Sistemi Operativi

Corso di Laurea in Informatica

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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

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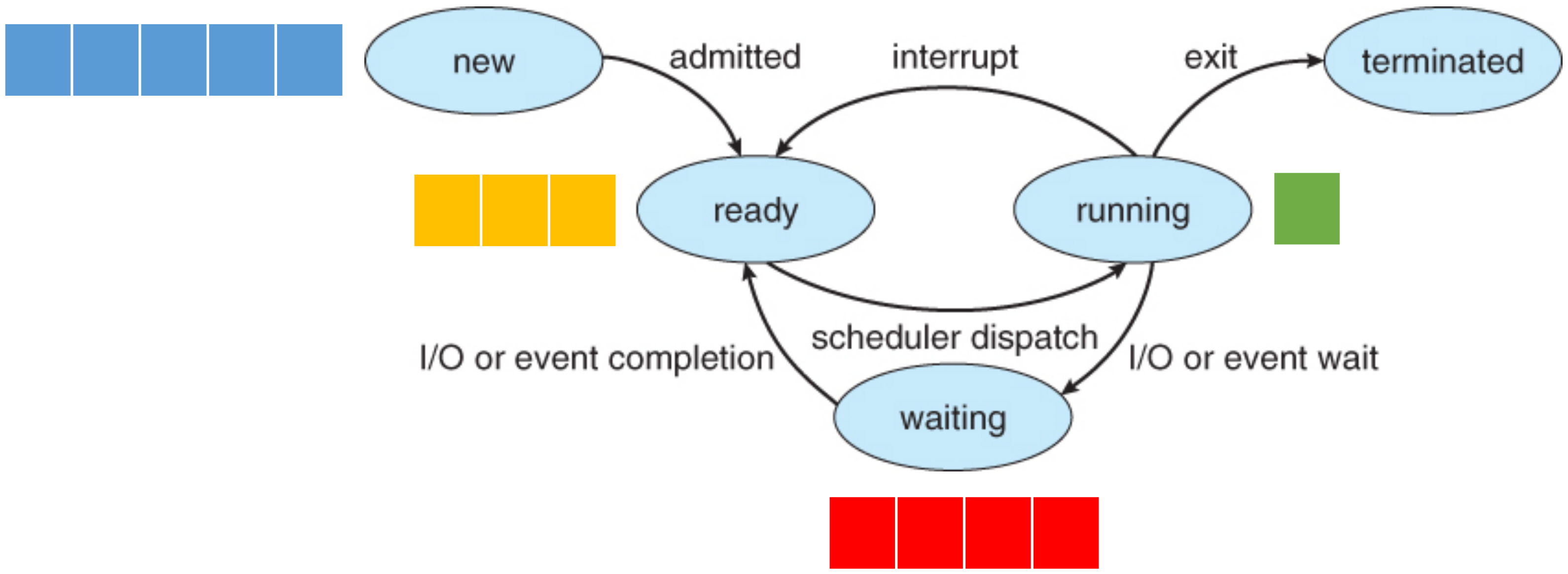
- A scheduling system allows one process to use the CPU while another is waiting for I/O, thereby maximizing system utilization
- **Challenge:** Make the system as "efficient" and "fair" as possible, subject to varying and often dynamic conditions

Process Execution State Diagram



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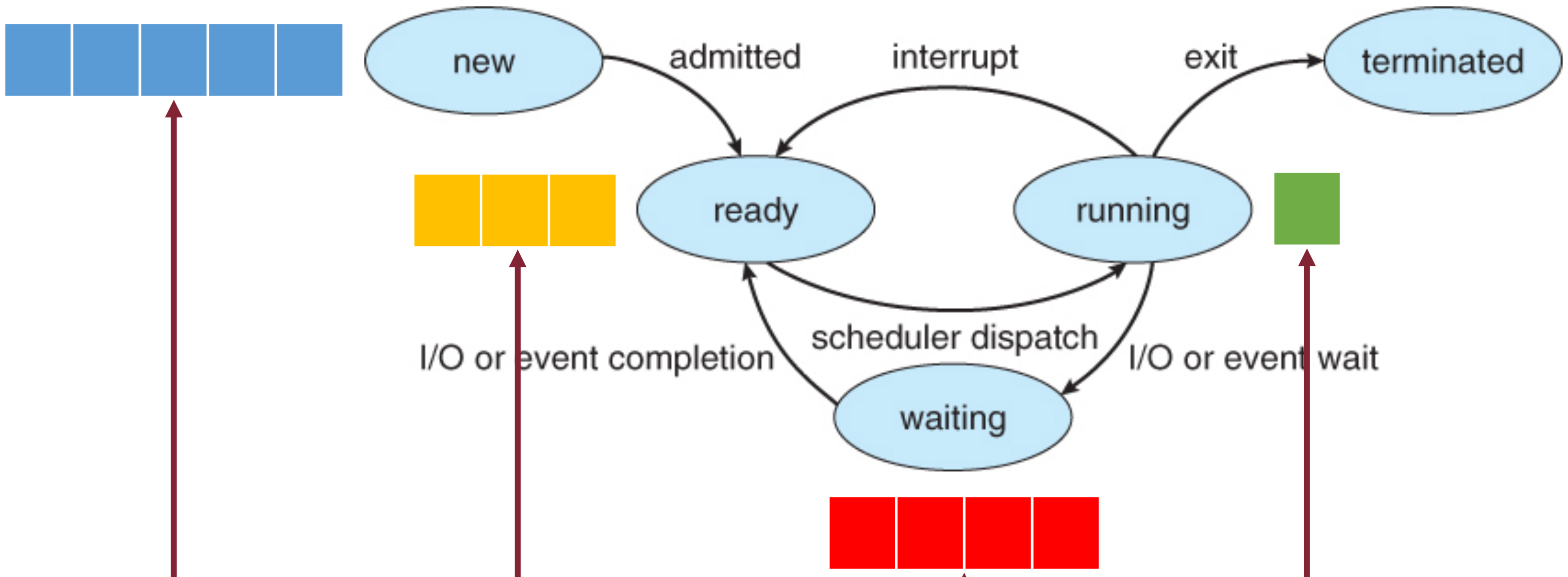
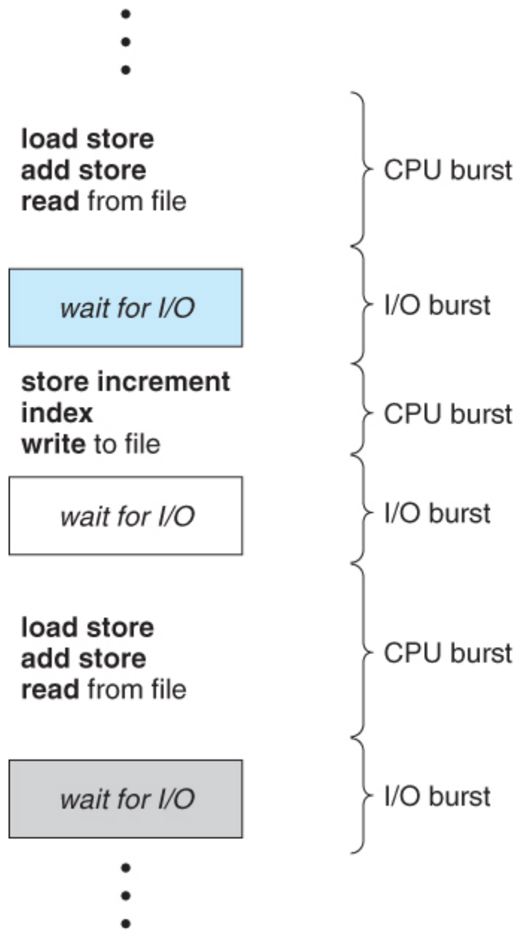


