

Sistemi Operativi

Corso di Laurea in Informatica

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SAPIENZA
UNIVERSITÀ DI ROMA

Recap from Last Lecture

- Process is the **unit of execution** (running on a single CPU)
- OS keeps track of process-related information using an ad hoc data structure called **Process Control Block (PCB)**
- Process can be in one of **5 possible states**: **new**, **ready**, **waiting**, **running**, or **terminated**
- **Context switch** to intertwine the execution of multiple processes
- Process communication either via **message passing** or **shared memory**

Today: CPU Scheduling

Policy to establish which process to execute on the CPU

- Basic scheduling concepts
- Scheduling **criteria/metrics**
- Scheduling **algorithms**
- Advanced scheduling concepts

Basic Concepts

- Almost every program has some alternating cycles of CPU computations and I/O waiting
- Even a simple fetch from main memory takes a long time relatively to CPU speed
- **Our assumptions:** Multi-programmed, uni-processor system

Basic Concepts

- In a system running a single process, the time spent waiting for I/O is wasted, and those CPU cycles are lost forever

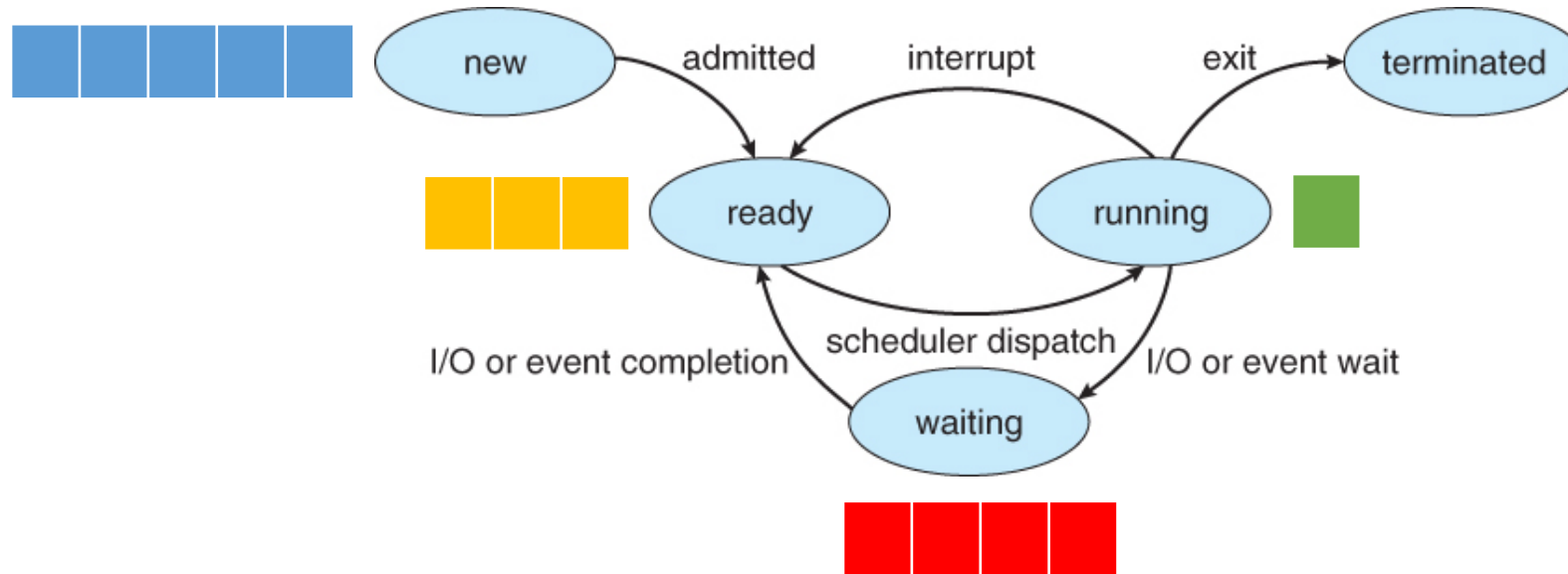
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- A scheduling system allows one process to use the CPU while another is waiting for I/O, thereby maximizing system utilization

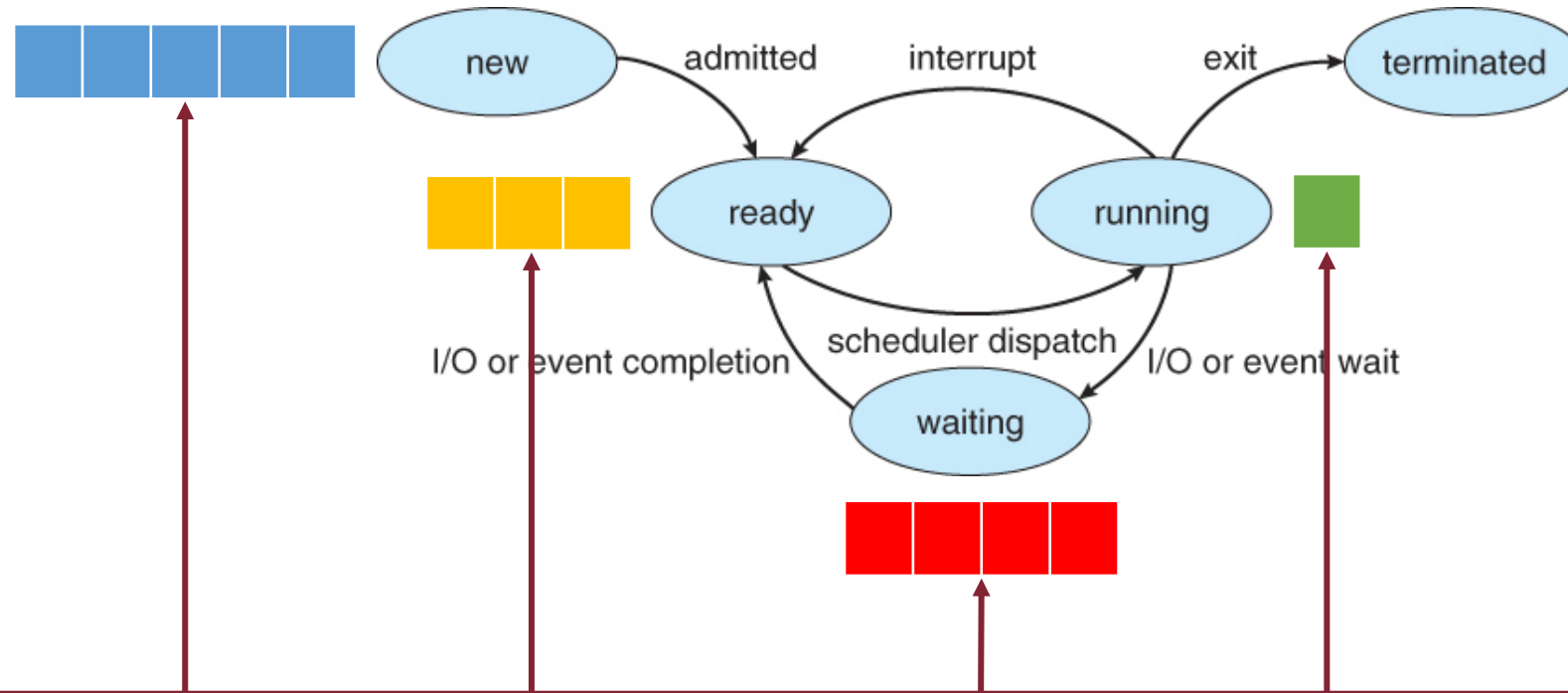
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- A scheduling system allows one process to use the CPU while another is waiting for I/O, thereby maximizing system utilization
- **Challenge:** Make the system as "efficient" and "fair" as possible, subject to varying and often dynamic conditions

Process Execution State Diagram

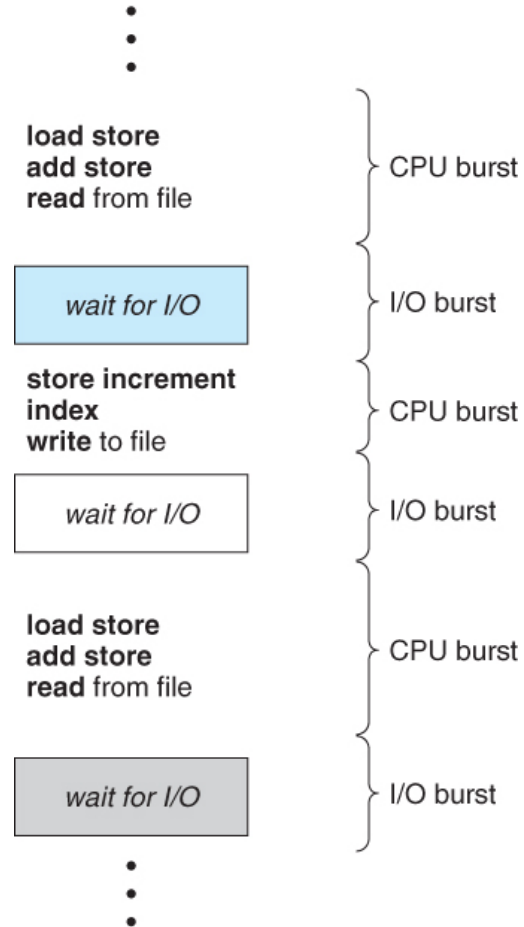


Process Execution State Diagram



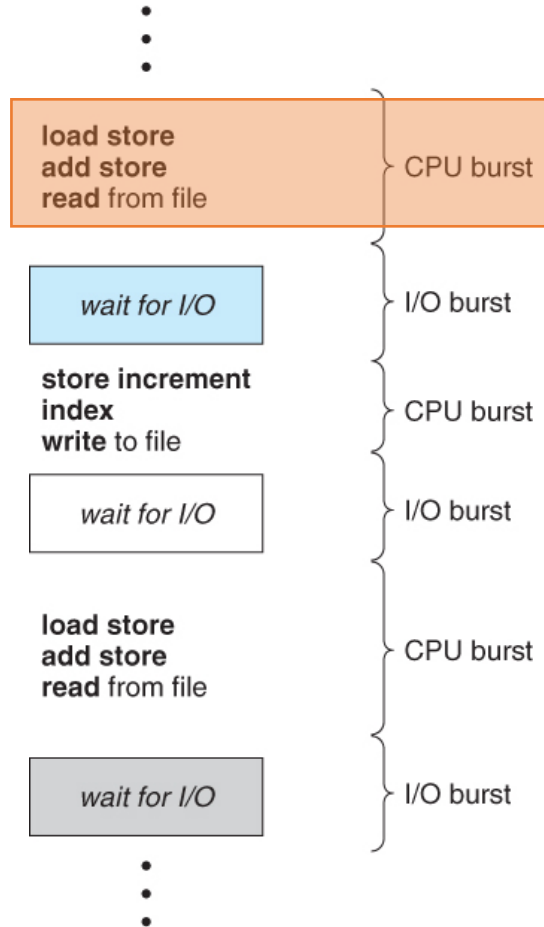
Processes managed by the OS reside in exactly one of the state queues

