CSCI [4|6] 730
Operating Systems

CPU Scheduling

Status

- Scheduling (3 lectures)
  - » Next project – may be simplified from the 'preview' assignment (multi-level / lottery scheduler).
- Exam 1 coming up – Thursday Oct 7 (2 weeks from today)
  - » OS Fundamentals & Historical Perspective
  - » OS Structures (Micro/Mono/Layers/Virtual Machines)
  - » Processes/Threads (IPC, local & remote)
  - » Scheduling (up to)
  - » ALL Summaries (all – form a group to review) 30%
  - » MINIX
- Grading Criteria Adjustment – to reflect effort on HW (Now 15%)

CPU Scheduling Questions?

- Why is scheduling needed?
- What is preemptive scheduling?
- What are scheduling criteria?
- What are disadvantages and advantages of different scheduling policies, including:
  - » First-come-first-serve?
  - » Shortest job first?
  - » Shortest time to completion first?
  - » Round robin?
  - » Priority based?

Why Schedule? Management Resources

- Resource: Anything that can be used by only a single process at any instant in time
- Hardware device or a piece of information
  - » Examples:
    - CPU (time),
    - Tape drive, Disk space, Memory (spatial)
    - Locked record in a database (information, synchronization)
- Focus today managing the CPU

Resource Classification

- Pre-emptable
  - » Can forcibly removed the resource from a process (and possibly return it later) without ill effects.
- Non-preemptable
  - » Cannot take a resource away from its current 'owner' without causing the computation to fail.

Resource Classification

- Preemptable (forcible removable)
  - » Characteristics (desirable):
    - small state (so that it is not costly too preempt it).
    - only one resource
  - » Examples:
    - CPU or Memory are typically a preemptable resources
- Non-preemptable (not forcible removable)
  - » Characteristics:
    - Complicated state
    - May need many instances of this resource
  - » Examples:
    - CD recorder - once starting to burn a CD needs to record to completion otherwise the end up with a garbled CD.
    - Blocks on disk

Resources Management Tasks

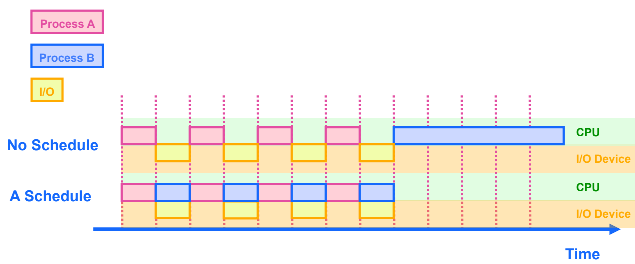
- **Allocation (Space):**
  - » **Space Sharing: Which process gets which resource (control access to resource)?**
- **Scheduling (Time):**
  - » **Time Sharing: In which order should requests be serviced; Which process gets resource and at what time (order and time)?**

Time and Space

The CPU Management Team

- **(how?)"The Dispatcher" (low level mechanism – the worker)**
  - » **Context Switch**
    - **Save execution of old process in PCB**
    - **Add PCB to appropriate queue (ready or blocked)**
    - **Load state of next process from PCB to registers**
    - **Switch from kernel to user mode**
    - **Jump to instruction in user process**
- **(when?) "The Scheduler" (higher level mechanism - upper management,) (time)**
  - » **Policy to determine when a specific process gets the CPU**
- **(where?) Sometimes also "The Allocator" (space)**
  - » **Policy to determine which processes compete for which CPU**
  - » **Needed for multiprocessor, parallel, and distributed systems**

What is the Point? Can *Scheduling* make a difference?



