CS162
Operating Systems and Systems Programming
Lecture 10

Scheduling

February 21st, 2018

Profs. Anthony D. Joseph and Jonathan Ragan-Kelley
http://cs162.eecs.Berkeley.edu

Recall: Example of RR with Time Quantum = 20

- Example:

Process	Burst Time
P_1	~~53~~ ~~33~~ ~~13~~
P_2	~~8~~
P_3	~~68~~ ~~48~~ ~~28~~ ~~8~~
P_4	~~24~~ ~~4~~

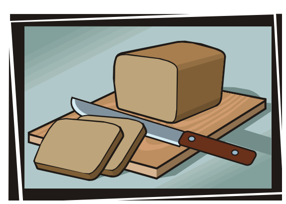
  – The Gantt chart is:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

0 20 28 48 68 88 108 112 125 145 153

  – 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

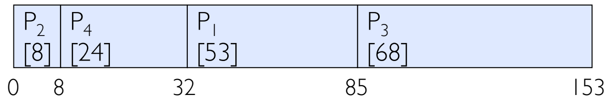
- Assuming zero-time context-switching, is RR always better than FCFS?
- Simple example:
  10 jobs, each take 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time
- Completion Times:

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-time switch!

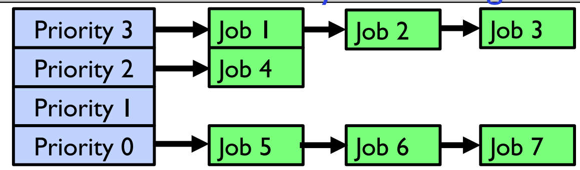
Earlier Example with Different Time Quantum

Best FCFS:



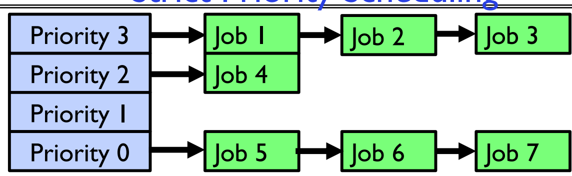
	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	$31\frac{1}{4}$
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	$61\frac{1}{4}$
	Q = 8	80	8	85	56	$57\frac{1}{4}$
	Q = 10	82	10	85	68	$61\frac{1}{4}$
	Q = 20	72	20	85	88	$66\frac{1}{4}$
	Worst FCFS	68	145	0	121	$83\frac{1}{2}$
Completion Time	Best FCFS	85	8	153	32	$69\frac{1}{2}$
	Q = 1	137	30	153	81	$100\frac{1}{2}$
	Q = 5	135	28	153	82	$99\frac{1}{2}$
	Q = 8	133	16	153	80	$95\frac{1}{2}$
	Q = 10	135	18	153	92	$99\frac{1}{2}$
	Q = 20	125	28	153	112	$104\frac{1}{2}$
	Worst FCFS	121	153	68	145	$121\frac{3}{4}$

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



How to fix problems?

Dynamic priorities – adjust base-level priority up or down based on heuristics about:

- Locking (priority donation!)
- Interactivity
- 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 lines get so long, get better service by going into one of the "slower" 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
      - ⇒ Effectively no more priorities
      - ⇒ Interactive jobs suffer

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?
  - Higher priority jobs get more 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

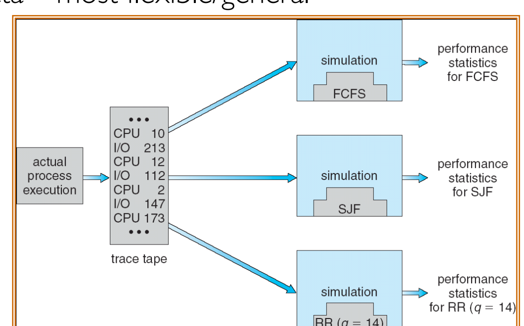
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# 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, tablets, 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)

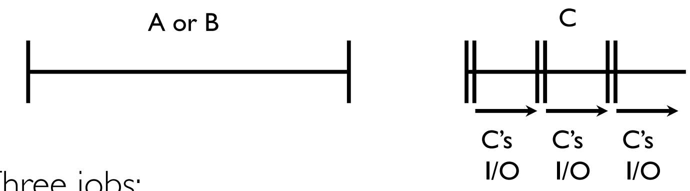
What if we Knew the Future?

