Operating Systems
(1DT020 & 1TT802)

Lecture 4
Process scheduling

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http://www.it.uu.se/edu/course/homepage/os/vt08

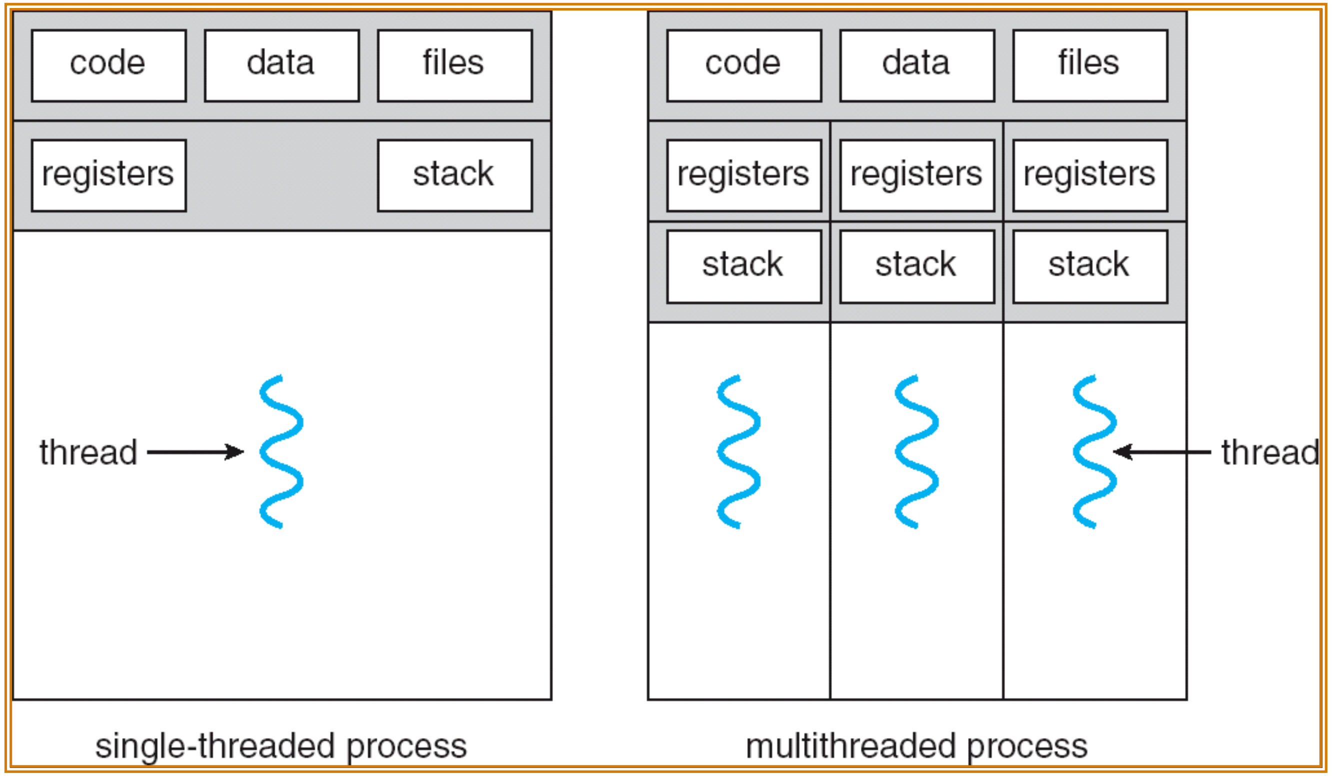
Review : Operating systems, processes

- An Operating system performs two tasks:
  - Provide virtual machine abstractions (Turn hardware/software peculiarities into what programmers want/need)
  - Resources (Hardware and Software) management, sharing and protection (Optimize for convenience, utilization, security, reliability, etc.)

