



# COS 318: Operating Systems

## CPU Scheduling

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(<http://www.cs.princeton.edu/courses/cos318/>)



# Today's Topics

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- ◆ CPU scheduling basics
- ◆ CPU Scheduling algorithms



# When to Schedule?

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- ◆ Process/thread creation
- ◆ Process/thread exit
- ◆ Blocking on I/O or synchronization
- ◆ I/O interrupt
- ◆ Clock interrupt (pre-emptive scheduling)



# Preemptive vs. Non-Preemptive Scheduling

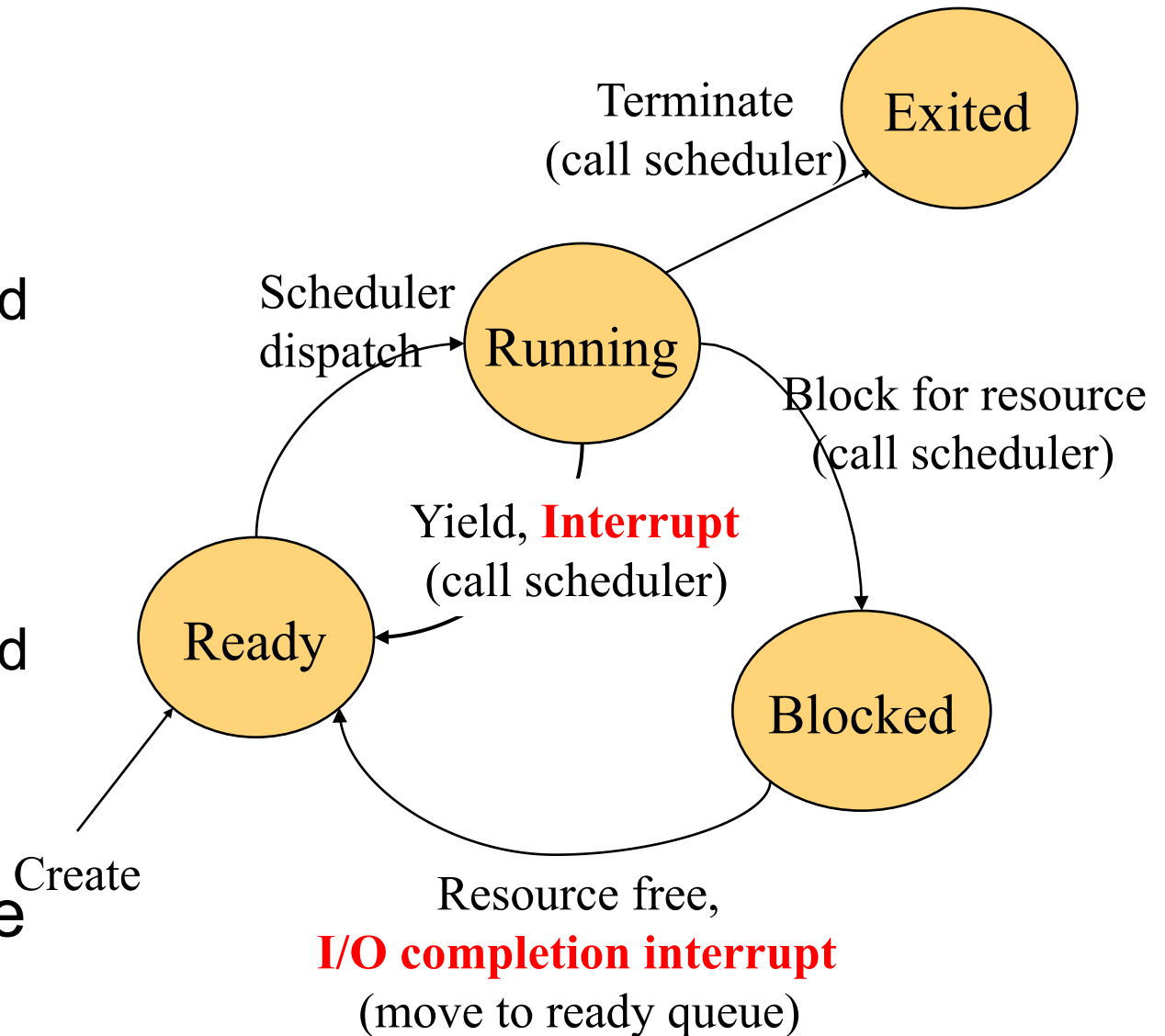
## ◆ Preemptive scheduling

- Running  $\Rightarrow$  ready
- Blocked  $\Rightarrow$  ready
- Running  $\Rightarrow$  blocked
- Terminate

## ◆ Non-preemptive scheduling

- Running  $\Rightarrow$  blocked
- Terminate

## ◆ Batch vs interactive vs real-time



# Scheduling Criteria

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## ◆ Assumptions

- One program per user and one thread per program
- Programs are independent

## ◆ Goals for batch and interactive systems

- Provide fairness
- Everyone makes some progress; no one starves
- Maximize CPU utilization
  - Not including idle process
- Maximize throughput
  - Operations/second (min overhead, max resource utilization)
- Minimize turnaround time
  - Batch jobs: time to execute (from submission to completion)
