CS162
Operating Systems and Systems Programming
Lecture 8

Thread Scheduling

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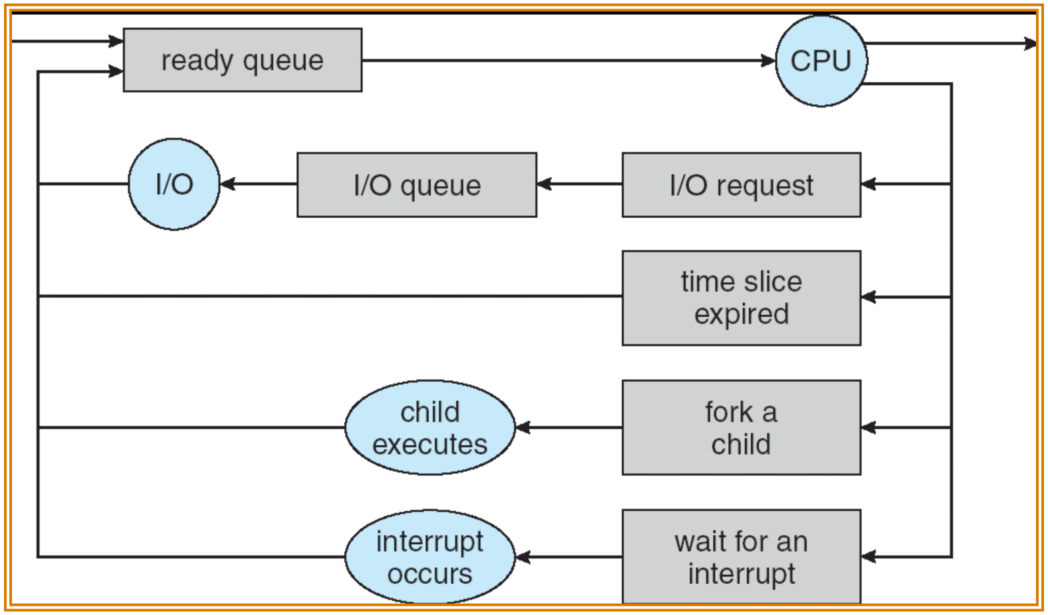
Goals for Today

