# CS162
# Operating Systems and Systems Programming
# Lecture 10

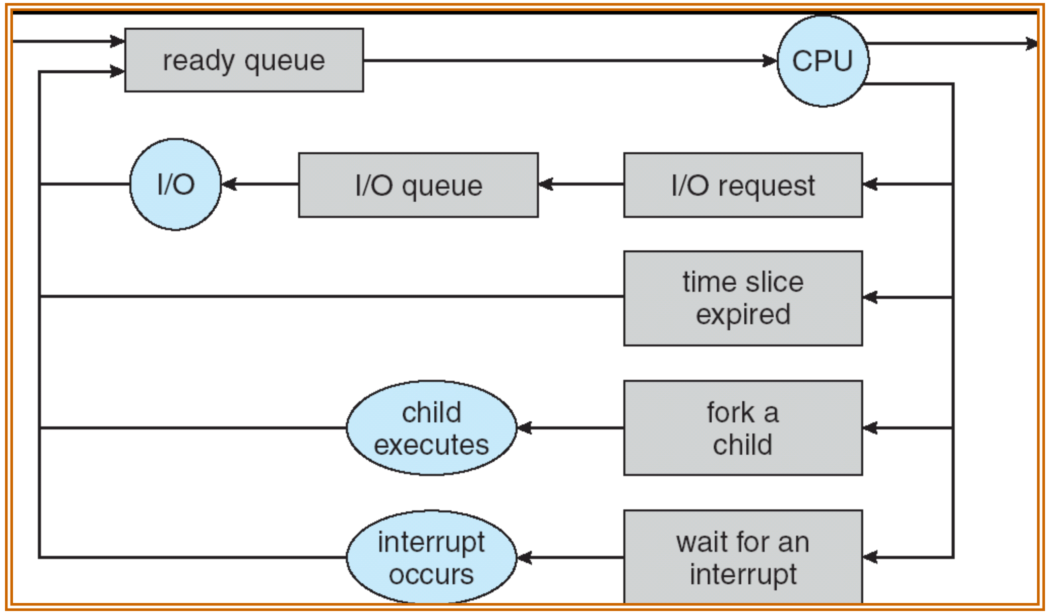
## Scheduling 1: Concepts and Classic Policies

# Goal for Today

```
if ( readyThreads(TCBs) ) {
        nextTCB = selectThread(TCBs);
        run( nextTCB );
} else {
        run_idle_thread();
}
```

- Discussion of Scheduling:
  - Which thread should run on the CPU next?
- Scheduling goals, policies
- Look at a number of different schedulers

# Recall: Scheduling



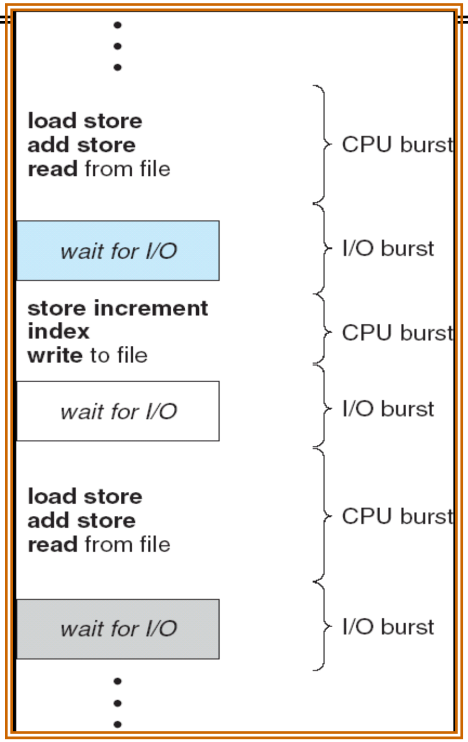

- Question: How is the OS to decide which of several tasks to take off a queue?
- Scheduling: deciding which threads are given access to resources from moment to moment
  - Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

