CS370 Operating Systems

Colorado State University

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Scheduling

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

FAQ

- What exactly is a thread? A block of code?
  - A function when called within a new thread, runs concurrently with other threads.
- Process vs thread
  - A process is isolated from other processes. Processes can run concurrently. Can have multiple threads.
  - A thread is not isolated from other threads belonging to the same process. Runs concurrently with other threads.
- What is a pthread? POSIX compliant implementation of threads.
- Java threads? Most JVMs implement threads with native, OS level threads,
- Examples of threads: Self exercise set 4

FAQ

- Why use threads:
  - Parallelism if multiple cores/hyper-threading available.
  - Concurrency: quicker responses to some of the things like refreshing output, checking spelling as one types etc.
- Implicit threading: thread creating automated: compiler assisted higher level programming
- Unix signals vs interrupts: Signals are a limited form of inter-process communication. Interrupts are often initiated by hardware. In both cases, some specific routines respond.
- Hyper-threading: Requires additional hardware. Widely used
- Signals example (assume pid = 162): kill -9 162 or kill –s sigkill 162
- Pthread example: pthread_kill(ThreadID, SIGKILL);

Implicit Threading: OpenMP

- Set of compiler directives and an API for C, C++, FORTRAN
- Provides support for parallel programming in shared-memory environments
- Identifies **parallel regions** – blocks of code that can run in parallel

```
#pragma omp parallel
```

Create as many threads as there are cores

```
#pragma omp parallel for
   for(i=0;i<N;i++) {
    c[i] = a[i] + b[i];
}
```

Splits loop task in parallel threads

Compile using
gcc -fopenmp openmp.c

```
#include <omp.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
   /* sequential code */

   #pragma omp parallel
   {
      printf("I am a parallel region.");
   }

   /* sequential code */

   return 0;
}
```

Self exercise 3, 4 available now.

Signal Handling

- **Signals** are used in UNIX systems to notify a process that a particular event has occurred.
- A **signal handler** is used to process signals
  1. Signal is generated by particular event
  2. Signal is delivered to a process
  3. Signal is handled by one of two signal handlers:
     1. default
     2. user-defined
- Every signal has **default handler** that kernel runs when handling signal
  - **User-defined signal handler** can override default
  - For single-threaded, signal delivered to process

Thread Cancellation (Cont.)

- Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state

Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

- A thread's cancelation type (mode) and state can be set.
- If thread has cancellation disabled, cancellation remains pending until thread enables it
- Default type is deferred
  - Cancellation only occurs when thread reaches **cancellation point**
    - I.e. `pthread_testcancel()`
    - Then **cleanup handler** is invoked
- On Linux systems, thread cancellation is handled through signals

Is complexity always good?

- Is something that is
  - More advanced
  - More complex

  Generally better?

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Hyper-threading

"Hyper-threading": "simultaneous multithreading":

- Hardware support for multiple threads in the same core (CPU)

- Performance:
  - performance improvements are very application-dependent
  - Higher energy consumption ARM 2006
  - Not better than out-of-order execution Intel 2013
  - Intel has dropped it in some chips Core i7-9700K 2018 8 cores, 8 threads
  - May be enabled/disabled using firmware

