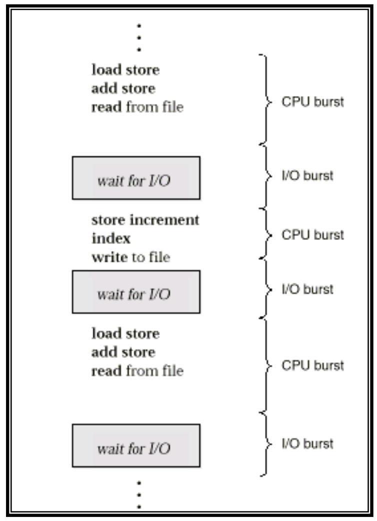
Announcements

- Project #2
  - Is due at 6:00 PM on Friday
- Program #3
  - Posted tomorrow (implements scheduler)
- Reading
  - Chapter 6

Basic Concepts

- CPU–I/O burst cycle – Process execution consists of a *cycle* of CPU execution and I/O wait.
- CPU burst distribution
  - What are the typical burst sizes of a process's execution?

Burst Cycle



Histogram of Typical CPU-Burst Times

CPU Scheduler

- Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them.
- 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*.

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 – % time CPU is in use
- 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 (for interactive environment)

Optimization Criteria

- Max
  - CPU utilization
  - throughput
- Min
  - turnaround time
  - waiting time
  - response time

Optimization criteria non-performance related

- Predictability, e.g.,
  - job should run in about the same amount of time, regardless of total system load
  - response times should not vary
- Fairness
  - don't starve any processes
- Enforce priorities
  - favor higher priority processes
- Balance resources
  - keep all resources busy

Types of Scheduling

- At least 4 types:
  - long-term - add to pool of processes to be executed
  - medium-term - add to number of processes partially or fully in main memory
  - short-term - which available process will be executed by the processor
  - I/O - which process's pending I/O request will be handled by an available I/O device
- Scheduling changes the ***state*** of a process

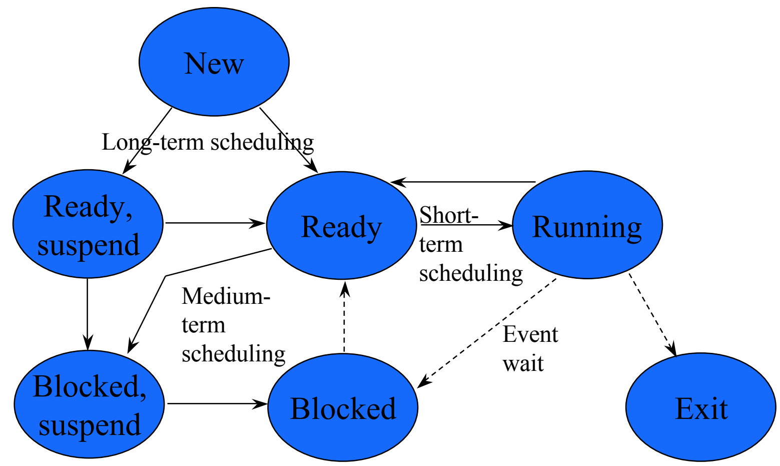
Medium vs. Short Term

- Medium-term scheduling
  - *Swaps* processes between main memory and disk
    - based on how many processes the OS wants available
    - must consider memory management if no virtual memory (VM), so look at memory requirements of swapped out processes
- Short-term scheduling (dispatcher)
  - Executes most frequently, to decide which process to execute next
  - Invoked whenever event occurs that interrupts current process or provides an opportunity to preempt current one in favor of another
  - Events: clock interrupt, I/O interrupt, OS call, signal

Long-term scheduling

- Determine which programs admitted to system for processing
- Once admitted, program becomes a process
  - Queued for short- or medium-term scheduler
- Scheduling batch jobs
  - Can system take a new process?
    - more processes implies less time for each existing one
    - add job(s) when a process terminates, or if percentage of processor idle time is greater than some threshold
  - Which job to schedule?
    - first-come, first-serve (FCFS), or to manage overall system performance (e.g. based on priority, expected execution time, I/O requirements, etc.)