- **No Schedule vs A Schedule**
- **Schedule another waiting process while current CPU relinquish to CPU due to I/O.**

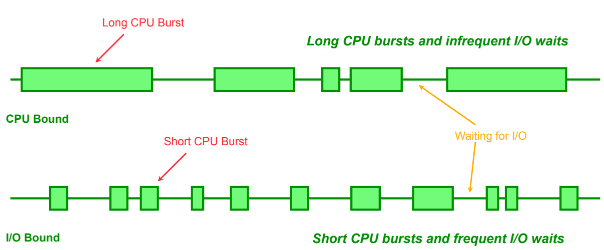
Review : The CPU *Workload* Model & Considerations

- **Workload contains collection of jobs (processes)**
- **Job model**
  - » **Job alternates between CPU usage and waiting for I/O**
  - » **CPU-bound job:**
    - **Spends most of its time computing**
    - **Characteristics: Long CPU bursts and infrequent I/O waits**
  - » **I/O-bound job (UNIX typically favor these processes)**
    - **Spends most of its time waiting for I/O**
    - **Characteristics: Short CPU bursts and frequent I/O waits**
  - » **Trend: as CPUs get faster processes tend to get more I/O bound? (Why?)**

CPUs improve at a faster rate than disks

- **Do not know type of job *before* it executes**
  - » **Do not know duration of CPU or I/O burst**
- **Need job scheduling for each ready job**
  - » **Schedule each CPU burst**

I/O and CPU Bound Processes



- **Key factor is the *length* of the CPU bursts not the *length* of the I/O bursts**
  - » **I/O 'boundiness' determine if they don't compute much between I/O requests not because they have long I/O requests.**

Dispatch Mechanism (Review)

Dispatcher is the module that gives control of the CPU to the process selected by the scheduler.

- **OS runs dispatch loop:**

```
while( forever )
{
   run process A for some time slice
   stop process A and save its context
   load context of another process B
   jump to proper location and restart program
}
```

- **How does the dispatcher gain control?**

Entering System Mode (Review)

Same as - How does OS get control?

- **Synchronous interrupts, or traps**
  - » **Event internal to a process that gives control to OS**
  - » **Examples: System calls, page faults (access page not in main memory), or errors (illegal instruction or divide by zero)**
- **Asynchronous interrupts**
  - » **Events external to a process, generated by hardware**
  - » **Examples: Characters typed, or completion of a disk transfer**

How are interrupts handled?

- **Each type of interrupt has corresponding routine (handler or interrupt service routine (ISR)**
- **Hardware saves current process and passes control to ISR**

How does the dispatcher run? (Review)

Option 1: Cooperative Multi-tasking

- **(internal events) Trust process to relinquish CPU through traps**
  - » **Trap: Event internal to process that gives control to OS**
  - » **Examples: System call, an explicit yield, page fault (access page not in main memory), or error (illegal instruction or divide by zero)**
- **Disadvantages: Processes can misbehave**
  - » **By avoiding all traps and performing no I/O, can take over entire machine**
  - » **Only solution: Reboot!**
- **Not performed in modern operating systems**

How does dispatcher run? (Review)

Option 2: (external stimulus) True Multi-tasking

- **Guarantee OS can obtain control periodically**
- **Enter OS by enabling periodic alarm clock**
  - » **Hardware generates timer interrupt (CPU or separate chip)**
  - » **Example: Every 10 ms**
- **User must not be able to mask timer interrupt**
- **Dispatcher counts interrupts between context switches**
  - » **Example: Waiting 20 timer ticks gives the process 200 ms time slice**
  - » **Common time slices range from 10 ms to 200 ms (Linux 2.6)**

Scheduler Types

- **Non-preemptive scheduler (cooperative multi-tasking)**
  - » **Process remains scheduled until voluntarily relinquishes CPU (yields) – Mac OS 9.**
  - » **Scheduler may switch in two cases:**
    - – **When process exits**
    - – **When process blocks (e.g. on I/O)**
- **Preemptive scheduler (Most modern OS, including most UNIX variants)**
  - » **Process may be 'de-scheduled' at any time**
  - » **Additional cases:**
    - – **Process creation (another process with higher process enters system)**
    - – **When an I/O interrupt occurs**
    - – **When a clock interrupt occurs**

