Department of Physics,
Computer Science & Engineering

CPSC 410 – Operating Systems I

# Virtualization: CPU Scheduling

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Adapted from “CS 537 Introduction to Operating Systems” Arpaci-Dusseau

# CPU Virtualization:

Questions answered in this lecture:

- What are different scheduling policies, such as:
  FCFS, SJF, STCF, RR and MLFQ?
- What type of workload performs well with each scheduler?

# CPU Virtualization: Two Components

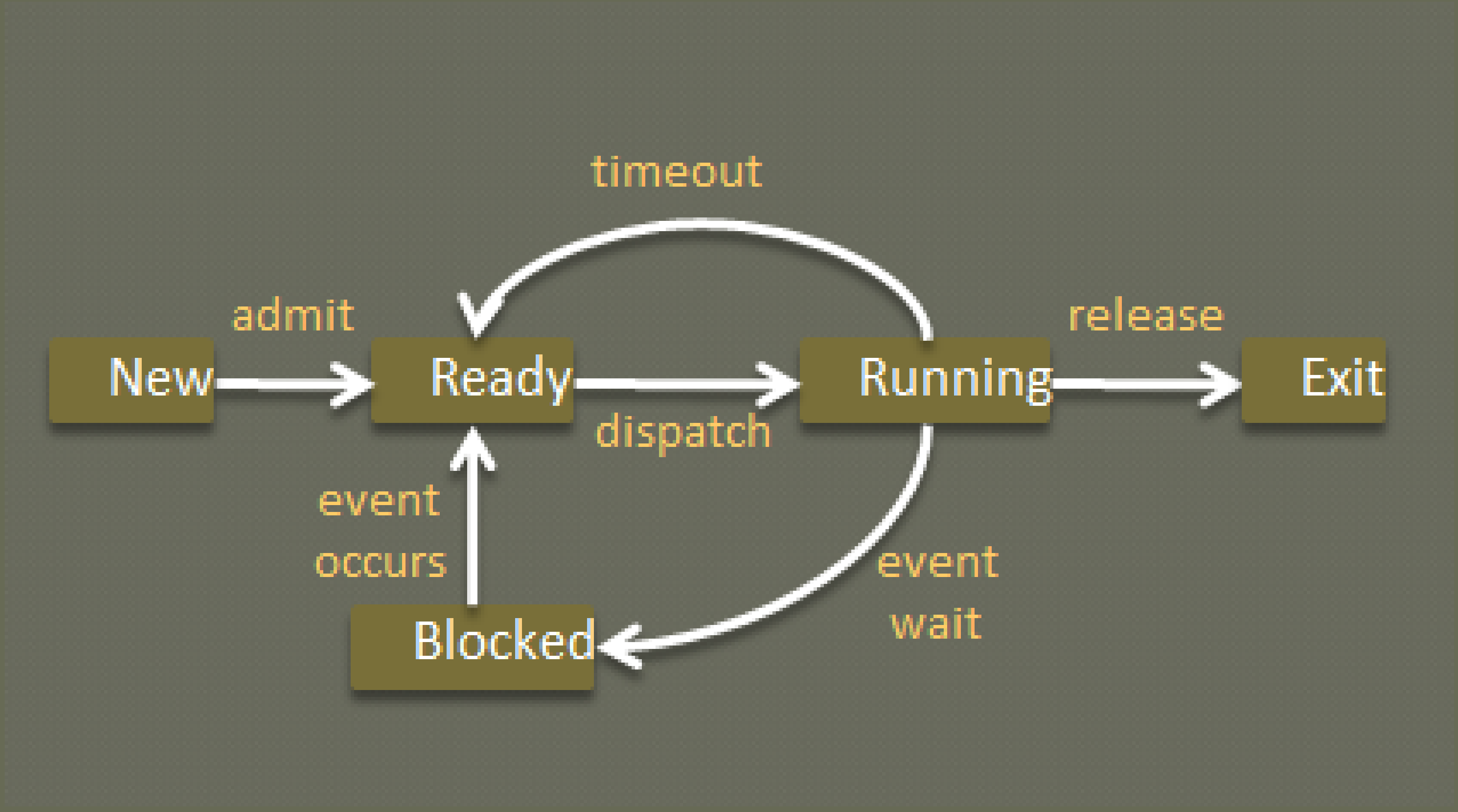
## Dispatcher (Previous lecture)

- Low-level mechanism
- Performs context-switch
  - Switch from user mode to kernel mode
  - Save execution state (registers) of old process in Process Control Block (PCB)
  - Insert process back in ready queue
  - Load state of next process to run from PCB to registers
  - Switch from kernel to user mode
  - Jump to instruction in new user process

## Scheduler (Today)

- Policy to determine which process gets CPU when

# Review: State Transitions




How to transition? (“mechanism”)
When to transition? (“policy”)

# Vocabulary

**Workload:** set of **job** descriptions (arrival time, run_time)

- Job: View as current CPU burst of a process
- Process alternates between CPU and I/O, so process moves between ready and blocked queues

**Scheduler:** logic that decides which ready job to run

**Metric:** measurement of scheduling quality

# Scheduling Performance Metrics

Minimize turnaround time

- Do not want to wait long for job to complete
- Completion_time – arrival_time

Minimize response time

- Schedule interactive jobs promptly so users see output quickly
- Initial_schedule_time – arrival_time

Minimize waiting time

- Do not want to spend much time in Ready queue

Maximize throughput

- Want many jobs to complete per unit of time

Maximize resource utilization

- Keep expensive devices busy

Minimize overhead

- Reduce number of context switches

Maximize fairness

- All jobs get same amount of CPU over some time interval

# Workload Assumptions

1. Each job runs for the same amount of time
2. All jobs arrive at the same time
3. All jobs only use the CPU (no I/O)
4. Run-time of each job is known

# Scheduling Basics

**Workloads:**
- arrival_time
- run_time

**Schedulers:**
- FIFO
- SJF
- STCF
- RR

**Metrics:**
- turnaround_time
- response_time

# Example: workload, scheduler, metric

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | 10 |
| B | ~0 | 10 |
| C | ~0 | 10 |

**FIFO:** First In, First Out

- also called FCFS (first come first served)
- run jobs in *arrival_time* order

**What is our turnaround?**: *completion_time - arrival_time*

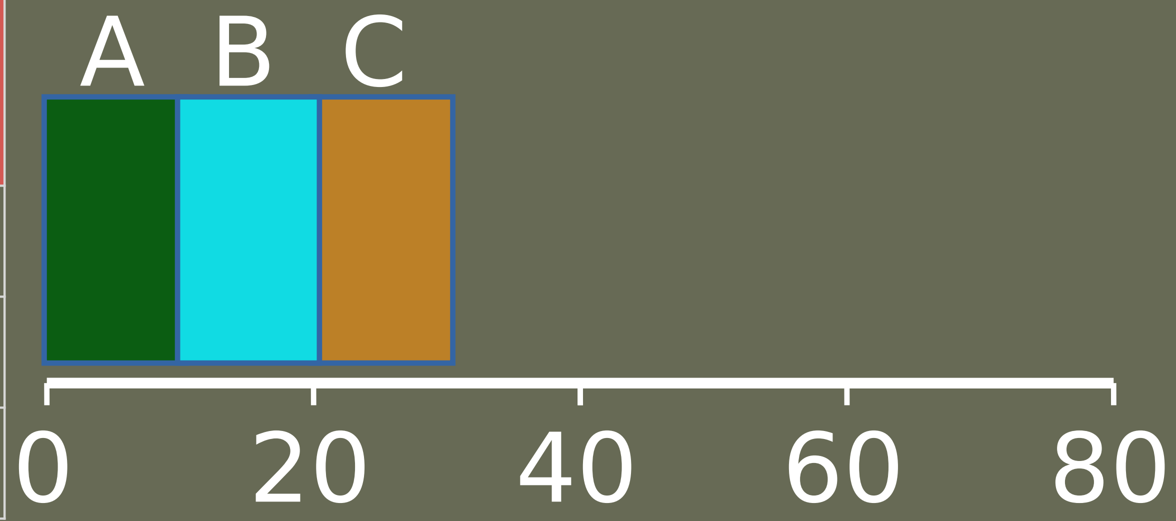
# FIFO: Event Trace

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | 10 |
| B | ~0 | 10 |
| C | ~0 | 10 |

| **Time** | **Event** |
|---|---|
| 0 | A arrives |
| 0 | B arrives |
| 0 | C arrives |
| 0 | run A |
| 10 | complete A |
| 10 | run B |
| 20 | complete B |
| 20 | run C |
| 30 | complete C |

# FIFO (Identical JOBS)

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | 10 |
| B | ~0 | 10 |
| C | ~0 | 10 |