- Traditional unix Process: *Operating system abstraction to represent what is needed to run a single program*
  - Sequential Program Execution Stream or thread (includes CPU registers)
  - Protected Resources : Main Memory State (contents of Address Space) and I/O state (i.e. file descriptors)

- Separate address spaces isolates processes : the OS must provide Inter-Process Communication mechanism (IPC) for process cooperation:
  - Shared-Memory Mapping accomplished by mapping addresses to common DRAM
  - Message Passing using explicit `send()` and `receive()`
  - Others mechanisms

Review : Single and Multithreaded Processes



- Threads encapsulate concurrency: “Active” component
- Address spaces encapsulate protection: “Passive” part
  - Keeps buggy program from trashing the system

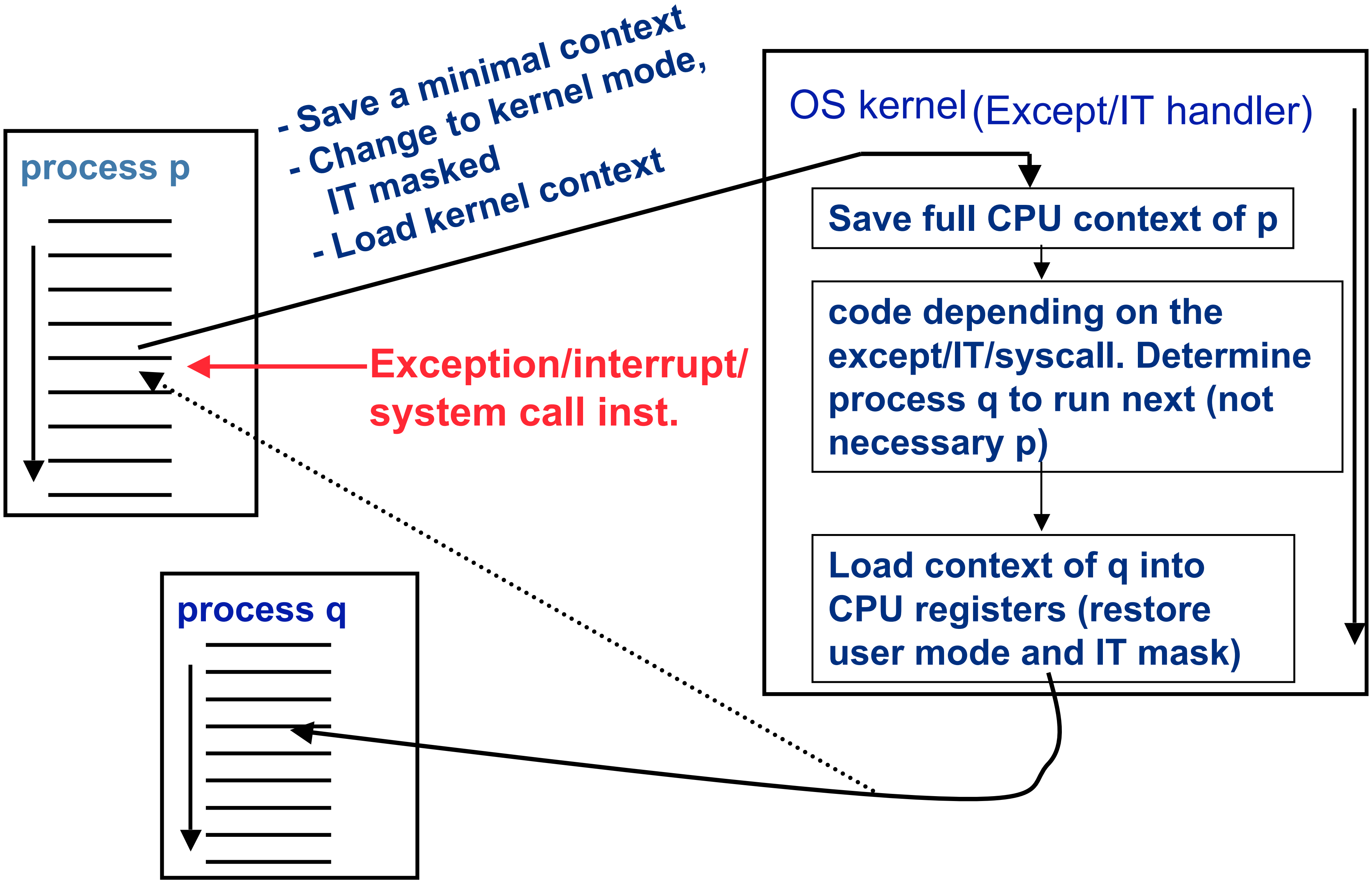
Review : How do we multiplex processes?

- The current state of process held in a process control block (PCB):
  - This is a “snapshot” of the execution and protection environment
  - Only one PCB active at a time
- Give out CPU time to different processes (CPU Scheduling or Process dispatching):
  - Only one process “running” at a time
  - Give more time to important processes
- Give pieces of resources to different processes (Protection):
  - Controlled access to non-CPU resources
  - Sample mechanisms:
    - » Memory Mapping: Give each process their own address space
    - » Kernel/User duality: Arbitrary multiplexing of I/O through system calls

pointers	process state
process id	
program counter	
other registers	
memory limits	
list of open files	
⋮	

Process Control Block

OS kernel : an exception/interrupt/syscall handler



process p

- Save a minimal context
- Change to kernel mode,
  IT masked
- Load kernel context

Exception/interrupt/
system call inst.