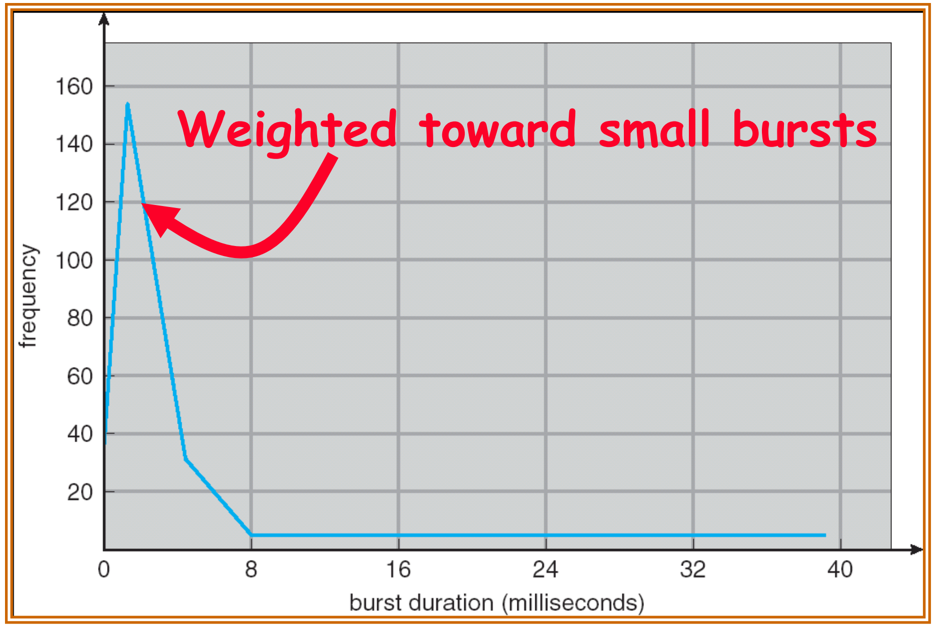
# Scheduling: All About Queues

# Scheduling Assumptions

- Many implicit assumptions for CPU scheduling:
  - One program per user
  - One thread per program
  - Programs are independent
- Clearly, these are unrealistic but they simplify the problem so it can be solved
  - 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

# 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 in next CPU burst
  - With timeslicing, thread may be forced to give up CPU before finishing current CPU burst

# Scheduling Policy Goals/Criteria

- Minimize Response Time
  - Minimize elapsed time to do an operation (or job)
- Maximize Throughput
  - Maximize operations (or jobs) per second
- Fairness
  - Share CPU among users in some equitable way

# 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

- 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

- 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

# Useful metrics

– Waiting time for *P:* time before *P* got scheduled

– Average waiting time:  Average of all processes' wait time.

– Completion time (response time): Waiting time + Run time.

– Average completion time (response time): Average of all processes' completion time

# 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

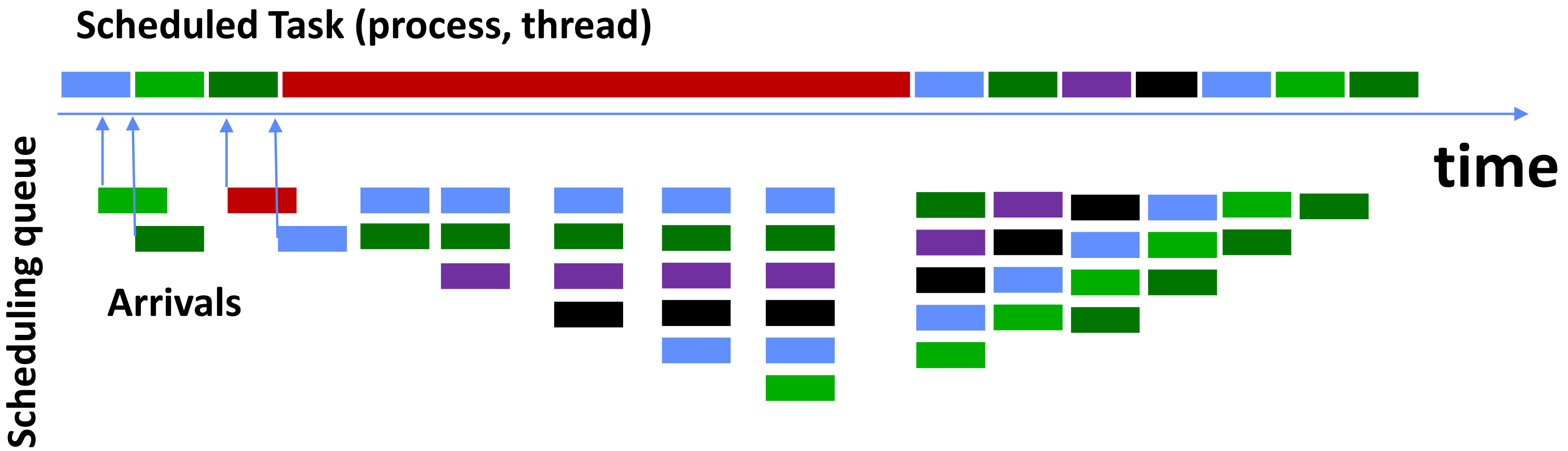
- Example:

| 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:


  - 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 stuck behind long process

# Convoy effect




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

# FCFS Scheduling (Cont.)

- Example continued:
  - Suppose that processes arrive in order: P2 , P3 , P1
    Now, the Gantt chart for the schedule is:


  - Waiting time for P1 = 6; P2 = 0; P3 = 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 (-)

# 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: Preemption!
  - 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

# The magic number

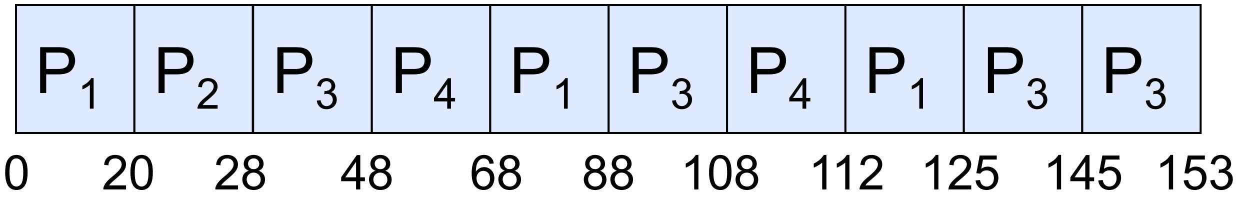
- What should q be?
  - $q$ large ⇒ FCFS
  - $q$ small ⇒ Interleaved
  - $q$ must be large with respect to context switch, otherwise overhead is too high (all overhead)

# 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 $P_1$= 0 + (68-20)+(112-88)=72
  $P_2$=(20-0)=20
  $P_3$=(28-0)+(88-48)+(125-108) + 0 =85
  $P_4$=(48-0)+(108-68)=88

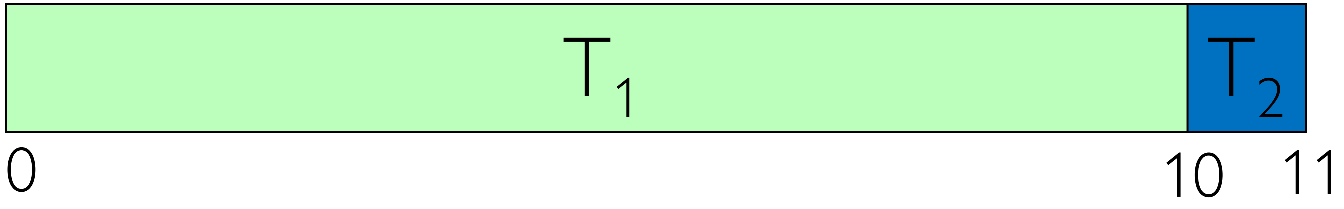
  – Average waiting time = (72+20+85+88)/4=66¼