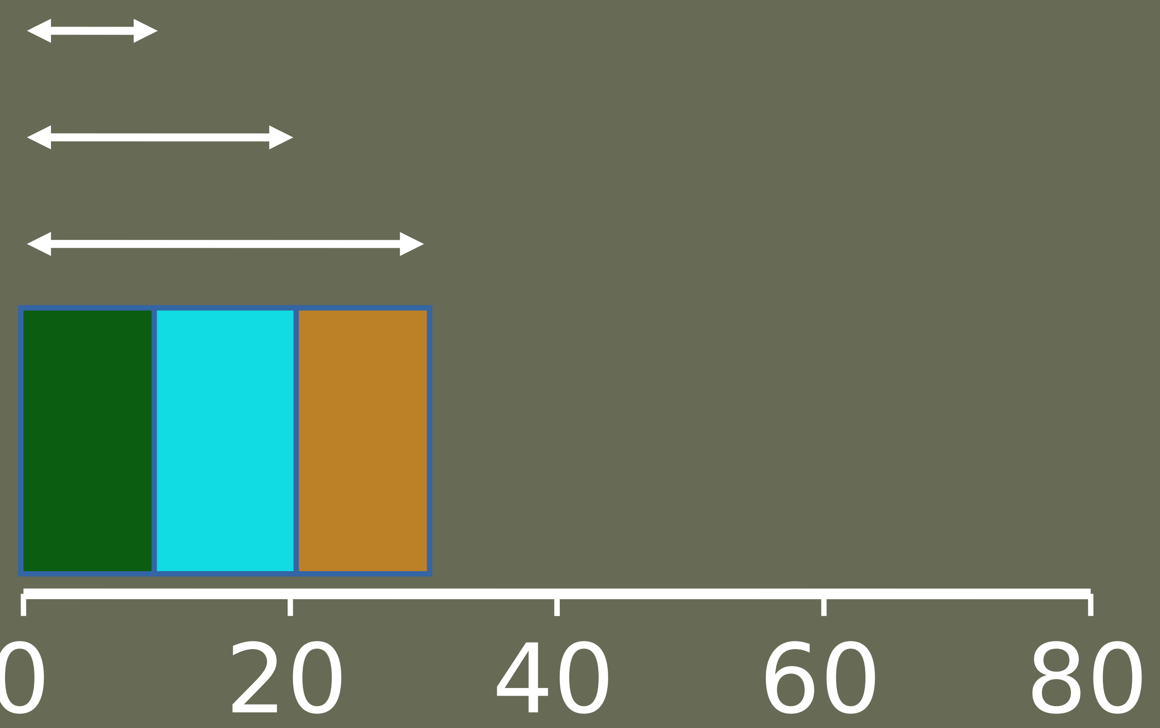

Gantt chart:
Illustrates how jobs are scheduled over time on a CPU

# FIFO (IDENTICAL Jobs)

A: 10s

B: 20s

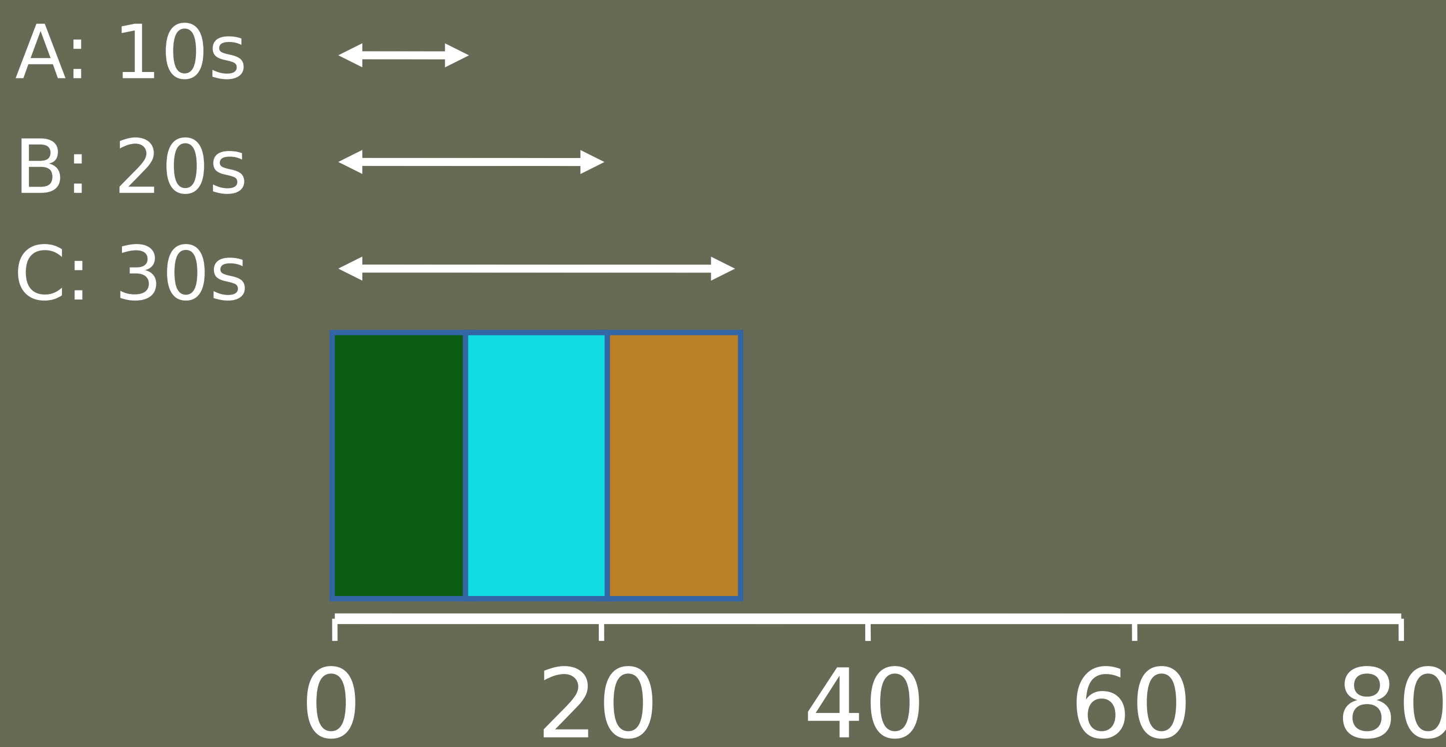
C: 30s




What is the average turnaround time?

Def: *turnaround_time = completion_time - arrival_time*

# FIFO (IDENTICAL Jobs)




What is the average turnaround time?

Def: *turnaround_time = completion_time - arrival_time*

(10 + 20 + 30) / 3 = **20s**

# Scheduling Basics

**Workloads:**

arrival_time
run_time

**Schedulers:**

FIFO
SJF
STCF
RR

**Metrics:**

turnaround_time
response_time

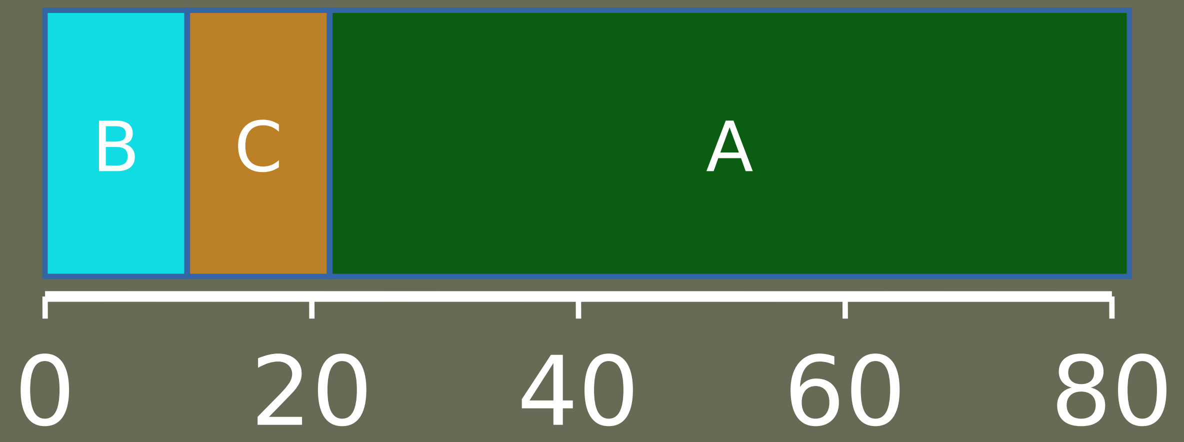
# Workload Assumptions

~~1. Each job runs for the same amount of time~~

2. All jobs arrive at the same time
3. All jobs only use the CPU (no I/O)
4. The run-time of each job is known

# Example: A Big Job Last

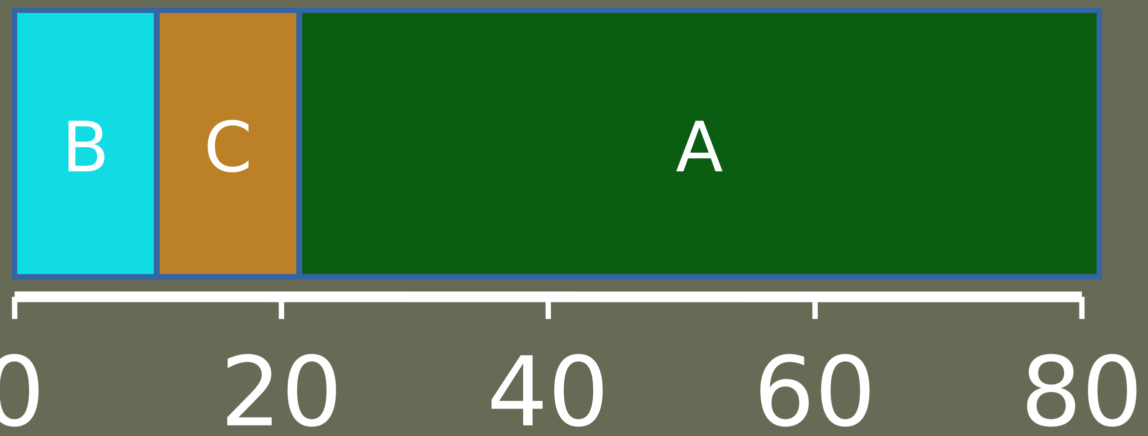
| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| B | ~0 | **10** |
| C | ~0 | 10 |
| A | ~0 | 60 |




What is the average turnaround time?

# Example: A Big Job Last

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| B | ~0 | **10** |
| C | ~0 | 10 |
| A | ~0 | 60 |




What is the average turnaround time?

