ECE 350 Real-time Operating Systems

UNIVERSITY OF WATERLOO

CONCORDIA CUM VERITATE

Lecture 4: Uniprocessor Scheduling

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Outline

- History
- Definitions
  - Response time, throughput, scheduling policy, …
- Uniprocessor scheduling policies
  - FCFS, SJF/SRTF, RR, …

A Bit of History on Scheduling

- By year 2000, scheduling was considered a solved problem

  "And you have to realize that there are not very many things that have aged as well as the scheduler. Which is just another proof that scheduling is easy."

  Linus Torvalds, 2001[1]

- End to Dennard scaling in 2004, led to multiprocessor era
  - Designing new (multiprocessor) schedulers gained traction
  - Energy efficiency became top concern

- In 2016, it was shown that bugs in Linux kernel scheduler could cause up to 138x slowdown in some workloads with proportional energy waist [2]

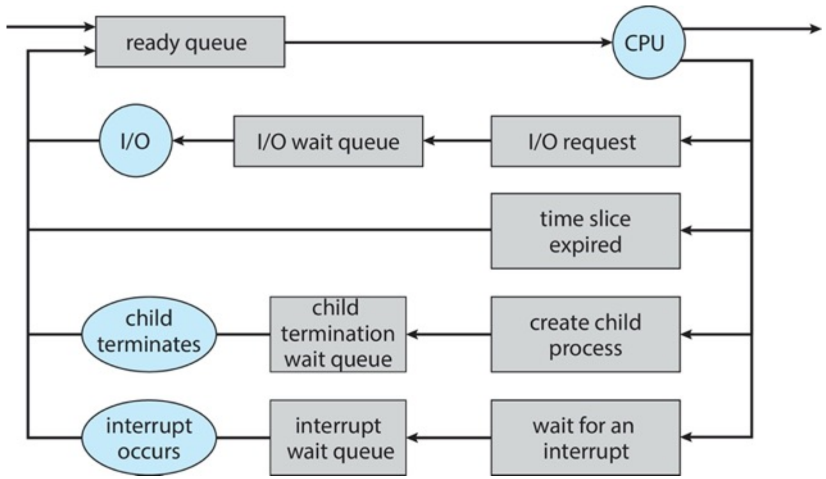
[1] L. Torvalds. The Linux Kernel Mailing List. http://tech-insider.org/linux/research/2001/1215.html, Feb. 2001.

[2] Lozi, Jean-Pierre, et al. "The Linux scheduler: a decade of wasted cores." Proceedings of the Eleventh European Conference on Computer Systems. 2016.

Definitions

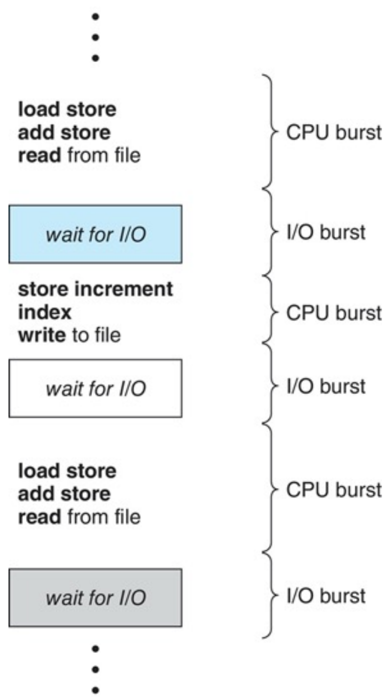
- Task, thread, process, job: unit of work
  - E.g., mouse click, web request, shell command, etc.)
- Workload: set of tasks
- Scheduling algorithm: takes workload as input, decides which tasks to do first
- Overhead: amount of extra work that is done by scheduler
- Preemptive scheduler: CPU can be taken away from a running task
- Work-conserving scheduler: CPUs won't be left idle if there are ready tasks to run
  - For non-preemptive schedulers, work-conserving is not always better (why?)
- Only preemptive, work-conserving schedulers to be considered in this lecture!

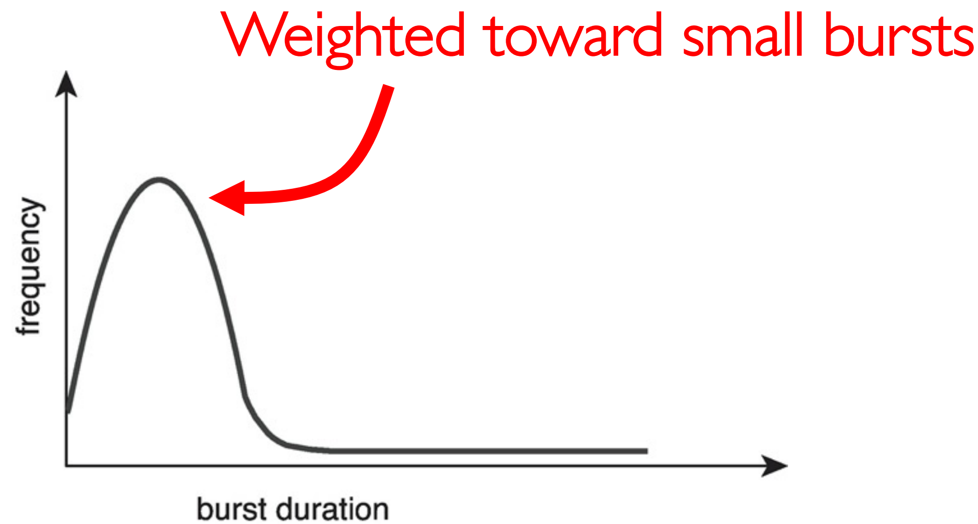
Recall: CPU Scheduling



- Earlier, we talked about life-cycle of threads
  - Threads work their way from ready to running to various waiting queues
- 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 thread gets resource from moment to moment

Execution Model





- Programs alternate between bursts of CPU and I/O
  - Use CPU for some period, then do I/O, then use CPU again, etc.
- CPU scheduling is about choosing thread which gets CPU for its next CPU burst
- With preemption, thread may be forced to give up CPU before finishing its burst