CPU vs. I/O Burst Cycle



All processes alternate between two states in a continuing **cycle**: **CPU burst** and **I/O burst**

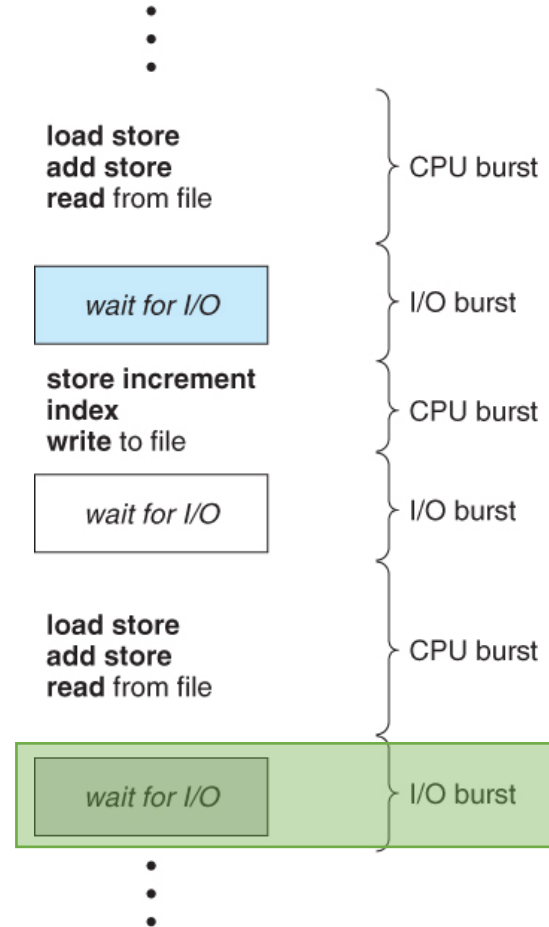
CPU vs. I/O Burst Cycle



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CPU burst → performing calculations

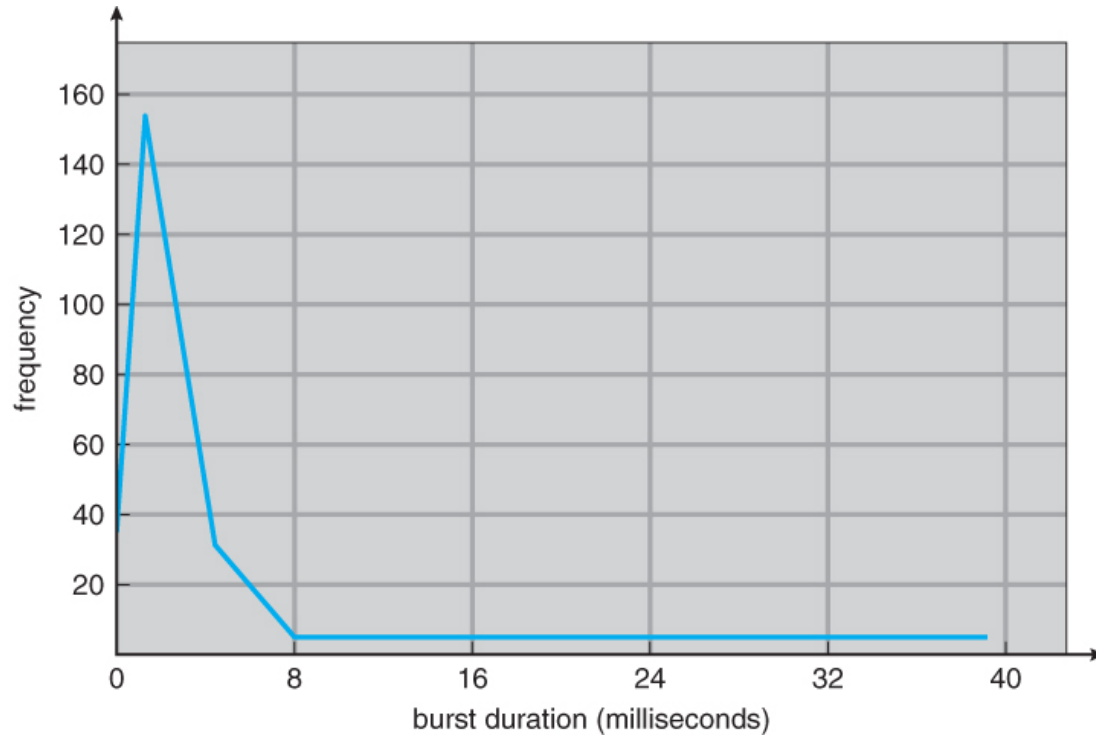
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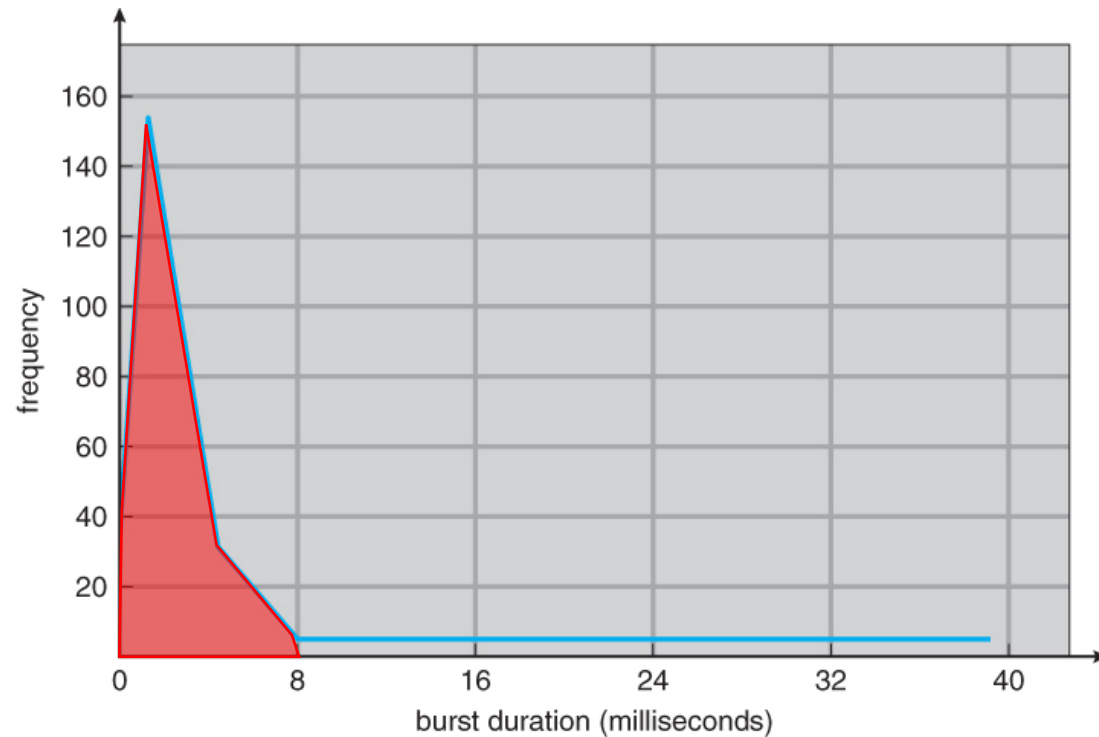
I/O burst → waiting for data transfer in or out of the system

CPU Burst Cycle: Frequency Pattern



Highly skewed distribution

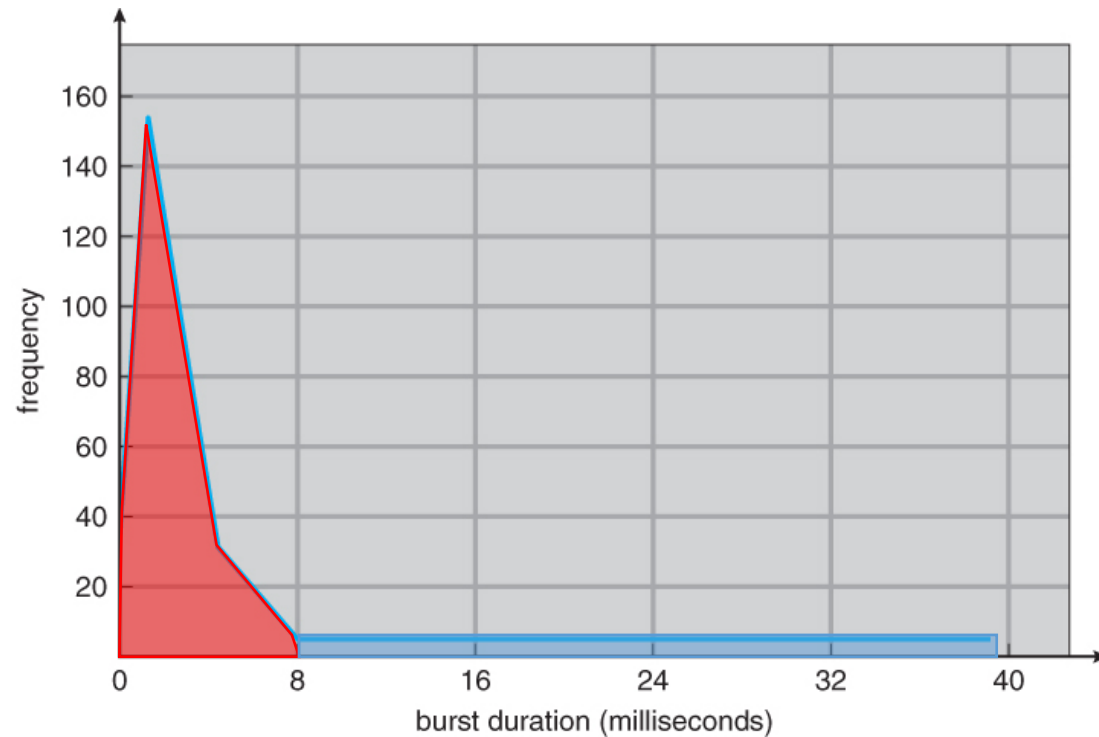
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The vast majority of processes have **short CPU bursts**

CPU Burst Cycle: Frequency Pattern



Highly skewed distribution

The vast majority of processes have **short** CPU bursts

Few processes exhibit **very long** CPU bursts

Long- vs. Short-term Scheduling

Long-term scheduling

How does the OS determine the level of multiprogramming (i.e., the number of processes to be loaded in main memory)

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- Whenever the CPU becomes idle, it picks another process from the **ready** queue to execute next
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Policy goals vs. Mechanism implementations

CPU Scheduling: When?