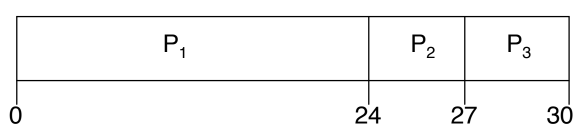
Process State Transitions



First-Come, First-Served (FCFS)

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:



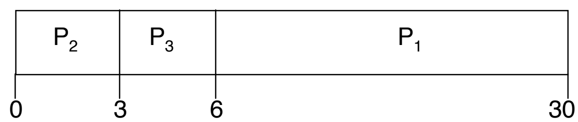
- Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
- Average waiting time: $(0 + 24 + 27)/3 = 17$

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.
- *Convoy effect* short process behind long process

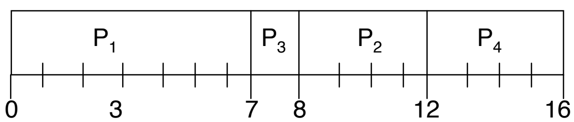
Shortest-Job-First (SJF)

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time.
- Two schemes:
  - nonpreemptive – process cannot be preempted until completes its CPU burst.
  - preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. Dubbed Shortest-Remaining-Time-First (SRTF). Should yield better turnaround times.
- SJF is optimal – gives minimum average waiting time for a given set of processes.

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)

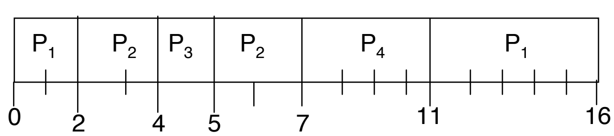


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Preemptive SJF (SRTF)

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

Length of Next CPU Burst

- Can only estimate the length.
- Can be done by using the length of previous CPU bursts, using exponential averaging.

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

t_n	actual length of n^{th} CPU burst
τ_{n+1}	predicted value of $n+1^{st}$ CPU burst
α	history parameter $0 <= \alpha <= 1$

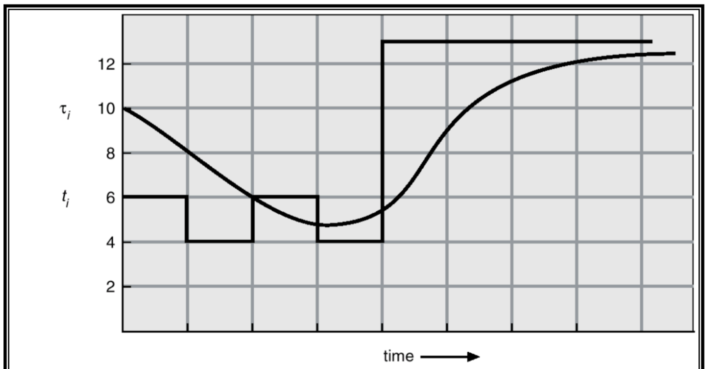
Exponential Averaging

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

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

- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor.

Predicting the Next CPU Burst Length ($\alpha = {}^1/_2$, $\tau_0 = 10$)



CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Round Robin (RR)

- Each process gets a small unit of CPU time (time quantum).
  - Once this time elapses, the process is preempted and placed on the back of the ready queue.
- If there are *n* processes in the ready queue and the time quantum is *q*, then no process waits more than *(n-1)q* time units.

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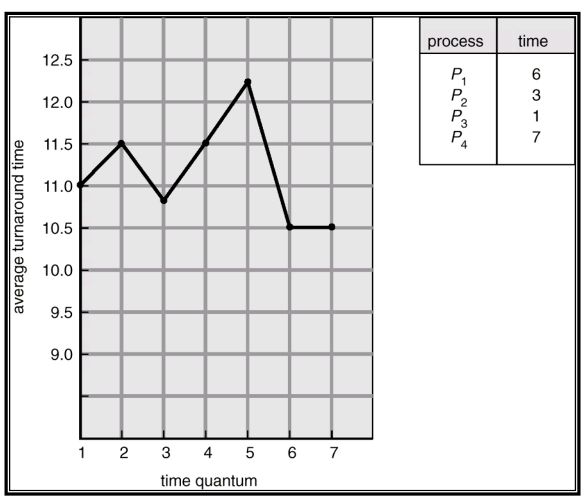
Choosing the Quantum

- How to choose *q*?
  - Very large: degenerates to FCFS
  - Very small: dispatch time dominates
  - Guideline: for better turnaround time, quantum should be slightly greater than time of "typical job" CPU burst.