  – Average completion time = (125+28+153+112)/4 = 104½

# Decrease Response Time

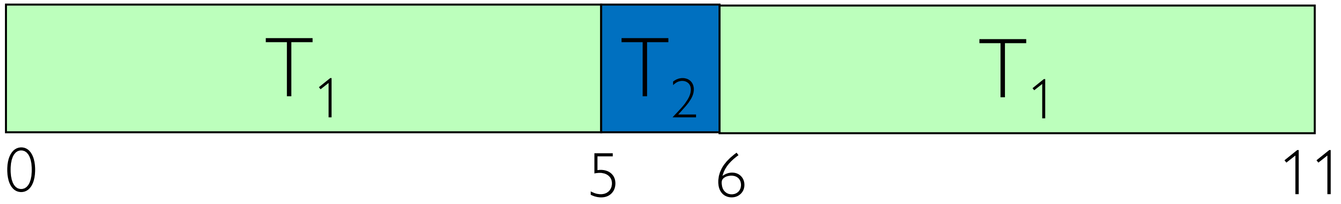
- $T_1$: Burst Length 10
- $T_2$: Burst Length 1

- $Q = 10$




  - Average Response Time = (10 + 11)/2 = 10.5

- $Q = 5$

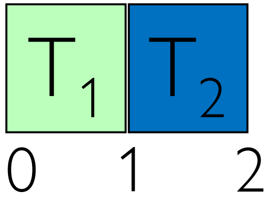



  - Average Response Time = (6 + 11)/2 = 8.5

# Same Response Time

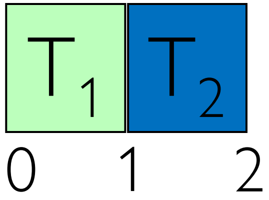
- $T_1$: Burst Length 1
- $T_2$: Burst Length 1

- $Q = 10$




  – Average Response Time = (1 + 2)/2 = 1.5

- $Q = 1$

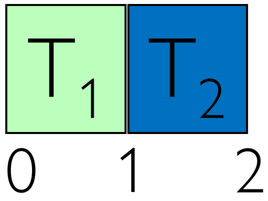



  – Average Response Time = (1 + 2)/2 = 1.5

# Increase Response Time

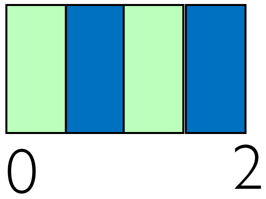
- $T_1$: Burst Length 1
- $T_2$: Burst Length 1