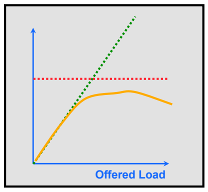
Scheduling Performance Metrics

- **There is a tension between maximizing:**
  - » **System's point of view: Overall efficiency (favoring the whole, the forest, the whole system).**
  - » **User's point of view: Giving good service to individual processes (favoring the 'individuals', the trees).**

```
Satisfy both : fast process response time
(low latency) and high process throughput.
```

System View: Threshold - Overall Efficiency

- System Load (`uptime`):
  - » The amount of work the system is doing
- Throughput:
  - » Want many jobs to complete per unit time
- System Utilization:
  - » Keep expensive devices busy
  - » Jobs arrive infrequently and both throughput and system utilization is low
- Example: Lightly loaded system - jobs arrive infrequently - both throughput and system utilization is low.
- Scheduling Goal: Ensure that throughput increase linearly with load



Utilization / Throughput

- Problem type:
  - » 3 jobs: 1st job enters at 0, 2nd at 4 and third at 8 second
  - » Each job takes 2 seconds to process.
  - » Each job is processed immediately – unless a job is on the CPU, then it waits
- Questions:
  - » (1) What is the CPU utilization at time t = 12?
    - – CPU utilization from t =0 to t=12.
    - – Percentage used over a time period.
  - » (2) What is the I/O device utilization at time t = 12?
  - » (3) What is the throughput (jobs/sec)

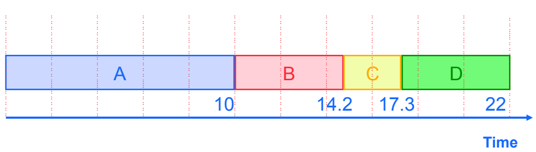
User View: Good Service (often measured as an average)

- Ensure that processes quickly start, run and completes.
- (average) Turnaround time: The time between job arrival and job completion.
- (average) Response time: The length of time when the job arrive and when if first start to produce output
  - » e.g. interactive jobs, virtual reality (VR) games, click on mouse see VR change
- Waiting time: Time in ready queue - do not want to spend a lot of time in the ready queue
  - » Better 'scheduling' quality metric than turn-around time since scheduler does not have control over blocking time or time a process does actual computing.
- Fairness: all jobs get the same amount of CPU over time
- Overhead: reduce number of context switches
- Penalty Ratio: Elapsed time / Required Service time (normalizes according to the 'ideal' service time) - next week

Which Criteria is Appropriate? Depends on *Expectation* of the System

- All Systems:
  - » Fairness (give processes a fair shot to get the CPU).
  - » Overall system utilization
  - » Policy enforcement (priorities)
- Batch Systems (not interactive)
  - » Throughput
  - » Turn-around time
  - » CPU utilization
- Real-time system (real time constraints)
  - » Meeting deadlines (avoid losing data)
  - » Predictability - avoid quality degradation in multimedia systems.

Gantt Chart (it has a name)!



- Shows how jobs are scheduled over time on the CPU.

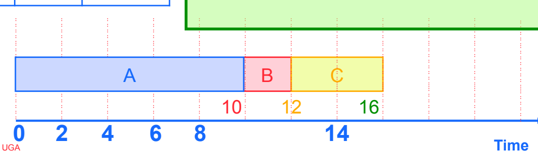
First-Come-First-Served (FCFS)

- Idea: Maintain FIFO list of jobs as they arrive
  - » Non-preemptive policy
  - » Allocate CPU to job at head of list (oldest job).

Job	Arrival	CPU burst
A	0	10
B	1	2
C	2	4

Average wait time:

Average turnaround time (enter/exit system):



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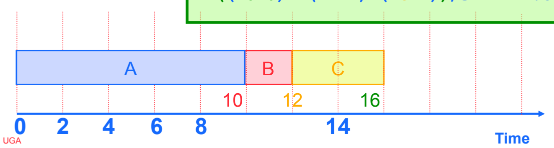
Job	Arrival	CPU burst
A	0	10
B	1	2
C	2	4

Average wait time:

(0 +(10-1)+(12-2))/3 = 6.33

Average turnaround time (enter/exit system):