CPU scheduling decisions take place under one of **4 conditions**:

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for an I/O request or invocation of the `wait` system call

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in response to an interrupt

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at completion of I/O or a
return from `wait`

CPU Scheduling: When?

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4. When a process is created or terminates

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No choice!
A new process must be selected

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Either continue with the current process or select a new one

Non-preemptive vs. Preemptive

Non-preemptive scheduling

If it takes place only when there is no choice (i.e., conditions 1 and 4)

Once a process starts it keeps running until it either voluntarily blocks or it finishes

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Preemptive scheduling

Whenever scheduling takes *also* place under conditions 2 and 3

Non-preemptive vs. Preemptive: Examples

	Windows	Mac	UNIX-like
Non-preemptive	up to Win 3.x	up to Mac OS 9.x	-
Preemptive	since Win 95	since Mac OS X	since forever

Preemption: Issues

- Preemption might cause troubles if it occurs while:
 - two processes share data, one may get interrupted in the middle of updating shared data structures
 - the kernel is busy implementing a system call (e.g., updating critical kernel data structures)

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- Disable interrupts before entering critical code section and re-enabling immediately afterwards

should only be done in rare situations, and only on very short pieces of code that will finish quickly

The Dispatcher

- The module that gives control of the CPU to the process selected by the scheduler

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- Its functions include:
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 - Jumping to the proper location in the newly loaded program
- The dispatcher is run on every context switch therefore the time it consumes (**dispatch latency**) must be as shortest as possible

Useful Definitions

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- **Waiting Time:** time difference between turnaround time and burst time

Useful Definitions

$T^{arrival}$ = arrival time

$T^{completion}$ = completion time

T^{burst} = burst time

$T^{turnaround}$ = turnaround time = $T^{completion} - T^{arrival}$

$T^{waiting}$ = waiting time = $T^{turnaround} - T^{burst}$

Scheduling Criteria/Metrics

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 - CPU utilization
 - Throughput
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Scheduling: Trade-off

- Ideally, choose a CPU scheduler that optimizes all metrics simultaneously
- Generally, the above is impossible and a trade-off is needed!
- **Idea:** Choose a scheduling algorithm based on its ability to satisfy a given policy

Scheduling Policies

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 - Provide output to the user as quickly as possible

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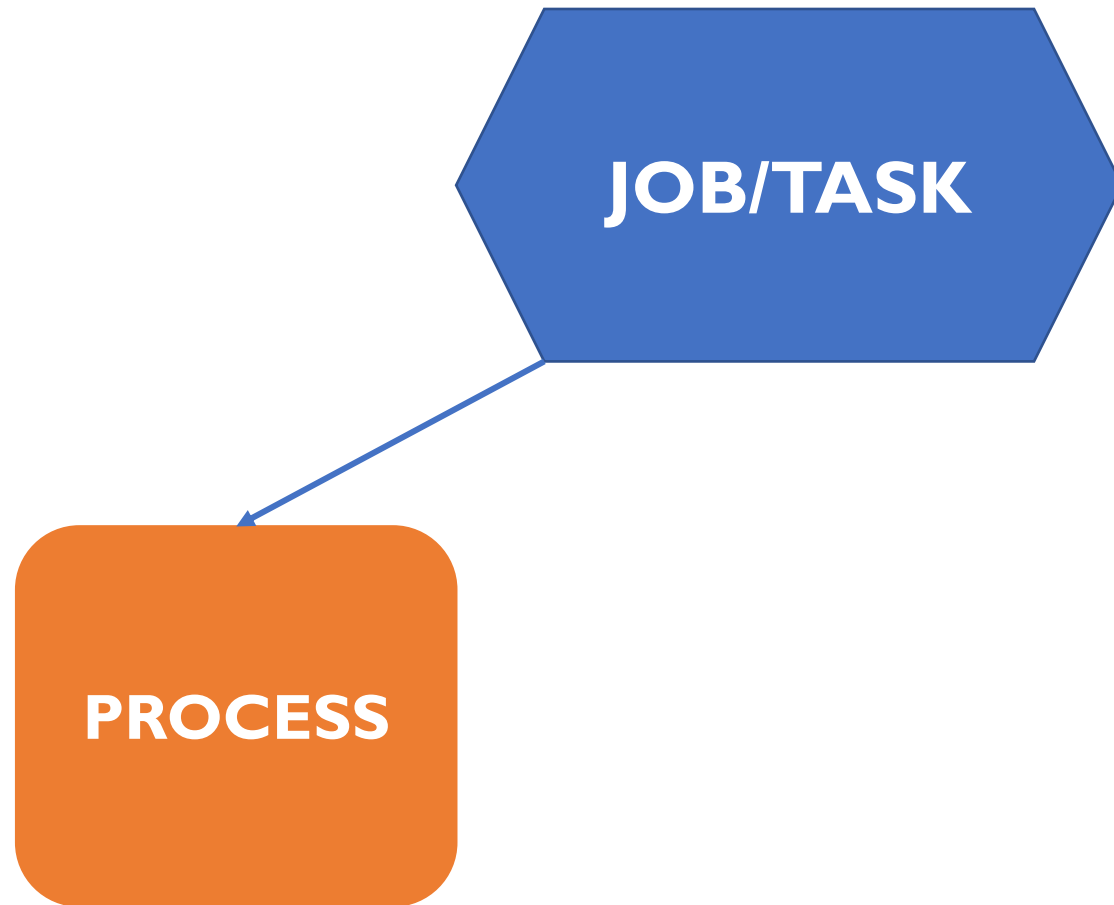
Typical of batch systems

A Quick Note on Terminology

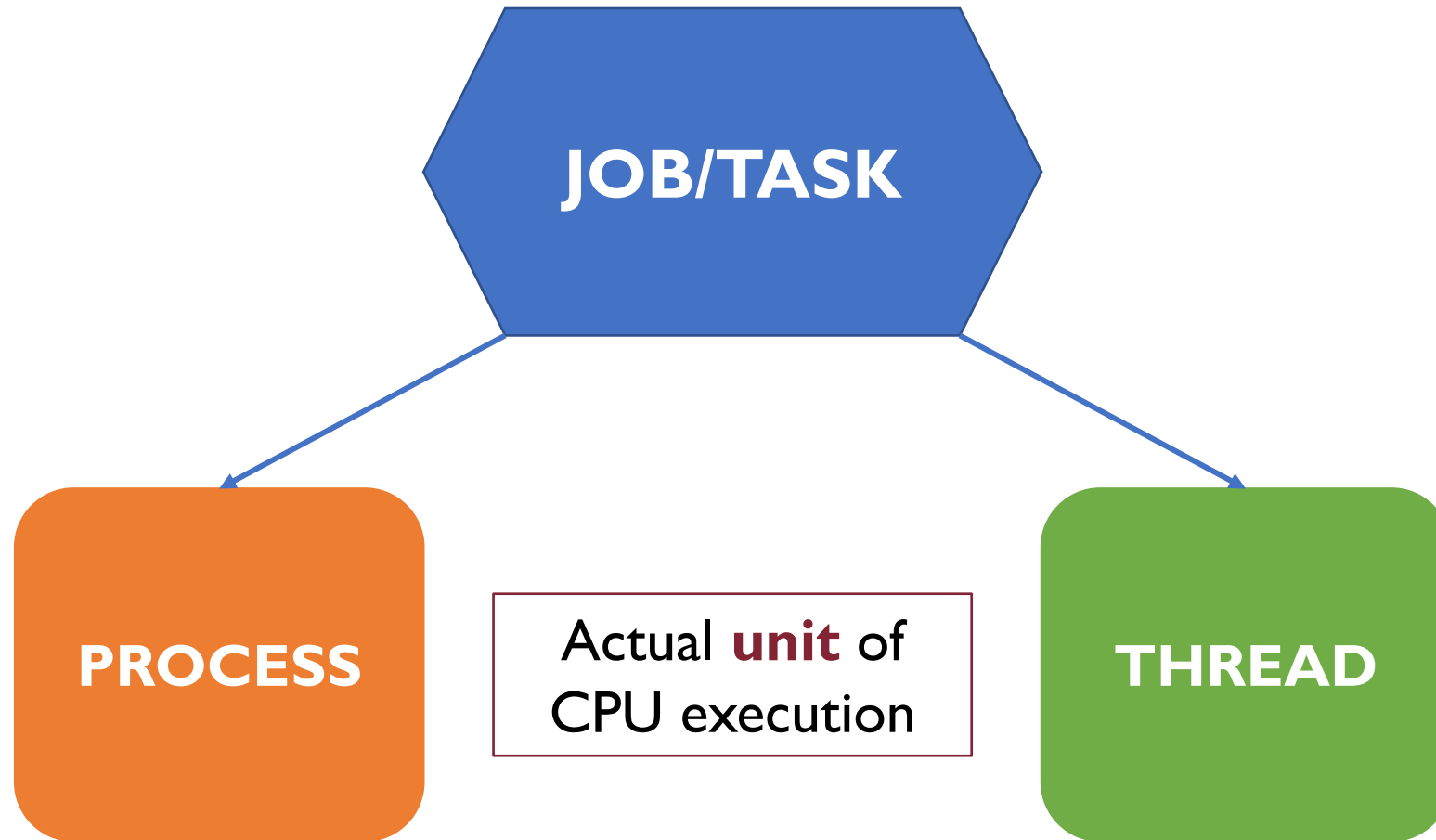


General **unit** of
CPU execution

A Quick Note on Terminology



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We will talk about threads very soon but for now most of the things we will be discussing remain valid even on a multi-threaded system

Scheduling Algorithms: An Overview

- First-Come-First-Serve (FCFS)
- Round Robin (RR)
- Shortest-Job-First (SJF)
- Priority Scheduling
- Multilevel Queue (MQ)
- Multilevel Feedback-Queue (MFQ)

Scheduling Algorithms: An Overview

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- Priority Scheduling
- Multilevel Queue (MLQ)
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First-Come-First-Serve (FCFS)

- Very simple! Just a FIFO queue, like customers waiting in line at the post office
- The scheduler executes jobs to completion in arrival order
- The scheduler takes over only when the currently running job asks for an I/O operation (or finishes its execution)
- A job may keep using the CPU indefinitely (i.e., until it blocks)