- $Q = 1$




  – Average Response Time = (1 + 2)/2 = 1.5

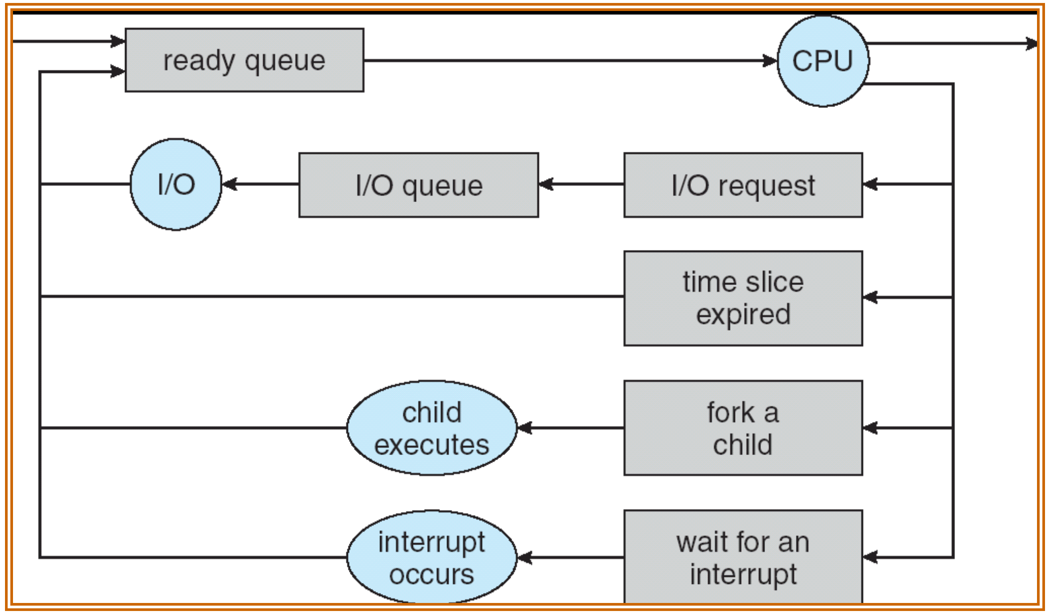
- $Q = 0.5$

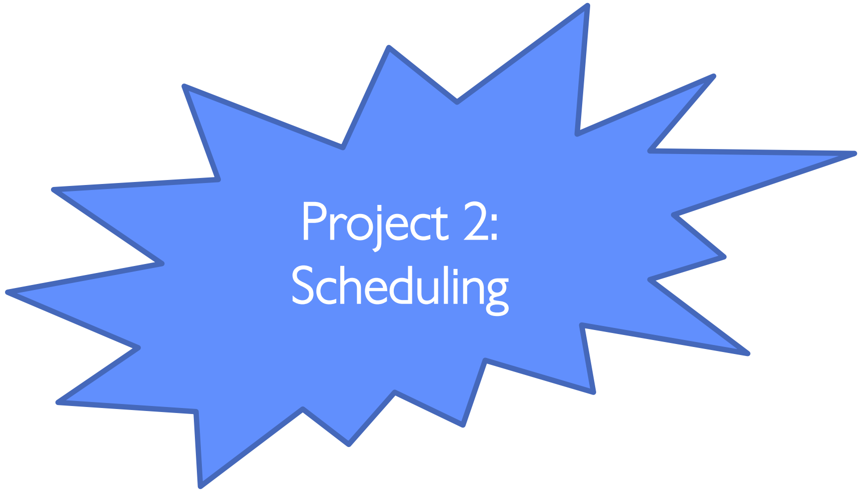



  – Average Response Time = (1.5 + 2)/2 = 1.75

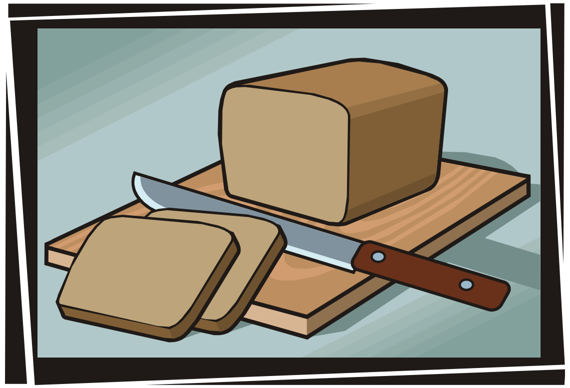
# How to Implement RR in the Kernel?

- FIFO Queue, as in FCFS
- But preempt job after quantum expires, and send it to the back of the queue
  – How? Timer interrupt!
  – And, of course, careful synchronization



# Round-Robin Discussion



- How do you choose time slice?
  - What if too big?
    - » Response time suffers
  - 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!

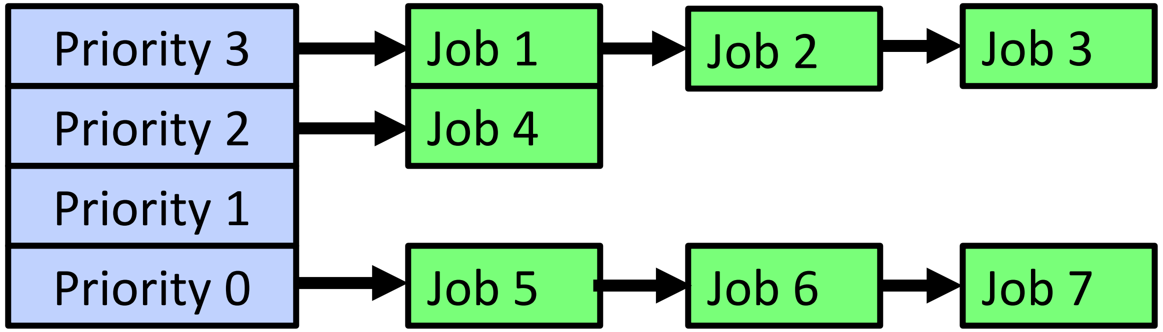
# Earlier Example with Different Time Quantum

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
    - » Happens when low priority task has lock needed by high-priority task
    - » Usually involves third, intermediate priority task preventing high-priority task from running
- 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
    - » Urban legend: In Multics, shut down machine, found 10-year-old job ⇒ Ok, probably not…
  - 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