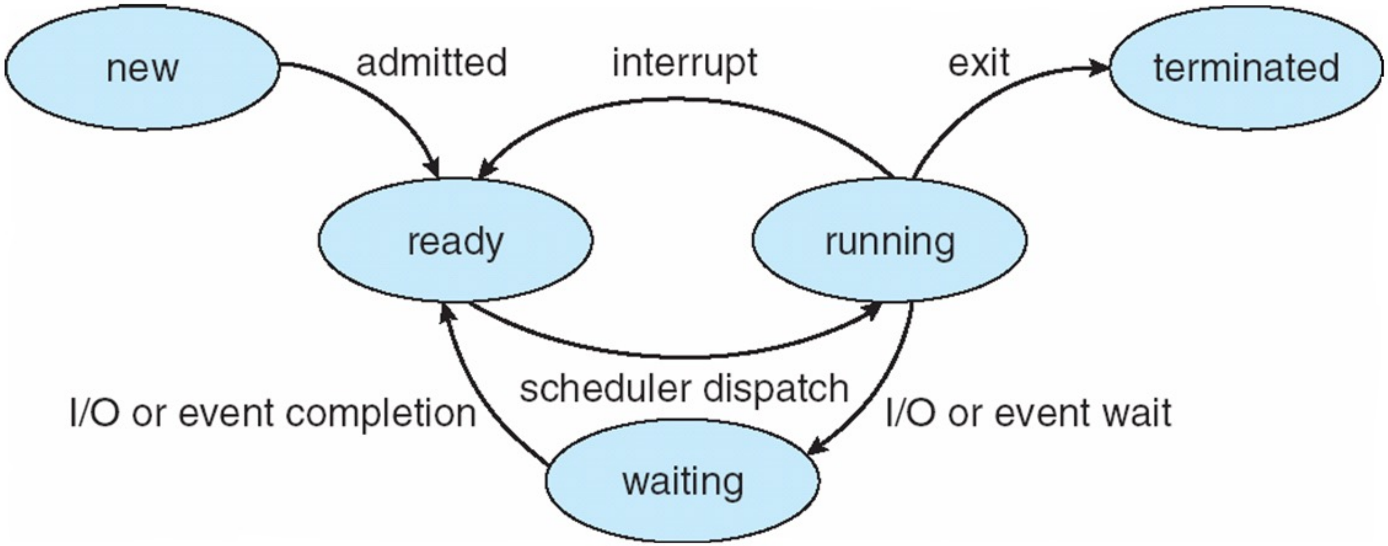
Forms of Parallelism

- Pipelining: instruction flows though multiple levels
- Multiple issue: Instruction level Parallelism (ILP)
  - Multiple instructions fetched at the same time
  - Static: compiler scheduling of instructions
  - Dynamic: hardware assisted scheduling of operations
    - “Superscalar” processors
    - CPU decides whether to issue 0, 1, 2, … instructions each cycle
- Thread or task level parallelism (TLP)
  - Multiple processes or threads running at the same time

Chapter 5: CPU Scheduling

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

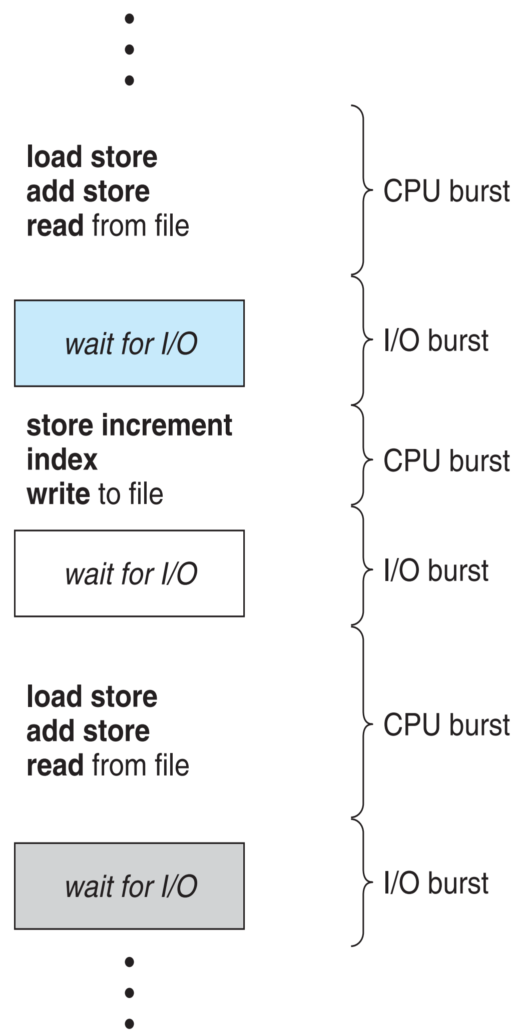
Diagram of Process State



Ready to Running: scheduled by scheduler
Running to Ready: scheduler picks another process, back in ready queue
Running to Waiting (Blocked) : process blocks for input/output
Waiting to Ready: Input available