((10-0) +(12-1)+(16-2))/3 = 11.67



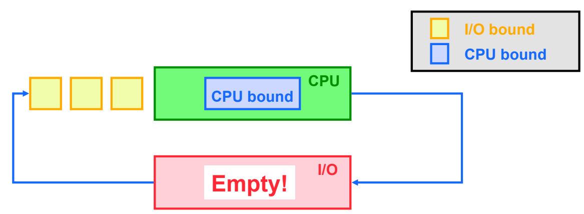
FCFS Discussion

- Advantage:
  - » Simple implementation (less error prone)
  - » Intuitive
- Disadvantages:
  - » Waiting time depends on arrival order
  - » Tend to favor long bursts (CPU bound processes)
    - – But : better to favor short bursts since they will finish quickly and not crowd the ready list.
  - » Convoy effect: Short jobs stuck waiting for long jobs (later)
    - – Hurt waiting time for short jobs
    - – Reduces utilization of I/O devices
  - » Does not work on time-sharing systems (kind of).

FCFS Problem

- Convoy effect -- an imbalance between I/O bound jobs and CPU bound jobs
  - » Recall I/O Jobs have short CPU bursts and spends most of its time waiting on I/O.
  - » CPU bursts are computationally intensive.
- Example:
  - » 1 CPU bound job (jobs with multiple long bursts) and
  - » 3 I/O bound jobs (jobs with short bursts)

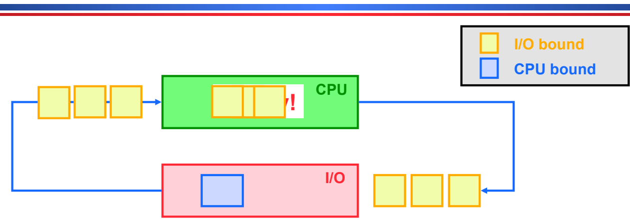
Convoy Effect…



- CPU bound job(s) get CPU and holds it
- I/O bound jobs move onto ready queue and waits
- Observation: all I/O devices idle even when the system contains lots of I/O jobs (can we do better?)

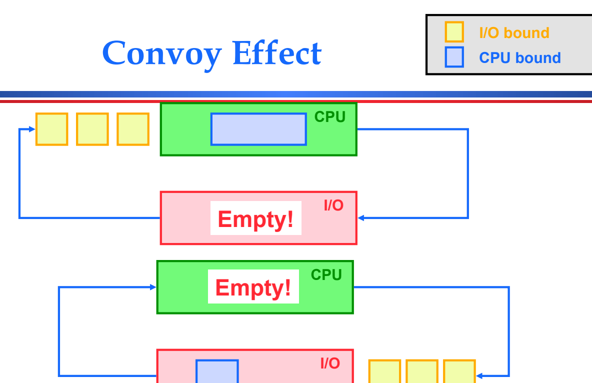
…

Convoy Effect



- I/O jobs get CPU and finish quickly and goes back to I/O
- Now the CPU may be idle!
- Later… I/O bound jobs again wait for CPU
- CPU idle when even if system contains CPU bound jobs

Convoy Effect



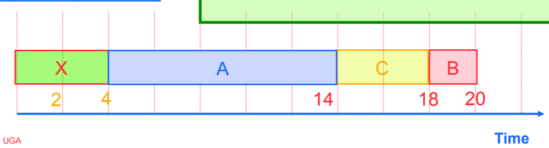
- All I/O devices idle even when the system contains lots of I/O jobs
- CPU may be idle even if the system contains CPU bound jobs

Another Example FIFO

Job	Arrival	CPU burst
X	0	4
A	1	10
B	3	2
C	2	4

Average wait time:

Average turnaround time:



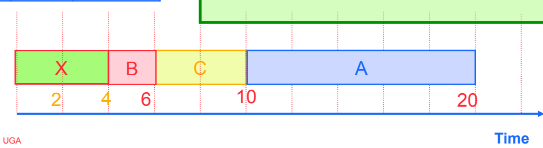
Shortest-Job-First (SJF)

