write and understand
- Negative points
  - It is not good for timesharing systems
  - Average waiting time may be too long.
  - Convoy effect results in lower CPU and device utilization.
  - Penalizes short processes; penalizes I/O bound processes
  - Response time may be high, especially there is a large variance in process execution times.

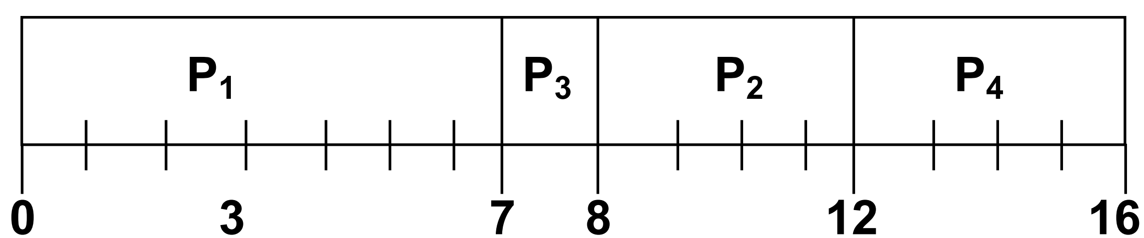
Shortest Job First (SJF) Scheduling

- When CPU is available it is assigned to the process that has the smallest next CPU burst.
- If the bursts are equal, FCFS is used to break the tie.
- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time.
- Two schemes:
  - Non-preemptive – once CPU is given to the process it cannot be preempted until it completes its CPU burst.
  - Preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is know as Shortest-Remaining-Time-First (SRTF).
- SJF is optimal – gives minimum average waiting time for a given set of processes.

Example of Non-Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (non-preemptive)

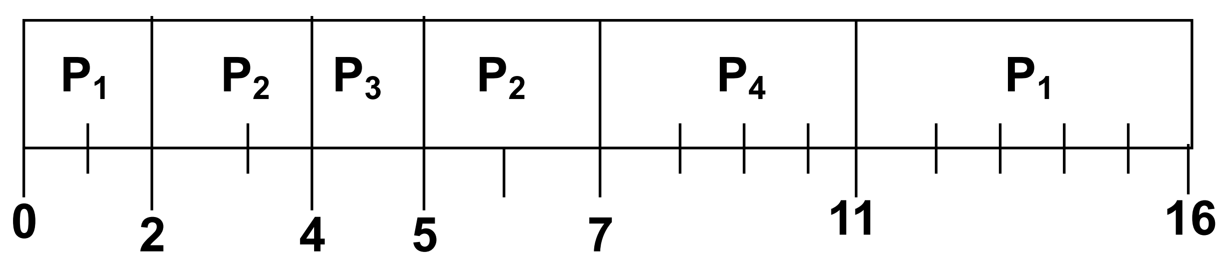


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Example of Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (preemptive)