- Shorten response time
  - Interactive jobs: time response (e.g. typing on a keyboard)
- Proportionality
  - Meets user's expectations



# Scheduling Criteria

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- ◆ Questions:
  - What are the goals for PCs versus servers?
  - Average response time vs. throughput
  - Average response time vs. fairness



# Problem Cases

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- ◆ Completely blind about job types
  - No CPU and I/O overlap.
- ◆ Optimization involves favoring jobs of type “A” over “B”
  - Lots of A’s? B’s starve.
- ◆ Interactive process trapped behind others
  - Response time bad for no good reason.
- ◆ Priorities: A depends on B and A’s priority  $>$  B’s
  - B never runs.



# Scheduling Algorithms

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- ◆ Simplified view of scheduling:
  - Save process state (to PCB)
  - **Pick which process to run next**
  - Dispatch process





# First-Come-First-Serve (FCFS) Policy

## ◆ What does it mean?

- Run to completion (old days)
- Run until blocked or yields

## ◆ Example 1

- P1 = 24sec, P2 = 3sec, and P3 = 3sec, submitted together
- Average response time =  $(24 + 27 + 30) / 3 = 27$



## ◆ Example 2

- Same jobs but come in different order: P2, P3 and P1
- Average response time =  $(3 + 6 + 30) / 3 = 13$



(Gantt Graph)



