Sistemi Operativi I

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

Basic Concepts

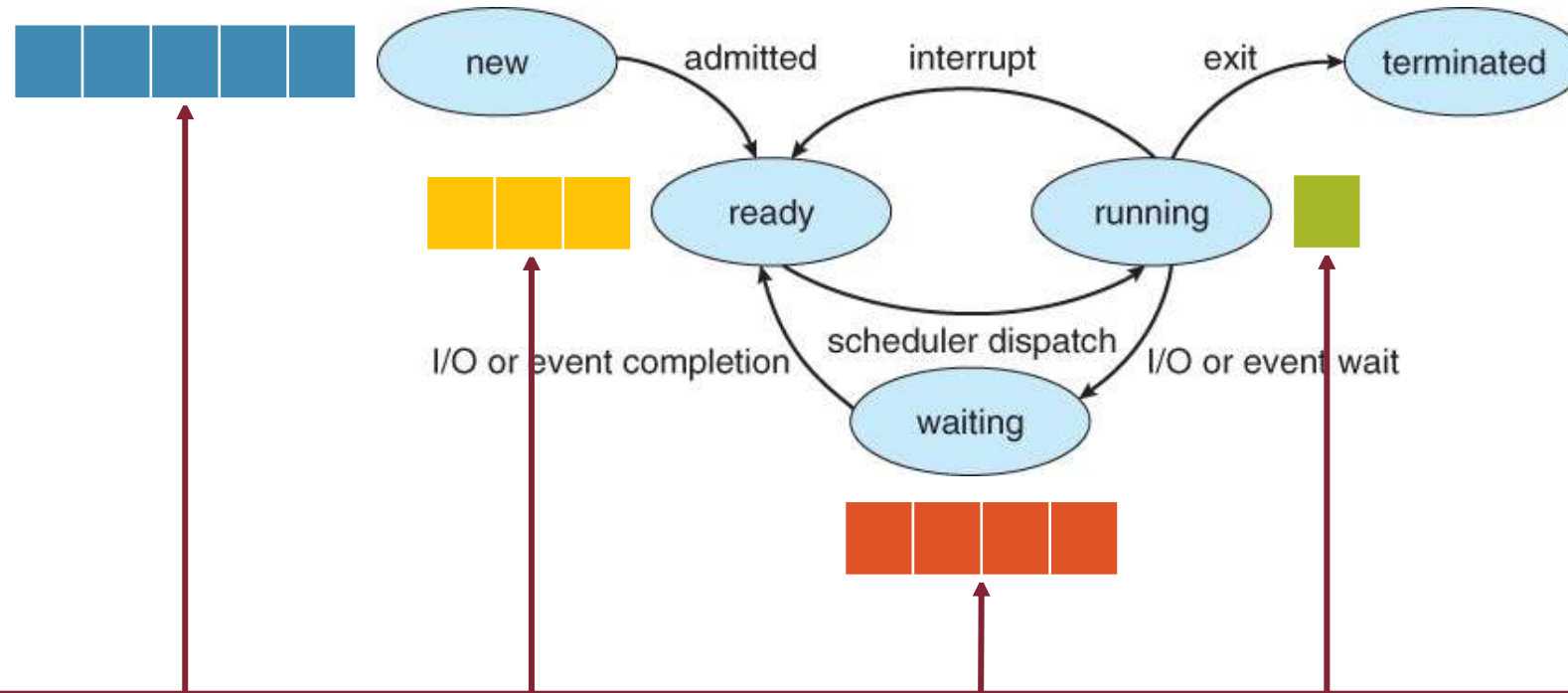- In a system running a single process, the time spent waiting for I/O is wasted, and those CPU cycles are lost forever

- 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
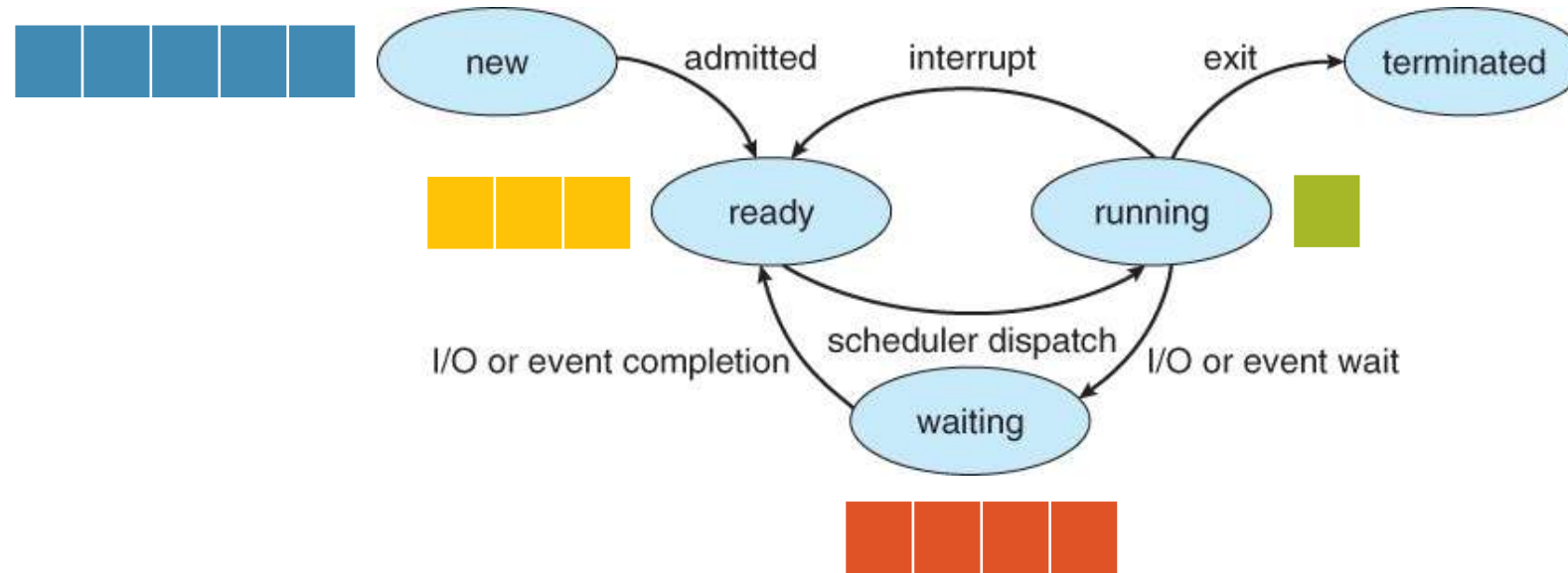
Process Execution State Diagram