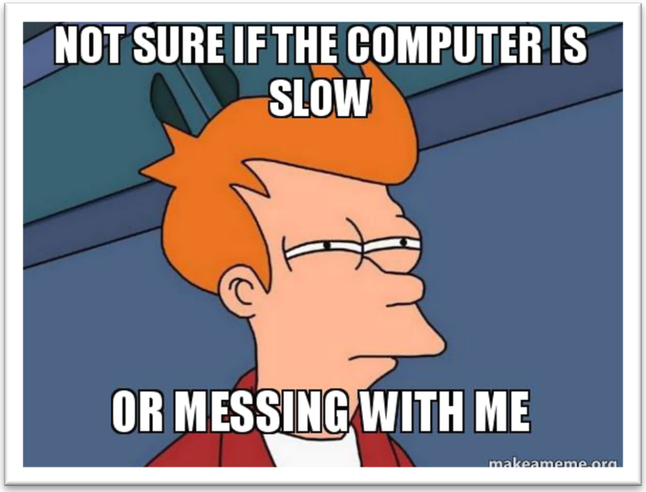
CPU Scheduling Assumptions

- There are many implicit assumptions for CPU scheduling
  - One program per user
  - One thread per program
  - Programs are independent

- These may not hold in all systems, but they simplify the problem

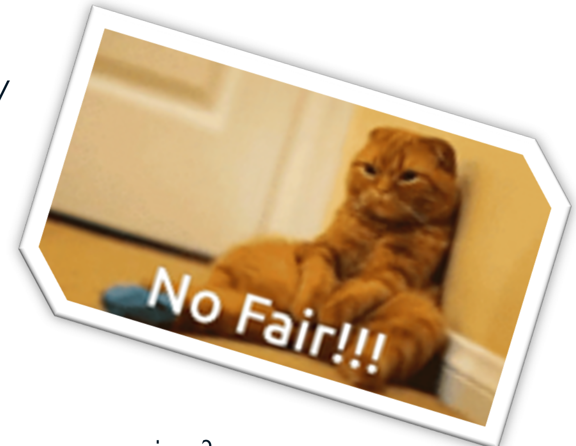
- High-level goal is to divide CPU time to optimize some desired properties

Performance



- Minimize average response time
  - Minimize avg. elapsed time to finish tasks
  - Response time is what users see
    - E.g., time to echo a keystroke in editor
    - E.g., time to compile a program
    - Real-time tasks must meet *deadlines* (more on this later)
- Maximize throughput
  - Maximize tasks per time unit (e.g., tasks per second)
  - Related to response time, but not identical
    - Minimizing response time could lead to more context switching which will than hurt throughput (more on this later)
  - Two parts to maximizing throughput
    - Minimize overhead (e.g., context-switching)
    - Efficient use of resources (e.g., CPU, disk, memory, etc.)

Fairness



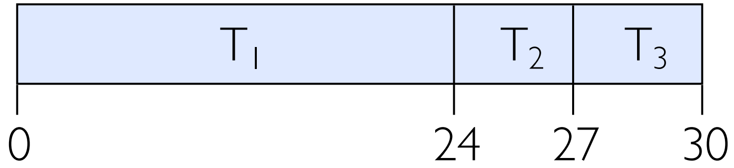
- Share CPU time among *users* in some *equitable* way
- What does equitable mean?
  - Equal share of CPU time?
    - What if some tasks don't need their full share?
  - Minimize variance in worst case performance?
    - What if some tasks were running when no one else was running?
- Who are users? Actual users or programs?
  - If A runs one thread and B runs five, B could get five times as much CPU time on many OS's
- Fairness is not minimizing average response time
  - Improving average response time could make system less fair (more on this later)

First-Come, First-Served (FCFS) Scheduling

- First-come, first-served (FCFS)
  - Also "first-in, first-out" (FIFO)
  - In early systems, FCFS meant one program scheduled until done (including its I/O activities)
  - Now, it means that program keeps CPU until the end of its CPU burst
- Example

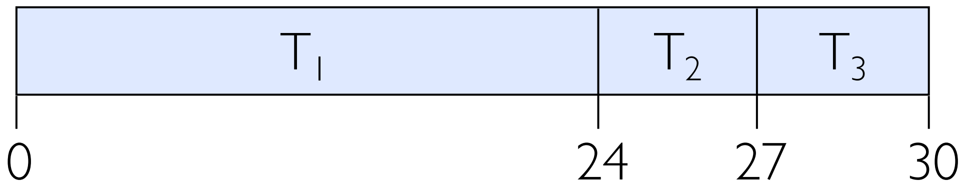
Thread	CPU Burst Time
T_1	24
T_2	3
T_3	3

  - Suppose threads arrive in order: T_1, T_2, T_3



FCFS Scheduling (cont.)

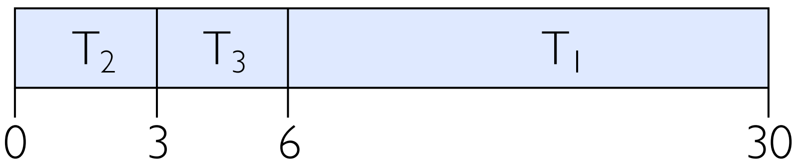
- Example continued



  - Wait time for T_1 is 0, for T_2 is 24, and for T_3 is 27
  - Average wait time is (0 + 24 + 27)/3 = 17
  - Average response time is (24 + 27 + 30)/3 = 27

FCFS Scheduling (cont.)