OS kernel (Except/IT handler)

Save full CPU context of p

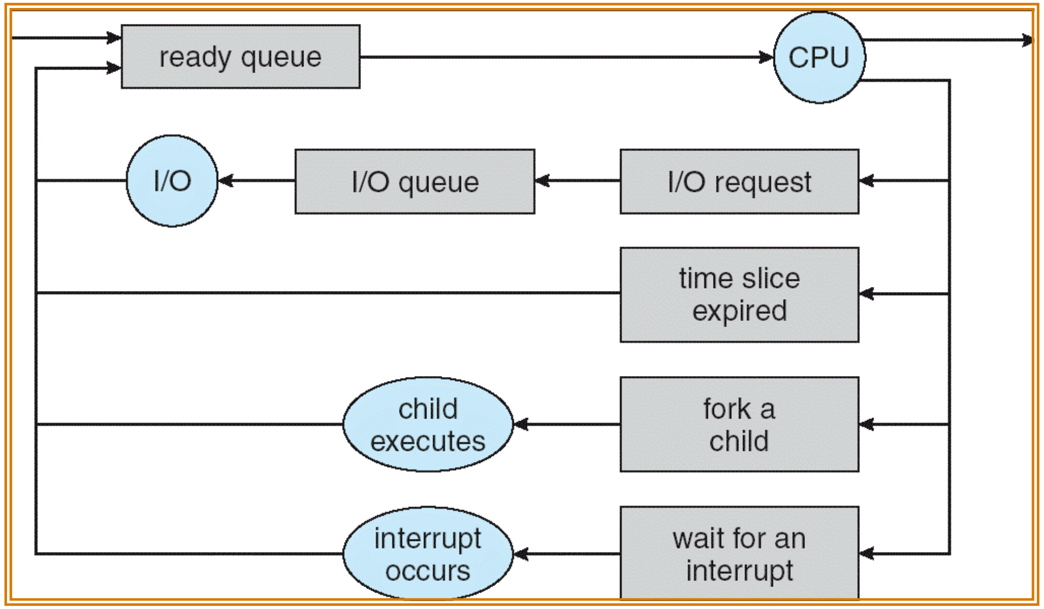
code depending on the except/IT/syscall. Determine process q to run next (not necessary p)

Load context of q into CPU registers (restore user mode and IT mask)

process q

- A timer interrupt forces preemptive process switching

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 tasks 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 from moment to moment

Goals for Today

- **Scheduling Policy goals**
- **Policy Options**
- **Implementation Considerations**

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne, others from Kubiatowicz - CS162 ©UCB Fall 2007 (University of California at Berkeley)

