CS162
Operating Systems and Systems Programming
Lecture 10

Scheduling

February 22th, 2017
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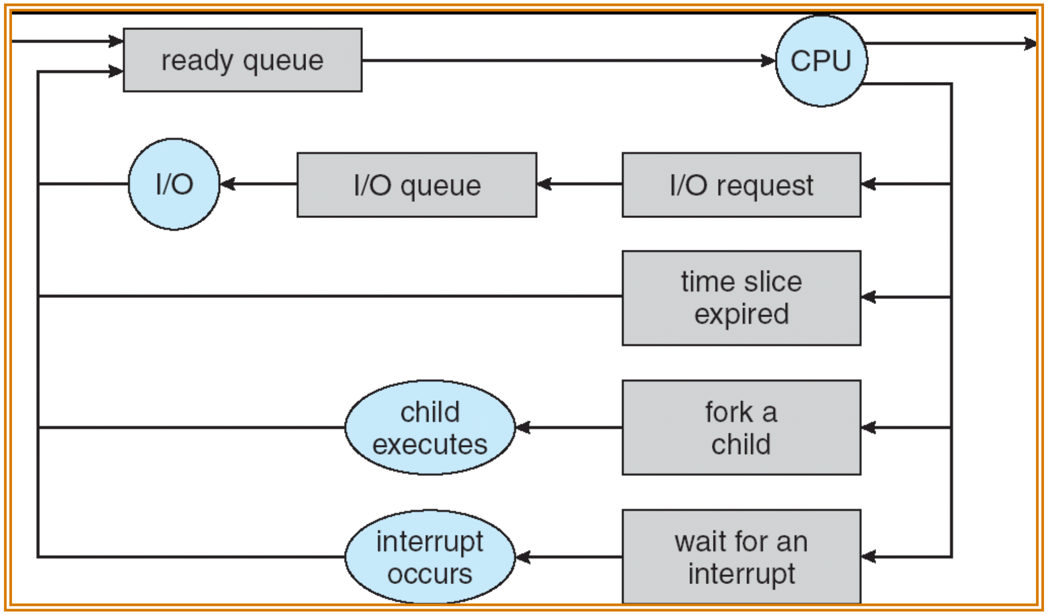
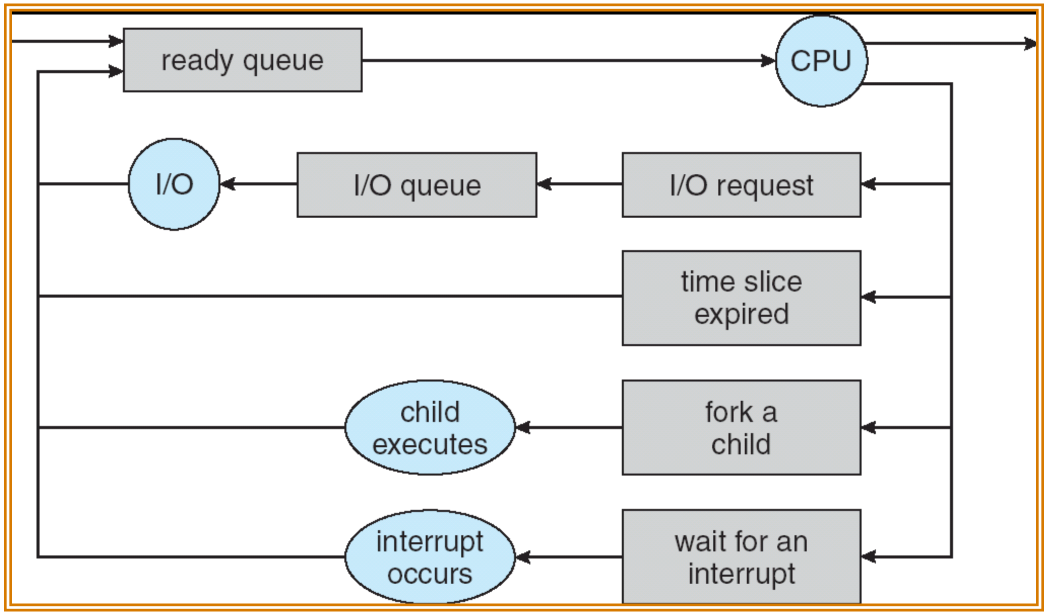
Recall: CPU Scheduling



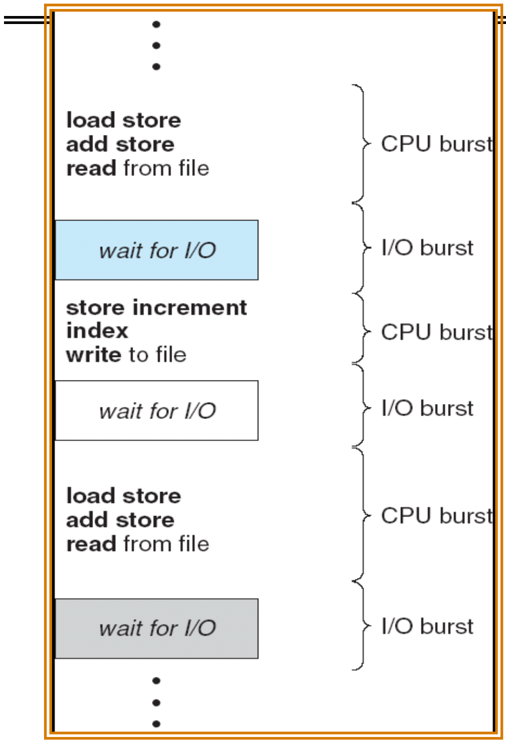
- Earlier, we talked about the life-cycle of a thread
  - Active threads work their way from Ready queue to Running to various waiting queues.