# 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)

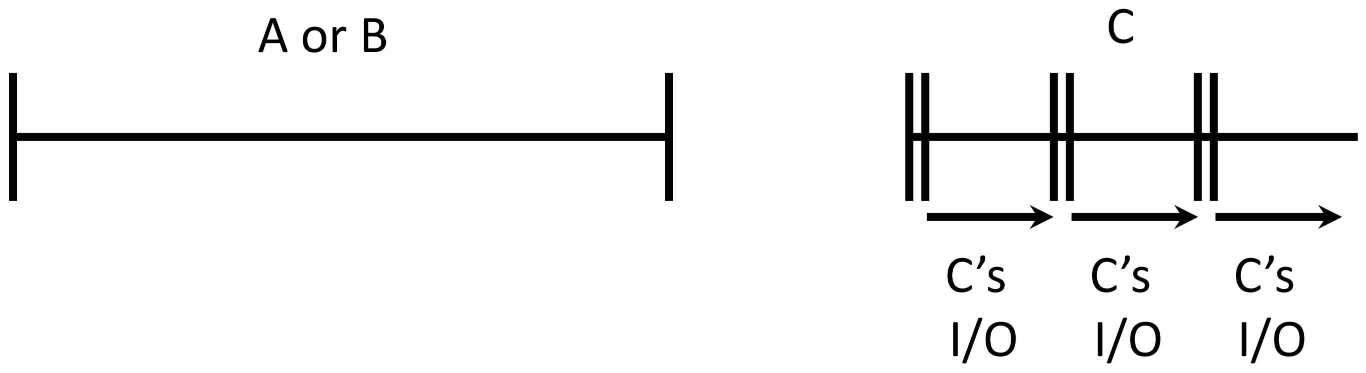
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
  - Sometimes called "Shortest Remaining Time to Completion First" (SRTCF)
- These can be applied to whole program 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

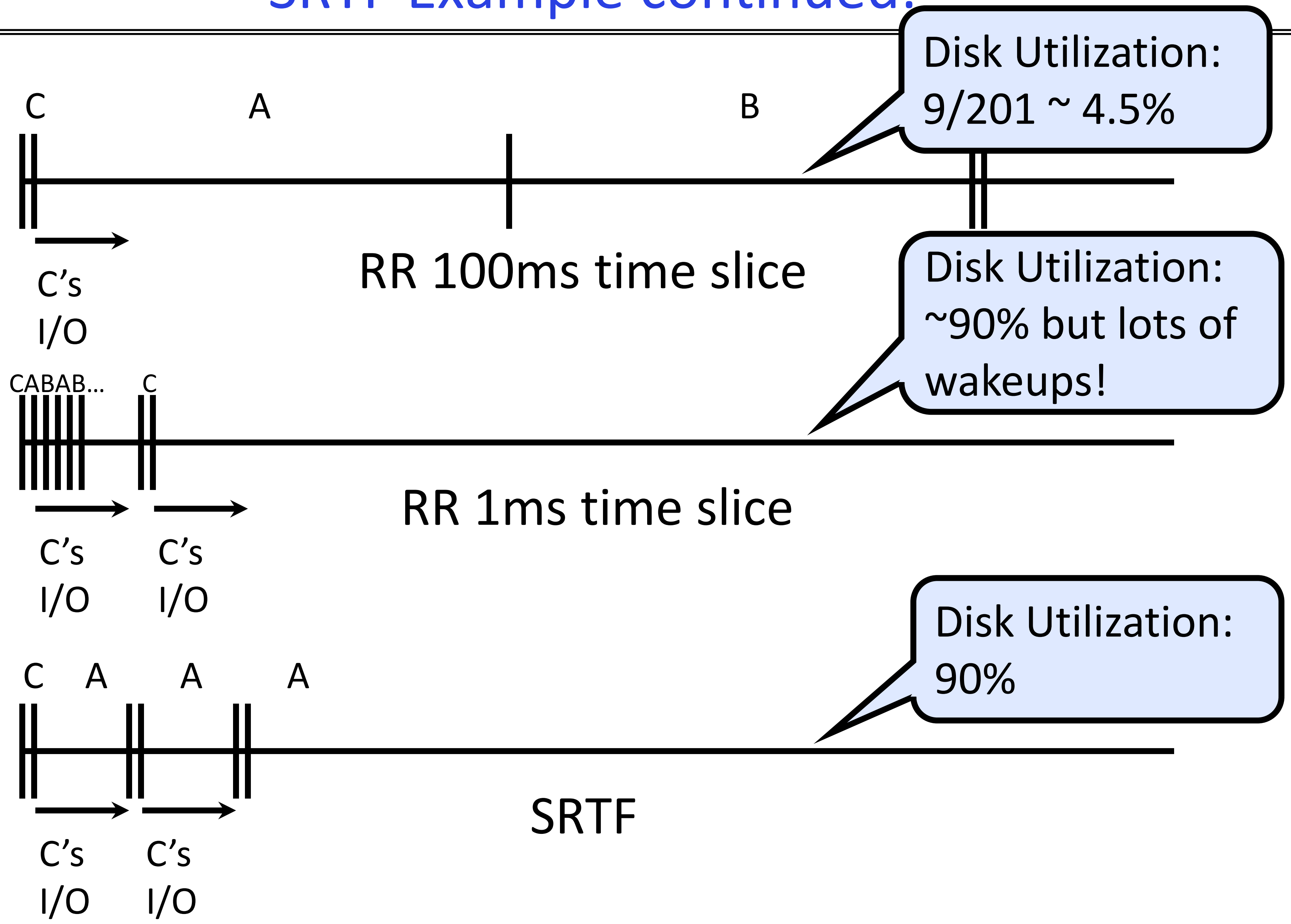
- Comparison of SRTF with FCFS
  - What if all jobs the same length?
    - » SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - » SRTF: short jobs not stuck behind long ones