- Average waiting time = (9 + 1 + 0 +2)/4 = 3

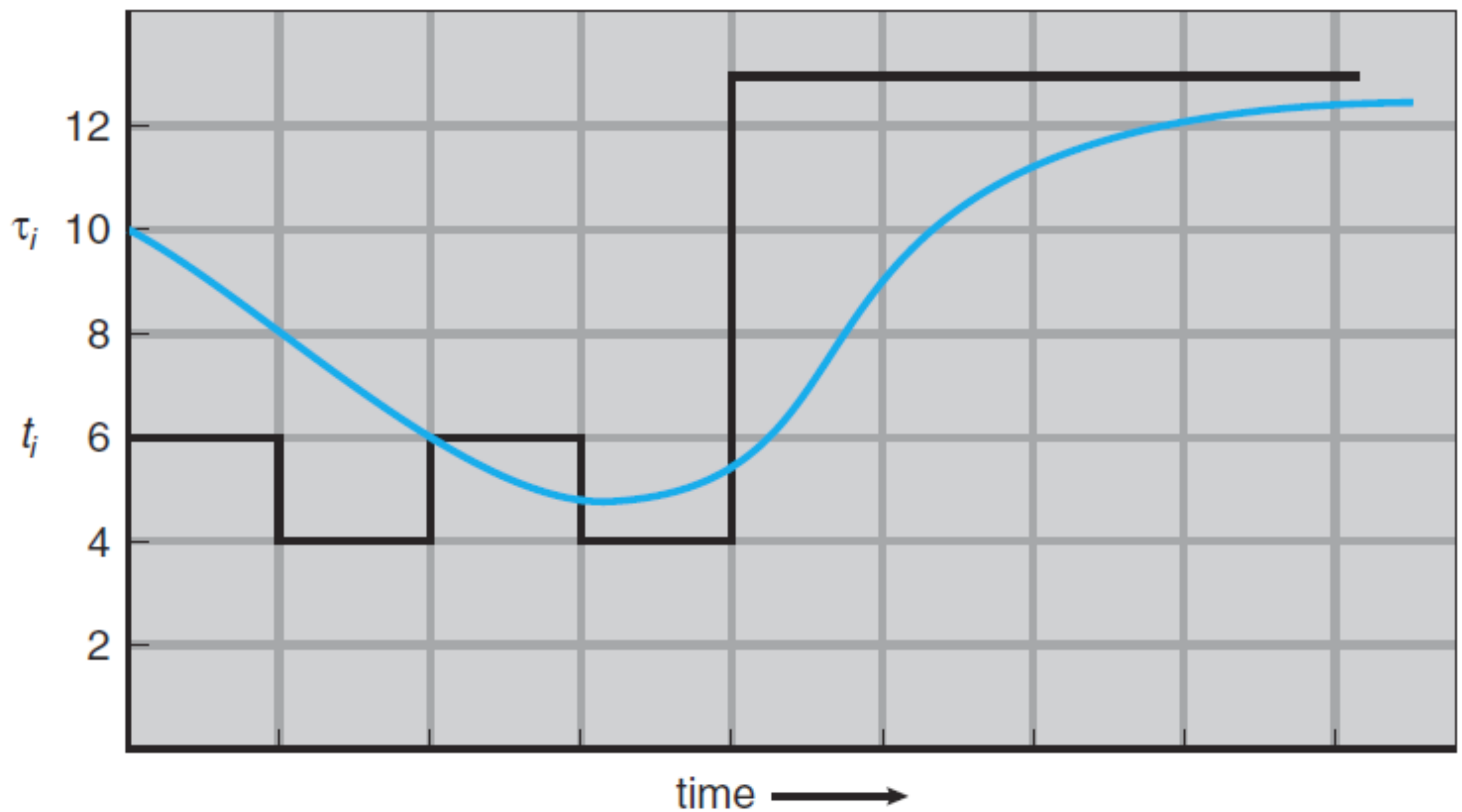
Determining Length of Next CPU Burst

- Difficulty: Knowing the next CPU burst of each process.
- Solution: approximation.
- Simplest approximation: running average of each "burst" for each process.
    - $\tau_{n+1}=1/n \sum t_i$ (i=1 to n)
    - Where, t_i : processor execution time for the i'th instance of this process (processor execution time for batch job, processor burst time for interactive job)
    - τ_i : predicted value for the i^{th} instance
    - τ_1 : predicted value for the first instance (not calculated)
- To avoid recalculating the entire summation each time we can rewrite
    - $\tau_{n+1} = 1/n\ t_n + (n-1)/n\ \tau_n$
- The above formula gives equal weight to each instance
- Normally most recent references likely reflect future behavior
- Common technique is exponential averaging.