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



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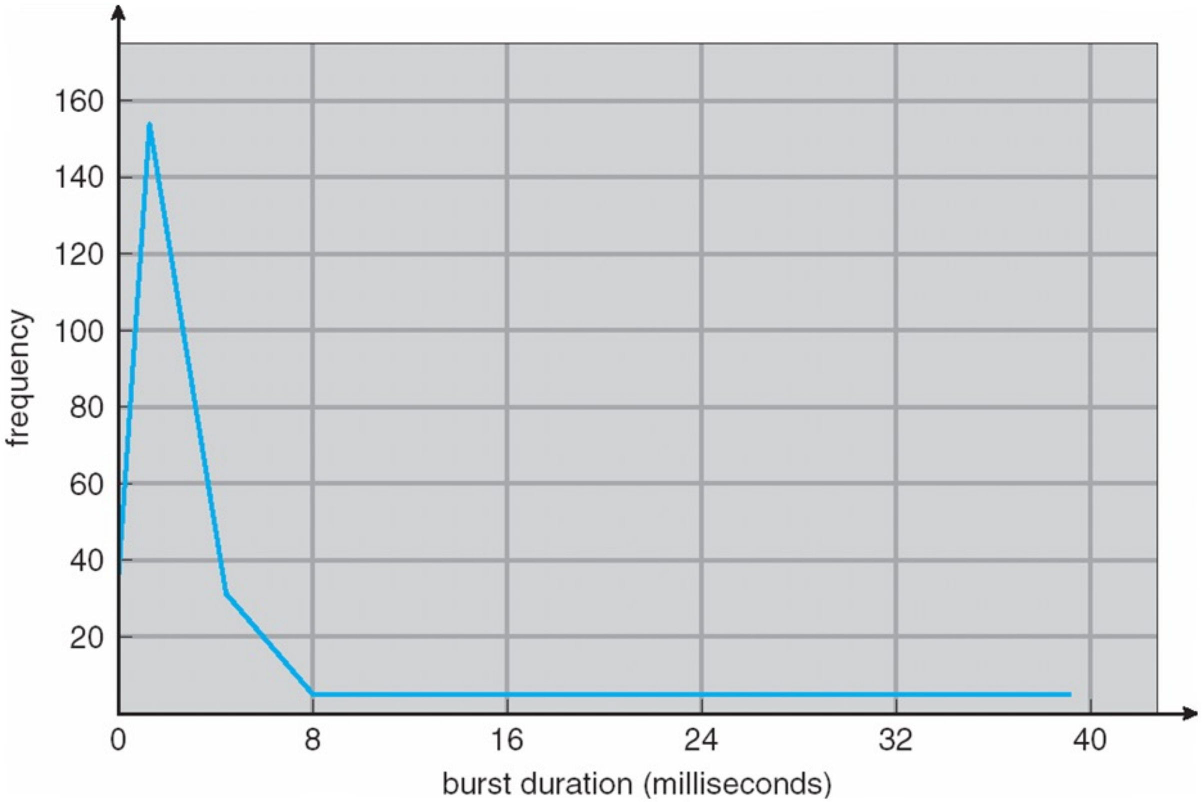
Histogram of CPU-burst Times



Typical distribution of CPU bursts. Most CPU bursts are just a few ms.

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. These need to be considered**
  - access to shared data by multiple processes
  - preemption while in kernel mode
  - interrupts occurring during crucial OS activities

Not Controlled by the process

Dispatcher

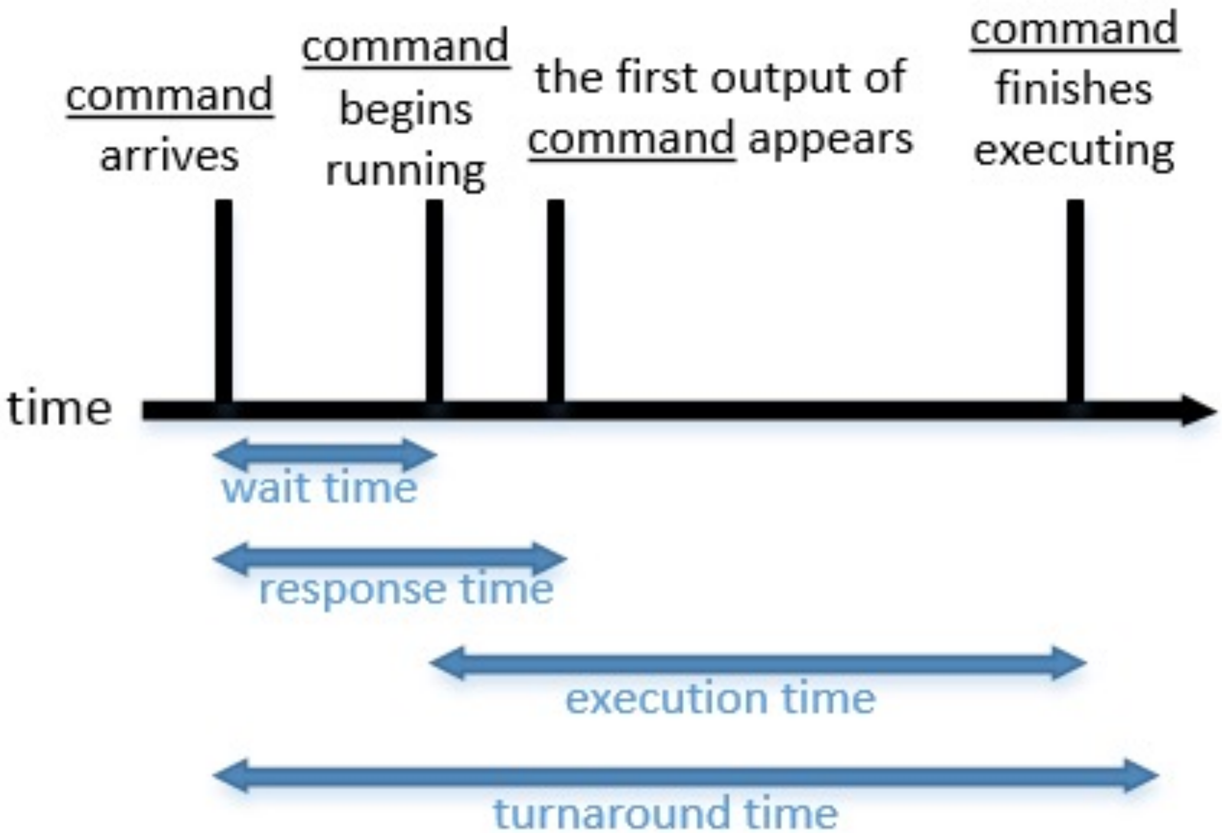
- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - switching context
  - switching to user mode
  - jumping to the proper location in the user program to restart that program
- **Dispatch latency** – time it takes for the dispatcher to stop one process and start another running