# STCF and SRTCF

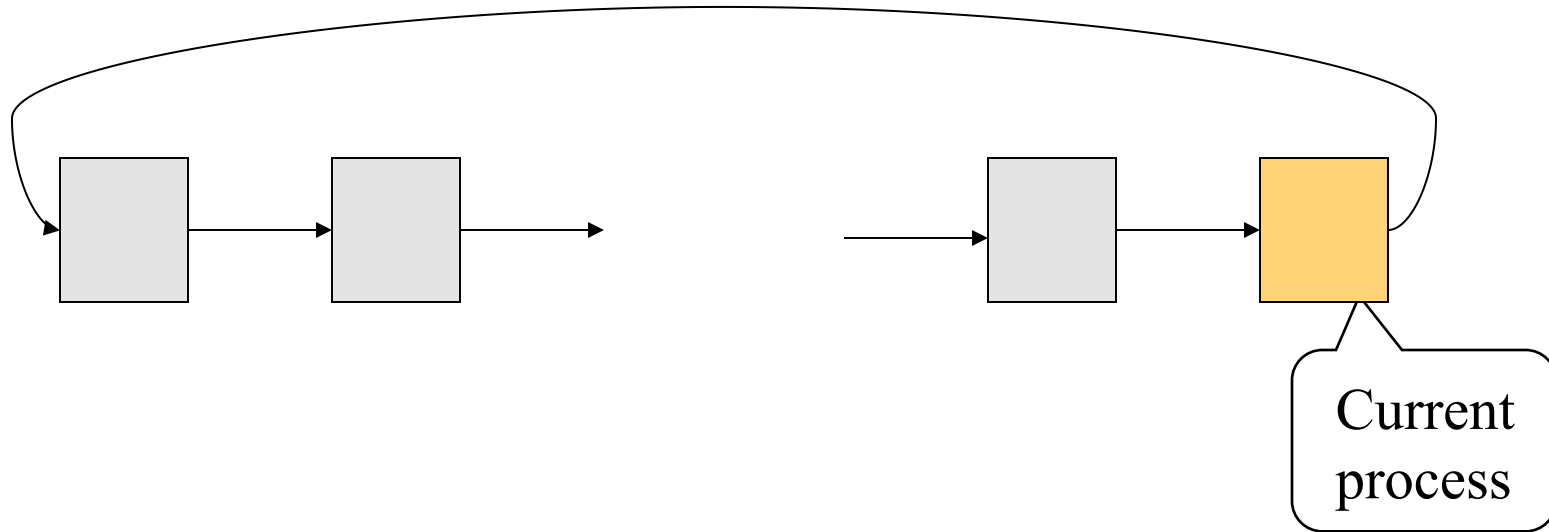
- ◆ Shortest Time to Completion First
  - Non-preemptive
- ◆ Shortest Remaining Time to Completion First
  - Preemptive version
- ◆ Example
  - P1 = 6sec, P2 = 8sec, P3 = 7sec, P4 = 3sec
  - All arrive at the same time



- ◆ Can you do better than SRTCF in terms of average response time?
- ◆ Issues with this approach?



# Round Robin



- ◆ Similar to FCFS, but add a time slice for timer interrupt
- ◆ FCFS for preemptive scheduling
- ◆ Real systems also have I/O interrupts in the mix
- ◆ How do you choose time slice?

# FCFS vs. Round Robin

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## ◆ Example

- 10 jobs and each takes 100 seconds

## ◆ FCFS (non-preemptive scheduling)

- job 1: 100s, job2: 200s, ... , job10: 1000s

## ◆ Round Robin (preemptive scheduling)

- time slice 1sec and no overhead
- job1: 991s, job2: 992s, ... , job10: 1000s

## ◆ Comparisons

- Round robin is much worse (turnaround time) for jobs about the same length
- Round robin is better for short jobs