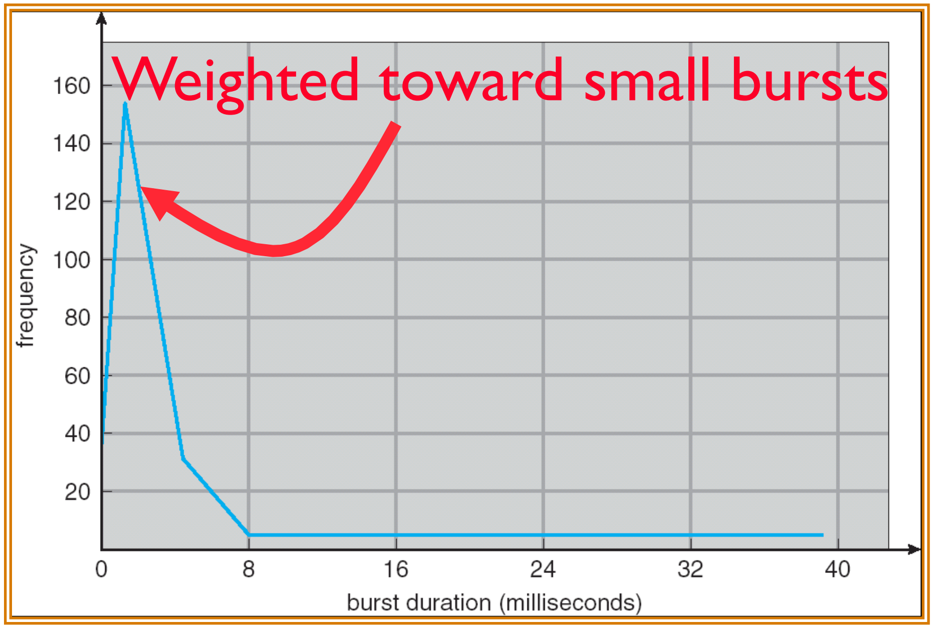
Recall: CPU Scheduling (Cont.)



- Question: How does OS decide which thread to dequeue?
  - Obvious queue to worry about is ready queue
  - Others can be scheduled as well, however
- Scheduling: deciding which threads are given access to resources from moment to moment

Assumption – CPU Bursts





- Execution model: programs alternate between bursts of CPU and I/O
  - Program typically uses the CPU for some period of time, then does I/O, then uses CPU again
  - Each scheduling decision is about which job to give to the CPU for use by its next CPU burst
  - With timeslicing, thread may be forced to give up CPU before finishing current CPU burst

Scheduling Assumptions

- CPU scheduling big area of research in early 70's
- Many implicit assumptions for CPU scheduling:
  - One program per user
  - One thread per program
  - Programs are independent

Scheduling Assumptions (Cont.)

- Clearly, unrealistic but they simplify the problem
  - For instance: is "fair" about fairness among users or programs?
    - » If I run one compilation job and you run five, you get five times as much CPU on many operating systems
- The high-level goal: Dole out CPU time to optimize some desired parameters of system

Scheduling Policy Goals/Criteria

- Minimize Response Time
  - Minimize elapsed time to do an operation (or job)
  - Response time is what the user sees:
    - » Time to echo a keystroke in editor
    - » Time to compile a program
    - » Real-time tasks: Must meet deadlines imposed by World

Scheduling Policy Goals/Criteria (Cont.)

- Maximize Throughput
  - Maximize operations (or jobs) per second
  - Throughput related to response time, but not identical:
    - » Minimizing response time will lead to more context switching than if you only maximized throughput
  - Two parts to maximizing throughput
    - » Minimize overhead (for example, context-switching)
    - » Efficient use of resources (CPU, disk, memory, etc)

Scheduling Policy Goals/Criteria (Cont.)

- Fairness
  - Share CPU among users in some equitable way
  - Fairness is not minimizing average response time:
    - Better *average* response time by making system *less* fair

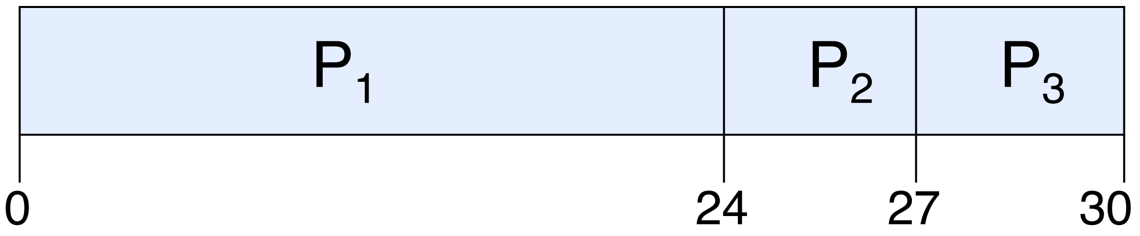
First-Come, First-Served (FCFS) Scheduling

- First-Come, First-Served (FCFS)
  - Also "First In, First Out" (FIFO) or "Run until done"
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks

- Example:

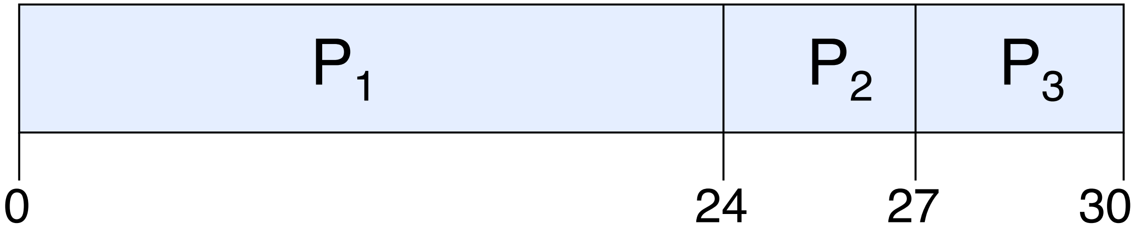
Process	Burst Time
P_1	24
P_2	3
P_3	3

  - Suppose processes arrive in the order: P_1 , P_2 , P_3
    The Gantt Chart for the schedule is:



FCFS Scheduling (Cont.)

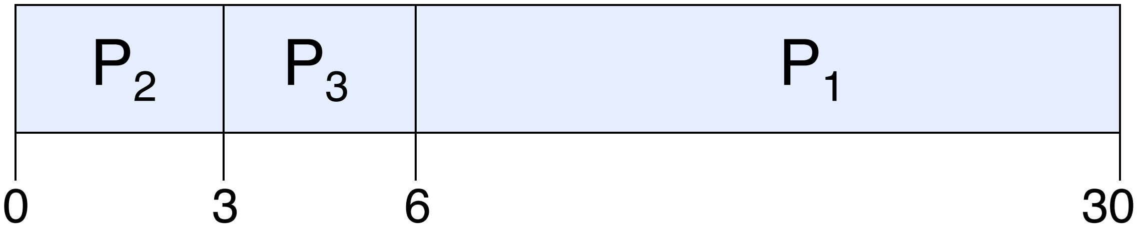
- Example continued:



  - Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
  - Average waiting time: $(0 + 24 + 27)/3 = 17$
  - Average Completion time: $(24 + 27 + 30)/3 = 27$
- *Convoy effect:* short process behind long process

FCFS Scheduling (Cont.)

- Example continued:
  - Suppose that processes arrive in order: P_2 , P_3 , P_1 Now, we have:



  - Waiting time for $P_1 = 6$; $P_2 = 0$, $P_3 = 3$
  - Average waiting time: $(6 + 0 + 3)/3 = 3$
  - Average Completion time: $(3 + 6 + 30)/3 = 13$
- In second case:
  - Average waiting time is much better (before it was 17)
  - Average completion time is better (before it was 27)
- FIFO Pros and Cons:
  - Simple (+)
  - Short jobs get stuck behind long ones (-)
    - » Safeway: Getting milk, always stuck behind cart full of small items

Round Robin (RR) Scheduling

- FCFS Scheme: Potentially bad for short jobs!
  - Depends on submit order
  - If you are first in line at supermarket with milk, you don't care who is behind you, on the other hand…
- Round Robin Scheme
  - Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds
  - After quantum expires, the process is preempted and added to the end of the ready queue.
  - n processes in ready queue and time quantum is $q \Rightarrow$
    - » Each process gets $1/n$ of the CPU time
    - » In chunks of at most q time units
    - » No process waits more than $(n-1)q$ time units

RR Scheduling (Cont.)

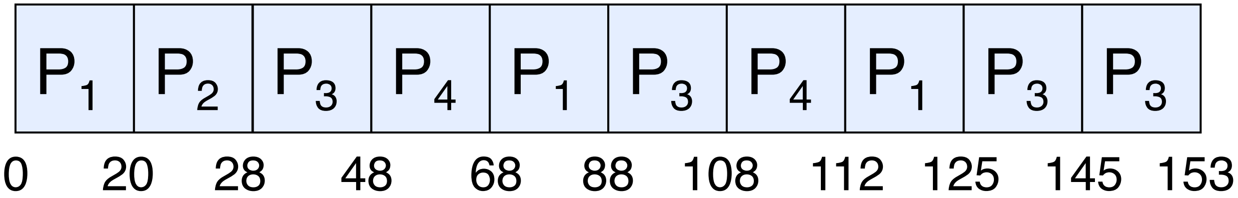
- Performance
  - q large ⇒ FCFS
  - q small ⇒ Interleaved (really small ⇒ hyperthreading?)
  - q must be large with respect to context switch, otherwise overhead is too high (all overhead)

Example of RR with Time Quantum = 20

- Example:

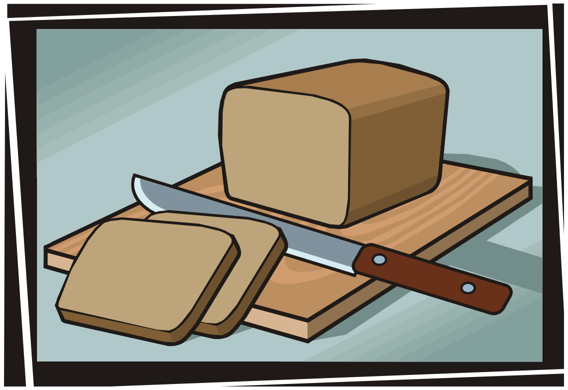
Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