- 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

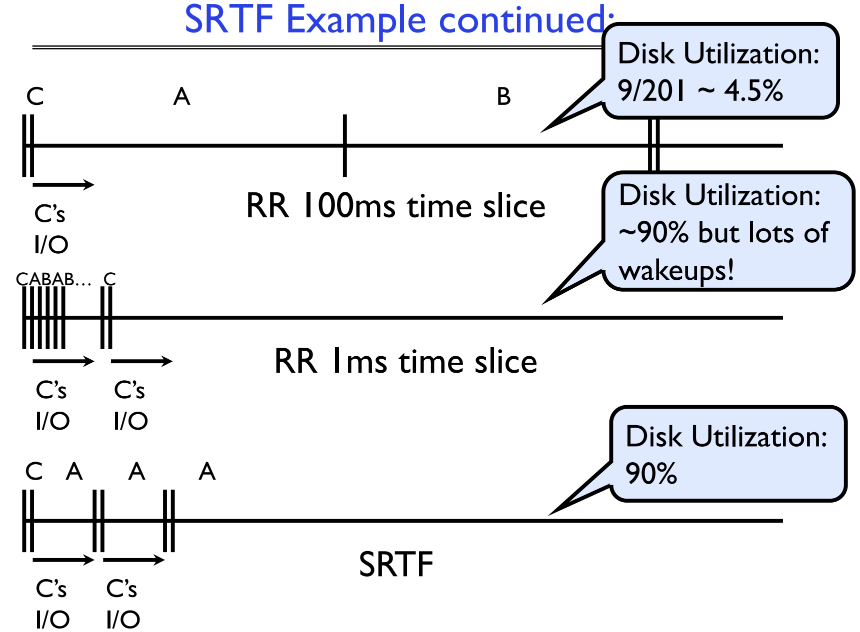
- SJF/SRTF are the best you can do at minimizing average response time
  – Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  – Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS and RR
  – What if all jobs the same length?
    » SRTF becomes the same as FCFS
    (FCFS is optimal 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
  - While C uses 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:



SRTF Challenges

- 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 Discussion

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

Administrivia

- **Midterm 1 Review session**: 3-6pm, Saturday, 2/24
  GPB 100 and/or Hearst Field Annex A1 (tentative)
- **Midterm 1**: 6:30-8:30pm, Wednesday, 2/28 (no class)
  - Li Ka Shing 245: IDs ending in 0,1,2,3
  - Hearst Field Annex A1: …4,5,6
  - VLSB 2060: …7,8
  - Barrows 20: …9
  - CS 189: Wurster 102 (no electronics)
  - DSP: Soda 465 & 606
- **Project 1**: code due Friday, 3/2
  - **Midterm includes project 1 material** – everyone in group should understand all parts of the project!

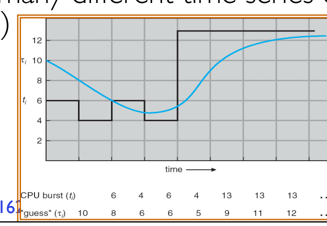
BREAK

SRTF Further discussion (Cont.)

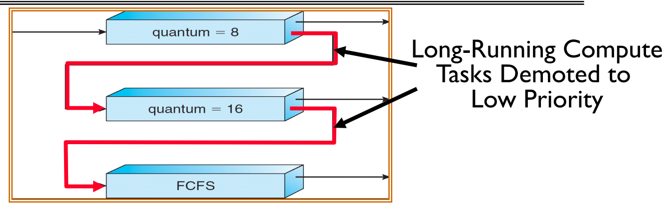
- Bottom line, can't really know how long job will take
  - However, can use SRTF as a yardstick
    for measuring other policies on a given trace
  - Optimal, so can't do any better
- SRTF Pros & Cons
  - Optimal (average response time) (+)
  - Hard to predict future (-)
  - Unfair (-)

Predicting the Length of the Next CPU Burst

- Adaptive: Changing policy based on past behavior
  - CPU scheduling, in virtual memory, in file systems, in CPUs, 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}, … be previous CPU burst lengths.
    Estimate next burst $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  - For instance,
    exponential averaging
    $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$
    with $(0<\alpha\leq 1)$

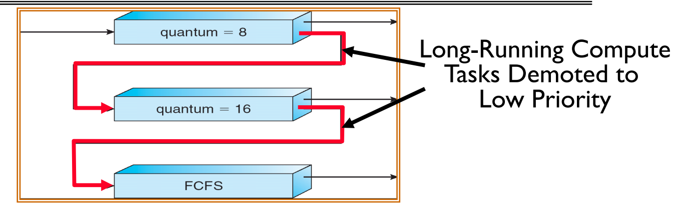


Multi-Level Feedback Scheduling



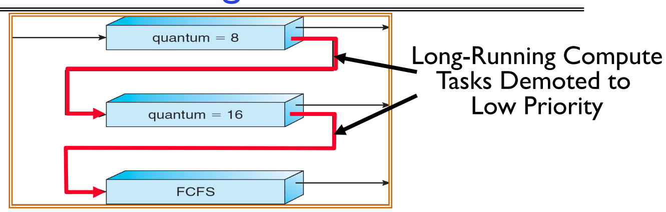
- Another method for exploiting past behavior (first use in CTSS)
  – Multiple queues, each with different priority
    » Higher priority queues often considered "foreground" tasks
  – Each queue has its own scheduling algorithm
    » e.g. foreground – RR, background – FCFS
    » Sometimes multiple RR 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



