Scheduling: RR, Priority, MLFQ, and Lottery

CS 571: Operating Systems (Spring 2020)
Lecture 5

Yue Cheng

- CPU scheduling worksheet posted on BB

Review: FIFO, SJF

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

FIFO

- First-In, First-Out: Run jobs in arrival (time) order

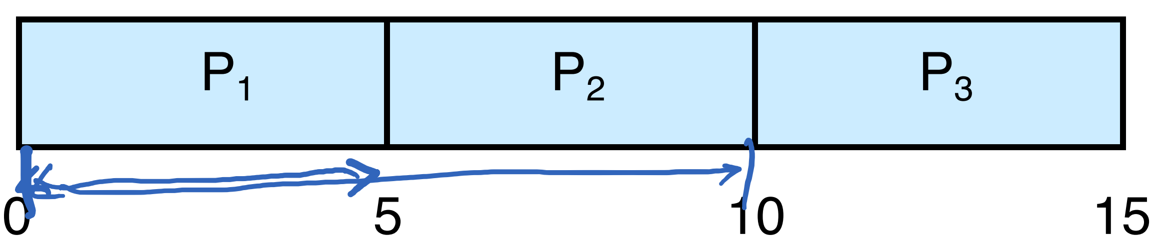
FIFO

First-In, First-Out: Run jobs in arrival (time) order

Def: waiting_time = start_time – arrival_time

Process	Burst Time
P_1	5
P_2	5
P_3	5

- Suppose that the processes arrive in order: P_1 , P_2 , P_3
  The Gantt Chart for the schedule:



- Waiting time for P_1 = 0; P_2 = 5; P_3 = 10
- Average waiting time: 5

15/3 = 5

FIFO

First-In, First-Out: Run jobs in arrival (time) order

What is the average turnaround time? (Q2)?

Def: turnaround_time = completion_time – arrival_time

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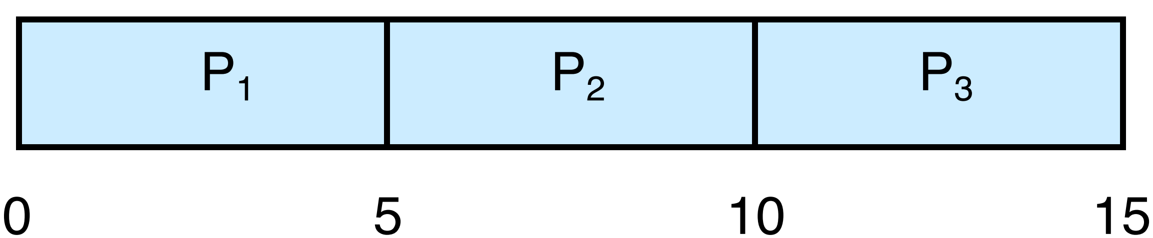

- Waiting time for P_1 = 0; P_2 = 5; P_3 = 10
- Average waiting time: 5

FIFO

First-In, First-Out: Run jobs in arrival (time) order

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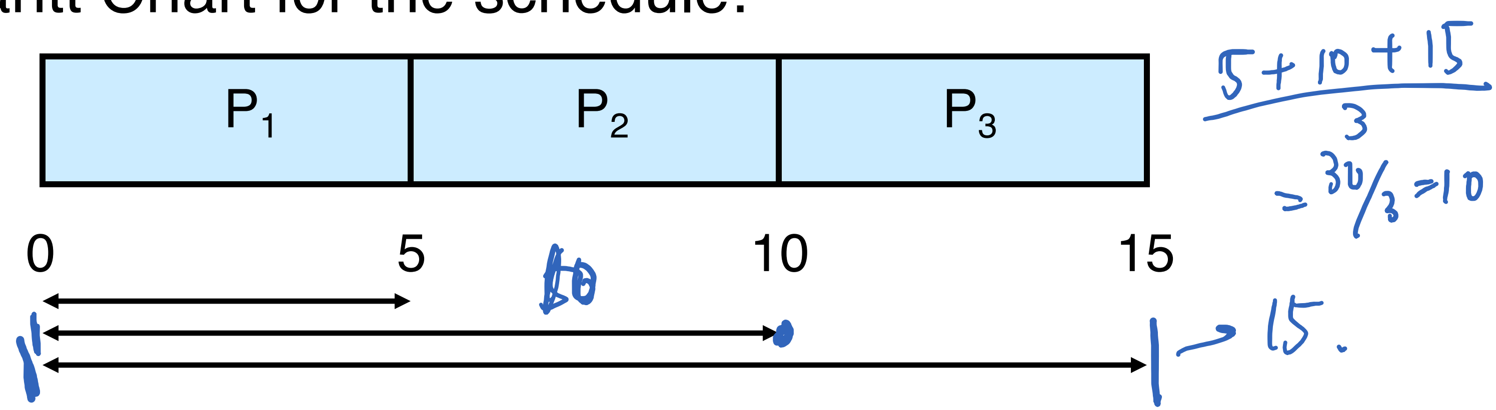

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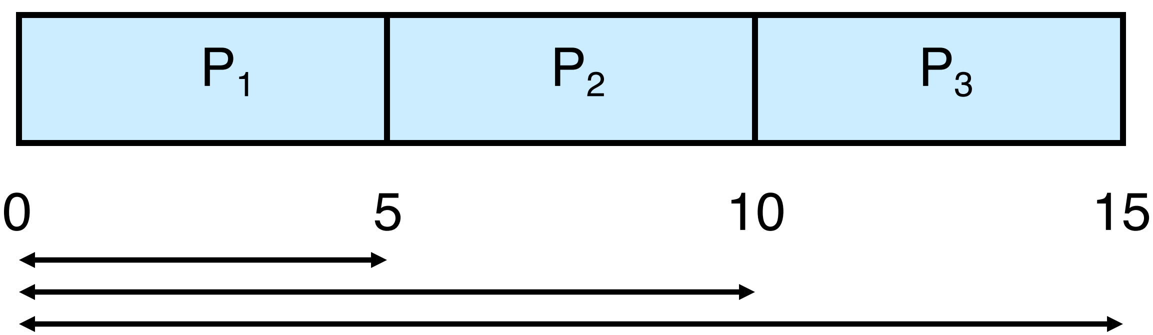

Average turnaround time: (5+10+15)/3 = 10

Workload Assumptions

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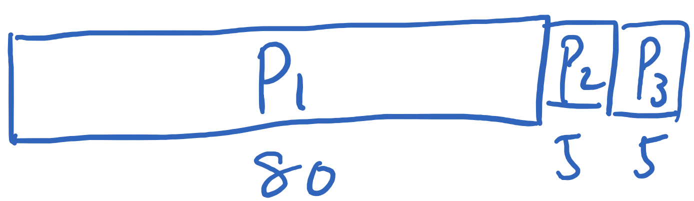
Example: Big First Job

JOB	arrival_time	run_time
P1	~0	80
P2	~0	5
P3	~0	5

What is the average turnaround time? (Q3)



$$\frac{80+85+90}{3} = \frac{165+90}{3} = \frac{255}{3}$$

Example: Big First Job

JOB	arrival_time	run_time
P1	~0	80
P2	~0	5
P3	~0	5

Example: Big First Job

JOB	arrival_time	run_time
P1	~0	80
P2	~0	5
P3	~0	5

Average turnaround time: (80+85+90) / 3 = 85

Convoy Effect

Better Schedule?

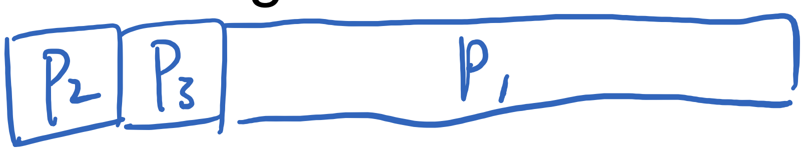
Passing the Tractor

- New scheduler: SJF (Shortest Job First)
- Policy: When deciding which job to run, choose the one with the smallest run_time

Example: SJF

JOB	arrival_time	run_time
P1	~0	80
P2	~0	5
P3	~0	5

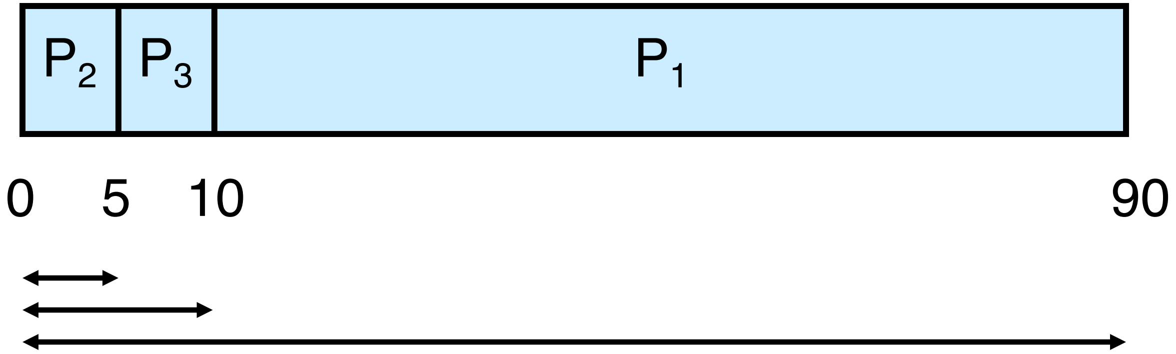
What is the average turnaround time with SJF? (Q4)



$$\frac{5 + 10 + 90}{3} = \frac{105}{3}$$

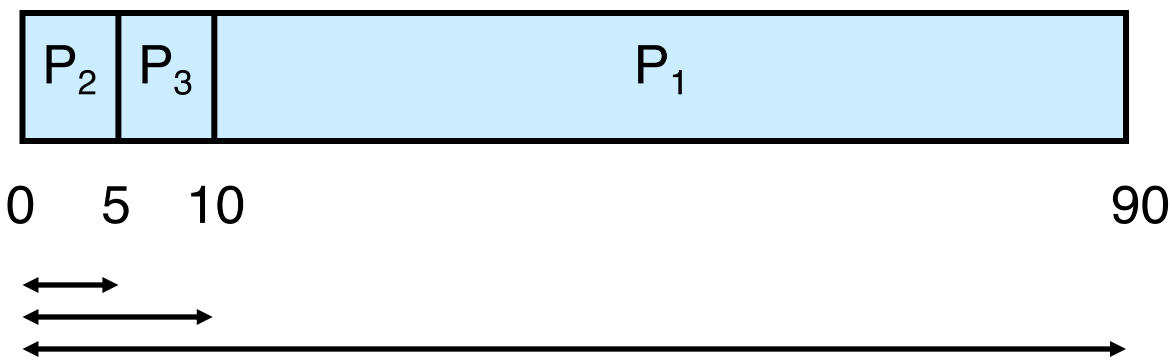
Example: SJF

JOB	arrival_time	run_time
P1	~0	80
P2	~0	5
P3	~0	5



Example: SJF

JOB	arrival_time	run_time
P1	~0	80
P2	~0	5
P3	~0	5



35<<85

Average turnaround time: (5+10+90) / 3 = 35

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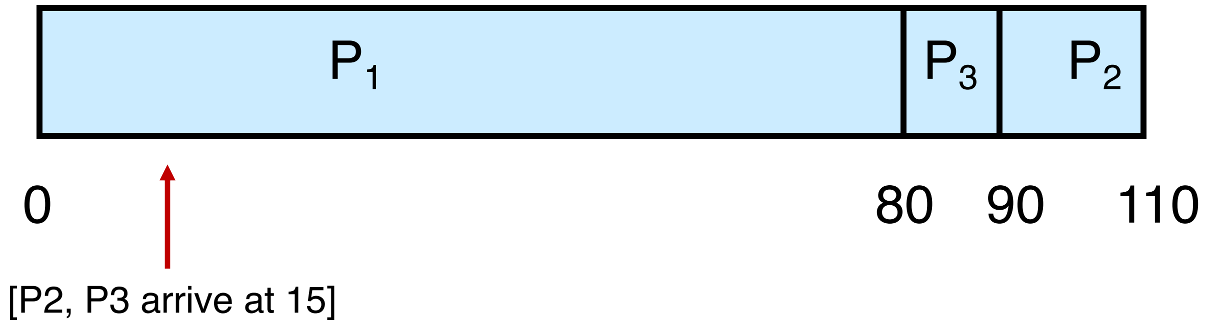
Shortest Job First (Arrival Time)

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10

What is the average turnaround time with SJF? (Q5)

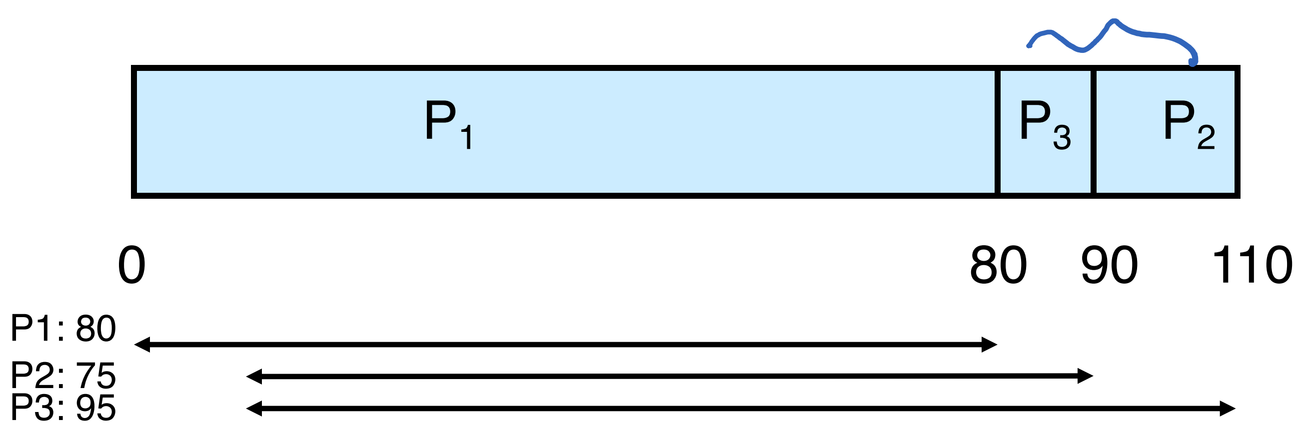
Shortest Job First (Arrival Time)

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



Shortest Job First (Arrival Time)