  - The Gantt chart is:



  - Waiting time for $P_1=(68-20)+(112-88)=72$
    $P_2=(20-0)=20$
    $P_3=(28-0)+(88-48)+(125-108)=85$
    $P_4=(48-0)+(108-68)=88$
  - Average waiting time = (72+20+85+88)/4=66¼
  - Average completion time = (125+28+153+112)/4 = 104½
- Thus, Round-Robin Pros and Cons:
  - Better for short jobs, Fair (+)
  - Context-switching time adds up for long jobs (-)

Round-Robin Discussion



- How do you choose time slice?
  - What if too big?
    - » Response time suffers
  - What if infinite (∞)?
    - » Get back FIFO
  - What if time slice too small?
    - » Throughput suffers!
- Actual choices of timeslice:
  - Initially, UNIX timeslice one second:
    - » Worked ok when UNIX was used by one or two people.
    - » What if three compilations going on? 3 seconds to echo each keystroke!
  - Need to balance short-job performance and long-job throughput:
    - » Typical time slice today is between 10ms – 100ms
    - » Typical context-switching overhead is 0.1ms – 1ms
    - » Roughly 1% overhead due to context-switching

Comparisons between FCFS and Round Robin

- Assuming zero-cost context-switching time, is RR always better than FCFS?
- Simple example:

10 jobs, each take 100s of CPU time
RR scheduler quantum of 1s
All jobs start at the same time

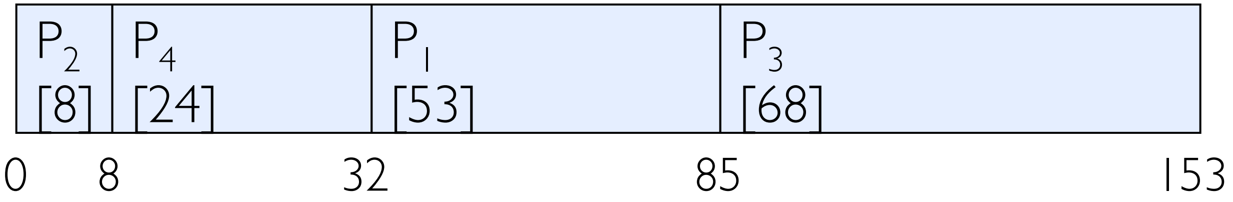
- Completion Times:

Job #	FIFO	RR
1	100	991
2	200	992
…	…	…
9	900	999
10	1000	1000

  – Both RR and FCFS finish at the same time
  – Average response time is much worse under RR!
    » Bad when all jobs same length
- Also: Cache state must be shared between all jobs with RR but can be devoted to each job with FIFO
  – Total time for RR longer even for zero-cost switch!

Earlier Example with Different Time Quantum

Best FCFS:

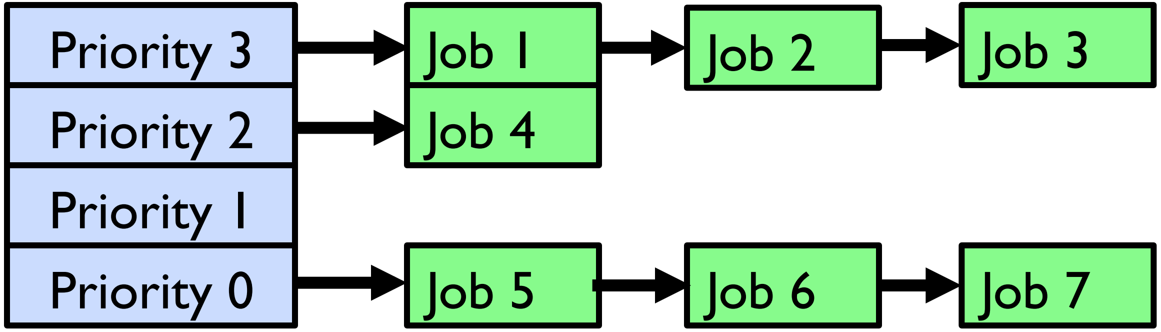


P_2 [8] | P_4 [24] | P_1 [53] | P_3 [68]

0 8 32 85 153

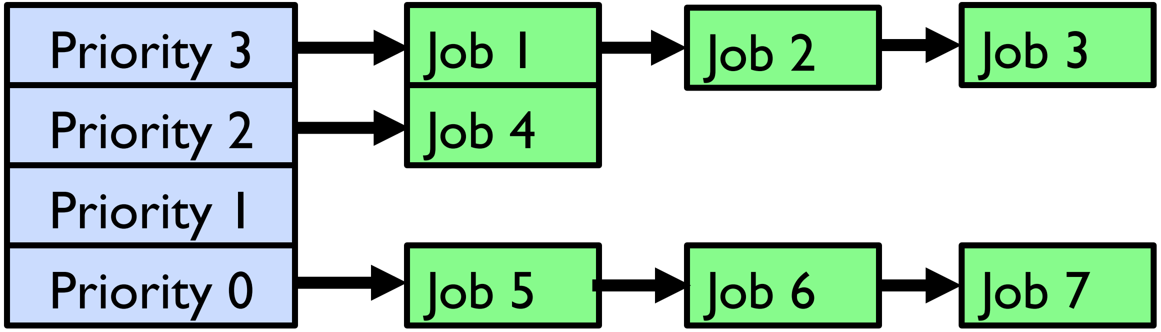
	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	61¼
	Q = 8	80	8	85	56	57¼
	Q = 10	82	10	85	68	61¼
	Q = 20	72	20	85	88	66¼
	Worst FCFS	68	145	0	121	83½
Completion Time	Best FCFS	85	8	153	32	69½
	Q = 1	137	30	153	81	100½
	Q = 5	135	28	153	82	99½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

