Operating Systems
Process/Thread Scheduling

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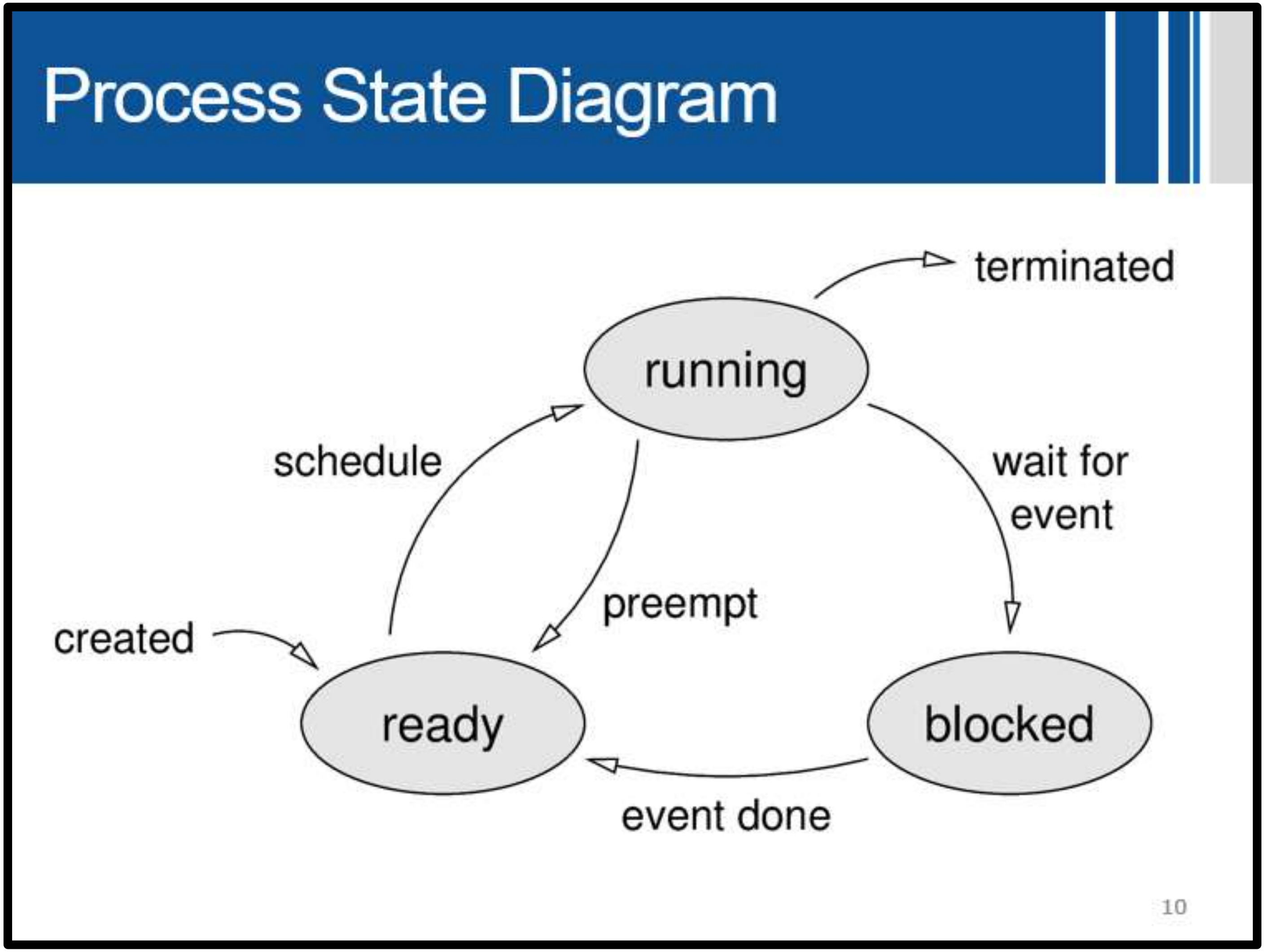
Schedulers are Everywhere

Every time a resource has more than one user, we need a scheduler to decide who is served next

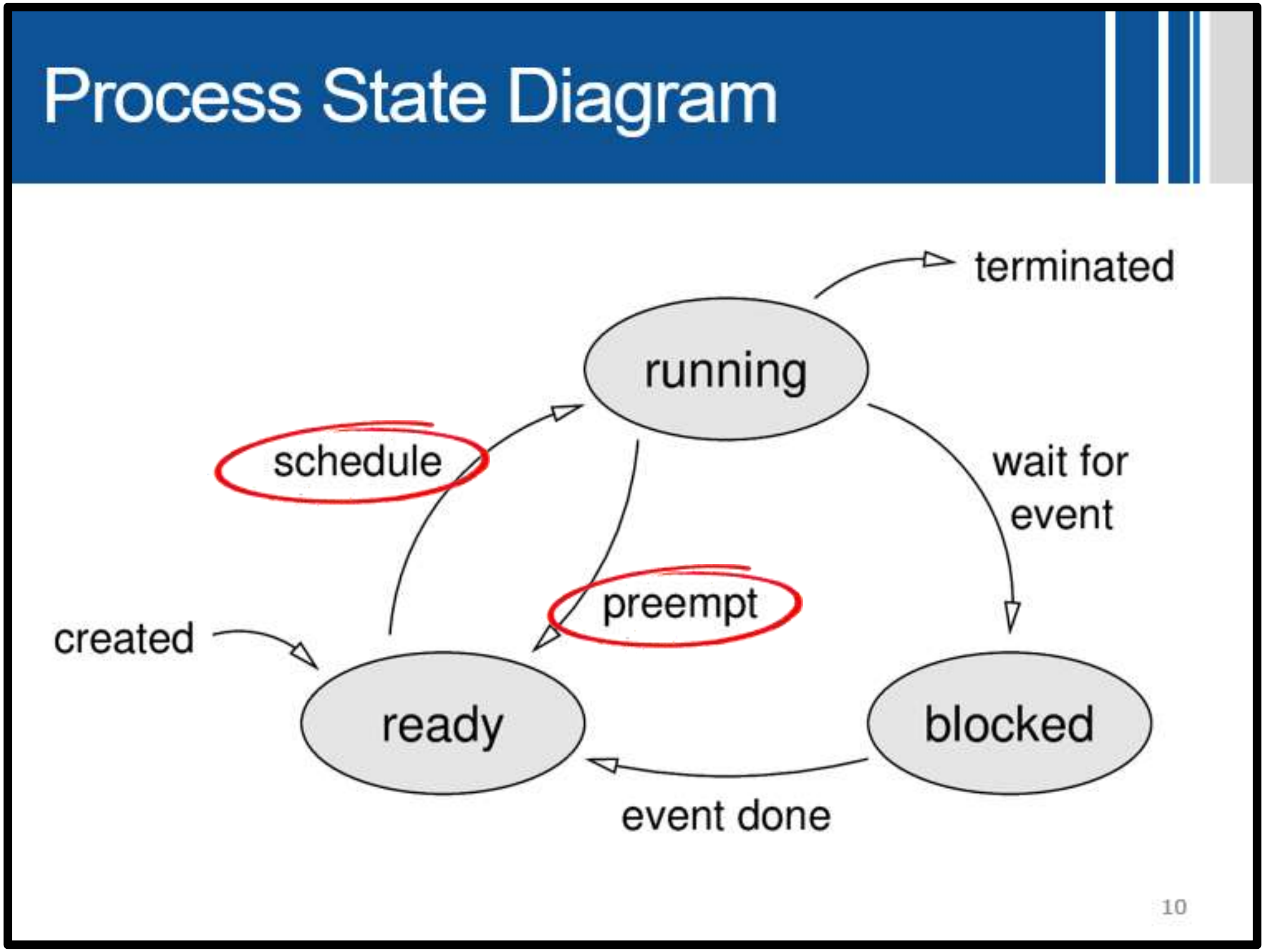
- **CPU Scheduler** (short-term scheduler)
- Mid/long-term scheduler (loading into memory)
- Scheduling jobs in the print queue
- Scheduling requests to I/O devices (e.g. disk scheduler)
- Packet Schedulers in computer networks
- Scheduling requests in a web-server
- Scheduling in a supermarket/post office

Recall…



Process State Diagram
terminated
running
schedule
wait for
event
preempt
created
ready
blocked
event done
10

Recall…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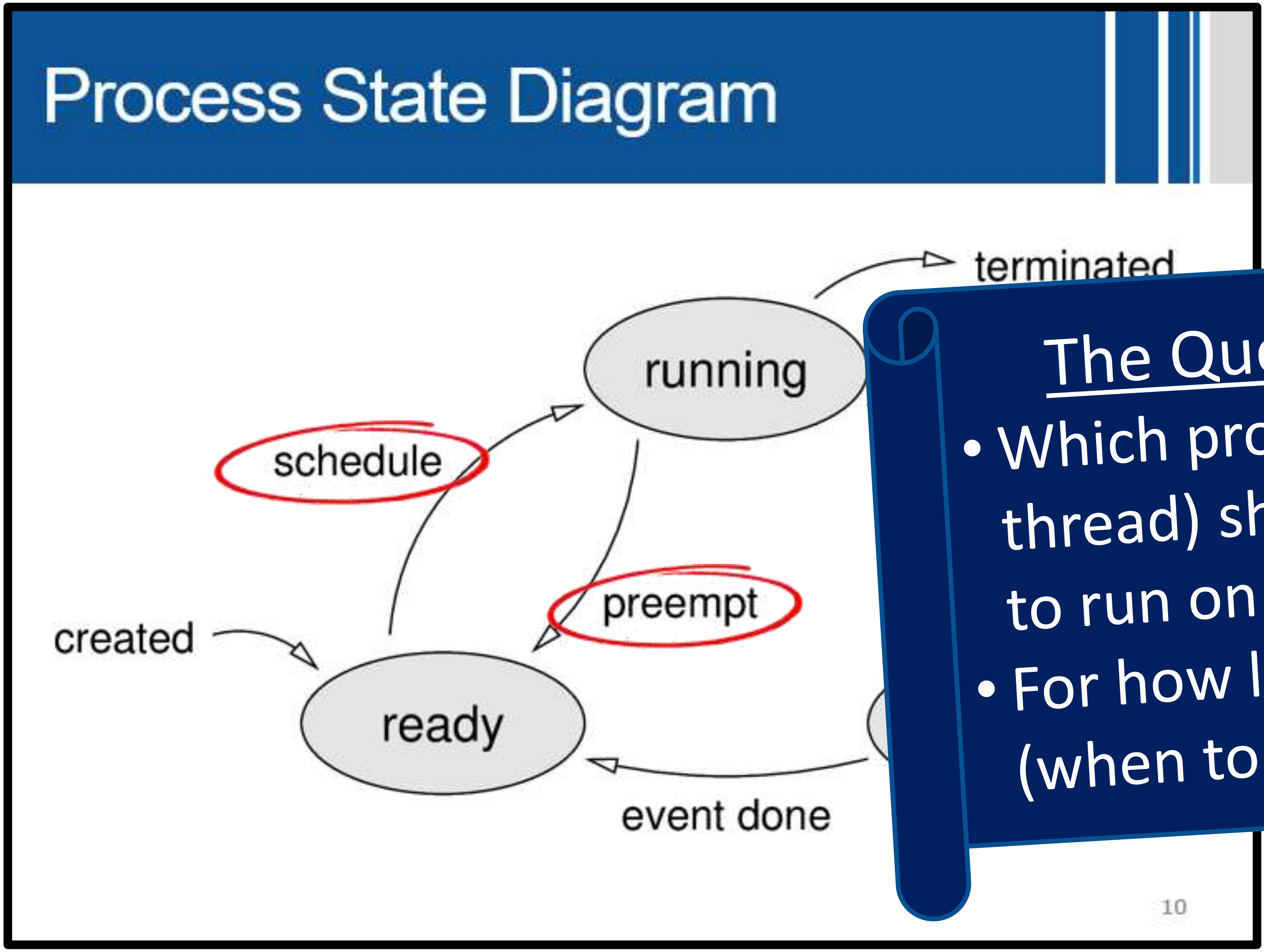

The Question:

- Which process (or thread) should get to run on the CPU?
- For how long? (when to preempt?)