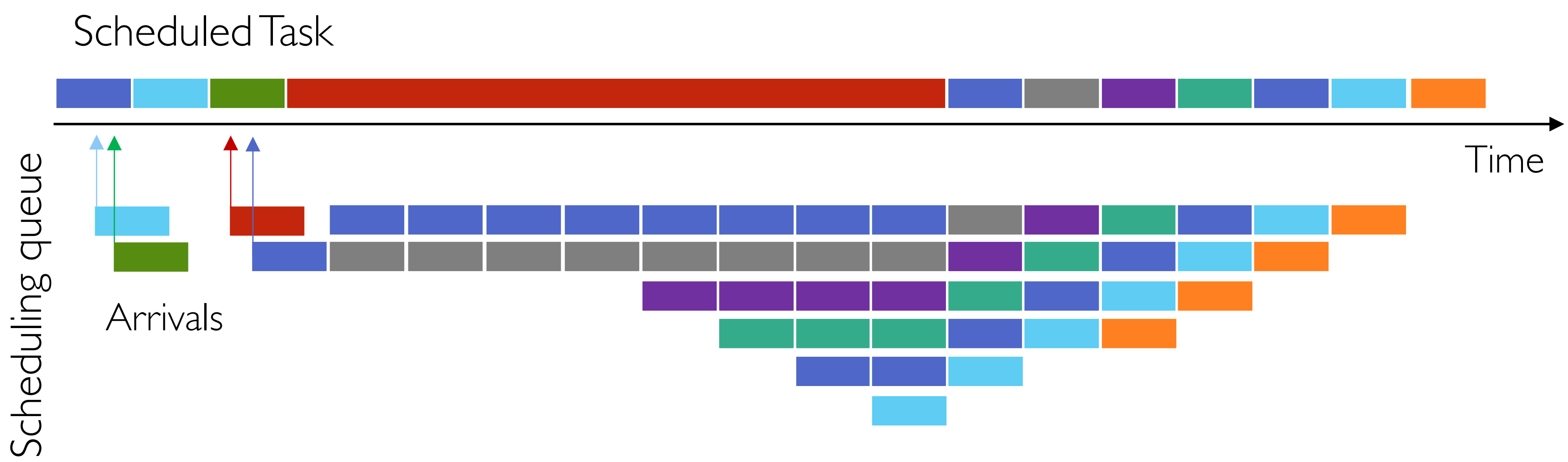
- If threads arrive in order: T_2, T_3, T_1, then we have



  - Wait time for T1 is 6, for T2 is 0, and for T3 is 3
  - Average wait time is (6 + 0 + 3)/3 = 3
  - Average response time is (3 + 6 + 30)/3 = 13
  - Average wait time is much better (before it was 17)
  - Average response time is better (before it was 27)
- Pros and cons of FCFS
  - \+ Simple
  - − Short tasks get stuck behind long ones

Convoy Effect

- With FCFS, convoys of small tasks tend to build up when a large one is running



Round Robin (RR) Scheduling

- FCFS is potentially bad for short tasks!
  - 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
  - Each thread gets small unit of CPU time, called *time quantum* (usually 10-100 milliseconds)
  - Once quantum expires, thread is preempted and added to end of ready queue
  - N threads in ready queue and time quantum is $q \Rightarrow$
    - Each thread gets $1/N$ of CPU time in chunks of at most q time units
    - No thread waits more than $(N-1)q$ time units

Photo: Pinterest.ca

Example: RR with Time Quantum of 20

- Example

Thread	Burst Time
T_1	53
T_2	8
T_3	68
T_4	24

T_1	T_2	T_3	T_4	T_1	T_3	T_4	T_1	T_3	T_3

0 20 28 48 68 88 108 112 125 145 153

- Wait time for T_1 = (68 - 20) + (112 - 88) = 72

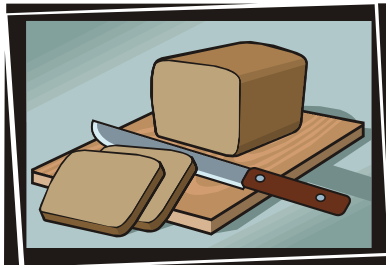
  T_2 = (20 - 0) = 20

  T_3 = (28 - 0) + (88 - 48) + (125 - 108) = 85

  T_4 = (48 - 0) + (108 - 68) = 88

- Average wait time is (72 + 20 + 85 + 88) / 4 = 66¼
- Average response time is (125 + 28 + 153 + 112) / 4 = 104½

Round Robin Discussion



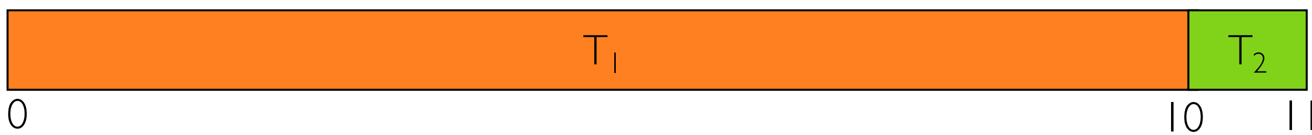
- Pros and cons of RR
  - + Better for short tasks, fair
  - − Context-switching time adds up for long tasks
- How does performance change with time quantum?
  - What if it's too long?
    - Response time suffers!
  - What if it's too short?
    - Throughput suffers!
  - What if it's infinite (∞)?
    - RR $\Rightarrow$ FCFS
  - Time quantum must be long compared to context switching time, otherwise overhead will be too high

Round Robin Time Quantum

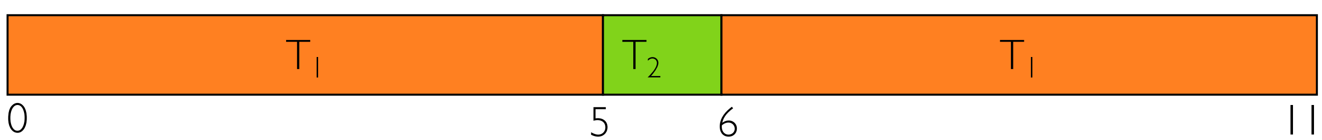
- Assume there is no context switching overhead
- What happens when we decrease Q?
  1. Avg. response time always decreases or stays the same
  2. Avg. response time always increases or stays the same
  3. Avg. response time can increase, decrease, or stays the same

Decrease Response Time

- T_1: burst time 10
- T_2: burst time 1
- Q = 10



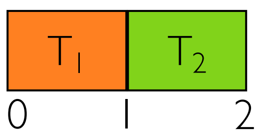
  - Average response time = (10 + 11)/2 = 10.5
- Q = 5



  - Average response time = (6 + 11)/2 = 8.5

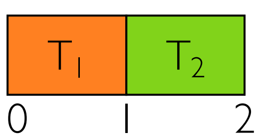
Same Response Time

- T_1: burst time 1
- T_2: burst time 1
- Q = 10



  - Average response time = (1 + 2)/2 = 1.5

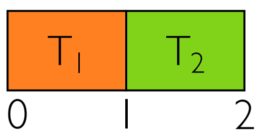
- Q = 1



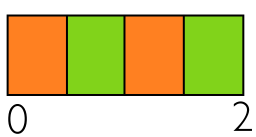
  - Average response time = (1 + 2)/2 = 1.5

