

Sistemi Operativi

Corso di Laurea in Informatica

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SAPIENZA
UNIVERSITÀ DI ROMA

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Recap from Last Lecture

- 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)**

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)

SJF: Idea

- Schedule the job that has the least **expected** amount of work to do until its next I/O operation or termination
- "Amount of work" means CPU burst

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Job	CPU burst (time units)
A	6
B	8
C	7
D	3

Assuming all jobs arrive at the same time
(arrival time = 0)

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The table shows four jobs (A, B, C, D) with their respective CPU burst times in time units. Job A has a burst of 6, Job B has 8, Job C has 7, and Job D has 3. The timeline arrow indicates the progression of time from the end of Job D's burst.

SJF: Idea

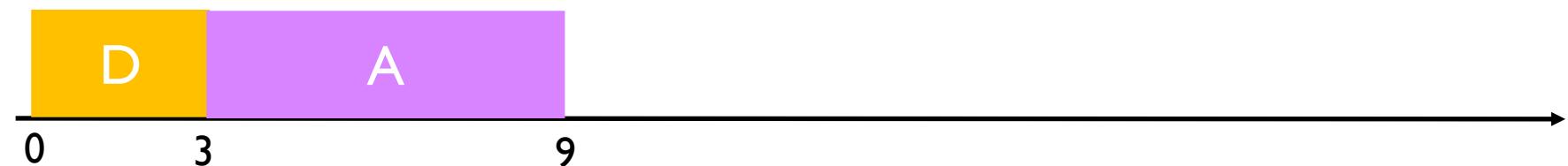
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avg. waiting time =

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$$\text{avg. waiting time} = (3 + 16 + 9 + 0)/4 = 7$$

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- **PROs:**
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(preemptive SJF is called **SRTF** or **Shortest Remaining Time First**)
- **CONs:**
 - Almost impossible to predict the amount of CPU time of a job
 - Long running CPU-bound jobs can starve (as I/O-bound ones have implicitly higher priority over them)

SJF: Estimating CPU Time of a Job

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x_t = *actual* length of the t -th CPU burst

s_{t+1} = *predicted* length of the $(t+1)$ -th CPU burst

$$\alpha \in \mathbb{R}, 0 \leq \alpha \leq 1$$

$$s_1 = x_0$$

$$s_{t+1} = \alpha x_t + (1 - \alpha) s_t$$

SJF: Estimating CPU Time of a Job

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$$\alpha \in \mathbb{R}, 0 \leq \alpha \leq 1$$

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weighted average between previous **observation** and previous **prediction**

Exponential Smoothing

$$s_1 = x_0$$

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Case I: $\alpha = 0 \Rightarrow s_{t+1} = s_t$

Exponential Smoothing

$$s_1 = x_0$$
$$s_{t+1} = \alpha \cancel{x_t} + (1 - \alpha)s_t$$

Case I: $\alpha = 0 \Rightarrow s_{t+1} = s_t$

Observed bursts are ignored and
constant burst is assumed

Exponential Smoothing

$$s_1 = x_0$$

$$s_{t+1} = \alpha x_t + (1 - \alpha)s_t$$

Case 1: $\alpha = 0 \Rightarrow s_{t+1} = s_t$

Observed bursts are ignored and
constant burst is assumed

Case 2: $\alpha = 1 \Rightarrow s_{t+1} = x_t$

Exponential Smoothing

$$s_1 = x_0$$
$$s_{t+1} = \boxed{\alpha x_t} + \cancel{(1 - \alpha)s_t}$$

Case 1: $\alpha = 0 \Rightarrow s_{t+1} = s_t$

Observed bursts are ignored and constant burst is assumed

Case 2: $\alpha = 1 \Rightarrow s_{t+1} = x_t$

The next burst is assumed to be the same as the last actual CPU burst observed

Exponential Smoothing

$$s_1 = x_0$$
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Case 1: $\alpha = 0 \Rightarrow s_{t+1} = s_t$