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

CPU vs. I/O Burst Cycle
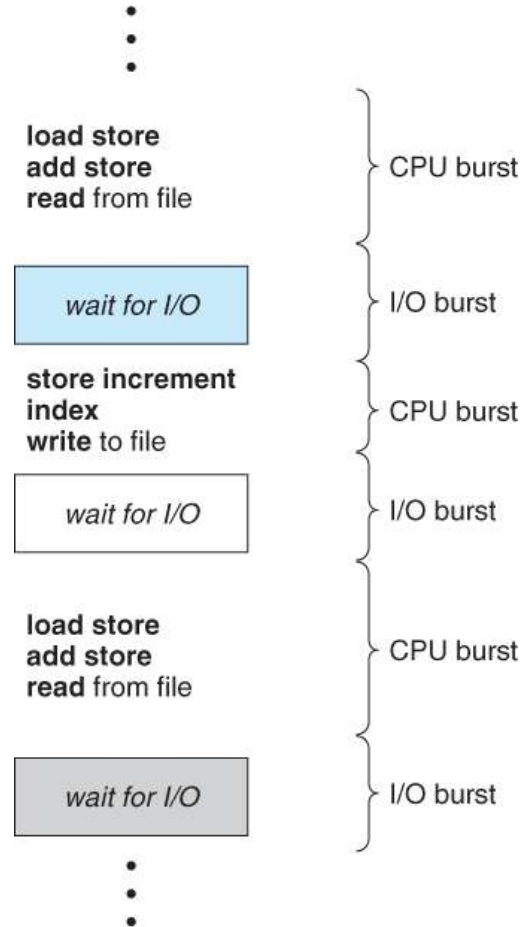
load store
add store
read from file

CPU burst

wait for I/O

I/O burst

store increment
index
write to file

CPU burst

wait for I/O

I/O burst

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

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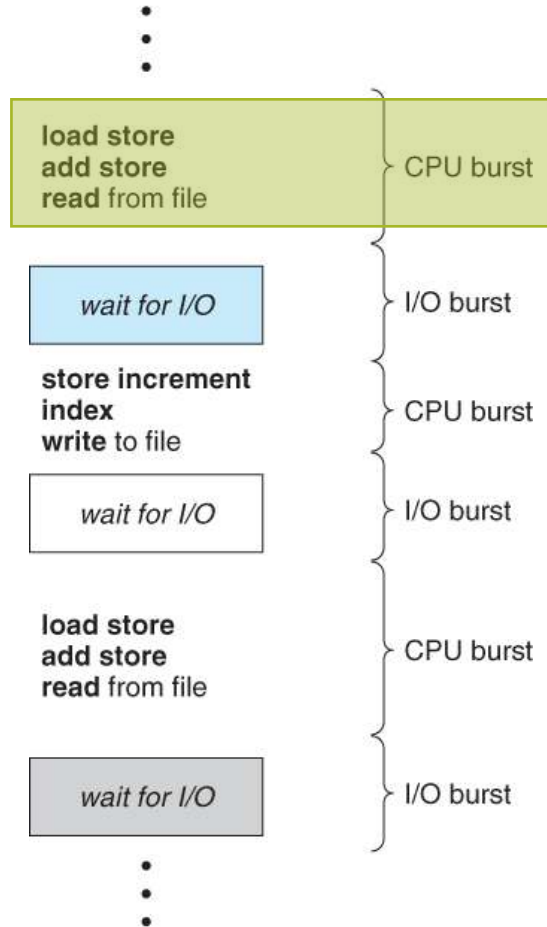
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All processes alternate between two states in a continuing cycle: CPU burst and I/O burst