(10 + (10+10) + (10+10+60)) / 3 = 36.67**s**

# Any Problematic Workloads for FIFO?

**Workload:** ?

**Scheduler:** FIFO

**Metric:** turnaround is high

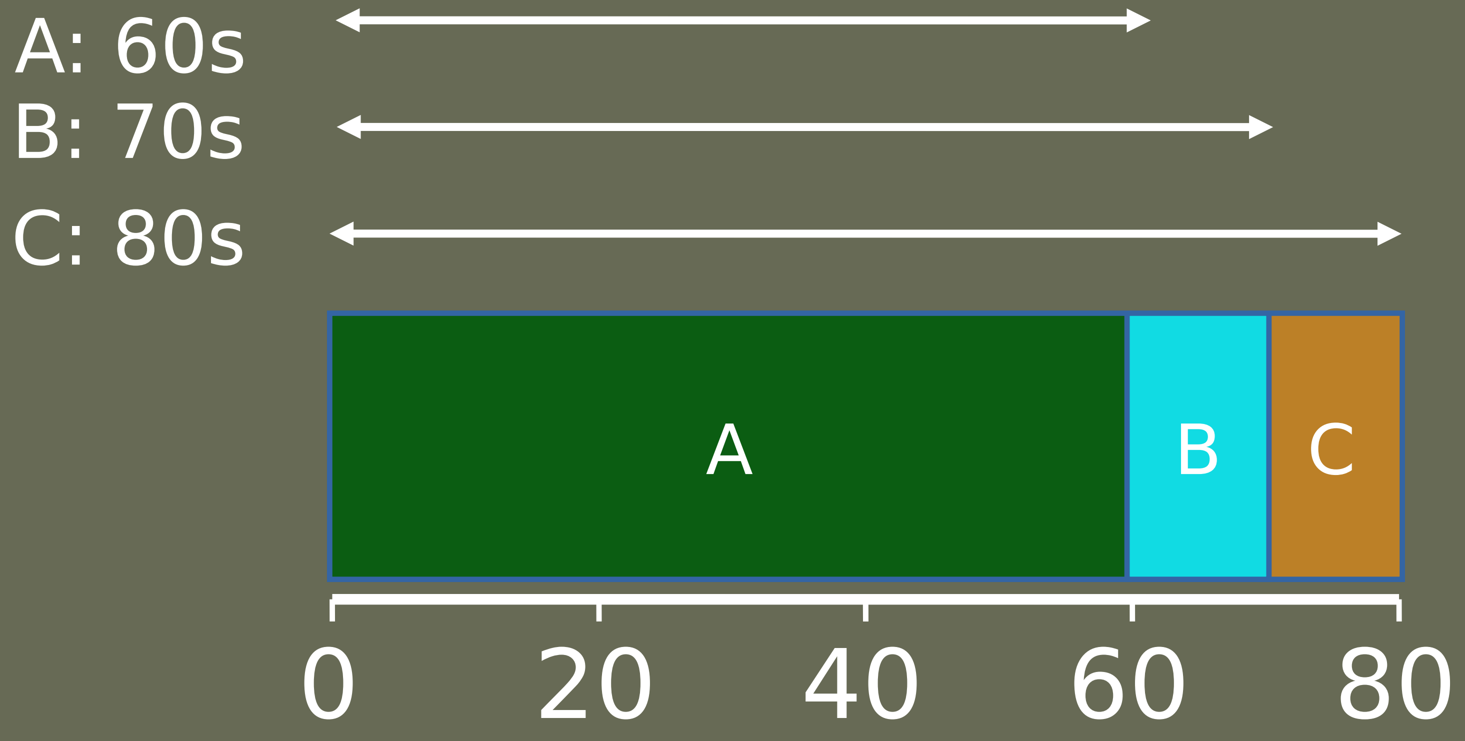
# Example: A Big Job First

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | **60** |
| B | ~0 | 10 |
| C | ~0 | 10 |

What is the average turnaround time?

# Example: Big First Job

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | **60** |
| B | ~0 | 10 |
| C | ~0 | 10 |




Average turnaround time:

(60 + (10+60) + (10+70)) / 3 = 70s

# Convoy Effect
## When a long job early on slows all jobs

# Passing the Tractor

**Problem with Previous Scheduler:**

FIFO: Turnaround time can suffer when short jobs must wait for long jobs

**New scheduler**:

SJF (Shortest Job First)

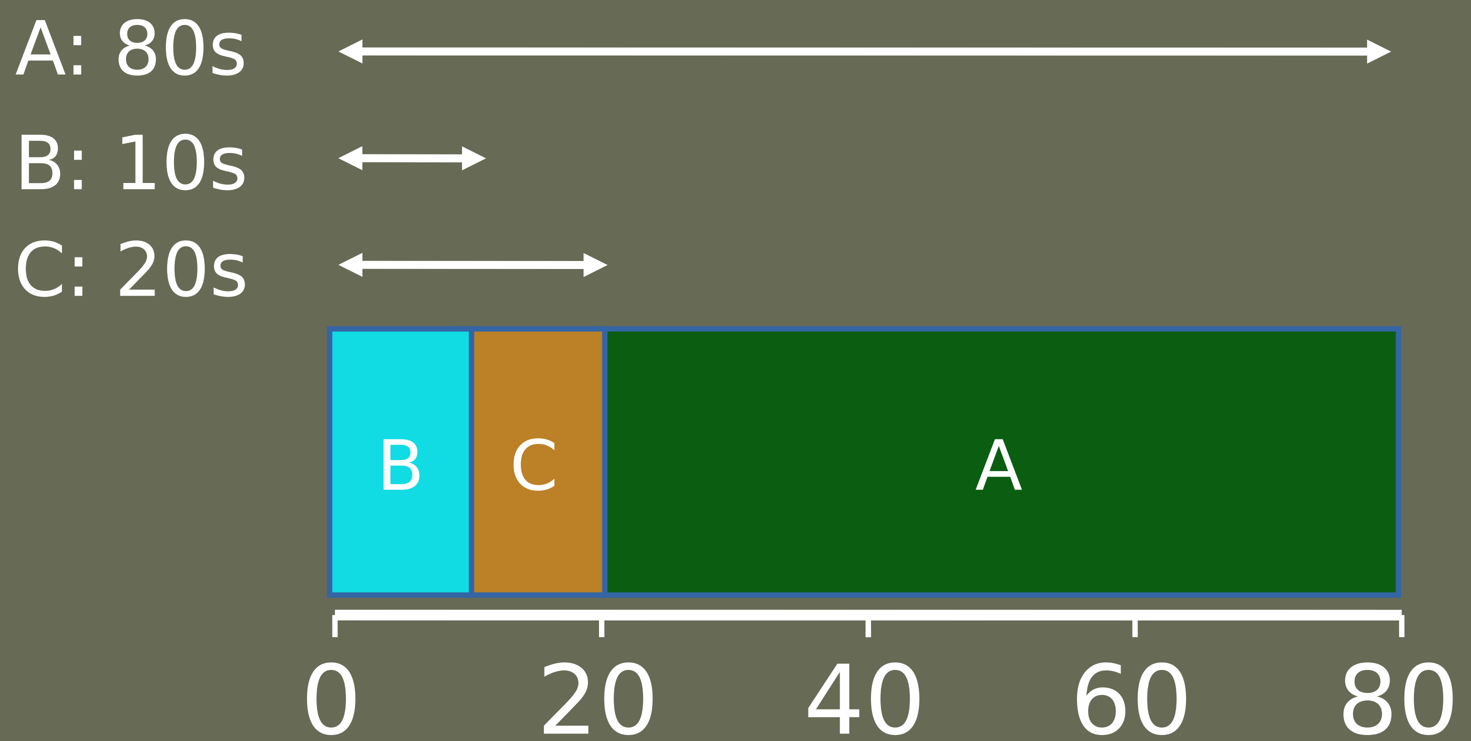
Choose job with smallest *run_time*

# Shortest Job First

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | **60** |
| B | ~0 | 10 |
| C | ~0 | 10 |

What is the average turnaround time with SJF?

# SJF Turnaround Time




What is the average turnaround time with SJF?

(80 + 10 + 20) / 3 = **~36.7s**

**Average turnaround with FIFO: 70s**

For minimizing average turnaround time (with no preemption):
SJF is provably optimal
Moving shorter job before longer job improves turnaround time of short job more than it harms turnaround time of long job

# Scheduling Basics

**Workloads:**

arrival_time
run_time

**Schedulers:**

FIFO
SJF
STCF
RR

**Metrics:**

turnaround_time
response_time

# Workload Assumptions

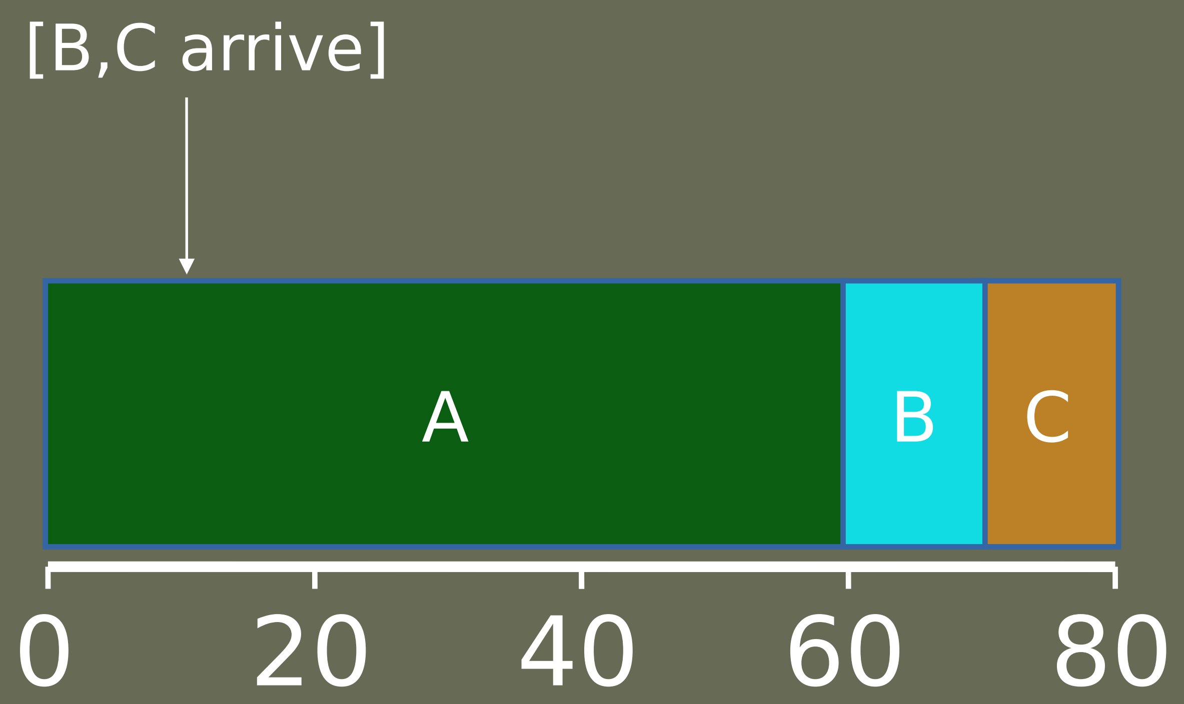
~~1. Each job runs for the same amount of time~~
~~2. All jobs arrive at the same time~~
3. All jobs only use the CPU (no I/O)
4. The run-time of each job is known

# Shortest Job First (Arrival Time)

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | 60 |
| B | **~10** | 10 |
| C | **~10** | 10 |

What is the average turnaround time with SJF?

# Stuck Behind a Tractor Again




| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | 60 |
| B | **~10** | 10 |
| C | **~10** | 10 |

What is the average turnaround time?