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Non-preemptive

First-Come-First-Serve (FCFS): Scenario I

Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

First-Come-First-Serve (FCFS): Scenario I

New 

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Arrival time = 0 for all

No I/O burst

First-Come-First-Serve (FCFS): Scenario I

New 

Ready 

Waiting

Running

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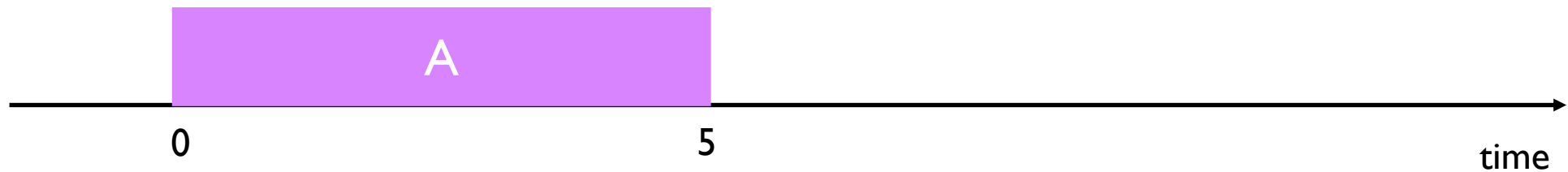
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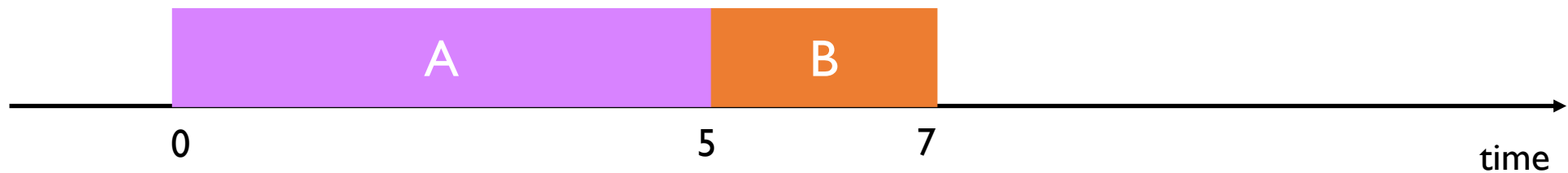
New **A** **B** **C**

Ready **C**

Waiting

Running **B**

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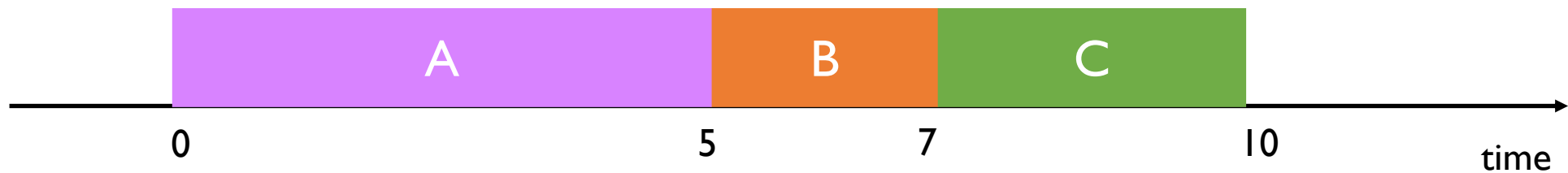
New A B C

Ready

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Average Waiting Time

N = number of jobs

$T_i^{arrival}$ = arrival time of job i

$T_i^{completion}$ = completion time of job i

T_i^{burst} = burst time of job i

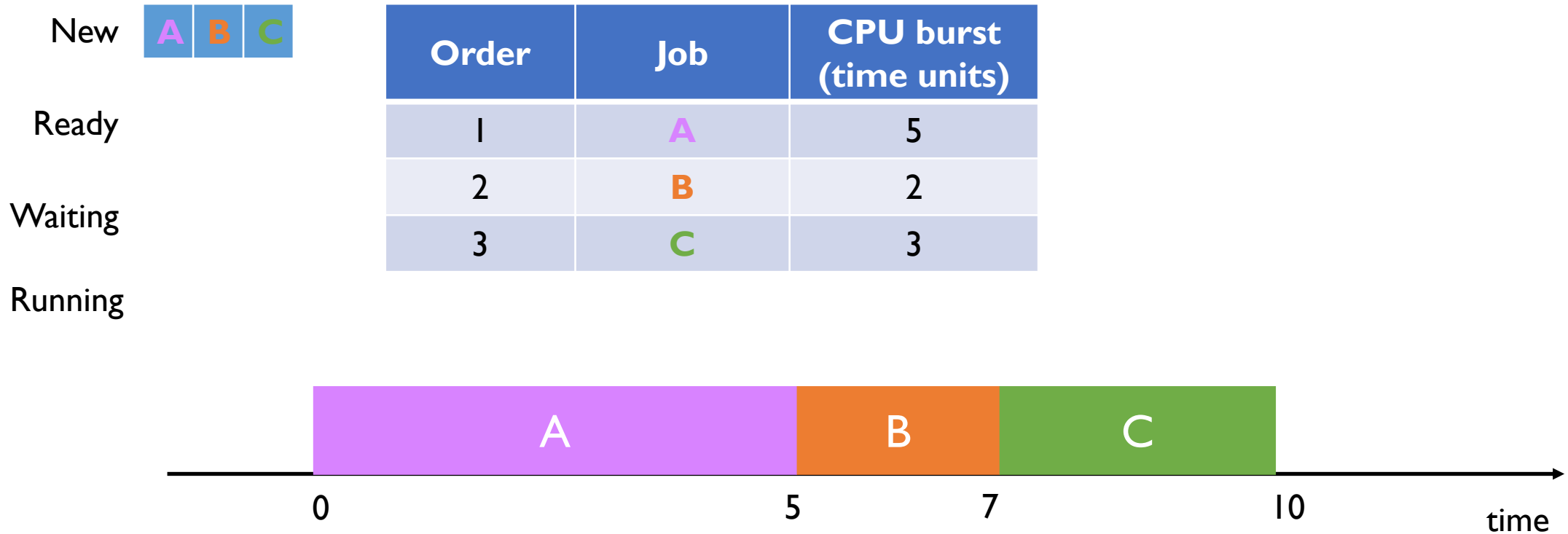
$T_i^{turnaround}$ = turnaround time of job $i = T_i^{completion} - T_i^{arrival}$

$$\overline{T}_i^{waiting} = \text{avg. waiting time of job } i = \frac{1}{N} \sum_{i=1}^N (T_i^{turnaround} - T_i^{burst})$$

Unless otherwise specified, we will assume all jobs arrive at the same time, i.e.,

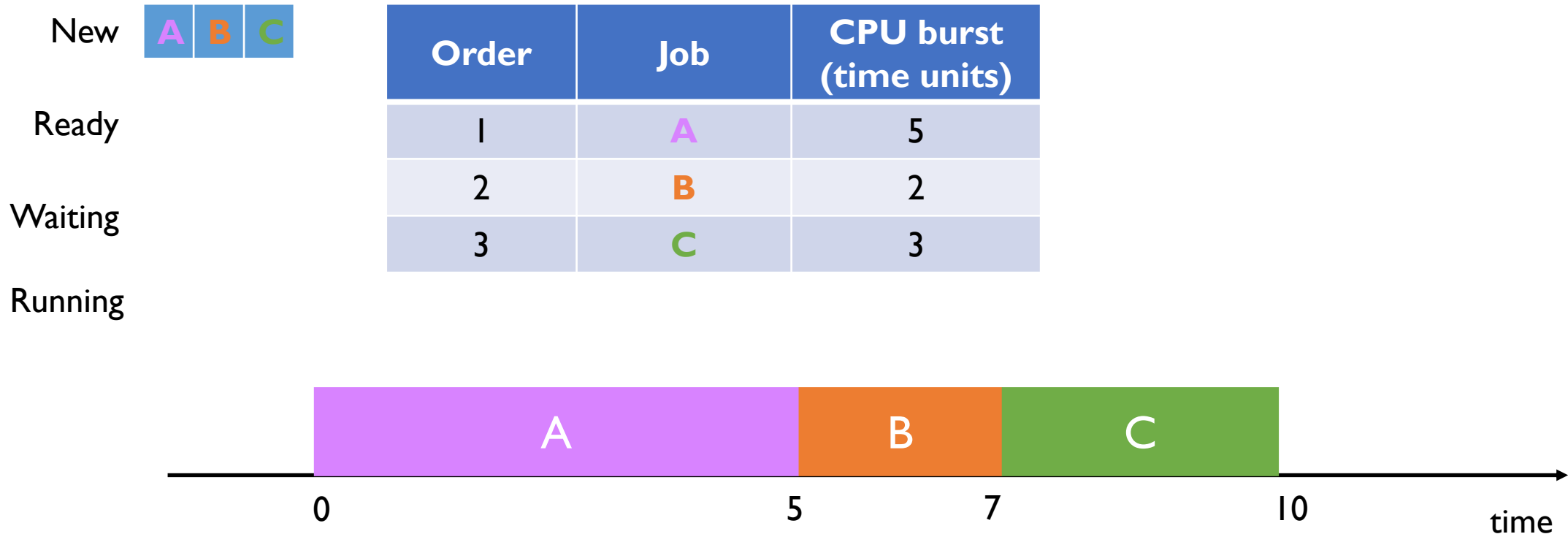
$$T_i^{arrival} = 0 \quad \forall i \in \{1, \dots, N\}$$

First-Come-First-Serve (FCFS): Scenario I



avg. waiting time =

First-Come-First-Serve (FCFS): Scenario I



$$\text{avg. waiting time} = (0 + 5 + 7)/3 = 4$$

First-Come-First-Serve (FCFS): Scenario II

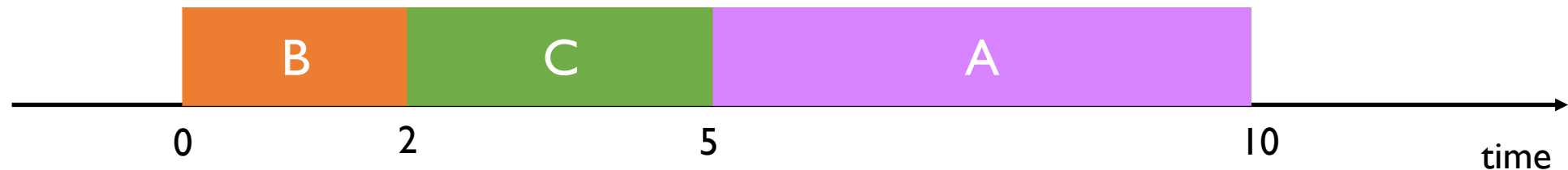
New



Order	Job	CPU burst (time units)
1	B	2
2	C	3
3	A	5

Arrival time = 0 for all

No I/O burst



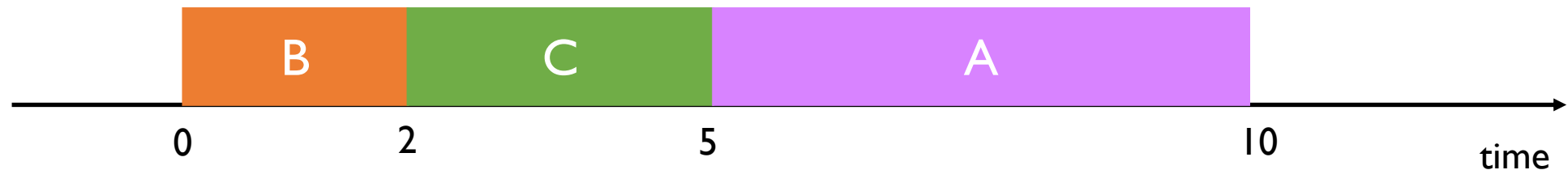
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First-Come-First-Serve (FCFS): Scenario II