CPU burst → performing calculations

CPU vs. I/O Burst Cycle


```
  •
  •
  •
load store
add store          ⎫ CPU burst
read from file

[wait for I/O]     ⎫ I/O burst

store increment
index              ⎫ CPU burst
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  •
  •
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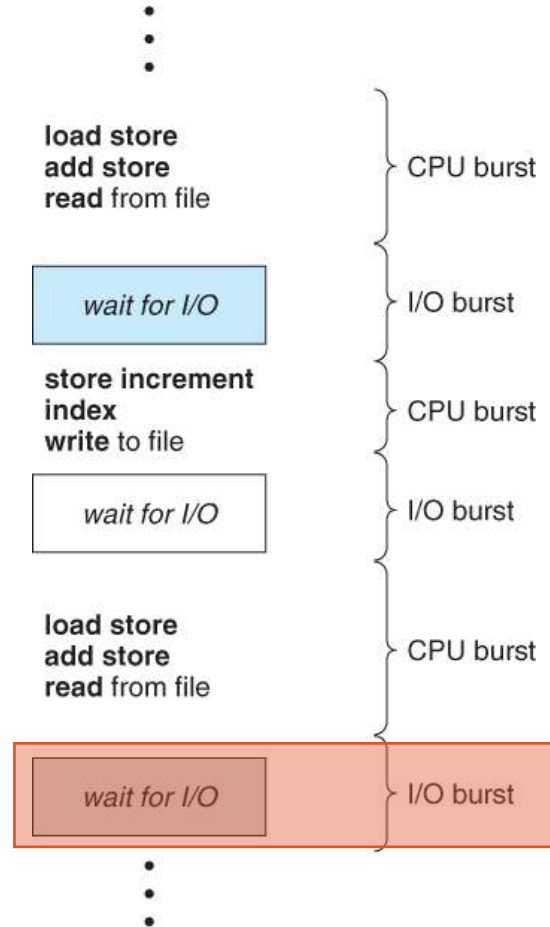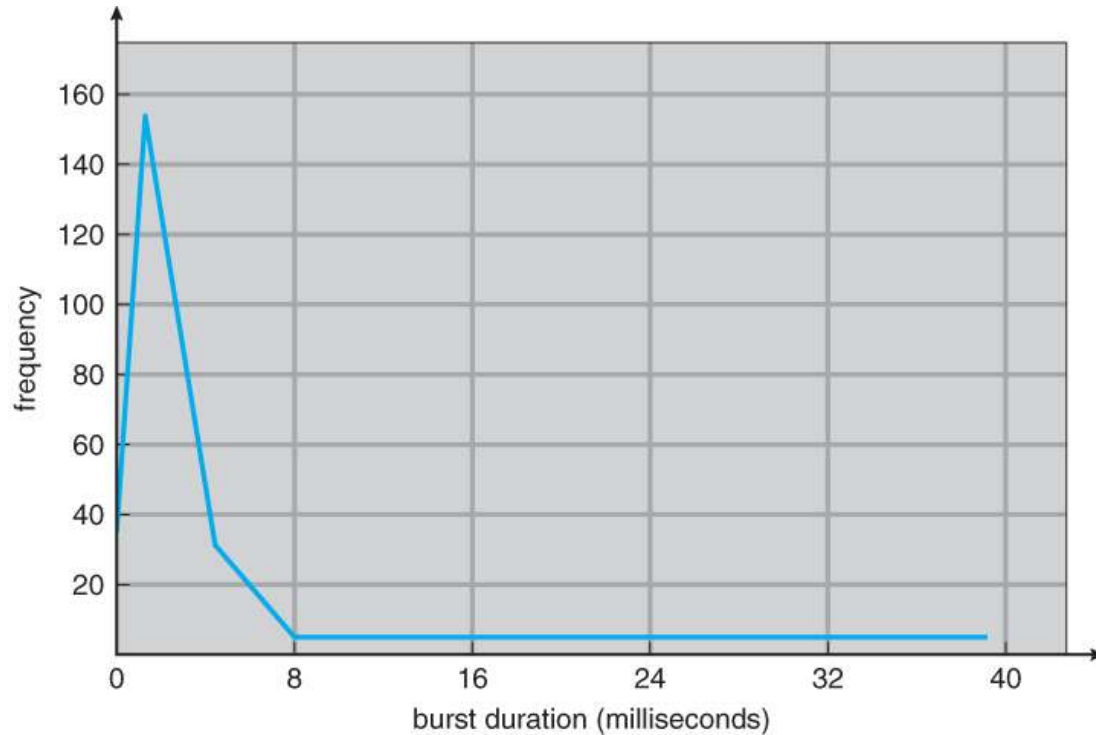
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I/O burst → waiting for data transfer in or out of the system

CPU Burst Cycle: Frequency Pattern

Highly skewed distribution

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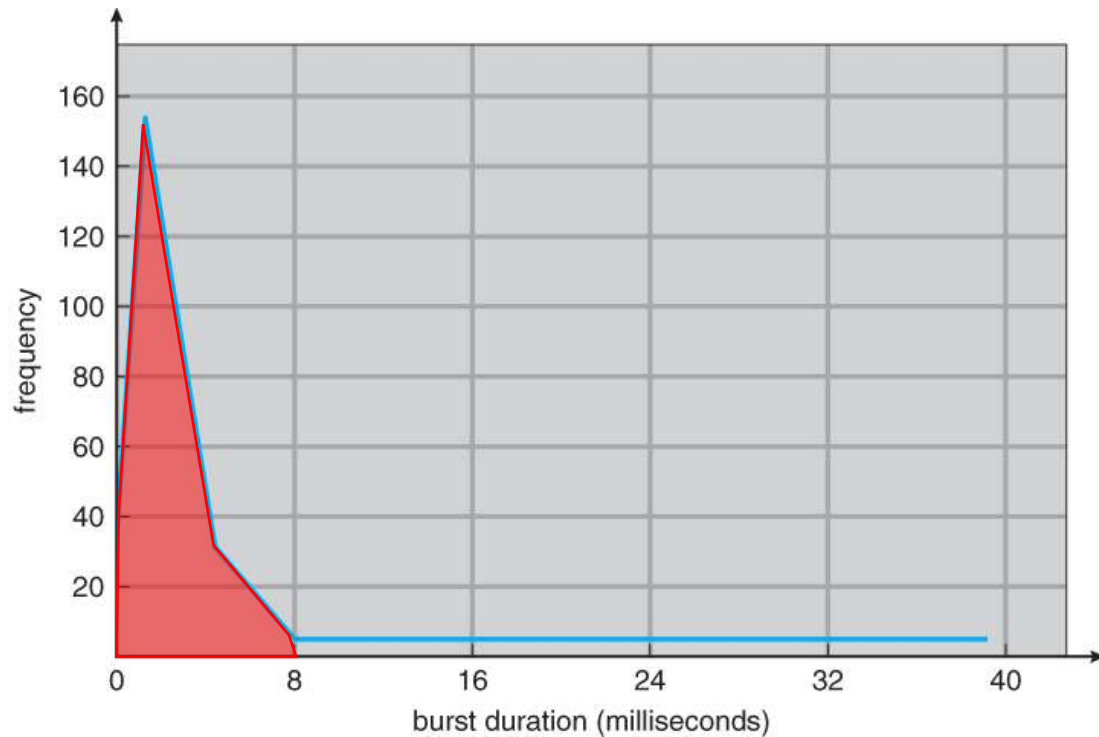
Highly skewed distribution

The vast majority of processes have short CPU bursts

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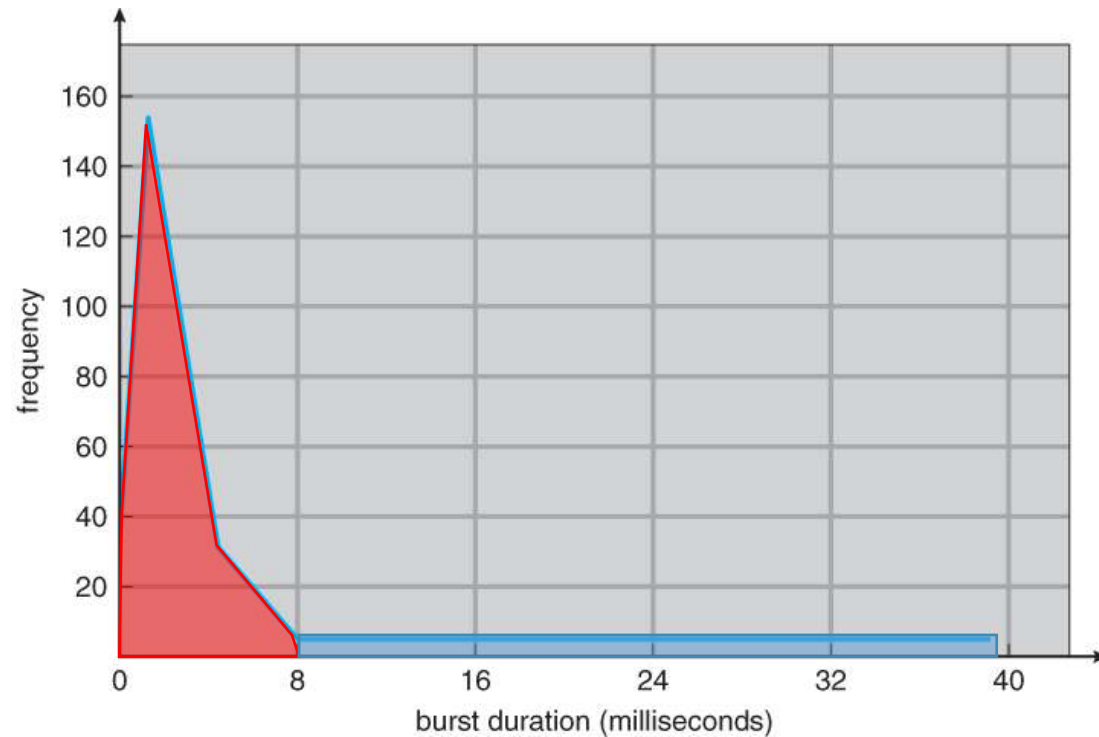
Highly skewed distribution

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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CPU Scheduler

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- The data structure for the ready queue and the algorithm used to select the next process are not necessarily based on a FIFO queue

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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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1. When a process switches from the running state

   to the waiting state

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

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1. When a process switches from the running state

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2. When a process switches from the running state

   to the ready state

   in response to an interrupt

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3. When a process switches from the waiting state