Observed bursts are ignored and constant burst is assumed

Case 2: $\alpha = 1 \Rightarrow s_{t+1} = x_t$

The next burst is assumed to be the same as the last actual CPU burst observed

Recent history does not count

Exponential Smoothing

t	0	1	2	3	4	5	6	7	...
-----	---	---	---	---	---	---	---	---	-----

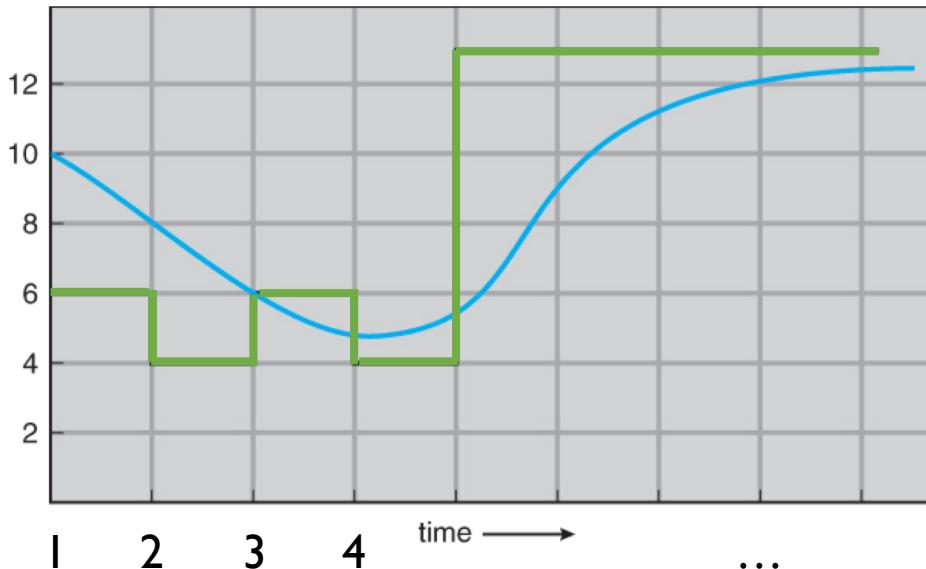
Exponential Smoothing

	t	0	1	2	3	4	5	6	7	...
observations	x_t	10	6	4	6	4	13	13	13	...

Exponential Smoothing

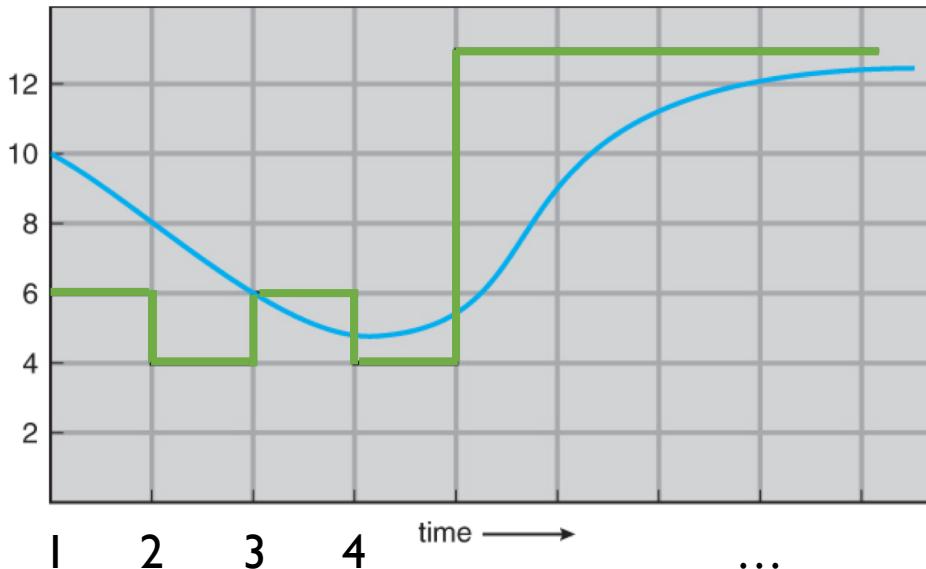
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observations	x_t	10	6	4	6	4	13	13	13	...
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

Exponential Smoothing



t	0	1	2	3	4	5	6	7	...	
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Exponential Smoothing