A Scheduler and a Dispatcher

- **CPU Scheduler:** Decide which process should run on the CPU (and sometimes for how long)
  - "Short-term scheduling": tens/hundreds of times a second
- **Dispatcher:** The module responsible for executing the CPU scheduler decisions:
  - Context switch
  - Switching back to user mode

A Scheduler and a Dispatcher

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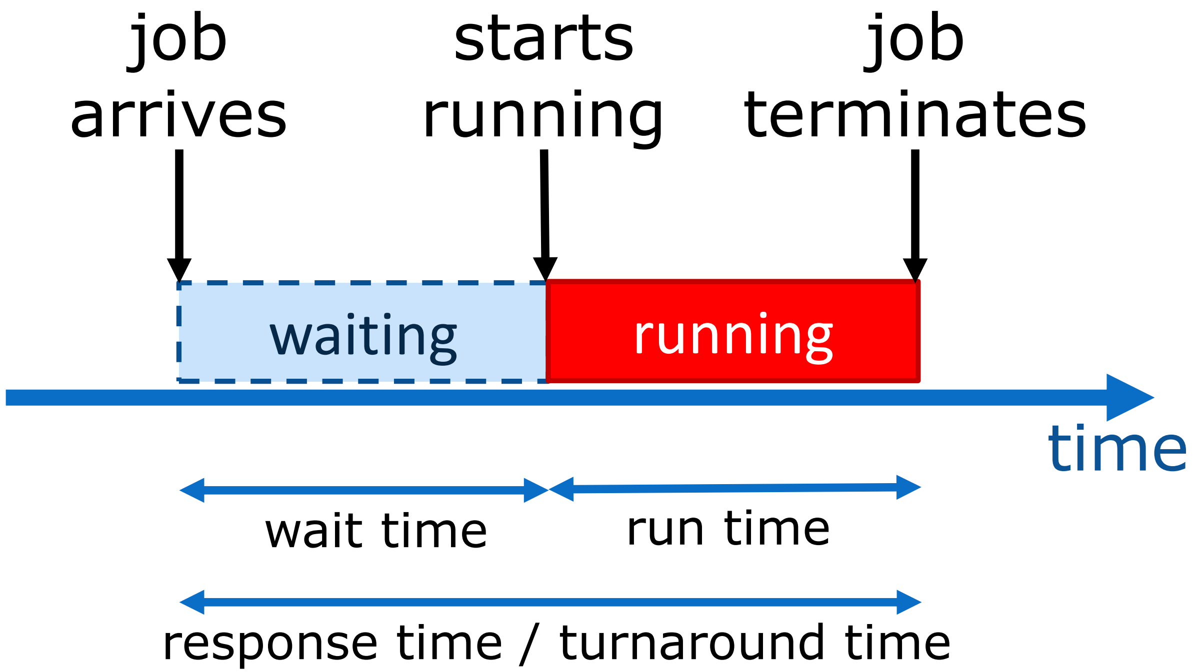
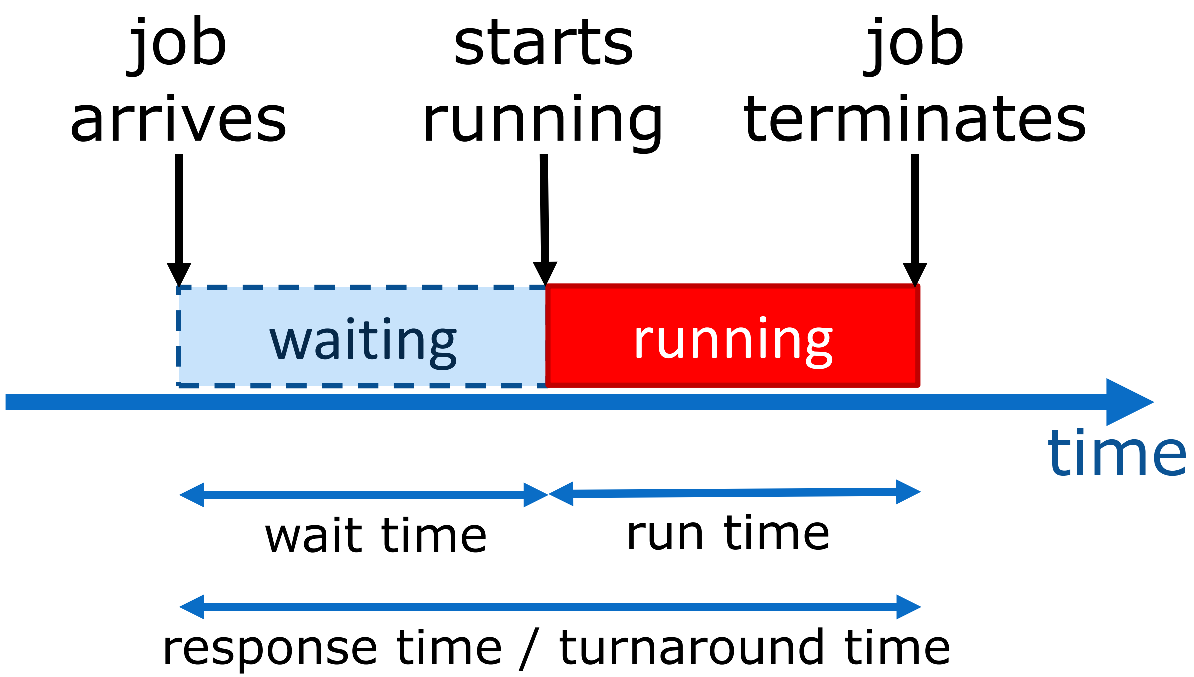
Ex2

Job Timeline

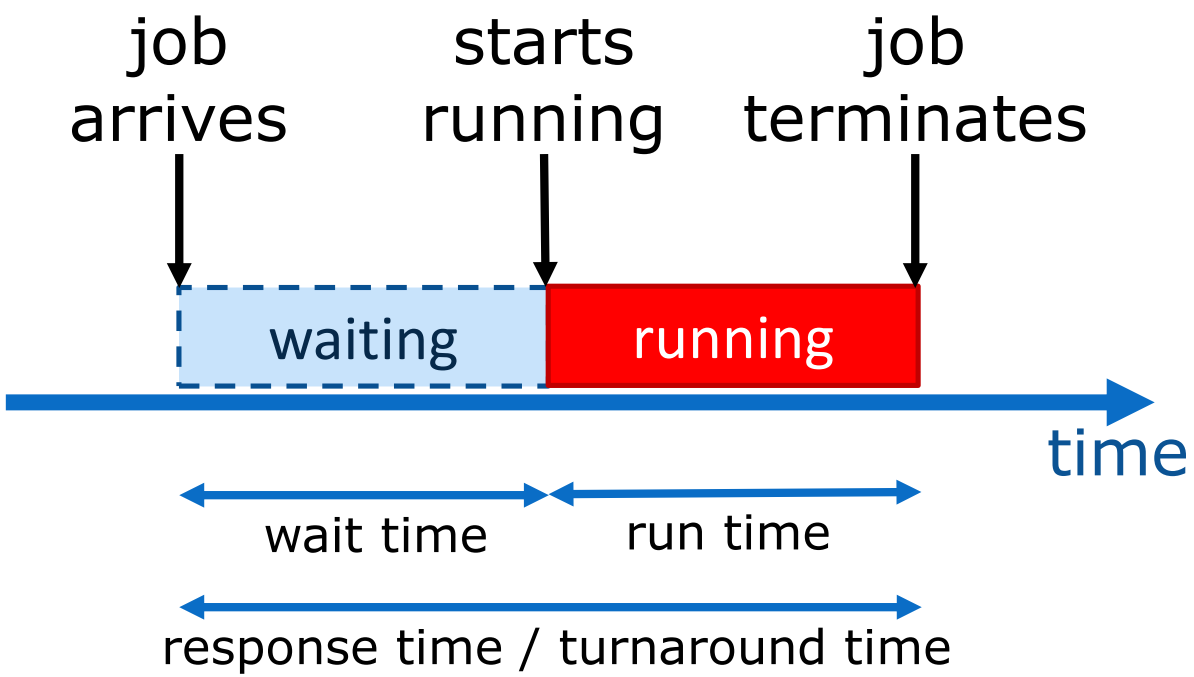


Job Timeline



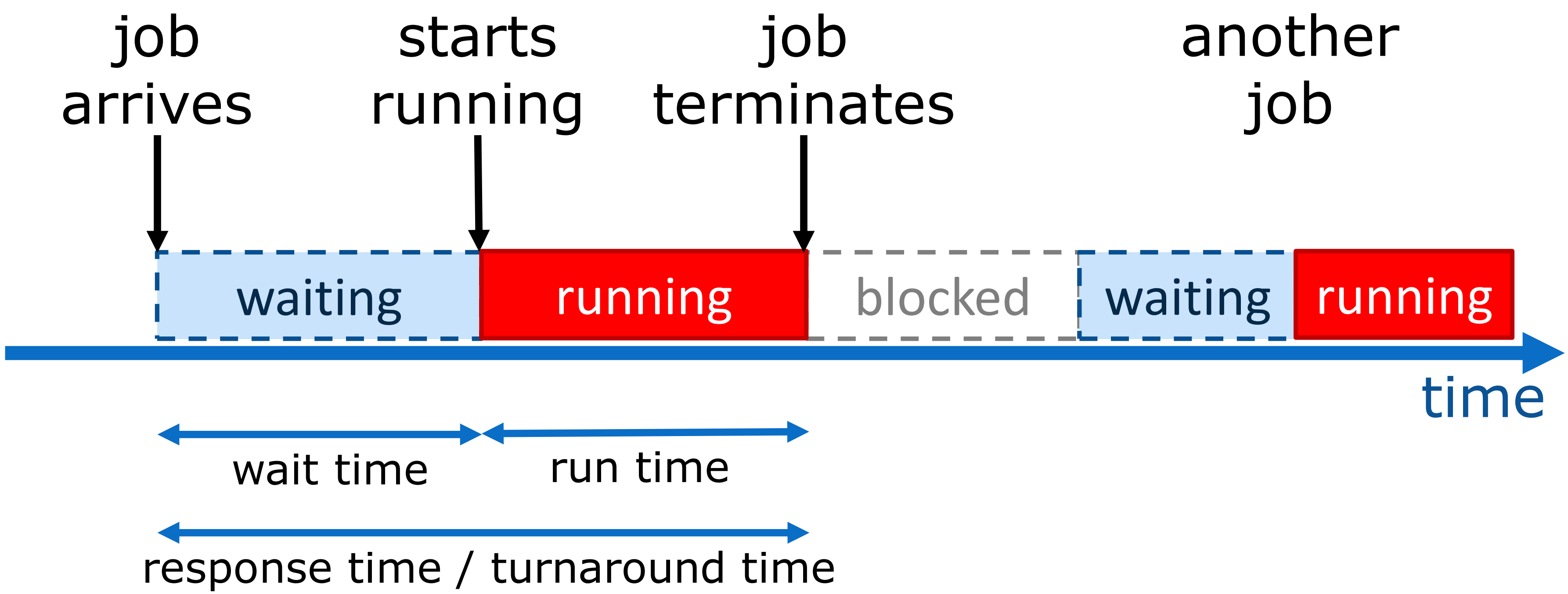
- A process in the "ready" state is waiting for the CPU

Job Timeline



- A process in the “ready” state is waiting for the CPU
- A process in the “running” state is using the CPU

Job Timeline



- Interactive (reactive) programs have multiple CPU bursts – one after each event
- Or perform I/O operations separated by CPU bursts
- We (usually) treat them as independent jobs

Scheduling Framework

A scheduler is an algorithm

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- What is the input?

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- What is the input?

The jobs to schedule

Scheduling Framework

A scheduler is an algorithm

- What is the input?

The jobs to schedule

- What is the output?

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A scheduler is an algorithm

- What is the input?
- What is the output?

The jobs to schedule

A decision which job to run now

Scheduling Framework

A scheduler is an algorithm

- What is the input?
- What is the output?
- What is the objective?

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“Good performance”

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- What is the output?
- What is the objective?
- What are the available actions?

The jobs to schedule

A decision which job to run now

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Scheduling Framework

A scheduler is an algorithm

- What is the input?
- What is the output?
- What is the objective?
- What are the available actions?