Increase Response Time

- T_1: burst time 1
- T_2: burst time 1
- Q = 1



  - Average response time = (1 + 2)/2 = 1.5
- Q = 0.5



  - Average response time = (1.5 + 2)/2 = 1.75

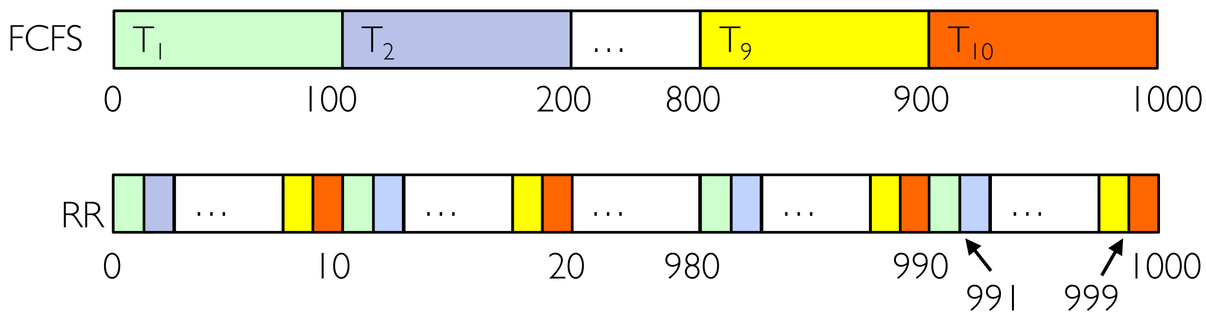
Round Robin Discussion (cont.)

- Actual choices of time quantum
  - Initially, UNIX time quantum was one second
    - Worked ok when UNIX was used by one or two users
    - What if you use text editor while there are three compilations going on?
      - It takes 3 seconds to echo each keystroke!

  - Need to balance short-task performance and long-task throughput
    - Typical time quantum today is between 10ms – 100ms
    - Typical context-switching overhead is 0.1ms – 1ms
    - Roughly 1% overhead due to context-switching

FCFS vs. RR

- Assuming zero-cost context-switching time, is RR always better than FCFS?
- Suppose there are 10 tasks, each take 100s of CPU time, RR quantum is 1s



- Completion times

Task #	FCFS	RR
1	100	991
2	200	992
...	...	...
9	900	999
10	1000	1000

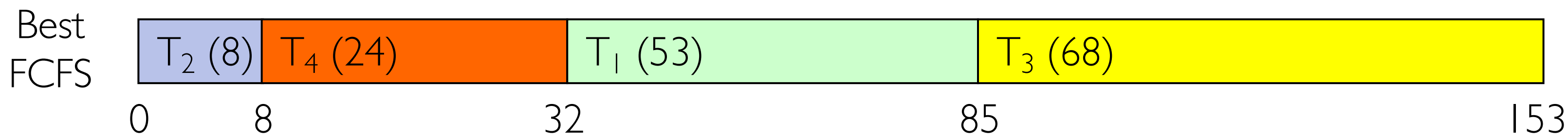
FCFS vs. RR (cont.)

- Completion times

Task #	FCFS	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 threads have the same length
- Also, cache must be shared between all tasks with RR but can be devoted to each task with FIFO
  - Total time for RR is longer even for zero-cost context switching!

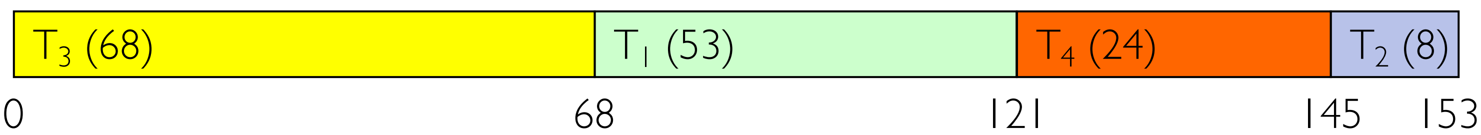
Earlier Example: RR vs. FCFS, Effect of Different Time Quanta



	Quantum	T1	T2	T3	T4	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	1					
	5					
	8					
	10					
	20					
	Worst FCFS					
Response Time	Best FCFS	85	8	153	32	69½
	1					
	5					
	8					
	10					
	20					
	Worst FCFS					

Earlier Example: RR vs. FCFS, Effect of Different Time Quanta (cont.)

Worst FCFS



	Quantum	T1	T2	T3	T5	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	1					
	5					
	8					
	10					
	20					
	Worst FCFS	68	145	0	121	83½
Response Time	Best FCFS	85	8	153	32	69½
	1					
	5					
	8					
	10					
	20					
	Worst FCFS	121	153	68	145	121¾

Earlier Example: RR vs. FCFS, Effect of Different Time Quanta (cont.)

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_1	P_3	P_1	P_3	P_1	P_3	P_3	P_3

0 8 16 24 32 40 48 56 64 72 80 88 96 104 112 120 128 133 141 149 153

	Quantum	T1	T2	T3	T5	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	1	84	22	85	57	62
	5	82	20	85	58	61¼
	8	80	8	85	56	57¼
	10	82	10	85	68	61¼
	20	72	20	85	88	66¼
	Worst FCFS	68	145	0	121	83½
Response Time	Best FCFS	85	8	153	32	69½
	1	137	30	153	81	100½
	5	135	28	153	82	99½
	8	133	16	153	80	95½
	10	135	18	153	92	99½
	20	125	28	153	112	104½
	Worst FCFS	121	153	68	145	121¾

Shortest Task First (SJF) Scheduling

- Could we always mirror best FCFS?
- Shortest task first (SJF)
  - Run task that 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 task arrives and has shorter time to completion than remaining time on current task, immediately preempt current task
  - Sometimes called "shortest remaining time to completion first" (SRTCF)
- These can be applied to whole program or current CPU burst
  - Key idea: get short tasks out of system
  - Big effect on short tasks, only small effect on long ones
  - Better average response time

SJF/SRTF Optimality

- SJF/SRTF minimize average response time! Why?
  - Consider alternative policy P (not SJF/SRTF) that is optimal
  - At some point, P chooses to run task that is not the shortest
  - Keep order of tasks the same, but run the shorter task first
  - This reduces average response time ⇒ contradiction!