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



FIFO: 85

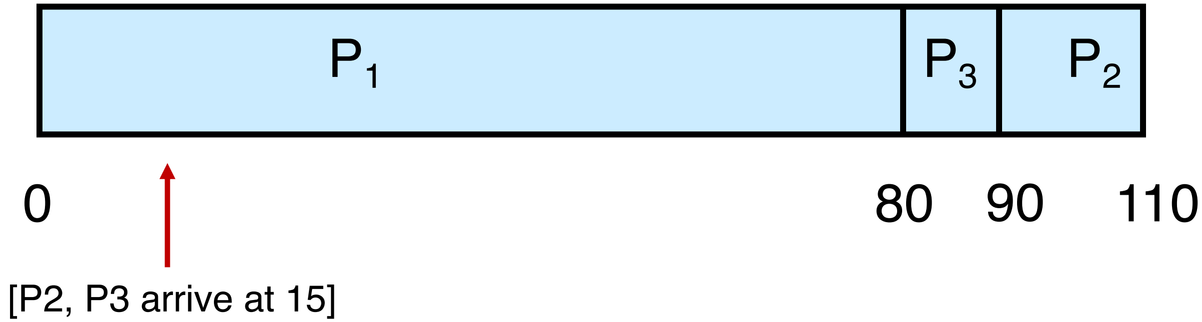
Average turnaround time: (80+75+95) / 3 = ~83.3

A Preemptive Scheduler

- Previous schedulers: FIFO and SJF are non-preemptive
- New scheduler: STCF (Shortest Time-to-Completion First)
- Policy: Switch jobs so we always run the one that will complete the quickest

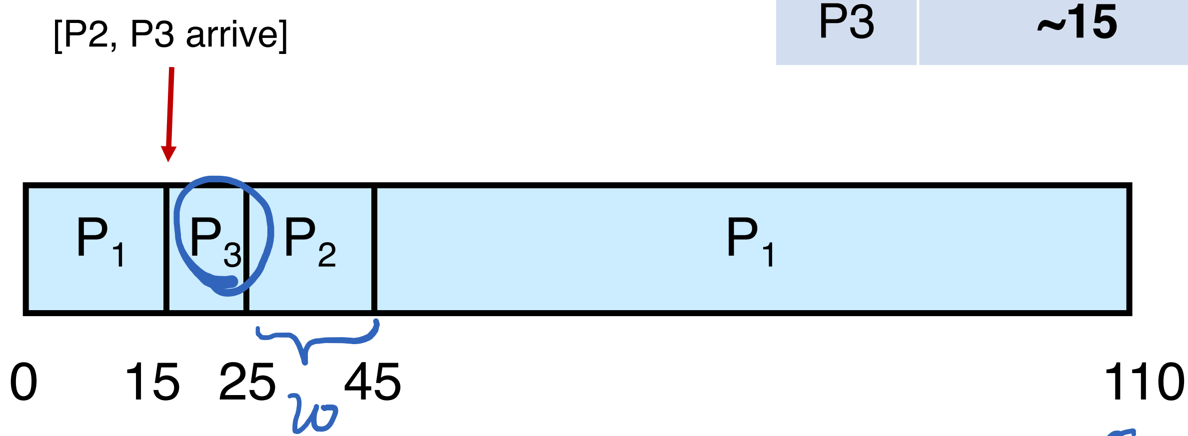
SJF

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



STCF

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



What is the average turnaround time with SRTF? (Q6)

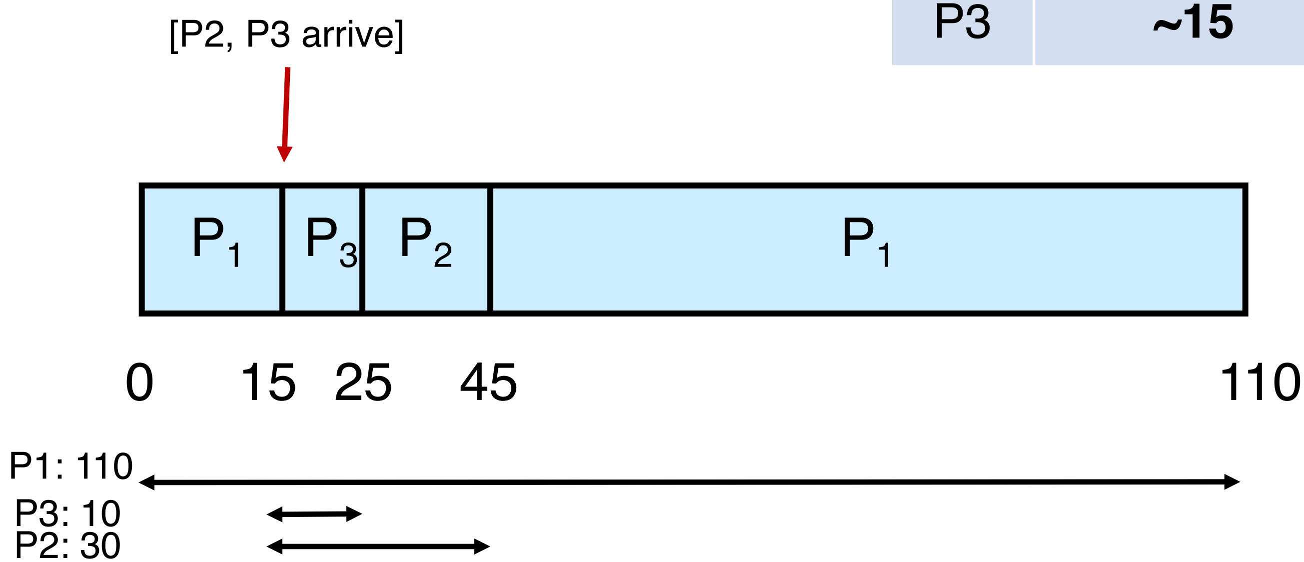
P1 : 110

P2 : 45 − 15 = 30

P3 : 25 − 15 = 10

STCF

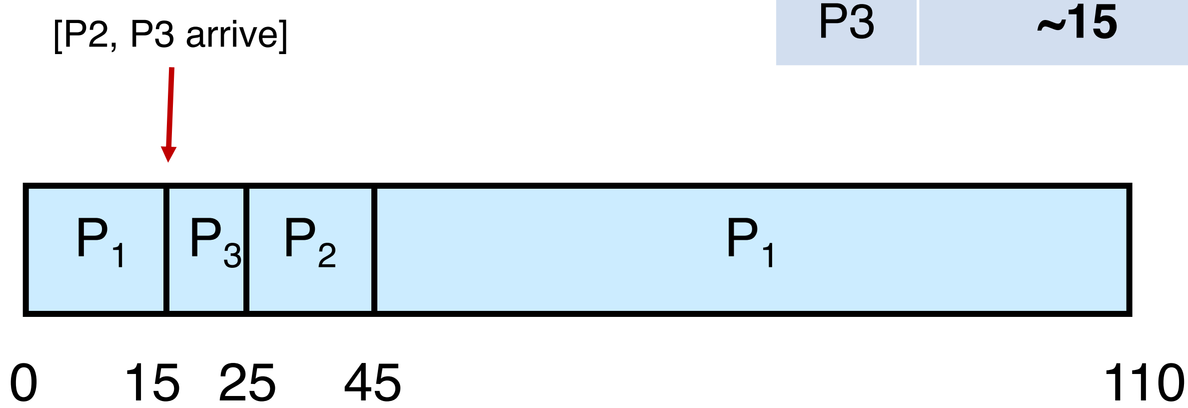
JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



Average turnaround time: (110+30+10) / 3 = 50

STCF

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



What is the average waiting time with STCF? (Q7)

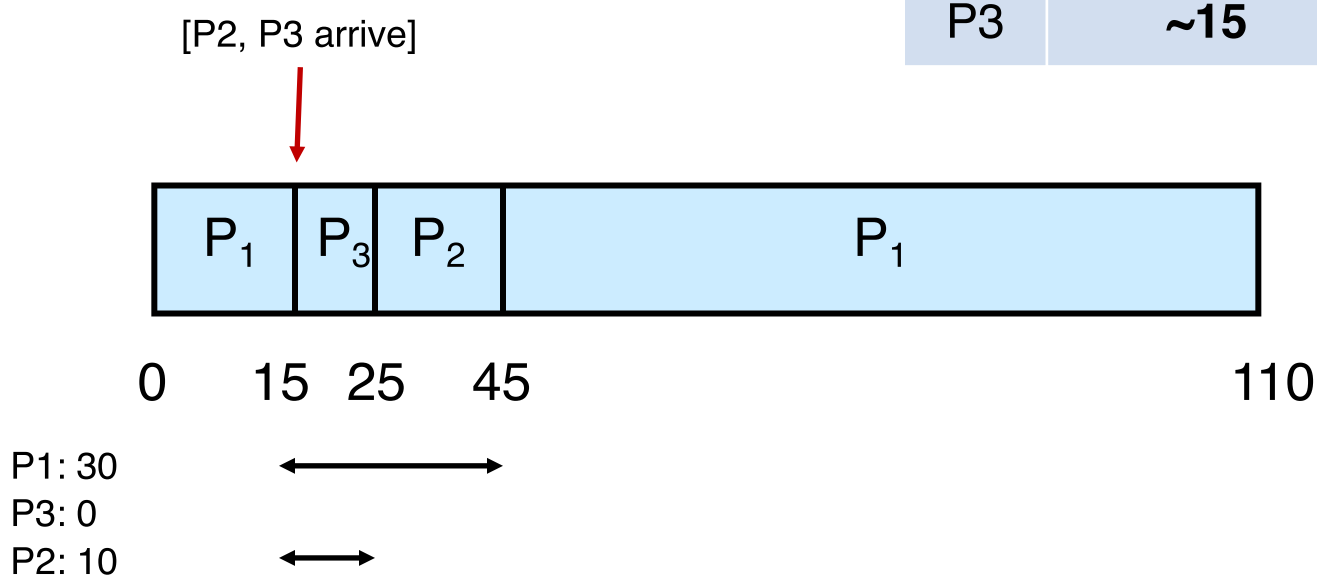
$P_1 : 0 + (45 - 15) = 30$

$P_2 : 25 - 15 = 10$

$P_3 : 0$

STCF

JOB	arrival_time	run_time
P1	~0	80
P2	**~15**	20
P3	**~15**	10



Average waiting time: (30+10+0) / 3 = ~13.3

Outline

- Scheduling algorithms
  - First In, First Out (FIFO)
  - Shortest Job First (SJF)
  - Shortest Time-to-Completion First (STCF)
    - Optimality discussion
  - Round Robin (RR)
  - Priority
  - Multi-Level Feedback Queue (MLFQ)
  - Lottery Scheduling

Optimality of SJF and STCF

- Non-preemptive SJF is optimal if all the processes are ready simultaneously
    - Gives minimum average waiting time for a given set of processes

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- Non-preemptive SJF is optimal if all the processes are ready simultaneously
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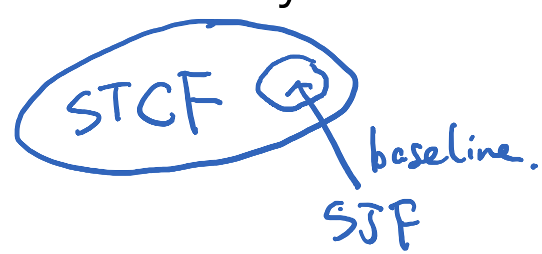
- What is the intuition behind the optimality of STCF?
  - A: STCF is optimal, considering a more realistic scenario where all the processes may be arriving at different times



Optimality of SJF and STCF

- Non-preemptive SJF is optimal if all the processes are ready simultaneously
  - Gives minimum average waiting time for a given set of processes

Q: What's the problem?

We don't exactly know how long a job would run!

- What is the intuition behind the optimality of SRTF?
  - A: SRTF is optimal, considering a more realistic scenario where all the processes may be arriving at different times

Estimating the Length of Next CPU Burst

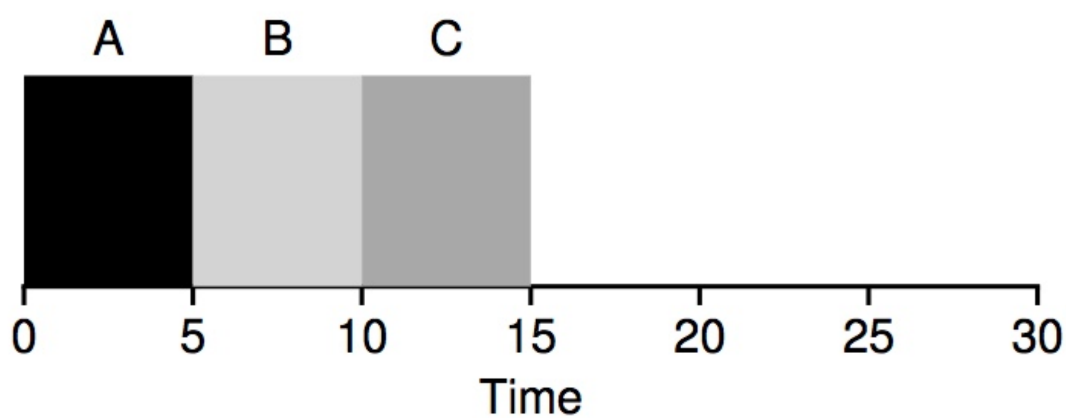
- Idea: Based on the observations in the recent past, we can try to predict
- Techniques such as exponential averaging are based on combining the observations in the past and our predictions using different weights
- Exponential averaging
  - t_n: actual length of the n^{th} CPU burst
  - z_{n+1}: predicted value for the next CPU burst
  - $z_{n+1} = k.t_n + (1-k).z_n$
  - Commonly, k is set to ½

Response Time

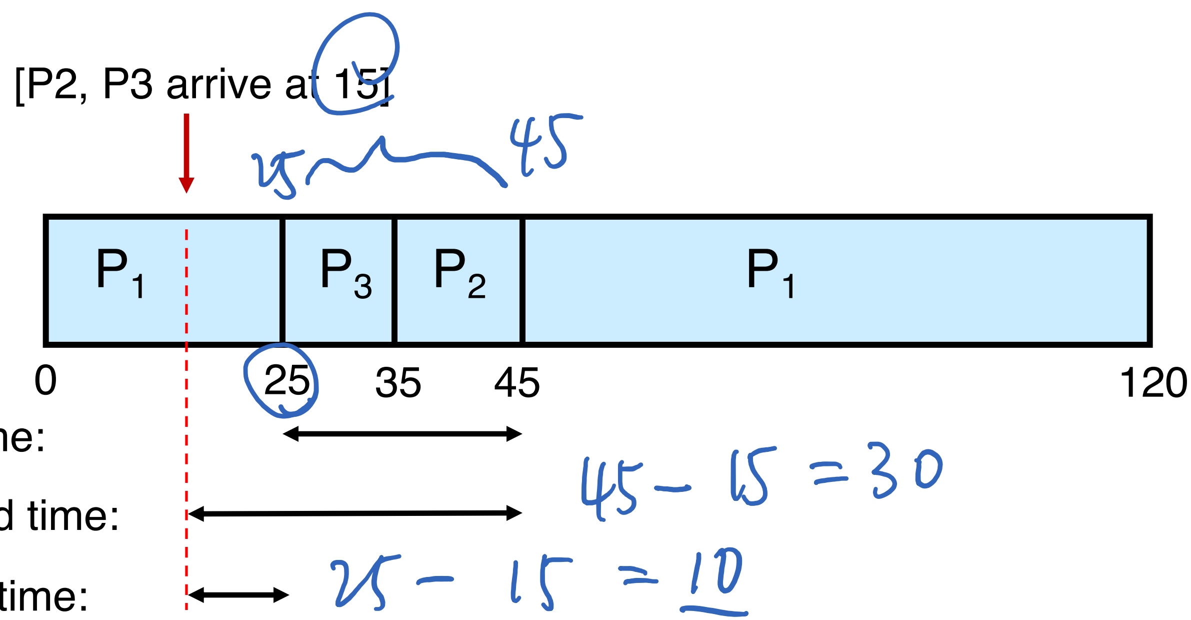
- Response time definition

$$T_{response} = T_{first\_run} - T_{arrival}$$

- SJF's average response time (all 3 jobs arrive at same time)
  - (0 + 5 + 10)/3 = 5