The jobs to schedule

A decision which job to run now

“Good performance”

Can we preempt?

Many Different Objectives

Many Different Objectives

- **Low Response Time**: Total time it takes to complete a job (wait time + run time)
  – What users care about
  – Not everything is in the scheduler's control…
- **Low Wait Time**
  – This *is* what the scheduler controls
- **Low Slowdown:** how much slower the system appears to be

(response time) / (run time)

Many Different Objectives

- **High Throughput:**

  (# completed jobs) / (time unit)

  - If the system is stable, this is equal to (# started jobs) / (time unit)
- **High CPU Utilization**: Fraction of time the CPU is busy
  - Not counting overhead

Many Different Objectives

- **High Throughput:**
  (# completed jobs) / (time unit)
  - If the system is stable, this is equal to (# started jobs) / (time unit)
- **High CPU Utilization**: Fraction of time the CPU is busy
  - Not counting overhead
- Actually determined by the arrival process!
- Both limited when system is overloaded

Other Objectives

- **Fairness:**
  - Give users their **fair share**
    - What if they don't need their fair share?
  - Avoid job **starvation**
    - Is this a problem in a stable system?
  - Support user/job **priorities**
    - Who sets the priorities?
- We'll typically assume equal shares and priorities

The Objectives Might Contradict Each Other

- To optimize throughput: run jobs to completion to reduce overhead (time wasted due to context switches)

- To optimize response time: schedule each new job as soon as possible, even if this leads to overhead due to context switching

The Objectives Might Contradict Each Other

- To optimize throughput: run jobs to completion to reduce overhead (time wasted due to context switches)

What are the right objectives for me?

- To optim ... each new job ... his leads to overhead due to context switching

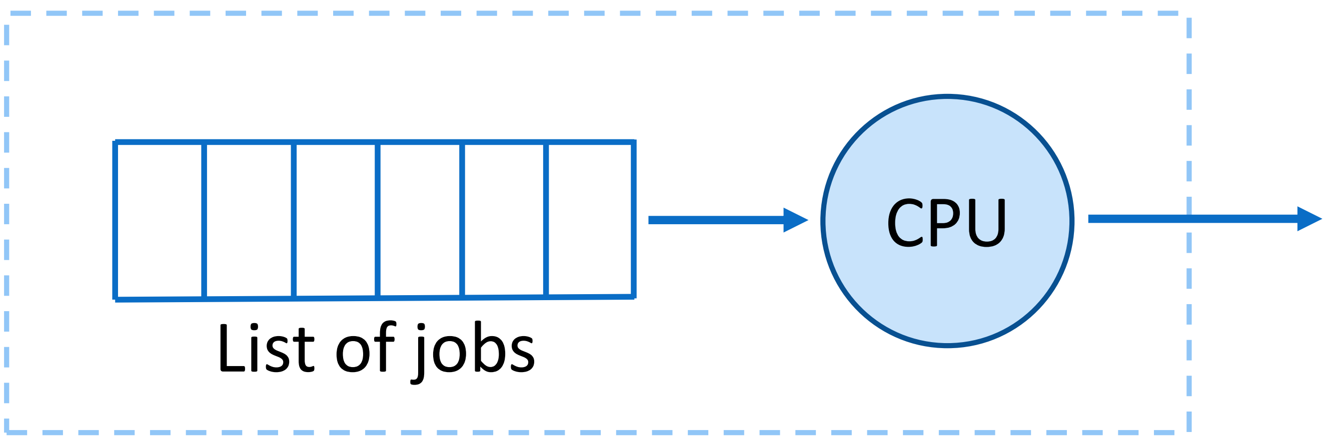
OFF-LINE ALGORITHMS

On-Line vs. Off-Line

- Off-line: get all the input at the outset
  - What you are used to
- On-line: get the input piecemeal
  - At every instant you just get part of the input
  - Need to produce partial/tentative output (make partial tentative decisions) based on your current knowledge of the input
  - May change/regret it later

System Model

- All jobs are given in advance
  - No additional arrivals
- Job runtimes are known in advance



Baseline Scheduler: First Come First Serve (FCFS)

Input:

Job	Runtime
P1	17
P2	2
P3	3

Baseline Scheduler:
First Come First Serve (FCFS)

Schedule:

Job	Runtime	Wait time	Response time
P1	17	0	17
P2	2	17	19
P3	3	19	22

Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Runtime	Wait time	Response time
P1	17	0	17
P2	2	17	19
P3	3	19	22

Average waiting time: (0+17+19)/3=12
Average response time: (17+19+22)/3=19.33
Throughput: 3 / 22 = 0.136

Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Runtime	Wait time	Response time
P1	17	0	17
P2	2	17	19

FCFS suffers from a "convoy effect": short jobs get stuck behind long ones

3

0 22

Average waiting time: (0+17+19)/3=12
Average response time: (17+19+22)/3=19.33
Throughput: 3 / 22 = 0.136

How Can We Improve?

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Put the short job before the long job!

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Put the short job before the long job!

Average wait time was: (0+7)/2=3.5
New average wait time: (0+4)/2=2

Average response time was: (7+11)/2=9
New average response time: (4+11)/2=7.5

Throughput was: 2 / 11 = 0.182
New throughput: 2 / 11 = 0.182

How Can We Improve?

Put

NOTE:

This applies **every time** a short job comes after a longer one

Av

New ave

Average response time was: (7+11)/2=9

New average response time: (4+11)/2=7.5

Throughput was: 2 / 11 = 0.182

New throughput: 2 / 11 = 0.182

Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Runtime	Wait time	Response time
P2	2	0	2
P3	3	2	5
P1	17	5	22

Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Runtime	Wait time	Response time
P2	2	0	2
P3	3	2	5
P1	17	5	22

Average waiting time: (0+2+5)/3=2.33 (was 12)
Average response time: (2+5+22)/3=9.67 (was 19.3)
Throughput: 3 / 22 = 0.136 (same)

SJF Notes

- SJF works in an **offline** setting
- SJF aims to optimize the **average waiting time**

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- **Can preemption help? No.**
- **What about average response time?**

SJF Notes

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- SJF aims to optimize the **average waiting time**

- **Can we do better?** **No. SJF is optimal.**
- **Can preemption help?** **No.**
- **What about average response time?**

  Also optimal.

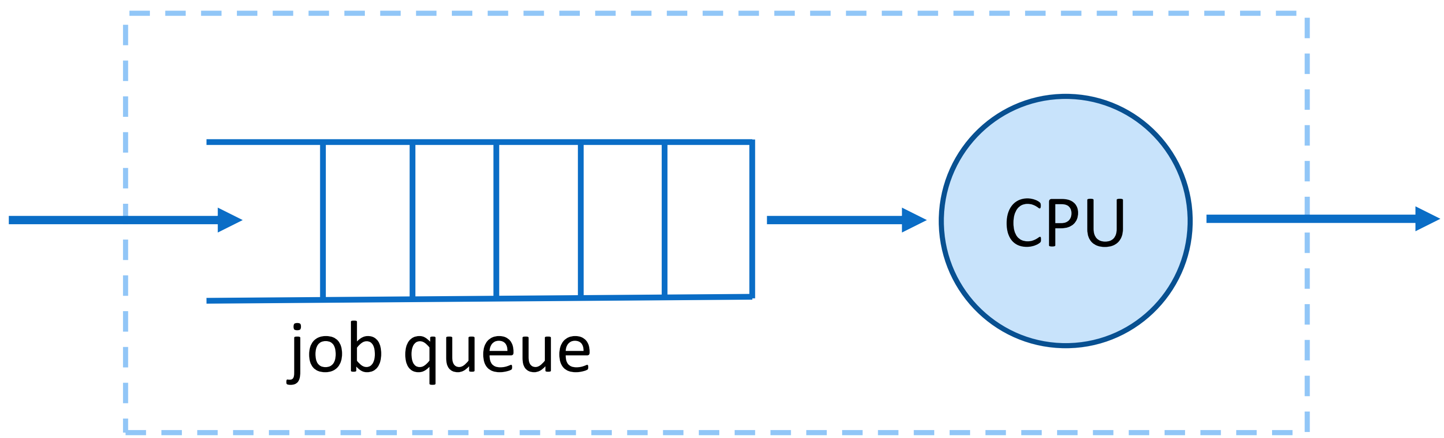
Optimality Proof

1. Assume a schedule S has the optimal (lowest) average wait time
2. If S is *not* SJF, there are a pair of jobs such that $p_i.runtime > p_{i+1}.runtime$
3. Switching these jobs reduces their contribution to the average, without changing anything else
4. Contradiction to assumption that S is optimal

ON-LINE ALGORITHMS

System Model I (simplified)

- Jobs arrive at unknown times new
  - Open system model
- Job runtimes are known in advance
- No preemption



Baseline Scheduler: First Come First Serve (FCFS)

Input:

Job	arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response

t=0

Baseline Scheduler:
First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

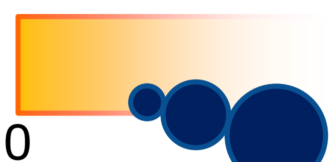
Wait	Start	End	Response
0	0		

t=0

Baseline Scheduler:
First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0		
P2	2	4				
P3	3	2				
P4	6	3				



t=0

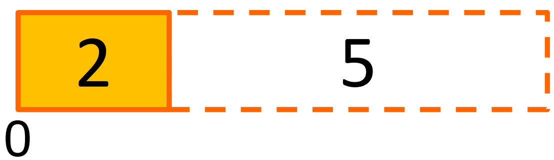
Scheduler will be called whenever "something happens"

1. Job arrival
2. Job termination

Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0		
P2	2	4				
P3	3	2				
P4	6	3				



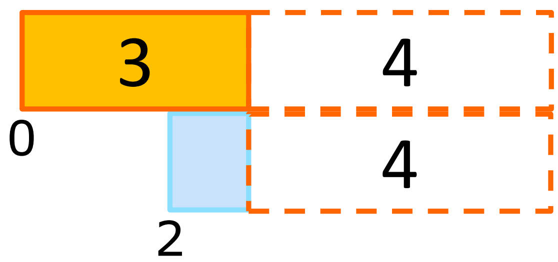
t=2

Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
0	0		
1			



t=3

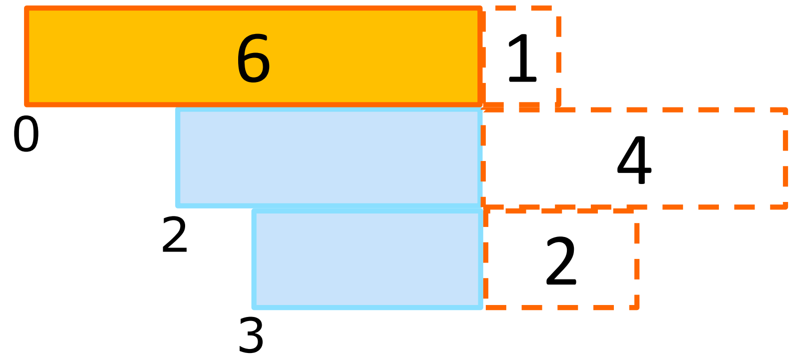
Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
0	0		
4			
3			