The Dispatcher (dentist's office)

Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible: Maximize
- **Throughput** – # of processes that complete their execution per time unit: Maximize
- **Turnaround time** –time to execute a process from submission to completion: Minimize
- **Waiting time** – amount of time a process has been waiting in the ready queue: Minimize
- **Response time** –time it takes from when a request was submitted until the first response is produced, not output (for time-sharing environment): Minimize

Terms *for a single process*



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Scheduling Algorithms

We will now examine several major scheduling approaches

- **Decide** which process in the ready queue is allocated the CPU
- Could be preemptive or nonpreemptive
  - preemptive: remove in middle of execution ("forced")
- Optimize ***measure*** of interest
  - We will use **Gantt charts** to illustrate *schedules*
  - Bar chart with start and finish times for processes

[Involuntary deboarding!]()

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Non-preemptive vs Preemptive sheduling

- **Non-preemptive:** Process keeps CPU until it relinquishes it when
  - **It terminates**
  - **It switches to the waiting state**
  - Used by initial versions of OSs like Windows 3.x
- **Preemptive** scheduling
  - Pick a process and let it run for a maximum of some fixed time
  - If it is still running at the end of time interval?
    - Suspend it and pick another process to run
- A **clock interrupt** at the end of the time interval to give control back of CPU back to scheduler

Scheduling Algorithms

- First- Come, First-Served (FCFS)
- Shortest-Job-First (SJF)
  - Shortest-remaining-time-first
- Priority Scheduling
- Round Robin (RR) with time quantum
- Multilevel Queue
  - Multilevel Feedback Queue
- “Completely fair”

Comparing Performance

- Average waiting time etc.

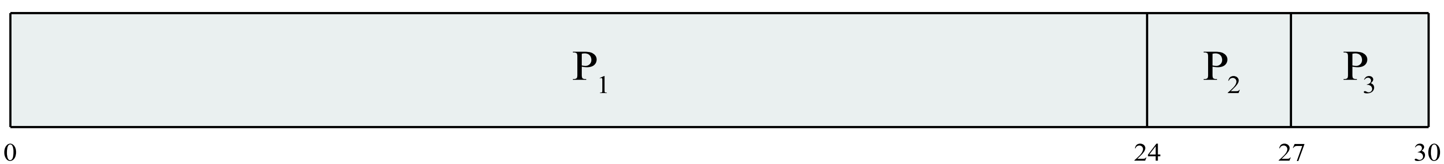
First- Come, First-Served (FCFS) Scheduling

- Process requesting CPU first, gets it first
- Managed with a FIFO queue
  - When process **enters** ready queue
    - PCB is tacked to the **tail** of the queue
  - When CPU is **free**
    - It is allocated to process at the **head** of the queue
- Simple to write and understand

Henry Gantt, 1910s

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 *but almost the same time*.
  The Gantt Chart for the schedule is:



- Waiting time for P_1 = ; P_2 = ; P_3 =
- Average waiting time: (+ +)/ =
- Throughput: / = per unit time