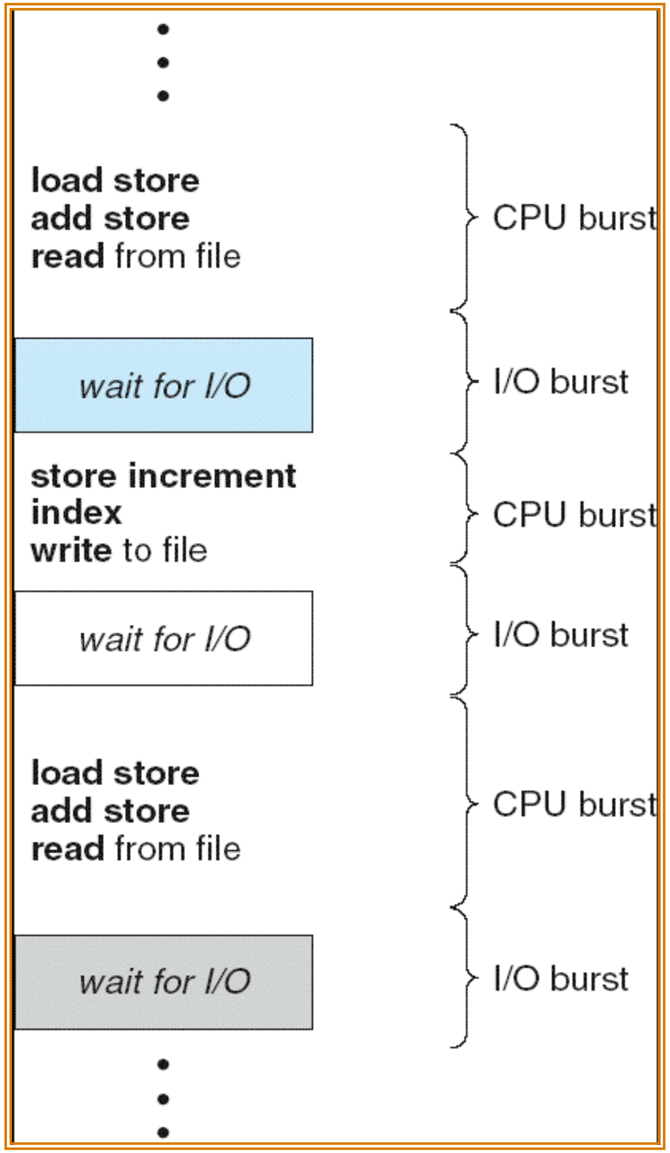
Scheduling Assumptions

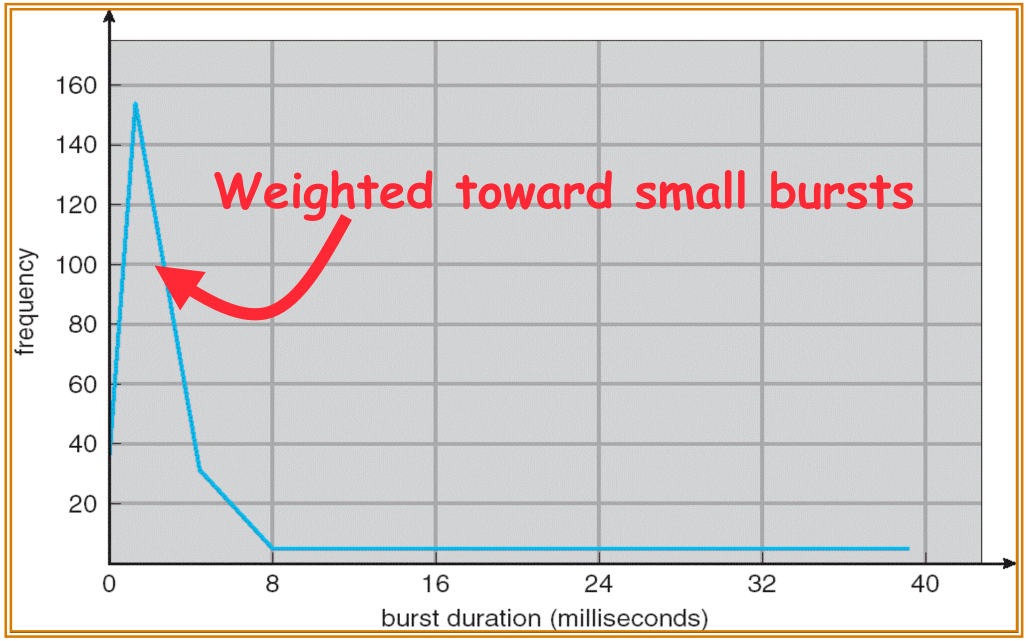
- CPU scheduling big area of research in early 70’s
- Many implicit assumptions for CPU scheduling:
  - One program per user
  - One thread per program
  - Programs are independent
- Clearly, these are unrealistic but they simplify the problem so it can be solved
  - For instance: is “fair” about fairness 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: Give out CPU time to optimize some desired parameters of system

USER1 USER2 USER3 USER1 USER2

Time

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 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
- 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)
- 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:

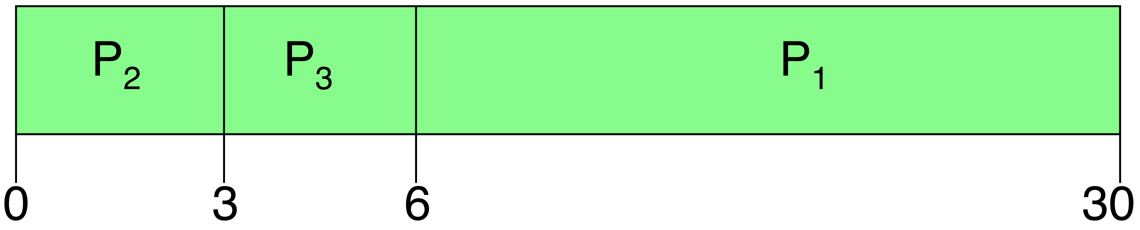
Process	Burst Time
P_1	24
P_2	3
P_3	3

  - 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)
- **FIFO Pros and Cons:**
  - Simple (+)
  - Short jobs get stuck behind long ones (-)