Handling Differences in Importance: Strict Priority Scheduling



- Execution Plan
  - – Always execute highest-priority runable jobs to completion
  - – Each queue can be processed in RR with some time-quantum
- Problems:
  - – Starvation:
    - » Lower priority jobs don't get to run because higher priority jobs
  - – Deadlock: Priority Inversion
    - » Not strictly a problem with priority scheduling, but happens when low priority task has lock needed by high-priority task
    - » Usually involves third, intermediate priority task that keeps running even though high-priority task should be running

Handling Differences in Importance: Strict Priority Scheduling (Cont.)



- How to fix problems?
  - Dynamic priorities – adjust base-level priority up or down based on heuristics about interactivity, locking, burst behavior, etc…

Scheduling Fairness

- What about fairness?
  - – Strict fixed-priority scheduling between queues is unfair (run highest, then next, etc):
    - » long running jobs may never get CPU
    - » In Multics, shut down machine, found 10-year-old job
  - – Must give long-running jobs a fraction of the CPU even when there are shorter jobs to run
  - – Tradeoff: fairness gained by hurting avg response time!

Scheduling Fairness

- How to implement fairness?
  - Could give each queue some fraction of the CPU
    - » What if one long-running job and 100 short-running ones?
    - » Like express lanes in a supermarket—sometimes express lanes get so long, get better service by going into one of the other lines
  - Could increase priority of jobs that don't get service
    - » What is done in some variants of UNIX
    - » This is ad hoc—what rate should you increase priorities?
    - » And, as system gets overloaded, no job gets CPU time, so everyone increases in priority⇒Interactive jobs suffer

Administrivia

- Midterm on **Monday 2/27 6:30-8PM**
  - Last names A-K 1 LeConte
  - **Last names L-T** 245 Li Ka Shing
  - Last Names U-Z 3 Leconte
- **Includes today's lecture**
- Closed book, no calculators, **one double-side letter-sized page of handwritten notes**
- Review – Saturday, 2/25 3-6pm 145 Dwinelle

BREAK

Lottery Scheduling

- Yet another alternative: Lottery Scheduling
  - Give each job some number of lottery tickets
  - On each time slice, randomly pick a winning ticket
  - On average, CPU time is proportional to number of tickets given to each job
- How to assign tickets?
  - To approximate SRTF, short running jobs get more, long running jobs get fewer
  - To avoid starvation, every job gets at least one ticket (everyone makes progress)
- Advantage over strict priority scheduling: behaves gracefully as load changes
  - Adding or deleting a job affects all jobs proportionally, independent of how many tickets each job possesses

Lottery Scheduling Example (Cont.)

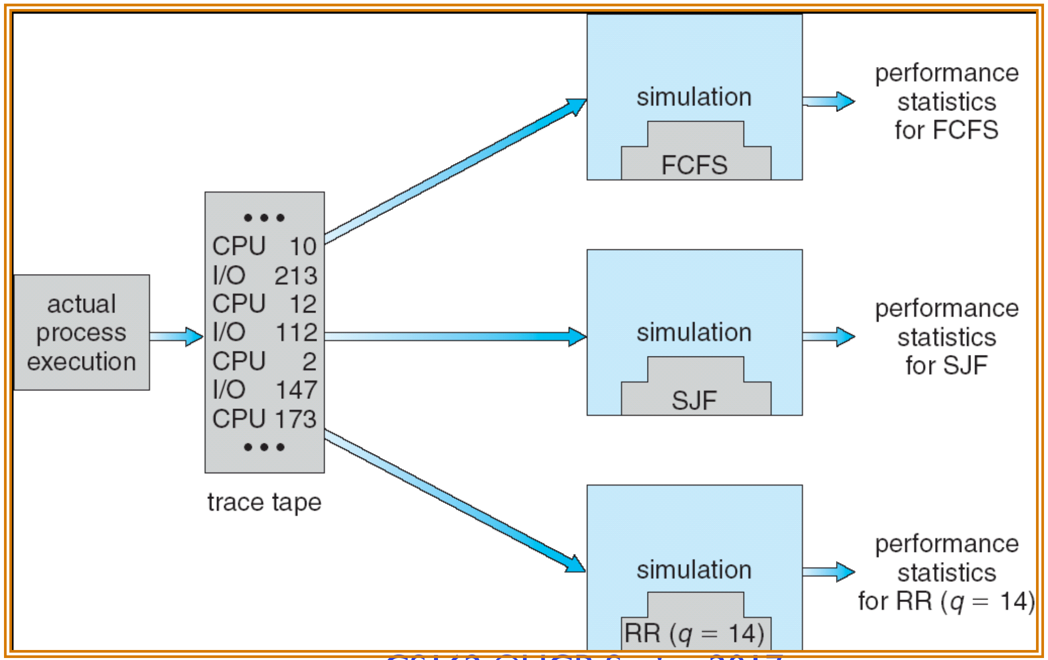
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# short jobs/ # long jobs	% of CPU each short jobs gets	% of CPU each long jobs gets
1/1	91%	9%
0/2	N/A	50%
2/0	50%	N/A
10/1	9.9%	0.99%
1/10	50%	5%

  - What if too many short jobs to give reasonable response time?
    - » If load average is 100, hard to make progress
    - » One approach: log some user out

How to Evaluate a Scheduling algorithm?