Turnaround Time Varies With The Time Quantum



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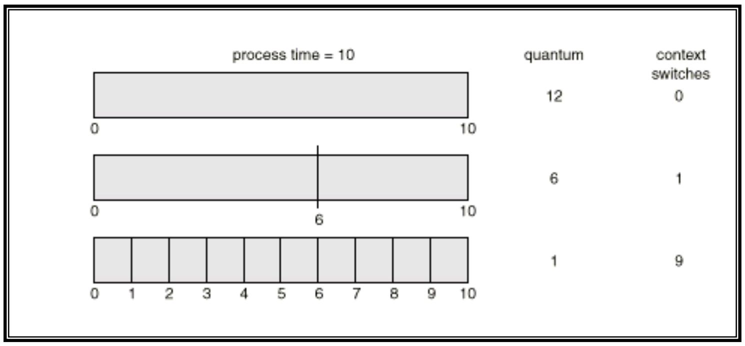
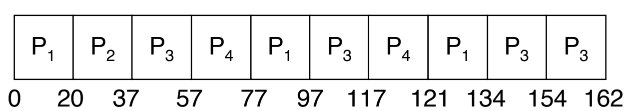
Time Quantum and Context Switch Time



Example RR with q = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

- The Gantt chart is:



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

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Priority Scheduling

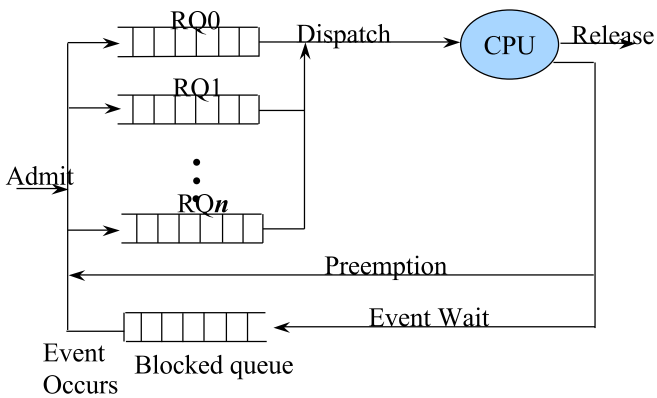
- A priority number (integer) is associated with each process
- OS schedules the process with the highest priority (smallest integer ≡ highest priority).
- SJF is a priority scheduling where priority is the predicted next CPU burst time.
  - Problem ≡ Starvation – low priority processes may never execute.
  - Solution ≡ Aging – as time progresses increase the priority of the process.

Multilevel Priority Queue

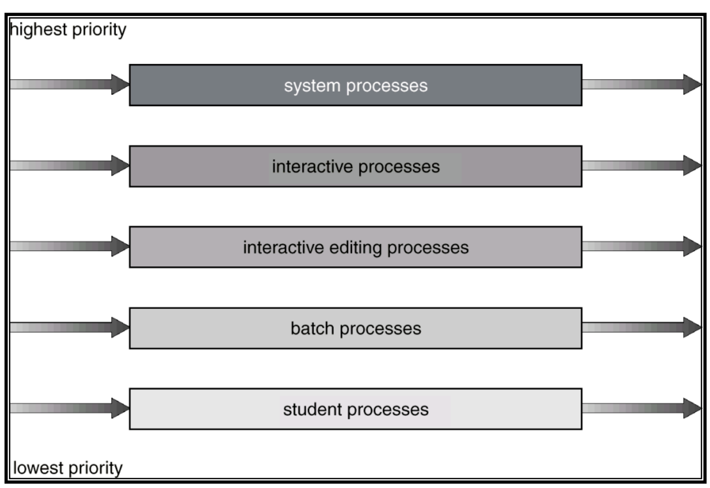
- Ready queue is divided into *n* queues, each with its own scheduling algorithm, e.g.
  - foreground (interactive) - RR
  - background (batch) - FCFS
- Scheduling done between the queues
  - Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation.
  - Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; e.g.,
    - 80% to foreground in RR
    - 20% to background in FCFS

Multilevel Priority Scheduling

- Many ready queues, ordered by priority



Example



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Multilevel Scheduling Design

PROBLEM: turnaround time for longer processes

- Want to avoid undue increase or starvation when new short jobs regularly enter system

- Solution 1: vary preemption times according to queue
  - processes in lower priority queues have longer time slices
- Solution 2: promote a process to higher priority queue
  - after it spends a certain amount of time waiting for service in its current queue, it moves up
- Solution 3: allocate fixed share of CPU time to jobs
  - if a process doesn't use its share, give it to other processes
  - variation on this idea: lottery scheduling
    - assign a process "tickets" (# of tickets is share)
    - pick random number and run the process with the winning ticket.