Processes managed by the OS reside in exactly one of the state queues

CPU vs. I/O Burst Cycle



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

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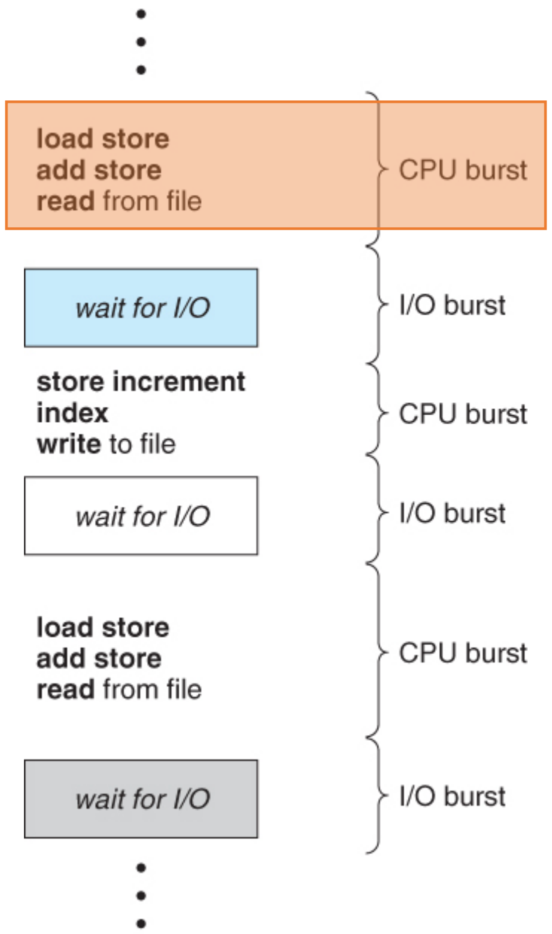

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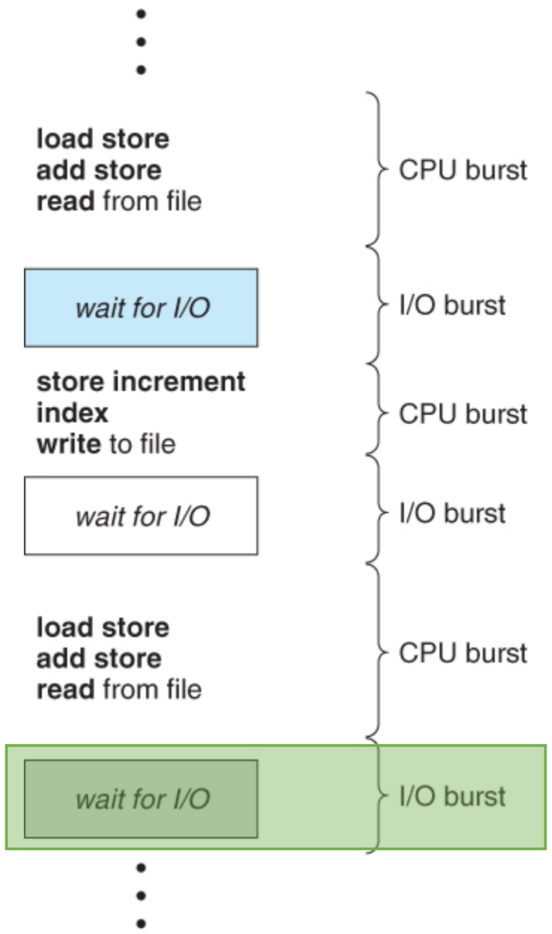
CPU burst → performing calculations

CPU vs. I/O Burst Cycle



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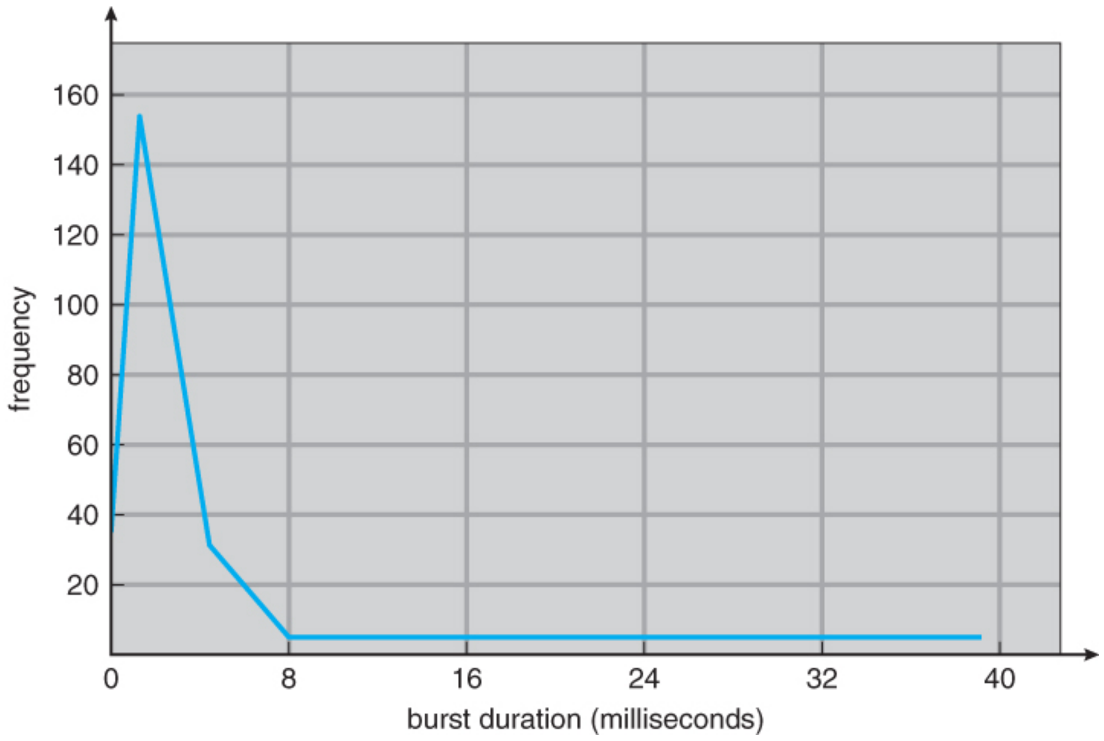
I/O burst → waiting for data transfer in or out of the system

CPU Burst Cycle: Frequency Pattern



Highly skewed distribution

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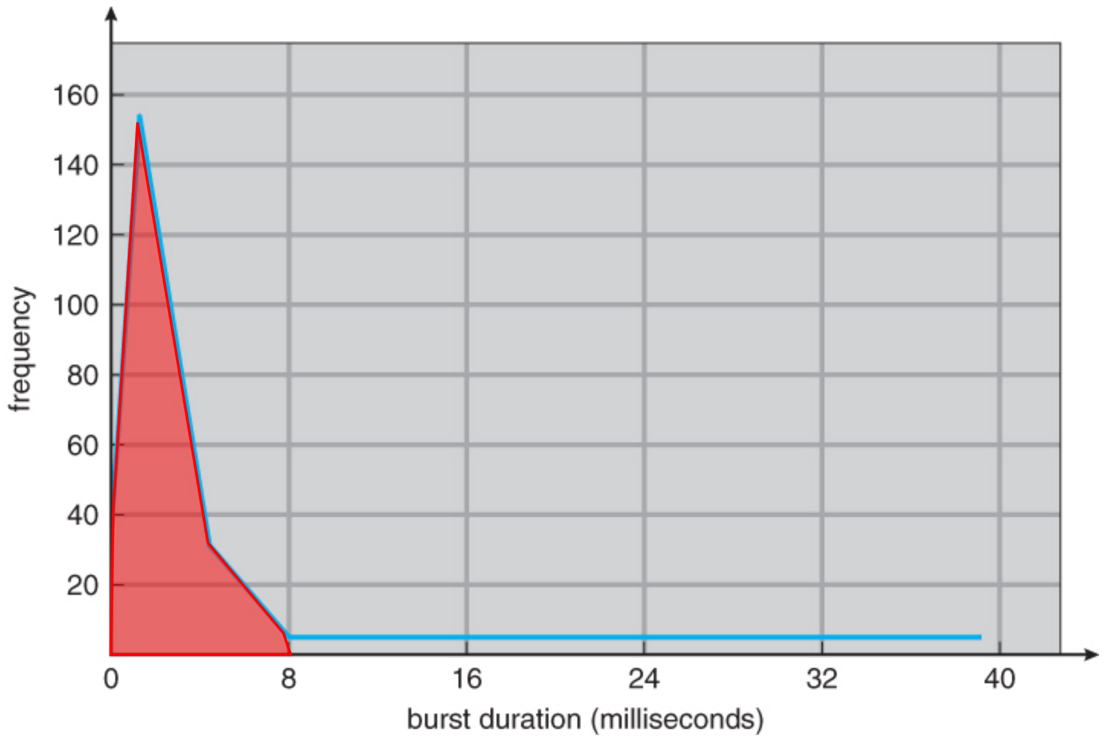