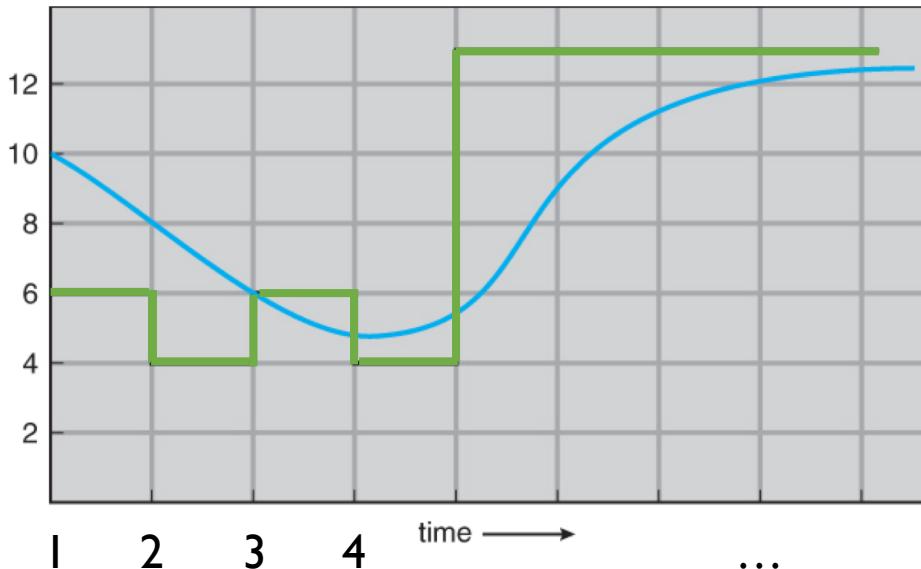


t	0	1	2	3	4	5	6	7	...	
observations	x_t	10	6	4	6	4	13	13	13	...
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$$s_1 = x_0$$

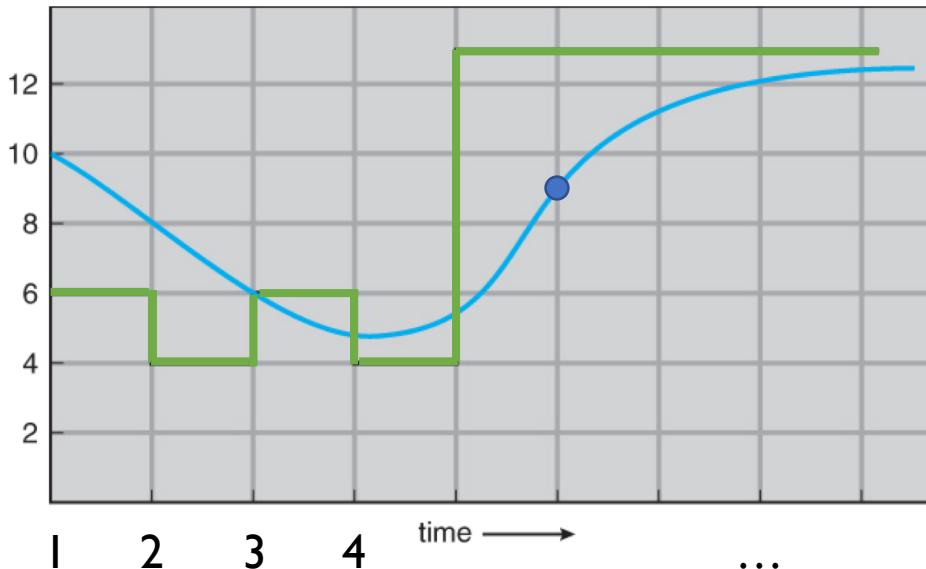
bootstrap

Exponential Smoothing



t	0	1	2	3	4	5	6	7	...	
observations	x_t	10	6	4	6	4	13	13	...	
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Exponential Smoothing