Round Robin (RR)

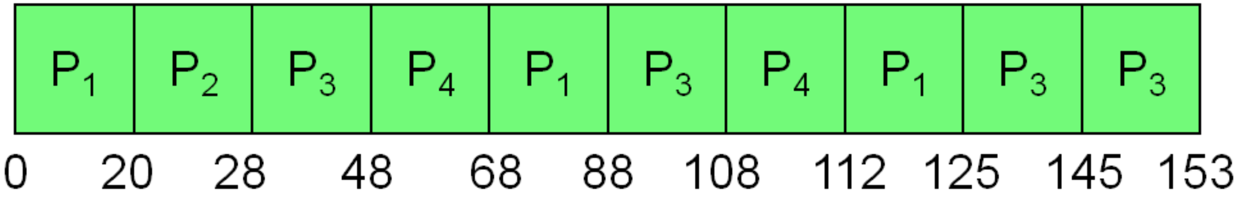
- **FCFS Scheme: Potentially bad for short jobs!**
  - Depends on submit order
  - If you are first in line at supermarket with milk, you don't care who is behind you, on the other hand…
- **Round Robin Scheme**
  - Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds
  - 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 ⇒ FCFS
  - q small ⇒ Interleaved (really small ⇒ hyperthreading?)
  - q must be large with respect to context switch, otherwise overhead is too high (all overhead)

Example of RR with Time Quantum = 20

- **Example:**

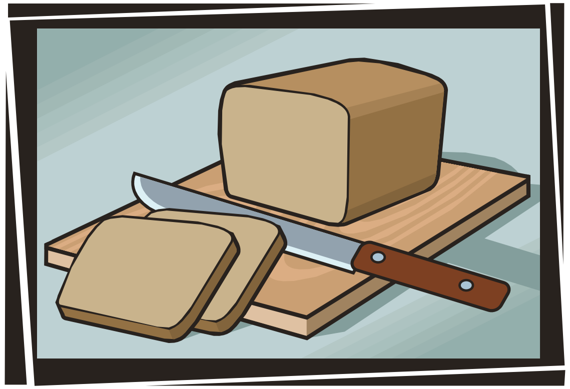
Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

  - The Gantt chart is:



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

Round-Robin discussion



- How do you choose time slice?
  - What if too big?
    - Response time suffers
  - What if infinite (∞)?
    - Get back FIFO
  - What if time slice too small?
    - Throughput suffers!
- Actual choices of timeslice:
  - Initially, UNIX timeslice one second:
    - Worked ok when UNIX was used by one or two people.
    - What if three compilations going on? 3 seconds to echo each keystroke!
  - 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:

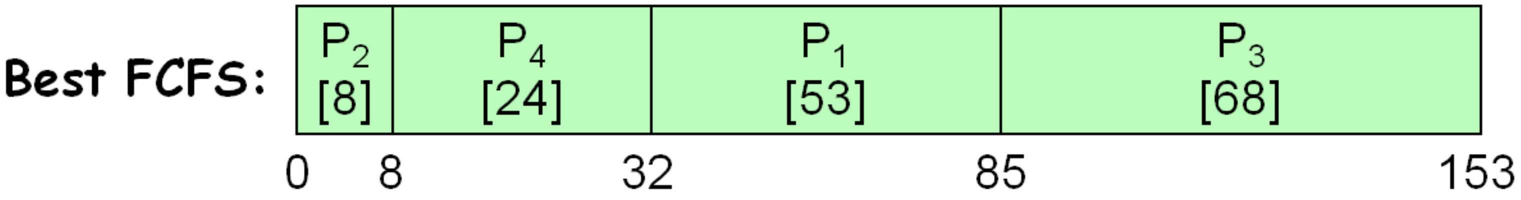
  10 jobs, each take 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time