- Scheduling Policy goals
- Policy Options
- Implementation Considerations

CPU Scheduling

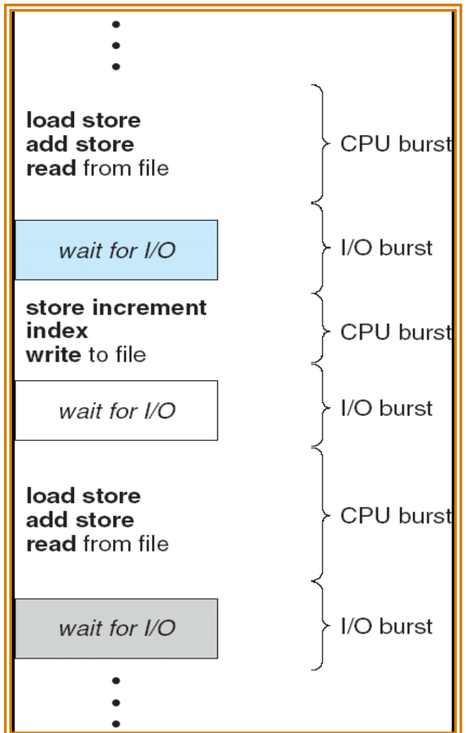


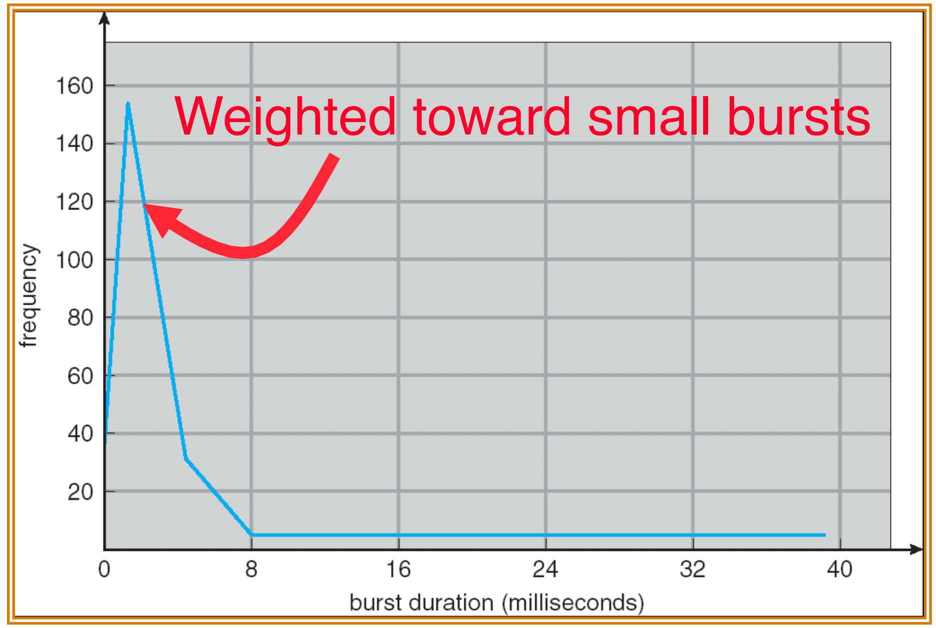
- Earlier, we talked about the life-cycle of a thread
  – Active threads work their way from Ready queue to Running to various waiting queues.
- Question: How is the OS to decide which of several threads to take off a queue?
  – Obvious queue to worry about is ready queue
  – Others can be scheduled as well, however
- Scheduling: deciding which threads are given access to resources

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
- In general 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

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 Metrics

- **Waiting Time**: time the job is waiting in the ready queue
  - Time between job's arrival in the ready queue and launching the job
- **Service (Execution) Time**: time the job is running
- **Response (Completion) Time**:
  - Time between job's arrival in the ready queue and job's completion
  - Response time is what the user sees:
    - » Time to echo a keystroke in editor
    - » Time to compile a program

Response Time = Waiting Time + Service Time

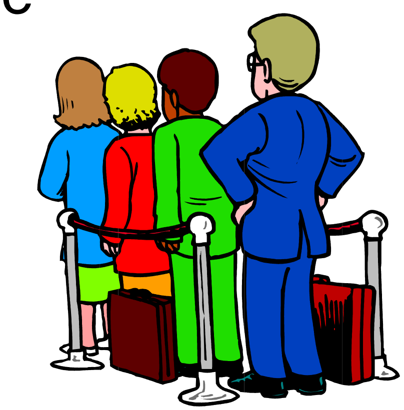
- **Throughput:** number of jobs completed per unit of time
  - Throughput related to response time, but not same thing:
    - » Minimizing response time will lead to more context switching than if you only maximized throughput

Scheduling Policy Goals/Criteria

- Minimize Response Time
  - Minimize elapsed time to do an operation (or job)
- Maximize Throughput
  - Two parts to maximizing throughput
    - » Minimize overhead (for example, context-switching)
    - » Efficient use of resources (CPU, disk, memory, etc)
- 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

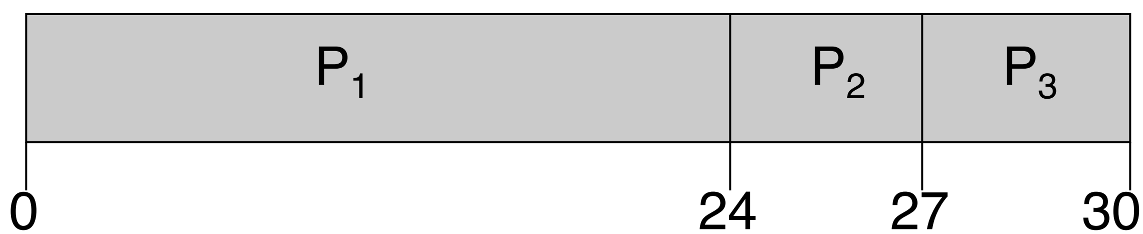
- First-Come, First-Served (FCFS)
  - Also "First In, First Out" (FIFO) or "Run until done"
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks



- 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:



  - 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, 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
  - 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)
- FCFS 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)

- 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
- Performance
  - q large $\Rightarrow$ FCFS
  - q small $\Rightarrow$ 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	Remaining Time
P_1	53	53
P_2	8	8
P_3	68	68
P_4	24	24

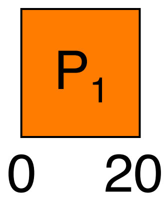
  – The Gantt chart is:

Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
P_1	53	33
P_2	8	8
P_3	68	68
P_4	24	24

  – The Gantt chart is:



Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
P_1	53	33
P_2	8	0
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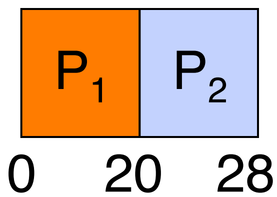
  – The Gantt chart is:

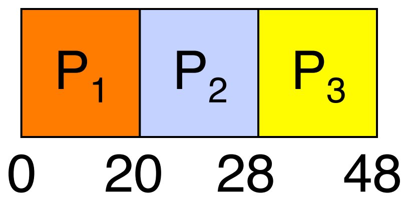


Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
P_1	53	33
P_2	8	0
P_3	68	48
P_4	24	24

  – The Gantt chart is:

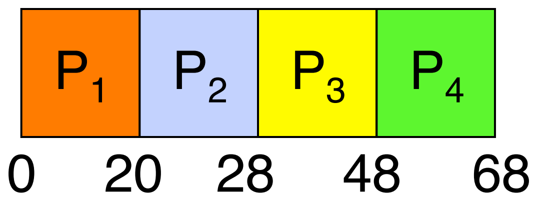


Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
P_1	53	33
P_2	8	0
P_3	68	48
P_4	24	4

  – The Gantt chart is:



Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
P_1	53	13
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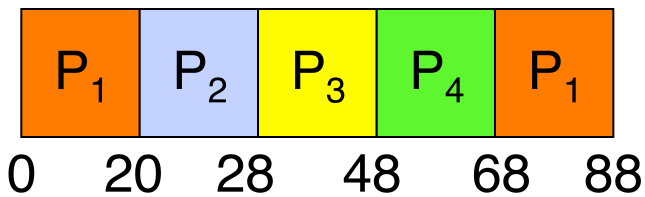
  – The Gantt chart is:



Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
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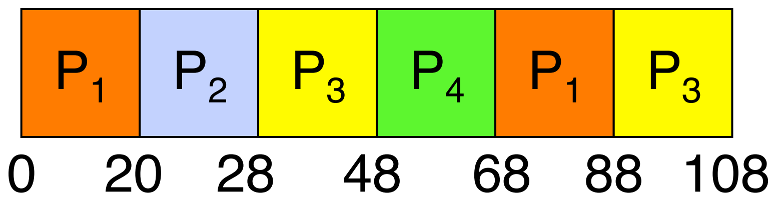


Example of RR with Time Quantum = 20

- Example:

Process	Burst Time	Remaining Time
P_1	53	0
P_2	8	0
P_3	68	0
P_4	24	0

– 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

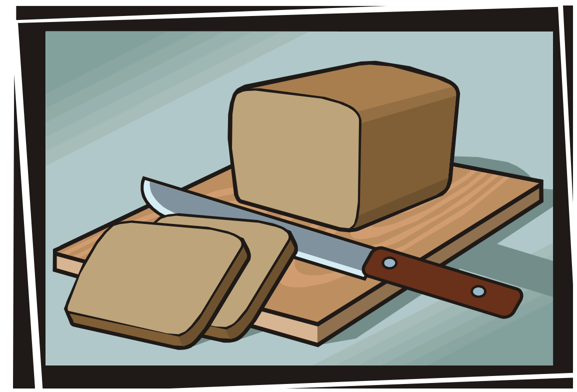
– Average waiting time = (72+20+85+88)/4=66¼