SJF/SRTF Discussion

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

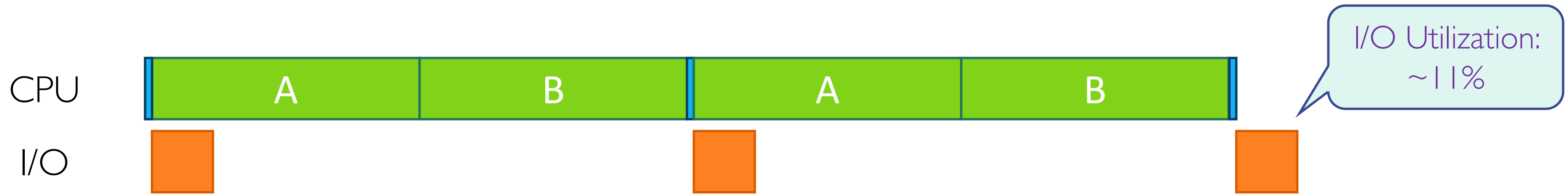
- Comparison of SRTF with FCFS
  - What if all tasks are the same length?
    - SRTF ⇒ FCFS (i.e., FCFS is best we can do if all tasks have the same length)
  - What if tasks have varying length?
    - Unlike FCFS, with SRTF, short tasks do not get stuck behind long ones

Mix of CPU and I/O Bound Tasks: FCFS vs. RR vs. SRTF

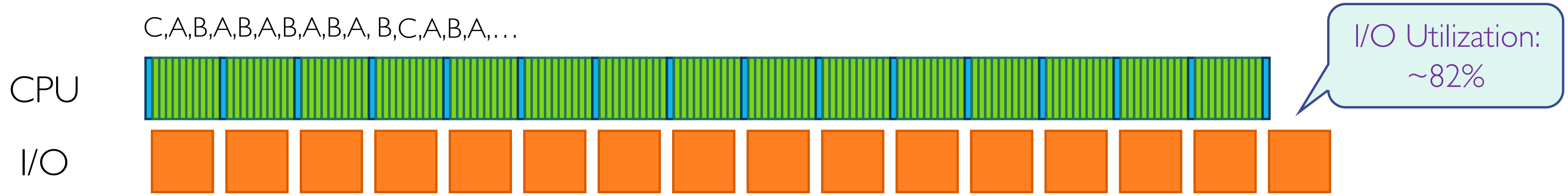
- Example: suppose there are three tasks
  - A and B are both CPU bound with CPU bursts that last for a week
  - C is I/O bound with iterations of 1ms CPU burst followed by 9ms I/O burst
  - If A or B run by themselves, CPU utilization is 100% and I/O utilization is 0%
  - If C runs by itself, CPU utilization is 10% and I/O utilization is 90%
- With happens under FCFS scheduling policy?
  - Once A or B get in, keep CPU for two weeks ⇒ poor avg. response time
- What about RR or SRTF?
  - Easier to see with a timeline

Mix of CPU and I/O Bound Tasks: FCFS vs. RR vs. SRTF (cont.)

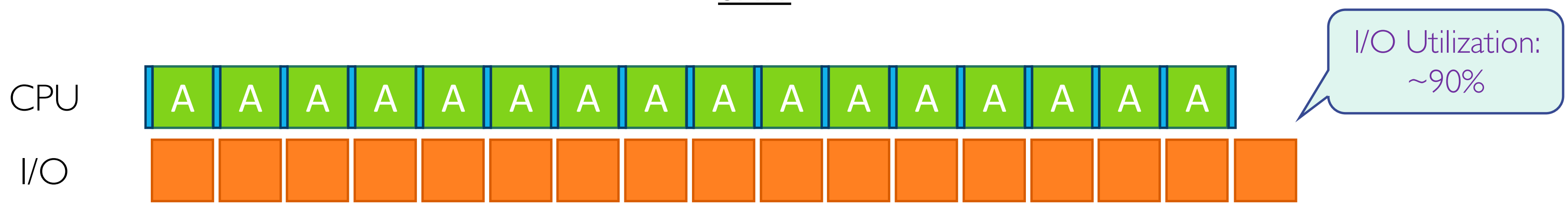
RR with 40ms time quantum



RR with 1ms time quantum



SRTF



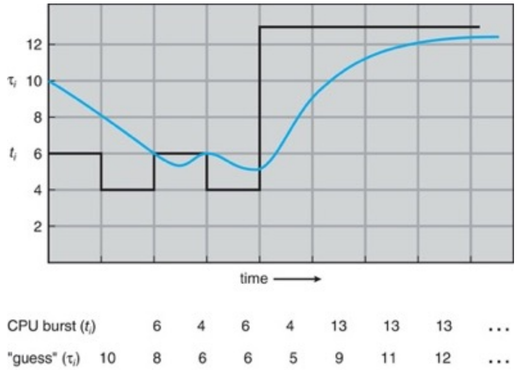
Problems with SRTF

- Starvation: large tasks may never run if short ones keep coming
- Overhead: short tasks preempt long ones ⇒ too many context switches
- Unfair: large tasks are penalized, there is high variance in response time

- Impractical: we need to somehow predict future
  - Some systems ask users
    - When you submit your task, you have to say how long it will take
    - Users could maliciously misreport length of their task
    - E.g., would it work if a supermarket uses SJF?
      - Customers could game the system: come with one item at a time
    - To prevent cheating, systems may kill tasks if they take too long
  - It's hard to predict task's runtime even for non-malicious users

Predicting Length of Next CPU Burst

- Adaptive: dynamically make predictions based on past behavior
  - Works because programs have predictable behavior
    - If program was I/O bound in past, it'll likely be I/O bound in future
    - If behavior were random, this approach wouldn't help



- Example: use estimator function on previous bursts
  - Let t_{n-1}, t_{n-2}, t_{n-3}, …, t_1 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 any time series estimator (e.g., Kalman filters, etc.)
  - For instance, exponential averaging $\tau_n = \alpha t_{n-1}+(1-\alpha)\tau_{n-1}$ with $(0 < \alpha \leq 1)$

Aside: Application Types

- Can we use past burst times to identify application types?
- Consider mix of *interactive* and *high-throughput* programs
  - How to best schedule them?
  - How to recognize one from the other?
    - Do you trust applications to say that they are "interactive"?
  - Should you schedule the set of applications identically on servers, workstations, pads, and cellphones?