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The vast majority of processes have **short** CPU bursts

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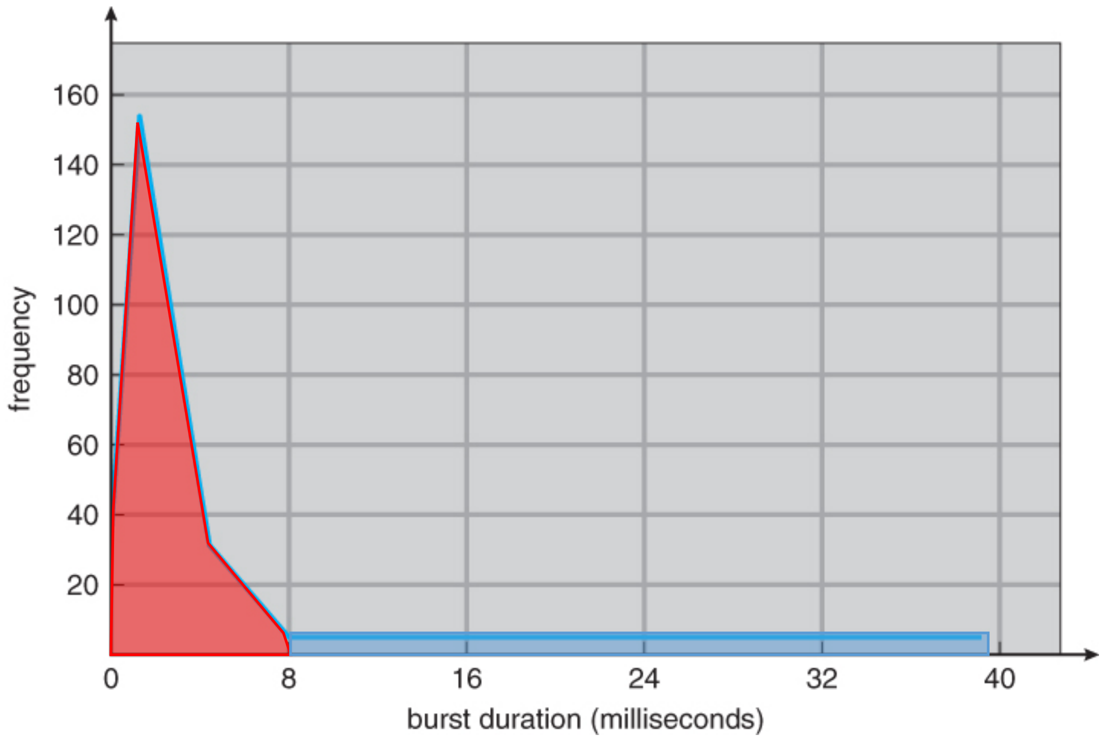

Highly skewed distribution

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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Policy goals vs. Mechanism implementations

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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`**

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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)

Preemption: Issues

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

The Dispatcher

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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

$$T^{arrival} = \text{arrival time}$$

$$T^{completion} = \text{completion time}$$

$$T^{burst} = \text{burst time}$$

$$T^{turnaround} = \text{tournaround time} = T^{completion} - T^{arrival}$$

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

Scheduling Criteria/Metrics

- There are several different criteria to consider when trying to select the "best" scheduling algorithm, including:
  - 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

- Minimize **average** response time
  - Provide output to the user as quickly as possible

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Typical of batch systems

A Quick Note on Terminology

JOB/TASK

General **unit** of CPU execution

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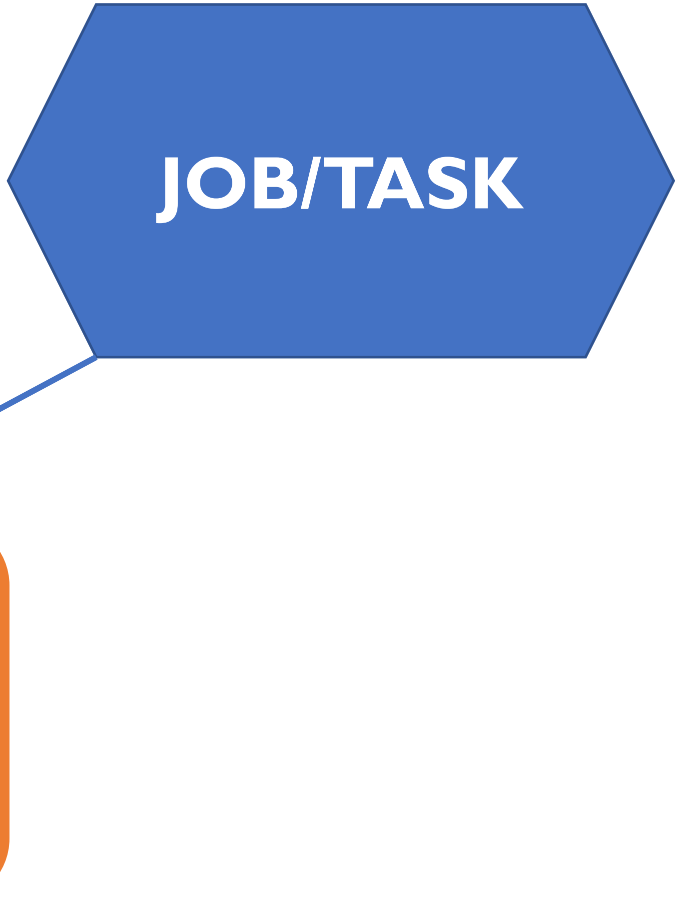

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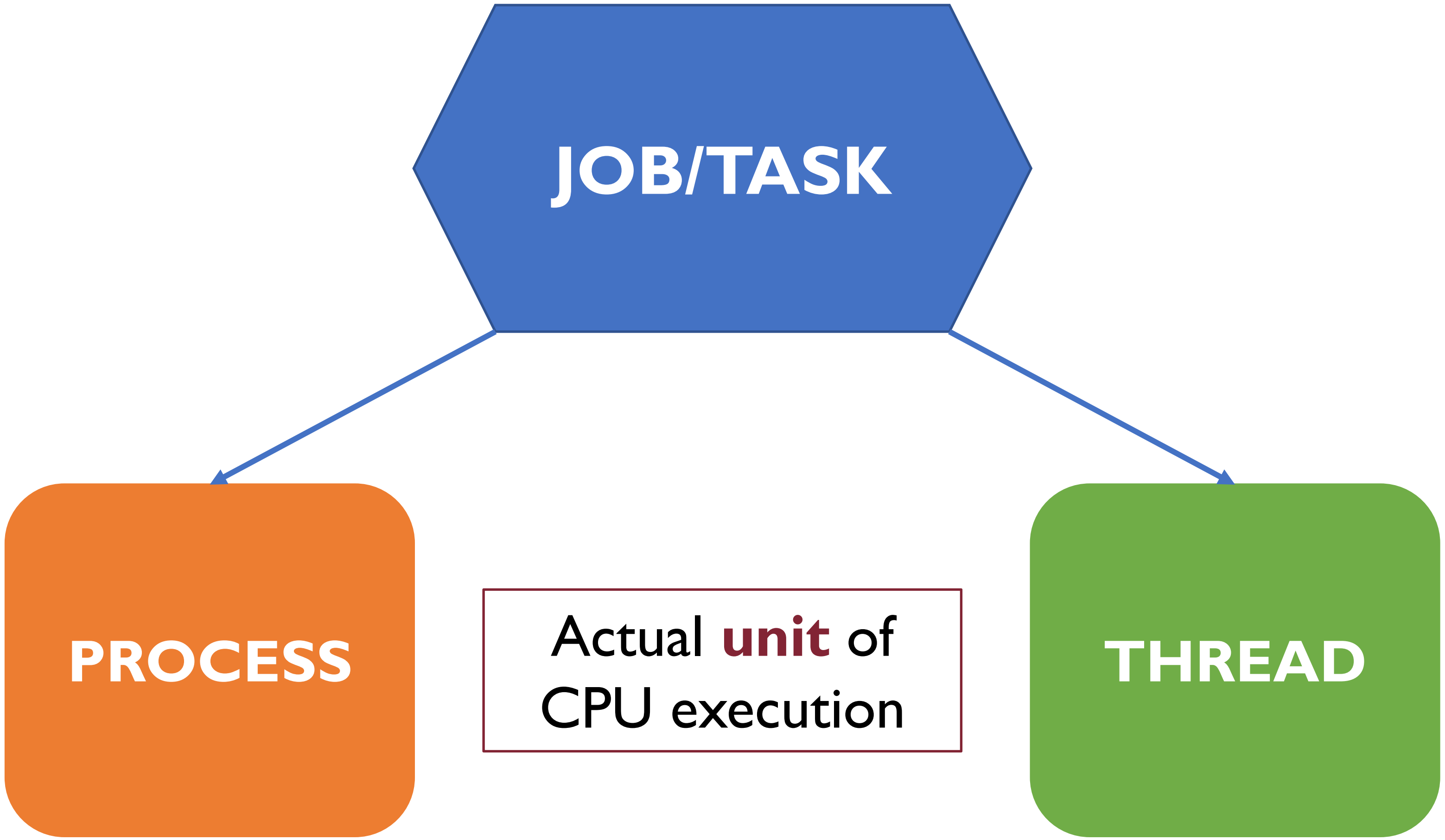