t=6

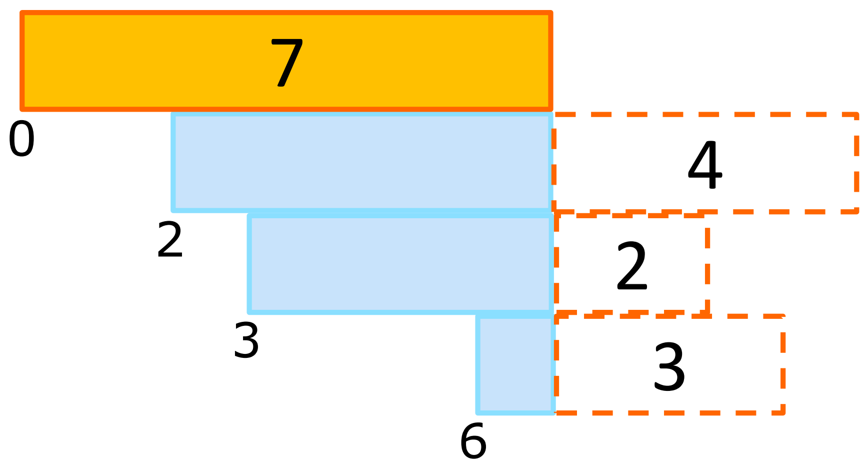


Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	5	7		
P3	3	2	4			
P4	6	3	1			

t=7

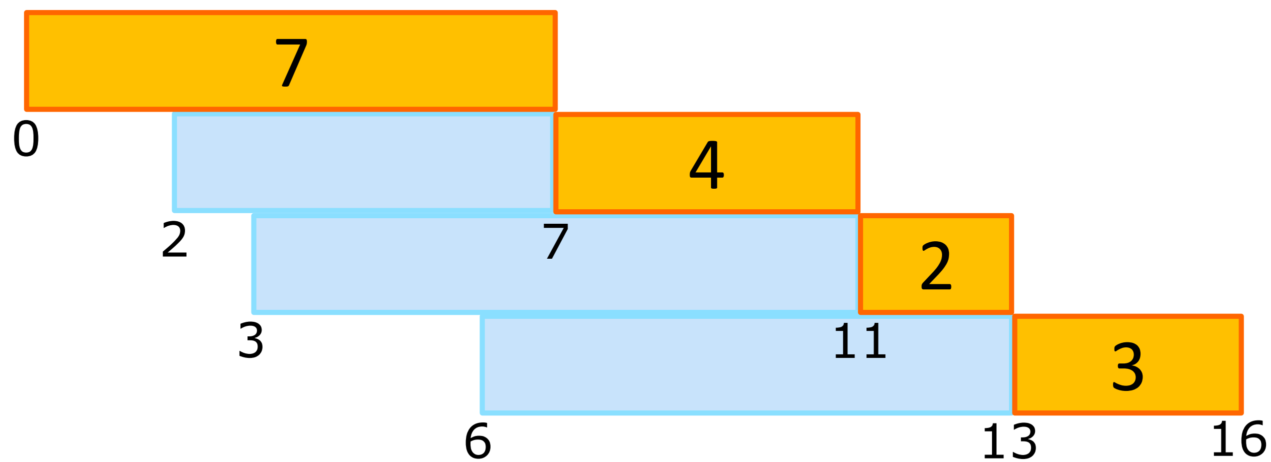


Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	5	7	11	9
P3	3	2	8	11	13	10
P4	6	3	7	13	16	10

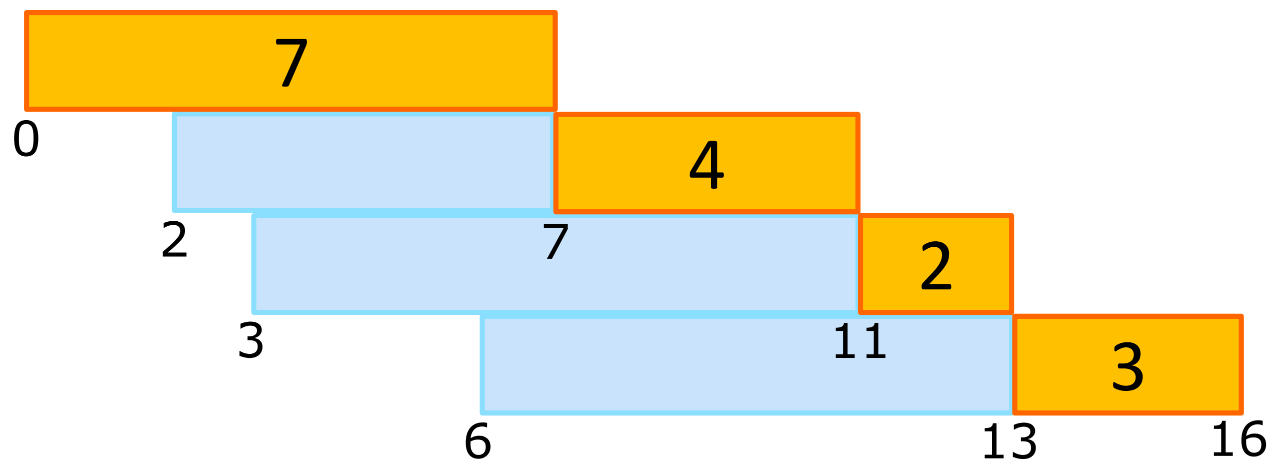
t=16



Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	5	7	11	9
P3	3	2	8	11	13	10
P4	6	3	7	13	16	10

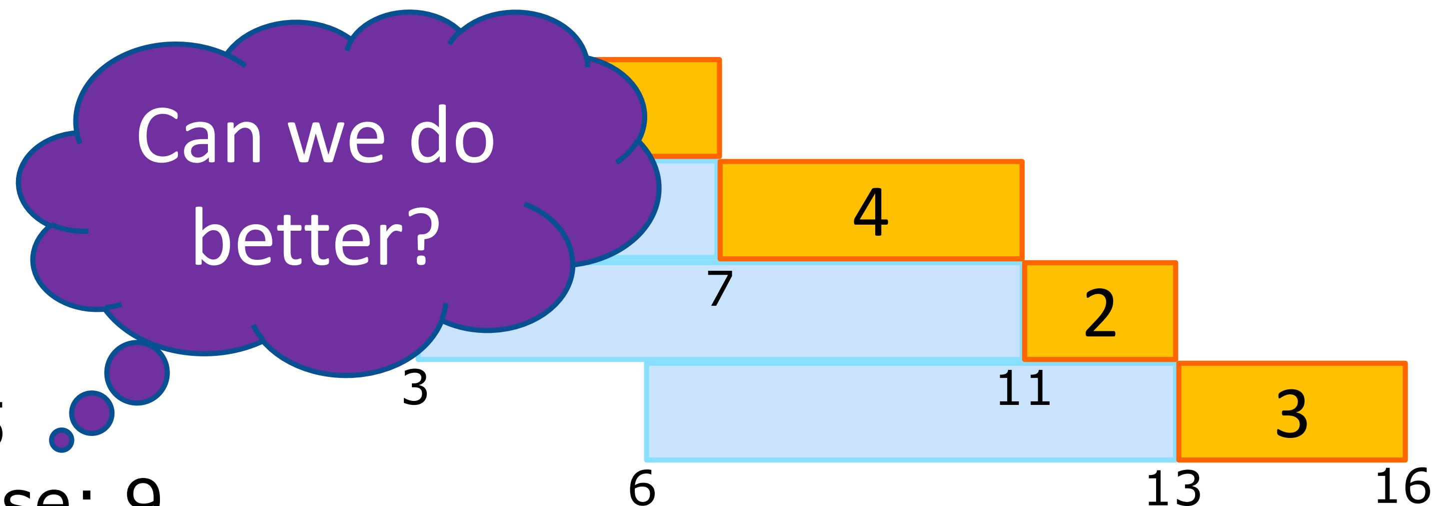


Avg. wait: 5
Avg. response: 9
Throughput: 0.25

Baseline Scheduler: First Come First Serve (FCFS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	5	7	11	9
P3	3	2	8	11	13	10
P4	6	3	7	13	16	10



Avg. wait: 5
Avg. response: 9
Throughput: 0.25

Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response

t=0

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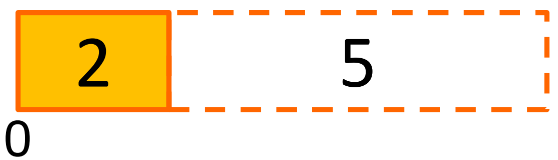
Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
0	0		

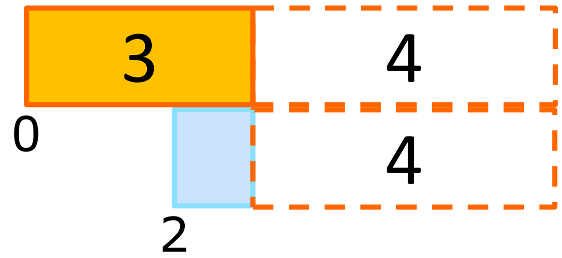


t=2

Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0		
P2	2	4	1			
P3	3	2				
P4	6	3				



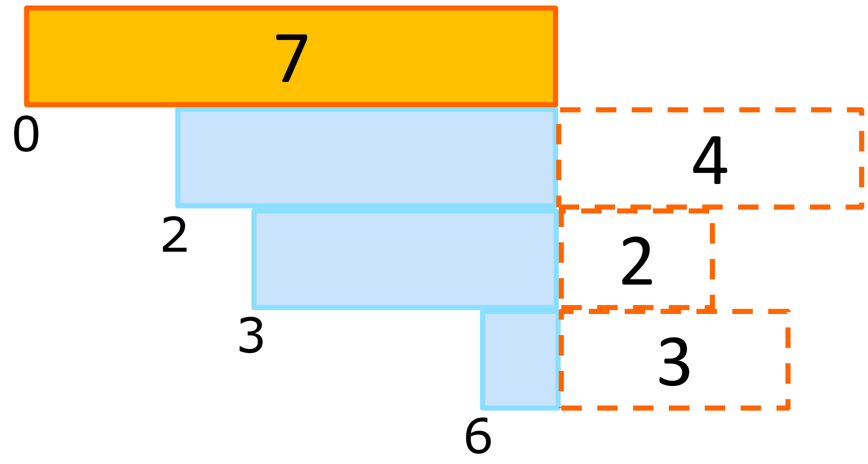
t=3

Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	5			
P3	3	2	4			
P4	6	3	1			

t=7

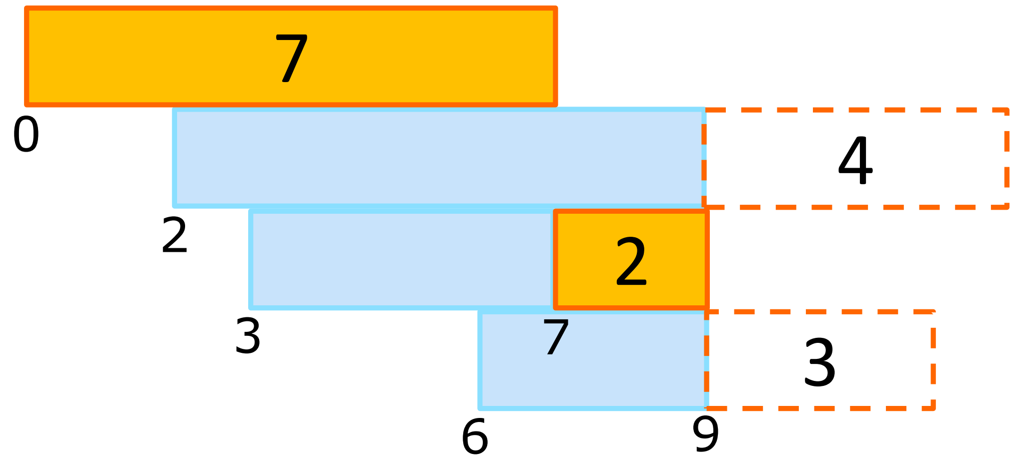


Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	7			
P3	3	2	4	7	9	6
P4	6	3	3			

t=9

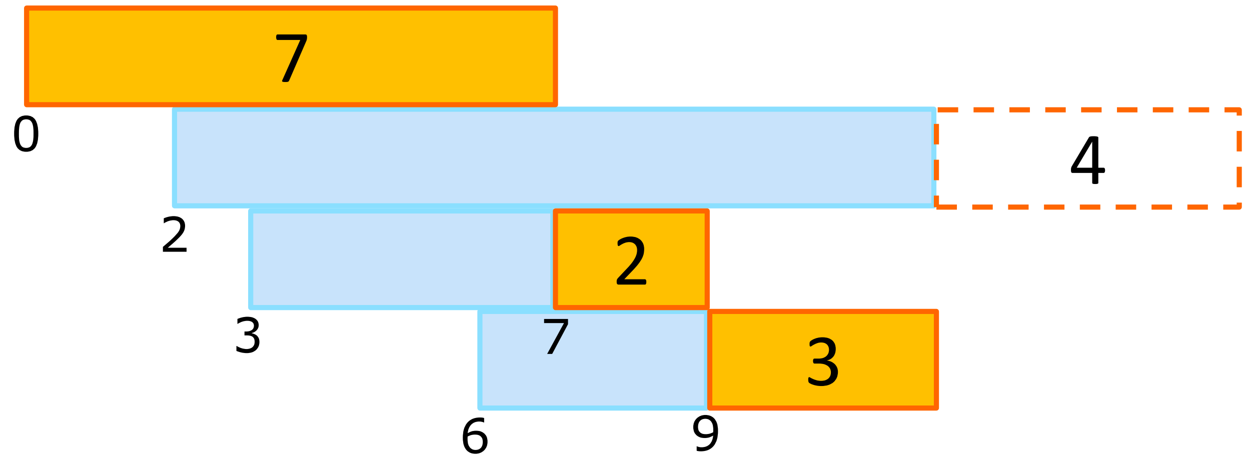


Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	10			
P3	3	2	4	7	9	6
P4	6	3	3	9	12	6