Aside: Application Types (cont.)

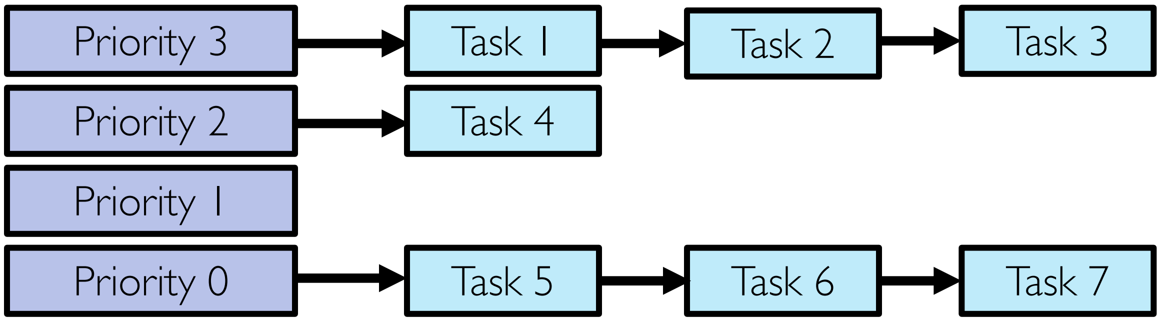
- Assumptions encoded into many schedulers (e.g., *O(1) Scheduler*)
  - Applications that sleep a lot and have short bursts must be interactive
    - Give them high priority
  - Applications that compute a lot must be high-throughput apps
    - Give them lower priority, since they won't notice intermittent bursts from interactive apps
- In general, it is hard to characterize applications
  - What about apps that sleep for a long time, and compute for a long time?
  - What about applications that must run under all circumstances

SRTF Final Notes

- Bottom line, we can't really know how long tasks will take
  - However, we can use SRTF as yardstick for measuring other policies
  - Optimal, so we can't do any better

- Pros & cons of SRTF
  - \+ Optimal (average response time)
  - − Hard to predict future
  - − Too many context switches
  - − Unfair

Strict Priority Scheduling

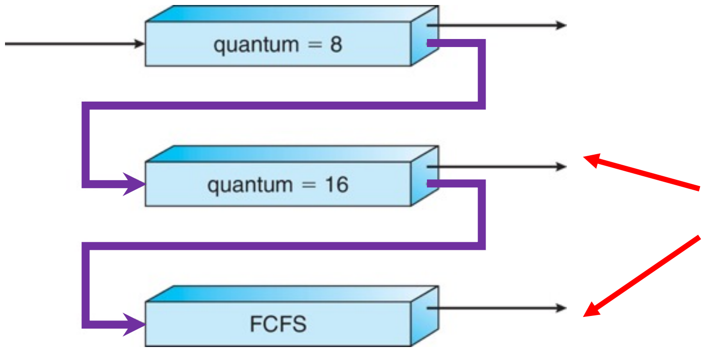


- Execution plan
  - Always execute highest-priority runnable tasks to completion
  - Each queue can be threaded in RR with some time-quantum
- Notice any problems?
  - Starvation
    - Lower-priority tasks may never run because of higher-priority tasks
  - Priority inversion
    - Low-priority task delays high-priority task by holding resources needed by high-priority task (more on this later)

Fairness

- Strict fixed-priority scheduling between queues is unfair (run highest, then next, etc.)
  - long running tasks may never get any CPU time
  - In Multics, shut down machine, found 10-year-old task
- One approach: give each queue some fraction of CPU
  - What if there are 100 short tasks and only one long task?
    - Like express lanes in a supermarket, sometimes express lanes get so long, get better service by going into one of other lines
- Another approach: increase priority of tasks 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 task gets CPU time, so everyone increases in priority ⇒ Interactive tasks suffer
- Tradeoff: fairness is usually gained by hurting average response time!

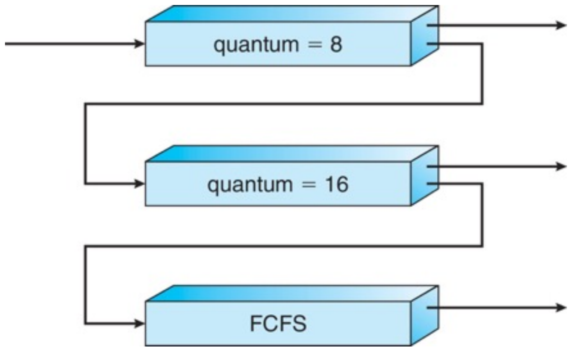
Multi-Level Feedback Queue



Long-Running compute tasks are demoted to lower priority queues

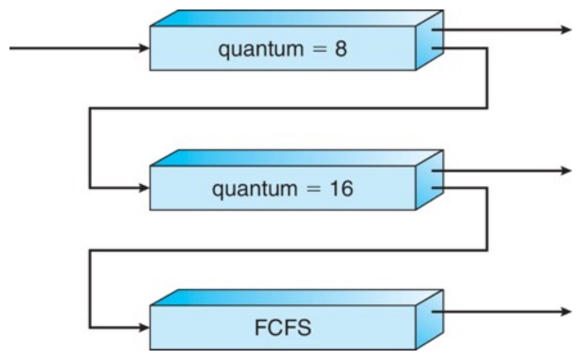
- Another method for exploiting past behavior (first use in CTSS)
  - Multiple queues, each with different priority
    - Higher priority queues often considered "foreground" tasks
  - Each queue has its own scheduling algorithm
    - E.g. foreground – RR, background – FCFS
    - Sometimes multiple RR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

Multi-Level Feedback Queue (cont.)