- Deterministic modeling
  - takes a predetermined workload and compute the performance of each algorithm for that workload
- Queueing models
  - Mathematical approach for handling stochastic workloads
- Implementation/Simulation:
  - Build system which allows actual algorithms to be run against actual data – most flexible/general



How to Handle Simultaneous Mix of Diff Types of Apps?

- Can we use Burst Time (observed) to decide which application gets CPU time?
- Consider mix of *interactive* and *high throughput* apps:
  - How to best schedule them?
  - How to recognize one from the other?
    - Do you trust app to say that it is "interactive"?
  - Should you schedule the set of apps identically on servers, workstations, pads, and cellphones?

How to Handle Simultaneous Mix of Diff Types of Apps?

- Assumptions encoded into many schedulers:
  - Apps that sleep a lot and have short bursts must be interactive apps – they should get high priority
  - Apps that compute a lot should get low(er?) priority, since they won't notice intermittent bursts from interactive apps
- Hard to characterize apps:
  - What about apps that sleep for a long time, but then compute for a long time?
  - Or, what about apps that must run under all circumstances (say periodically)

What if we Knew the Future?

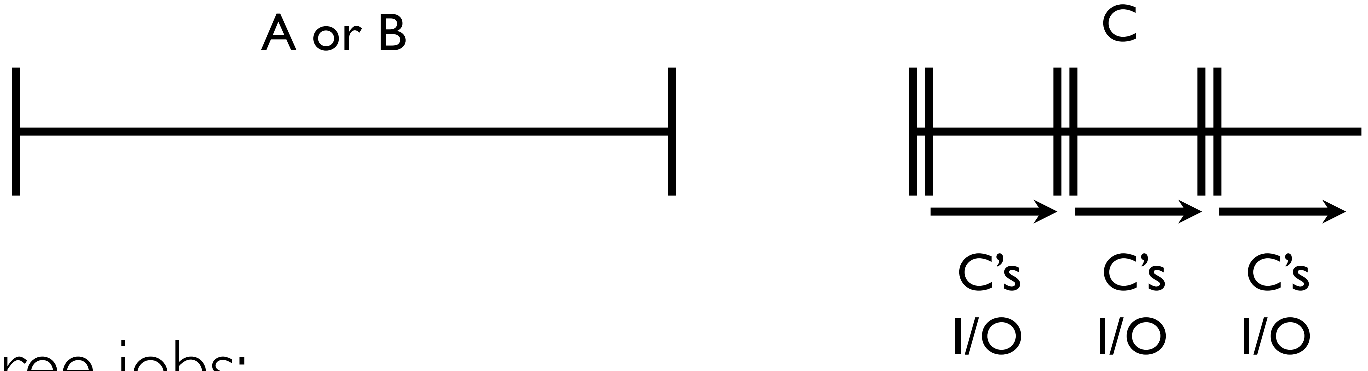
- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Run whatever job has least amount of computation to do
  - Sometimes called "Shortest Time to Completion First" (STCF)
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
  - Sometimes called "Shortest Remaining Time to Completion First" (SRTCF)
- These can be applied to whole program or current CPU burst
  - Idea is to get short jobs out of the system
  - Big effect on short jobs, only small effect on long ones
  - Result is better average response time