Waiting, Turnaround, Response

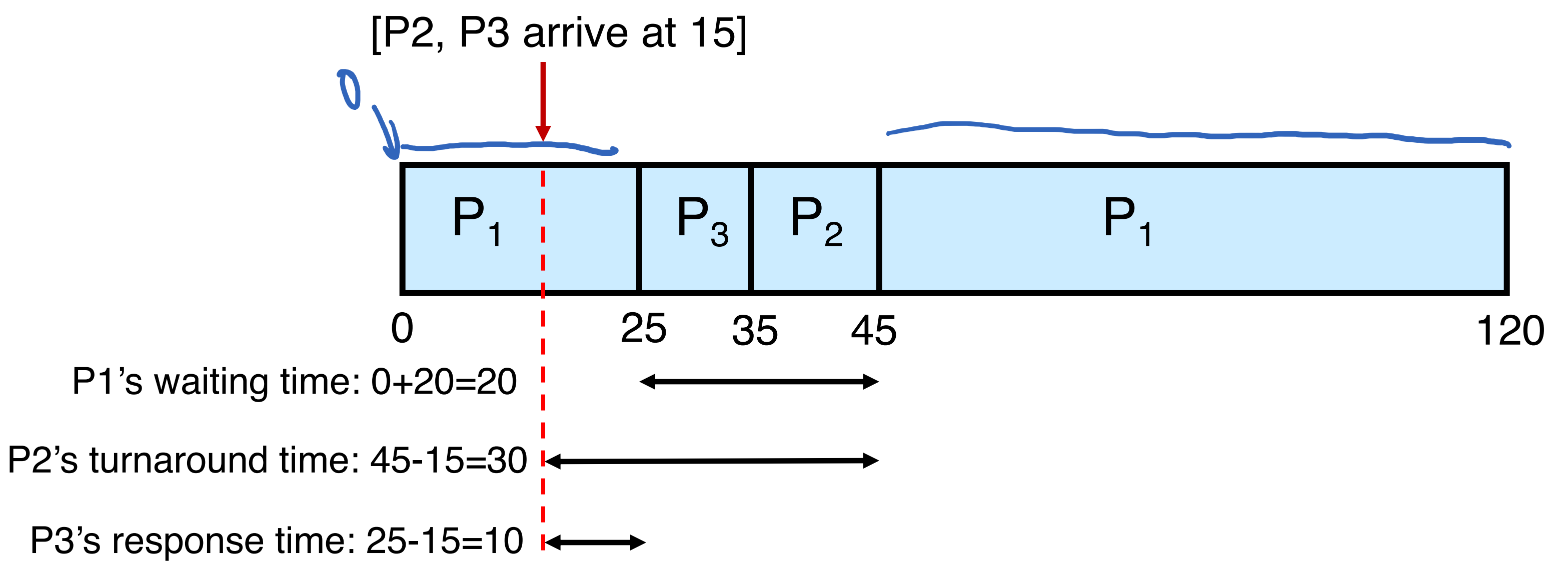


P1's waiting time:

P2's turnaround time:

P3's response time:

Waiting, Turnaround, Response



Q: What is P1's response time?

Round Robin (RR)

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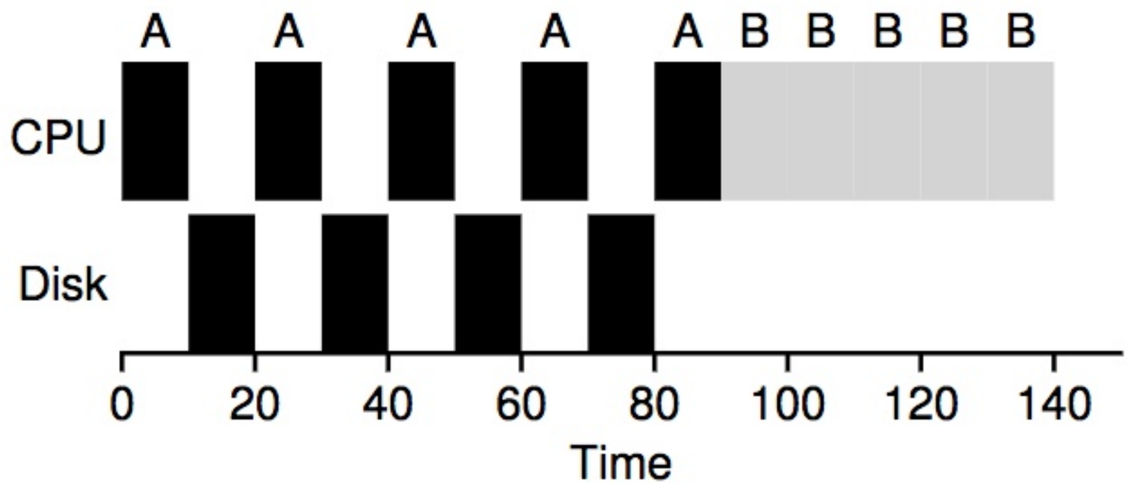
Extension to Multiple CPU & I/O Bursts

- When the process arrives, it will try to execute its first CPU burst
  - It will join the ready queue
  - The priority will be determined according to the underlying scheduling algorithm and considering only that specific (i.e. first) burst
- When it completes its first CPU burst, it will try to perform its first I/O operation (burst)
  - It will join the device queue
  - When that device is available, it will use the device for a time period indicated by the length of the first I/O burst.
- Then, it will re-join the ready queue and try to execute its second CPU burst
  - Its new priority may now change (as defined by its second CPU burst)!

Round Robin (RR)

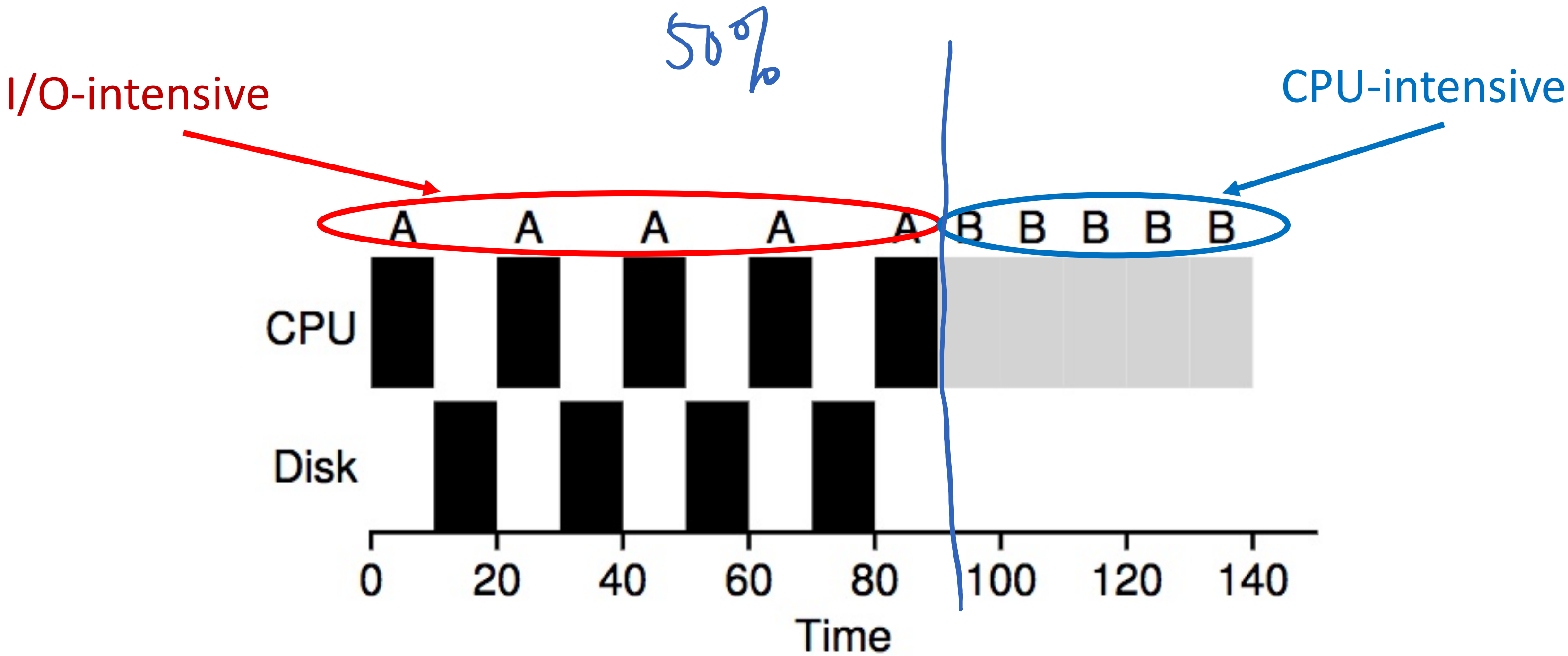
- Each process gets a small unit of CPU time (time quantum). After this time has elapsed, the process is preempted and added to the end of the ready queue
- Newly-arriving processes (and processes that complete their I/O bursts) are added to the end of the ready queue
- If there are n processes in the ready queue and the time quantum is q, then no process waits more than (n-1)q time units
- Performance
  - q large ⇒ FIFO
  - q small ⇒ Processor Sharing (The system appears to the users as though each of the n processes has its own processor running at the $(1/n)^{th}$ of the speed of the real processor)

Not I/O Aware



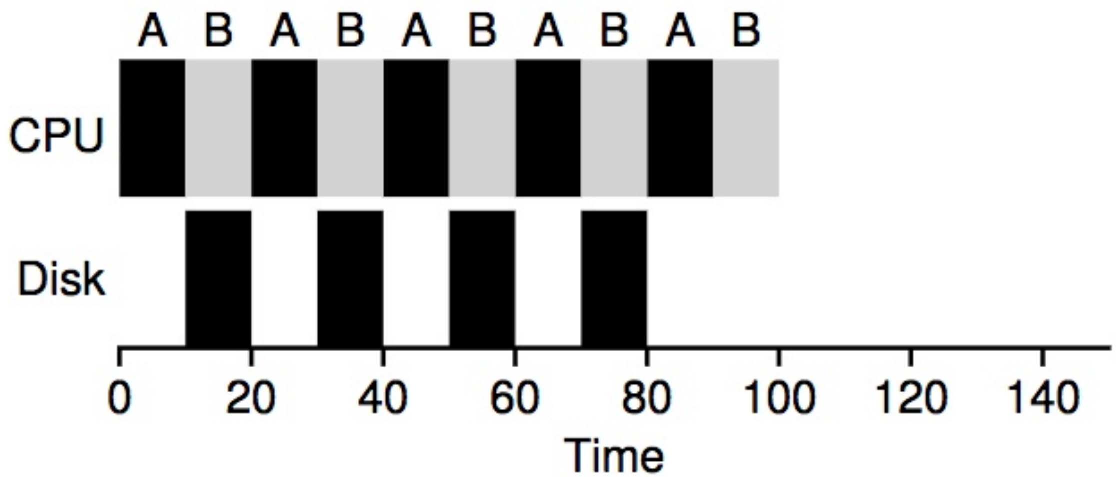
Poor use of resources

Not I/O Aware



Poor use of resources

I/O Aware (Overlap)



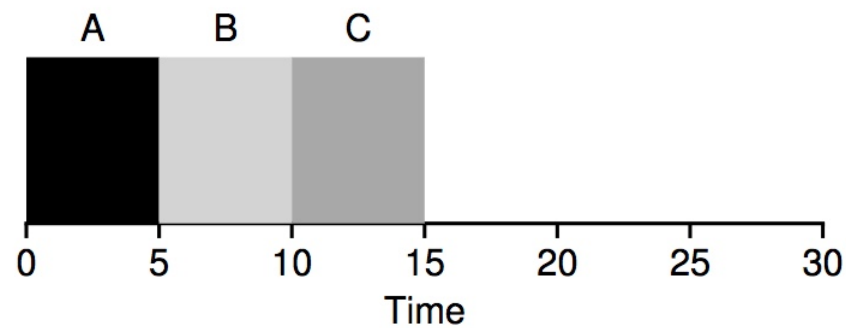
Overlap allows better use of resources!