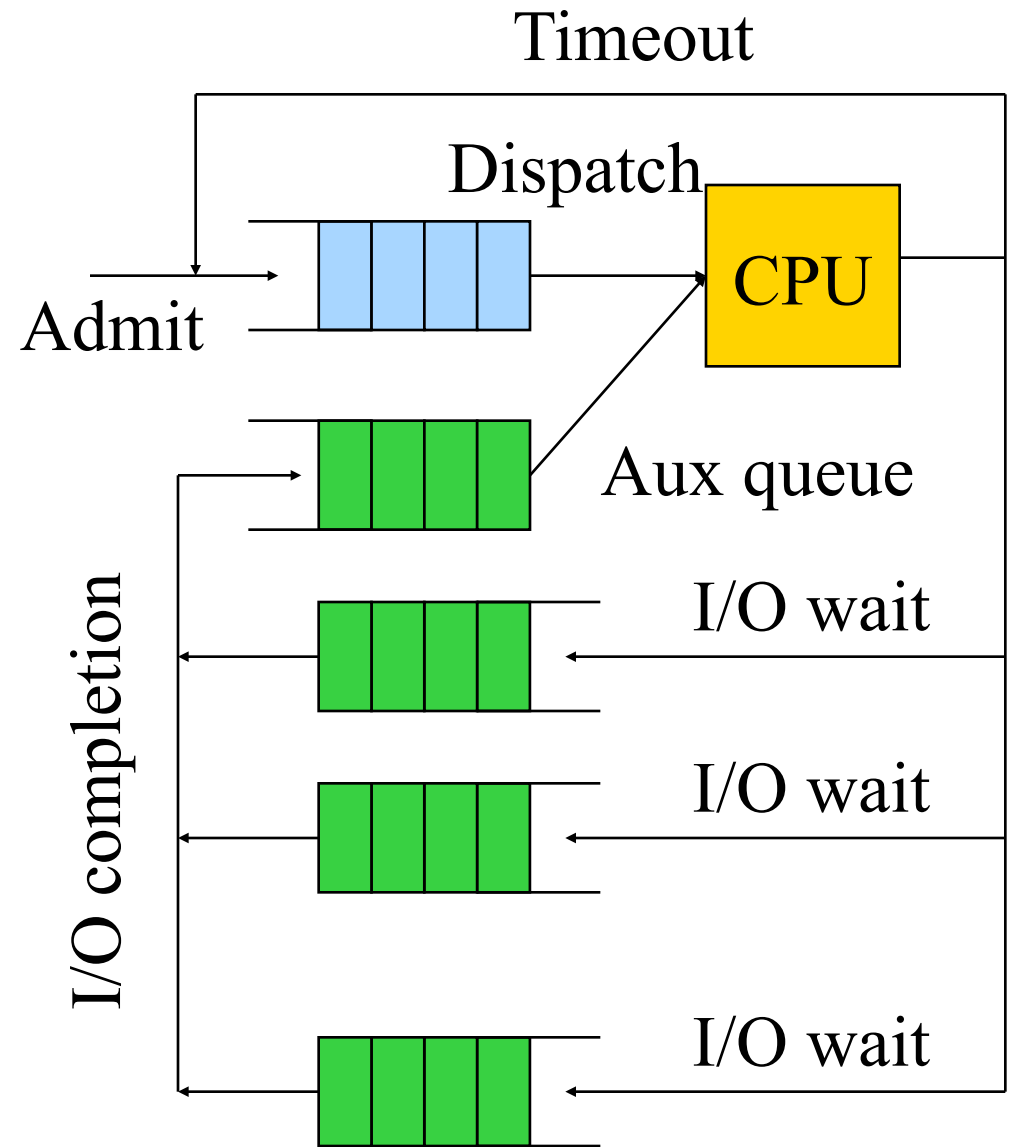
# Resource Utilization Example

- ◆ A, B, and C run forever (in this order)
  - A and B each uses 100% CPU forever
  - C is a CPU plus I/O job (1ms CPU + 10ms disk I/O)
- ◆ Time slice 100ms
  - A (100ms CPU), B (100ms CPU), C (1ms CPU + 10ms I/O),  
...
- ◆ Time slice 1ms
  - A (1ms CPU), B (1ms CPU), C (1ms CPU),  
A (1ms CPU), B (1ms CPU), C(10ms I/O) || A, B, ..., A, B
- ◆ What do we learn from this example?



# Virtual Round Robin

- ◆ Aux queue is FIFO
- ◆ I/O bound processes go to aux queue (instead of ready queue) to get scheduled
- ◆ Aux queue has preference over ready queue