Discussion

- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF

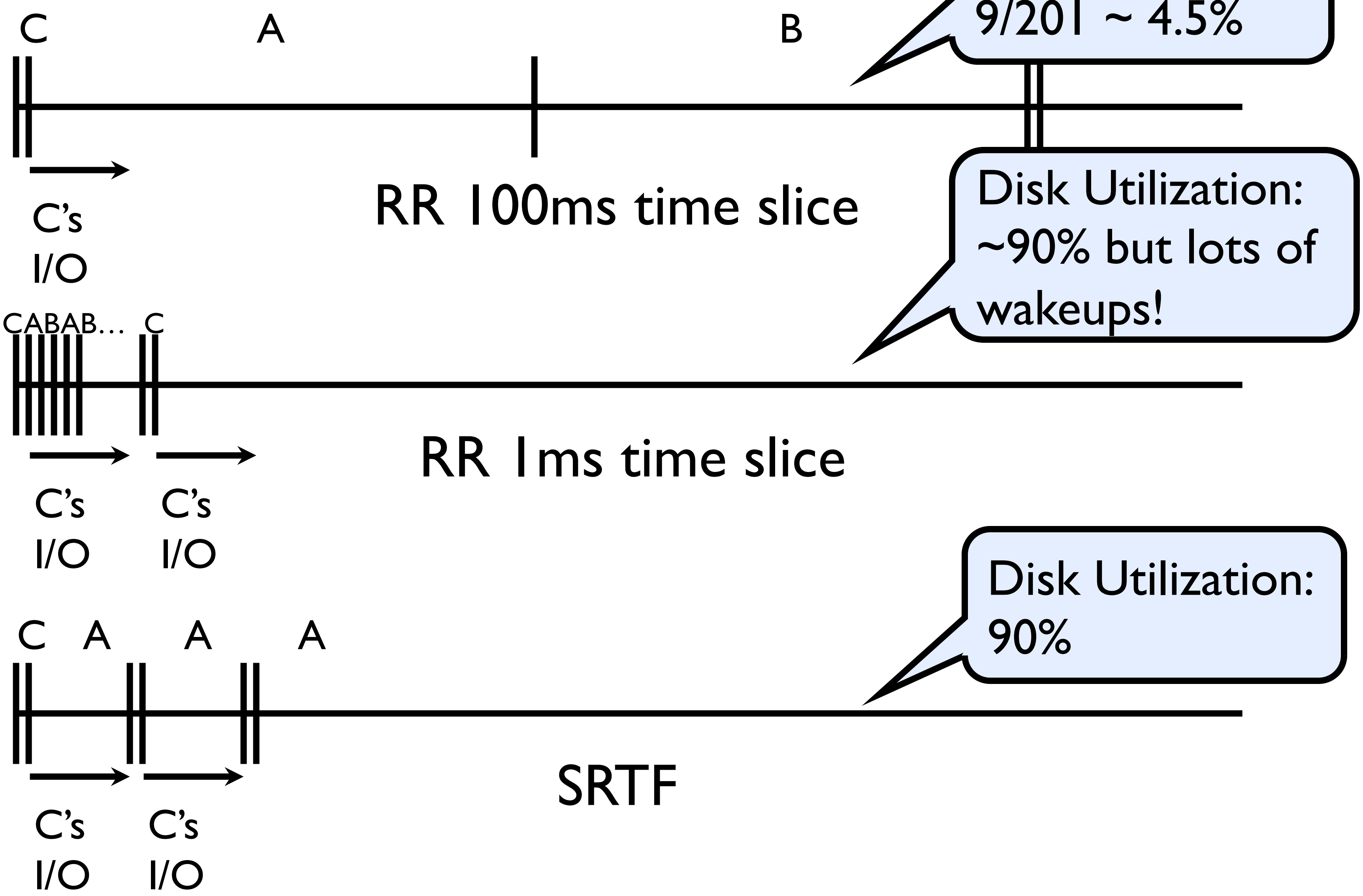
- Comparison of SRTF with FCFS and RR
  - What if all jobs the same length?
    - SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - SRTF (and RR): short jobs not stuck behind long ones

Example to illustrate benefits of SRTF



- Three jobs:
  - A, B: both CPU bound, run for week
    C: I/O bound, loop 1ms CPU, 9ms disk I/O
  - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FIFO:
  - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
  - Easier to see with a timeline

SRTF Example continued:



RR 100ms time slice

Disk Utilization: 9/201 ~ 4.5%

RR 1ms time slice

Disk Utilization: ~90% but lots of wakeups!

SRTF

Disk Utilization: 90%

SRTF Further discussion

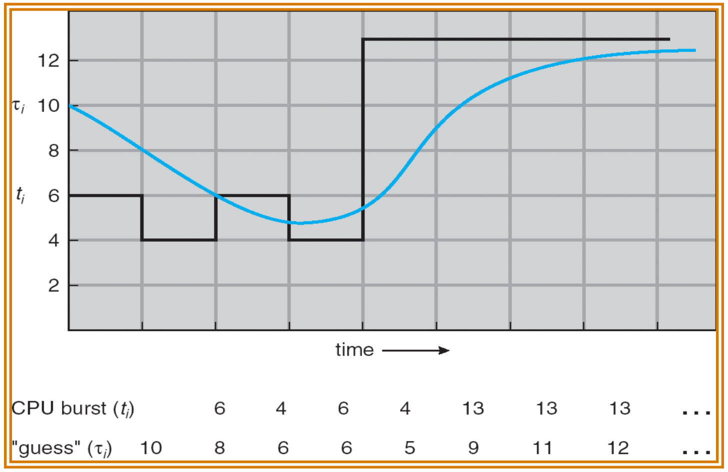
- Starvation
  - – SRTF can lead to starvation if many small jobs!
  - – Large jobs never get to run
- Somehow need to predict future
  - – How can we do this?
  - – Some systems ask the user
    - » When you submit a job, have to say how long it will take
    - » To stop cheating, system kills job if takes too long
  - – But: hard to predict job's runtime even for non-malicious users

SRTF Further discussion (Cont.)

- Bottom line, can't really know how long job will take
  - However, can use SRTF as a yardstick for measuring other policies
  - Optimal, so can't do any better
- SRTF Pros & Cons
  - Optimal (average response time) (+)
  - Hard to predict future (-)
  - Unfair (-)

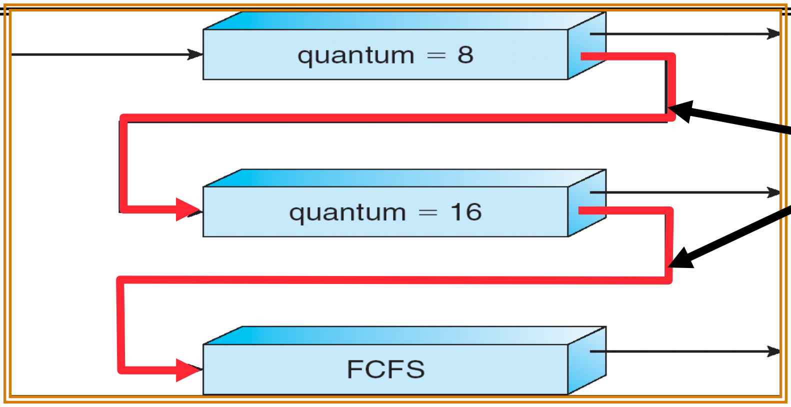
Predicting the Length of the Next CPU Burst