- Idea: Minimize average wait time by running shortest CPU-burst next
  - » Non-preemptive policy
  - » Use FCFS if jobs are of same length

Job	Arrival	CPU burst
X	0	4
A	1	10
B	3	2
C	2	4

Average wait time:

Average turnaround time:



Optimality (Book)

- Proof Outline: (by contraction) SJF is not optimal
  - » Suppose we have a set of bursts ready to run and we run them in some order OTHER than SJF.
    - – OTHER is the one that is Optimal
  - » Then there must be some burst b_1 that is run before the shortest burst b_2 (otherwise OTHER is SJF).
    - – $b_1 > b_2$
    - – If we reversed the order we would:
      - increase the waiting time of b_1 by b_2 and (+b2)
      - decrease the waiting time of b_2 by b_1 (-b1)
  - » Net decrease in the total (waiting time)!!!!!
- Continuing in this manner to move shorter bursts ahead of longer ones, we eventually end up with the bursts sorted in increasing order of size (bubble sort). And now we are left with SJF.

Optimality!!!

- SJF only optimal when all jobs are available simultaneously.
- See book for example why this is true.

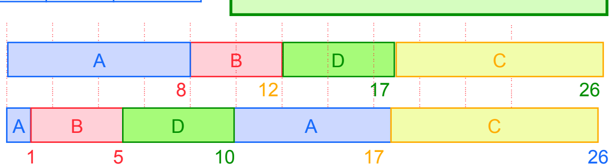
Shortest-Time-to-Completion-First (STCF/SCTF)

- Idea: Add *preemption* to SJF
  - » Schedule newly ready job if it has shorter than remaining burst for running job

Job	Arrival	CPU burst
A	0	8
B	1	4
C	2	9
D	3	5

SJF Average wait:

STCF Average wait:



SJF Discussion

- Advantages
  - » Provably optimal for minimizing average wait time (with no preemption)
    - – Moving shorter job before longer job improves waiting time of short job more than it harms waiting time of long job
  - » Helps keep I/O devices busy
- Disadvantages
  - » Problem: Cannot predict future CPU burst time
  - » Approach: Make a good guess - Use past behavior to predict future behavior
- Starvation: Long jobs may *never* be scheduled

Predicting Bursts in SJF

- **Key Idea**: The past is a good predictor of the future (an optimistic idea) – 'habits'
  - » Weighted averages of the most recent burst and the previous guesses (recursive)
  - » Approximate next CPU-burst duration from the durations of the previous burst and the previous guess). Average them.

$$guess = \frac{previous\ burst}{2} + \frac{previous\ guess}{2}$$

  - » Where we are going:
    - – A recursive formula: accounts for entire past history, previous burst always important – previous guesses and their importance drops of 'exponentially' with the time of their burst.

$$G(n+1) = w * A(n) + (1-w)G(n)$$

Example

- Suppose process p is given default expected burst length of 5 time units when it is initially run.
- **Assume**: The ACTUAL bursts length are:
  - » 10, 10, 10, 1, 1,1
  - » Note that these are of-course these are not known in advance.
- The predicted burst times for this process works as follows:
  - » Let G(1) = 5 as default value
  - » When process p runs, its first burst actually runs 10 time units (see above)
- so A(1) = 10.

- We could weigh the importance of the past with the most recent burst differently (but they need to add up to 1).

$$G(n+1) = w * A(n) + (1-w)G(n)$$

- w = 1 (past doesn't matter).
- How do we get started – no bursts before we start so what is the 'previous' burst G(1).
  - » G(1) is a default burst size (e.g., 5).

$$guess = \frac{previous\ burst}{2} + \frac{previous\ guess}{2}$$

- Let b_1 be the most recent burst, b_2 the burst before that b_3 the burst before that b_4

$$guess = \frac{b_1}{2} + \frac{\frac{b_2}{2} + \frac{b_3 + \frac{b_4}{2}}{2}}{2}$$

$$guess = \frac{b_1}{2} + \frac{b_2}{4} + \frac{b_3}{8} + \frac{b_4}{16}$$

$$G(n+1) = w * A(n) + (1-w)G(n)$$

Example

- G(1) = 5 as default value
- A(1) = 10.