(60 + (70 – 10) + (80 – 10)) / 3 = **63.3s**

# Preemptive Scheduling

**Prev schedulers**:

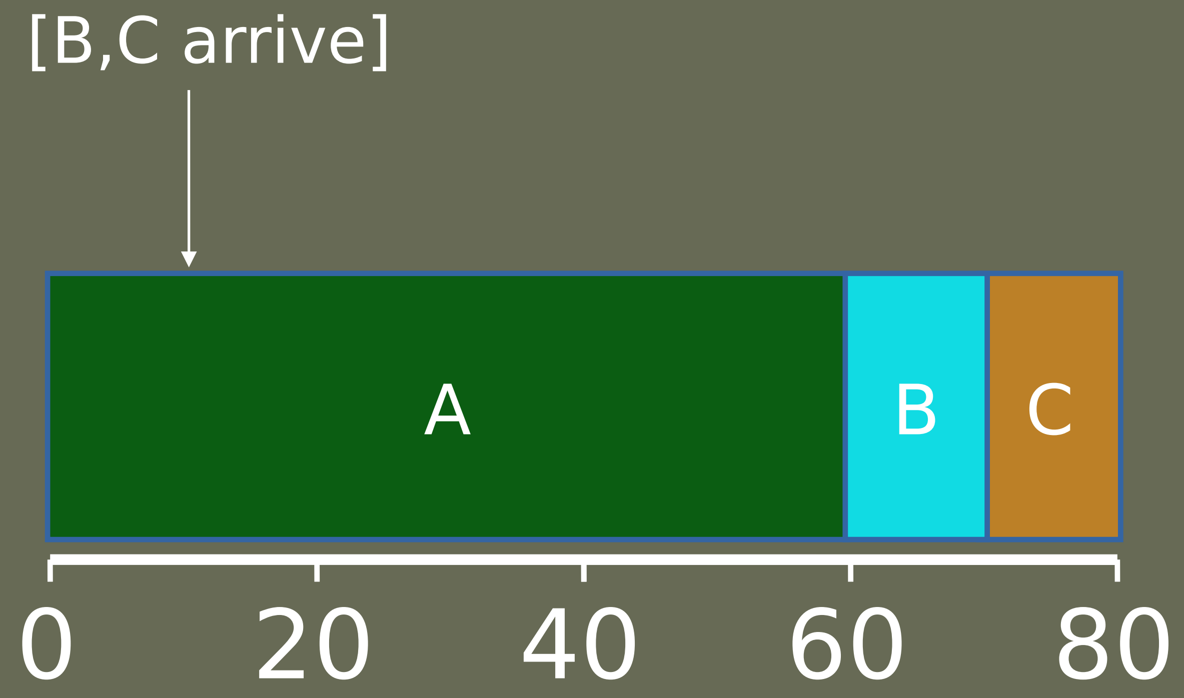
- **FIFO and SJF are non-preemptive**
- Only schedule new job when previous job voluntarily relinquishes CPU (performs I/O or exits)

**New scheduler**:

- Preemptive: Potentially schedule different job at any point by taking CPU away from running job
- STCF (Shortest Time-to-Completion First)
- Always run job that will complete the quickest

# NON-PREEMPTIVE: SJF

| JOB | arrival_time (s) | run_time (s) |
| --- | --- | --- |
| A | ~0 | 60 |
| B | **~10** | 10 |
| C | **~10** | 10 |




Average turnaround time:

(60 + (70 – 10) + (80 – 10)) / 3 = **63.3s**

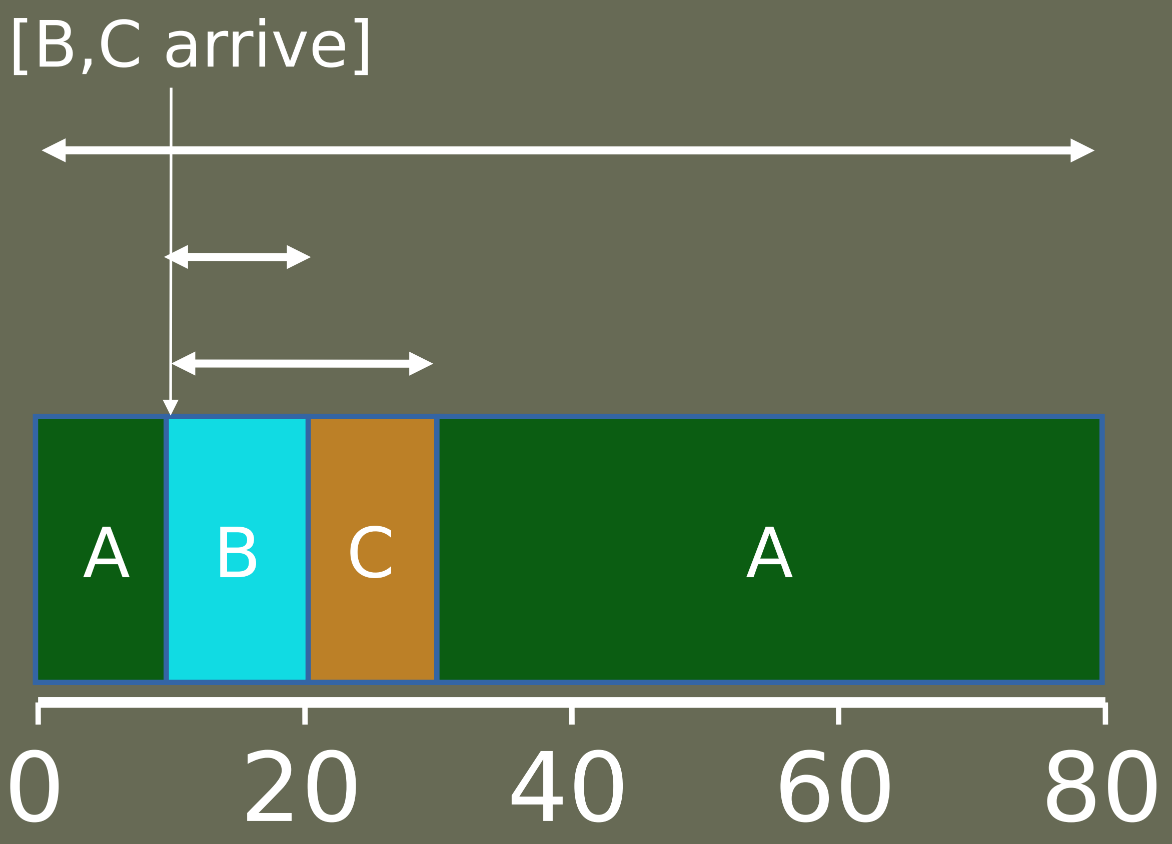
# PREEMPTIVE: STCF

| JOB | arrival_time (s) | run_time (s) |
|---|---|---|
| A | ~0 | 60 |
| B | **~10** | 10 |
| C | **~10** | 10 |

Turnaround time?
A: 80s

B: 10s

C: 20s




Average turnaround time with STCF? **36.6s**

Average turnaround time with SJF: **63.3s**

# Scheduling Basics

**Workloads:**

arrival_time
run_time

**Schedulers:**

FIFO
SJF
STCF
RR

**Metrics:**

turnaround_time
response_time

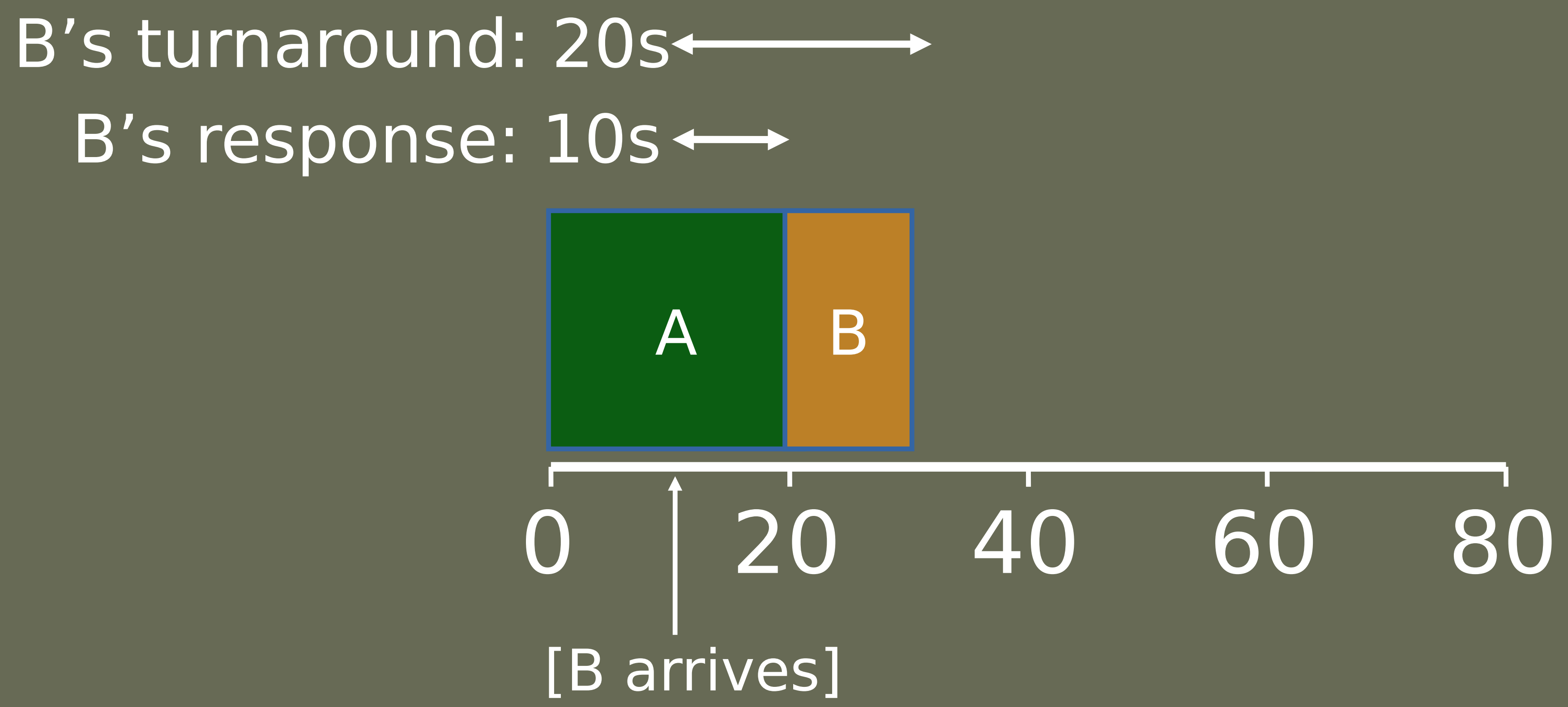
# Response Time

Sometimes you care about when a job starts instead of when it finishes

New metric:

*response_time = first_run_time - arrival_time*

# Response vs. Turnaround



# Round-Robin Scheduler

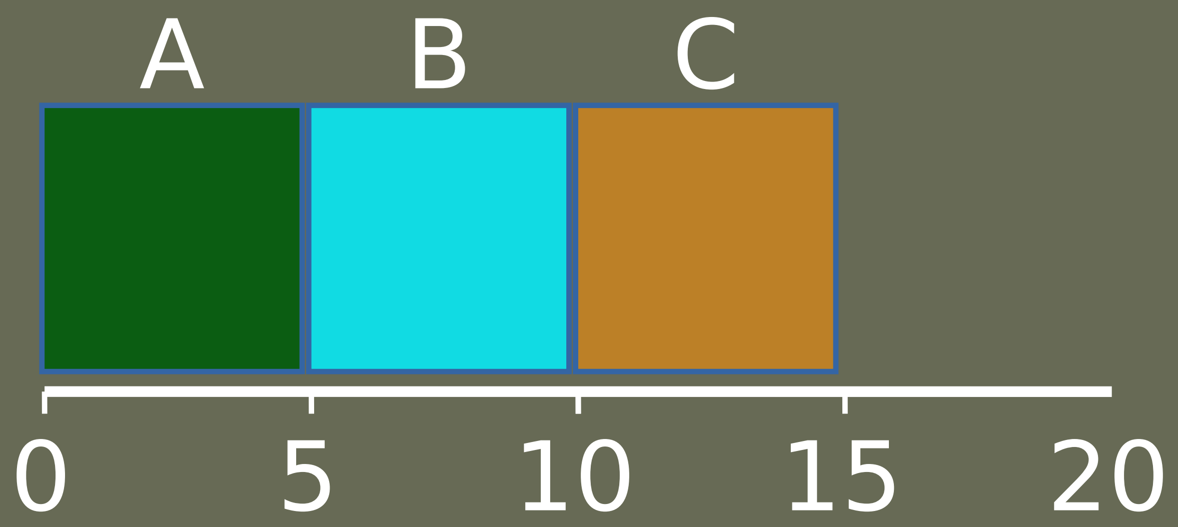
**Prev schedulers**:

FIFO, SJF, and STCF can have poor response time

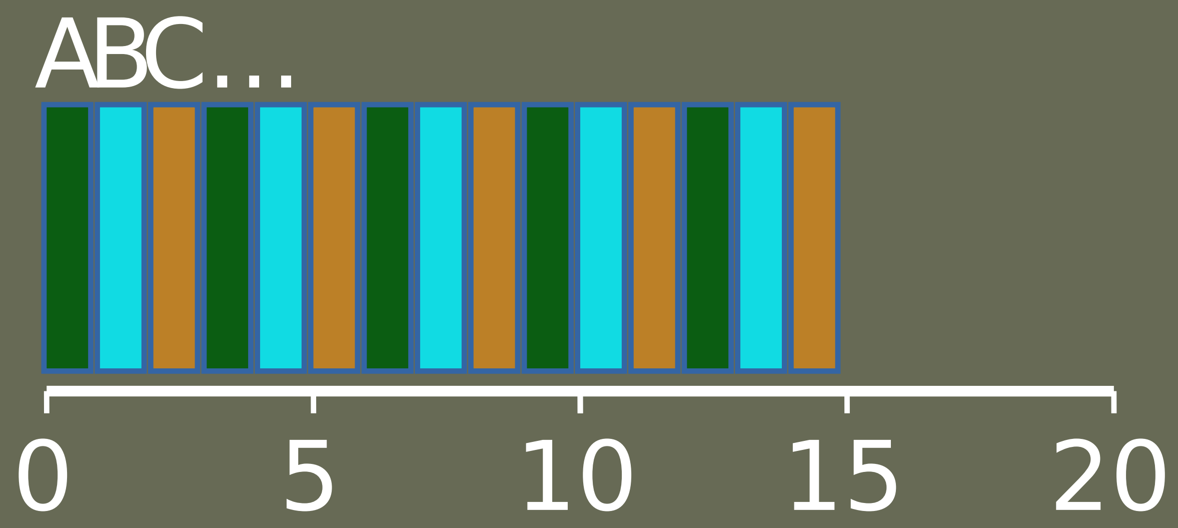
**New scheduler**: RR (Round Robin)

Alternate ready processes every fixed-length time-slice

# FIFO vs RR




FIFO
(0+5+10)/3 = **5**

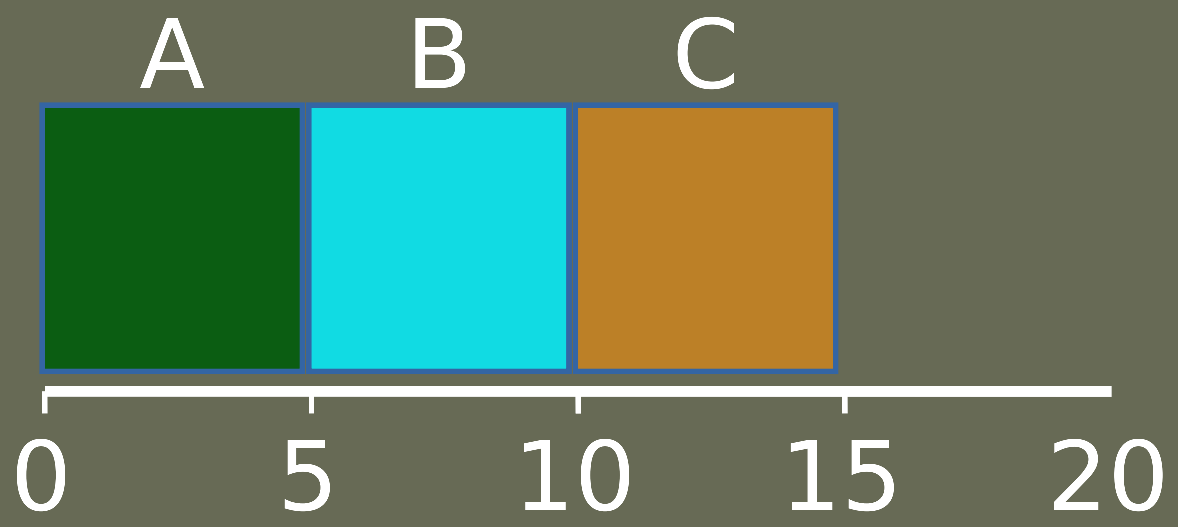


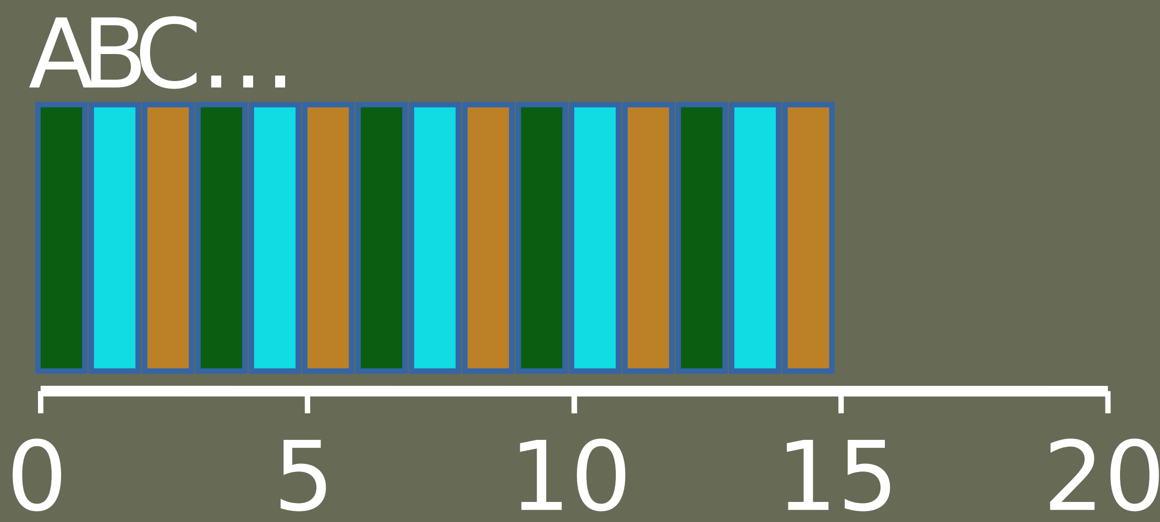

RR (time slice=1)
(0+1+2)/3 = **1**

What is the average response time (Assume all jobs arrive at time = 0s)?

RR much more responsive, plus gives short jobs a chance to run and finish fast

# FIFO vs RR




FIFO

(0+5)+(0+10)+(0+15))/3 =10

RR (time slice=1)

(0+13)+(0+14)+(0+15))/3=14

What is the average turn-around time (Assume all jobs arrive at time = 0s)?