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We will talk about threads very soon but for now most of the things we will be discussing remain valid even on a multi-threaded system

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)

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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
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Non-preemptive

First-Come-First-Serve (FCFS): Scenario 1

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

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Arrival time = 0 for all

No I/O burst

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

New A B C

Ready A B C

Waiting

Running

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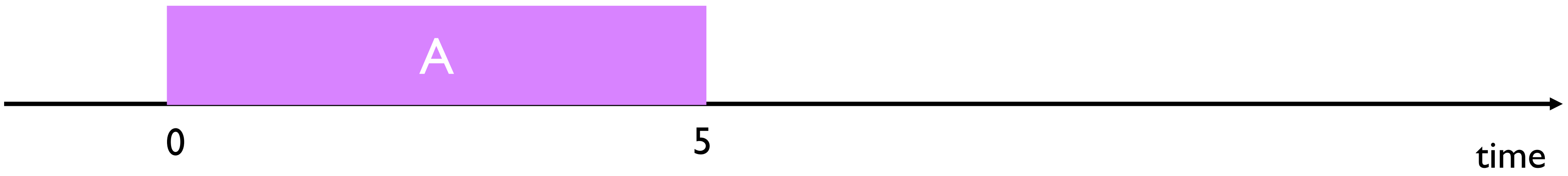

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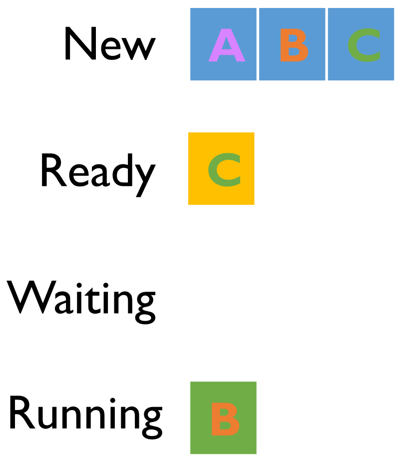

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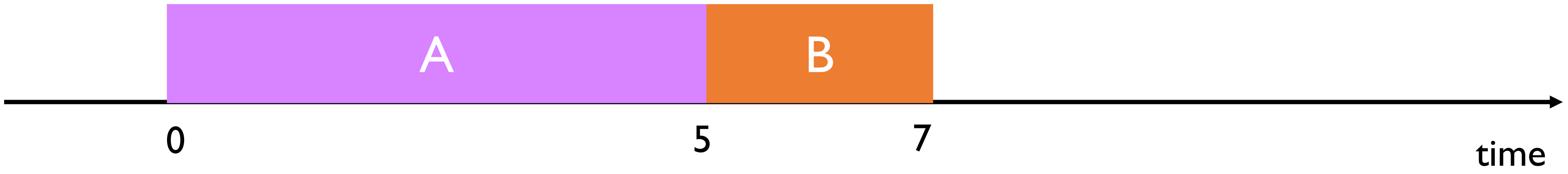

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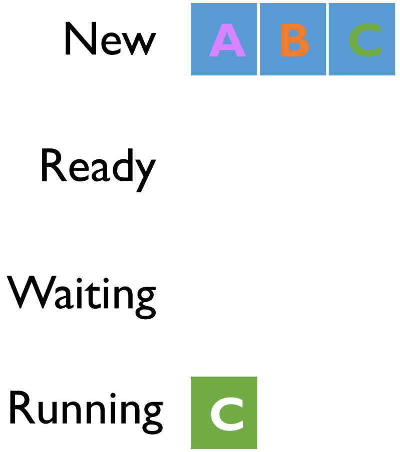

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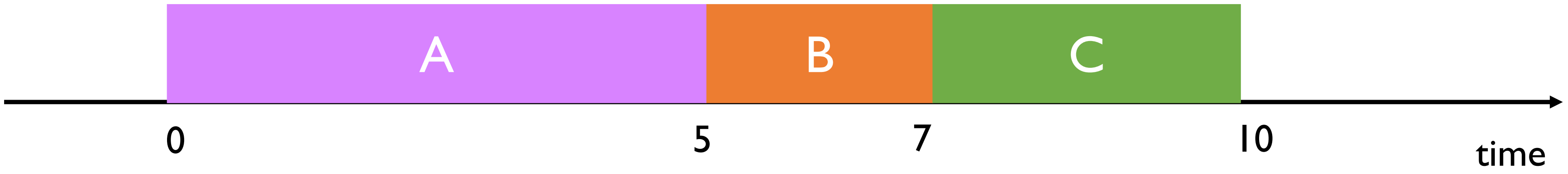

Average Waiting Time

$$N = \text{number of jobs}$$

$$T_i^{arrival} = \text{arrival time of job } i$$
$$T_i^{completion} = \text{completion time of job } i$$
$$T_i^{burst} = \text{burst time of job } i$$
$$T_i^{turnaround} = \text{tournaround time of job } i = T_i^{completion} - T_i^{arrival}$$

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

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

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

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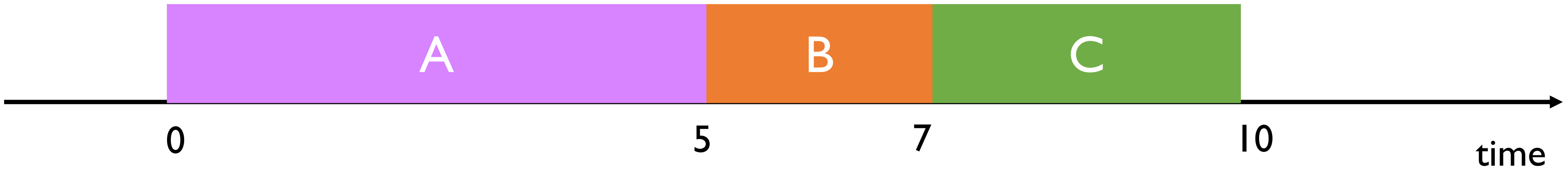

avg. waiting time =

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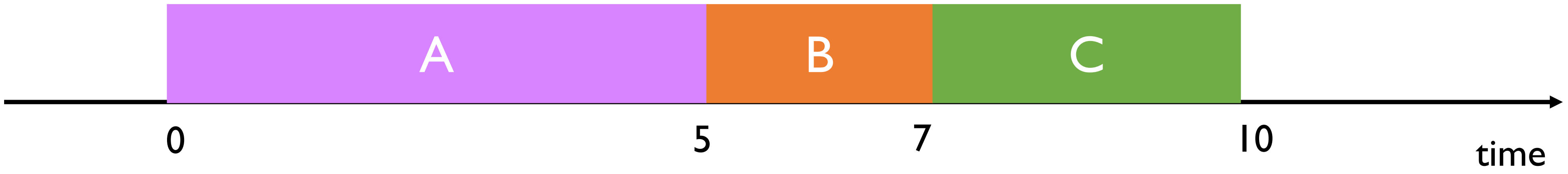