Exponential averaging

1. $t_n =$ actual lenght of n^{th} CPU burst
2. $\tau_{n+1} =$ predicted value for the next CPU burst
3. $\alpha, 0 \leq \alpha \leq 1$
4. 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	…

Examples of Exponential Averaging

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

- $\alpha = 0$
  - $\tau_{n+1} = \tau_n$; Recent history does not count.
  - If $\alpha \rightarrow 0$; greater weight is given to past values.
  - If $\alpha \rightarrow 1$; greater weight is given to recent values.
- $\alpha = 1$
  - $\tau_{n+1} = t_n$
  - Only the actual last CPU burst counts.
- If we expand the formula, we get:

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

- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor.
- If $\alpha = 0.8$, then $\tau_{n+1} = 0.8\, t_n + 0.16\, t_{n-1} + 0.032\, t_{n-2} + \ldots$

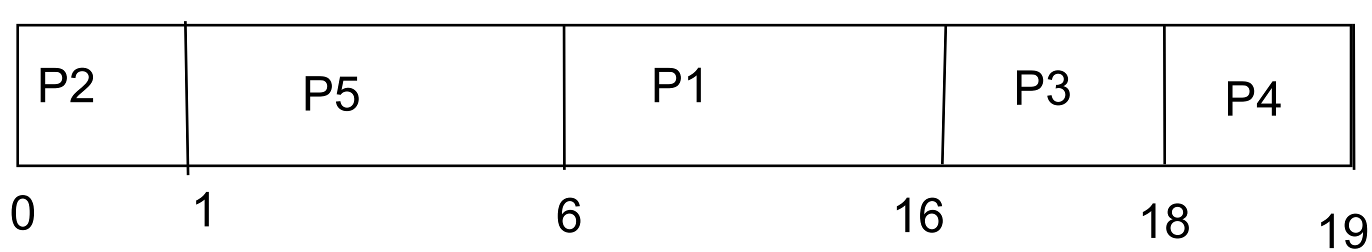
Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer $\equiv$ highest priority).
- Equal priority process is scheduled in FCFS order.
- SJF is a priority scheduling where priority is the predicted next CPU burst time.

Example: Priority Scheduling

Process	Burst time	Priority
P_1	10	3
P_2	1	1
P_3	2	3
P_4	1	4
P_5	5	2

- Priority
- Average waiting time = 8.2 msec



Priority Scheduling

- Priority scheduling can be either preemptive or non-preemptive.
- A preemptive priority scheduling algorithm will preempt the CPU if the priority of the newly arrived process is higher than the priority of the currently running process.
- A non-preemptive priority scheduling algorithm will simply put the new process at the head of the ready queue.

Priority Scheduling

- Problem ≡ Starvation : low priority processes may never execute. In an heavily loaded system, a stream of high priority processes can prevent low priority process from ever getting the CPU.

- Solution ≡ Aging : as time progresses increase the priority of the process.
    - Ex: if priorities range from 0 (low)-127 (high), every 15 minutes we can increment the priority of the waiting process.

Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds. After this time has elapsed, the process is preempted and added to the end of the ready queue.
- The ready queue is treated as a circular queue.
  - If the CPU burst is less than 1 time quantum, the process leaves the system.
  - If the CPU burst is greater than the time quantum, interrupt occurs and context switch will be executed.
- 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.

Example of RR

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

Time Quantum (q) = 20

- The Gantt chart is:

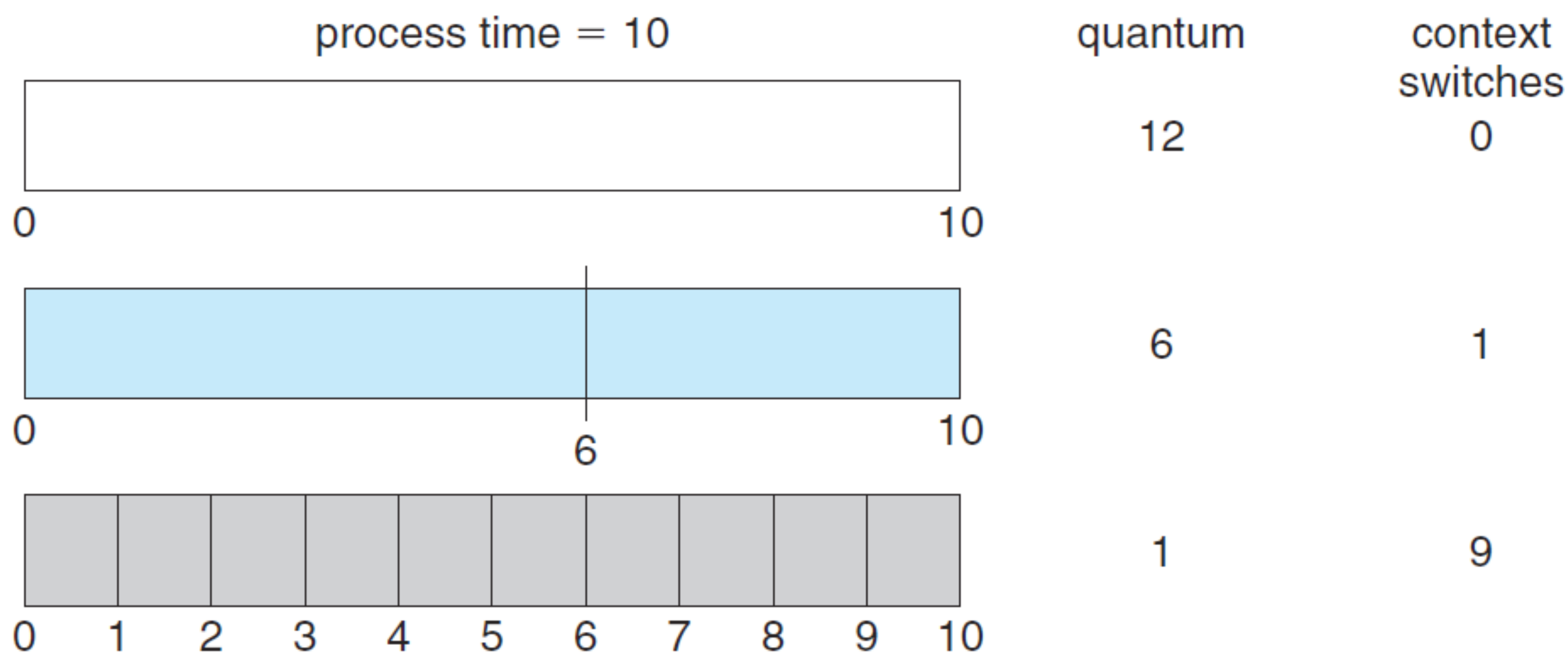
P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

0 20 37 57 77 97 117 121 134 154 162

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

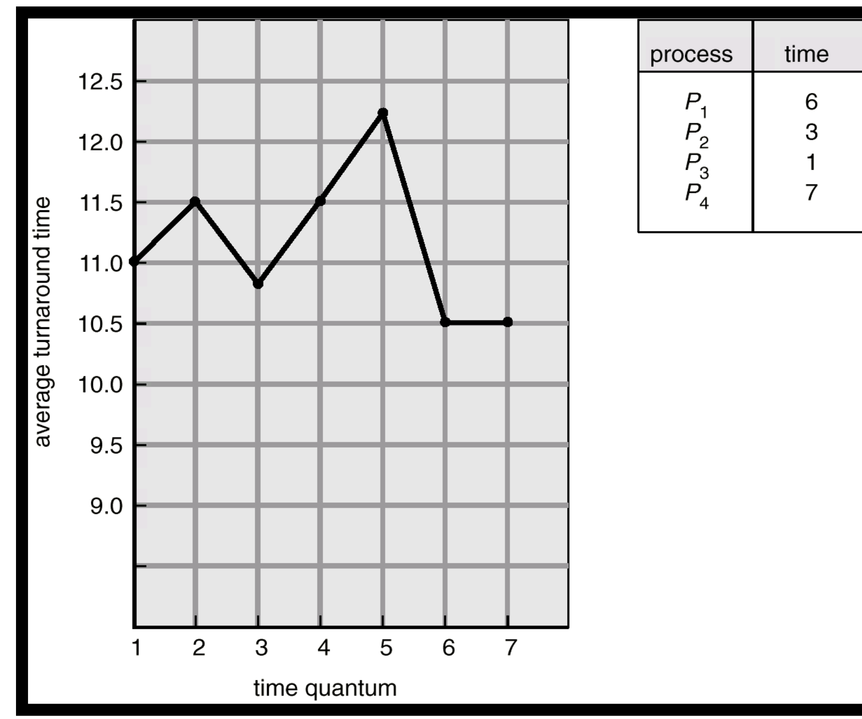
Round Robin Performance

- Performance depends on the size of the time quantum.
- If the time quantum is large, RR policy is the same as the FCFS policy.
- If the time quantum is too small, there will be more number of context switches.