So average turn around time for RR is in general worse, especially for equal length jobs

# Scheduling Basics

**Workloads:**

arrival_time
run_time

**Schedulers:**

FIFO
SJF
STCF
RR

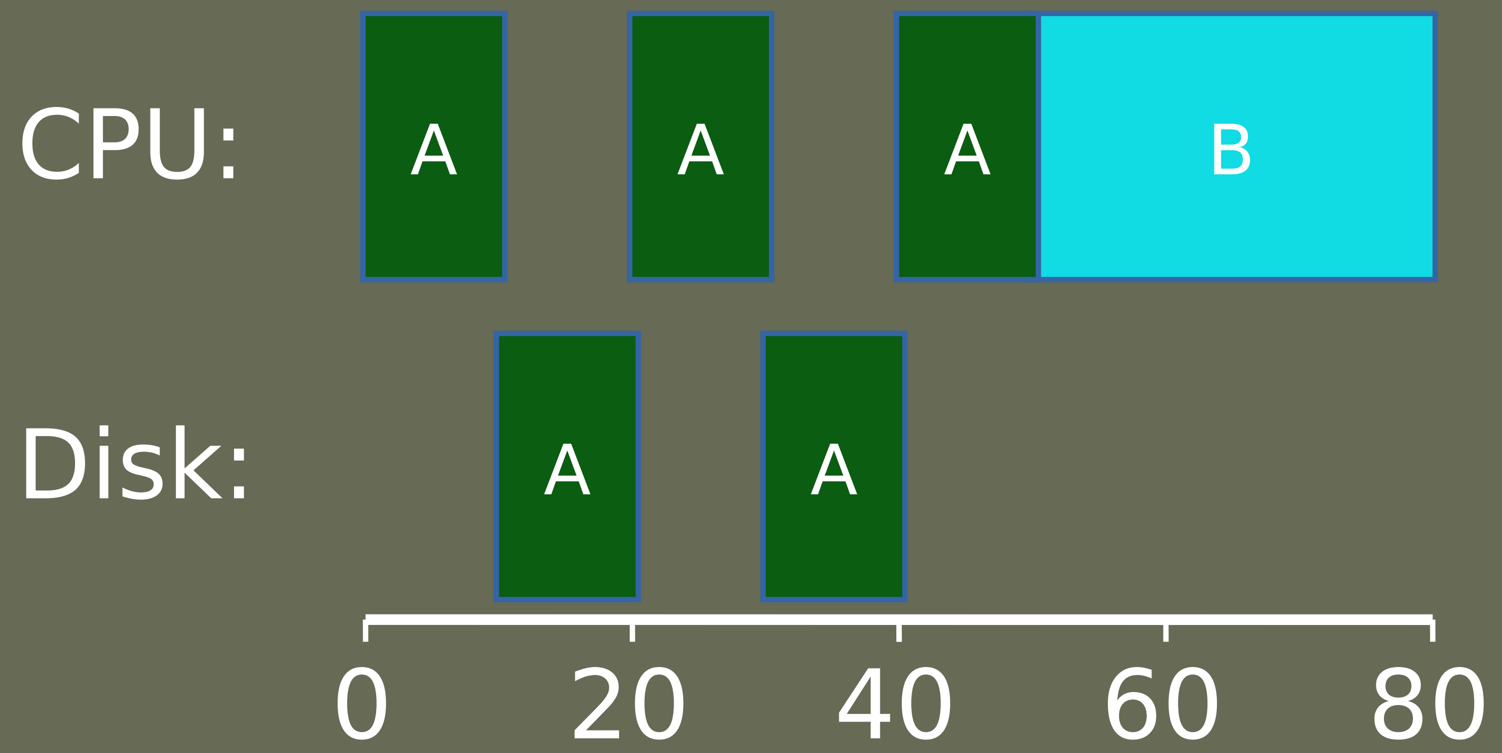
**Metrics:**

turnaround_time
response_time

# Workload Assumptions

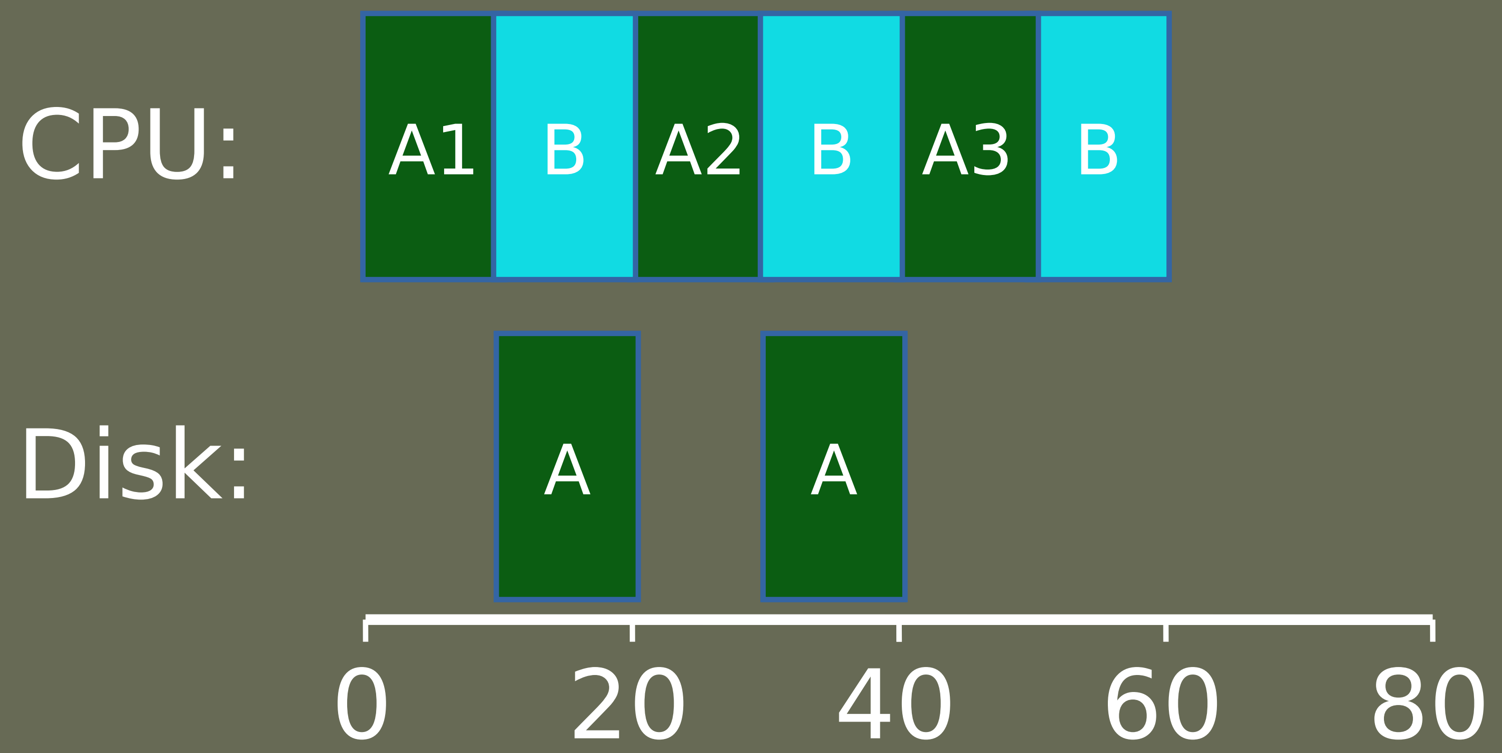
1. ~~Each job runs for the same amount of time~~
2. ~~All jobs arrive at the same time~~
3. ~~All jobs only use the CPU (no I/O)~~
4. The run-time of each job is known

# Not I/O Aware




Don’t let Job A hold on to CPU while blocked waiting for disk!

# I/O Aware (Overlap)




Treat Job A as 3 separate CPU bursts
When Job A completes I/O, another Job A is ready

Each CPU burst is shorter than Job B, so with STCF, Job A preempts Job B

# Workload Assumptions

~~1. Each job runs for the same amount of time~~
~~2. All jobs arrive at the same time~~
~~3. All jobs only use the CPU (no I/O)~~
~~4. The run-time of each job is known~~

(need smarter, fancier scheduler)

# MLFQ
# (Multi-Level Feedback Queue)

Goal: general-purpose scheduling

Must support two job types with distinct goals

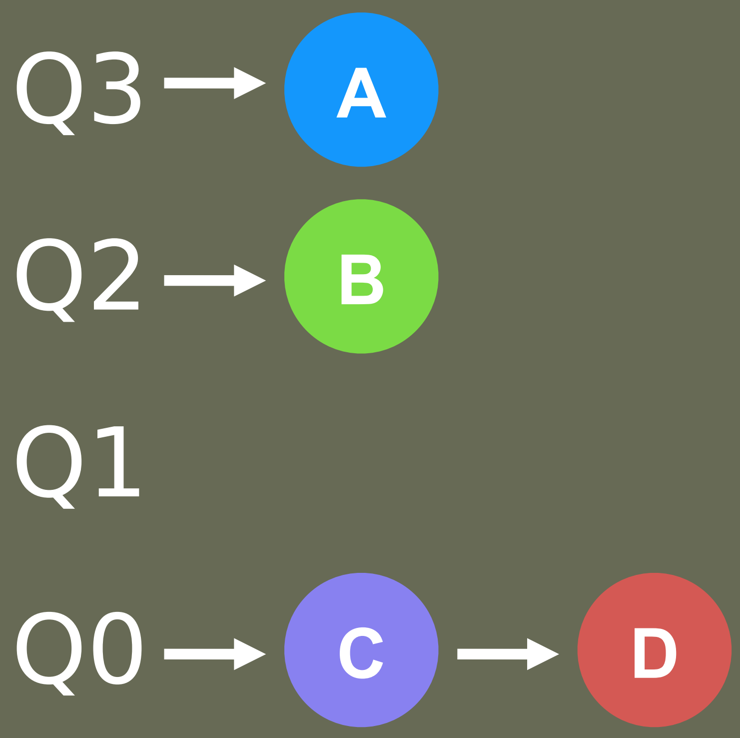
- "interactive" programs care about response time
- "batch" programs care about turnaround time

Approach: multiple levels of round-robin;
each level has higher priority than lower levels and preempts them

# Priorities

Rule 1: If priority(A) > Priority(B), A runs

Rule 2: If priority(A) == Priority(B), A & B run in RR




“Multi-level”

How to know how to set priority?