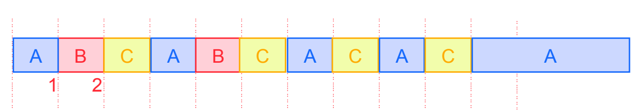
```
G(2) = 1/2 * G(1) + 1/2 A(1) = 1/2 * 5.00 + 1/2 * 10 = 7.5
G(3) = 1/2 * G(2) + 1/2 A(2) = 1/2 * 7.50 + 1/2 * 10 = 8.75
G(4) = 1/2 * G(3) + 1/2 A(3) = 1/2 * 8.75 + 1/2 * 10 = 9.38
```


Round-Robin (RR)

- **Idea**: Run each job/burst for a time-slice (e.g., q=1) and then move to back of FIFO queue
  - » Preempt job if still running at end of time-slice

Job	Arrival	CPU burst
A	0	10
B	1	2
C	1	4

Average wait:

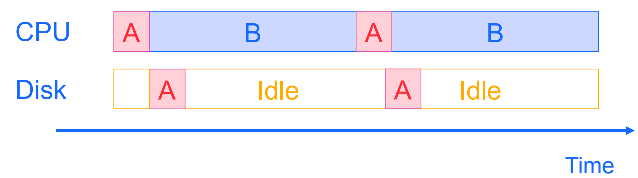


RR Discussion

- Advantages
  - » Jobs get fair share of CPU
  - » Shortest jobs finish relatively quickly
- Disadvantages
  - » Poor average waiting time with similar job lengths
    - – Example: 3 jobs that each requires 3 time slices
    - – RR: All complete after about 9 time slices
    - – FCFS performs better!
      - ABCABCABC = 2+5+6=13/3
      - AAABBBCCC = 0+3+6=9/3
  - » Performance depends on length of time-slice
    - – If time-slice too short, pay overhead of context switch
    - – If time-slice too long, degenerate to FCFS (see next slide)

RR Time-Slice Consideratoins

- IF time-*slice too long*, degenerate to problem of FCFS (short jobs wait behind long jobs).
  - » Example:
    - – Job A w/ 1 ms compute and 10 ms I/O
    - – Job B always computes
    - – Time-slice is 50 ms



- What about a really short time slices?

Goal: Adjust length of time-slice to match CPU burst

Priority Based (typical in modern OSs)

- Idea: Each job is assigned a priority
  - » Schedule highest priority ready job
  - » May be preemptive or non-preemptive
  - » Priority may be static or dynamic
- Advantages
  - » Static priorities work well for real time systems
  - » Dynamic priorities work well for general workloads
- Disadvantages
  - » Low priority jobs can starve
  - » How to choose priority of each job?
- Goal: Adjust priority of job to match CPU burst
  - » Approximate SCTF by giving short jobs high priority

How Well do the Algorithms Stack UP

- Utilization
- Throughput
- Turnaround time: The time between job arrival and job completion.
- Response time: The length of time when the job arrive and when if first start to produce output
  - » e.g. interactive jobs, virtual reality (VR) games, click on mouse see VR change
- Meeting Deadlines (not mentioned)
- Starvation

How to the Algorithms Stack Up?

	CPU Utilization	Through put	Turn Around Time	Response Time	Deadline Handling	Starvation Free
FIFO	Low	Low	High	High	No	Yes
Shortest Remaining Time	Medium	High	Medium	Medium	No	No
Fixed Priority Preemptive	Medium	Low	High	High	Yes	No
Round Robin	High	Medium	Medium	Low	No	Yes

Penalty Ratio (normalized to an ideal system)

$$\text{Penalty ratio} = \frac{\text{Total elapsed time (actual)}}{\text{Service time: doing actual work (on CPU + doing I/O)}}$$

- Comparison to an ideal system: How much time worse is the turn-around time compared to an ideal system that would only consist of 'service time' (includes waiting)
  - » Note this really measure of how well the scheduler is doing.
- Lower penalty ratio is better (actual elapsed time takes the same time as an idea system).
- Examples:
  - » Value of "1" indicates 'no' penalty (the job never waits)
  - » 2 indicates it takes twice as long than an ideal system.