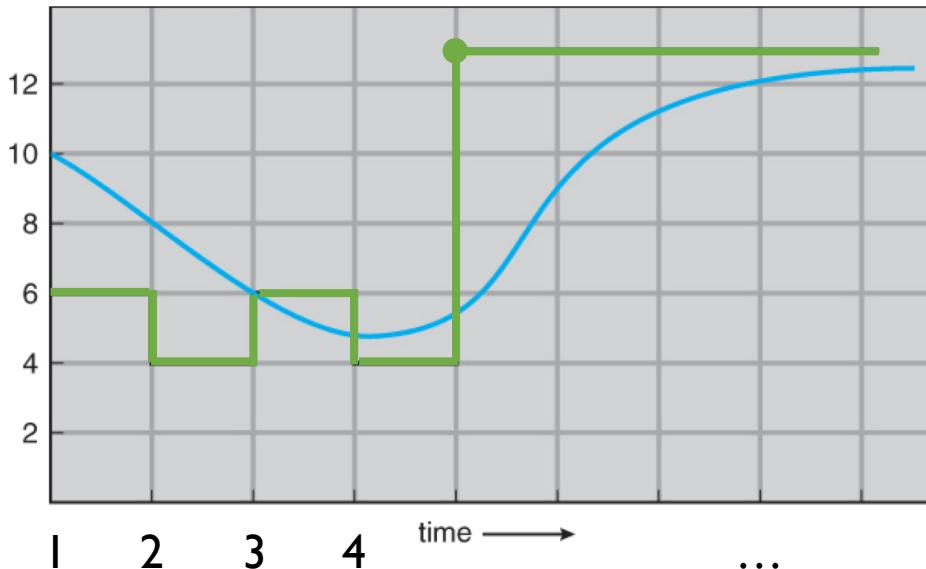


t	0	1	2	3	4	5	6	7	...	
observations	x_t	10	6	4	6	4	13	13	13	...
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$$9 =$$

$$s_6 =$$

Exponential Smoothing



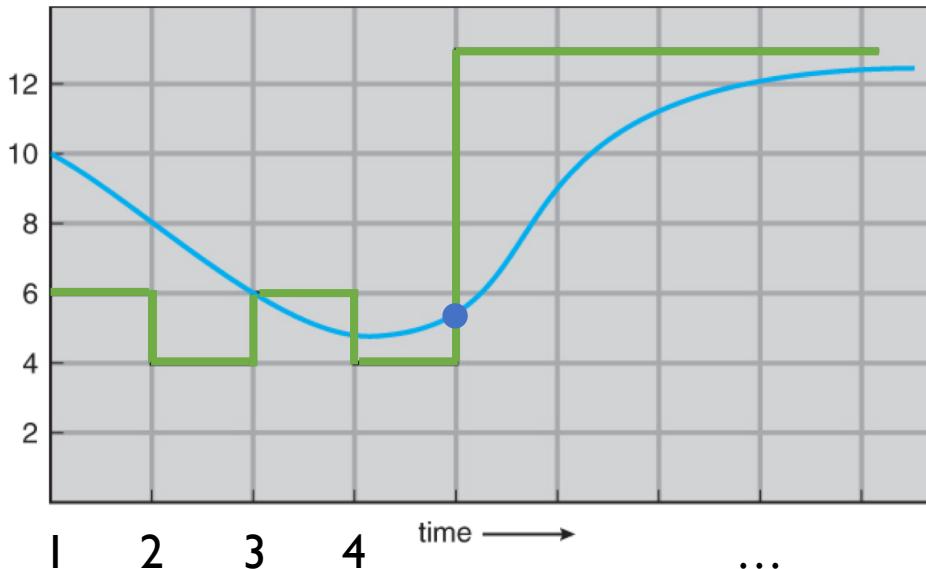
Usually, alpha is set to 0.5

t	0	1	2	3	4	5	6	7	...	
observations	x_t	10	6	4	6	4	13	13	13	...
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

$$9 = 0.5 * 13$$

$$s_6 = \alpha x_5$$

Exponential Smoothing



Usually, alpha is set to 0.5

t	0	1	2	3	4	5	6	7	...	
observations	x_t	10	6	4	6	4	13	13	...	
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

$$9 = 0.5 * 13 + 0.5 * 5$$

$$s_6 = \alpha x_5 + (1 - \alpha) s_5$$

Exponential Smoothing

$$s_{t+1} = \alpha x_t + (1 - \alpha)s_t$$

$$s_t = \alpha x_{t-1} + (1 - \alpha)s_{t-1}$$

⋮

$$s_2 = \alpha x_1 + (1 - \alpha)s_1$$

$$s_1 = x_0$$

Exponential Smoothing

$$s_{t+1} = \alpha x_t + (1 - \alpha)s_t$$

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...