- 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



	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	$121\frac{3}{4}$

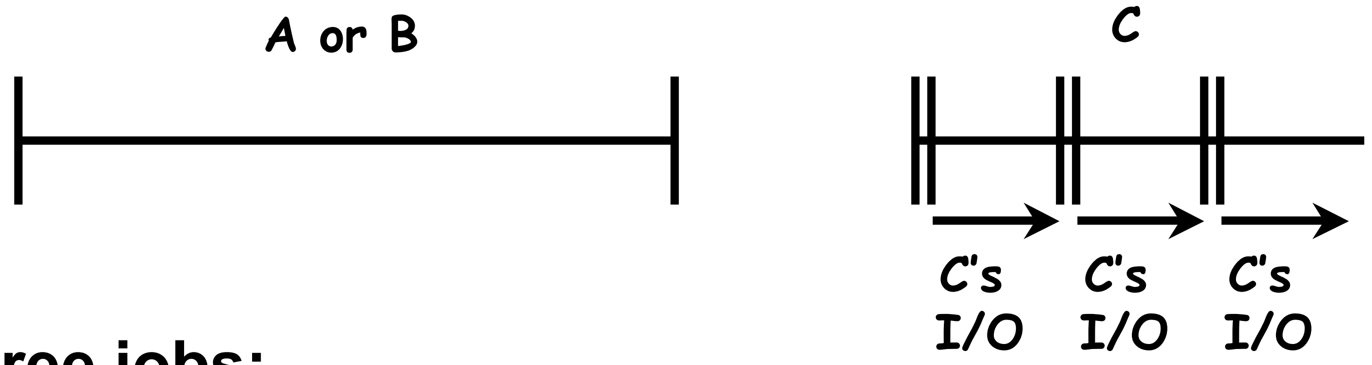
What if we knew the future?

- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Run whatever job has the least amount of computation to do
  - 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 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

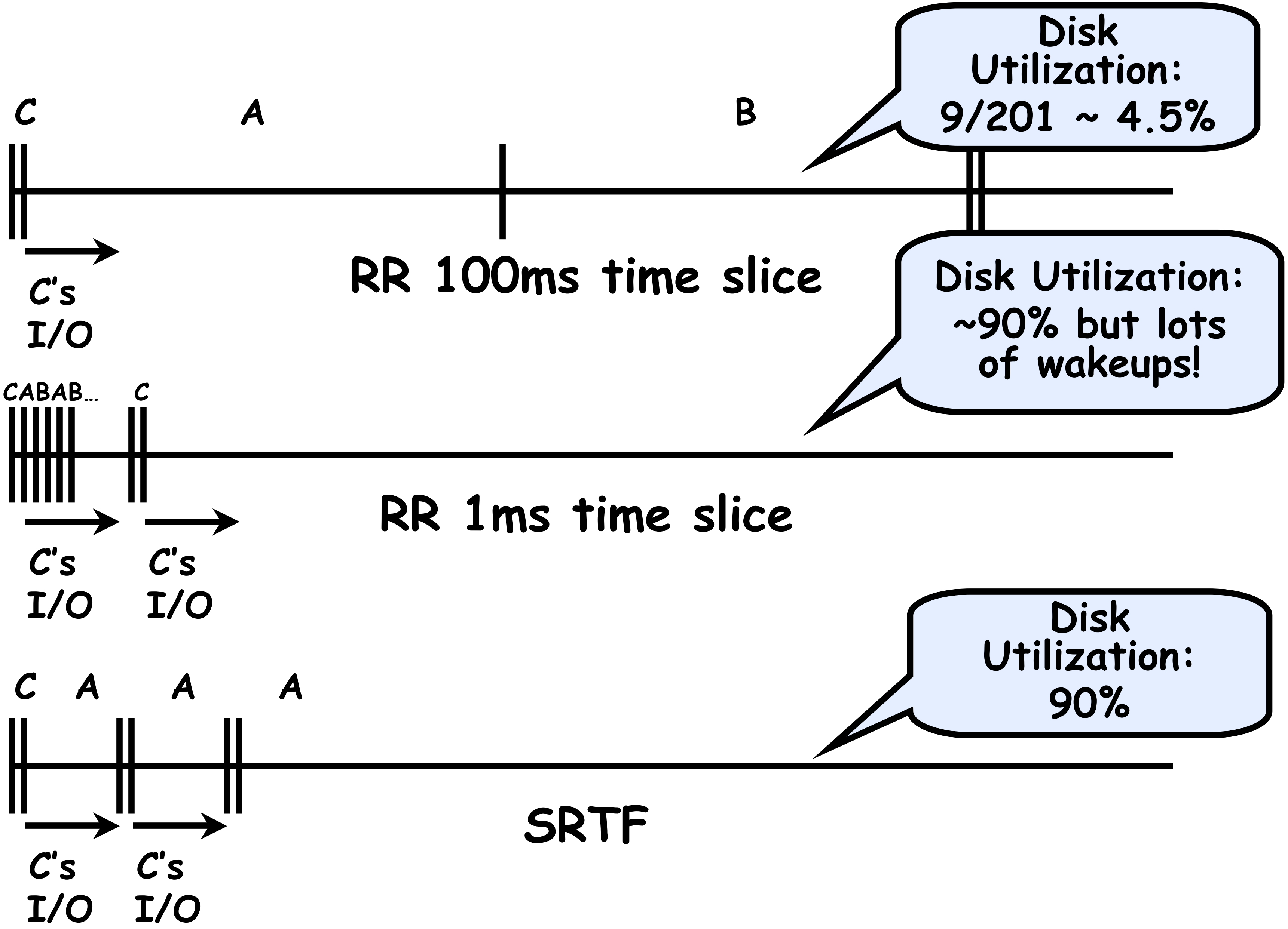
- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS and RR
  - What if all jobs the same length?
    - SRTF becomes 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: both CPU bound, run for week
    C: I/O bound, loop 1ms CPU, 9ms disk I/O
  - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FIFO:
  - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
  - Easier to see with a timeline