- Result approximates SRTF
  - CPU bound tasks drop like a rock
  - Short-running I/O bound tasks stay near top
- Scheduling must be done between queues
  - Fixed priority scheduling
    - Serve all from highest priority, then next priority, etc.
  - Time slicing
    - Each queue gets fraction of CPU time
    - E.g., 70% to highest, 20% next, 10% lowest

Multi-Level Feedback Queue (cont.)



- Countermeasure: user action that foil intent of OS designers
  - For multilevel feedback, put simple I/O's to keep task's priority high
  - Example of MIT Othello Contest
    - Cheater put `printf`'s, ran much faster than competitors!
    - Of course, if everyone did this, wouldn't work!

Lottery Scheduling

- Give each task *i* some number of lottery tickets N_i
- On each time slice, randomly pick a winning ticket
- Lottery scheduling achieves proportional-share allocations
  - On average, CPU time is proportional to # of tickets given to task

- How to assign tickets?
  - Give tasks tickets proportional to their priorities
  - To approximate SRTF, give short tasks more and long tasks fewer
  - To avoid starvation, give every task at least one ticket (everyone makes progress)

- Compared to strict priority, lottery scheduling behaves gracefully as load changes
  - Adding or deleting one task affects all tasks proportionally, independent of how many tickets each task possesses

Lottery Scheduling Example

- Assume short tasks get 10 tickets, long tasks get 1 ticket

# short tasks/ # long tasks	% of CPU each short tasks gets	% of CPU each long tasks 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 tasks to give reasonable response time?
  - If load average is 100, hard to make progress
  - One approach is to log some users out

Unfairness of Lottery Scheduling

- Define unfairness for two tasks with the same burst time as
  - Unfairness = finish time of first one / finish time of last one
- As function of burst time

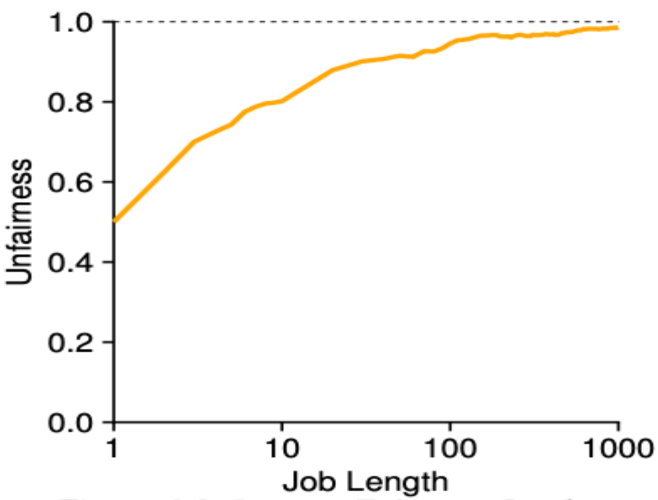


Figure 9.2: **Lottery Fairness Study**

Stride Scheduling

- Achieves proportional-share scheduling without resorting to randomness

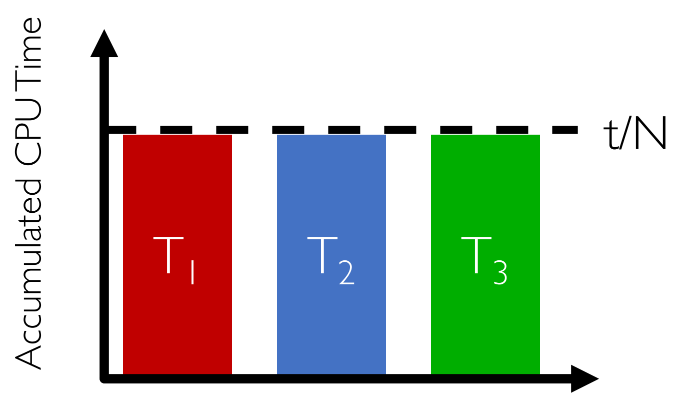
- Defines *stride* for each thread to be *Big#W/N$_i$*
  - The larger your share of tickets, the smaller your stride
  - E.g., with W = 10,000, and A, B, and C each having 100, 50, and 250 tickets, strides for A, B, and C are 100, 200, and 40, respectively

- Maintains *pass* counter for each thread

- Runs thread with lowest pass and adds its *stride* to its *pass*
  - Low-stride threads (lots of tickets) run more often
  - Thread with twice the tickets gets to run twice as often
  - Some messiness of counter wrap-around, new threads, …

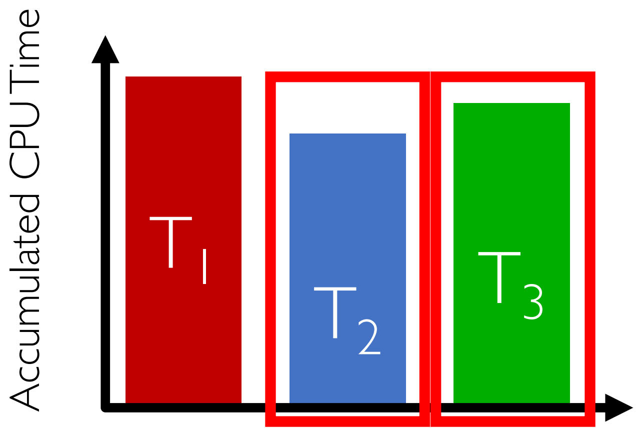
Max-Min Fair (MMF) Scheduling

- Always choose thread with lowest accumulated CPU time
  - If chosen thread doesn't have CPU burst, schedule second lowest …
  - Break ties randomly if multiple threads equally have lowest CPU time
- Goal is to give each thread equal share of CPU time
  - With *N runnable* threads, each thread should get $1/N^{th}$ of CPU time
- At any time *t* we want to have



MMF Scheduling (cont.)

- Strict MMF causes too many context switches
  - It effectively turns to running one instruction of each thread
- Relaxed MMF runs thread with lowest accumulated CPU time for fixed time quantum before choosing next thread



- Notice any problem?
  - Fixed quantum leads to poor response time as # of threads increases

MMF Scheduling (cont.)