Pause for students to do the computation

First- Come, First-Served (FCFS) Scheduling

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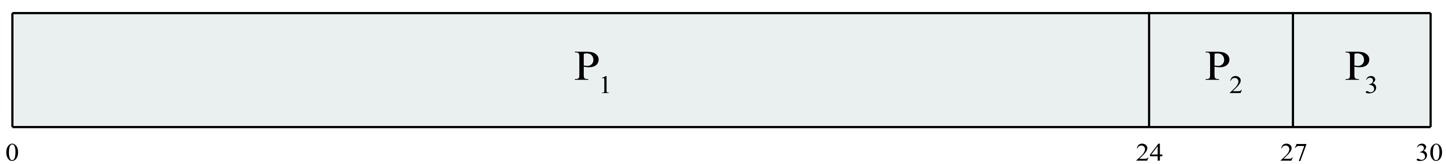

- Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
- Average waiting time: (0 + 24 + 27)/3 = 17
- Throughput: 3/ 30 = 0.1 per unit time

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FCFS Scheduling (Cont.)

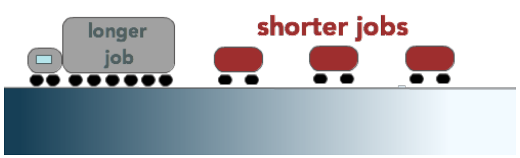
Suppose that the processes arrive in the order:

$$P_2 , P_3 , P_1$$

- 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
- But note -Throughput: 3/30 = 0.1 per unit same
- **Convoy effect** - short processes behind a long process
  - Consider one CPU-bound and many I/O-bound processes

The Convoy Effect, visualized



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
- Reduction in waiting time for short process *GREATER THAN* Increase in waiting time for long process
- 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
  - Estimate or could ask the user

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Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- All arrive at time 0.
- SJF scheduling chart: Draw it here.

- Average waiting time for P_1,P_2,P_3,P_4 = (+ + +) / =

Pause for students to do the computation

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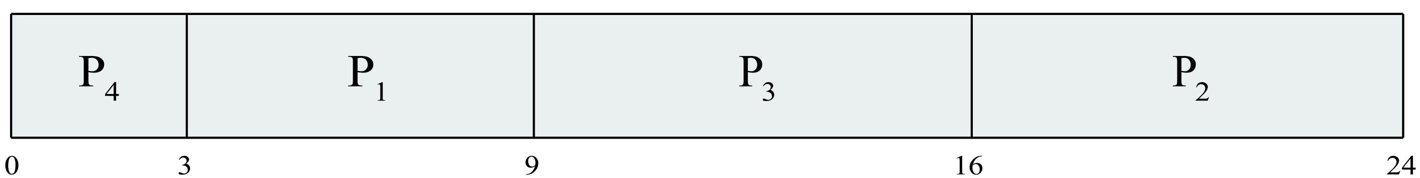
Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- All arrive at time 0.
- SJF scheduling chart