– 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

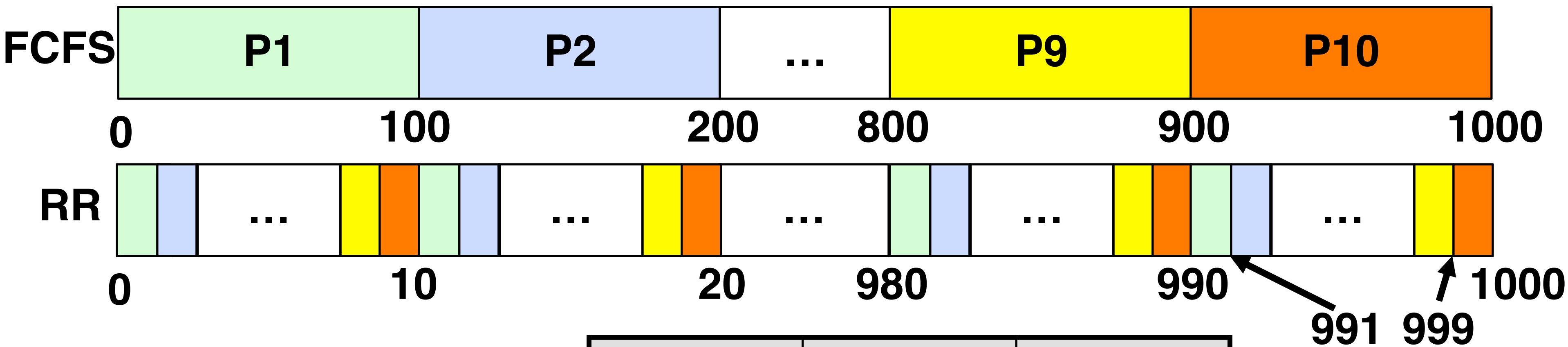
- How do you choose time slice?
  – What if too big?
    » Response time suffers
  – What if infinite (∞)?
    » Get back FCFS/FIFO
  – What if time slice too small?
    » Throughput suffers!



- 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!
  – In practice, 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 takes 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time



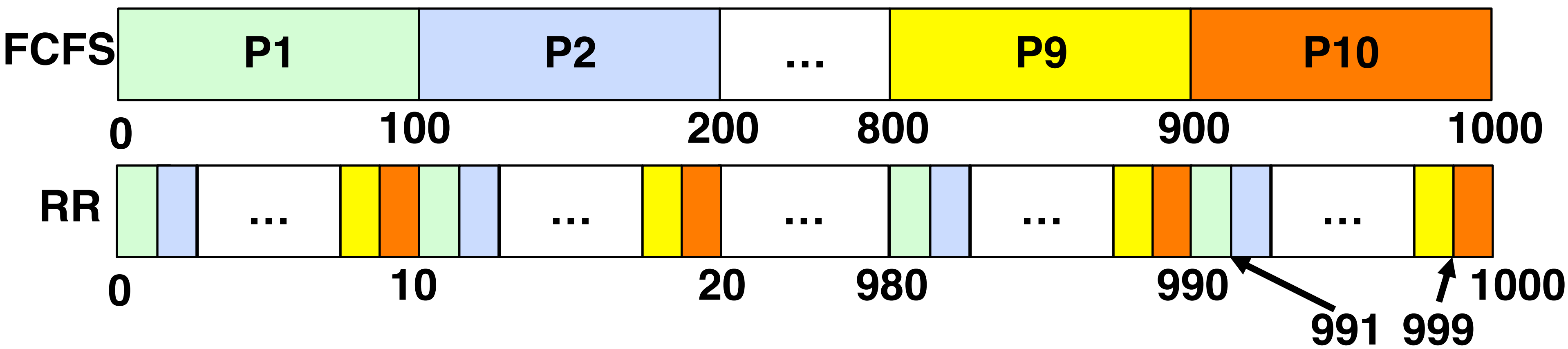
- Completion Times:

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

Comparisons between FCFS and Round Robin

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

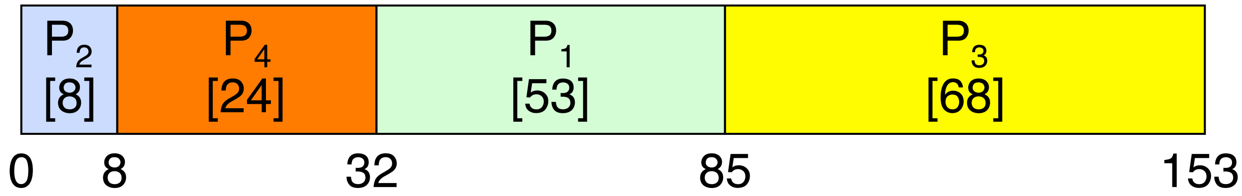
10 jobs, each takes 100s of CPU time
RR scheduler quantum of 1s
All jobs start at the same time



- 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 FCFS
  – Total time for RR longer even for zero-cost switch!