RR

Process	Burst Time
A	5
B	5
C	5

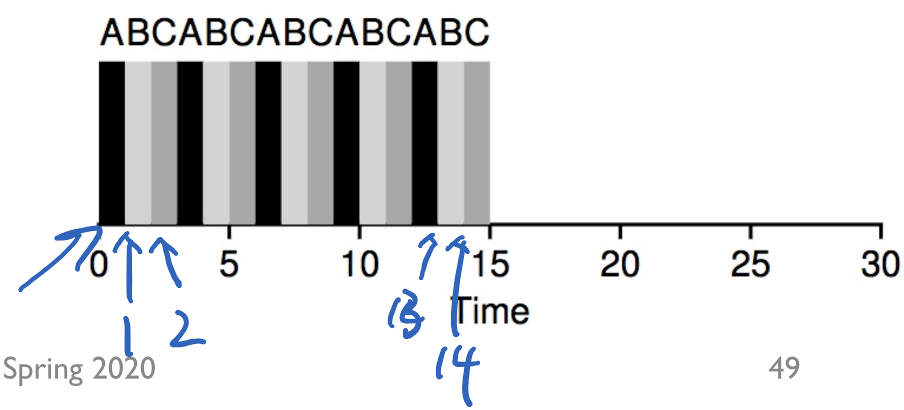
- SJF's average response time
  - (0 + 5 + 10) / 3 = 5

turnaround time: (5 + 10 + 15)/3 = 30/3 = 10



- RR's average response time (time quantum = 1)
  - (0 + 1 + 2) / 3 = 1

turnaround time = (13 + 14 + 15)/3 = 42/3 = 14



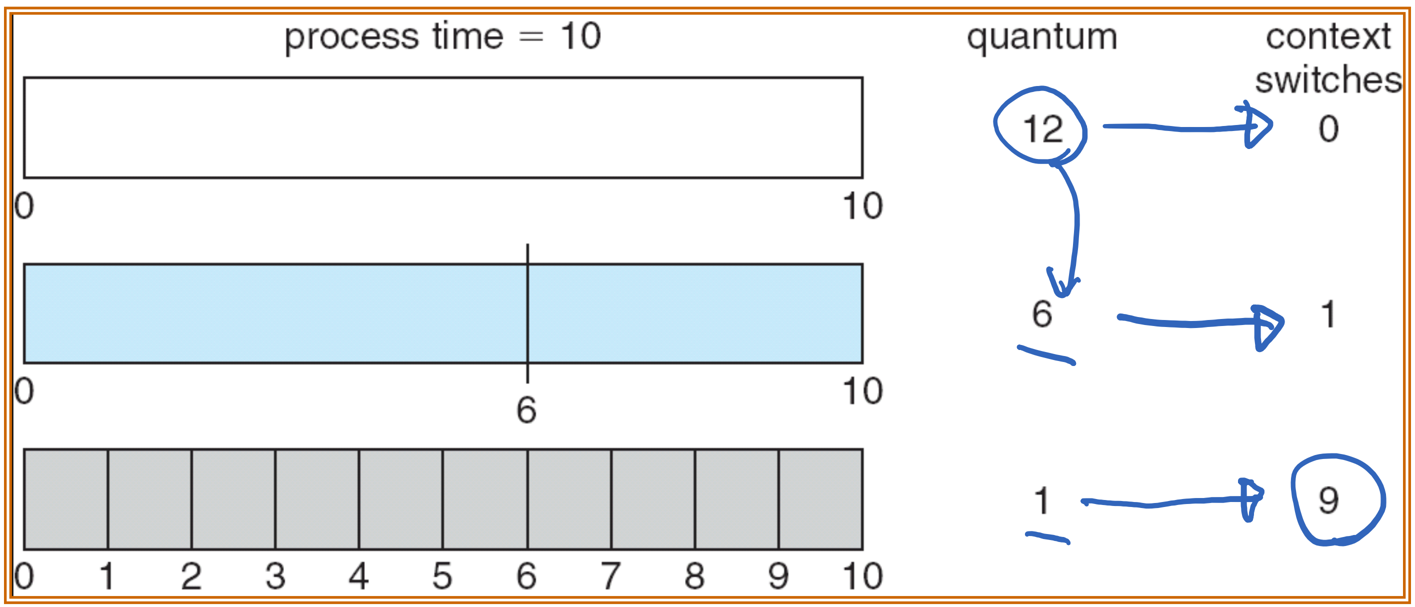
Tradeoff Consideration

- Typically, RR achieves higher average turnaround time than SJF, but better response time
  - Turnaround time only cares about when processes finish

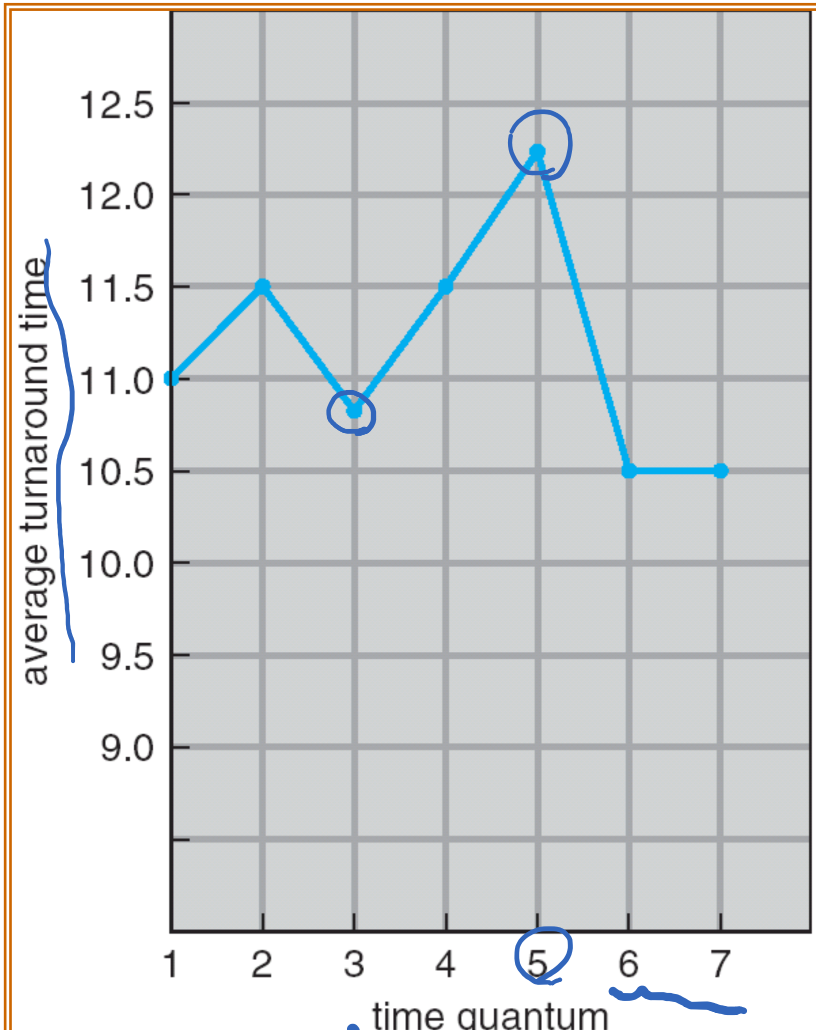
- RR is one of the worst policies
  - -IF- turnaround time is the metric

Choosing a Time Quantum

- The effect of quantum size on context-switching time must be carefully considered
- The time quantum must be large with respect to the context-switch time
- Turnaround time also depends on the size of the time quantum

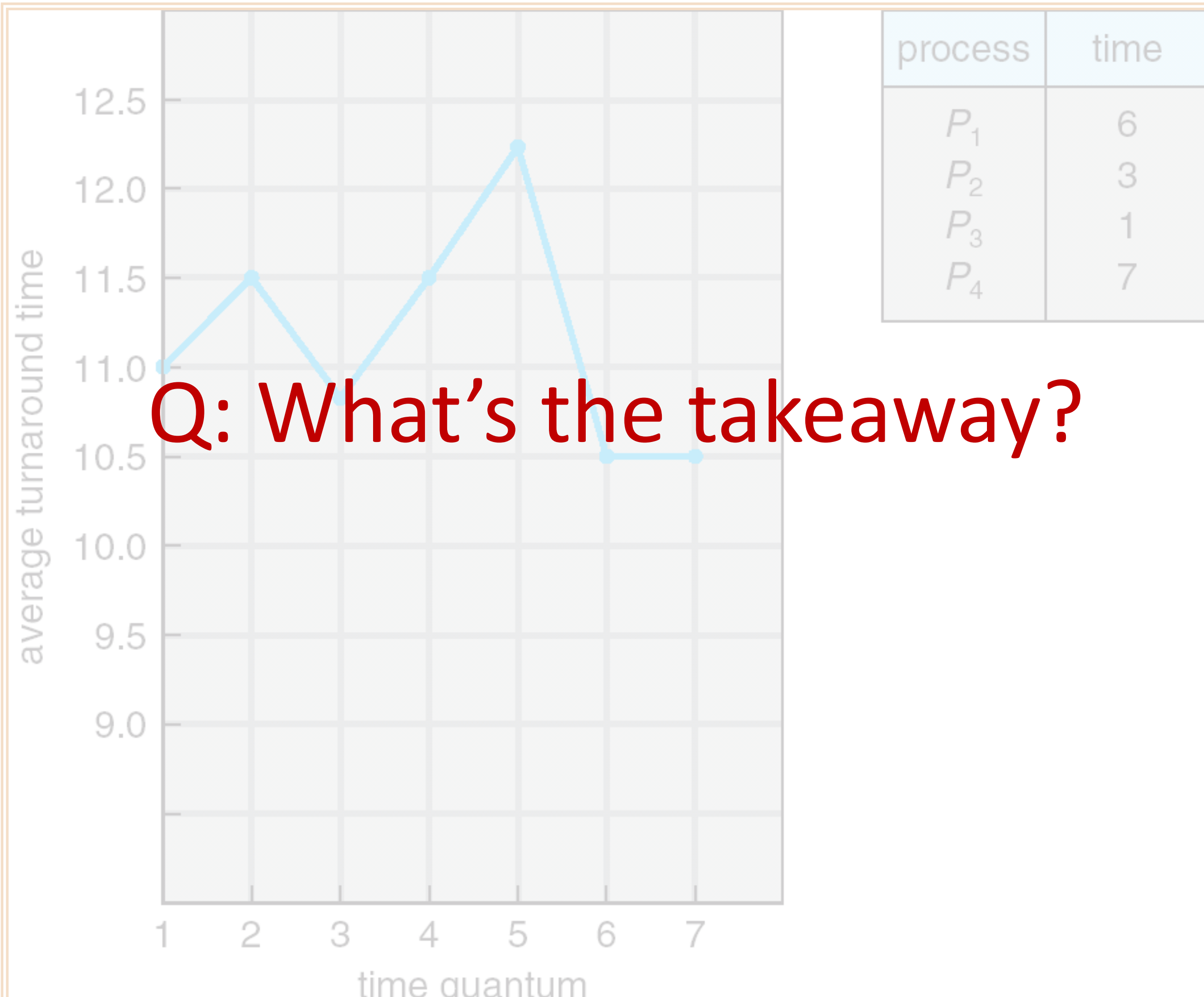


Time Quantum vs. Turnaround Time



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Time Quantum vs. Turnaround Time



process	time
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Q: What's the takeaway?

Workload Assumptions

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Priority-Based Scheduling

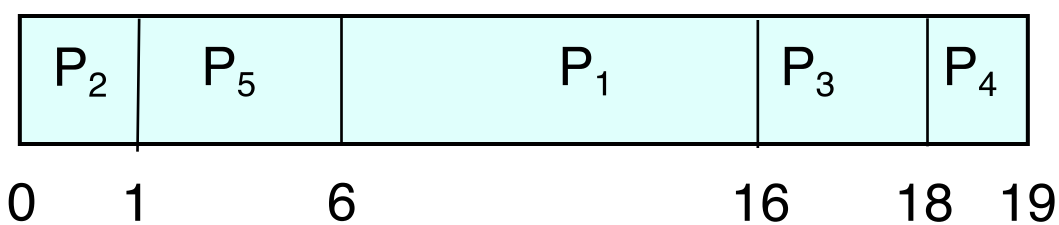
Priority-Based Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority
  - (smallest integer ≡ highest priority)
  - Preemptive
  - Non-preemptive

Example for Priority-Based Scheduling

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	4
P_4	1	5
P_5	5	2

- Priority scheduling Gantt Chart



- Average waiting time = 8.2

Priority-Based Scheduling (cont.)

- Priority Assignment
  - Internal factors: timing constraints, memory requirements, the ratio of average I/O burst to average CPU burst …
  - External factors: Importance of the process, financial considerations, hierarchy among users …

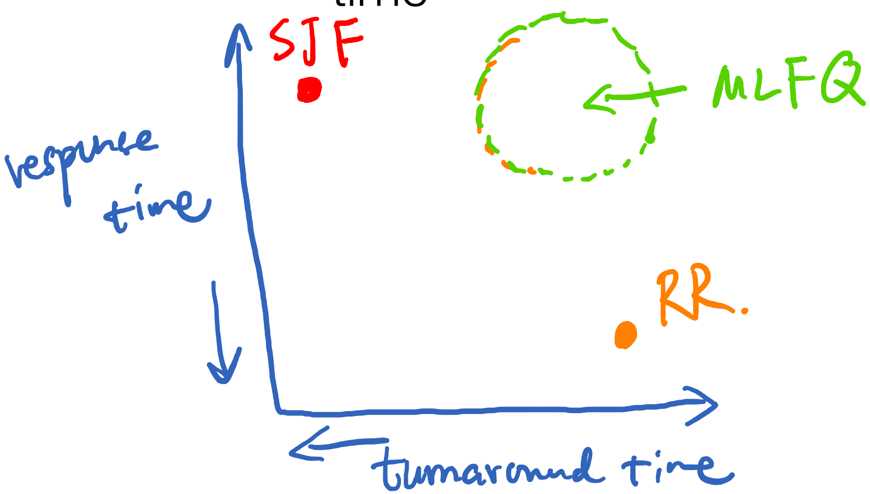
- Problem: Indefinite blocking (or starvation) – low priority processes may never execute

- One solution: Aging
  - As time progresses increase the priority of the processes that wait in the system for a long time

Multi-Level Feedback Queue (MLFQ)

Multi-Level Feedback Queue (MLFQ)

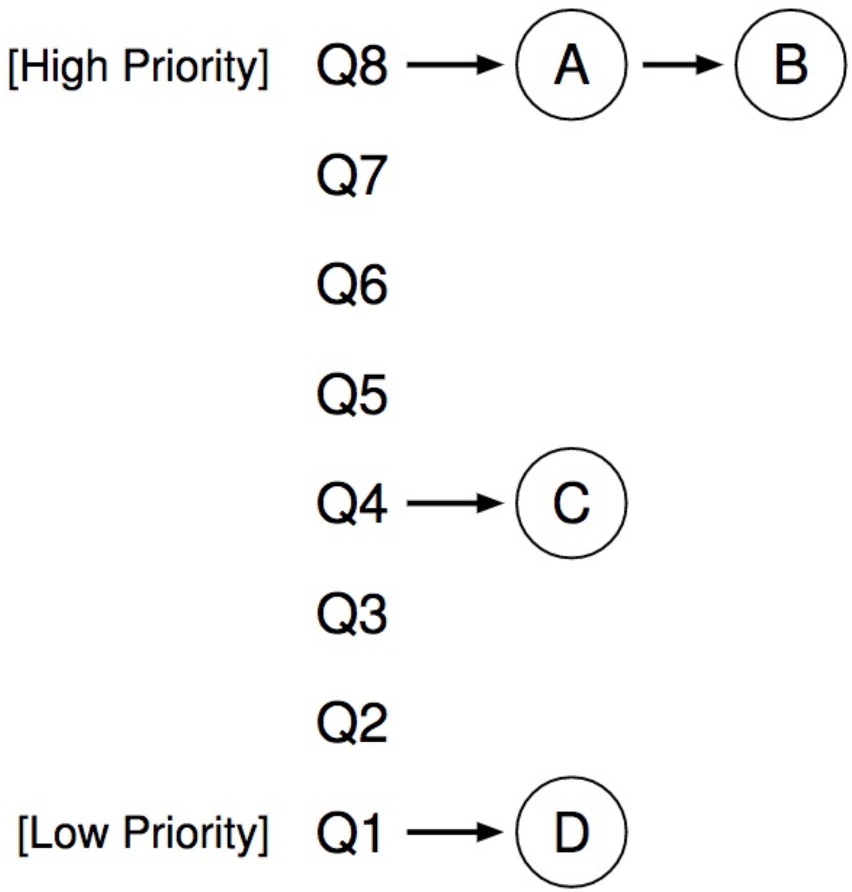
- Goals of MLFQ
  - Optimize turnaround time
    - In reality, SJF does not work since OS does not know how long a process will run
  - Minimize response time
    - Unfortunately, RR is really bad on optimizing turnaround time



MLFQ: Basics

- MLFQ maintains a number of queues (multi-level queue)
  - Each assigned a different priority level
  - Priority decides which process should run at a given time

MLFQ Example



How to know process type to set priority?