- Average waiting time for P_1,P_2,P_3,P_4 = (3 + 16 + 9 + 0) / 4 = 7

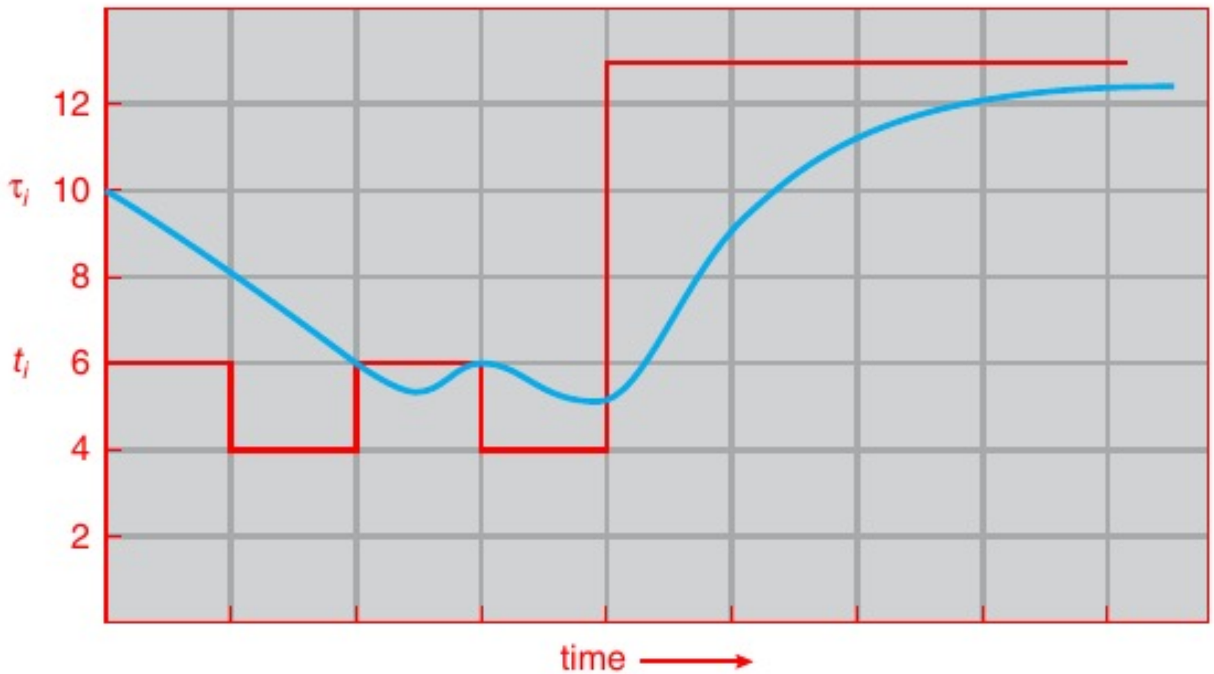
Determining Length of Next CPU Burst

- Can only estimate the length – should be similar to the recent bursts
  - Then pick process with shortest predicted next CPU burst
- Can be done by using the length of previous CPU bursts, using *exponential averaging*

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

- Commonly, α set to ½

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	…

Blue line: guess
Red line: actual

$\alpha = 0.5$

Ex:
$0.5 \times 6 + 0.5 \times 10 = 8$

Examples of Exponential Averaging

- α =0
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- α =1
  - $\tau_{n+1} = \alpha\ t_n$
  - Only the actual last CPU burst counts
- $\tau_{n+1} = \alpha\, t_n + (1-\alpha)\tau_n.$
- If we expand the formula, substituting for τ_n , 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

Widely used for predicting stock-market etc

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Shortest-remaining-time-first (**preemptive** SJF)

- Preemptive version called **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 (will preempt because 4<7)
P_3	2	9 (will not preempt)
P_4	3	5

- *Preemptive* SJF Gantt Chart

P_1	P_2	P_4	P_1	P_3
0–1	1–5	5–10	10–17	17–26

- Average waiting time for P1,P2,P3,P4

  = [(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

MIT had a low priority job waiting from 1967 to 1973 on IBM 7094! ☺

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Ex Priority Scheduling non-preemptive

Process	Burst Time	Priority
P_1	10	3
P_2	1	1 (highest)
P_3	2	4
P_4	1	5
P_5	5	2

- P1,P2, P3, P4,P5 all arrive at time 0.
- Priority scheduling Gantt Chart

- Average waiting time for P1, .. P5: (6+0+16+18+1)/5 = 8.2 msec

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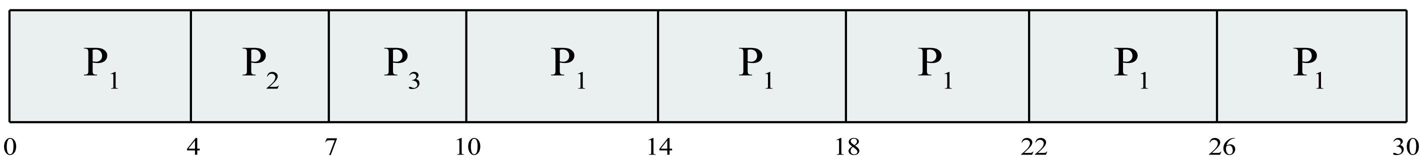
Round Robin (RR) with time quantum

- Each process gets a small unit of CPU time (**time quantum** *q*), usually 10-100 milliseconds. After this, the process is preempted, 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 $(n\text{-}1)q$ 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 (overhead *typically in 0.5% range*)

Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

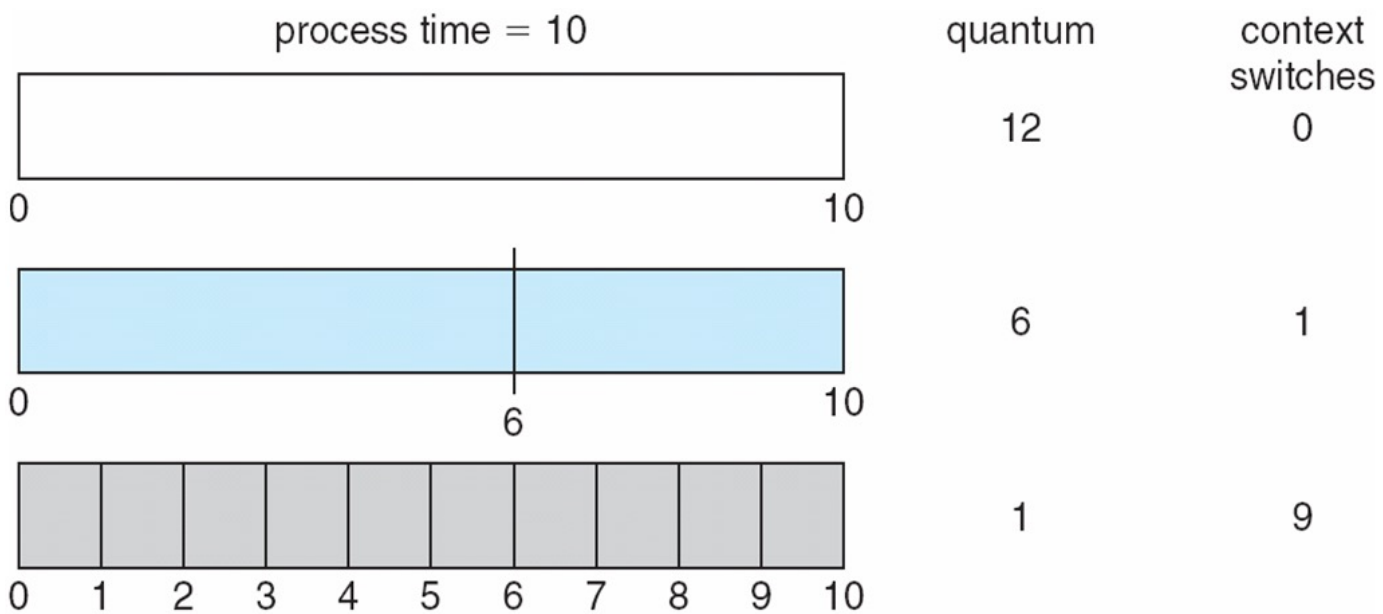
- Arrive a time 0 in order P1, P2, P3: The Gantt chart is:



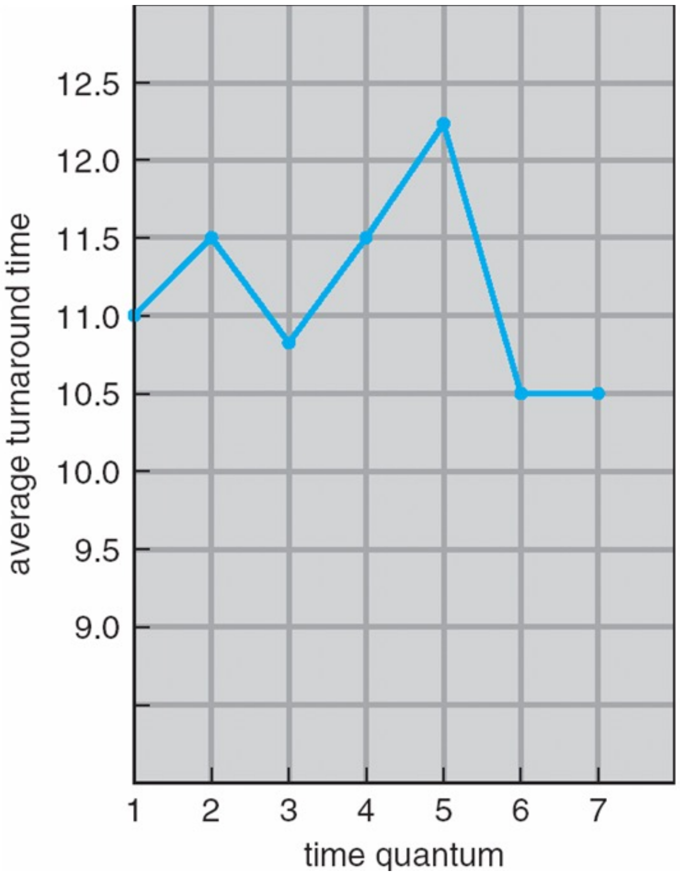
- Waiting times: P1:10-4 =6, P2:4, P3:7, average 17/3 = 5.66 units
- Typically, higher average turnaround than SJF, but better ***response***
- q should be large compared to context switch time
- q usually 10ms to 100ms, context switch < 10 μsec

Response time: Arrival to beginning of execution
Turnaround time: Arrival to finish of execution

Time Quantum and Context Switch Time



Much smaller quantum compared to burst: many switches



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Rule of thumb: 80% of CPU bursts should be shorter than q