# 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 FCFS:
  - 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:

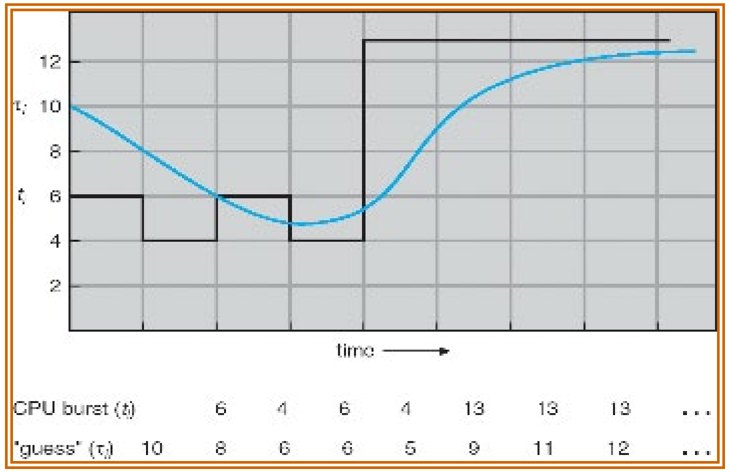


# SRTF Further discussion

- 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
- 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 $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  - 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 $(0<\alpha\leq 1)$



# 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.)

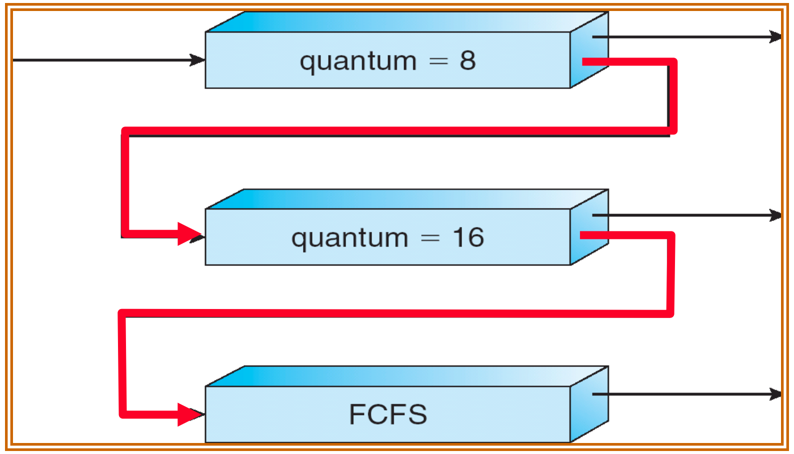
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

| # 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

# Multi-Level Feedback Scheduling

- Multiple queues, each with different priority
  - 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. Otherwise, push up one level