Earlier Example with Different Time Quantum

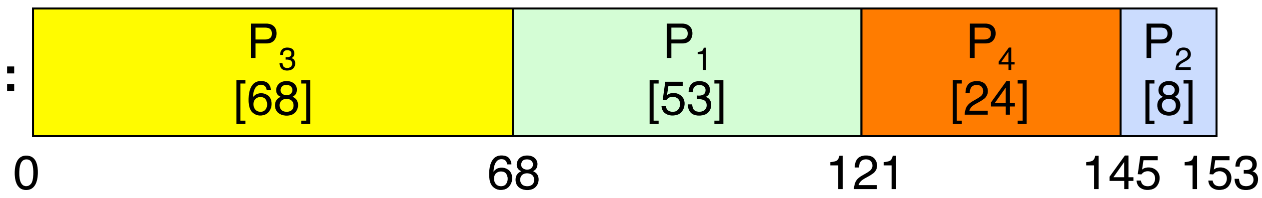
Best FCFS:



	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	31¼
Completion Time	Best FCFS	85	8	153	32	69½

Earlier Example with Different Time Quantum

Worst FCFS:



	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	Worst FCFS	68	145	0	121	83½
Completion Time	Best FCFS	85	8	153	32	69½
	Worst FCFS	121	153	68	145	121¾

Earlier Example with Different Time Quantum

Worst FCFS:

P_3 [68]	P_1 [53]	P_4 [24]	P_2 [8]
0 – 68	68 – 121	121 – 145	145 – 153

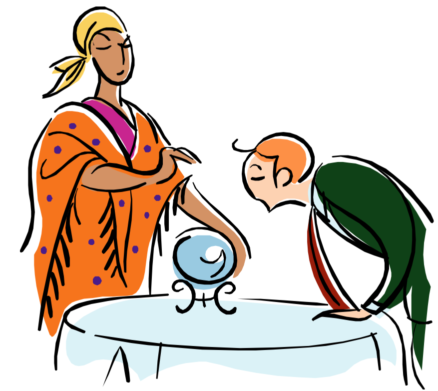
P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_1	P_3	P_1	P_3	P_1	P_3	P_3	P_3

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

	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	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

5min Break

What if we Knew the Future?

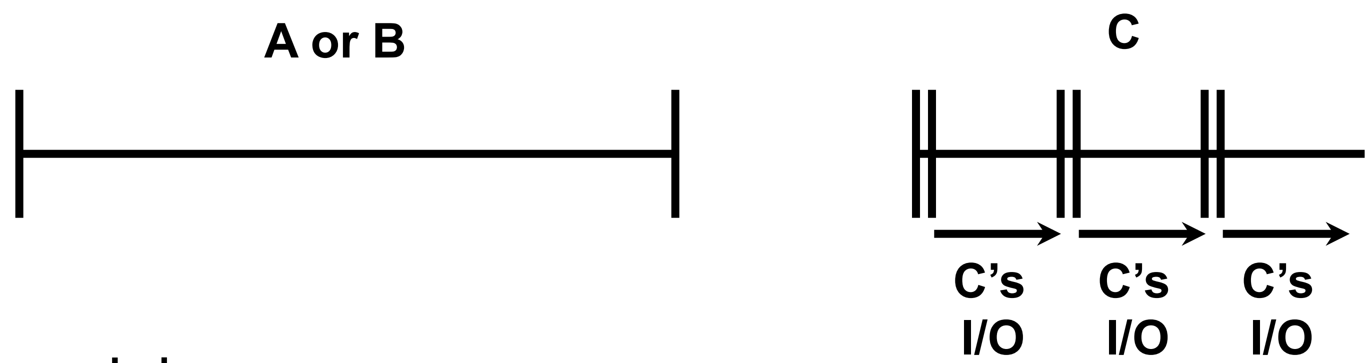


- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  – Run whatever job has the least amount of computation to do
- Shortest Remaining Time First (SRTF):
  – Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
- These can be applied either to a whole program or the current CPU burst of each program
  – 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