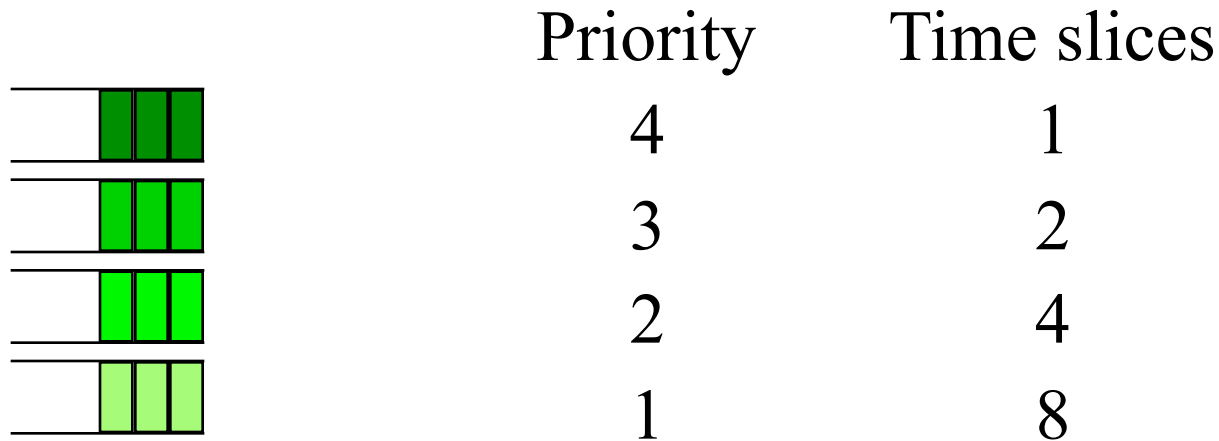


# Priority Scheduling

- ◆ Not all processes are equal, so rank them
- ◆ The method
  - Assign each process a priority
  - Run the process with highest priority in the ready queue first
  - Adjust priority dynamically (I/O wait raises the priority, reduce priority as process runs)
- ◆ Why adjusting priorities dynamically
  - T1 at priority 4, T2 at priority 1 and T2 holds lock L
  - Scenario
    - T1 tries to acquire L, fails, blocks.
    - T3 enters system at priority 3.
    - T2 never gets to run!



# Multiple Queues



- ◆ Jobs start at highest priority queue
- ◆ If timeout expires, drop one level
- ◆ If timeout doesn't expire, stay or pushup one level
- ◆ What does this method do?





# Lottery Scheduling

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## ◆ Motivations

- SRTCF does well with average response time, but unfair

## ◆ Lottery method

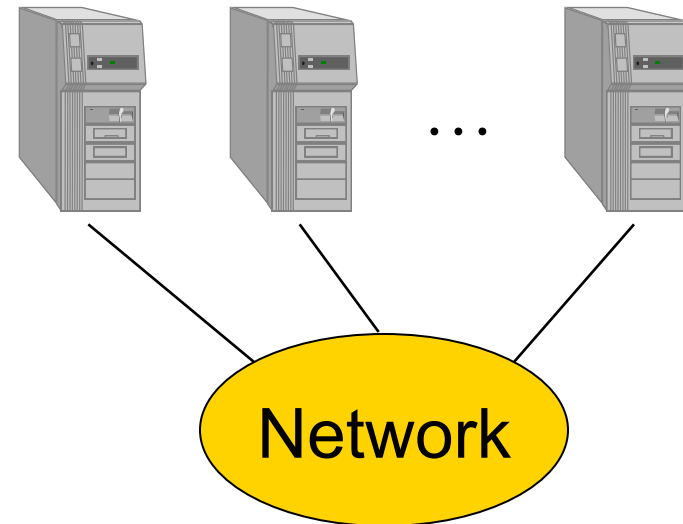
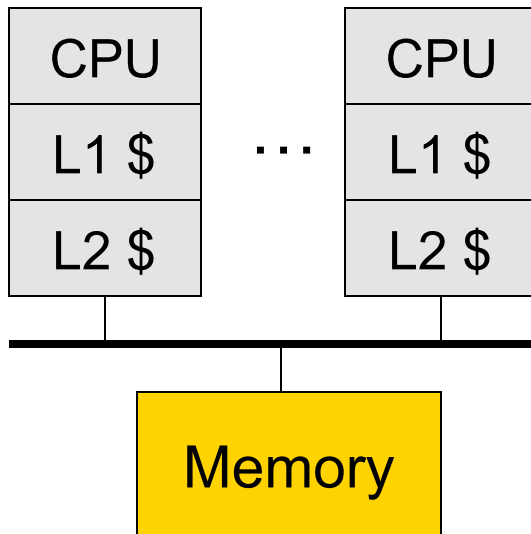
- Give each job a number of tickets
- Randomly pick a winning tickets
- To approximate SRTCF, give short jobs more tickets
- To avoid starvation, give each job at least one ticket
- Cooperative processes can exchange tickets

## ◆ Question

- How do you compare this method with priority scheduling?