avg. waiting time = (0 + 5 + 7)/3 = **4**

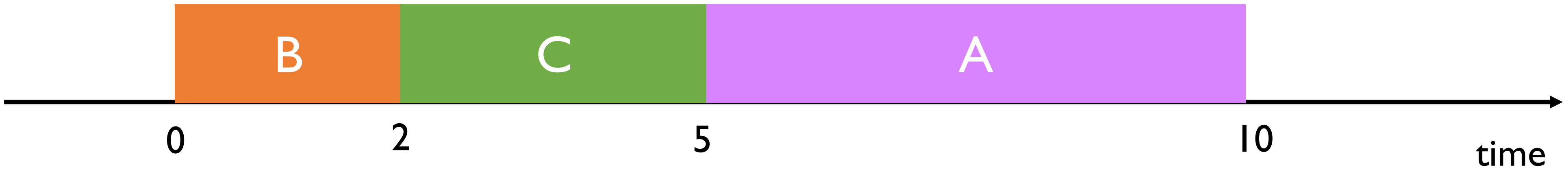
First-Come-First-Serve (FCFS): Scenario II

New B C A

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

Arrival time = 0 for all

No I/O burst

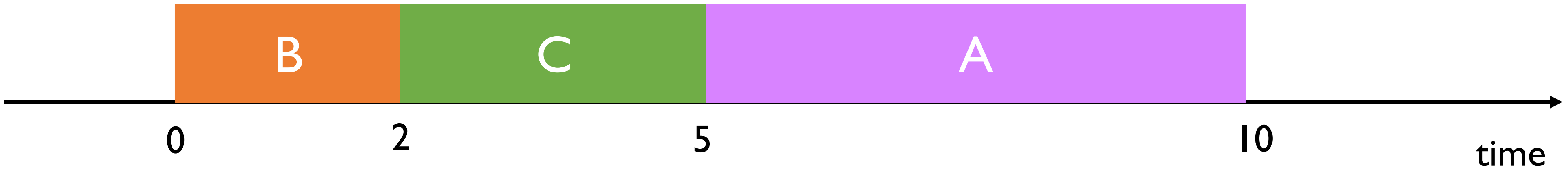


avg. waiting time =

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

New 

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



avg. waiting time = (5 + 0 + 2)/3 ~ **2.3**

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

New A B C

Ready A B C

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

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

New A B C

Ready A B C

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

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: A B C

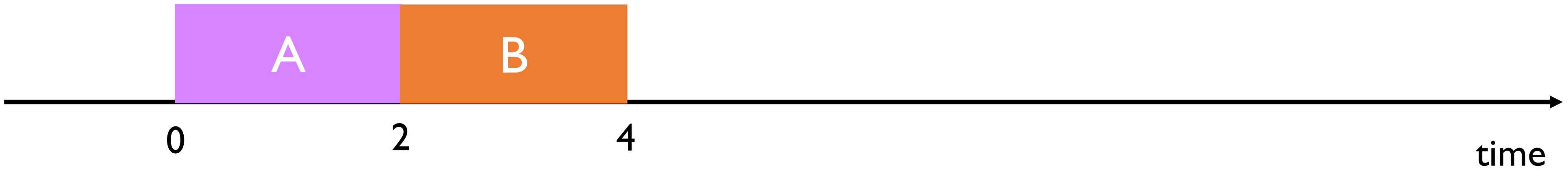
Ready: C

Waiting: A

Running: B

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 A B C

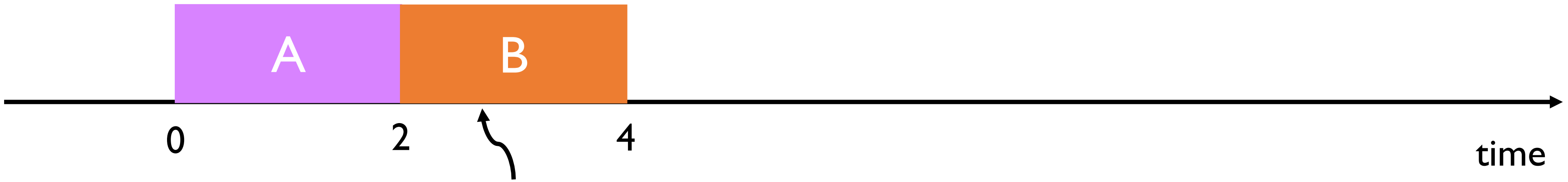
Ready C

Waiting A

Running B

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

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

New: A B C

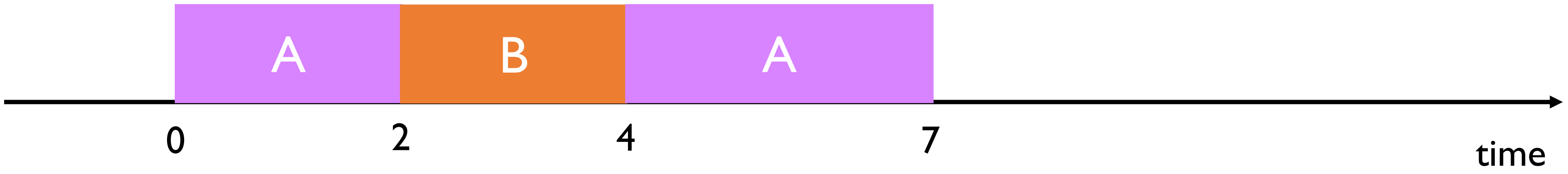
Ready: C

Waiting

Running: A

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 A B C

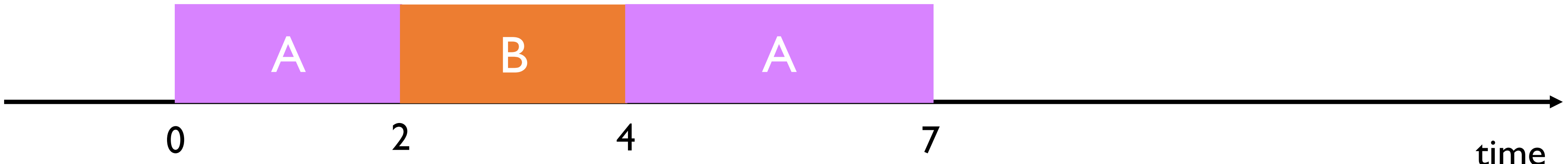
Ready C

Waiting

Running A

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 A B C

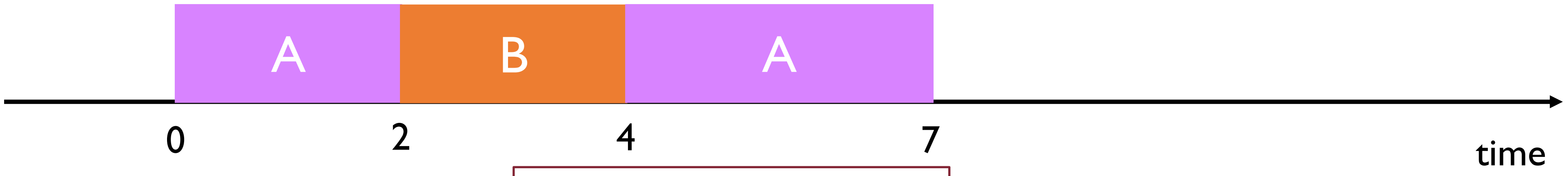
Ready C

Waiting

Running A

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

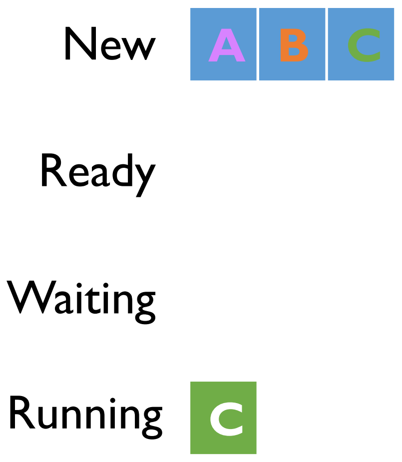
A does also I/O



Why A and not C?