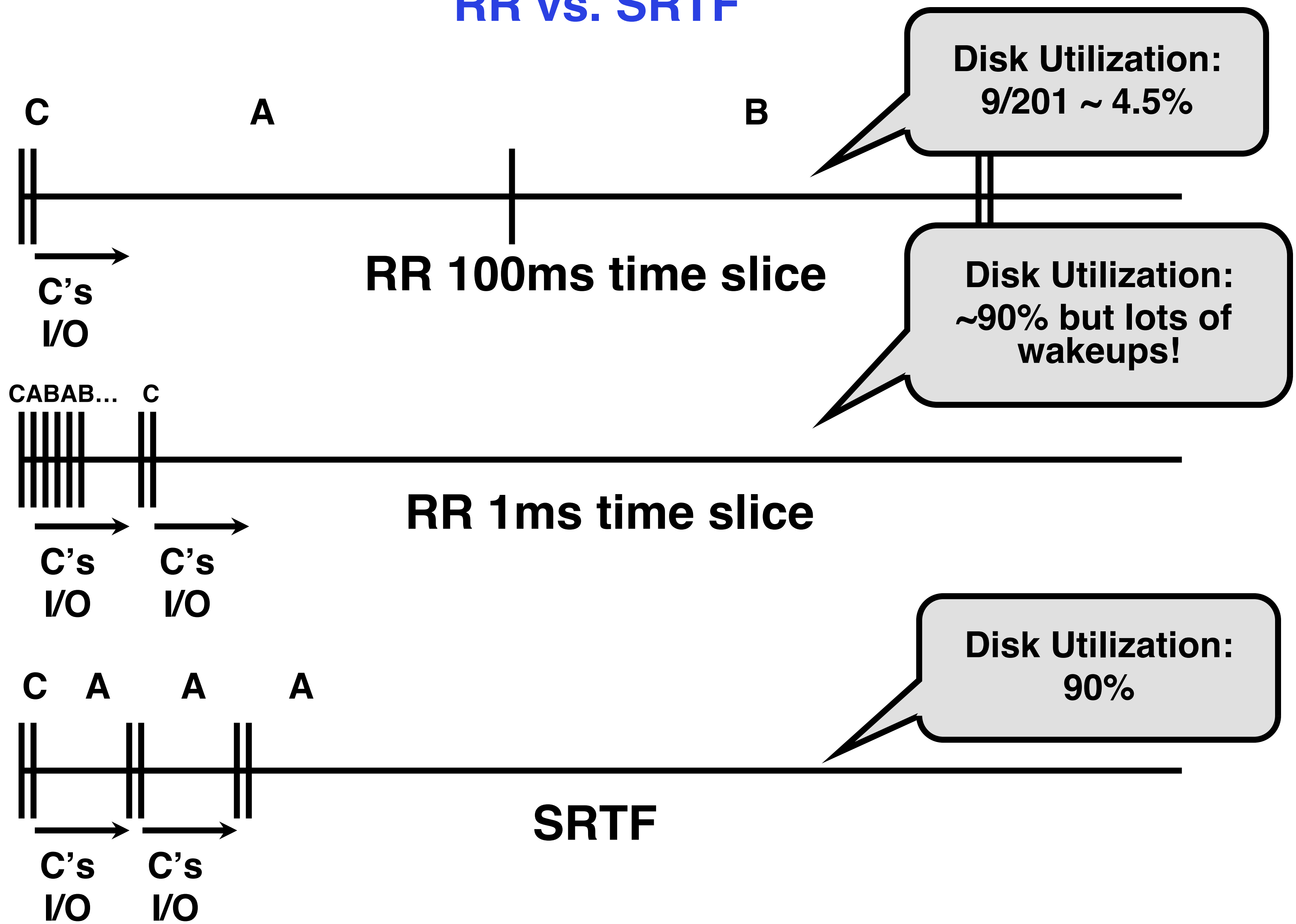
- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS and RR
  - What if all jobs the same length?
    - » SRTF becomes 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: CPU bound, each run for a 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 use 100% of the CPU
- With FIFO:
  - Once A or B get in, keep CPU for one week each
- What about RR or SRTF?
  - Easier to see with a timeline