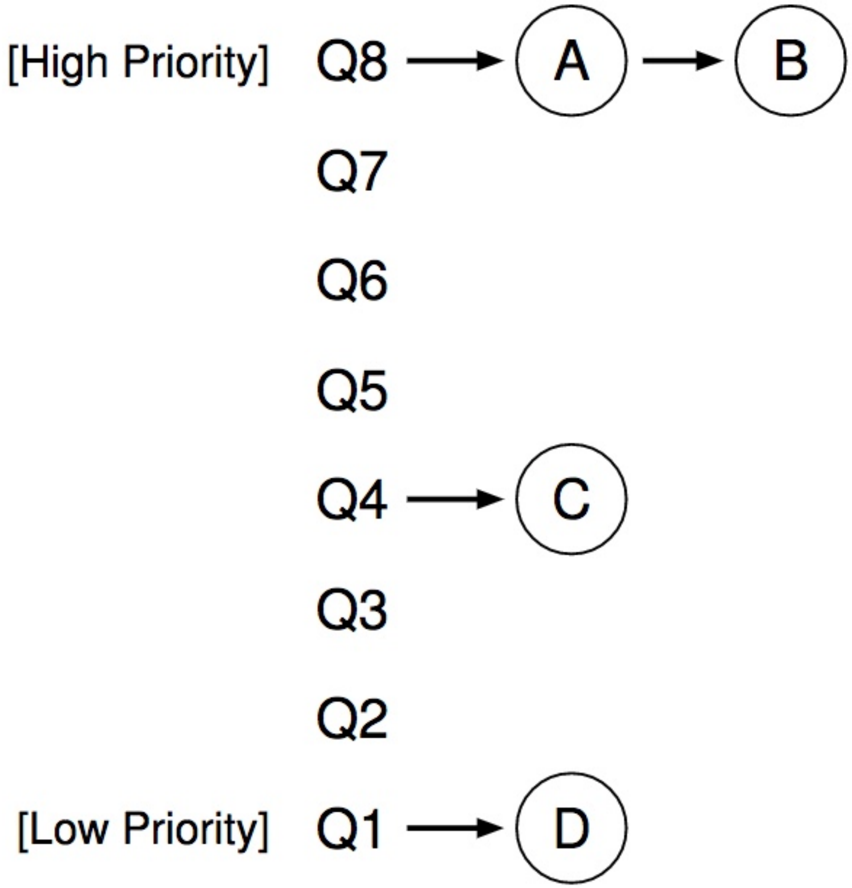
1. nice
2. history

How to Check Nice Values in Linux?

nice value

- `% ps ax -o pid,ni,cmd`

MLFQ Example



How to know process type to set priority?

1. nice
2. history

In this example, A and B are given high priority to run, while C and D may starve

MLFQ: Basic Rules

- MLFQ maintains a number of queues (multi-level queue)
  - Each assigned a different priority level
  - Priority decides which process should run at a given time

- **Rule 1:** If Priority(A) > Priority(B), A runs (B doesn't).
- **Rule 2:** If Priority(A) = Priority(B), A & B run in RR.

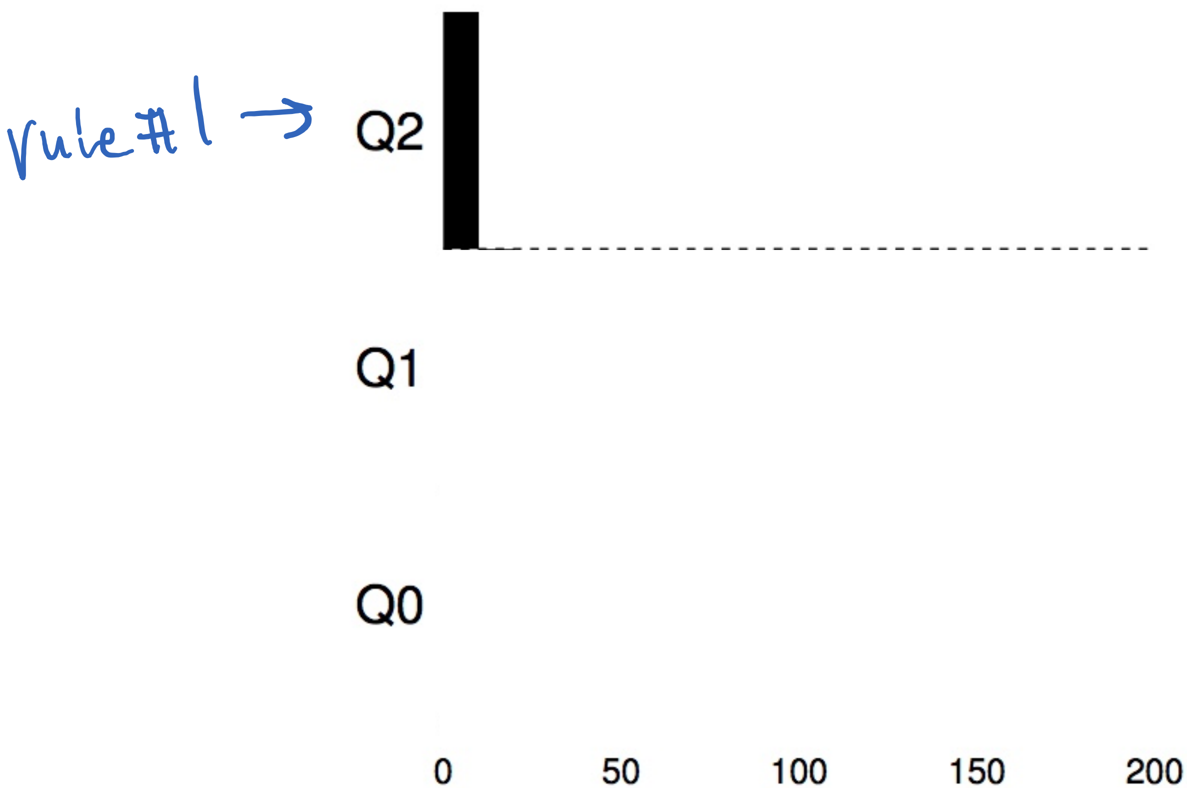
Attempt #1: Change Priority

- Workload
  1. • Interactive processes (many short-run CPU bursts)
  2. • Long-running processes (CPU-bound)
- Each time quantum = 10ms

- **Rule 3:** When a job enters the system, it is placed at the highest priority (the topmost queue).
- **Rule 4a:** If a job uses up an entire time slice while running, its priority is *reduced* (i.e., it moves down one queue).
- **Rule 4b:** If a job gives up the CPU before the time slice is up, it stays at the *same* priority level.

Example 1: One Single Long-Running Process

- A process enters at highest priority (time quantum = 10ms)



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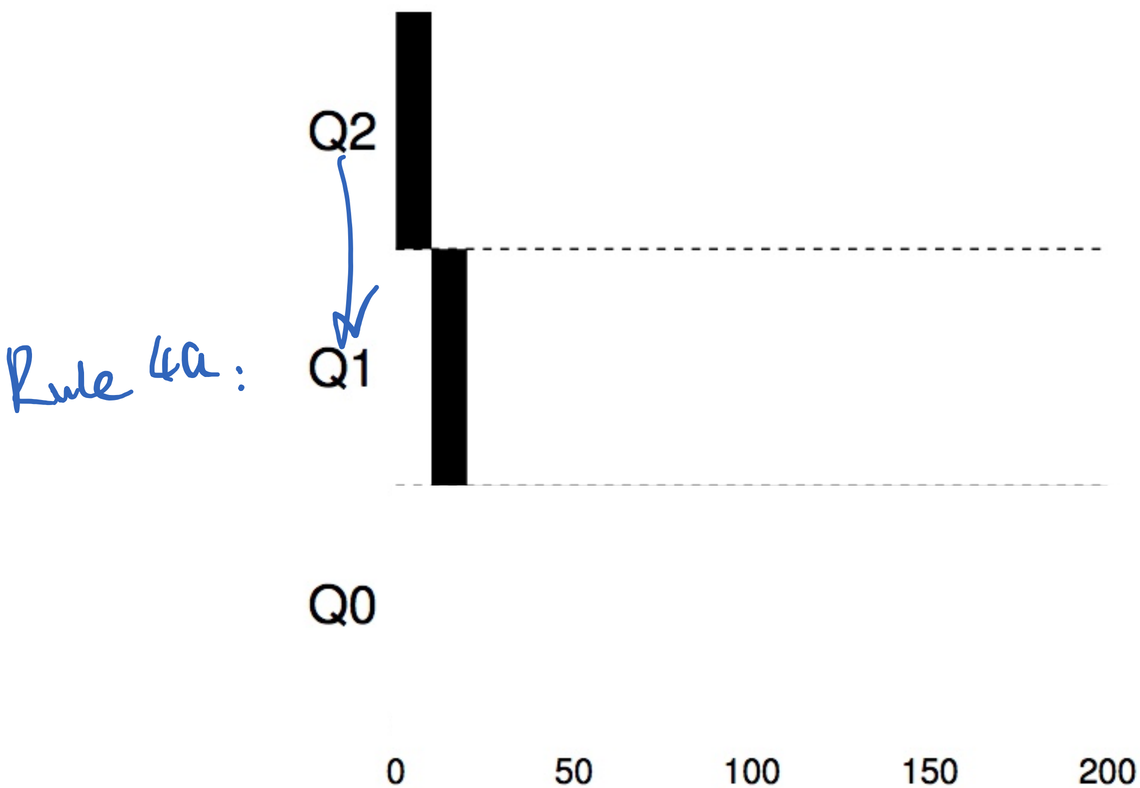

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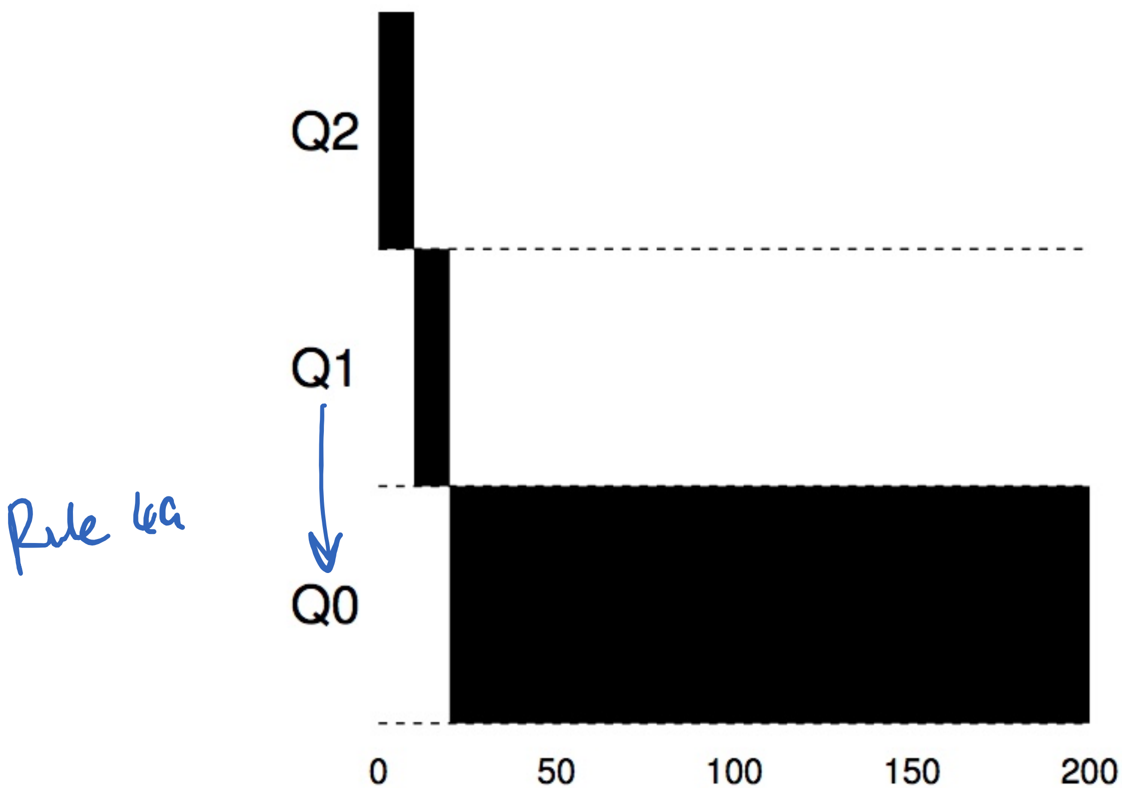
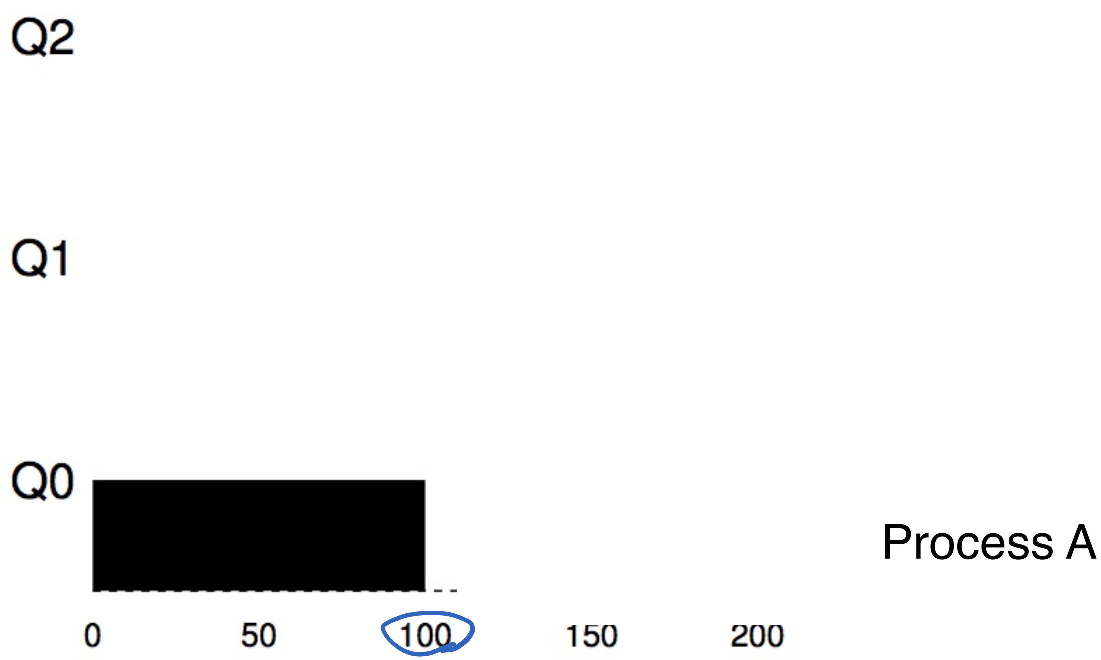