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

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



Order	Job	CPU burst (time units)
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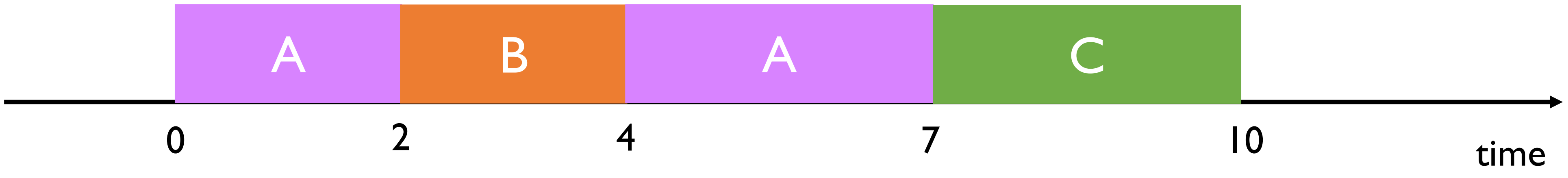
3	C	3

A does also I/O



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

New A B C

Ready

Waiting

Running

Order	Job	CPU burst (time units)
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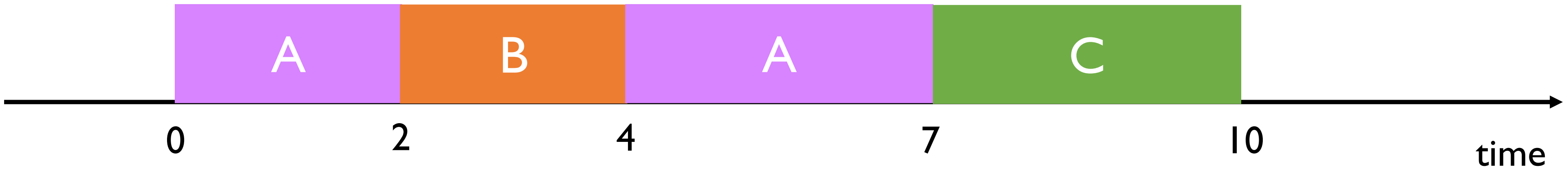
A does also I/O



avg. waiting time =

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

New | A | B | C

Ready

Waiting

Running

Order	Job	CPU burst (time units)
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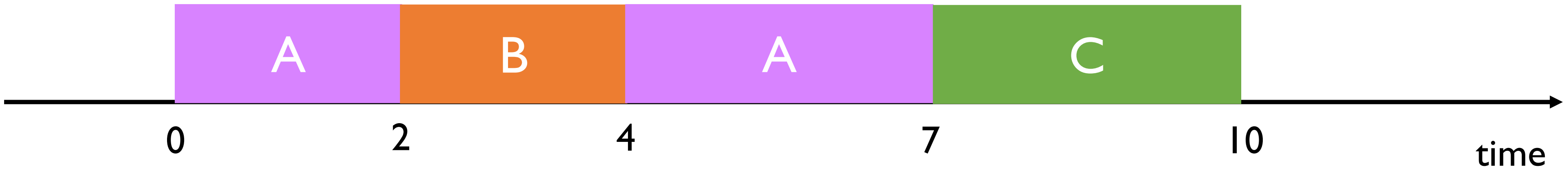
A does also I/O



avg. waiting time = (2 + 2 + 7)/3 ~ **3.7**

FCFS: PROs and CONs

- **PRO:**
  - very simple!

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  - (average) waiting time is highly variable as short CPU-burst jobs may sit behind very long ones

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- **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 (MQ)
- Multilevel Feedback-Queue (MFQ)

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
- Used in many time-sharing systems in combination with timer interrupts

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- Used in many time-sharing systems in combination with timer interrupts

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

- The performance of RR is sensitive to the time quantum selected

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Round Robin (RR): The Time Quantum

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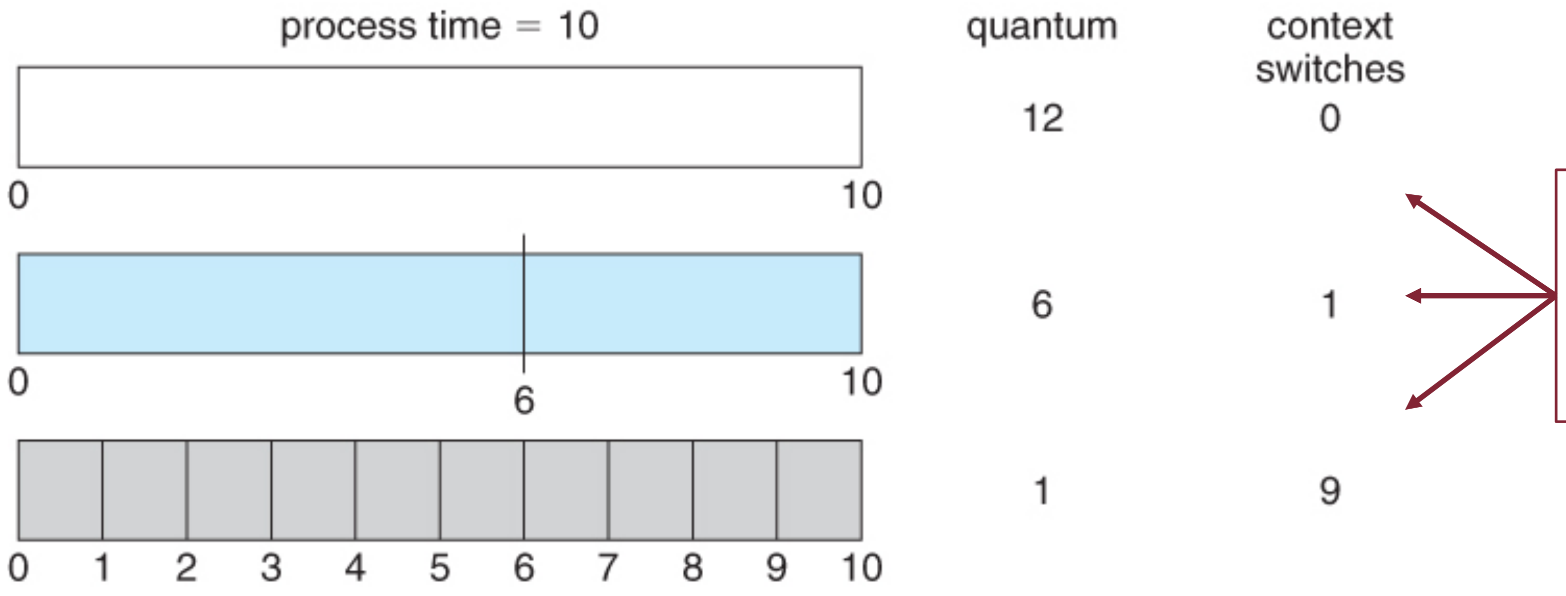
- Too large time quantum degenerates to FCFS as jobs are never preempted from the CPU (high average waiting time)
- Too small time quantum implies more context switches, which eventually dominate over the actual CPU utilization (low throughput)

Trade-off:
Overhead for context switching should be <u>relatively small</u> compared to time slice

Example: time slice = 10÷100 msec. and context switch = 0.01÷0.1 msec.