New





Order	Job	CPU burst (time units)
1	B	2
2	C	3
3	A	5



$$\text{avg. waiting time} = (5 + 0 + 2)/3 \sim 2.3$$



First-Come-First-Serve (FCFS): Scenario III

New 

Ready 

Order	Job	CPU burst (time units)
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First-Come-First-Serve (FCFS): Scenario III

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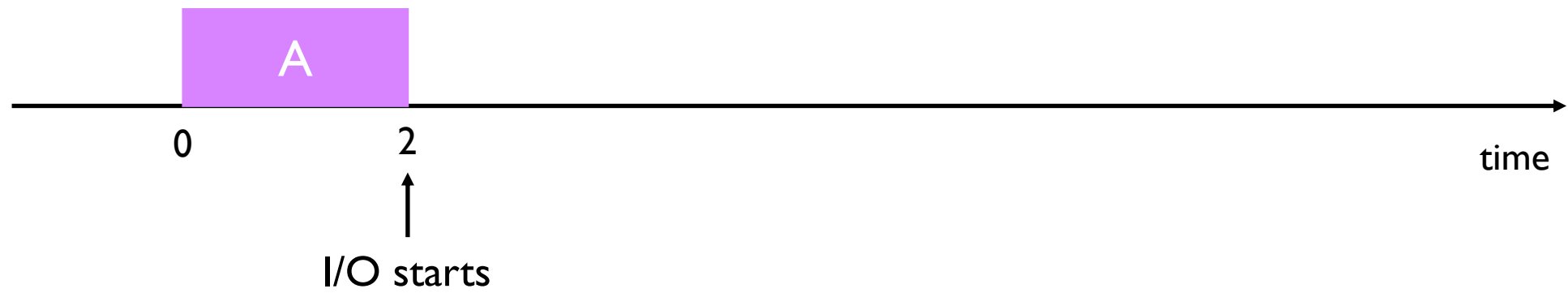
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First-Come-First-Serve (FCFS): Scenario III



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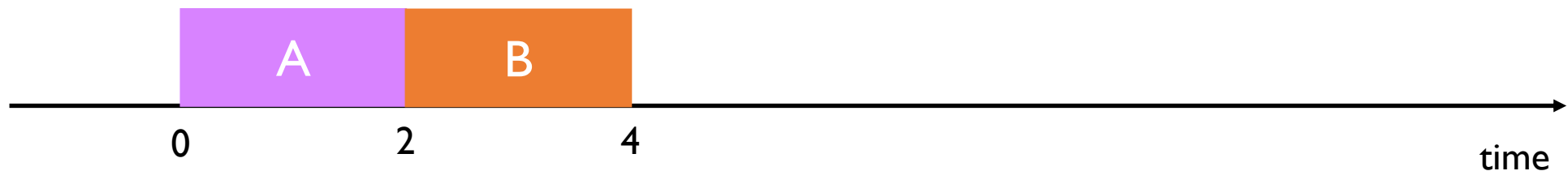


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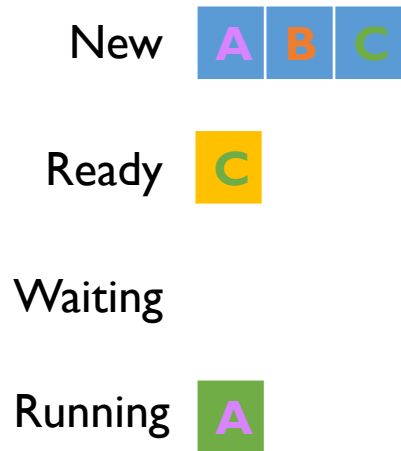
A does also I/O



I/O task requested by
A might have finished
before B finished

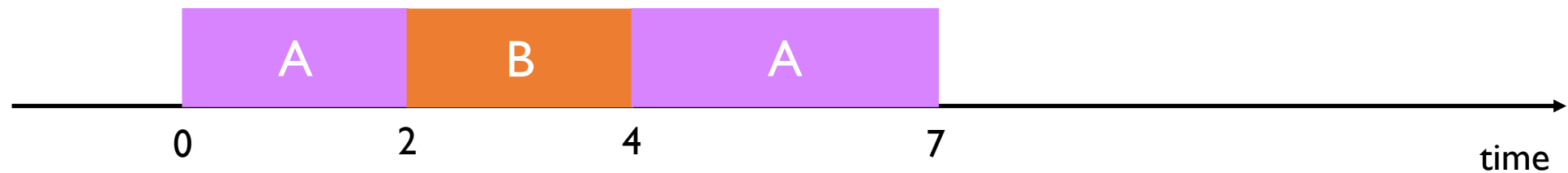
Non-preemptive scheduler!

First-Come-First-Serve (FCFS): Scenario III





Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

A does also I/O




First-Come-First-Serve (FCFS): Scenario III

New 

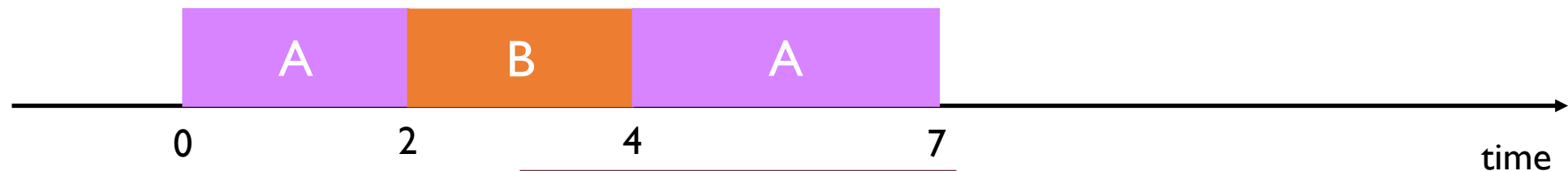
Ready 

Waiting

Running 




Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3


A does also I/O




Why A and not C?