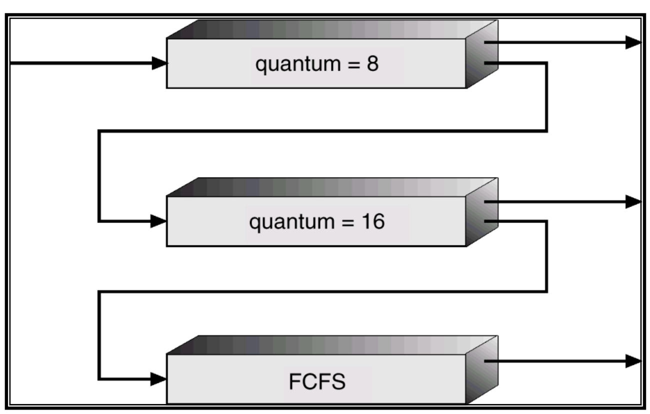
Multilevel Feedback Queue

- A process can move between the various queues, implementing *aging*.
- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method to determine when to upgrade a process
  - method to determine when to demote a process
  - method to determine which queue a process will enter when that process needs service

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 RR. 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 does not complete, it is preempted and moved to queue Q_2.

Multilevel Feedback Queues



Multi-Processor Scheduling

- Multiple processes need to be scheduled together
  - Called gang-scheduling
  - Allowing communicating processes to interact w/o/ waiting
- Try to schedule processes back to same processor
  - Called affinity scheduling
    - Maintain a small ready queue per processor
    - Go to global queue if nothing local is ready

Algorithm Evaluation

- Deterministic modeling – takes a particular predetermined workload and defines the performance of each algorithm for that workload.
- Queueing models
- Simulation
- Implementation

UNIX System V

- Multilevel feedback, with
  - RR within each priority queue
  - 10ms preemption
  - priority based on process type and execution history, lower value is higher priority
- Priority recomputed once per second, and scheduler selects new process to run

UNIX System V

- Priority P(i) = Base + CPU(i-1)/2 + nice
  - P(i) is priority of process j at interval i
  - Base is base priority of process j
  - CPU(i) = U(i)/2 + CPU(i-1)/2
    - U(i) is CPU use of process j in interval i
    - exponentially weighted average CPU use of process j through interval i
  - nice is user-controllable adjustment factor
- Penalizes CPU-bound processes
  - Targets general-purpose time sharing (and interactive) environment

UNIX System V

- Base priority divides all processes into (non-overlapping) fixed bands of decreasing priority levels
  - swapper, block I/O device control, file manipulation, character I/O device control, user processes
- Bands optimize access to block devices (disk), allow OS to respond quickly to system calls

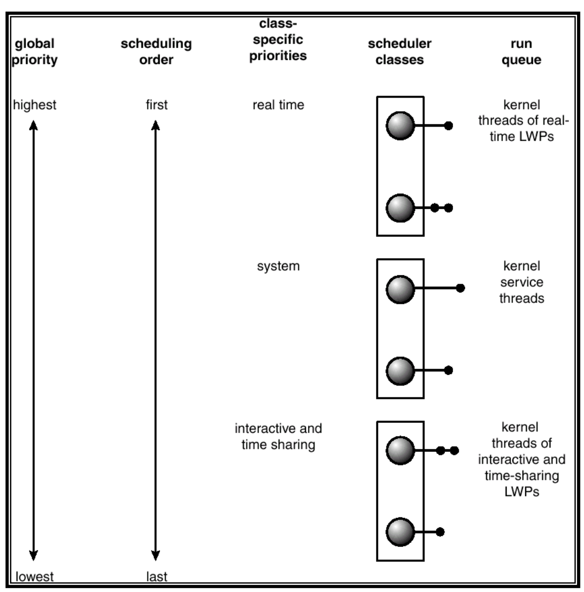
GeekOS (<= project 2)

- Uses priority-based, RR scheduling
  - Each kthread has a priority
    - Level 0 is the "idle" process which "runs" when there is no real work to be done
    - Level 1 is for normal user processes
    - Level 10 is the highest priority
  - Chooses highest-priority thread that is in the ready queue (**`s_runQueue`**).

GeekOS (Project 3)

- Multi-level feedback scheduling
  - Multiple queues, each denoting a higher priority scheduling class (still have priorities within each class)
- Queue placement policy:
  - Thread is demoted to next lower class if it consumes all its quantum.
  - Thread is promoted to the next higher class if it blocks.
  - Idle thread treated specially.

Solaris 2 Scheduling



Windows 2000 Priorities

	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

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