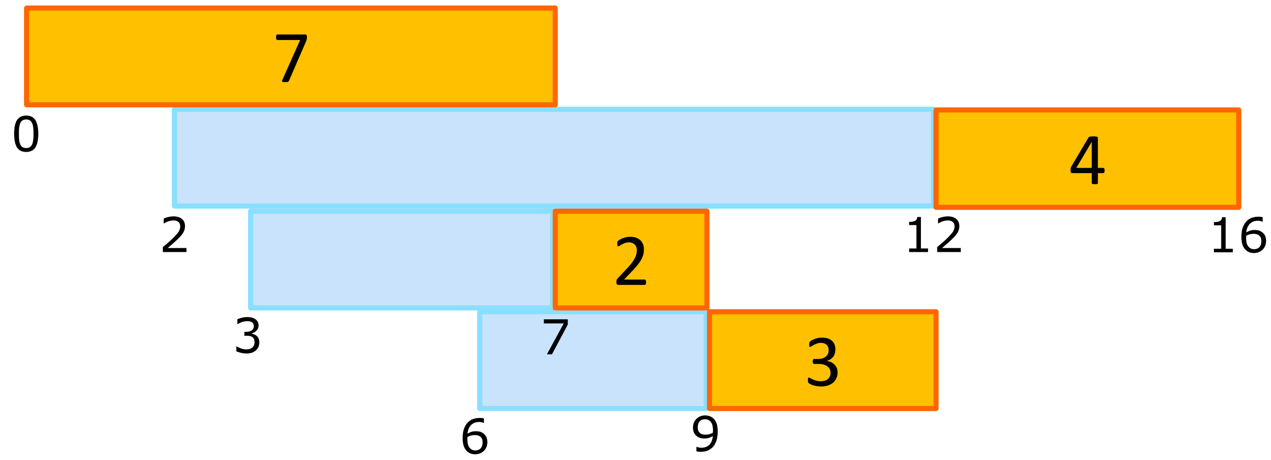
t=12



Improved Scheduler: Shortest Job First (SJF)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	7	7
P2	2	4	10	12	16	14
P3	3	2	4	7	9	6
P4	6	3	3	9	12	6



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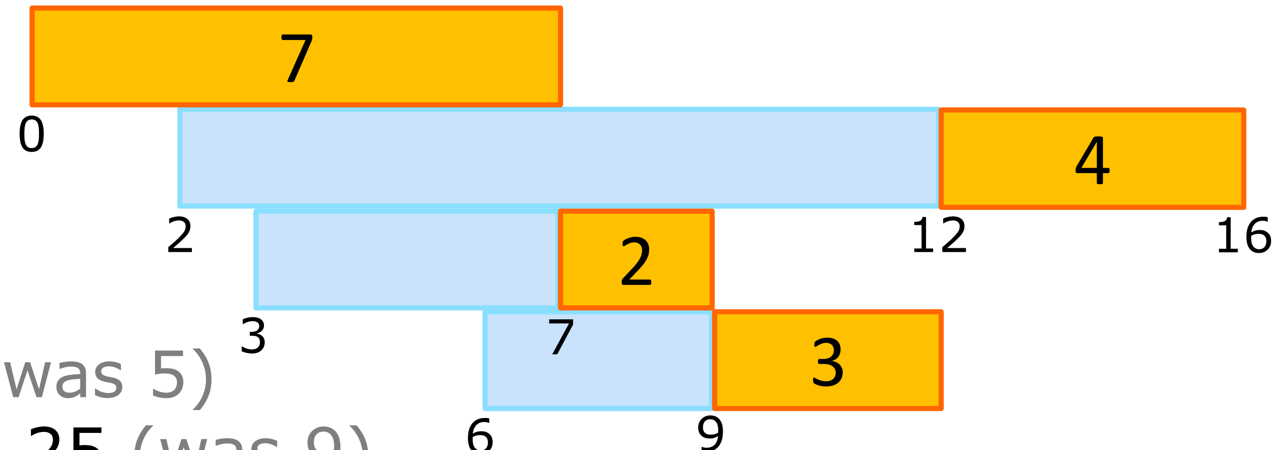
Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
0	0	7	7
10	12	16	14
4	7	9	6
3	9	12	6



Avg. wait: 4.25 (was 5)
Avg. response: 8.25 (was 9)
Throughput: 0.25 (same)

Priority Scheduling

- Many scheduling algorithms can be interpreted as **priority scheduling** algorithms:
  1. Assign each job a priority
  2. Schedule the highest priority job

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- In SJF:

Priority Scheduling

- Many scheduling algorithms can be interpreted as **priority scheduling** algorithms:
    1. Assign each job a priority
    2. Schedule the highest priority job
- In FCFS: priority = time since arrival
- In SJF: priority = runtime (inverted)

SJF had a Problem

- An on-line algorithm does not know the future
- When P1 arrived it was scheduled
- But then the scheduler was stuck till P1 terminated
- Even when shorter jobs became available!

The Solution

- Use preemption!
- Revert earlier decisions that turn out to be sub-optimal

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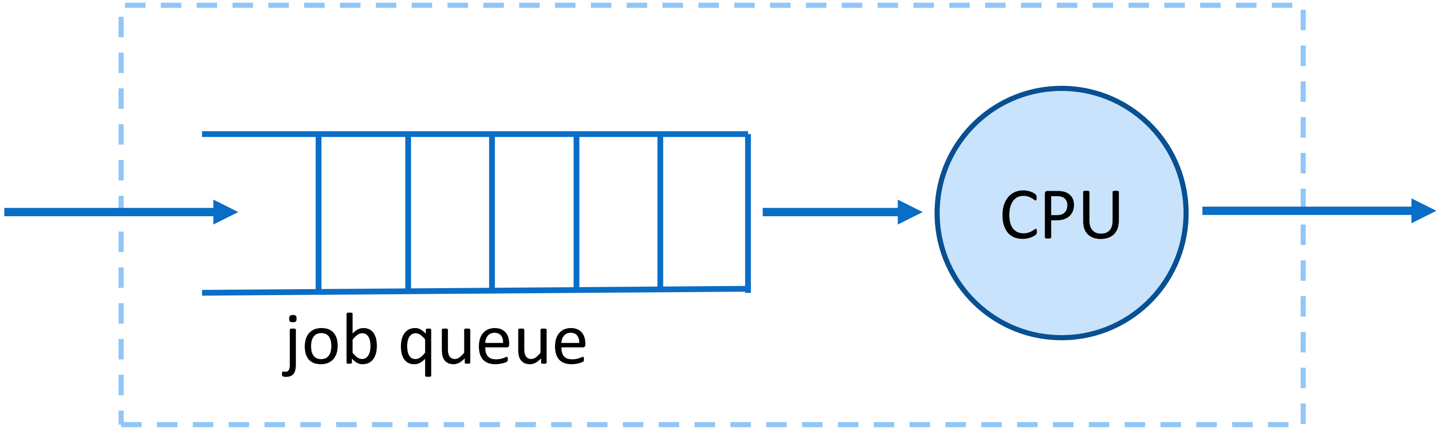
The Solution

- Use preemption!
- Revert earlier decisions that turn out to be sub-optimal
- *Compensate for not knowing the future*
- The cost: context switching overhead

System Model II (simplified)

- Jobs arrive at unknown times
  - Open system model
- Job runtimes are known in advance
- We can use preemption 



Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response

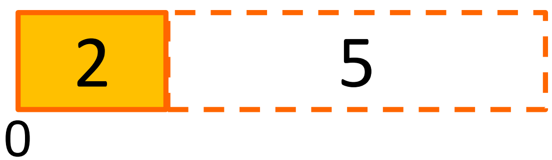
t=0

Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
0	0		

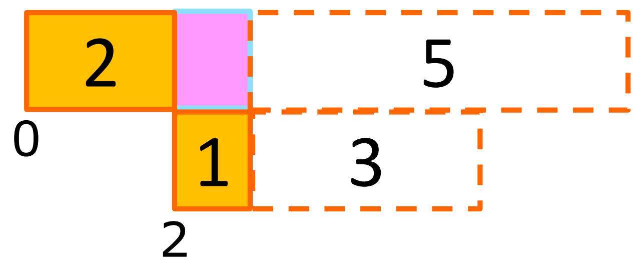


t=2

Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	(1)	0		
P2	2	4	0	2		
P3	3	2				
P4	6	3				



t=3

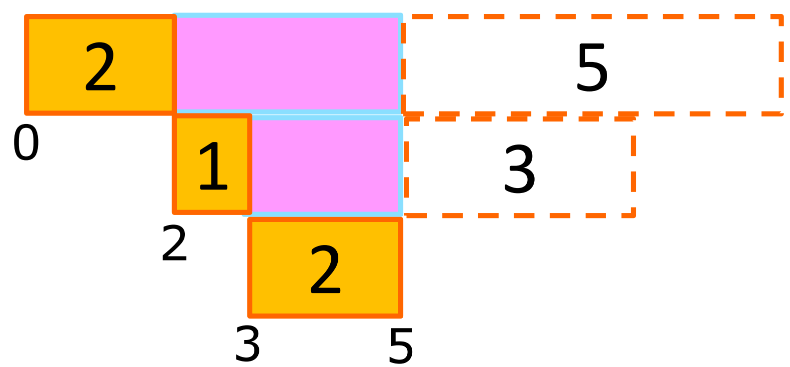
Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
(3)	0		
(2)	2		
0	3	5	2

t=5



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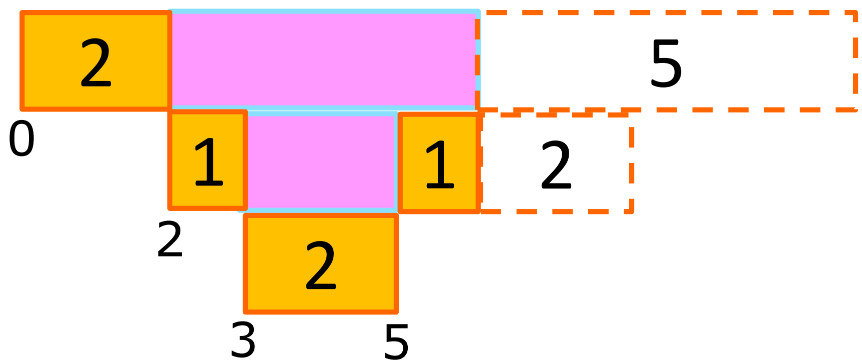
Schedule:

Job	Arrival	Runtime
P1	0	7
P2	2	4
P3	3	2
P4	6	3

Wait	Start	End	Response
(4)	0		
(2)	2		
0	3	5	2

t=6

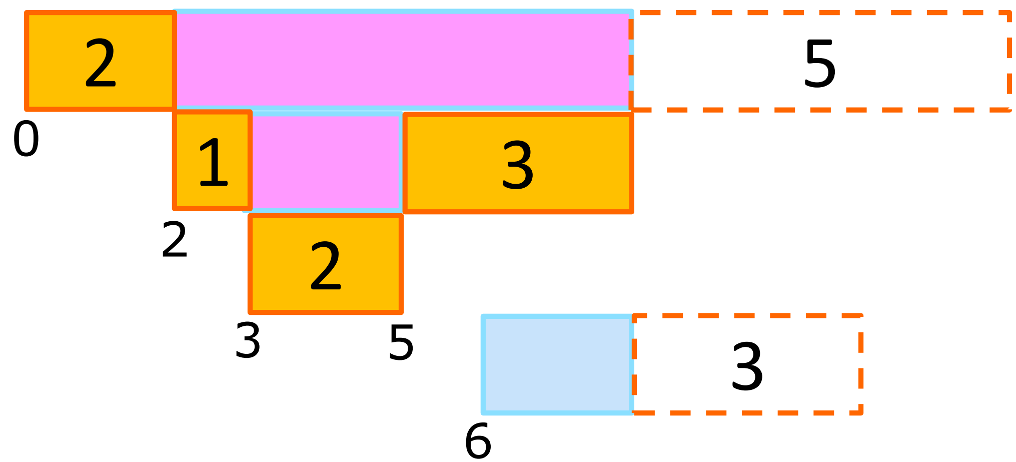


Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	(6)	0		
P2	2	4	(2)	2	8	6
P3	3	2	0	3	5	2
P4	6	3	2			

t=8

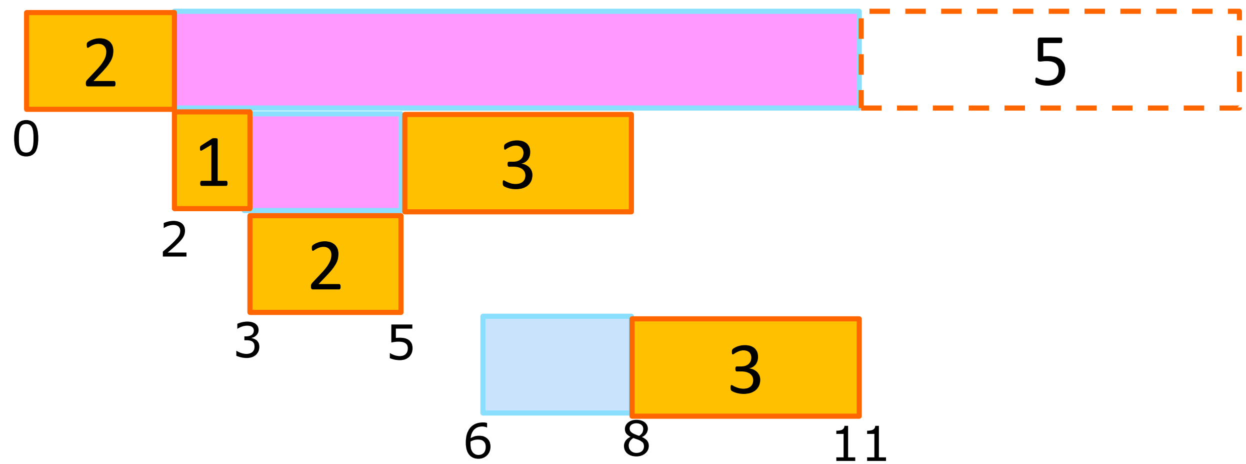


Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	(9)	0		
P2	2	4	(2)	2	8	6
P3	3	2	0	3	5	2
P4	6	3	2	8	11	5

t=11

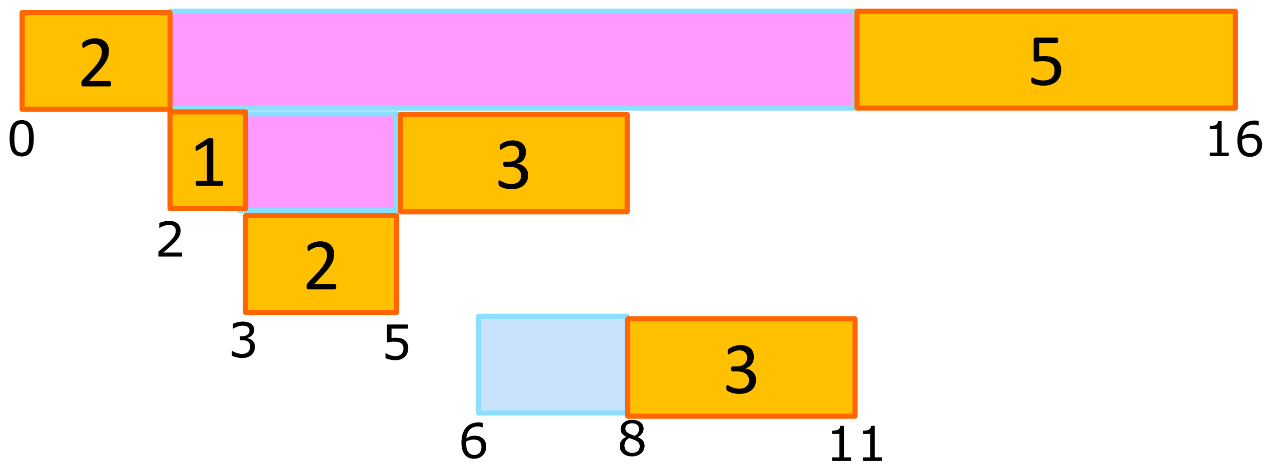


Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	(9)	0	16	16
P2	2	4	(2)	2	8	6
P3	3	2	0	3	5	2
P4	6	3	2	8	11	5

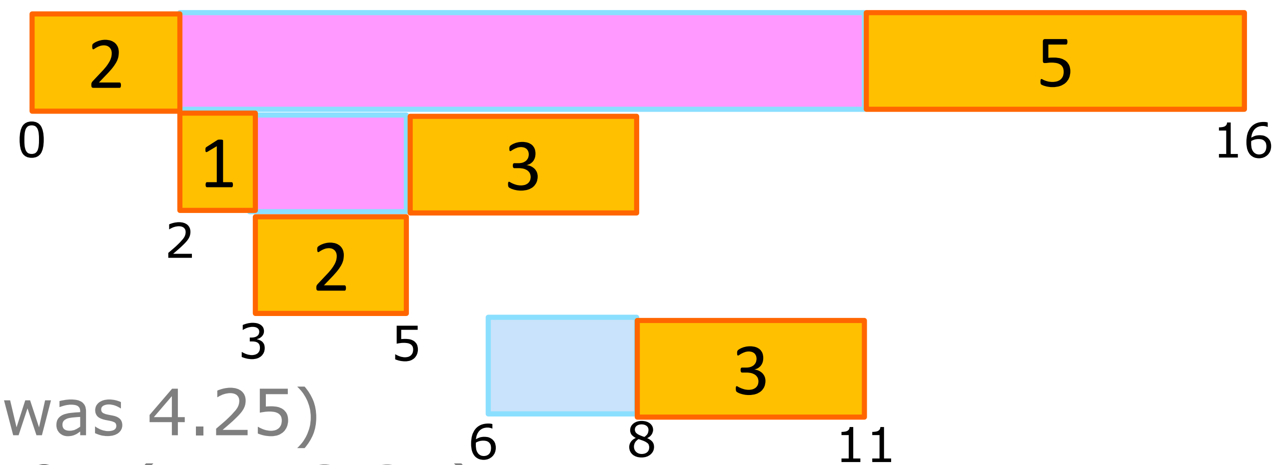
t=16



Preemptive SJF: Shortest Remaining Processing Time (SRPT)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	(9)	0	16	16
P2	2	4	(2)	2	8	6
P3	3	2	0	3	5	2
P4	6	3	2	8	11	5

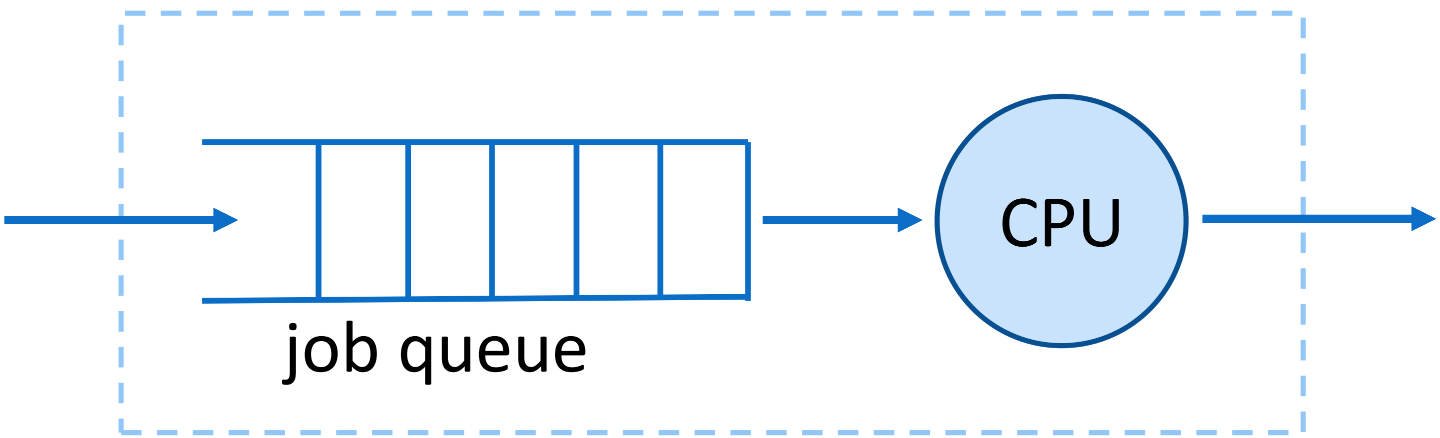


Avg. wait: 3.25 (was 4.25)
Avg. response: 7.25 (was 8.25)
Throughput: 0.25 (same)

But what if we don’t know job runtimes in advance?

System Model III (realistic)

- Jobs arrive at unknown times
  - Open system model
- Job runtimes **not** known in advance new
- We can use preemption



The Problem

- We don’t know the future
- When a new job arrives, we don’t know whether it will be short or long
- So we don’t know whether to preempt and let it run
- Short jobs can get stuck after long jobs

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Possible Solution: Estimate

- Assume job has multiple CPU bursts
- Use exponentially weighted average of previous bursts to estimate length of next burst

  1. t_n = actual length of the n^{th} CPU burst
  2. τ_{n+1} = predicted value for the next CPU burst
  3. α = weight factor, $0 \leq \alpha \leq 1$
  4. Define: $\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\, \tau_n \quad [\tau_1 = 0]$

  Result: $\tau_{n+1} = \sum_{i=1}^{n} (1-\alpha)^{n-i} \alpha \boldsymbol{t}_i$

- Might not give good results
- Lots of overhead

Alternative Partial Solution

- Assume jobs can run together!
- Then the short jobs won't get stuck

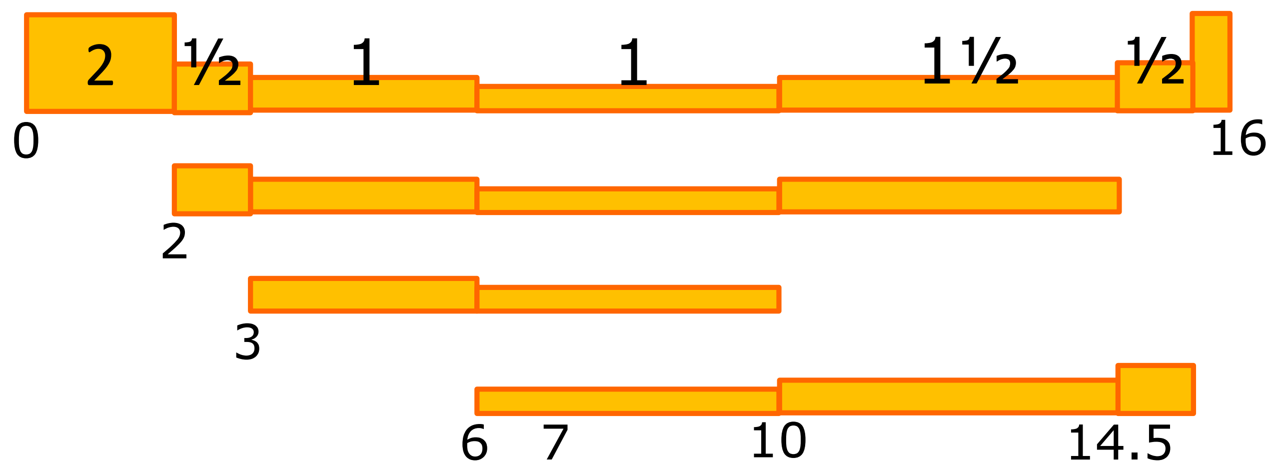
This is called "processor sharing"