First-Come-First-Serve (FCFS): Scenario III

New   

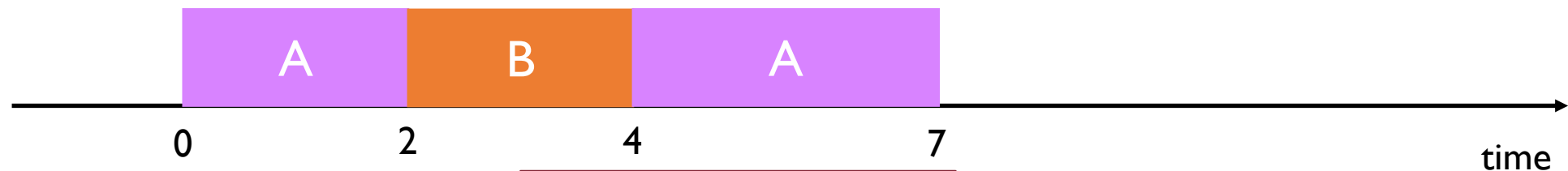
Ready 

Waiting

Running 

Order	Job	CPU burst (time units)
1		5
2		2
3		3

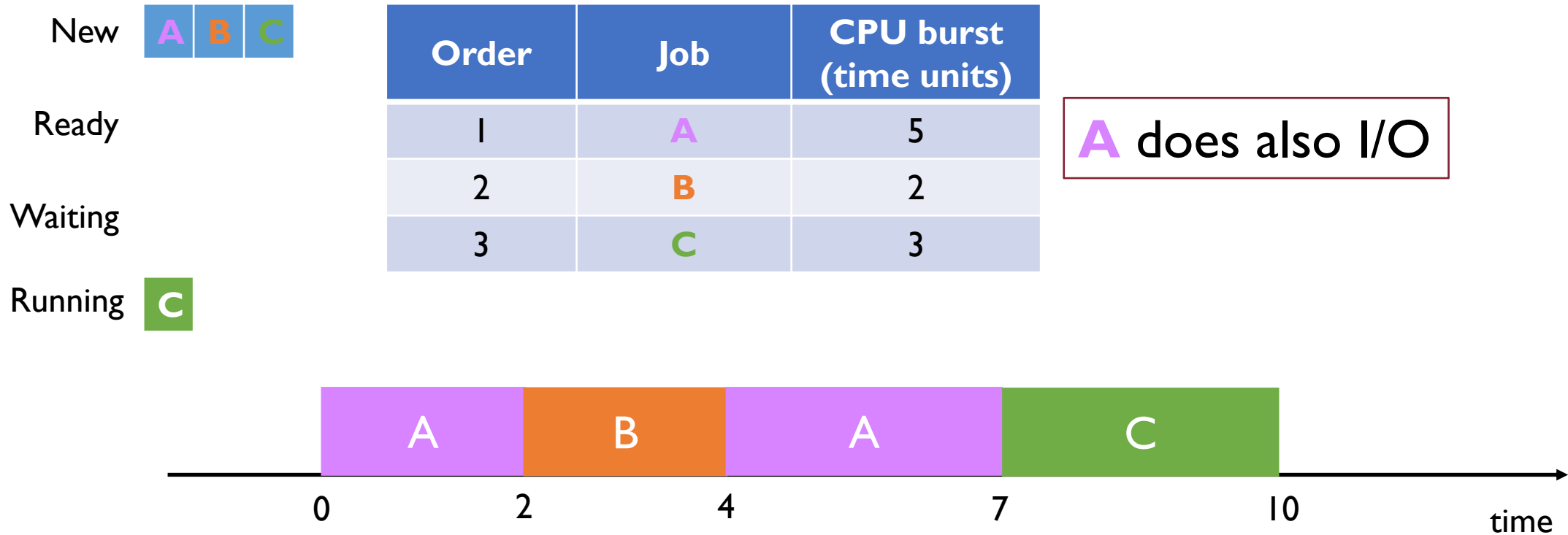
 does also I/O



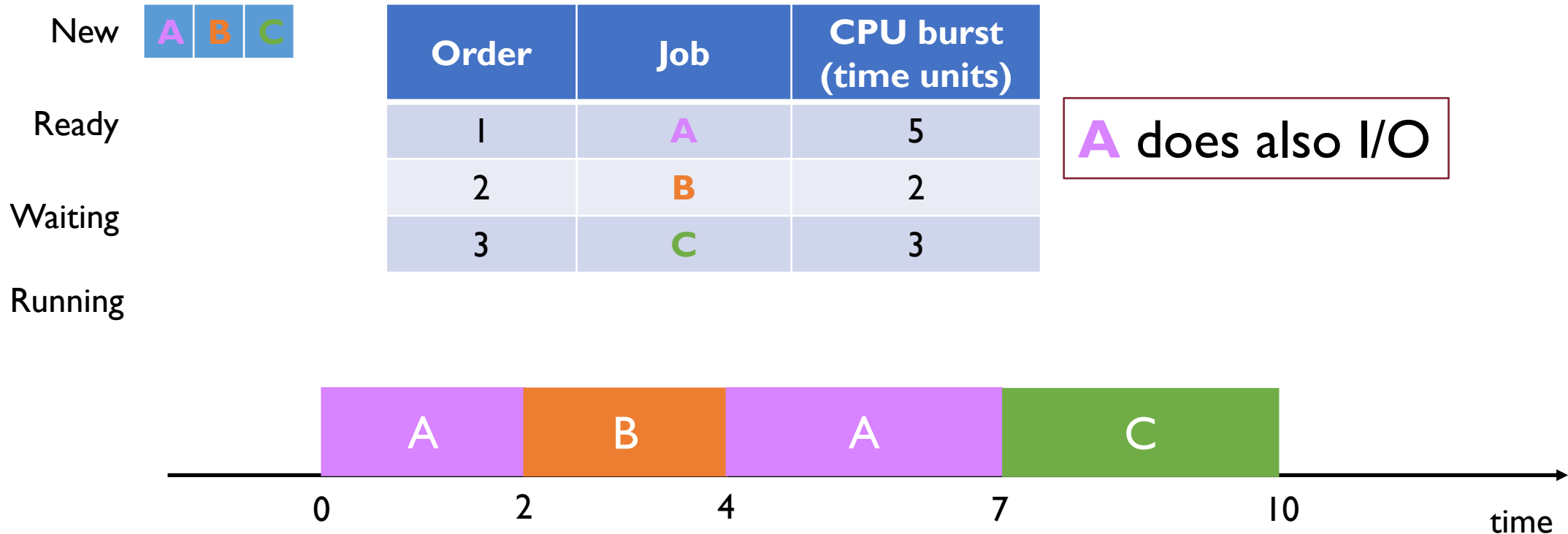
Why  and not .

Because the FCFS scheduler cares only about the arrival time on the **new** queue

First-Come-First-Serve (FCFS): Scenario III

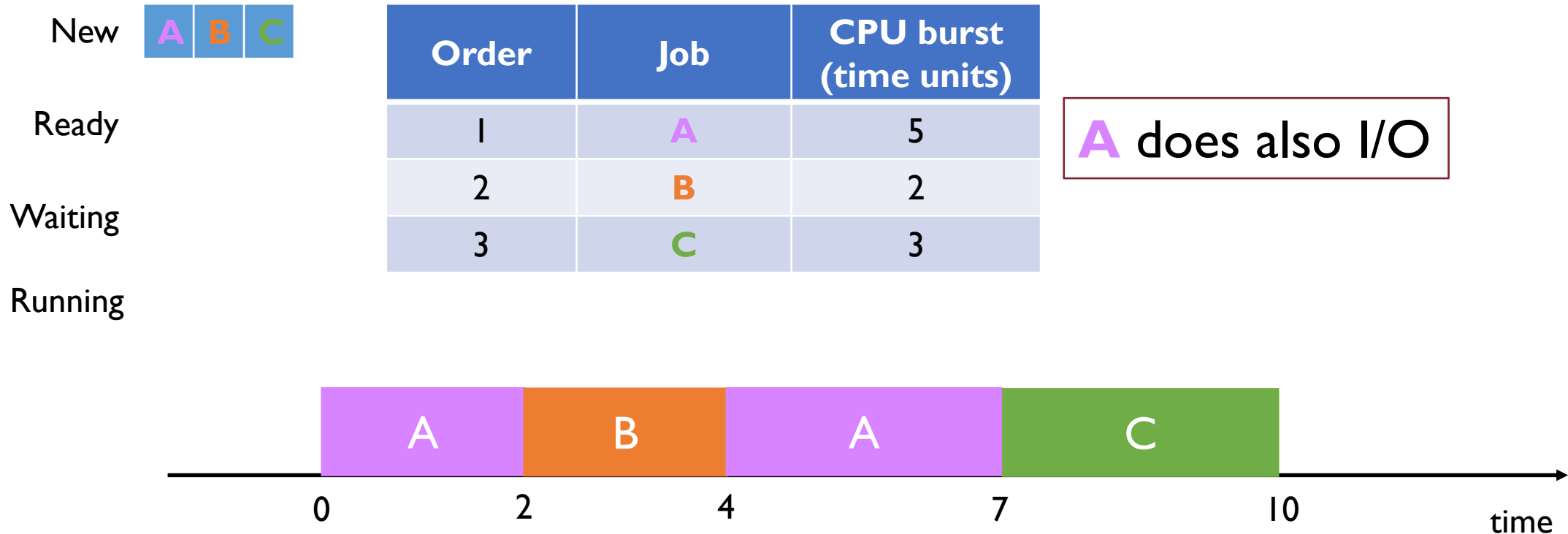


First-Come-First-Serve (FCFS): Scenario III



avg. waiting time =

First-Come-First-Serve (FCFS): Scenario III



$$\text{avg. waiting time} = (2 + 2 + 7)/3 \sim 3.7$$

FCFS: PROs and CONs

- **PRO:**
 - very simple!

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FCFS: PROs and CONs

- **PRO:**

- very simple!

- **CONs:**

- (average) waiting time is highly variable as short CPU-burst jobs may sit behind very long ones
- **convoy effect** → poor overlap between CPU and I/O since CPU-bound jobs will force I/O bound jobs to wait

Scheduling Algorithms: An Overview

- First-Come-First-Serve (FCFS)
- **Round Robin (RR)**
- Shortest-Job-First (SJF)
- Priority Scheduling
- Multilevel Queue (MLQ)
- Multilevel Feedback-Queue (MLFQ)

Round Robin (RR)

- Similar to FCFS, except that CPU bursts are assigned with limits called **time quantum** or (**time slice**)
- When a job is given the CPU, a timer is set for a certain value:
 - If the job finishes before the time quantum expires, then it is swapped out of the CPU just like the normal FCFS algorithm
 - If the timer goes off first, then the job is swapped out of the CPU and moved to the back end of the ready queue
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Preemptive

Round Robin (RR)

- The **ready** queue is maintained as a **circular queue**
- When all jobs have had a turn, the scheduler gives the first job another turn, and so on...
- RR is fair as it shares the CPU equally among all the jobs
- The average waiting time can be longer than with other scheduling algorithms

Round Robin (RR): The Time Quantum

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Round Robin (RR): The Time Quantum

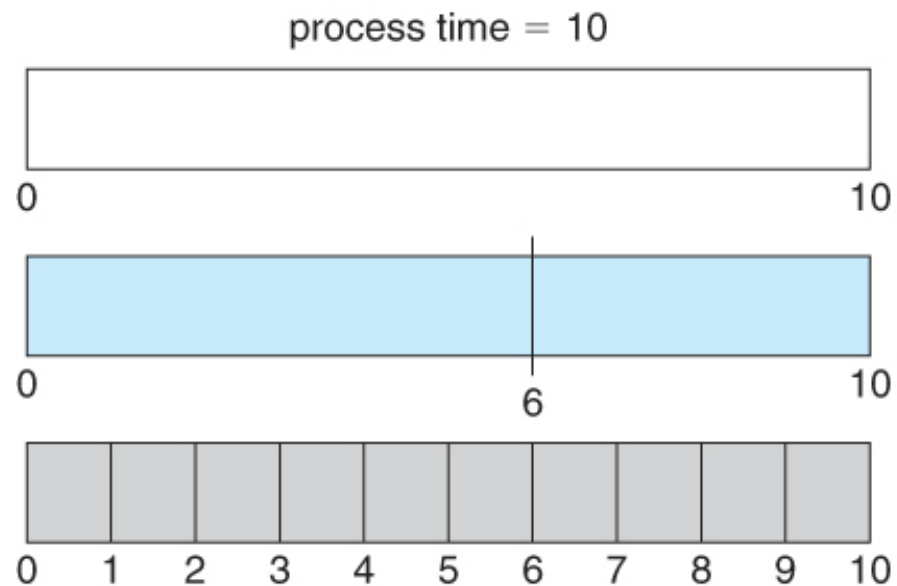
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- Too large time quantum degenerates to FCFS as jobs are never preempted from the CPU (high average waiting time)
- Too small time quantum implies more context switches, which eventually dominate over the actual CPU utilization (low throughput)

Trade-off:

Overhead for context switching should be relatively small compared to time slice

Example: time slice = $10 \div 100$ msec. and context switch = $0.01 \div 0.1$ msec.