Example 2: Along Came a Short-Running Process

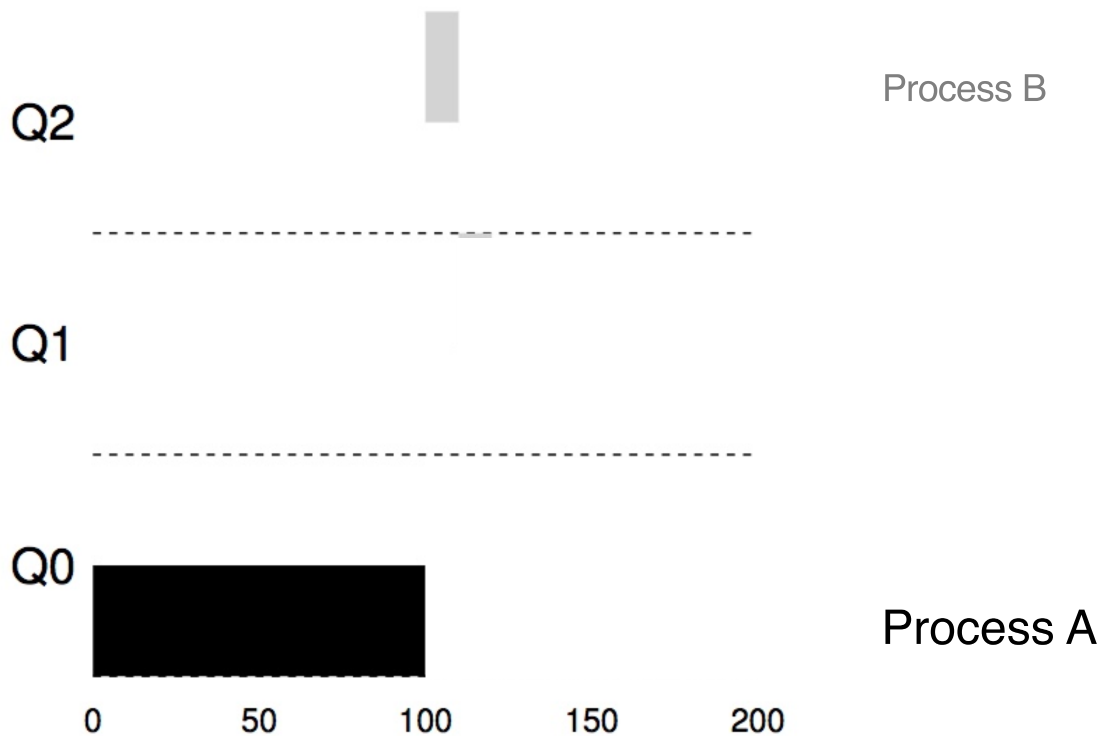
- Process A: long-running process (start at 0)



Example 2: Along Came a Short-Running Process

- Process A: long-running process (start at 0)
- Process B: short-running interactive process (start at 100)

Rule #1



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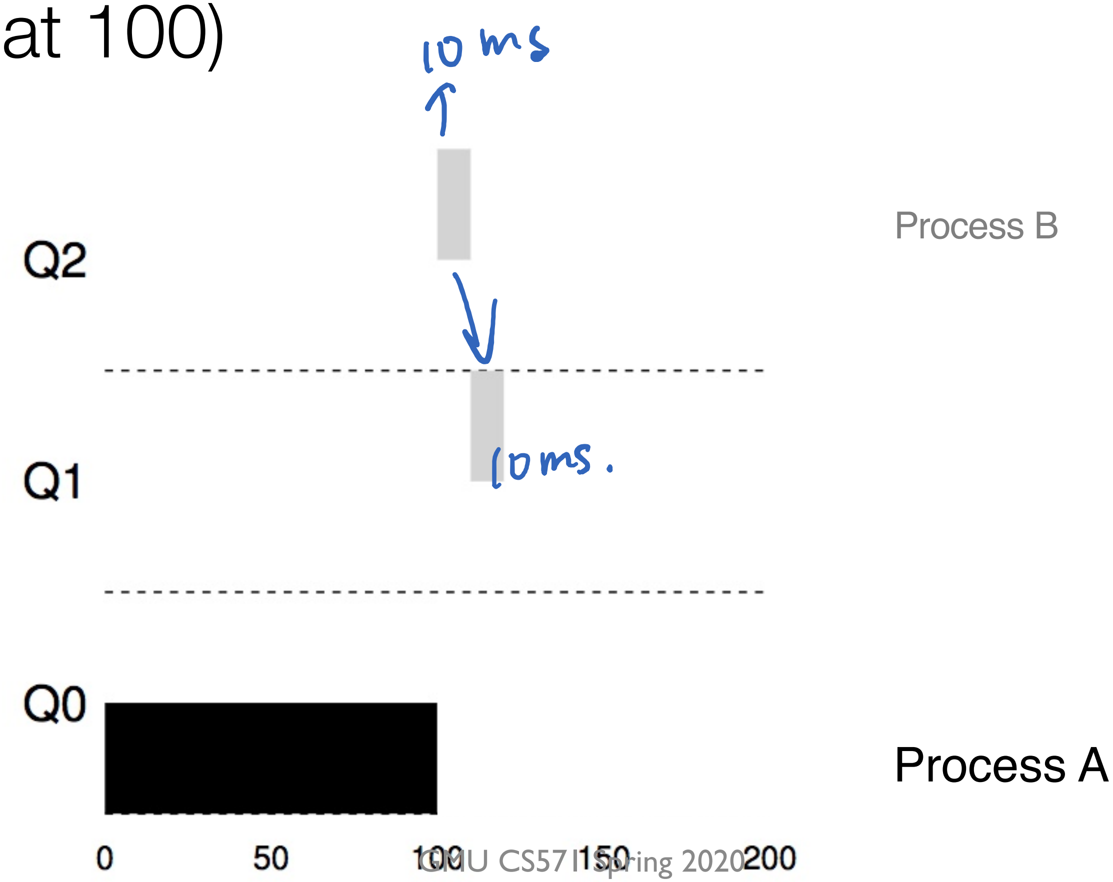

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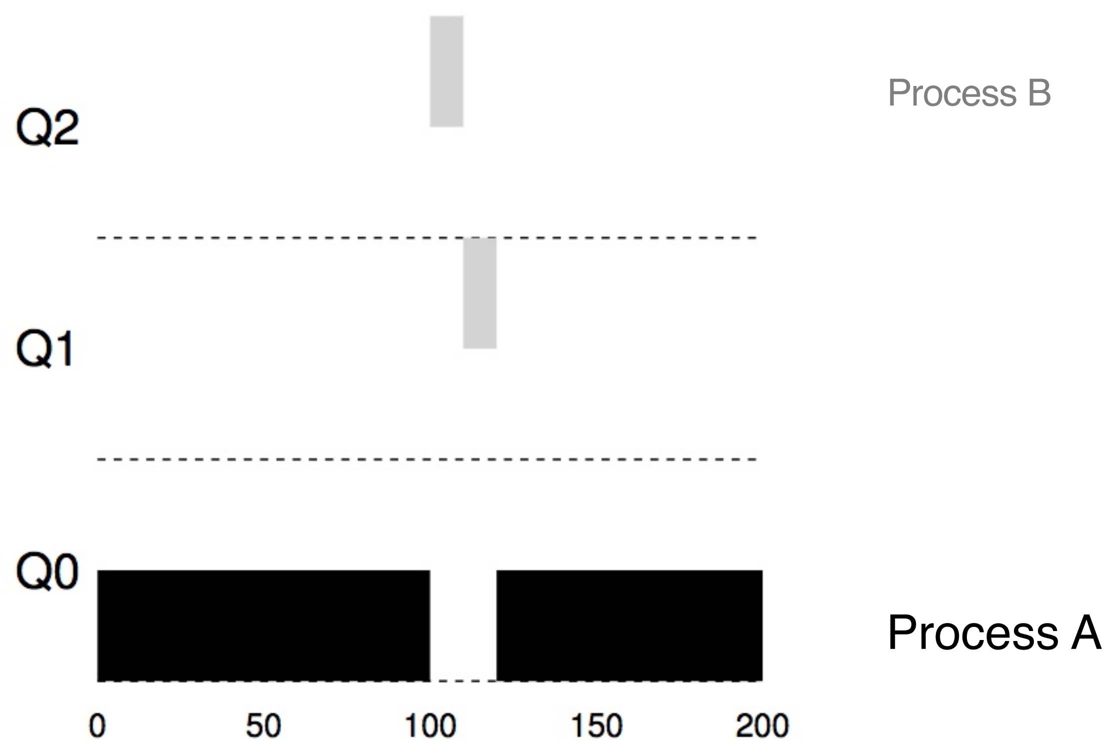
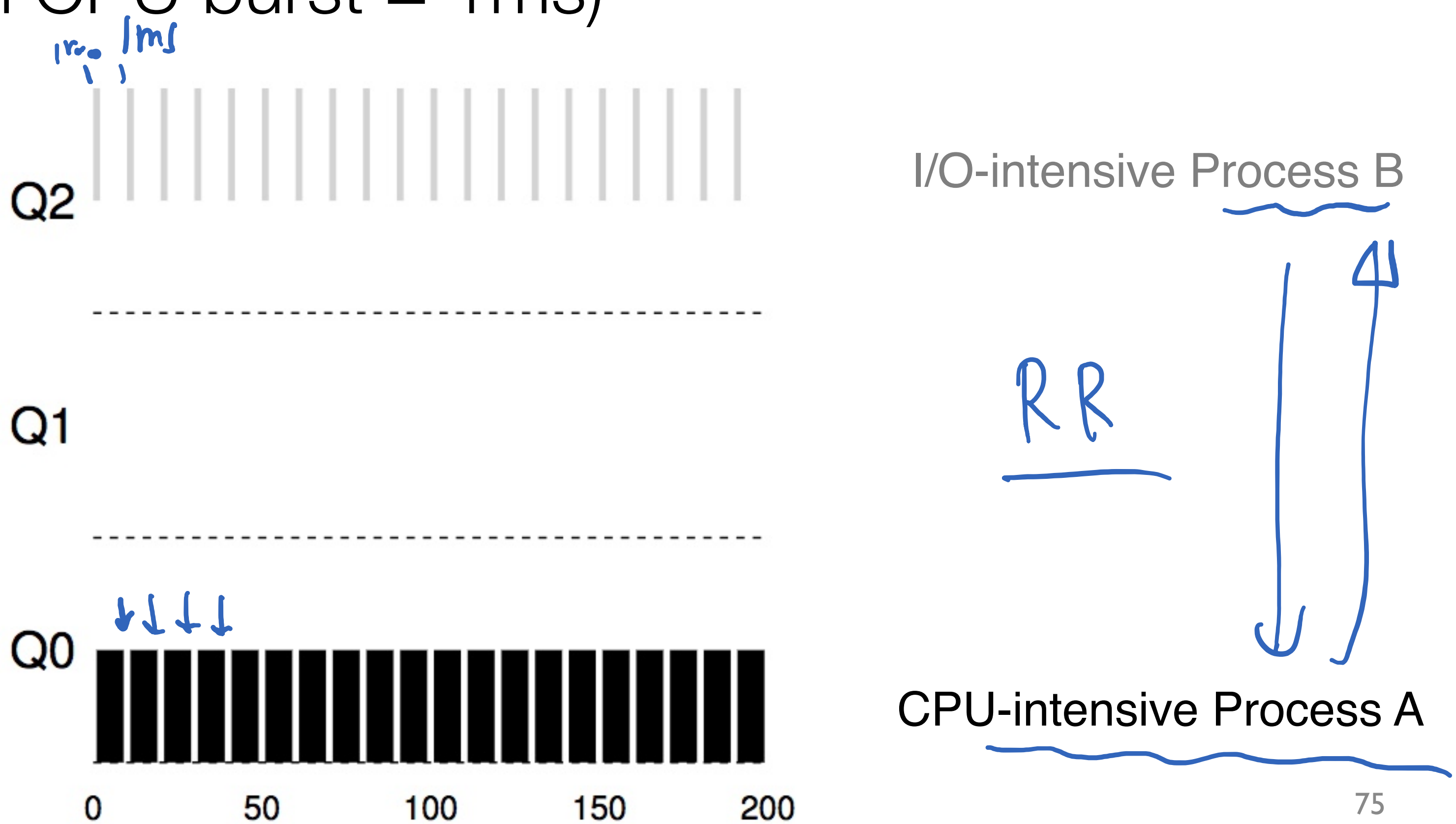


Example 3: What about I/O?