Round Robin Performance

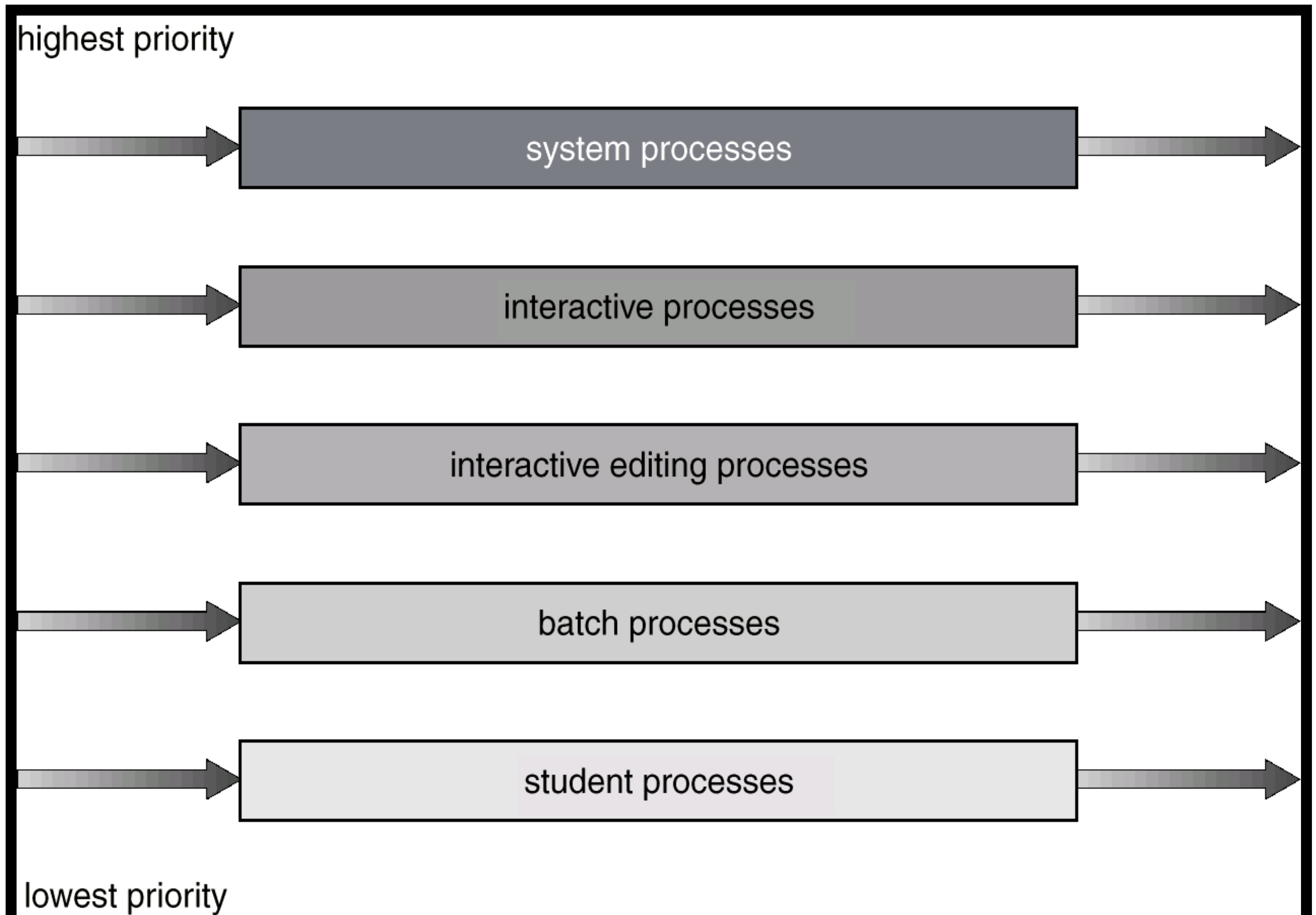
- If the context switch time is 10 % of time quantum, then 10 % of CPU time will be spent on the context switch.
- However, if we increase the time quantum the average turnaround time may not be improved.
- In general the average turnaround time will be improved if process finishes next CPU burst within single time quantum.
- Performance Summary:
  - *q* large ⇒ FCFS
  - *q* small ⇒ more number of context switches.
  - *q* must be large with respect to context switch, otherwise overhead is too high.
- Rule of thumb: 80 % of the CPU bursts should be shorter than the time quantum.