# 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 the 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!

# Multi-Core Scheduling

- Algorithmically, not a huge difference from single-core scheduling
- Implementation-wise, helpful to have *per-core* scheduling data structures
  - Cache coherence
- *Affinity scheduling*: once a thread is scheduled on a CPU, OS tries to reschedule it on the same CPU
  - Cache reuse

# How to Handle Simultaneous Mix of Diff Types of Apps?

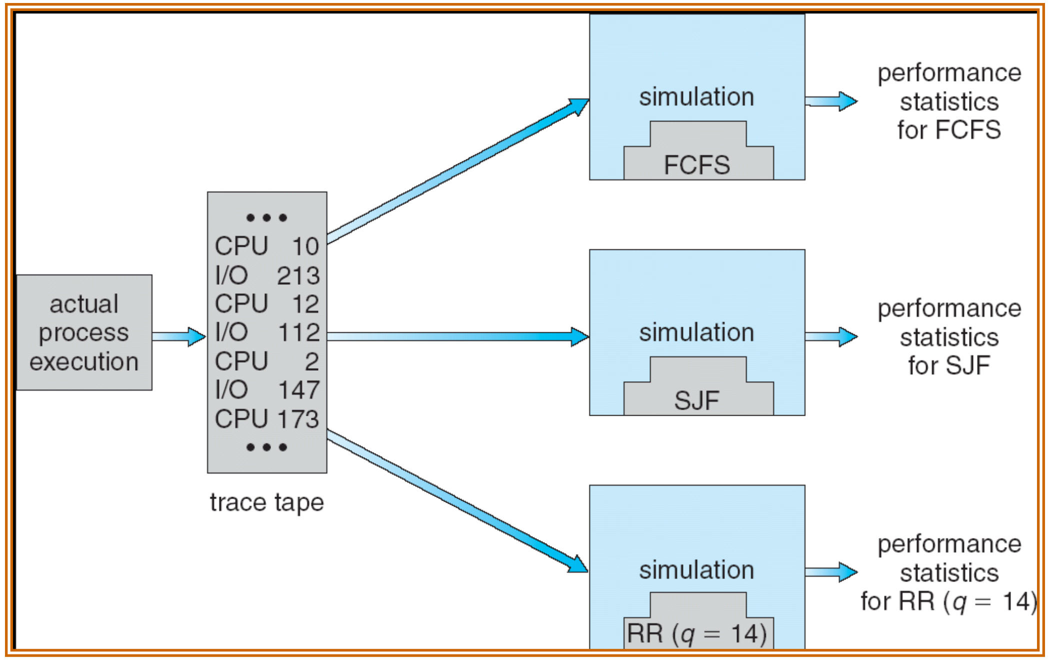
- Consider mix of interactive and high throughput apps:
  - How to best schedule them?
  - How to recognize one from the other?

- For instance, is Burst Time (observed) useful to decide which application gets CPU time?
  - Short Bursts $\Rightarrow$ Interactivity $\Rightarrow$ High Priority?

- 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

# 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



# So, Does the OS Schedule Processes or Threads?

- Many textbooks use the “old model”—one thread per process
- Usually it's really: **threads** (e.g., in Linux)
- One point to notice: switching threads vs. switching processes incurs different costs:
  - Switch threads: Save/restore registers
  - Switch processes: Change active address space too!
    - » Expensive
    - » Disrupts caching

# Conclusion

- 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
- Multi-Level Feedback Scheduling:
  – Multiple queues of different priorities and scheduling algorithms
  – Automatic promotion/demotion of process priority in order to approximate SJF/SRTF
- Lottery Scheduling:
  – Give each thread a priority-dependent number of tokens (short tasks⇒more tokens)