- 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



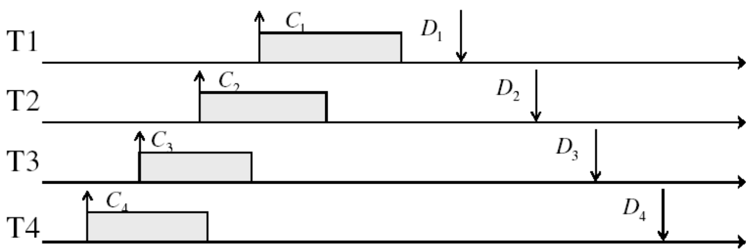
- Countermeasure: user action that can foil intent of OS designers
  – For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
  – Of course, if everyone did this, wouldn't work!
- Example of Othello program:
  – Playing against competitor, so key was to do computing at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

Real-Time Scheduling (RTS)

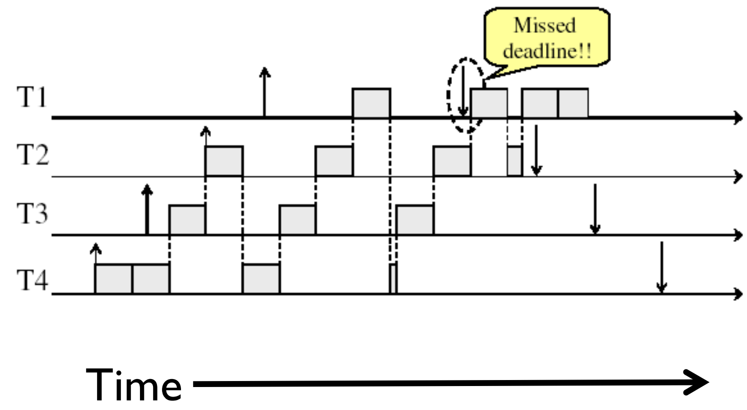
- Efficiency is important but predictability is essential:
  – We need to predict with confidence worst case response times for systems
  – In RTS, performance guarantees are:
    » Task- and/or class centric and often ensured a priori
  – In conventional systems, performance is:
    » System/throughput oriented with post-processing (… wait and see …)
  – Real-time is about enforcing predictability, and does not equal fast computing!!!
- Hard Real-Time
  – *Attempt to meet all deadlines*
  – EDF (Earliest Deadline First), LLF (Least Laxity First), RMS (Rate-Monotonic Scheduling), DM (Deadline Monotonic Scheduling)
- Soft Real-Time
  – *Attempt to meet deadlines with high probability*
  – Minimize miss ratio / maximize completion ratio (firm real-time)
  – Important for multimedia applications
  – CBS (Constant Bandwidth Server)

Example: Workload Characteristics

- Tasks are preemptable, independent with arbitrary arrival (=release) times
- Tasks have deadlines (D) and known computation times (C)
- Example Setup:

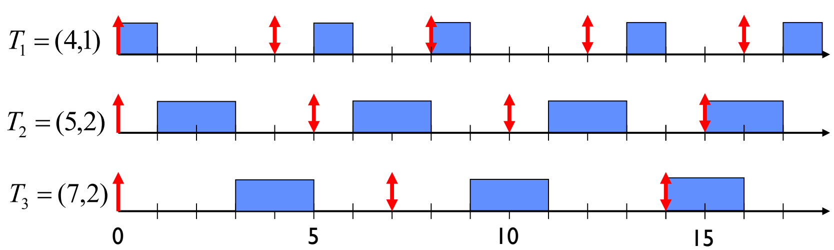


Example: Round-Robin Scheduling Doesn't Work



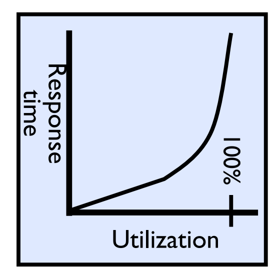
Earliest Deadline First (EDF)

- Tasks periodic with period P and computation C in each period: (P, C)
- Preemptive priority-based dynamic scheduling
- Each task is assigned a (current) priority based on how close the absolute deadline is
- The scheduler always schedules the active task with the closest absolute deadline



A Final Word On Scheduling

- When do the details of the scheduling policy and fairness really matter?
  – When there aren't enough resources to go around
- When should you simply buy a faster computer?
  – (Or network link, or expanded highway, or …)
  – One approach: Buy it when it will pay for itself in improved response time
    » Assuming you're paying for worse response time in reduced productivity, customer angst, etc…
    » Might think that you should buy a faster X when X is utilized 100%, but usually, response time goes to infinity as utilization⇒100%



- An interesting implication of this curve:
  – Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise
  – Argues for buying a faster X when hit "knee" of curve

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
- Real-time scheduling
  - Need to meet a deadline, predictability essential
  - Earliest Deadline First (EDF) and Rate Monotonic (RM) scheduling