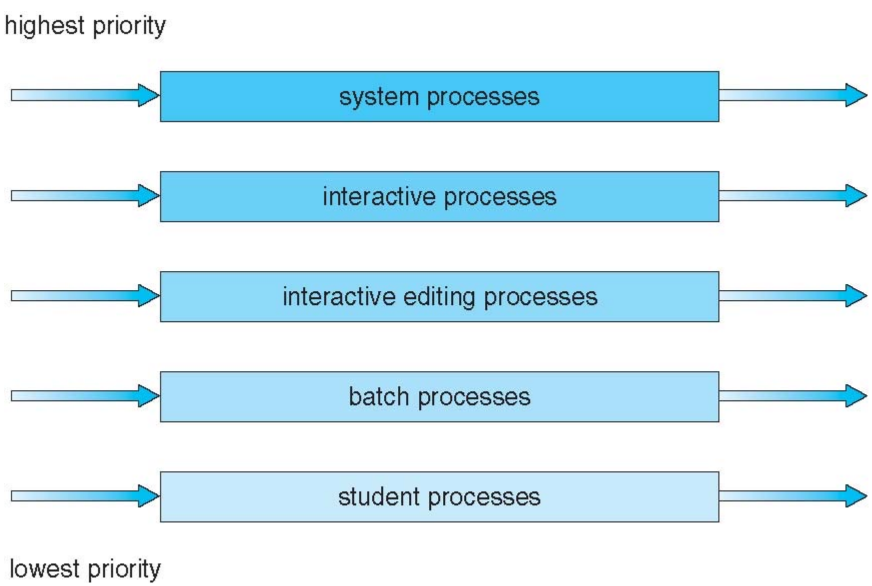
Illustration
Consider q=7:
Turnaround times for P1,P2,P3,P4:
6,9,10,17 av = 10.5
Similarly for q =1, ..6 (verify yourself)

Students: Repeat for q = 1, ..6 at home to verify the plot.

Multilevel Queue

- Ready queue is partitioned into separate queues, e.g.:
  - **foreground** (interactive)
  - **background** (batch)
- Process permanently in a given queue
- Each queue has its own scheduling algorithm, e.g.:
  - 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. Or
  - 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



Real-time processes may have the highest priority.

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
  - Details at ARPACI-DUSSEAU

Inventor FJ Corbató won the Touring award!

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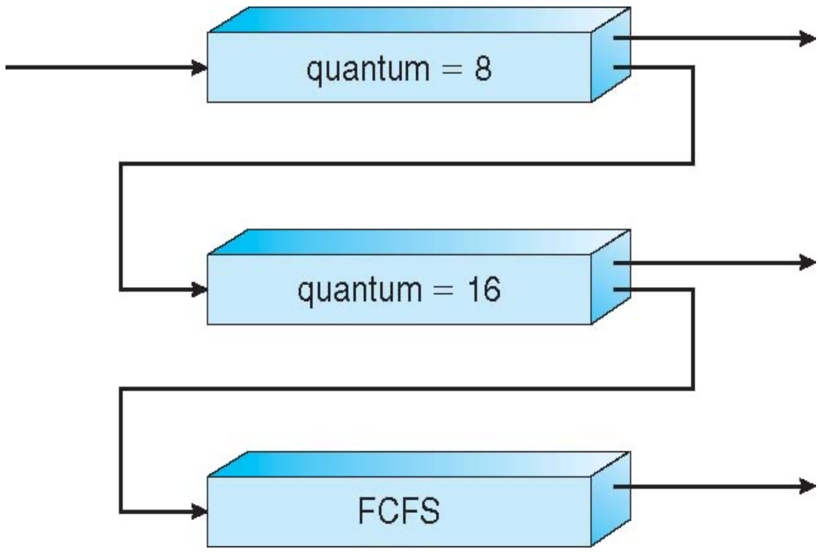
Example of Multilevel Feedback Queue

- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS (no time quantum limit)

- 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



Upgrading may be based on aging. Periodically processes may be moved to the top level.

Variations of the scheme were used in earlier versions of Linux.

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Completely fair scheduler Linux 2.6.23

Goal: fairness in dividing processor time to tasks ([Con Kolivas, Anaesthetist](#))

- Variable time-slice based on number and priority of the tasks in the queue.
  - Maximum execution time based on waiting processes (Q/n).
  - Fewer processes waiting, they get more time each
- Queue ordered in terms of "virtual run time"
    - execution time on CPU added to value
  - smallest value picked for using CPU
  - small values: tasks have received less time on CPU
  - I/O bound tasks (shorter CPU bursts) will have smaller values
- *Balanced (red-black) tree* to implement a ready queue;
  - Efficient. O(log n) insert or delete time
- Priorities (*niceness*) cause different decays of values: higher priority processes get to run for longer time
  - virtual run time is the weighted run-time

Scheduling schemes have continued to evolve with continuing research. A comparison.

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