RR vs. SRTF



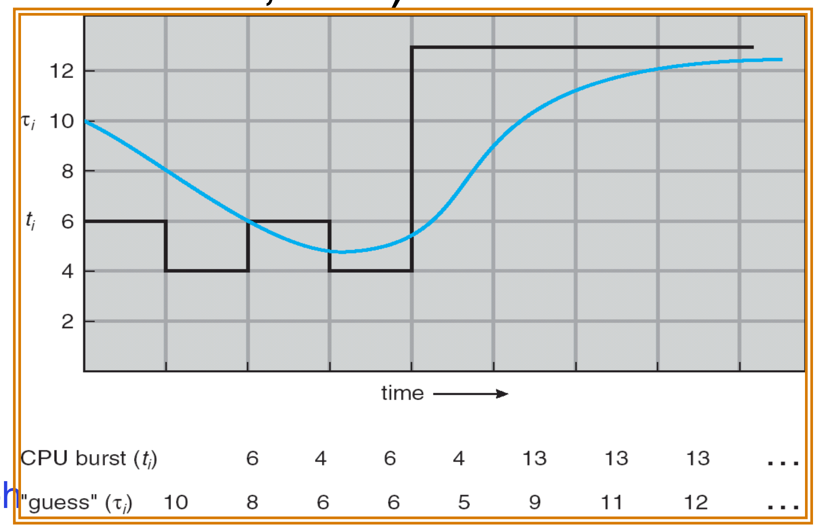
C
A
B
Disk Utilization:
9/201 ~ 4.5%
C's
I/O
RR 100ms time slice
Disk Utilization:
~90% but lots of
wakeups!
CABAB… C
RR 1ms time slice
C's
I/O
C's
I/O
Disk Utilization:
90%
C A A A
SRTF
C's
I/O
C's
I/O

SRTF Further discussion

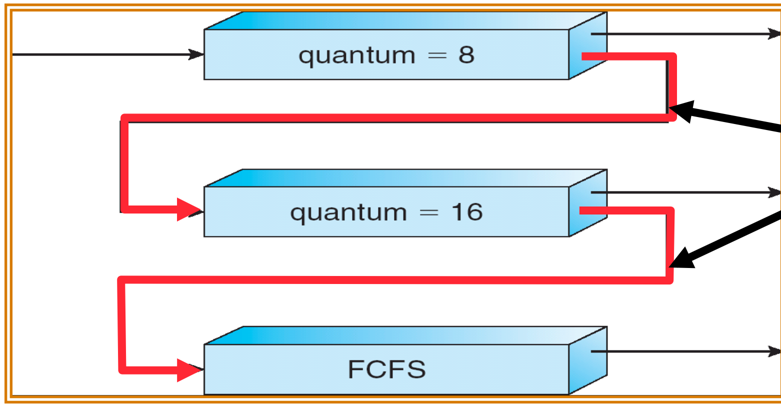
- Starvation
  - SRTF can lead to starvation if many small jobs!
  - Large jobs never get to run
- Somehow need to predict future
  - How can we do this?
  - Some systems ask the user
    - » When you submit a job, have to say how long it will take
    - » To stop cheating, system kills job if takes too long
  - But: even non-malicious users have trouble predicting runtime of their jobs
- 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.)
  - Example: Exponential averaging $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$ with $(0<\alpha\leq1)$



Multi-Level Feedback Scheduling



Long-Running Compute tasks demoted to low priority

- Another method for exploiting past behavior
  - First used in Cambridge Time Sharing System (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

Countermeasure

- Countermeasure: user action that can foil intent of the OS designer
  - 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!
- Ex: MIT Othello game project (simpler version of Go game)
  - Computer playing against competitor's computer, so key was to do computing at higher priority the competitors.
    - » Cheater put in printf's, ran much faster!