Multilevel Queue

- Ready queue is partitioned into several separate queues:
  Example: foreground (interactive); background (batch)
  - Foreground processes may have priority over background processes.
- 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



Multilevel Queue

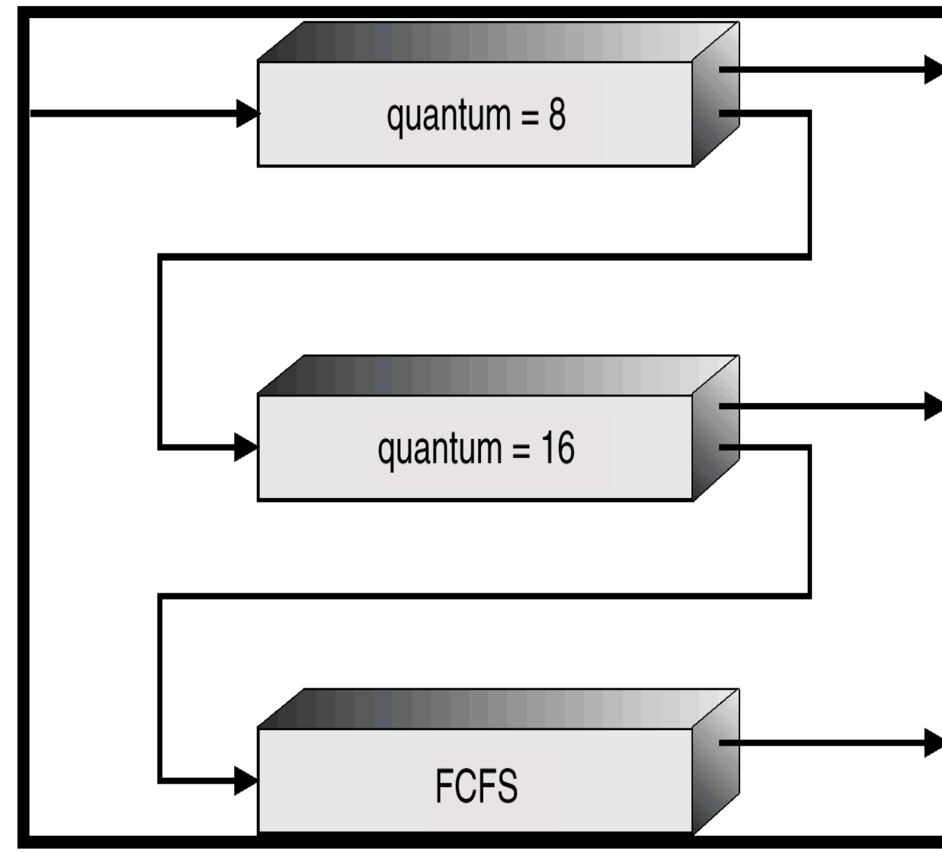
- Each queue has absolute priority over lower-priority queues.
  - No process in the batch queue can run unless the above queues are empty.
  - If the interactive process enters while the batch process is running, the batch process would be preempted.
  - Solaris 2 uses a form of this algorithm.
- Another policy is time slice:
  - Each queue gets certain portion of CPU time.
    - The foreground queue may receive 80% of CPU time, and background queue receives 20% of CPU time.
- Aging: A process can move between the various queues; aging can be implemented this way.