- Adaptive: Changing policy based on past behavior
  - CPU scheduling, in virtual memory, in file systems, etc
  - Works because programs have predictable behavior
    - » If program was I/O bound in past, likely in future
    - » If computer behavior were random, wouldn't help
- Example: SRTF with estimated burst length
  - Use an estimator function on previous bursts: Let t_{n-1}, t_{n-2}, t_{n-3}, etc. be previous CPU burst lengths. Estimate next burst $\boldsymbol{\tau}_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  - For instance, exponential averaging $\boldsymbol{\tau}_n = \alpha t_{n-1} + (1-\alpha)\boldsymbol{\tau}_{n-1}$ with $(0<\alpha\leq 1)$



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

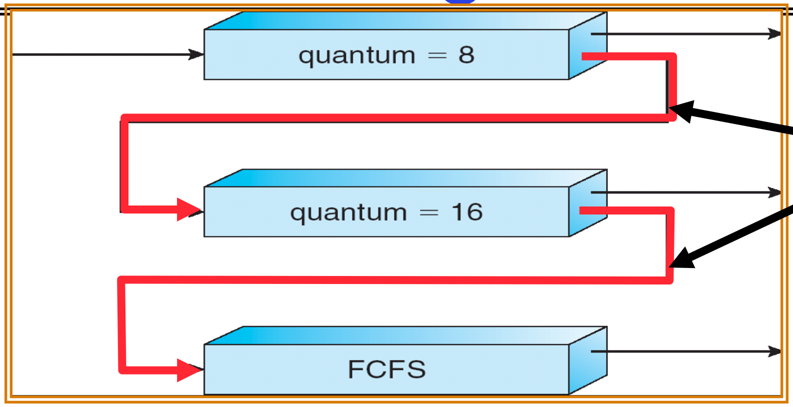
Multi-Level Feedback Scheduling



Long-Running Compute Tasks Demoted to Low Priority

- Another method for exploiting past behavior (first use in CTSS)
  - Multiple queues, each with different priority
    - » Higher priority queues often considered "foreground" tasks
  - Each queue has its own scheduling algorithm
    - » e.g. foreground – RR, background – FCFS
    - » Sometimes multiple RR priorities with quantum increasing exponentially (highest:1ms, next: 2ms, next: 4ms, etc)
- Adjust each job's priority as follows (details vary)
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn't expire, push up one level (or to top)

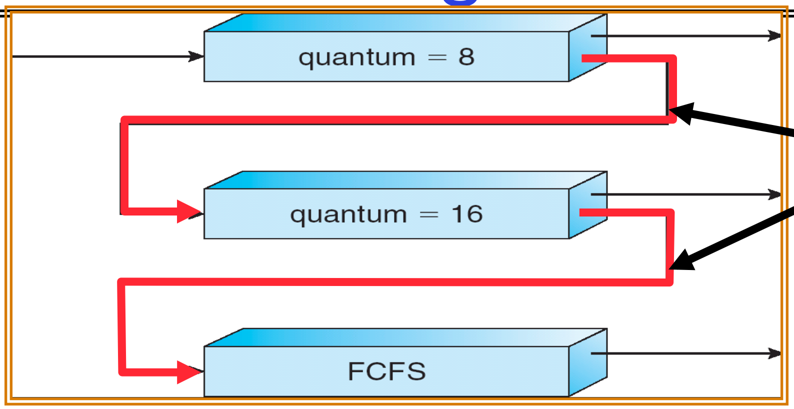
Scheduling Details



Long-Running Compute Tasks Demoted to Low Priority

- Result approximates SRTF:
  - – CPU bound jobs drop like a rock
  - – Short-running I/O bound jobs stay near top
- Scheduling must be done between the queues
  - – Fixed priority scheduling:
    - » serve all from highest priority, then next priority, etc.
  - – Time slice:
    - » each queue gets a certain amount of CPU time
    - » e.g., 70% to highest, 20% next, 10% lowest

Scheduling Details



Long-Running Compute Tasks Demoted to Low Priority

- Countermeasure: user action that can foil intent of OS designers
  - For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
  - Of course, if everyone did this, wouldn't work!
- Example of Othello program:
  - Playing against competitor, so key was to do computing at higher priority the competitors.
    - » Put in `printf`'s, ran much faster!

Summary (1 of 2)

- Round-Robin Scheduling:
  - Give each thread a small amount of CPU time when it executes; cycle between all ready threads
  - Pros: Better for short jobs

- Shortest Job First (SJF) / Shortest Remaining Time First (SRTF):
  - Run whatever job has the least amount of computation to do/least remaining amount of computation to do
  - Pros: Optimal (average response time)
  - Cons: Hard to predict future, Unfair

Summary (2 of 2)

- Lottery Scheduling:
  - Give each thread a priority-dependent number of tokens (short tasks ⇒ more tokens)

- Multi-Level Feedback Scheduling:
  - Multiple queues of different priorities and scheduling algorithms
  - Automatic promotion/demotion of process priority in order to approximate SJF/SRTF