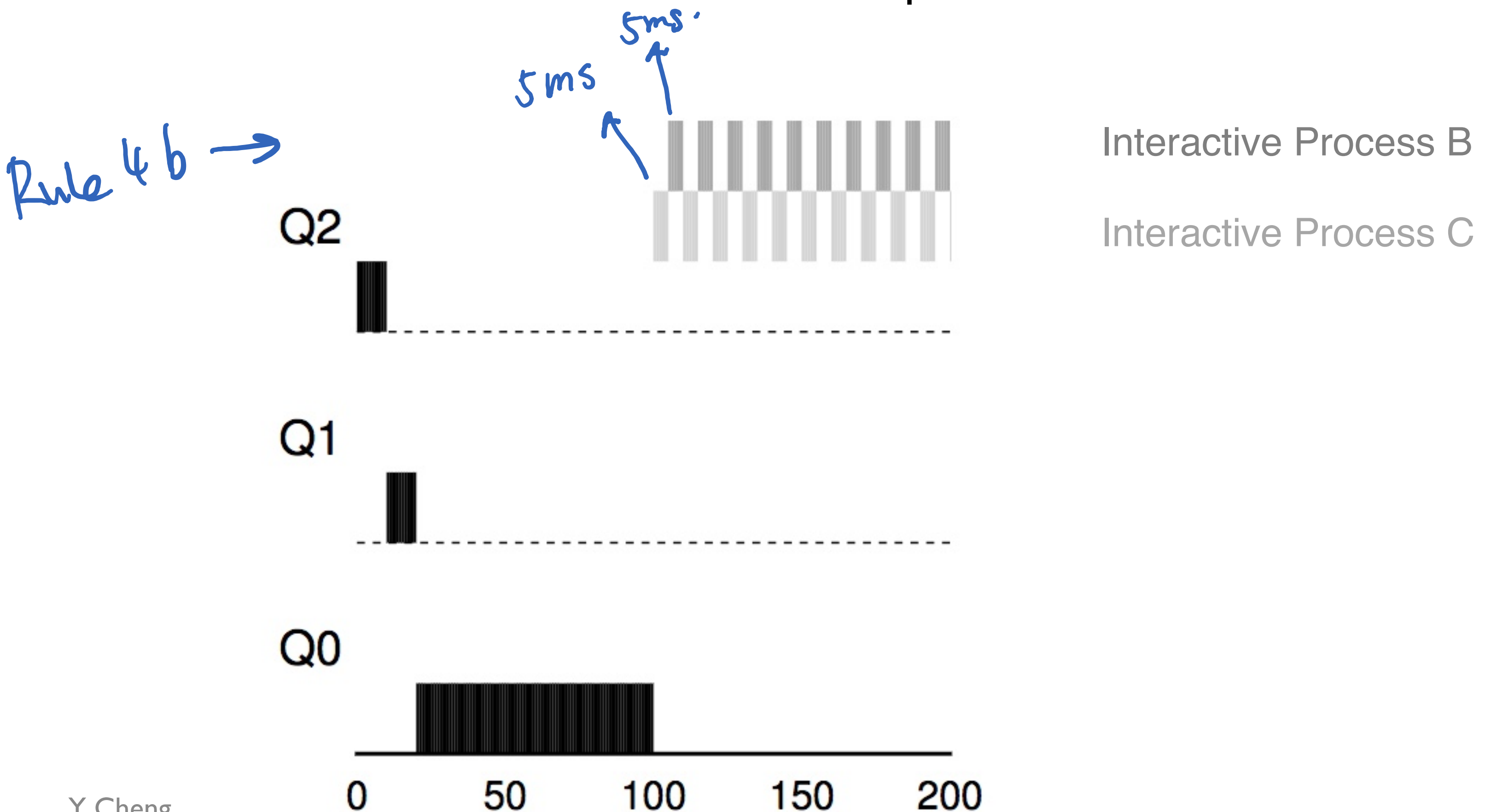
- Process A: long-running process
- Process B: I/O-intensive interactive process (each CPU burst = 1ms)

Rule 4b



Example 4: What's the Problem?

- Process A: long-running process
- Process B + C: Interactive process



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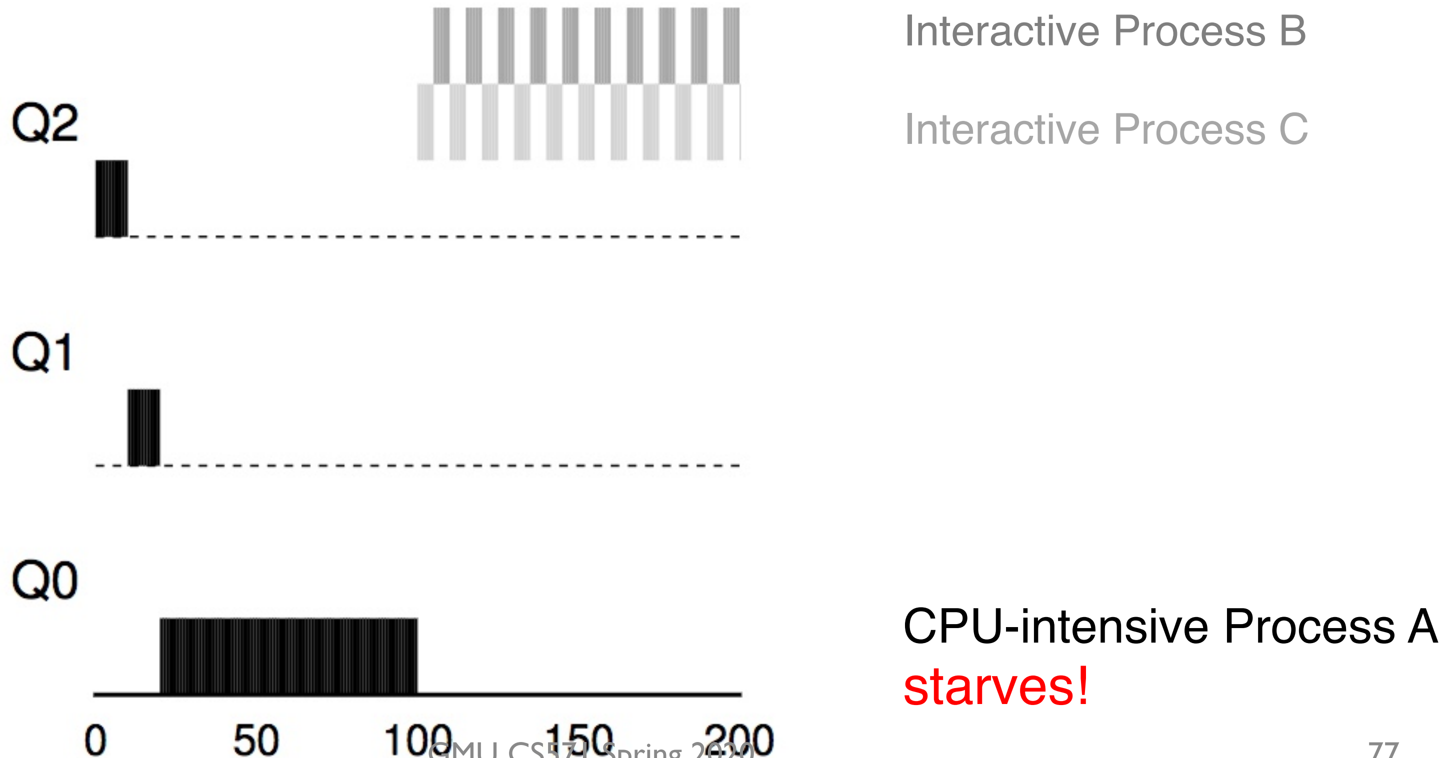
- Process B + C: Interactive process

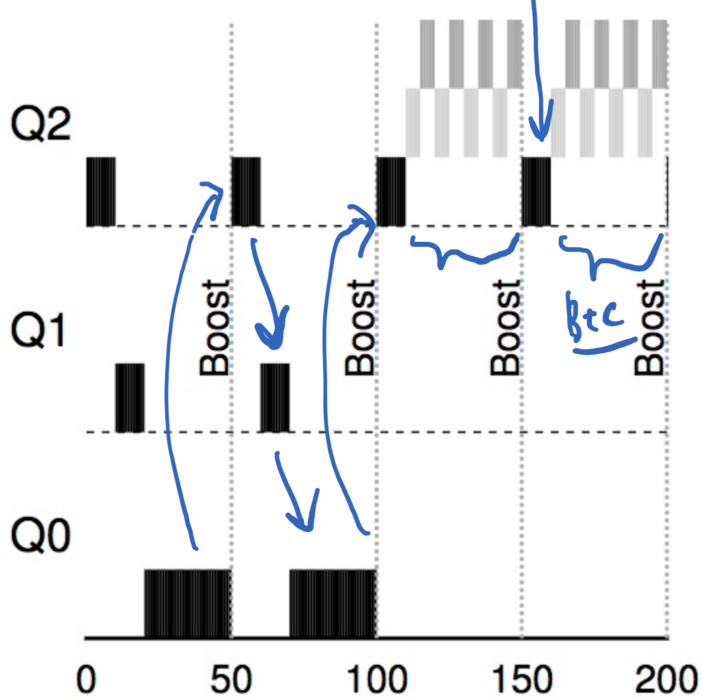


Attempt #2: Priority Boost

- Simple idea: Periodically boost the priority of all processes

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

configurable



Interactive Process B

Interactive Process C

S == 50 ms.

CPU-intensive Process A proceeds!

Tuning MLFQ

- MLFQ scheduler is defined by many parameters:
  - Number of queues
  - Time quantum of each queue
  - How often should priority be boosted?
  - A lot more…
- The scheduler can be configured to match the requirements of a specific system
  - Challenging and requires experience

Lottery Scheduling

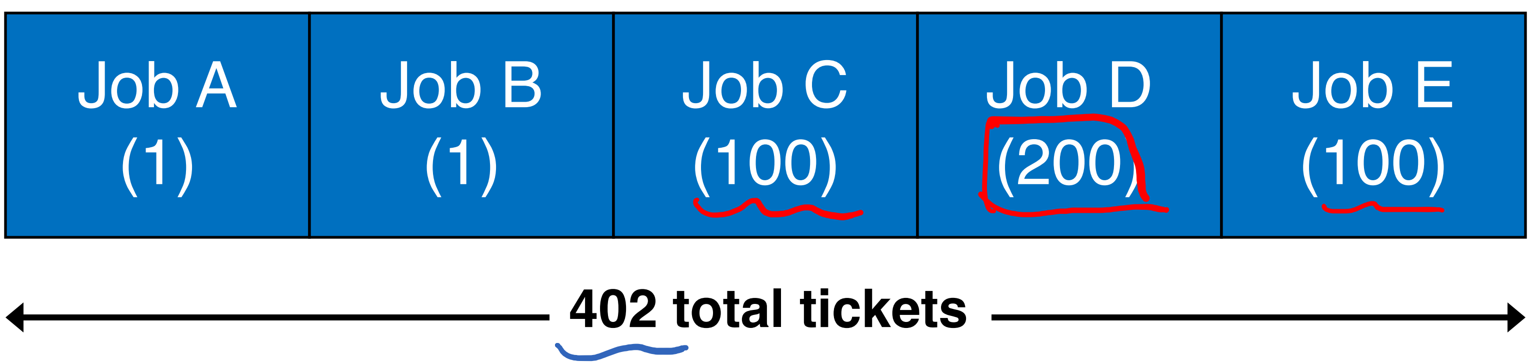
Lottery Scheduling

- Goal: Proportional share
  - One of the fair-share schedulers
- Approach
  - Gives processes lottery tickets
  - Whoever wins runs
  - Higher priority → more tickets

Lottery Code

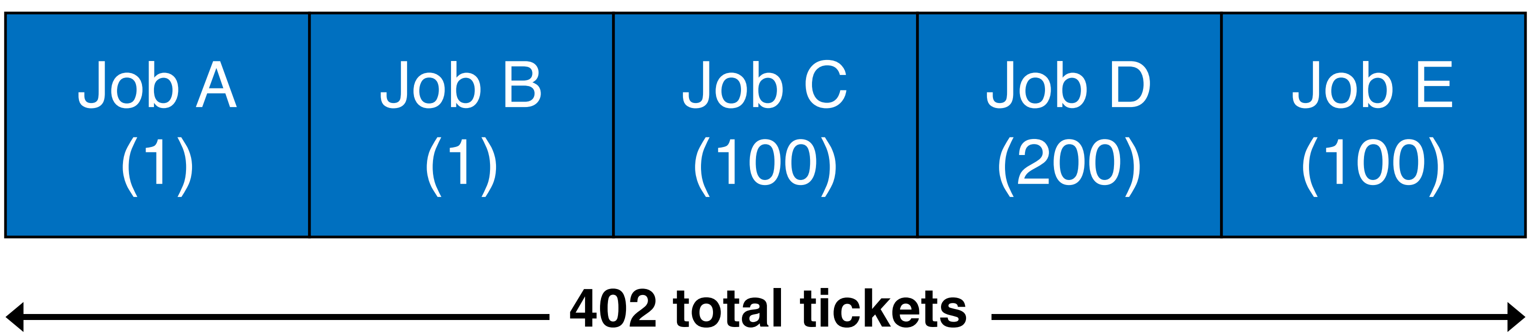
```
// counter: used to track if we've found the winner yet
int counter = 0;

// 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
node_t *current = head;

// loop until the sum of ticket values is > the winner
while (current) {
    counter = counter + current->tickets;
    if (counter > winner)
        break; // found the winner
    current = current->next;
}
// 'current' is the winner: schedule it...
```

Lottery Scheduling Example

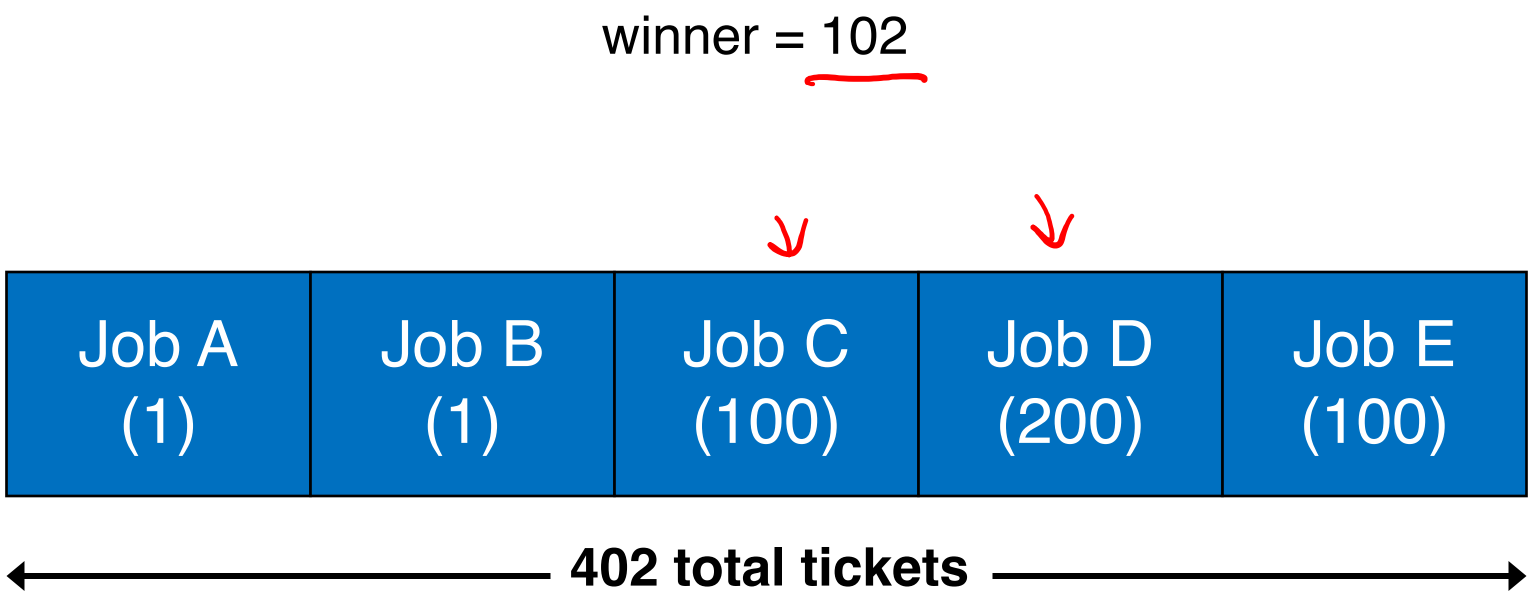


Lottery Scheduling Example

winner = random(402)