Approach: use history “feedback”

# History

- Use past behavior of process to predict future behavior
  - Common technique in systems
- Processes alternate between I/O and CPU work
- Guess how CPU burst (job) will behave based on past CPU bursts (jobs) of this process

# More MLFQ Rules

Rule 1: If priority(A) > Priority(B), A runs
Rule 2: If priority(A) == Priority(B), A & B run in RR

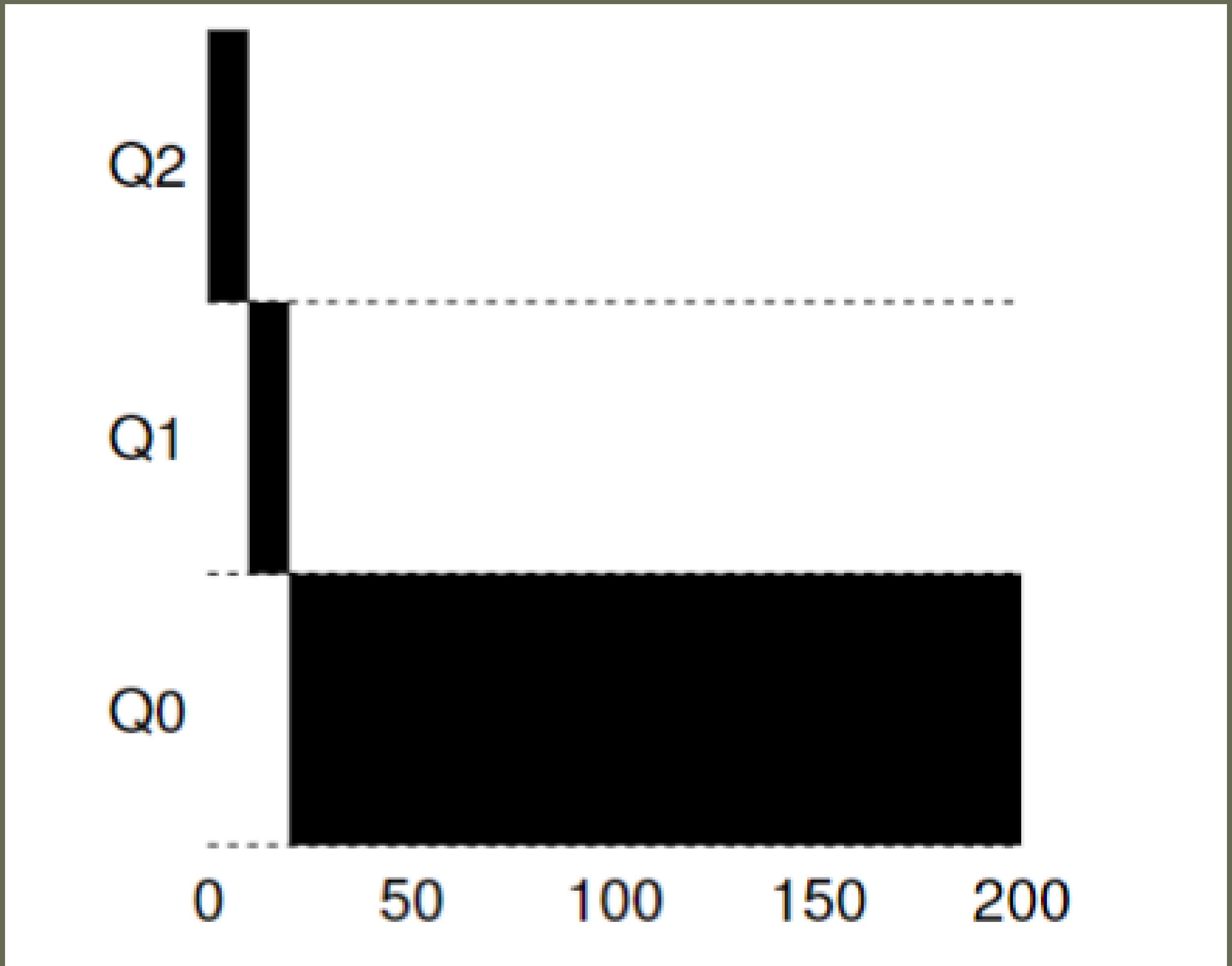
More rules:
Rule 3: Processes start at top priority
Rule 4: If job uses whole slice, demote process
(longer time slices at lower priorities)

Rule 4 reasoning-

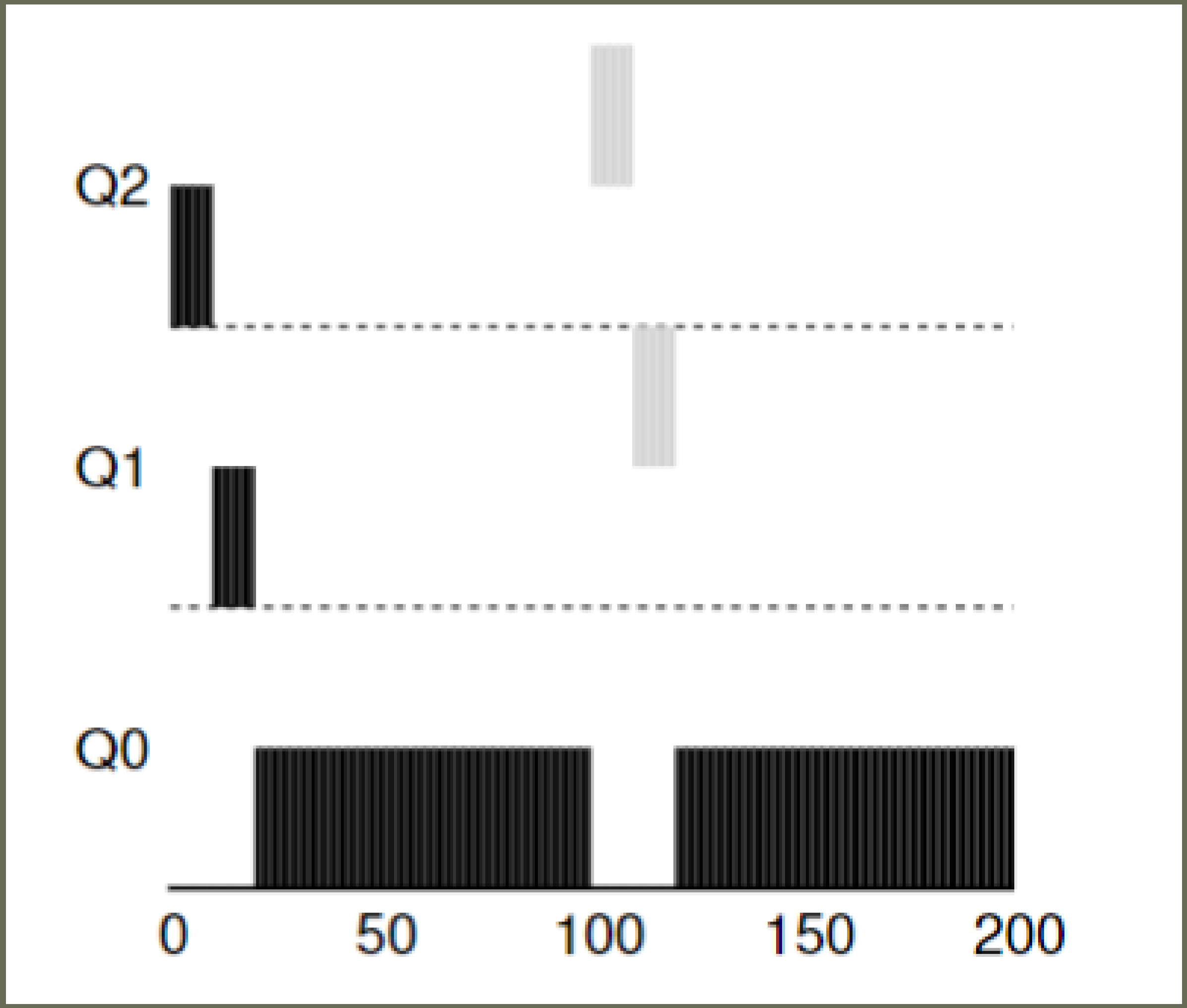
If job **DOES NOT** use all time slice its probably interacting with user, keep TS low to boost interactivity

If job **DOES** use all time slice, its likely not interacting with user, does not need to be as interactive, push to lower priority queue (which has a longer TS )