When *k* jobs are present, they all advance at a rate of *1/k*

Processor Sharing (PS)

Schedule:

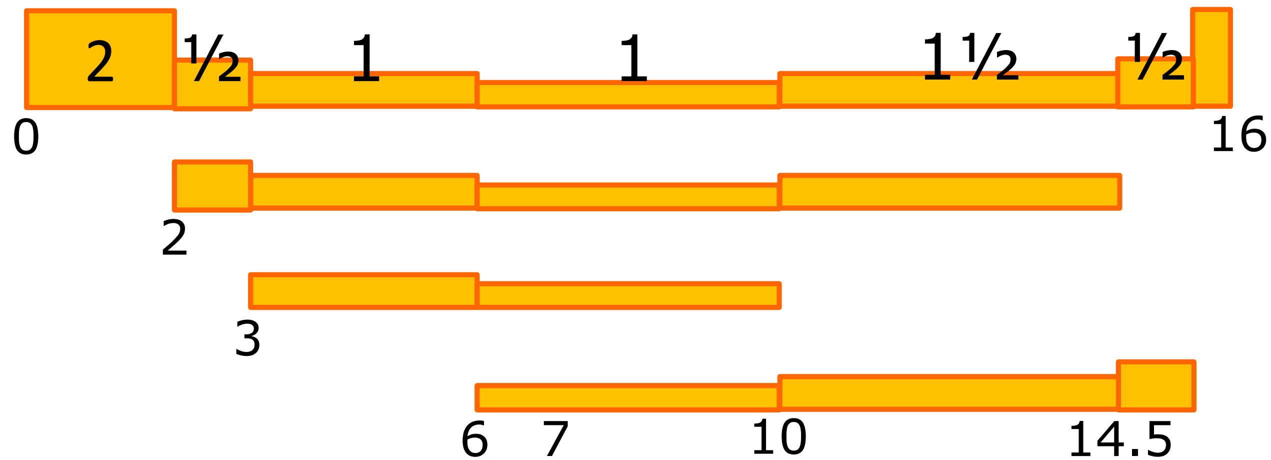
Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	16	16
P2	2	4	0	2	14.5	12.5
P3	3	2	0	3	10	7
P4	6	3	0	6	15.5	9.5



Processor Sharing (PS)

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	0	0	16	16
P2	2	4	0	2	14.5	12.5
P3	3	2	0	3	10	7
P4	6	3	0	6	15.5	9.5



Avg. wait: undef
Avg. response: 11.25 (SRPT was 7.25)
Throughput: 0.25

Processor Sharing (PS)

- Good: short jobs don't get stuck
- Bad: everyone runs at slower rate
- So is it really beneficial?

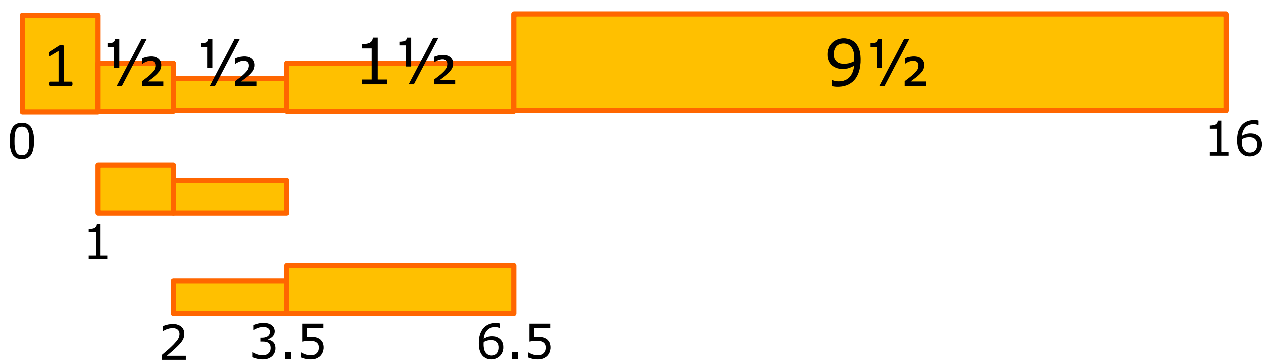
Processor Sharing (PS)

- Good: short jobs don’t get stuck
- Bad: everyone runs at slower rate
- So is it really beneficial?
- Depends on *workload statistics*
- Specifically on distribution of job lengths

Good Case

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	13	0	0	16	16
P2	1	1	0	1	3.5	2.5
P3	2	2	0	2	6.5	4.5

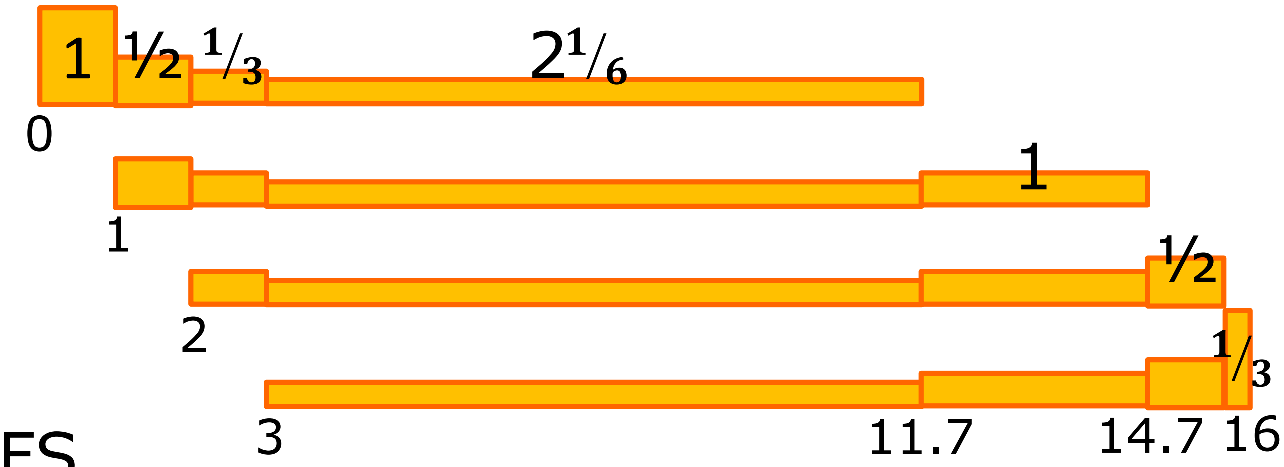


Approximates SRPT!

Bad Case

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	4	0	0	11.7	11.7
P2	1	4	0	1	14.7	13.7
P3	2	4	0	2	15.7	13.2
P4	3	4	0	3	16	13



Worse than FCFS…

Theory

- Processor sharing is good for **skewed** distribution
  - Many small values
  - Few very large values
- Specifically when **CV > 1**
- Coefficient of variation definition:

$$\mathrm{CV} = \frac{\mathrm{std\_dev}}{\mathrm{mean}}$$

Data

- Most processes are indeed very short
- Some are very long
- The distribution has a Pareto tail

$$\Pr(r > t) = 1/t$$

- Caveat: there is little data, and different systems are probably very different
- So indeed processor sharing should be good

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- Caveat: there is little data, and different systems are probably very different
- So indeed processor sharing should be good
- Too bad it can't be done…

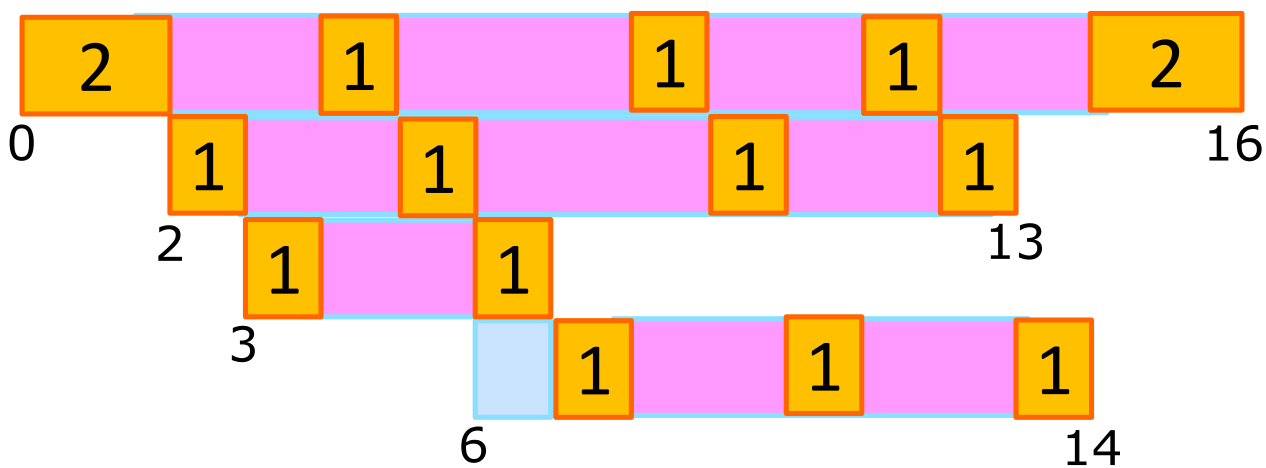
Round-Robin (RR) Scheduling

- Approximation of processor sharing
- Run each process for a certain **time quantum**
  - Predefined short time
  - E.g. around 10-100 ms
- Then preempt and move to back of queue

Round-Robin (RR) Scheduling

Schedule:

Job	Arrival	Runtime	Wait	Start	End	Response
P1	0	7	(9)	0	16	16
P2	2	4	(7)	2	13	11
P3	3	2	(2)	6	7	4
P4	6	3	(5)	7	14	7



Round-Robin (RR) Scheduling

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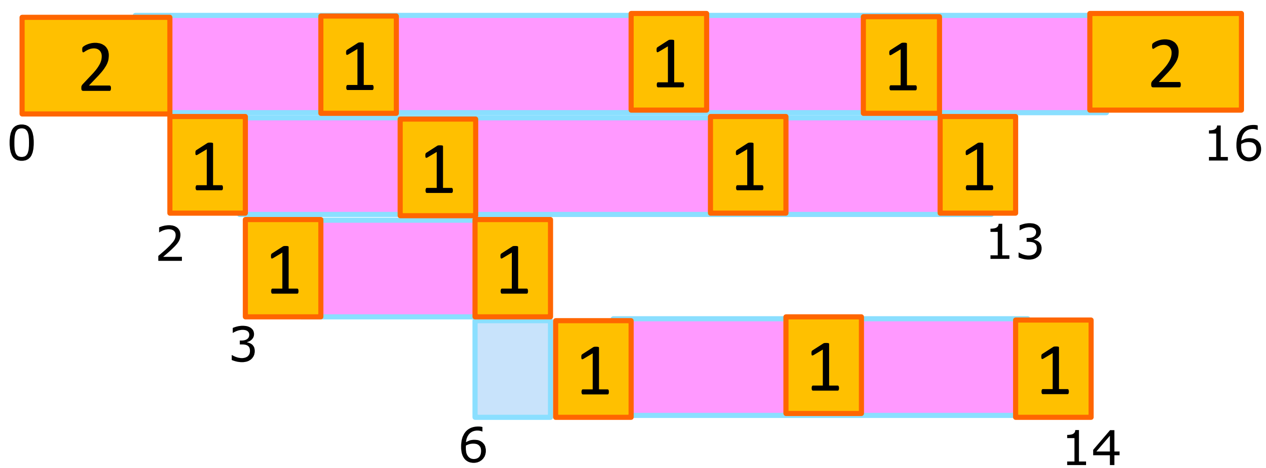
P3	3	2	(2)	6	7	4
P4	6	3	(5)	7	14	7