- Solution: dynamically change time quantum
- Target latency: interval during which all threads should run at least once
- Time quantum = Target latency / N
  - E.g., with 20ms target latency and 4 threads, time quantum is 5ms
- Notice any problem?
  - With 20ms target latency and 200 threads, time quantum becomes 0.1ms
  - Recall RR: large context switching overhead if time quantum gets to small
- Minimum granularity: minimum length of any time quantum
  - E.g., with target latency 20ms, 1ms minimum granularity, and 200 processes, time quantum is1ms

Weighted Max-Min Fair Scheduling

- What if we want to give more to some and less to others (proportional share)?
- Key Idea: assign weight w_i to each thread i
- MMF uses single time quantum for all threads

$$Q = \frac{\text{Target latency}}{N}$$

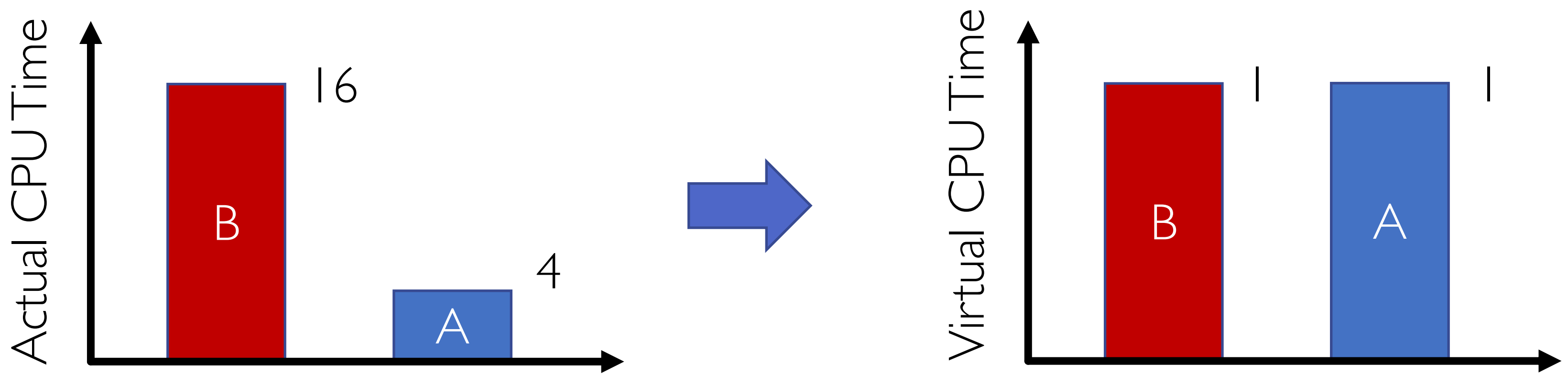
- Weighted MMF uses different time quanta for different threads

$$Q_i = \frac{w_i \times \text{Target latency}}{\sum_{j=1}^{N} w_j}$$

- E.g., with 20ms target latency, 1ms minimum granularity, and 2 threads: A with weight 1 and B with weight 4
  - Time quantum for A is 4 ms
  - Time quantum for B is 16 ms

Weighted MMF Scheduling (cont.)

- Also track threads' *virtual runtime* rather than their true wall-clock runtime
- Higher weight: virtual runtime increases more slowly
- Lower weight: virtual runtime increases more quickly
- Linux *completely fair scheduler* deploys very similar ideas
  - Ready queue is implemented as red-black tree, in which threads are sorted in increasing order of their virtual runtime



How to Evaluate Scheduling Algorithms?

- Deterministic modeling
  - Pick workload and compute performance of each algorithm
- Queueing models
  - Mathematical approach for handling stochastic workloads (more on this later)
- Simulations/Implementations
  - Build system which allows actual algorithms to be run against actual data – most flexible/general

Starvation and Sample Bias

- Suppose you want to compare scheduling policies
  - Create some infinite sequence of arriving tasks
  - Start measuring
  - Stop at some point
  - Compute ART for finished tasks between start and stop
- Is this valid or invalid?
  - SJF and FCFS would complete different sets of tasks
    - Their ARTs are not directly comparable
    - E.g., suppose you stopped at any point in FCFS vs. SJF slide

Solutions for Sample Bias

- For both systems, measure for long enough that
  # of completed tasks >> # of uncompleted tasks

- Start and stop system in idle periods
  - Idle period: no work to do
  - If algorithms are work-conserving, both will complete the same set of tasks

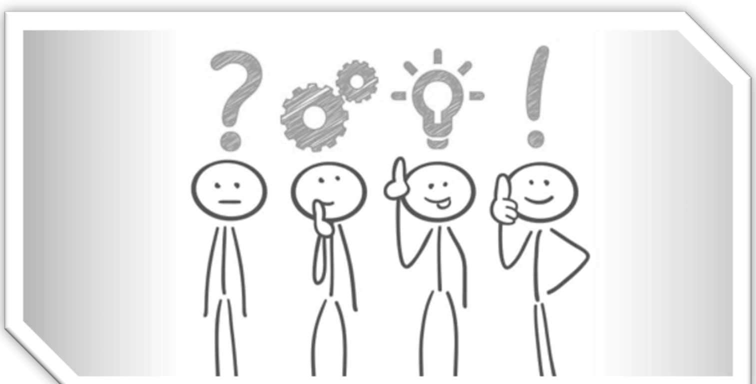
Choosing Right Scheduling Algorithm

If you care about	Then choose
CPU throughput	FCFS
Avg. response time	SRTF approximation
I/O throughput	SRTF approximation
Fairness (CPU time)	Linux CFS
Fairness – wait time to get CPU	RR
Favoring important threads	Priority
Proportional sharing	Lottery and stride scheduling

Summary

- First-come, first-served (FCFS)
  - Threads are served in the order of their arrival
- Round robin (RR)
  - Give each thread a small amount of CPU time when it executes; cycle between all ready threads
- Shortest task first (SJF) / shortest remaining time first (SRTF)
  - Run whatever thread that has the least amount of computation to do/least remaining amount of computation to do
- Multi-level feedback queue (MFQ)
  - Multiple queues of different priorities and scheduling algorithms
- Lottery and stride scheduling
  - Give each thread a priority-dependent number of tickets
- Max-min fair (MMF)
  - Give each thread equal share of CPU time

Questions?



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