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after I/O completion
or a return from `wait`

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

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   to the waiting state

2. When a process switches from the running state
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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:

  - the kernel is busy implementing a system call (e.g., updating critical kernel data structures)

  - two processes share data, one may get interrupted in the middle of updating shared data structures

Preemption: Issues

- Possible countermeasures:

  - Make the process wait until the system call has either completed or blocked before allowing the preemption

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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:

  - Switching context

  - Switching to user mode

  - Jumping to the proper location in the newly loaded program

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- 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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> NOTE
> I/O waiting time is **not** considered here!

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

  - Tournaround time

  - Waiting time

  - Response time

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  May range from 10 per second to 1 per hour

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> Mostly, for interactive processes

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minimize

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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  - Users are more accepting of a consistent predictable system than an inconsistent one

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- Maximize throughput translates into:

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Typical of batch systems

A Quick Note on Terminology

JOB/TASK

General unit of CPU execution

A Quick Note on Terminology

JOB/TASK

PROCESS

A Quick Note on Terminology

JOB/TASK

PROCESS

Actual **unit** of CPU execution

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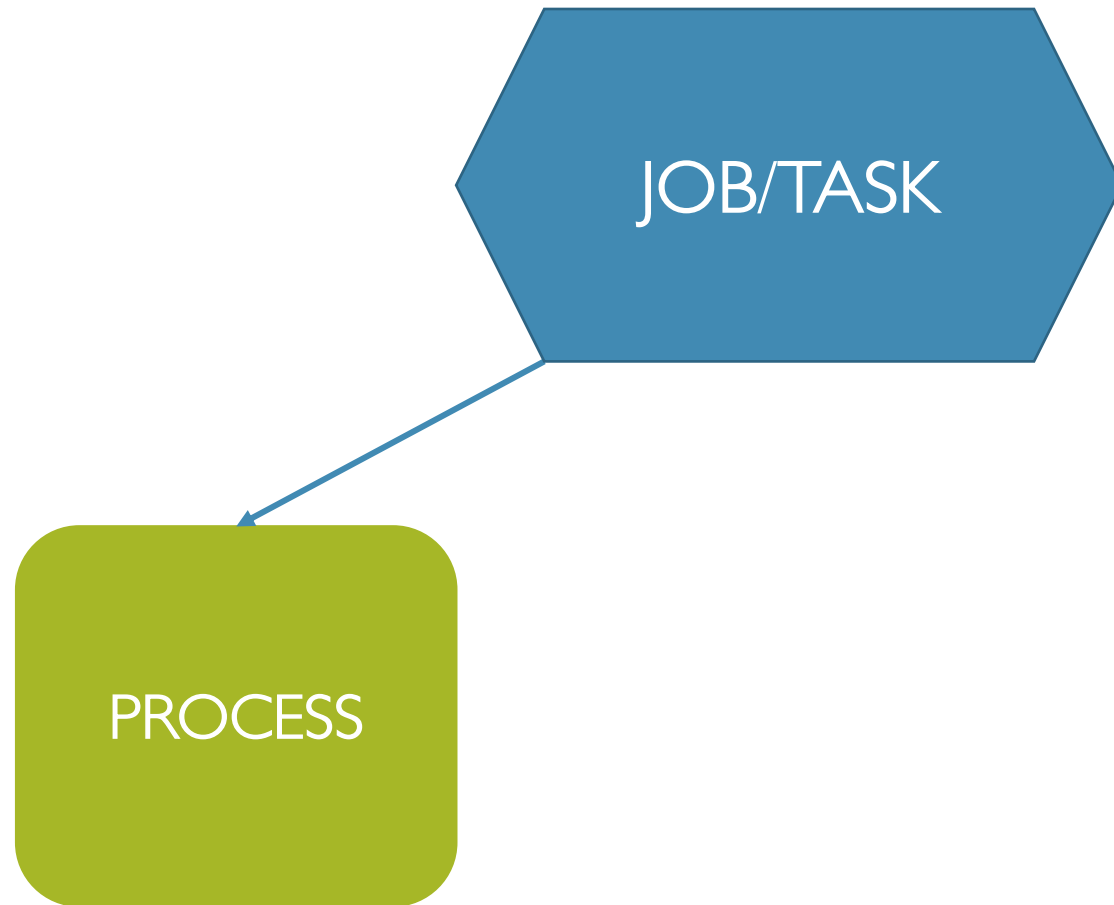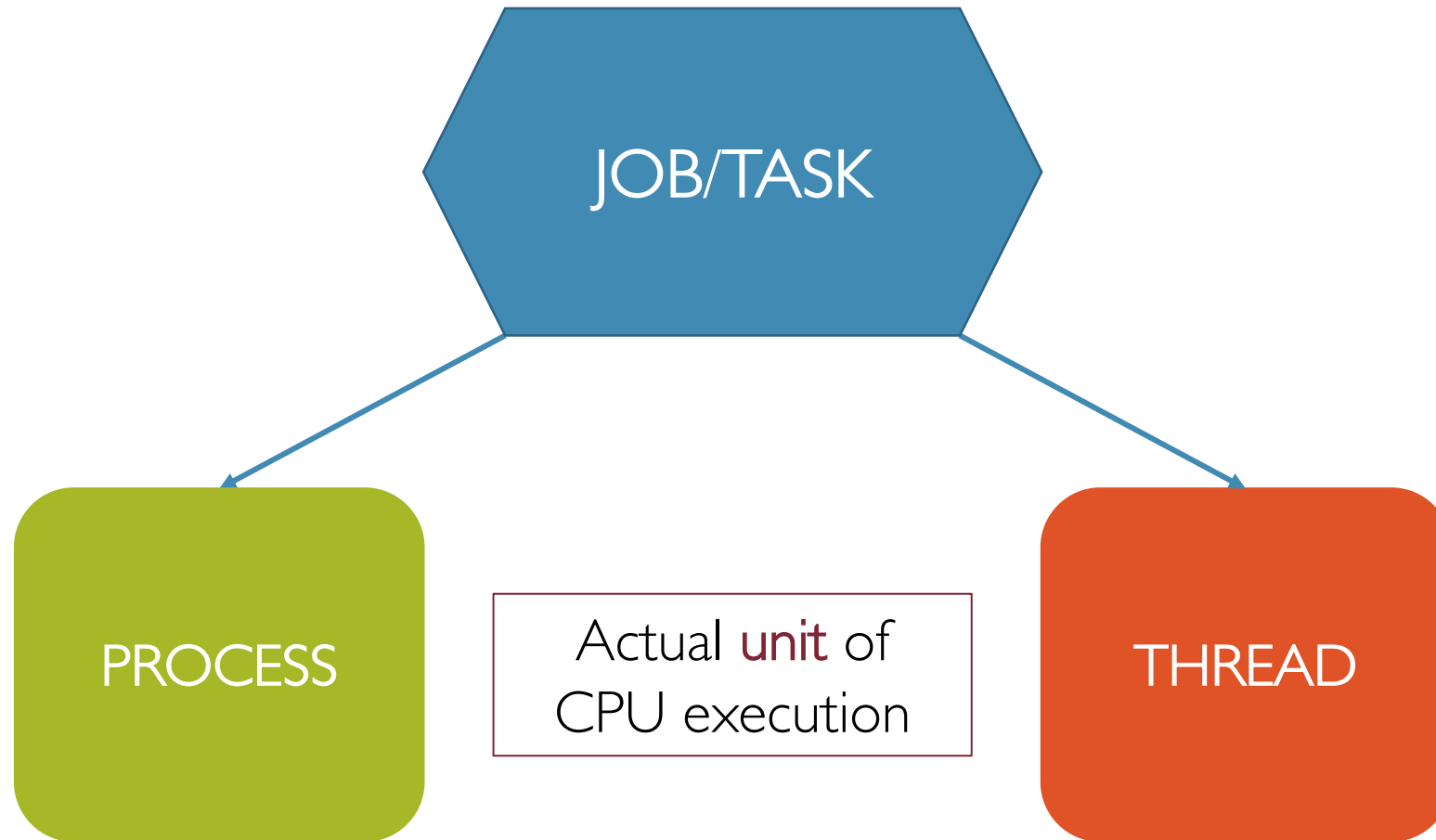
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> We will talk about threads very soon but for now most of the things we will be discussing remain valid even on a multi-threaded system

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

- 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

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New A B C

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Arrival time = 0 for all*

No I/O burst

* Actually, in this example, A arrives first, then B, and finally C comes: arrival time differences are considered negligible

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

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

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

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

A

0   5

time

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

New A B C

Ready C

Waiting

Running B

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

0   5   7   time

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

New A B C

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

Ready

Waiting

Running C

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

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

$\overline{T}^{waiting}$ = avg. waiting time $= \dfrac{1}{N} \sum\limits_{i=1}^{N} (T_i^{turnaround} - T_i^{burst})$

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