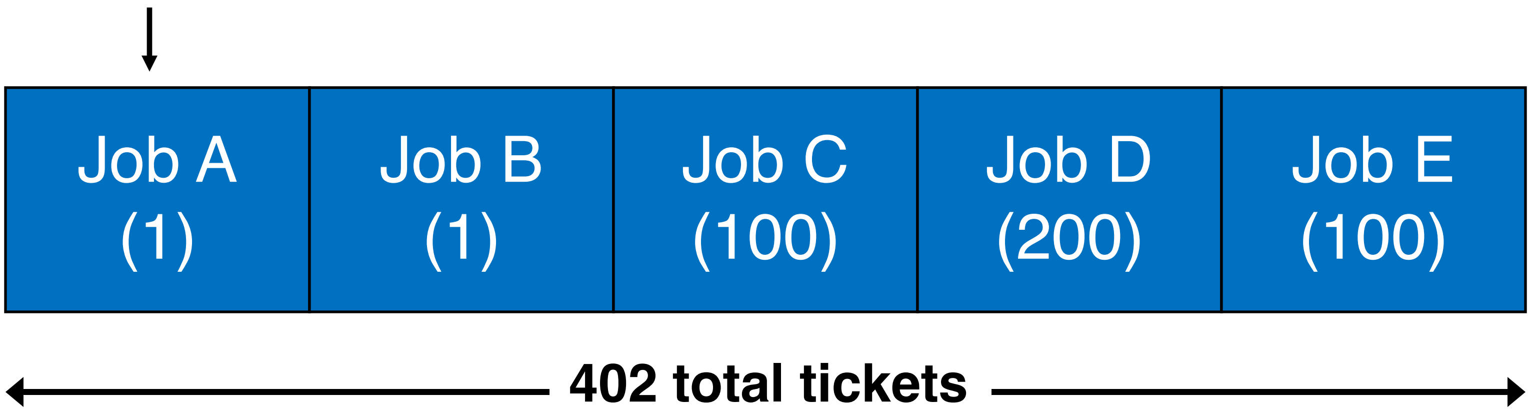
Lottery Scheduling Example



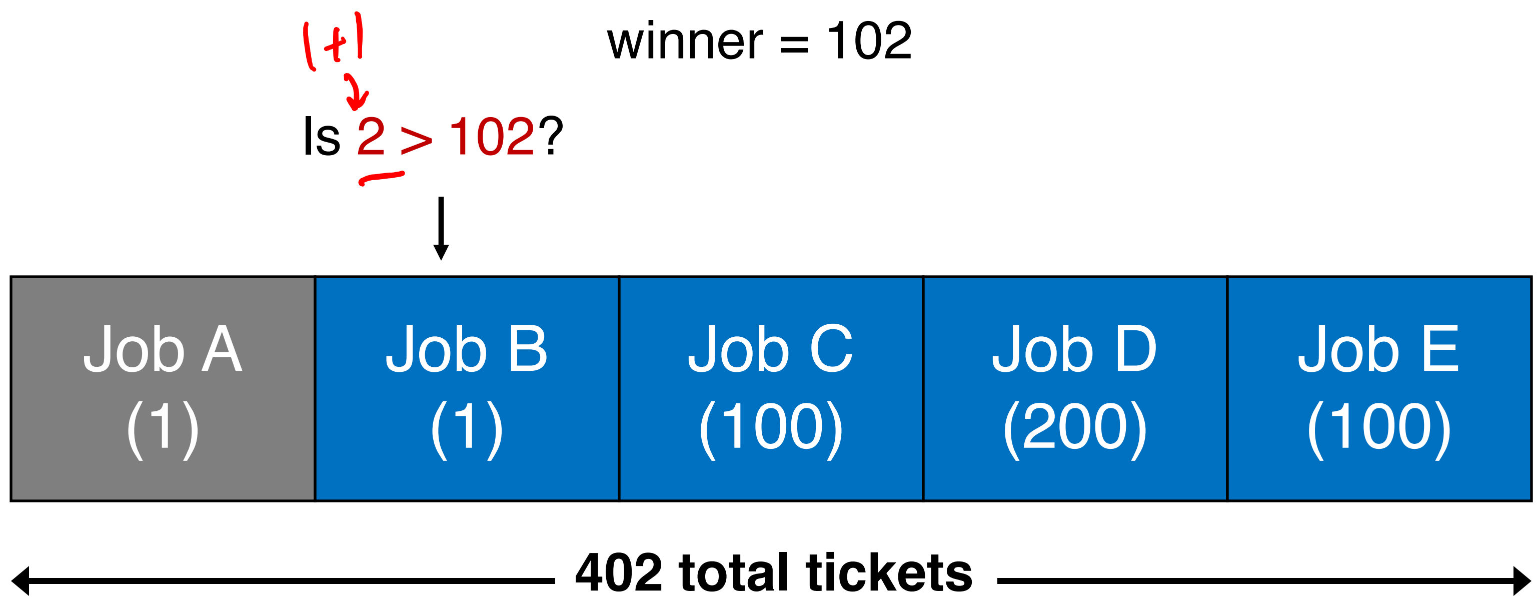
Lottery Scheduling Example

winner = 102

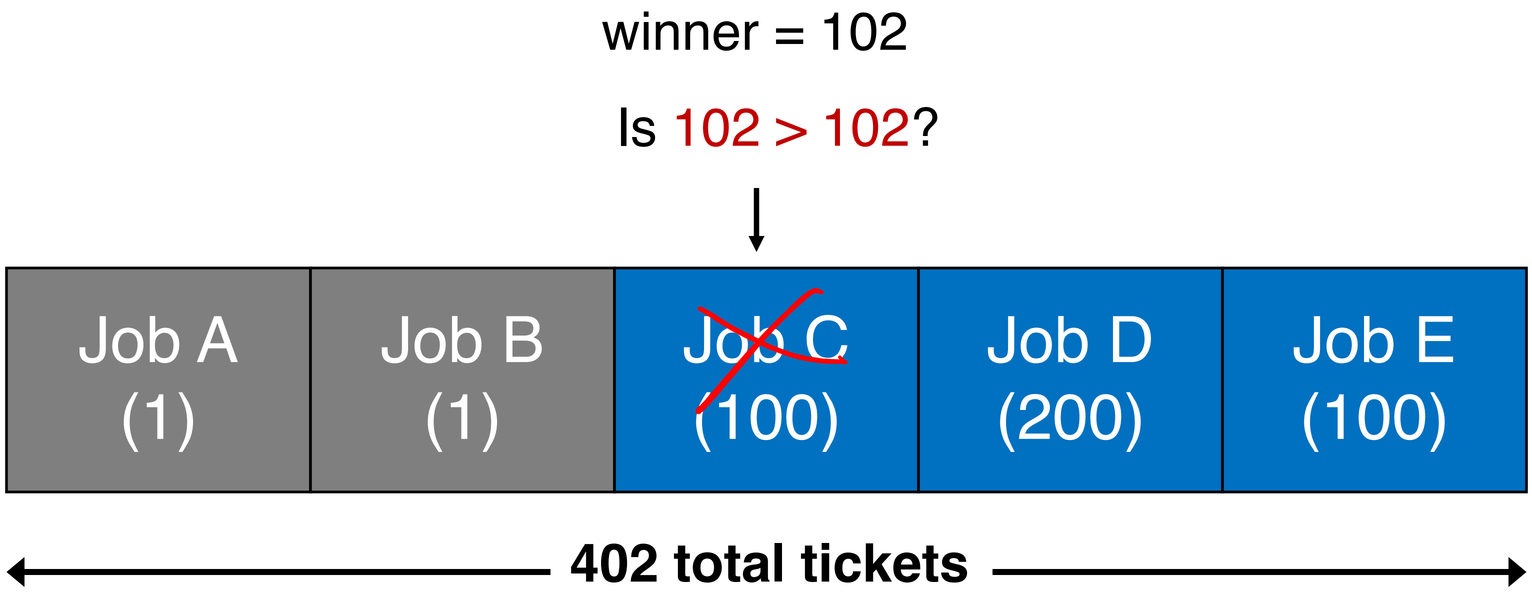
Is 1 > 102?



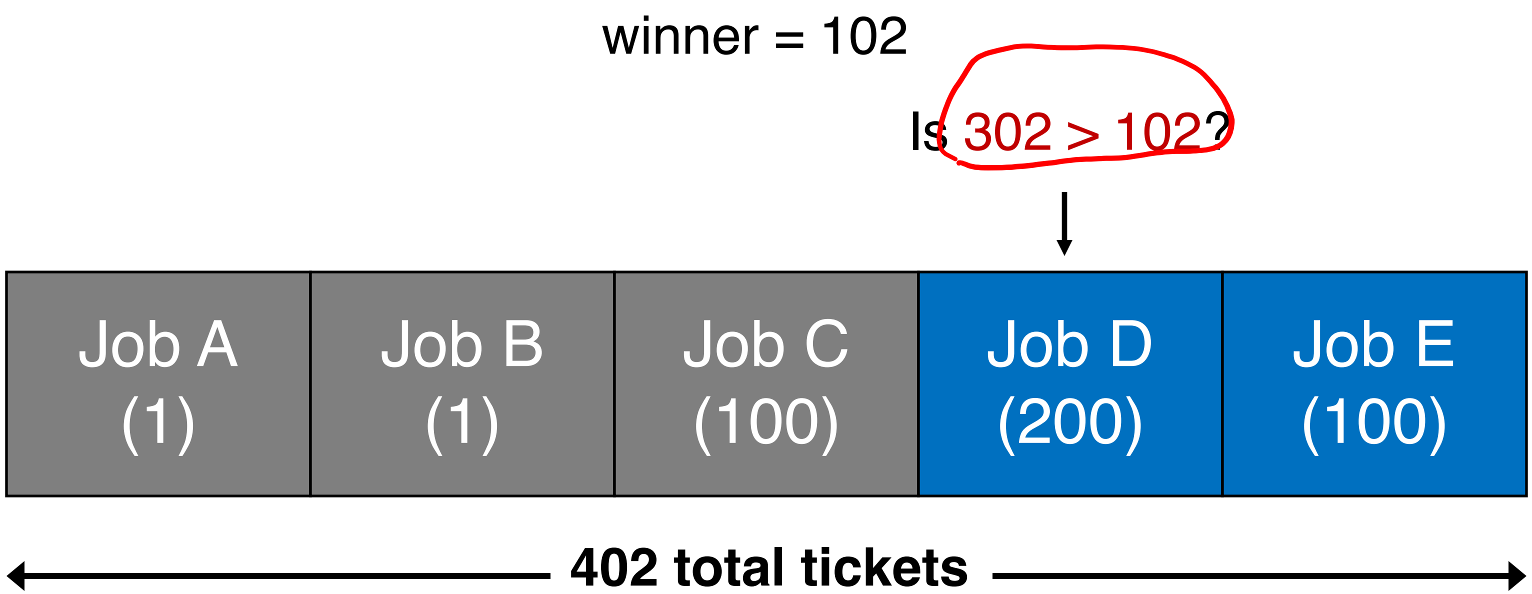
Lottery Scheduling Example



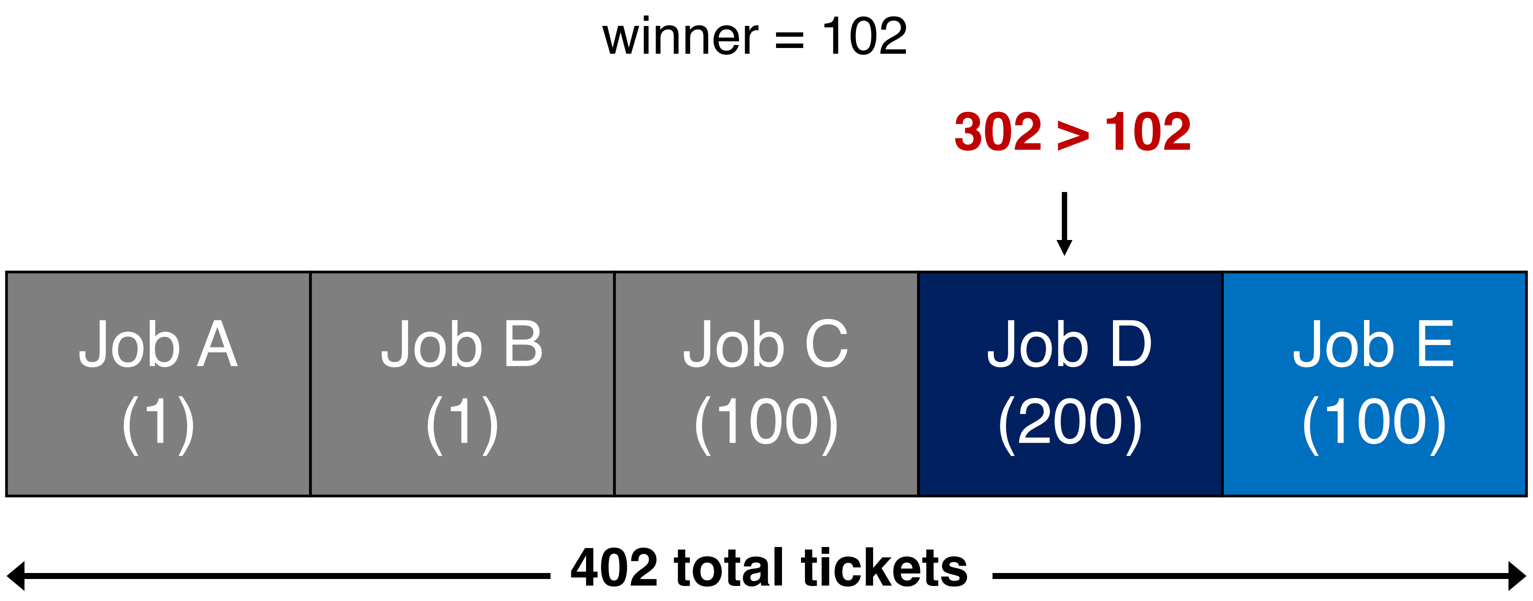
Lottery Scheduling Example



Lottery Scheduling Example



Lottery Scheduling Example



OS picks Job D to run!