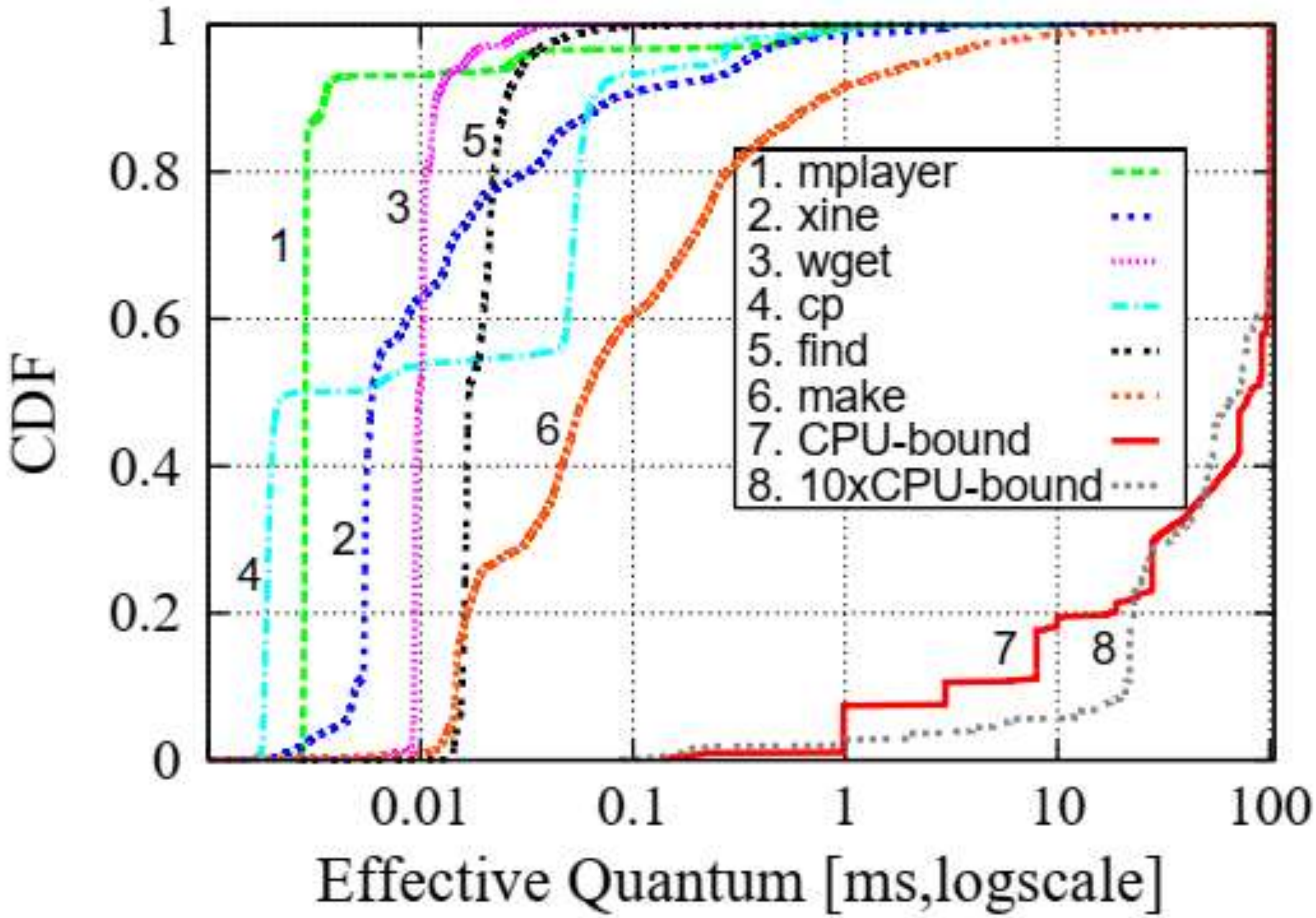
Avg. wait: 5.75
Avg. response: 9.5 (SRPT was 7.25)
Throughput: 0.25

RR Time Quantum

- With n jobs and quantum q no job waits more than $(n-1)q$
  - Shorter q → shorter wait
- If context switch takes c time, overhead will be $c/(q+c)$
  - Shorter q → more overhead
- If q is long, bursts will finish before end of quantum
  - Leads to behavior like FCFS
  - May be OK: only want to break ***long*** bursts

Data on Effective Quantum

Distribution of actual running time for different apps
(till finished burst, external interrupt, or end of quantum)



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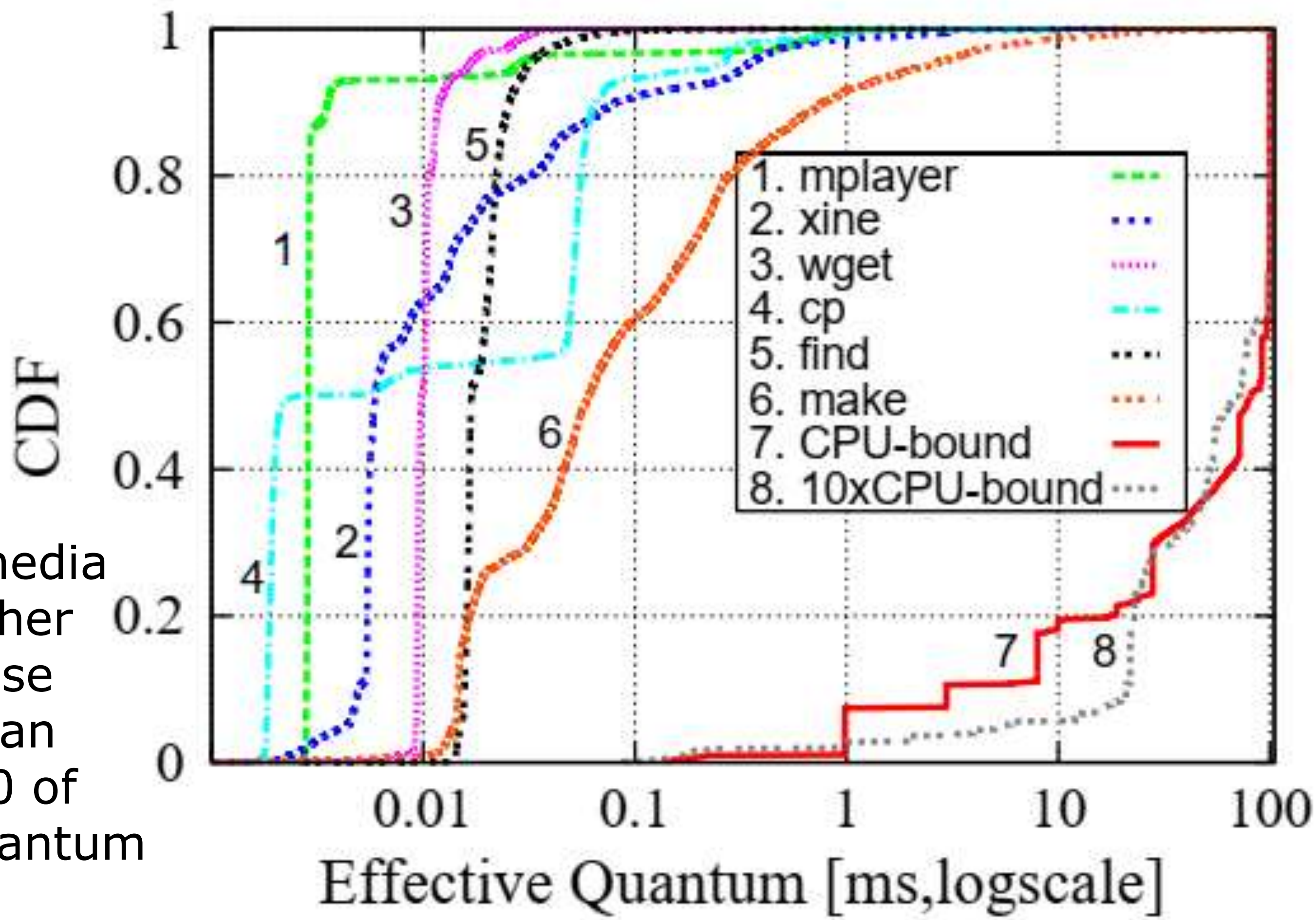

multimedia and other apps use less than 1/1000 of the quantum

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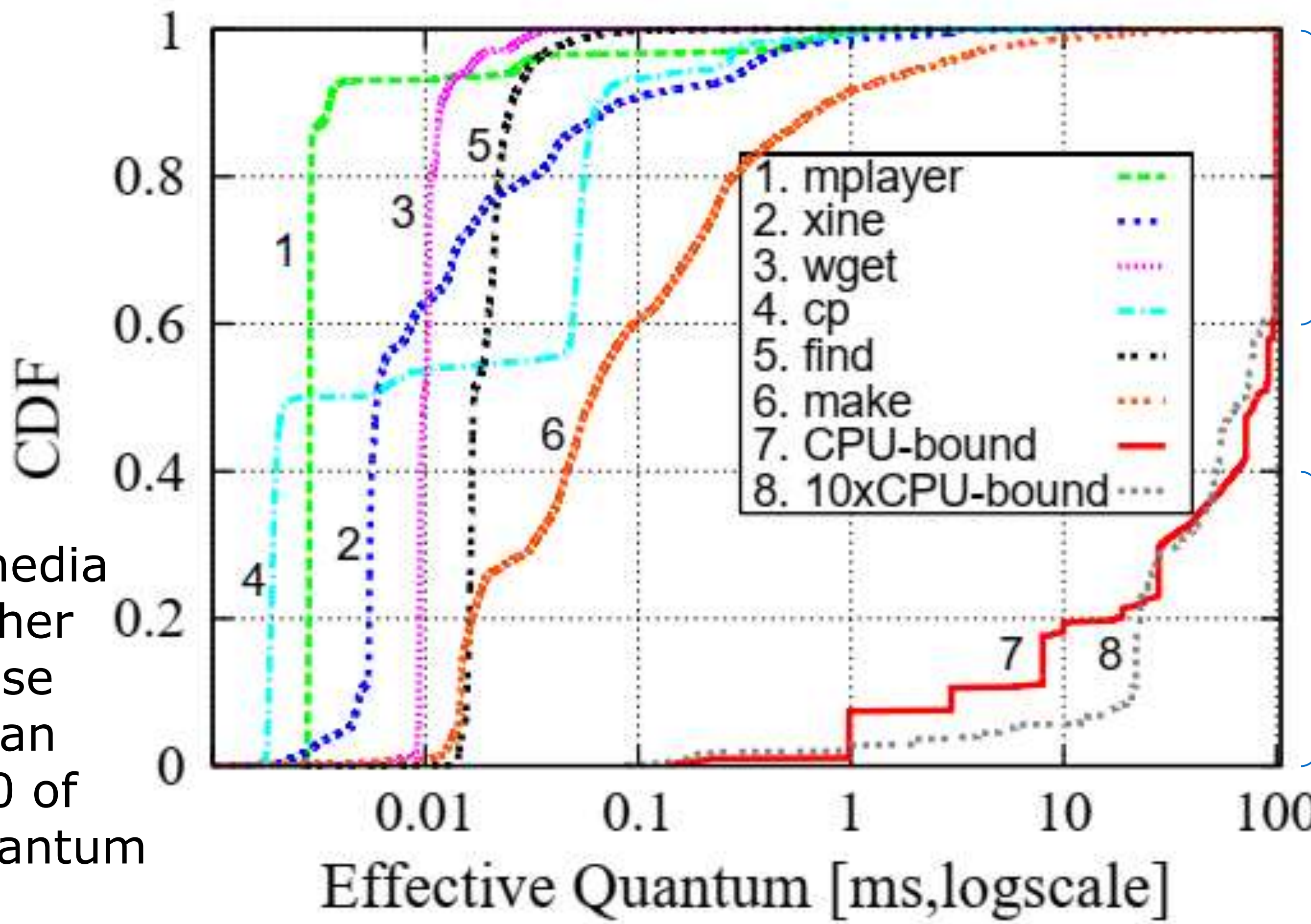

~40% of CPU-bound jobs use full quantum

~40% are interrupted and use less than half the quantum

RR Implementation

- The scheduler selects a process to run and gives it the CPU

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RR Implementation

- The scheduler selects a process to run and gives it the CPU
  - The OS loses control of the system
  - Possibly until it performs a system call
- So how can we enforce a limited time quantum?
- Answer: **Hardware support through periodic clock interrupts**
  - The only way for the OS to re-gain control over the CPU
  - Once the OS is in control, it can perform a context switch

RR Notes

- RR works in an **online** setting
- RR uses preemption to cope with **lack of knowledge**
  - Will additional jobs arrive?
  - How long will jobs run?
- RR gives **uniform treatment** to all jobs

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- **Can we do better?**