Example using

Job	Arrival	CPU burst
A	0	3
B	1	5
C	3	2
D	9	5
E	12	5

- First Come First Serve

- Penalty Ratio – turn-around time (over ideal)

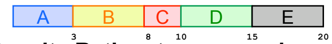
Job	Start Time	Finish Time	Waiting Time	Penalty Ratio
A				
B				
C				
D				
E				
avg				

Example using (CPU Only)

Job	Arrival	CPU burst
A	0	3
B	1	5
C	3	2
D	9	5
E	12	5

- Shortest Burst worst PR.
- Even worse:
  - long burst at 0, takes 100 units
  - short burst at 1
    - Wait 99.
    - (101-1)/1 = 100

- First Come First Serve



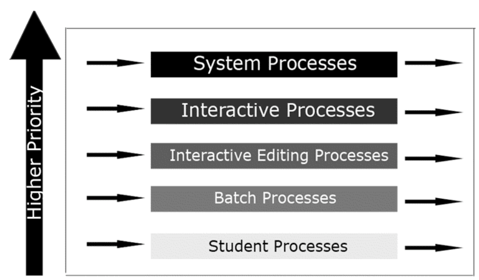
- Penalty Ratio – turn-around time (over ideal – the burst itself)

Job	Start Time	Finish Time	Waiting Time	Penalty Ratio	
A	0	3	0	1.0	3/3
B	1	5	2	1.4	7/5
C	3	2	5	3.5	
D	9	5	1	1.2	
E	12	5	3	1.6	
avg			2.2	1.74	

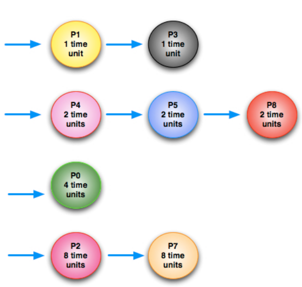
Multilevel Queue Scheduling

- Classify processes and put them in different scheduling queues
  - » Interactive, batch, etc.
- Different scheduling priorities depending on process group priority
- Schedule processes with highest priority first, then lower priority processes.
- Other possibility : Time slice CPU time between the queues (higher priority queue gets more CPU time).

Multilevel Queue Scheduling



Multilevel *Feedback* Queue



- Give new processes high priority and small time slice (preference to smaller jobs)
- If process doesn't finish job bump it to the next lower level priority queue (with a larger time-slice).
- Common in interactive system

Case Studies: Early Scheduling Implementations

- Windows and Early MS-DOS
  - » Non-Multitasking (so no scheduler needed)
- Mac OS 9
  - » Kernel schedule processes:
    - – A Round Robin Preemptive (fair, each process gets a fair share of CPU
  - » Processes
    - – schedules multiple (MACH) threads that use a cooperative thread schedule manager
      - each process has its own copy of the scheduler.

Case Studies: Modern Scheduling Implementations

- **Multilevel Feedback Queue w/ Preemption:**
  - » **FreeBSD, NetBSD Solaris, Linux pre 2.5**
  - » **Example Linux: 0-99 real time tasks (200ms quanta), 100-140 nice tasks (10 ms quanta -> expired queue)**
- **Cooperative Scheduling (no preemption)**
  - » **Windows 3.1x, Mac OS pre3 (thread level)**
- **O(1) Scheduling**
  - » **time to schedule independent of number of tasks in system**
  - » **Linux 2.5-2.6.24 ((v2.6.0 first version ~2003/2004)**
- **Completely Fair Scheduler**
  - » **Maximizes CPU utilization while maximizing interactive performance / Red/Black Tree instead of Queue**
  - » **Linux 2.6.23+**