SRTF Example continued:



Disk Utilization: 9/201 ~ 4.5%

RR 100ms time slice

Disk Utilization: ~90% but lots of wakeups!

RR 1ms time slice

Disk Utilization: 90%

SRTF

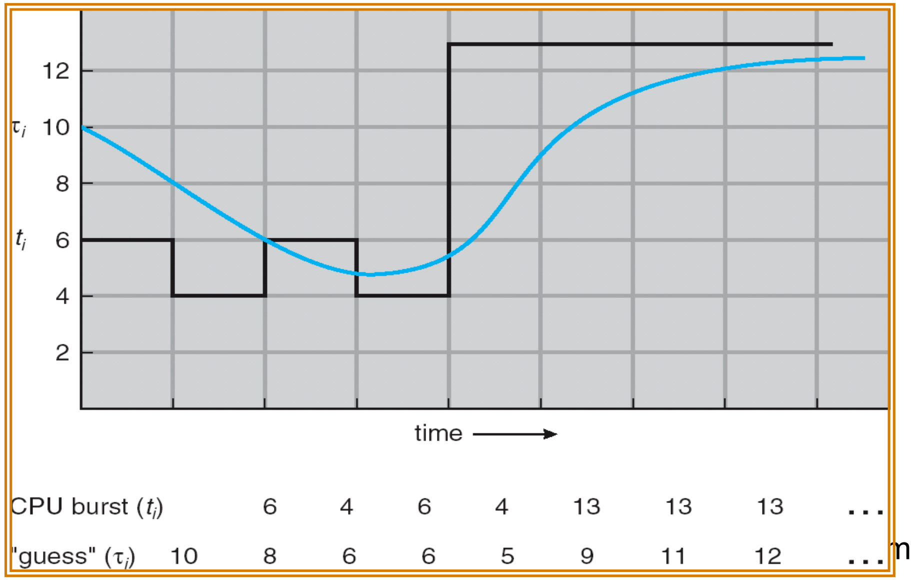
SRTF Further discussion

- 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

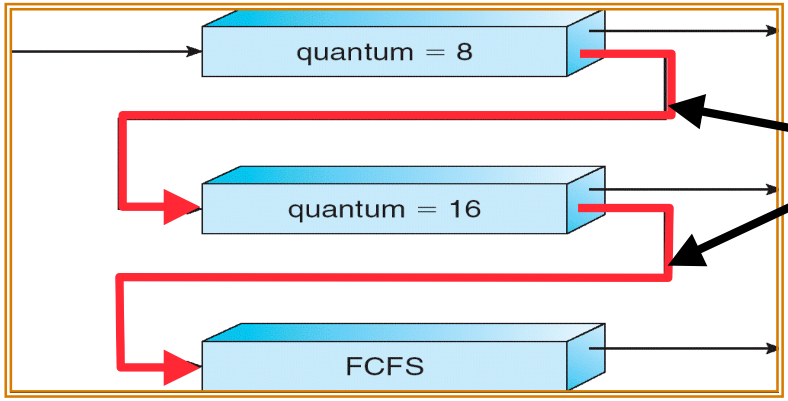
- **Adaptive**: Changing policy based on past behavior
  - CPU scheduling, in virtual memory, in file systems, etc
  - Works because programs have predictable behavior
    - » If program was I/O bound in past, likely in future
    - » If computer behavior were random, wouldn't help
- Example: SRTF with 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)
  - For instance, **exponential averaging** $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$ with $(0<\alpha\leq 1)$

☞ Lowest weights to old information (**aging**)



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

Multi-Level Feedback Scheduling



Long-Running Compute Tasks Demoted to Low Priority

- Another method for exploiting past behavior
  - First used 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)

Multi-Level Feedback 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: 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!