Round Robin (RR): The Time Quantum



By decreasing the time quantum the number of context switches increase

Round Robin (RR): The Time Quantum

$$N = \text{number of jobs}$$

$$\delta = \text{time slice}$$

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

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 | A | B | C |

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

New | A | B | C

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 A B C

Ready A B C

Waiting

Running

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

Round Robin (RR): Example

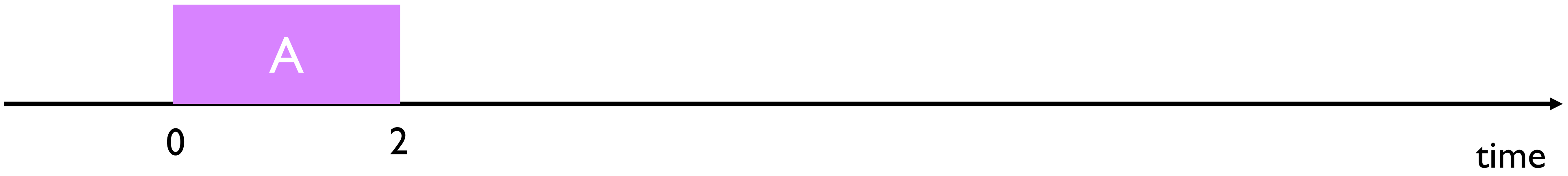
New: A B C

Ready: B C

Waiting

Running: A

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



Round Robin (RR): Example

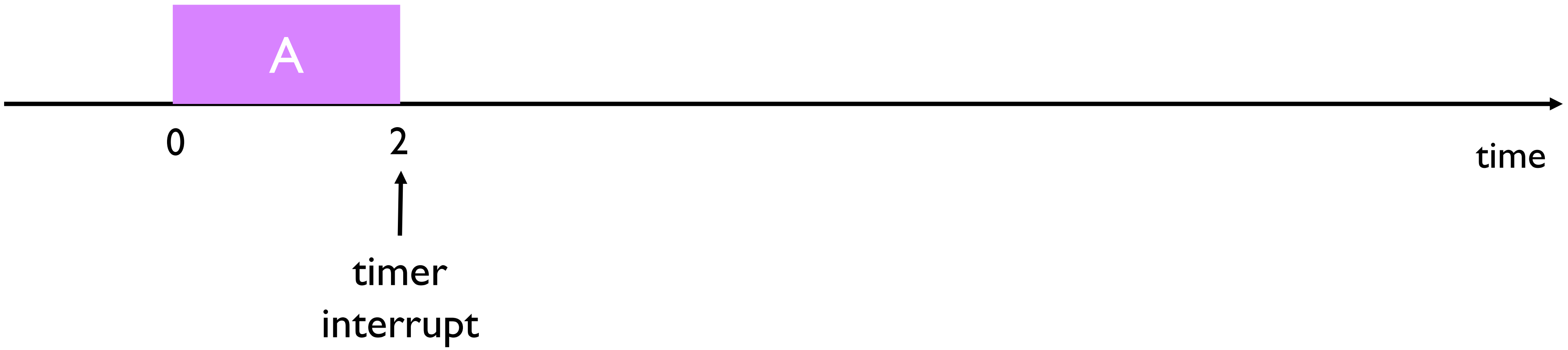
New A B C

Ready B C

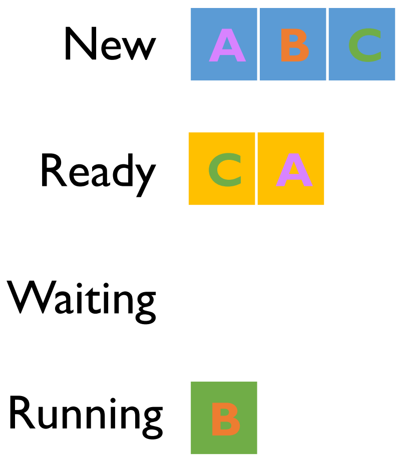
Waiting

Running A

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



Round Robin (RR): Example



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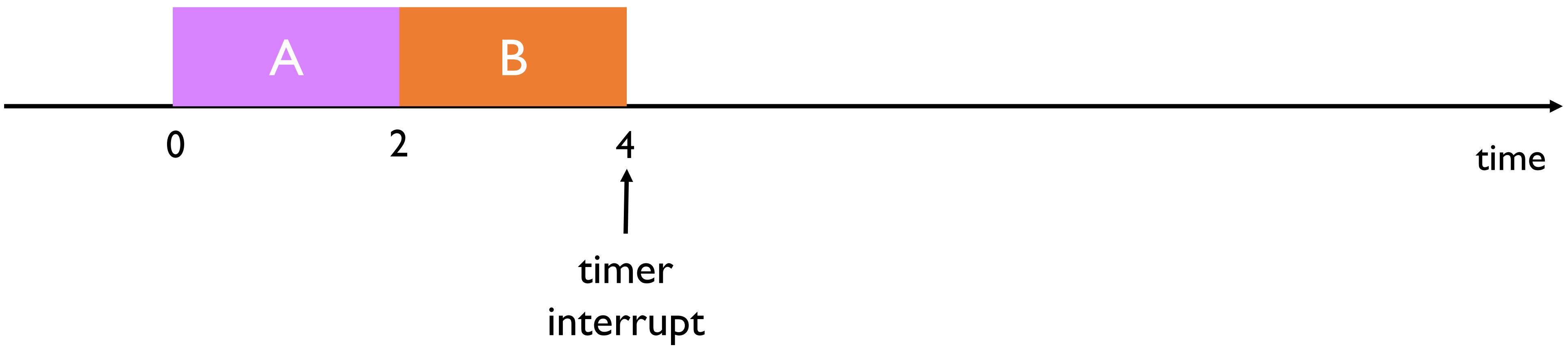

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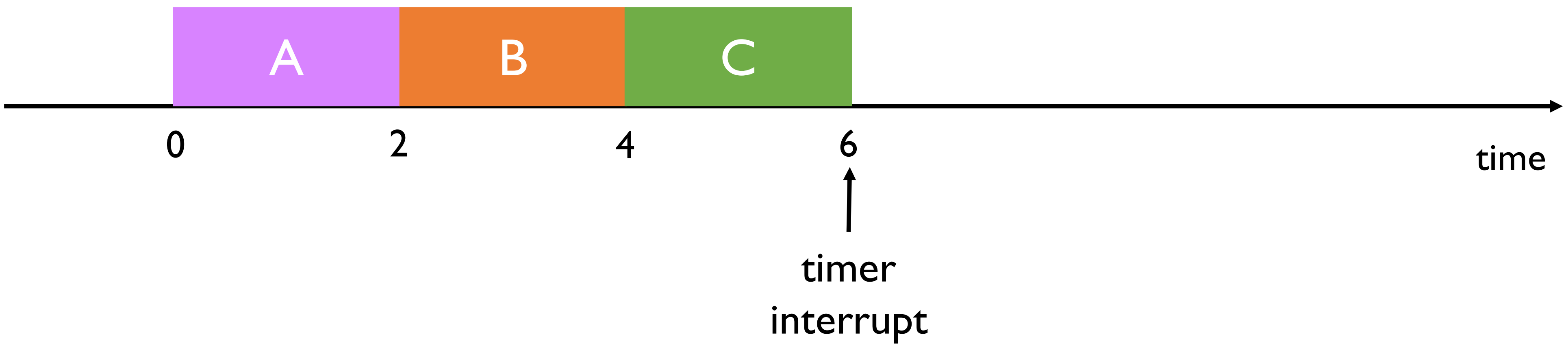

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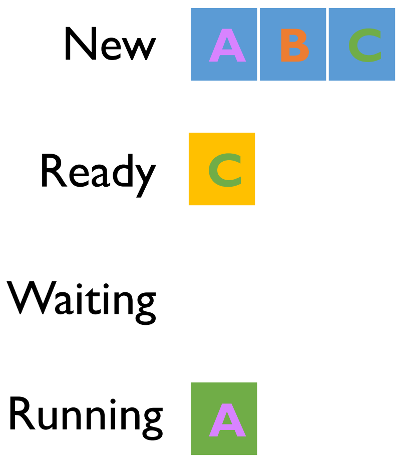