Multilevel Feedback Queue Scheduling

- Process moving is allowed
- The basic idea is to separate processes with different CPU-burst characteristics.
  - If a process uses too much CPU time, it will be demoted to lower priority queue.
  - If a process waits too long, it will be promoted to higher priority queue.
    - Aging prevents starvation

Example of Multilevel Feedback Queue

- Three queues:
  - Q_0 – time quantum 8 milliseconds
  - Q_1 – 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.
- The process that arrives in Q_0 will preempt a process in Q_2.
- Highest priority is given to the process of having 8 msec CPU burst.



Multilevel Feedback Queue Scheduling

- 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
- Multi-level is a general scheduling algorithm
- It can be configured to match a specific system under design.
  - It requires some means of selecting the values for all the parameters.

Thread Scheduling

- Distinction between user-level and kernel-level threads
- When threads are supported, threads are scheduled and 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

```
#include <pthread.h>
#include <stdio.h>
#define NUM THREADS 5
int main(int argc, char *argv[])
{
   int i;
   pthread t tid[NUM THREADS];
   pthread attr t attr;
   /* get the default attributes */
   pthread attr init(&attr);
   /* set the scheduling algorithm to PROCESS or SYSTEM */
   pthread attr setscope(&attr, PTHREAD SCOPE SYSTEM);
   /* set the scheduling policy - FIFO, RT, or OTHER */
   pthread attr setschedpolicy(&attr, SCHED OTHER);
   /* create the threads */
   for (i = 0; i < NUM THREADS; i++)
       pthread create(&tid[i],&attr,runner,NULL);
```

Pthread Scheduling API

```
   /* 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)
{
   printf("I am a thread\n");
   pthread exit(0);
}
```

Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- Homogeneous processors within a multiprocessor
  - The processors are identical
- Asymmetric multiprocessing – only one processor accesses the system data structures, alleviating the need for data sharing
    - Master server,
    - simple to implement
- 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

Multiple-Processor Scheduling

- Processor affinity – process has affinity for processor on which it is currently running
  - **soft affinity**: Efforts will be made to run the process on the same CPU, but not guaranteed.
  - **hard affinity**: Process do not migrate among the processors.
  - Variations including processor sets
    - Processor set is assigned to a process. It can run on any processor.

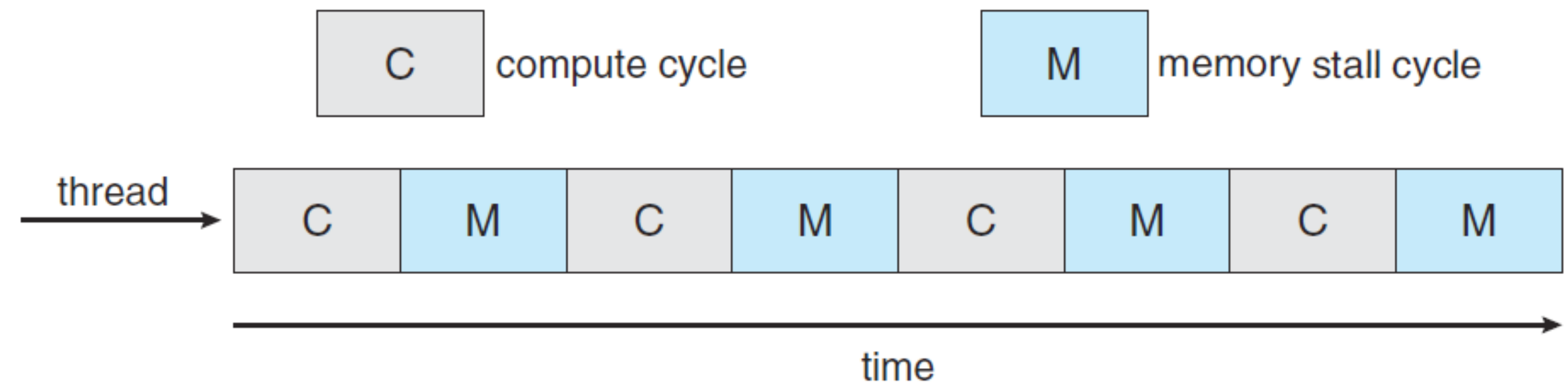
Multiprocessor Scheduling: Load Balancing

- Load balancing attempts to keep the workload evenly distributed across all the processors in an SMP system.
- Push migration and pull migration
  - Push migration
    - A specific process periodically checks the load on each processor and evenly distributes the processes.
  - Pull migration
    - Idle processor pulls a waiting task from a busy processor.