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

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

New   A B C

Ready

Waiting

Running

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

0   5   7   10   time

avg. waiting time =

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| A | B | C |

0   5   7   10   time
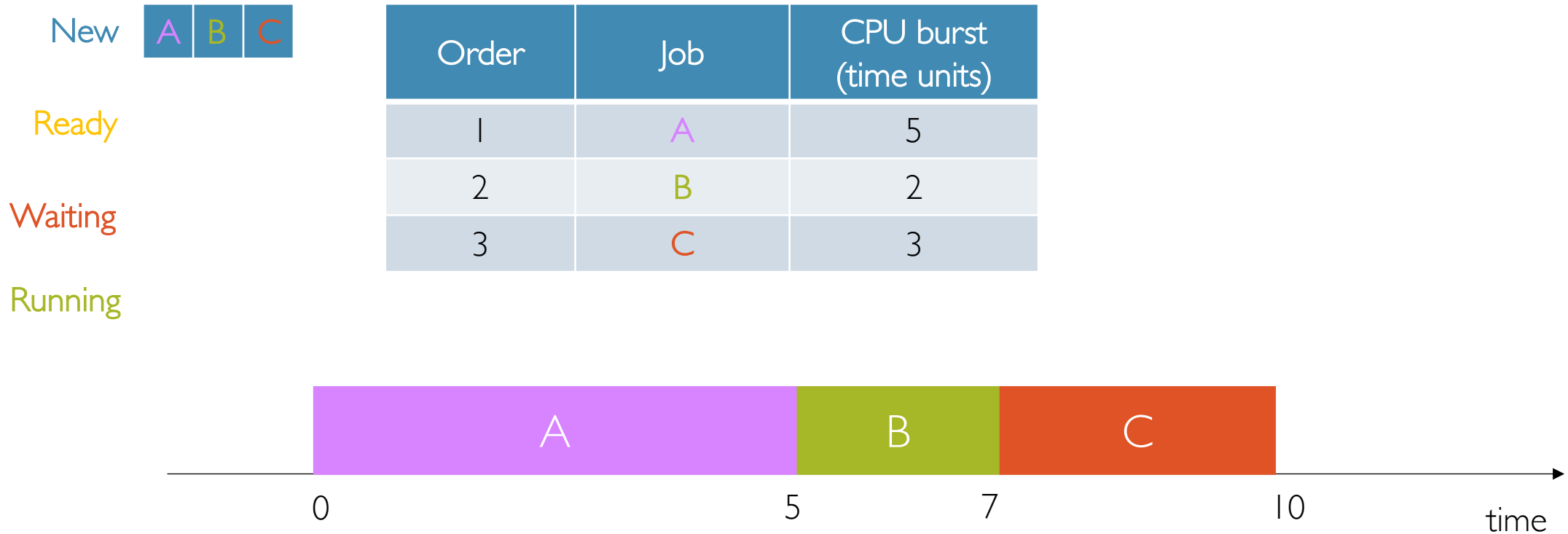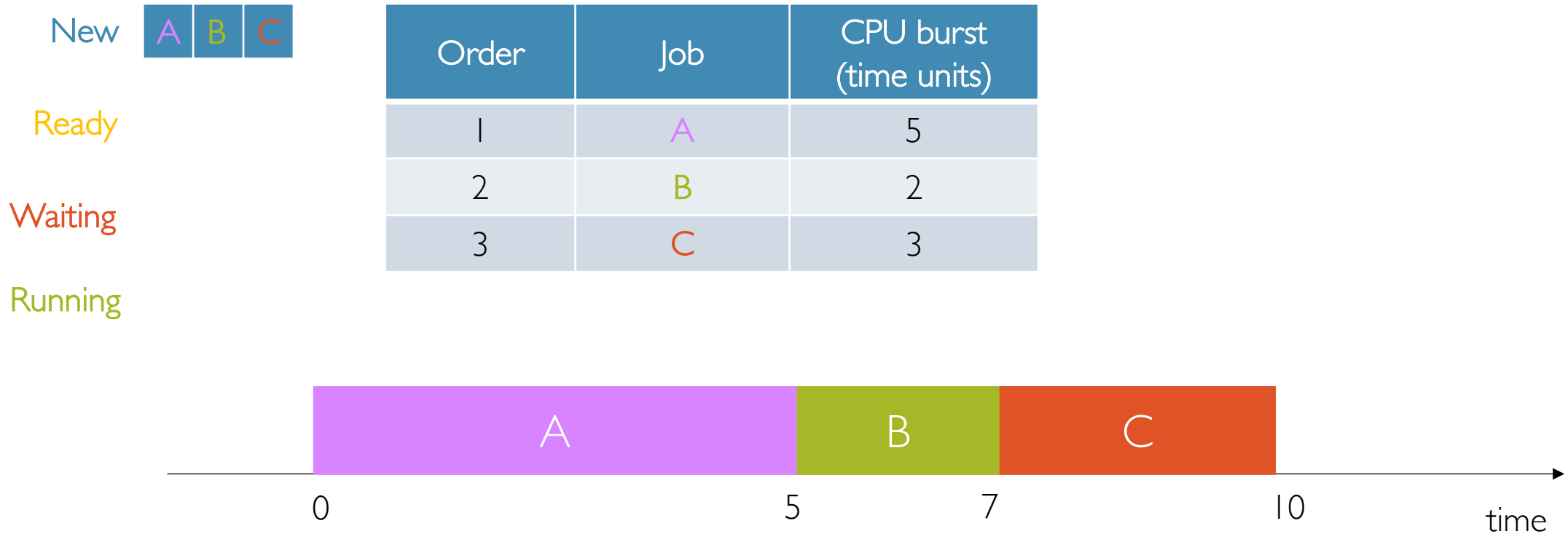
avg. waiting time = $(0 + 5 + 7)/3 = 4$

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
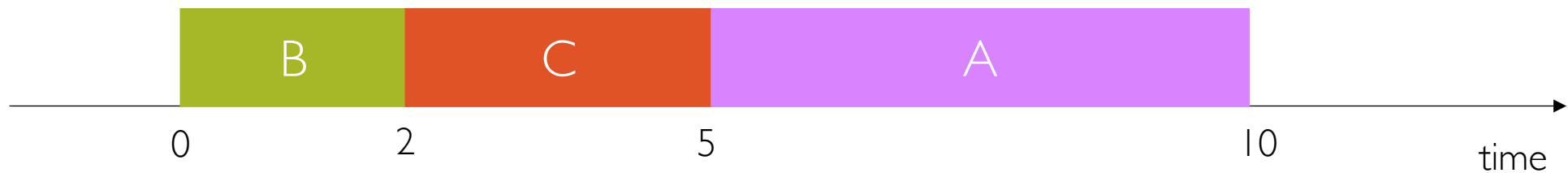
No I/O burst

avg. waiting time =

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

New   B   C   A

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

B (0–2)   C (2–5)   A (5–10)

0   2   5   10   time
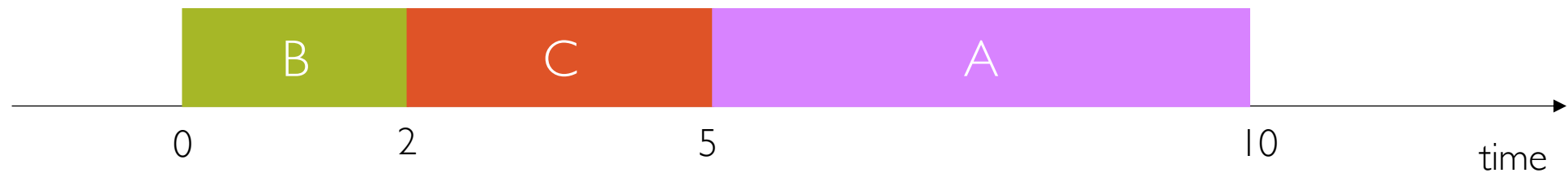
avg. waiting time = (5 + 0 + 2)/3 ~ 2.3

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

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A does also I/O

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

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

A does also I/O

A

0   2

time

↑
I/O starts

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

A   B   A

0   2   4   7   time

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

A B A

0   2   4   7
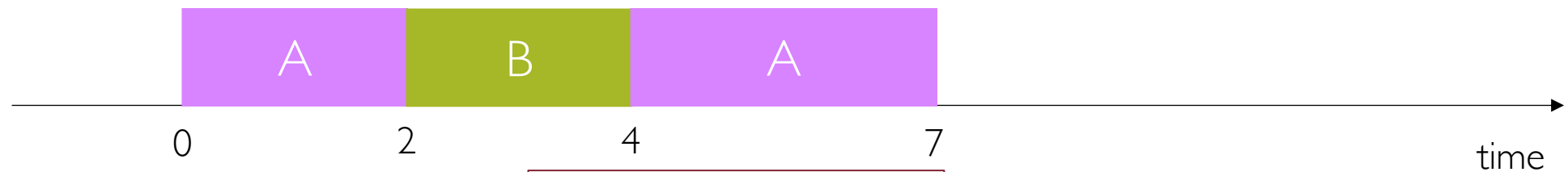
time

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

| A | B | A |

0   2   4   7

time

Why A and not C?

Because the FCFS scheduler cares only about the arrival time on the ready queue

First-Come-First-Serve (FCFS): Scenario III
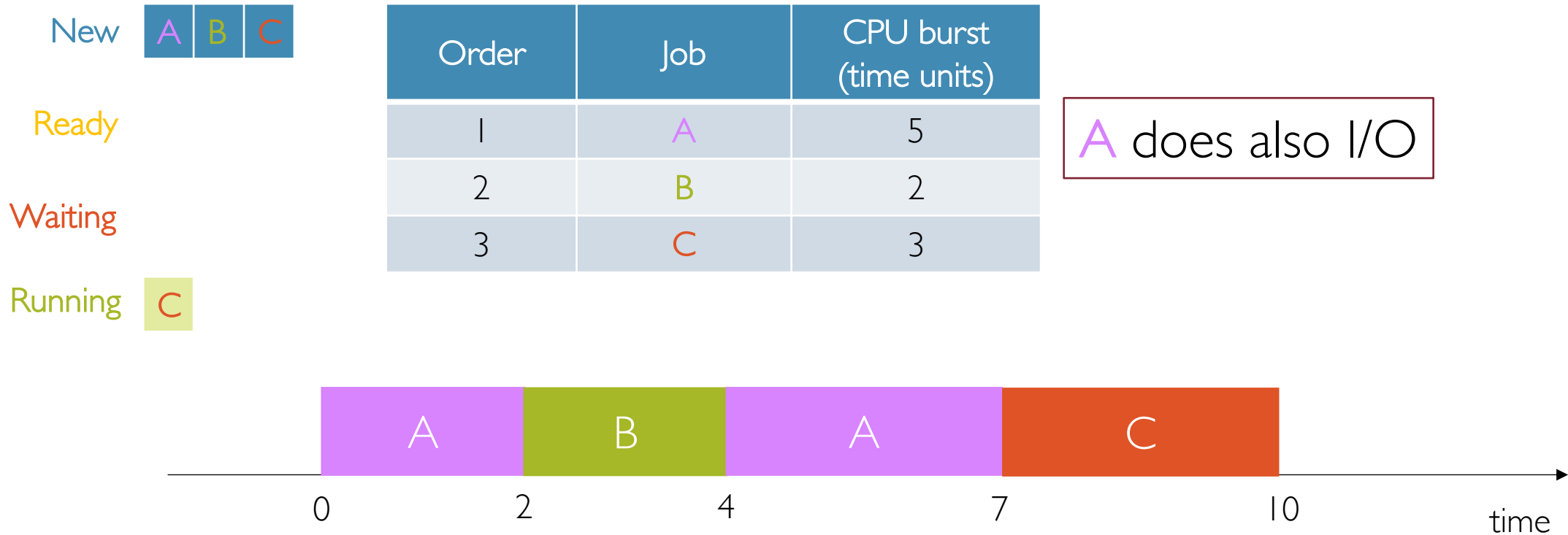
New: A B C

Ready

Waiting

Running: C

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

A does also I/O

A	B	A	C

0   2   4   7   10   time

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

New A B C

Ready

Waiting

Running