Order	Job	CPU burst (time units)
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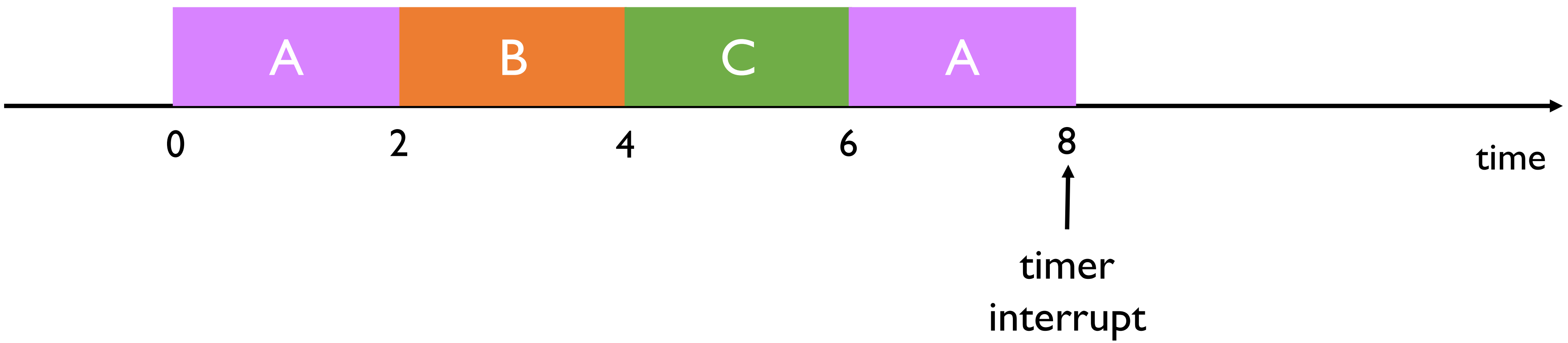


Round Robin (RR): Example

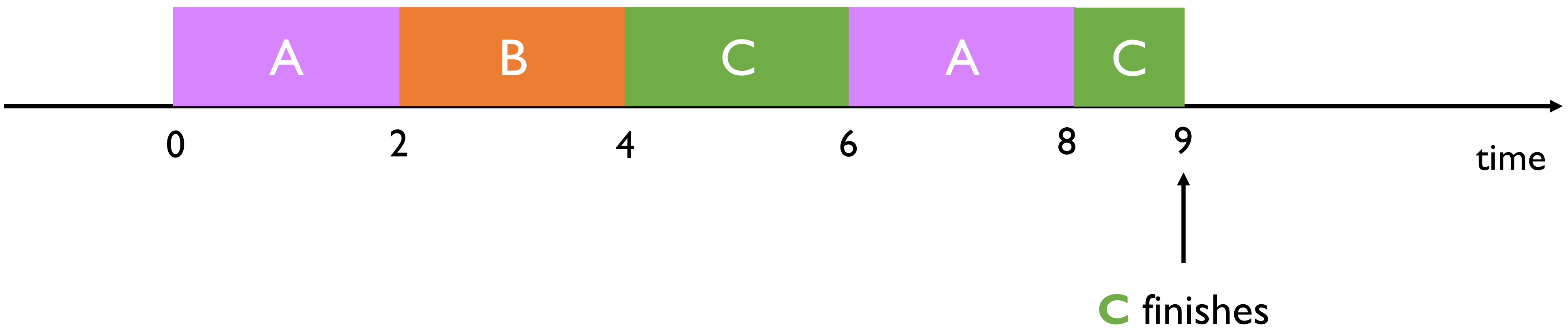
New A B C

Ready A

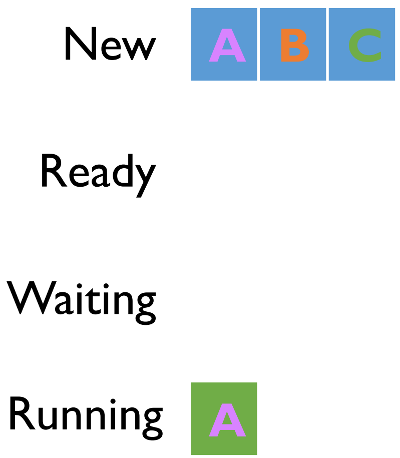
Waiting

Running C

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



Round Robin (RR): Example



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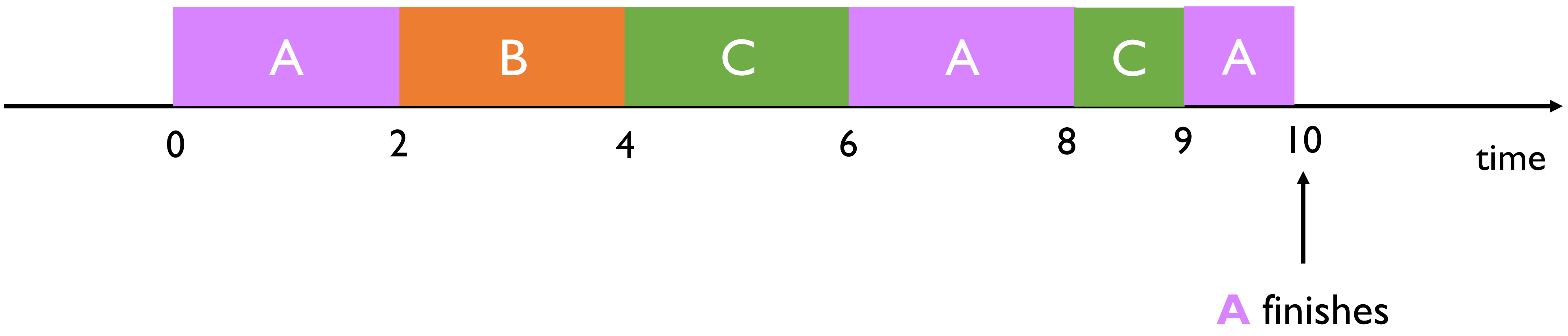

Round Robin (RR): Example

New A B C

Ready

Waiting

Running

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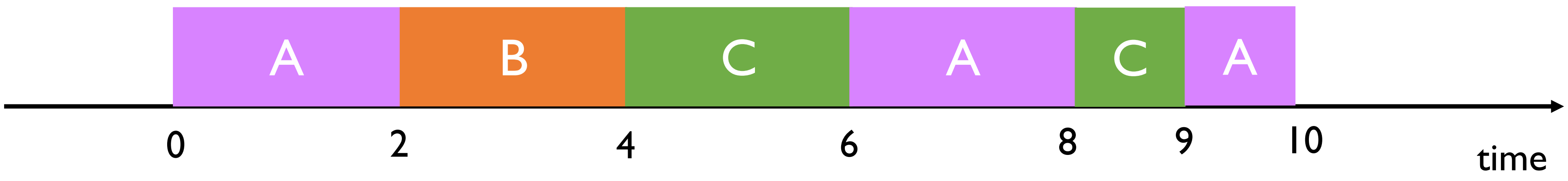


avg. waiting time =

Round Robin (RR): Example

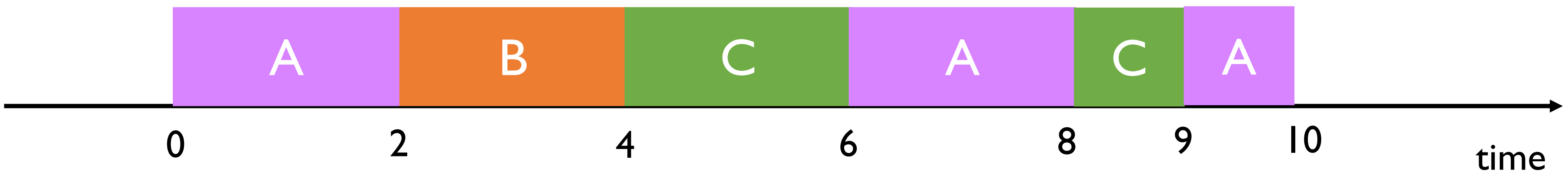
New A B C

Ready

Waiting

Running

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



avg. waiting time = (5 + 2 + 6)/3 ~ **4.3**

RR vs. FCFS

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.					

RR vs. FCFS

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**			

RR vs. FCFS

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**		

RR vs. FCFS

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**	

RR vs. FCFS

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**

RR vs. FCFS

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

Look at the variance rather than the average!

RR vs. FCFS

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.					

RR vs. FCFS

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**			

RR vs. FCFS

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**		

RR vs. FCFS

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**	

RR vs. FCFS

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 1)

- 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 1)

- 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**)