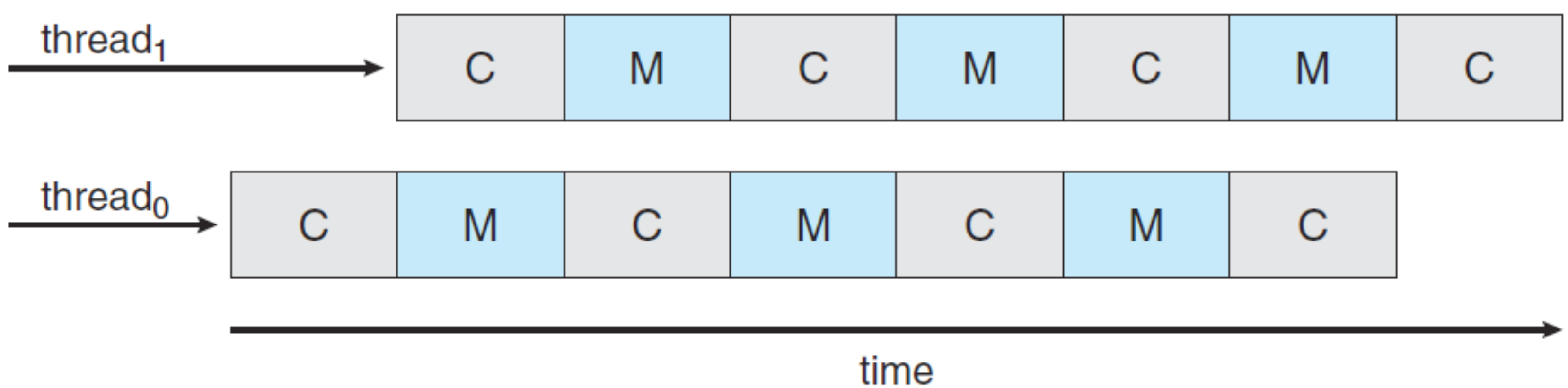
Multicore Processors

- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple threads per core also growing
    - **Memory stall**: When a processor accesses main memory, it spends significant amount of time in waiting.
    - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

Multithreaded Multicore System



- Two threads are associated with one core



- One core may have many logical processors
- A dual core may have four logical processors

LINUX (earlier than 2.5)

- Two separate process scheduling algorithms
  - Time sharing algorithm for fair preemptive scheduling among multiple processes.
  - Other is designed for real-time tasks
- LINUX allows only user processes to preempt
- A process can not be preempted in kernel mode, even real-time process is available to run.
- Every process is assigned with scheduling class, that defines which of the algorithms to apply to the process.
- First class is for time—sharing processes
  - LINUX uses prioritized credit based algorithm
  - Each process posses a certain number of scheduling credits.
  - While choosing, the process with most credits is selected.
  - Every time the interrupt occurs the process loses one credit
  - When its credits reaches zero it is suspended and another process is chosen.

LINUX (earlier than 2.5)

- If no runnable process have any credits, LINUX performs re-crediting operation. It adds credits to every process
    - Credits=(Credits/2)+priority
- This algorithm uses two factors: process history and priority.
- Suspended process will accumulate more credits.
- It also gives high priority to interactive processes
- Linux implements two real-time scheduling classes
    - FCFS and round robin.
- In the FCFS class the process runs until it blocks.
- LINUX real-time scheduling is soft—rather than hard.
- The scheduler guarantees priorities, but kernel never gives guarantees
    - Kernel process can not preempted

THANK YOU