# One Long Job (Example)

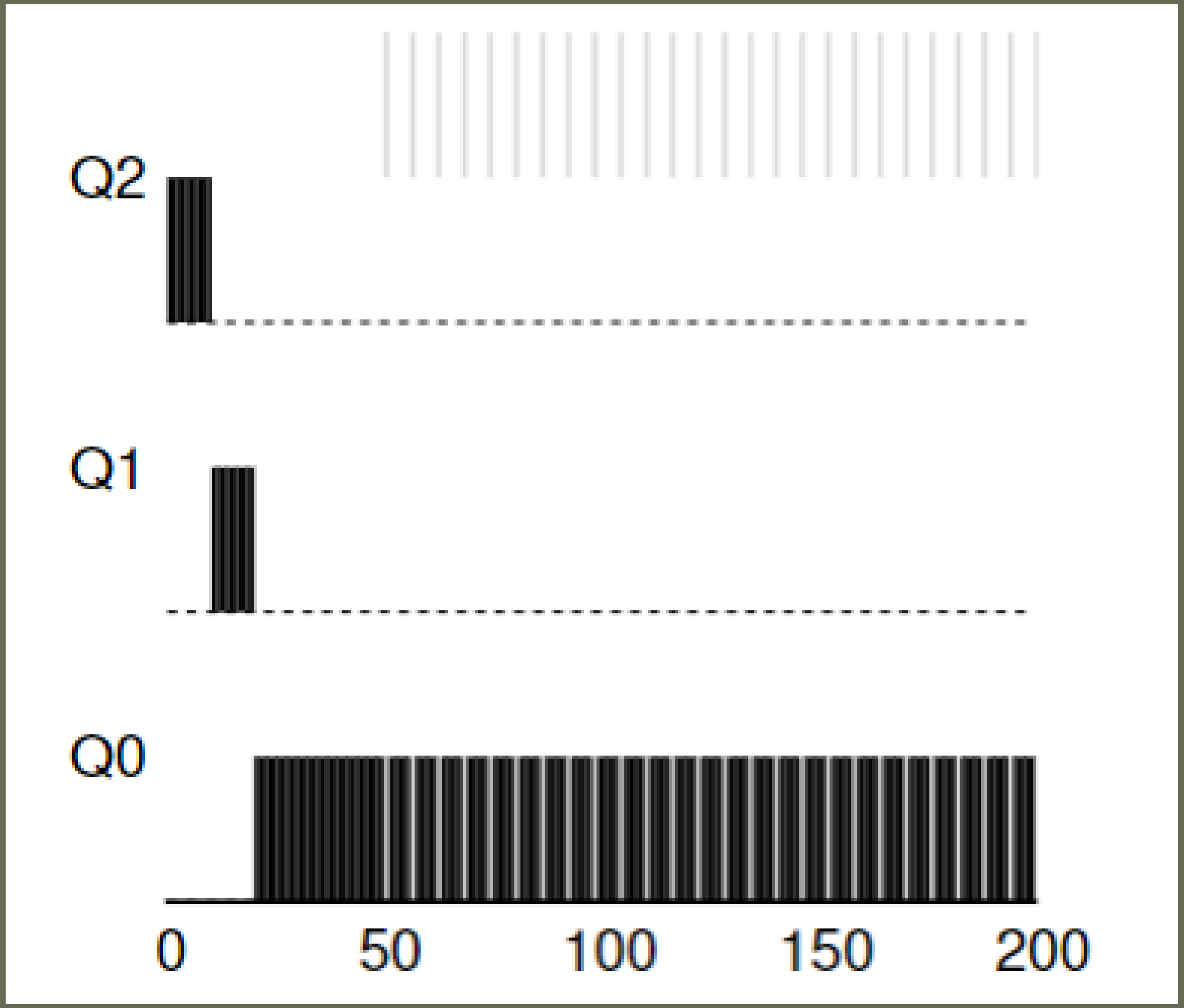


# Short job



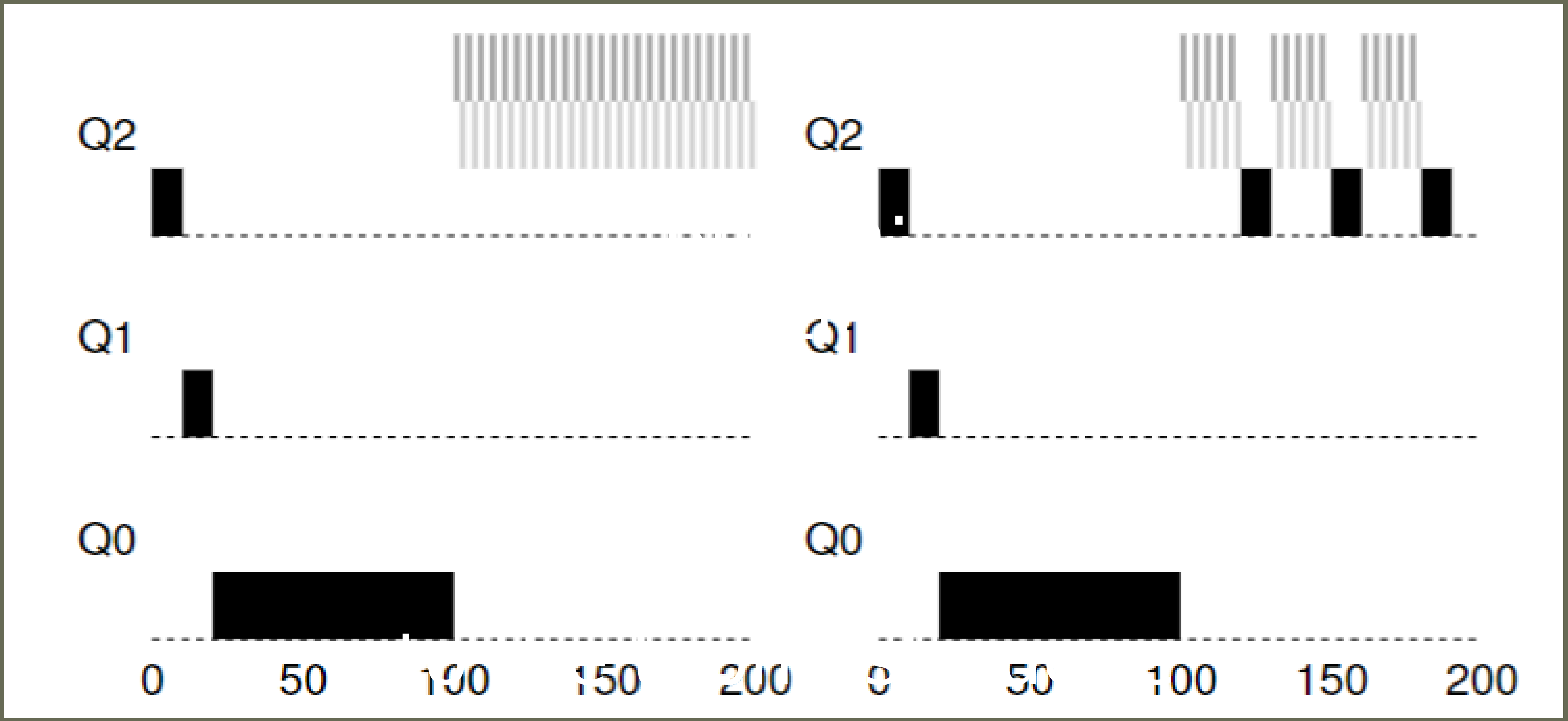

Short job starts in high priority Q2
Its lifetime run approximates SJF (gets all CPU time)

# An Interactive Process Joins



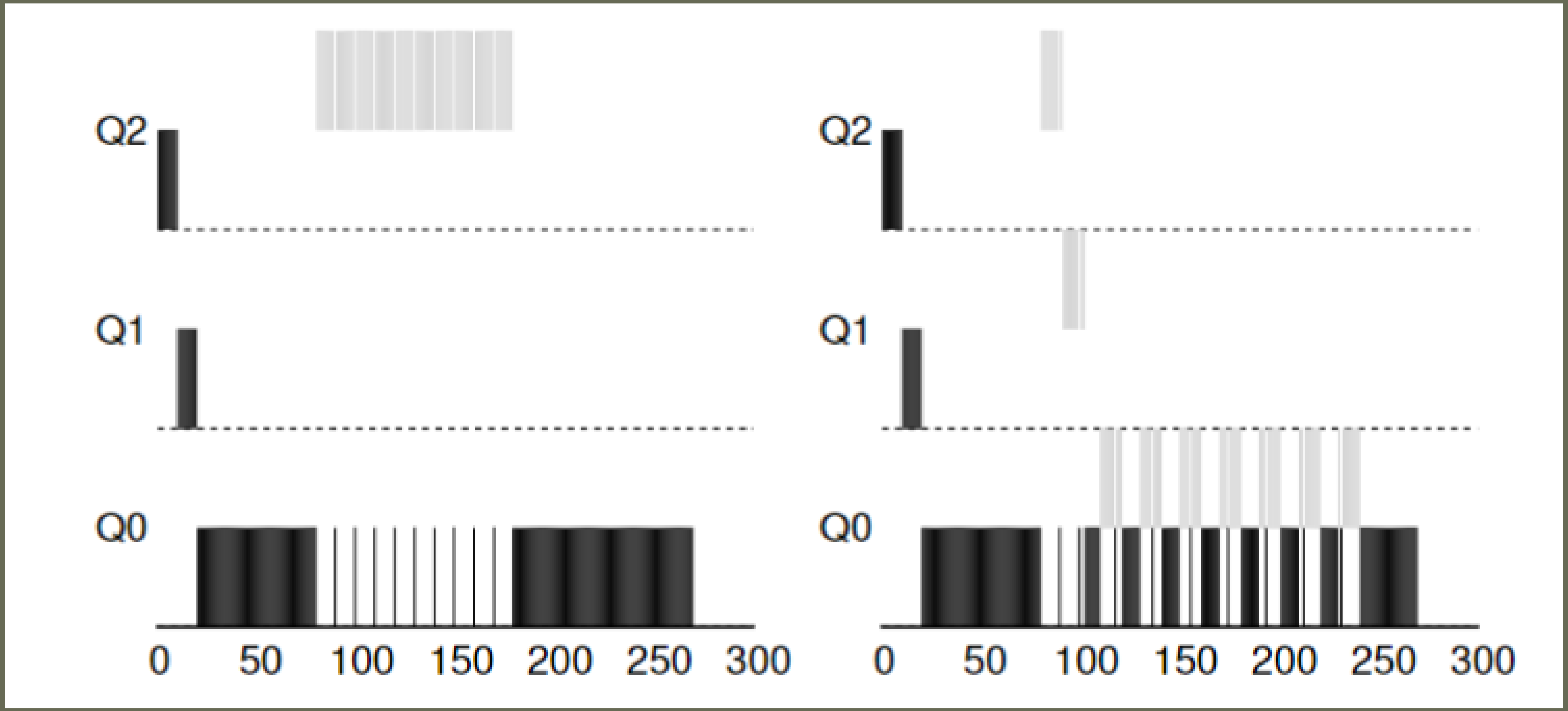

Interactive process never uses entire time slice, so never demoted, so stays in a very responsive (short time slice queue)

# Starvation -low priority processes never run




Occasionally boost priority of low priority processes
So they get processor time or
Rule 5: After some time period S, move all the jobs
in the system to the topmost queue (what value is S?)

# Gaming system –process uses up most of TS, then invokes IO call




Easy to cheat – so track cpu usage instead of I/O calls

Rule 4 redo: Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced

# MLFQ – the rules

Rule 1: If Priority(A) >Priority(B), A runs (B doesn’t).

Rule 2: If Priority(A)=Priority(B), A & B run in round-robin fashion using the time slice (quantum length) of the given queue.

Rule 3: When a job enters the system, it is placed at the highest priority (the topmost queue).

Rule 4: Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority Is reduced (i.e., it moves down one queue).

Rule 5: After some time period S, move all the jobs in the system to the topmost queue.

# Lottery Scheduling

Goal: proportional (fair) share

Approach:

- give processes lottery tickets
- whoever wins runs
- higher priority => get more tickets

Simple to implement

# Lottery Code

```
// counter: used to track if we've found the winner yet
int counter = 0;

// winner: use some call to a random number generator to
//         get a value, between 0 and the total # of tickets
int winner = getrandom(0, totaltickets);

// current: use this to walk through the list of jobs
current = head;
while (current) {
    counter = counter + current->tickets;
    if (counter > winner)
        break; // found the winner
    current = current->next;
}
// 'current' is the winner: schedule it...
```

Head- holds list of jobs, sorted by ticket numbers held

# Lottery example

```
// counter: used to track if we've found the winner yet
int counter = 0;

// winner: use some call to a random number generator to
//         get a value, between 0 and the total # of tickets
int winner = getrandom(0, totaltickets);

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    if (counter > winner)
        break; // found the winner
    current = current->next;
}
// 'current' is the winner: schedule it...
```

Who runs if winner is:

- 50
- 350
- 0

head → Job A (1) → Job B (1) → Job C (100) → Job D (200) → Job E (100) → null

# Other Lottery Ideas

Ticket Transfers
Ticket Currencies
Ticket Inflation
(read more in OSTEP)

# Summary

Understand goals (metrics) and workload, then design scheduler around those
General purpose schedulers need to support processes with different goals
Past behavior is good predictor of future behavior
Random algorithms (lottery scheduling) can be simple to implement, and avoid corner cases.