What about 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!
- 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?
    - » And, as system gets overloaded, no job gets CPU time, so everyone increases in priority ⇒ 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?
  - 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

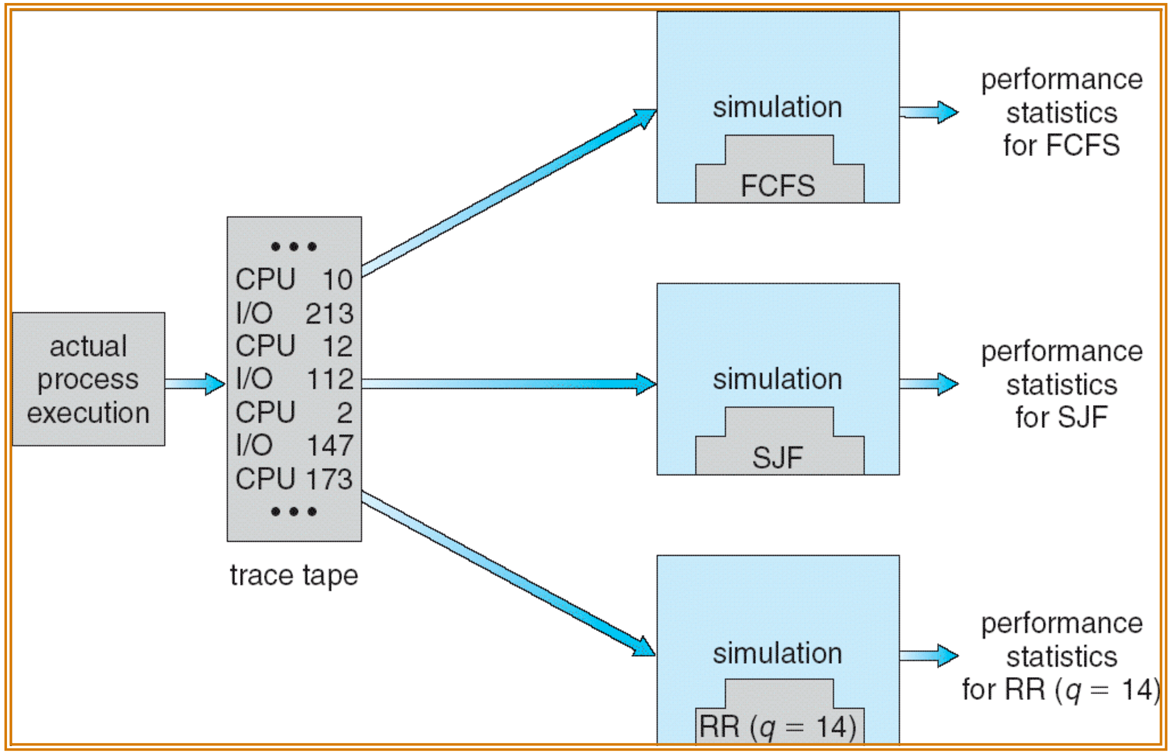
- **Lottery Scheduling Example**
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# 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

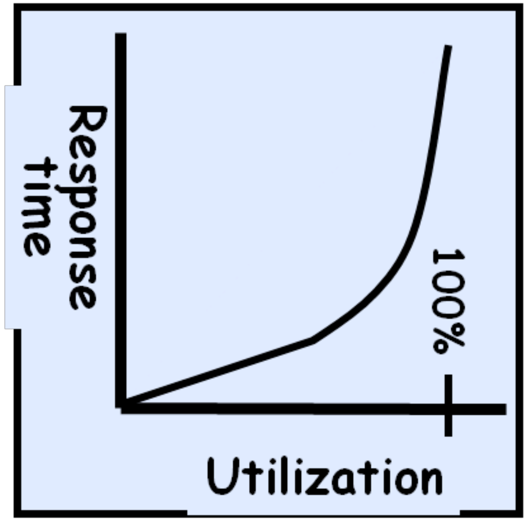
How to Evaluate a Scheduling algorithm?

- **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 waiting 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 priority-dependent number of tokens (short tasks ⇒ more tokens)
  - Reserve a minimum number of tokens for every thread to ensure forward progress/fairnes