# Multiprocessor and Cluster



## Multiprocessor architecture

- ◆ Cache coherence
- ◆ Single OS

## Cluster or multicomputer

- ◆ Distributed memory
- ◆ An OS in each box

# Multiprocessor/Cluster Scheduling

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- ◆ Design issue
  - Process/thread to processor assignment
- ◆ Gang scheduling (co-scheduling)
  - Threads of the same process will run together
  - Processes of the same application run together
- ◆ Dedicated processor assignment
  - Threads will be running on specific processors to completion
  - Is this a good idea?



# Real-Time Scheduling

## ◆ Two types of real-time

- Hard deadline
  - Must meet, otherwise can cause fatal error
- Soft Deadline
  - Meet most of the time, but not mandatory

## ◆ Admission control

- Take a real-time process only if the system can guarantee the “real-time” behavior of all processes
- The jobs are schedulable, if the following holds:

$$\sum \frac{C_i}{T_i} \leq 1$$

where  $C_i$  = computation time, and  $T_i$  = period



# Rate Monotonic Scheduling (Liu & Layland 73)

## ◆ Assumptions

- Each periodic process must complete within its period
- No process is dependent on any other process
- Each process needs the same amount of CPU time on each burst
- Non-periodic processes have no deadlines
- Process preemption occurs instantaneously (no overhead)

## ◆ Main ideas of RMS

- Assign each process a fixed priority = frequency of occurrence
- Run the process with highest priority

## ◆ Example

- P1 runs every 30ms gets priority 33 (33 times/sec)
- P2 runs every 50ms gets priority 20 (20 times/sec)



# Earliest Deadline Scheduling

## ◆ Assumptions

- When a process needs CPU time, it announces its deadline
- No need to be periodic process
- CPU time needed may vary

## ◆ Main idea of EDS

- Sort ready processes by their deadlines
- Run the first process on the list (earliest deadline first)
- When a new process is ready, it preempts the current one if its deadline is closer

## ◆ Example

- P1 needs to finish by 30sec, P2 by 40sec and P3 by 50sec
- P1 goes first
- More in MOS 7.4.4



## 4.3 BSD Scheduling with Multi-Queue

- ◆ “1 sec” preemption
  - Preempt if a process doesn't block or complete within 1 second
- ◆ Priority is recomputed every second
  - $P_i = \text{base} + (\text{CPU}_{i-1}) / 2 + \text{nice}$ , where  $\text{CPU}_i = (U_i + \text{CPU}_{i-1}) / 2$
  - Base is the base priority of the process
  - $U_i$  is process utilization in interval  $i$
- ◆ Priorities
  - Swapper
  - Block I/O device control
  - File operations
  - Character I/O device control
  - User processes



# Linux Scheduling

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## ◆ Time-sharing scheduling

- Each process has a priority and # of credits
- I/O event will raise the priority
- Process with the most credits will run next
- A timer interrupt causes a process to lose a credit
- If no process has credits, then the kernel issues credits to all processes:  $\text{credits} = \text{credits}/2 + \text{priority}$

## ◆ Real-time scheduling

- Soft real-time
- Kernel cannot be preempted by user code





# Windows Scheduling

- ◆ Classes and priorities
  - Real time: 16 static priorities
  - Variable: 16 variable priorities, start at a base priority
    - If a process has used up its quantum, lower its priority
    - If a process waits for an I/O event, raise its priority
- ◆ Priority-driven scheduler
  - For real-time class, do round robin within each priority
  - For variable class, do multiple queue
- ◆ Multiprocessor scheduling
  - For N processors, run N-1 highest priority threads on N-1 processors and run remaining threads on a single processor
  - A thread will wait for processors in its affinity set, if there are other threads available (for variable priorities)



# Summary

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- ◆ Different scheduling goals
  - Depend on what systems you build
- ◆ Scheduling algorithms
  - Small time slice is important for improving I/O utilization
  - STCF and SRTCF give the minimal average response time
  - Priority and its variations are in most systems
  - Lottery scheduling is flexible
  - Admission control is important in real-time scheduling