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 average response time!
- 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 UNIX
    - » This is ad hoc—what rate should you increase priorities?

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

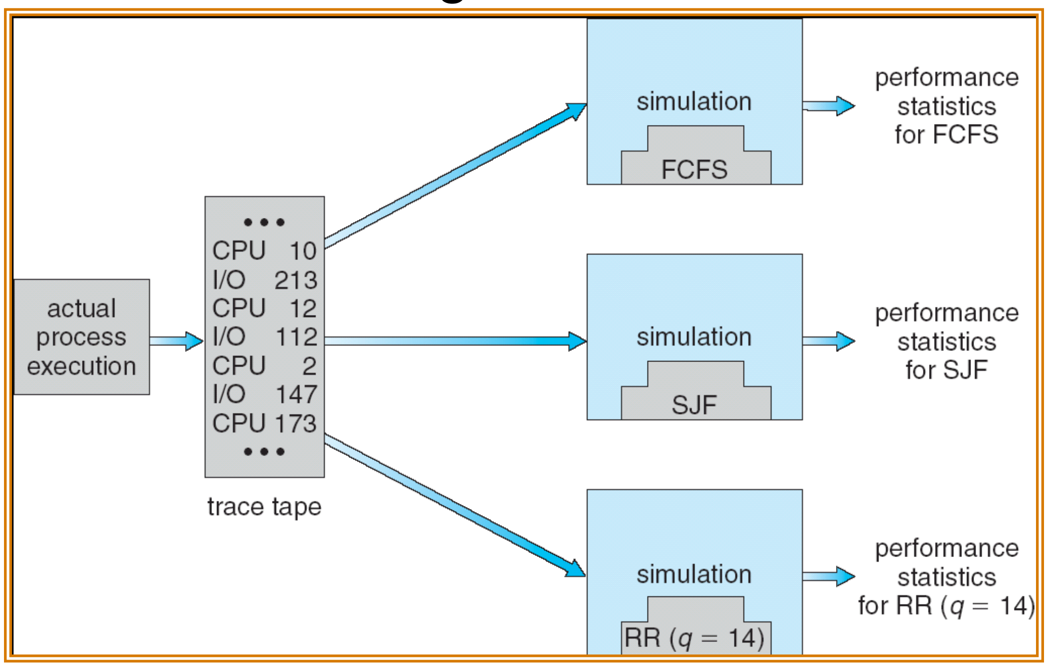
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# 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?
    - » In UNIX, if load average is 100, hard to make progress
    - » One approach: log some user out

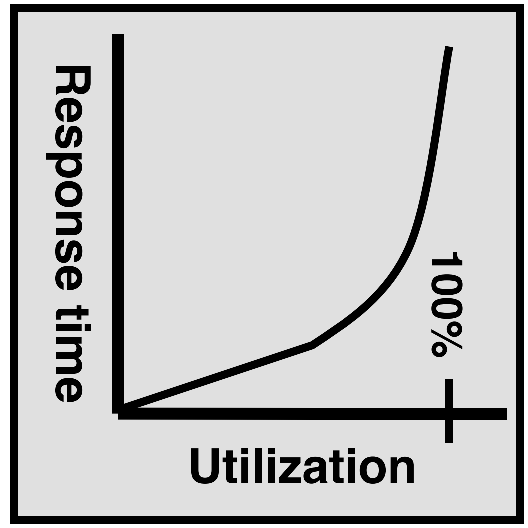
How to Evaluate a Scheduling algorithm?

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



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

- Scheduling: selecting a process from the ready queue and allocating the CPU to it
- FCFS Scheduling:
  - Run threads to completion in order of submission
  - Pros: Simple (+)
  - Cons: Short jobs get stuck behind long ones (-)
- 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 (+)
  - Cons: Poor when jobs are same length (-)

Summary (cont'd)

- 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
  - Automatic promotion/demotion of process priority in order to approximate SJF/SRTF
- Lottery Scheduling:
  - Give each thread a number of tokens (short tasks $\Rightarrow$ more tokens)
  - Reserve a minimum number of tokens for every thread to ensure forward progress/fairness