Round Robin (RR): The Time Quantum



quantum

12

6

1

context
switches

0

1

9

By decreasing the time quantum the number of context switches increase

Round Robin (RR): The Time Quantum

N = number of jobs

δ = time slice

$$\sup\{T_i^{start}\} = \delta * (i - 1), \quad \forall i \in \{1, \dots, N\}$$

upper-bound on the
time a job is scheduled for the first time

worst-case scenario:
all job in front of the queue will use the whole time slice

Round Robin (RR): Example

Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

Round Robin (RR): Example

New 

Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

Round Robin (RR): Example

New 

Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

No I/O burst

Time quantum = 2

Context switch = 0

Round Robin (RR): Example

New 

Ready 

Waiting

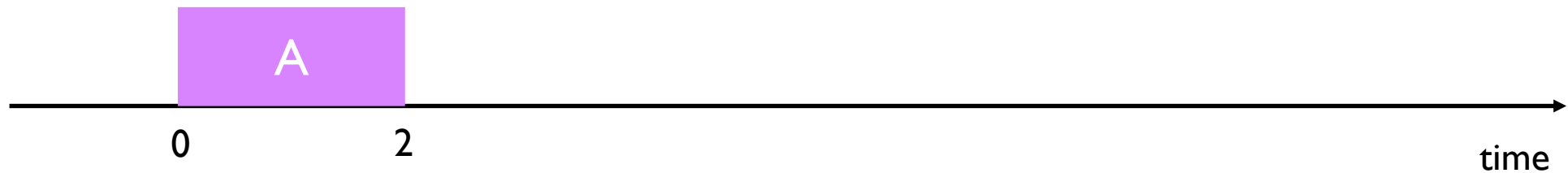
Running

Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

Round Robin (RR): Example



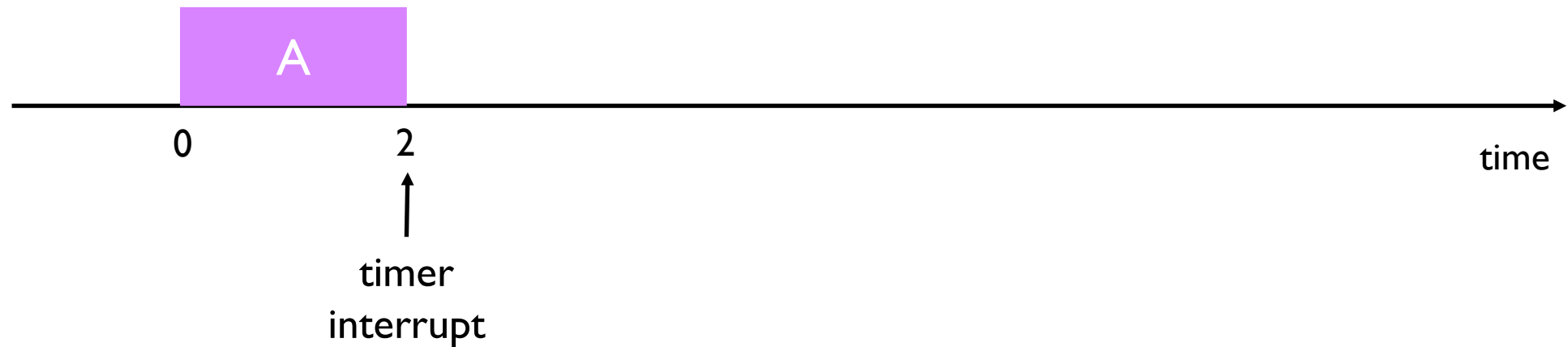
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1	A	5
2	B	2
3	C	3



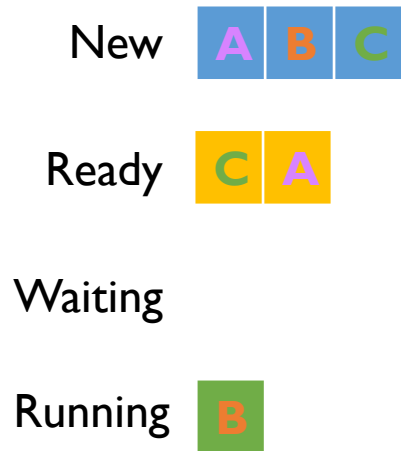
Round Robin (RR): Example



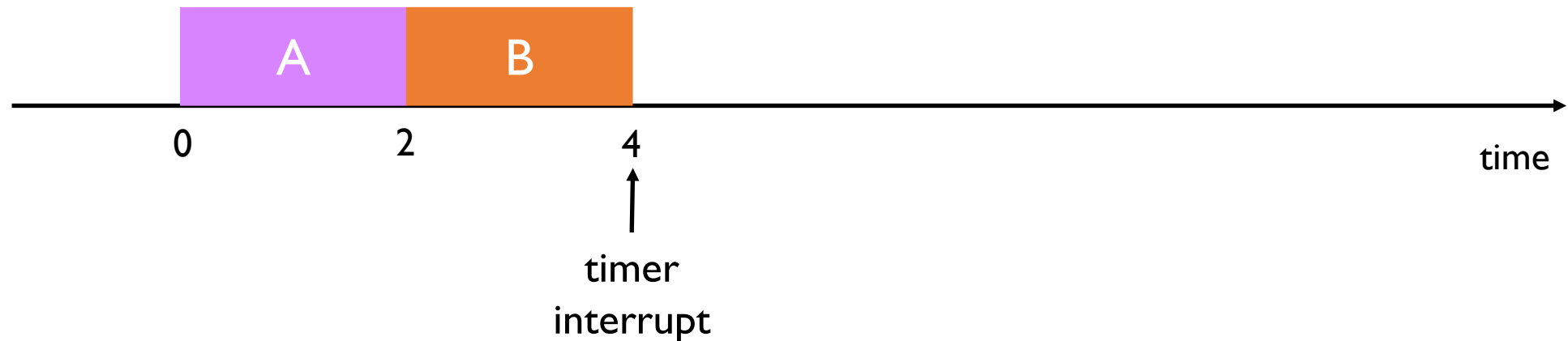
Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3



Round Robin (RR): Example



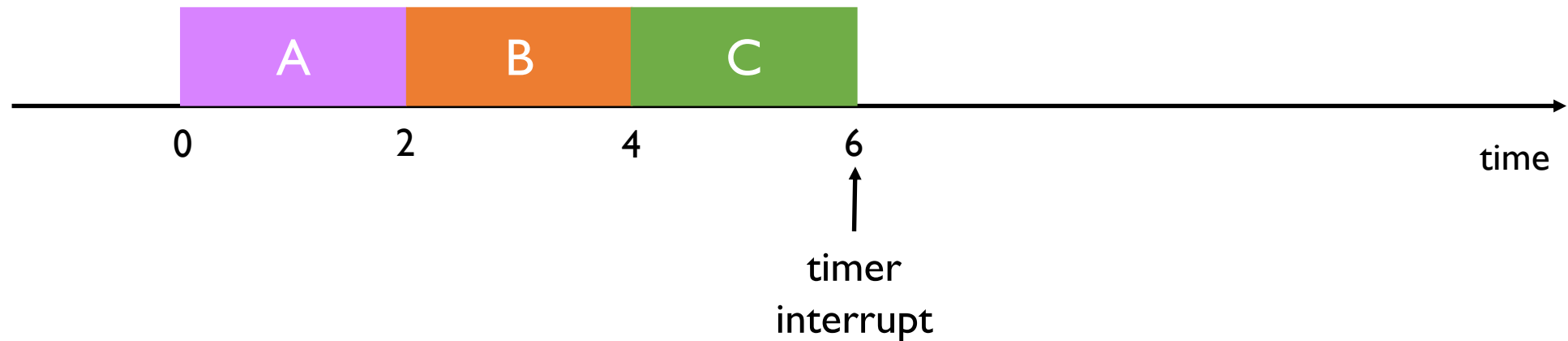
Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3



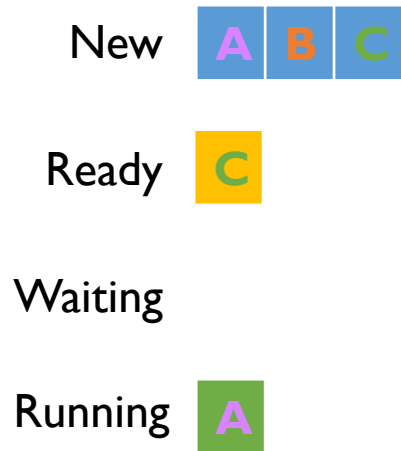
Round Robin (RR): Example



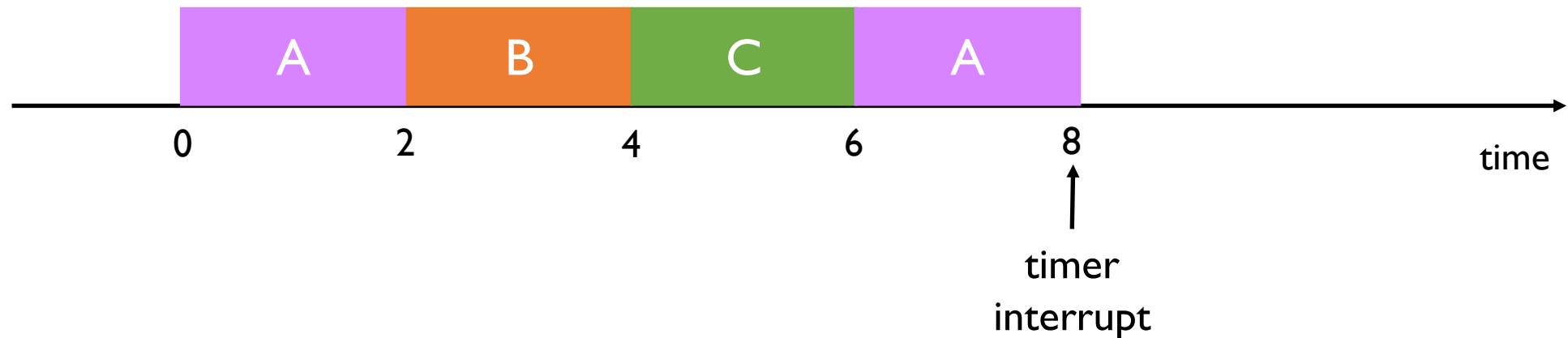
Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3



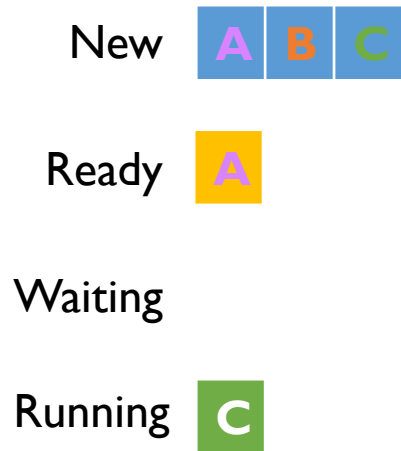
Round Robin (RR): Example



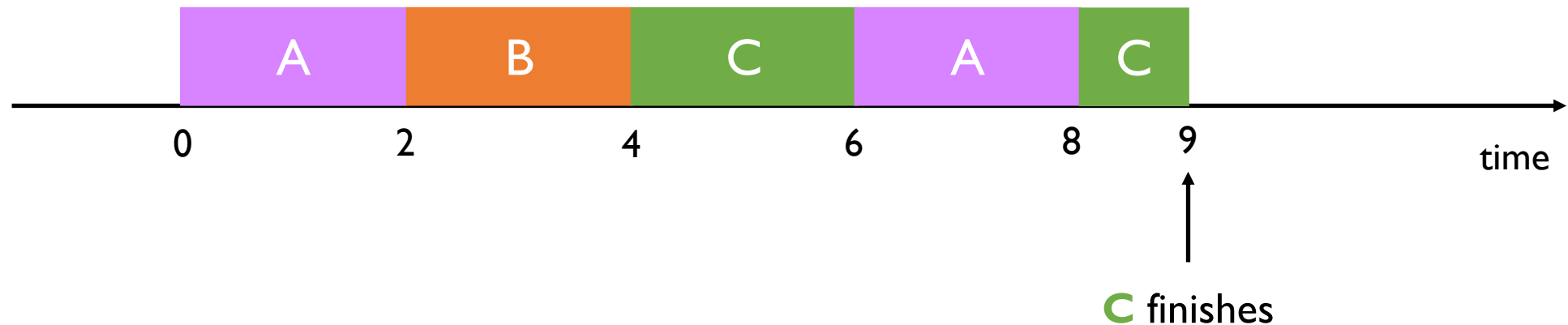
Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3