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

A does also I/O

A	B	A	C

0   2   4   7   10   time

avg. waiting time =

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

New   A B C

Ready

Waiting

Running

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

A does also I/O

A	B	A	C

0   2   4   7   10   time
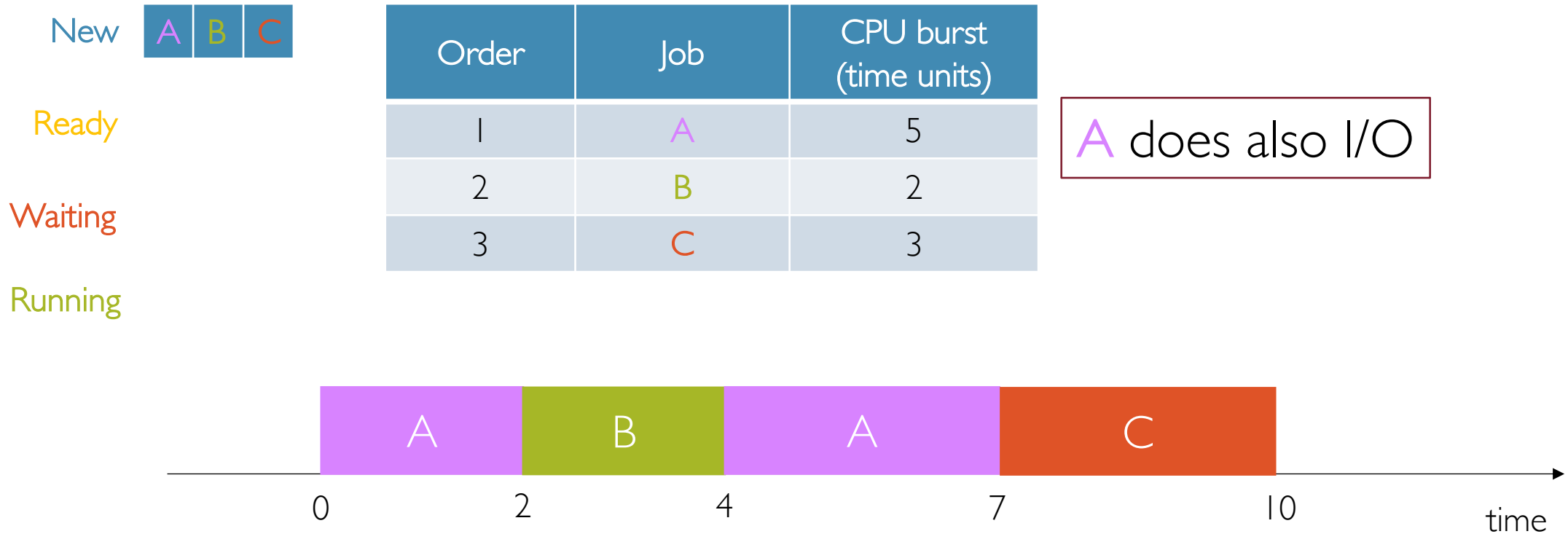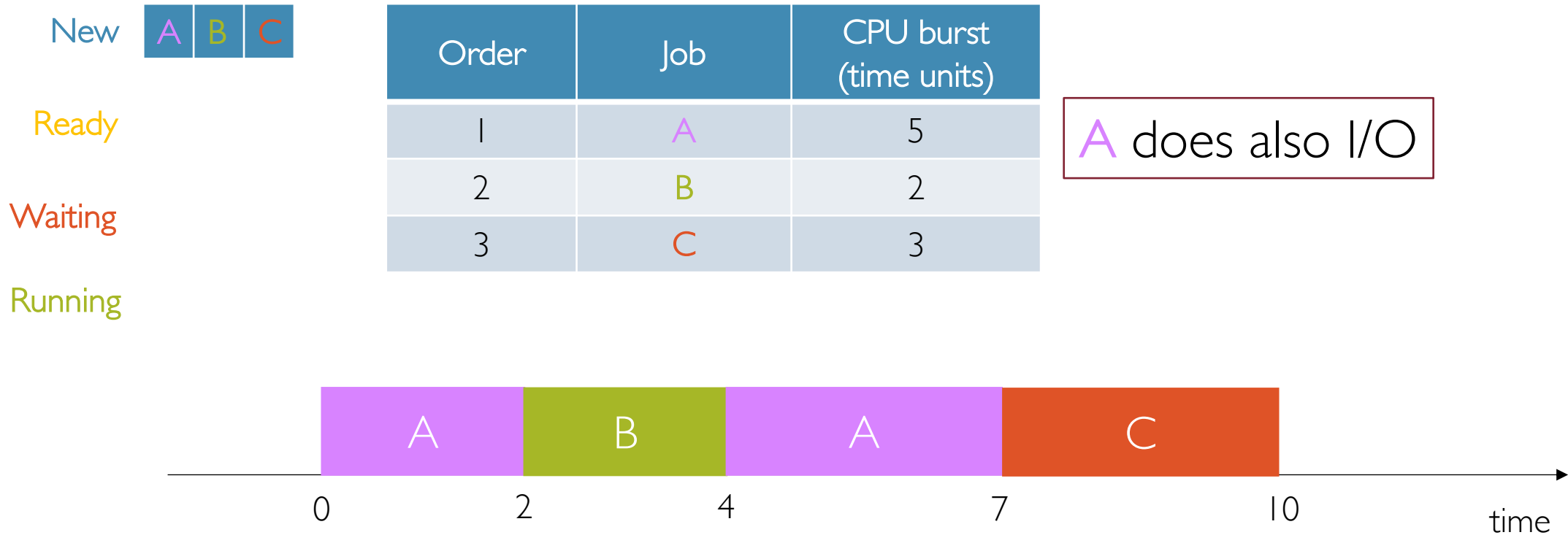
avg. waiting time = (2 + 2 + 7)/3 ~ 3.7

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

New [A B C]

Ready

Waiting

Running

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

A does also I/O

A	B	A	C
0   2   4   7   10   time
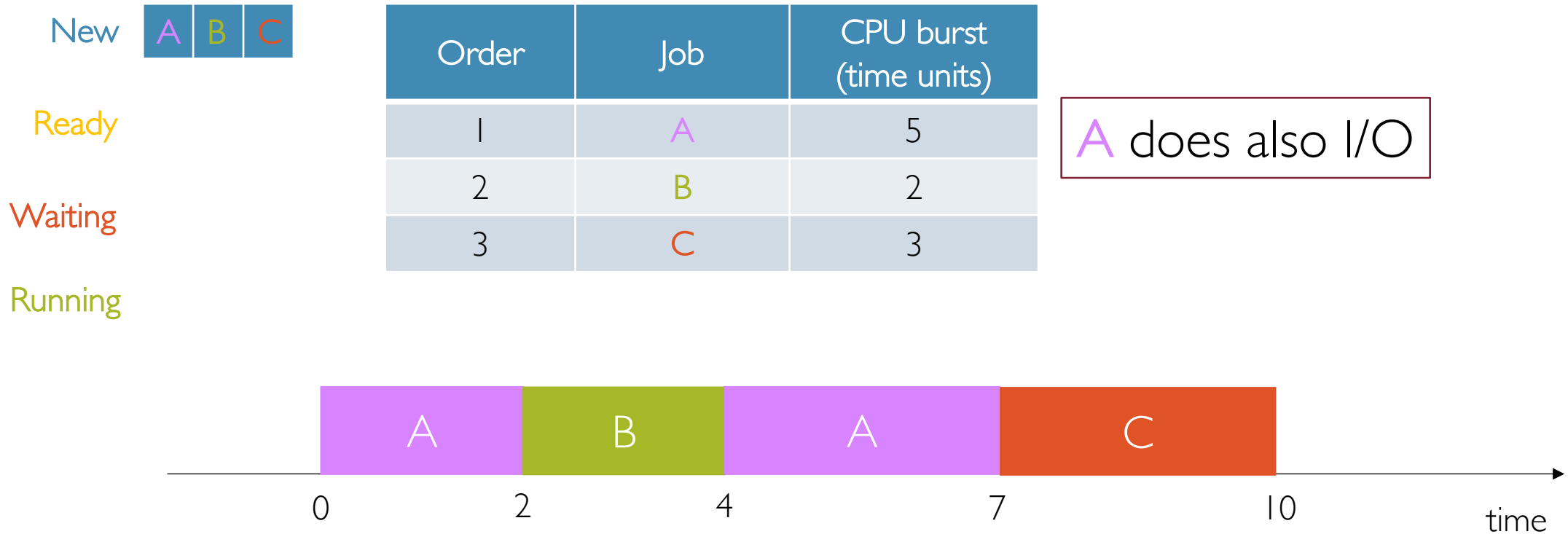
NOTE:
We should remove from A's waiting time the time it spent doing I/O

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

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

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

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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

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

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Round Robin (RR): The Time Quantum

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

- 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÷100 msec. and context switch = 0.01÷0.1 msec.

Round Robin (RR): The Time Quantum

process time = 10
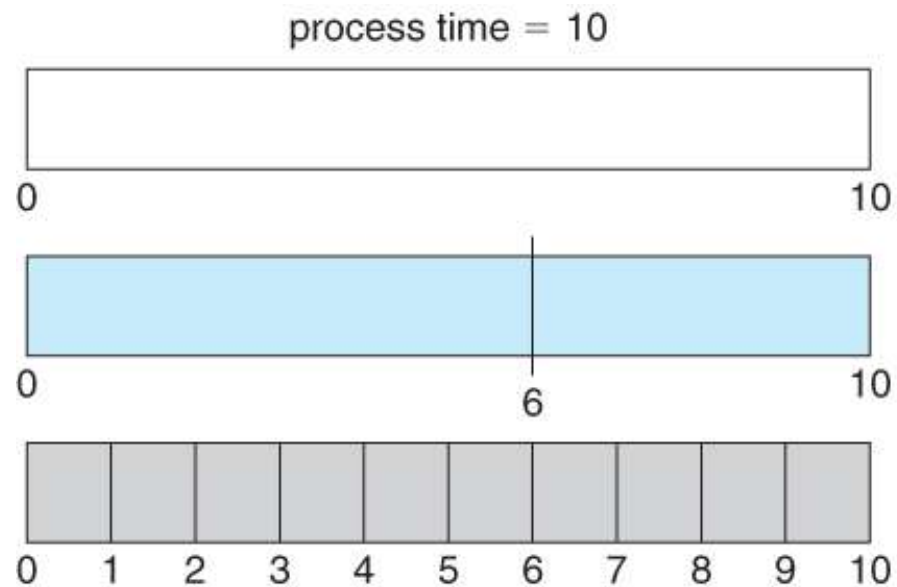
quantum	context switches
12	0
6	1
1	9

By decreasing the time quantum the number of context switches increase

Round Robin (RR): The Time Quantum

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

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

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

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

New A B C

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