Round Robin (RR): Example



Order	Job	CPU burst (time units)
1	A	5
2	B	2
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Round Robin (RR): Example

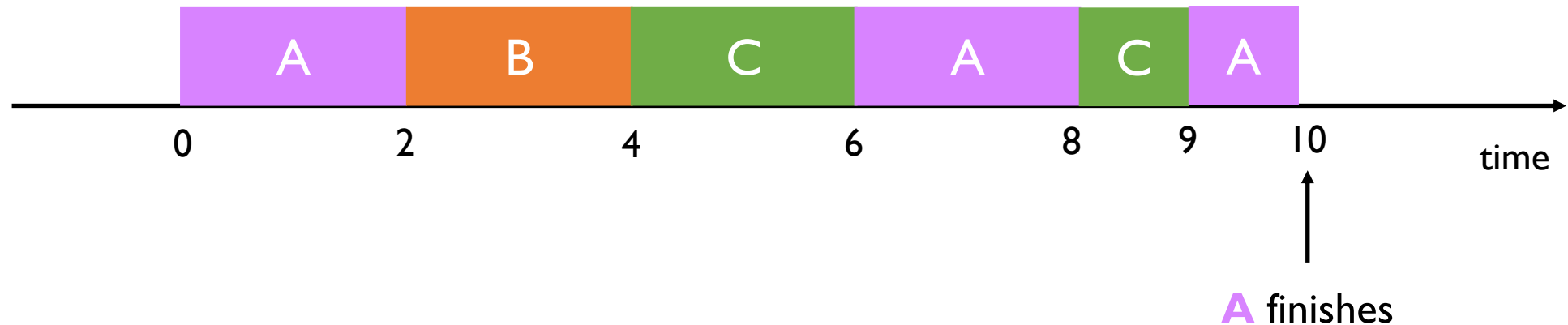
New 

Ready

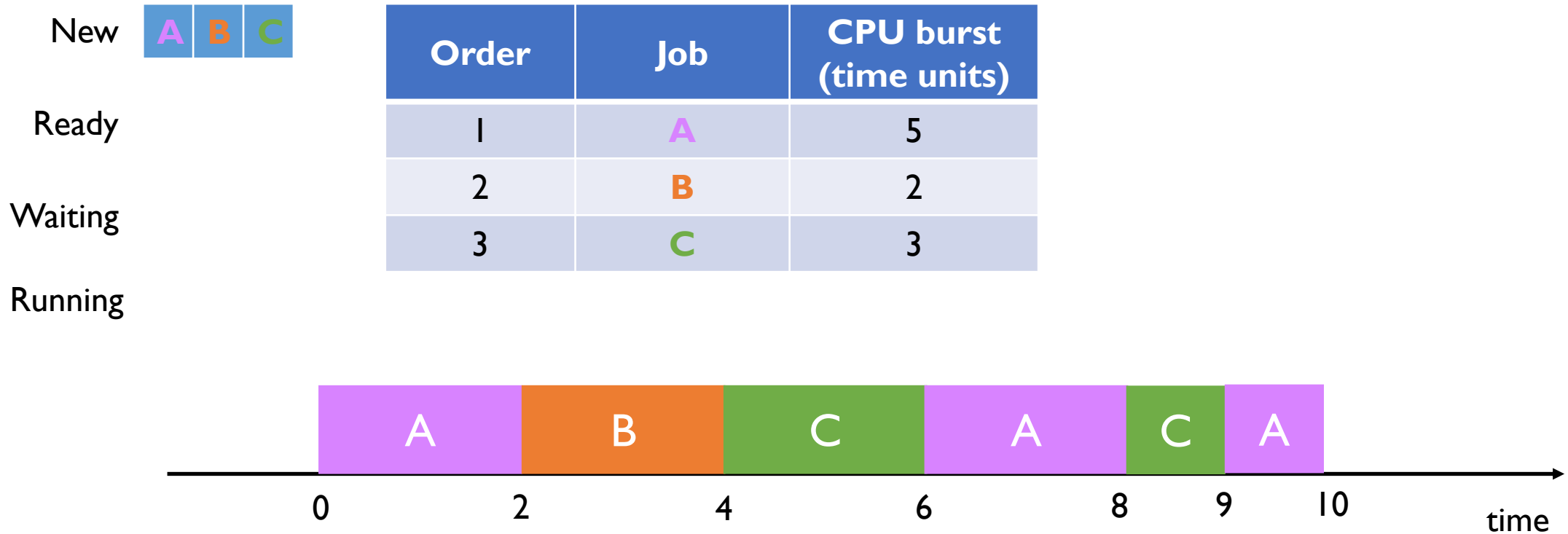
Waiting

Running 

Order	Job	CPU burst (time units)
1	A	5
2	B	2
3	C	3

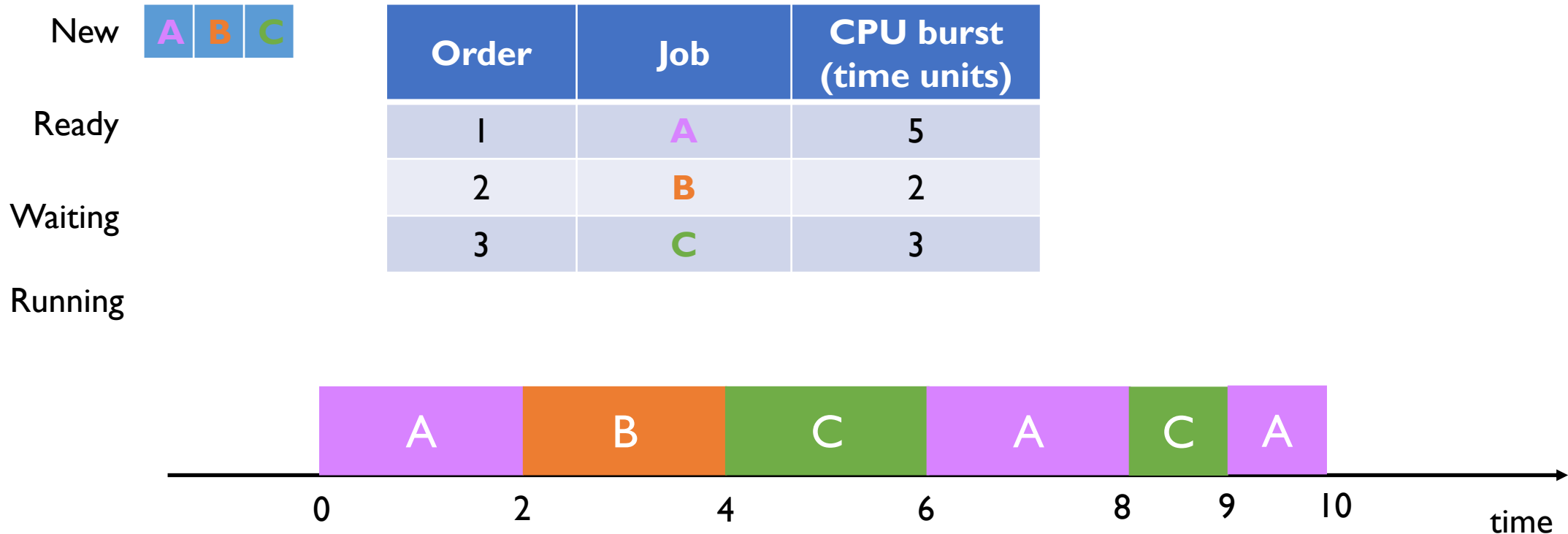


Round Robin (RR): Example



avg. waiting time =

Round Robin (RR): Example



$$\text{avg. waiting time} = (5 + 2 + 6)/3 \sim 4.3$$

FCFS vs. RR

Assumptions:

5 jobs, 100 time units of CPU burst each

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	100				
B	100				
C	100				
D	100				
E	100				
Avg.					

FCFS vs. RR

Assumptions:

5 jobs, 100 time units of CPU burst each

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	100	100			
B	100	200			
C	100	300			
D	100	400			
E	100	500			
Avg.		300			

FCFS vs. RR

Assumptions:

5 jobs, 100 time units of CPU burst each

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	100	100	496		
B	100	200	497		
C	100	300	498		
D	100	400	499		
E	100	500	500		
Avg.		300	498		

FCFS vs. RR

Assumptions:

5 jobs, 100 time units of CPU burst each

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	100	100	496	0	
B	100	200	497	100	
C	100	300	498	200	
D	100	400	499	300	
E	100	500	500	400	
Avg.		300	498	200	

FCFS vs. RR

Assumptions:

5 jobs, 100 time units of CPU burst each

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	100	100	496	0	396
B	100	200	497	100	397
C	100	300	498	200	398
D	100	400	499	300	399
E	100	500	500	400	400
Avg.		300	498	200	398

FCFS vs. RR

Assumptions:

5 jobs, 100 time units of CPU burst each

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

FCFS seems to outperform RR in both metrics but... is it fair?

Look at the variance rather than the average!

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	100	100	496	0	396
B	100	200	497	100	397
C	100	300	498	200	398
D	100	400	499	300	399
E	100	500	500	400	400
Avg.		300	498	200	398

FCFS vs. RR

Assumptions:

5 jobs, different CPU burst

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	50				
B	40				
C	30				
D	20				
E	10				
Avg.					

FCFS vs. RR

Assumptions:

5 jobs, different CPU burst

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	50	50			
B	40	90			
C	30	120			
D	20	140			
E	10	150			
Avg.		110			

FCFS vs. RR

Assumptions:

5 jobs, different CPU burst

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	50	50	150		
B	40	90	140		
C	30	120	120		
D	20	140	90		
E	10	150	50		
Avg.		110	110		

FCFS vs. RR

Assumptions:

5 jobs, different CPU burst

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	50	50	150	0	
B	40	90	140	50	
C	30	120	120	90	
D	20	140	90	120	
E	10	150	50	140	
Avg.		110	110	80	

FCFS vs. RR

Assumptions:

5 jobs, different CPU burst

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time		waiting time	
Job	CPU burst	FCFS	RR	FCFS	RR
A	50	50	150	0	100
B	40	90	140	50	100
C	30	120	120	90	90
D	20	140	90	120	70
E	10	150	50	140	40
Avg.		110	110	80	80

Summary (Part I)

- Scheduling allows one process to use the CPU while another is waiting for I/O, thereby maximizing system utilization

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Summary (Part I)

- Scheduling allows one process to use the CPU while another is waiting for I/O, thereby maximizing system utilization
- **non-preemptive** vs. **preemptive** scheduler
- Different scheduling policies optimize different metrics
- 2 out of 6 scheduling algorithms:
 - **First-Come-First-Serve (FCFS)**
 - **Round Robin (RR)**