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

A

0   2   time

Round Robin (RR): Example

New A B C

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

Ready B C

Waiting

Running A

A

0   2

timer
interrupt

time

Round Robin (RR): Example

New `A` `B` `C`

Ready `C` `A`

Waiting

Running `B`

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

timeline showing A from 0 to 2, B from 2 to 4, with time axis marked 0, 2, 4; timer interrupt at 4

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

0   A   2   B   4   C   6   time

timer interrupt

Round Robin (RR): Example

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 | B | C | A |

0   2   4   6   8   time

timer interrupt

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

A	B	C	A	C

0　　　2　　　4　　　6　　　8　9　　　time

C finishes

Round Robin (RR): Example

New
A B C

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

Ready

Waiting

Running A

| A | B | C | A | C | A |

0   2   4   6   8 9   10   time

A finishes

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

A	B	C	A	C	A

0   2   4   6   8 9 10

time

avg. waiting time =

Round Robin (RR): Example

New   A B C

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

Ready

Waiting

Running

A	B	C	A	C	A

0   2   4   6   8 9   10   time
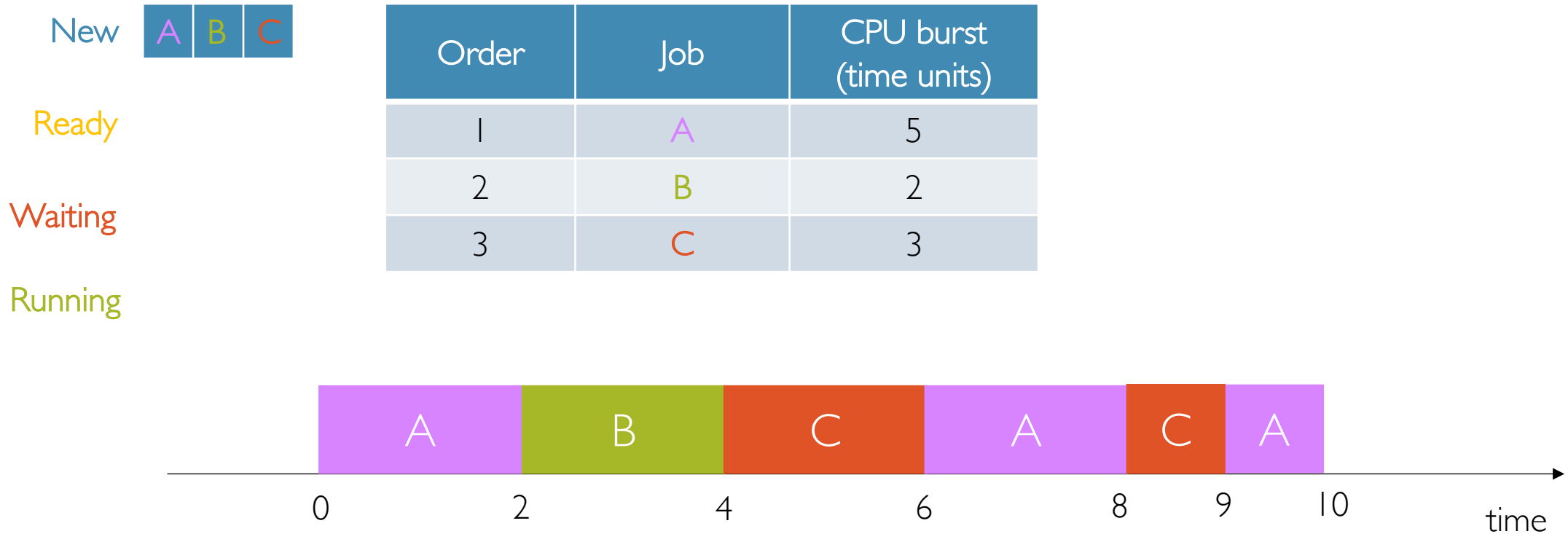
avg. waiting time = (5 + 2 + 6)/3 ~ 4.3

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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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!

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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)

Job	CPU burst	turnaround time		waiting time	
		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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- 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)