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predictions/forecasts

Exponential Smoothing

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$$s_2 = \alpha x_1 + (1 - \alpha)s_1$$

$$s_1 = x_0$$

actual observations

Exponential Smoothing

$$s_{t+1} = \alpha x_t + (1 - \alpha)s_t$$

$$= \alpha x_t + (1 - \alpha) \underbrace{[\alpha x_{t-1} + (1 - \alpha)s_{t-1}]}_{s_t}$$

Exponential Smoothing

$$\begin{aligned}s_{t+1} &= \alpha x_t + (1 - \alpha)s_t \\&= \alpha x_t + (1 - \alpha) \underbrace{[\alpha x_{t-1} + (1 - \alpha)s_{t-1}]}_{s_t} \\&= \alpha x_t + \alpha(1 - \alpha)x_{t-1} + (1 - \alpha)^2 s_{t-1}\end{aligned}$$

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Exponential Smoothing

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Past t **observations**

Exponential Smoothing

$$s_{t+1} = \alpha x_t + \alpha(1 - \alpha)x_{t-1} + \alpha(1 - \alpha)^2x_{t-2} + \dots + (1 - \alpha)^{t-1}s_2$$

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Past t observations

bootstrap

Exponential Smoothing

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Past t observations

bootstrap

weighted average

Assuming alpha > 0, the weight of each past term decreases as we move backward in history proportionally to the terms of a geometric progression $\{1, (1 - \alpha), (1 - \alpha)^2, (1 - \alpha)^3, \dots\}$

Exponential Smoothing

In general, for any given T it holds the following

$$s_T = \alpha \cdot \left[\sum_{i=0}^{T-2} (1 - \alpha)^i x_{T-1-i} \right] + (1 - \alpha)^{T-1} x_0$$

SJF vs. SRTF: Non-preemptive vs. Preemptive

- **SJF (non-preemptive)** → Once the CPU is given to a process this will execute until it completes its CPU burst

SJF vs. SRTF: Non-preemptive vs. Preemptive

- **SJF (non-preemptive)** → Once the CPU is given to a process this will execute until it completes its CPU burst
- **SRTF (preemptive)** → Preemption occurs whenever a new process arrives in the ready queue and its predicted CPU burst is shorter than the one remaining of the current executing process

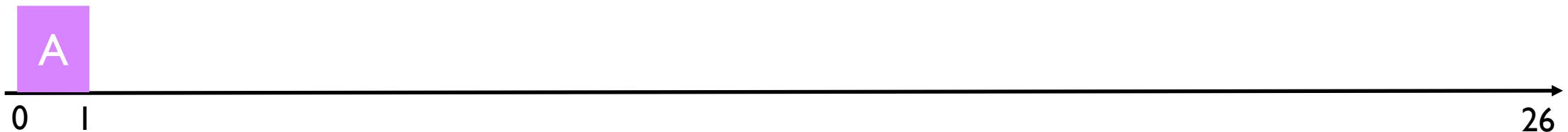
SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5

0

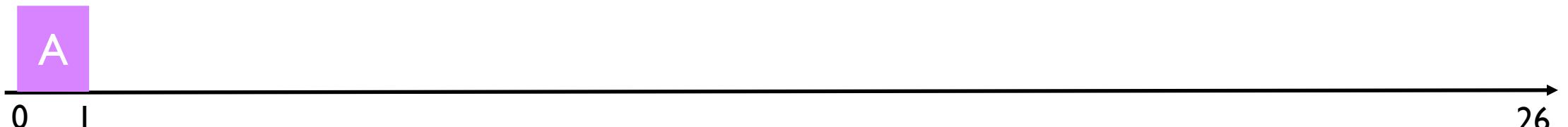
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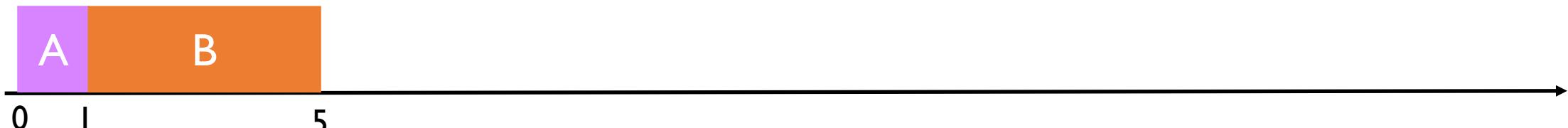
Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5



At time $t=1$ B arrives and its CPU burst (4) is less than the remaining CPU burst of A ($8-1=7$)

SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5



B is scheduled and will execute until it finishes
its 4 CPU burst units

SRTF: Example

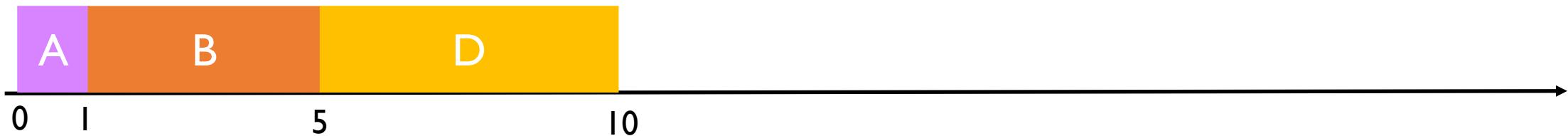
Job	Arrival time	CPU burst (time units)
A	0	8
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C	2	9
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Both C and D are arrived with 9 and 5 CPU burst units, respectively
A has still 7 CPU burst units left...

SRTF: Example

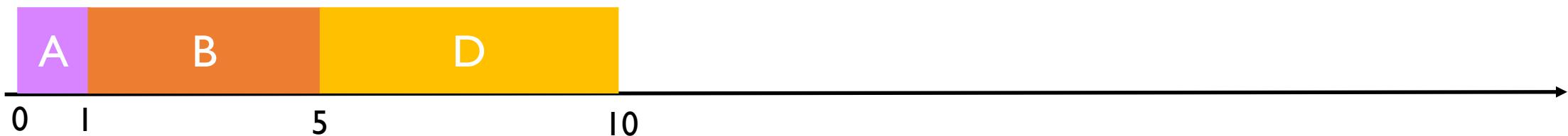
Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5



D is scheduled and will execute until it finishes its 5 CPU burst units
(no more jobs arrived in the meantime)

SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5



A has still 7 CPU burst units left and C has 9...

SRTF: Example

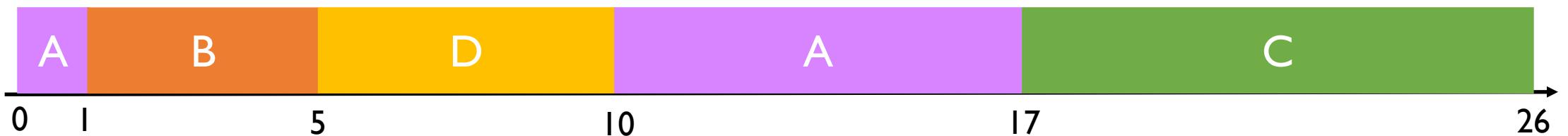
Job	Arrival time	CPU burst (time units)
A	0	8
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C	2	9
D	3	5



A is scheduled again until it finishes

SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5



Eventually, C is scheduled as well

SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
B	1	4
C	2	9
D	3	5



avg. waiting time =

SRTF: Example

Job	Arrival time	CPU burst (time units)
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$$\text{avg. waiting time} = [(17-0-8)]/4$$

SRTF: Example

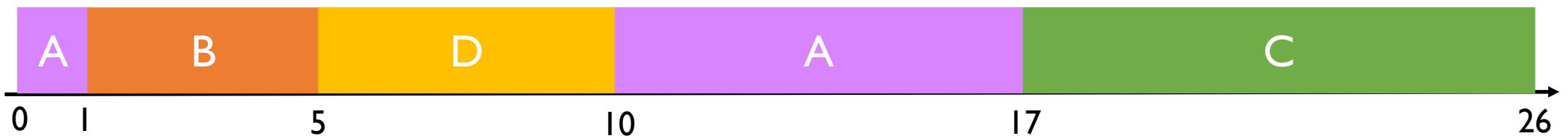
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$$\text{avg. waiting time} = [(17-0-8) + (5-1-4)] / 4$$

SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
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$$\text{avg. waiting time} = [(17-0-8) + (5-1-4) + (26-2-9)] / 4$$

SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
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C	2	9
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$$\text{avg. waiting time} = [(17-0-8) + (5-1-4) + (26-2-9) + (10-3-5)] / 4 = 26/4 \sim 6.5$$

FCFS vs. RR vs. SJF

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	SJF	FCFS	RR	SJF
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	

FCFS vs. RR vs. SJF

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	SJF	FCFS	RR	SJF
A	50	50	150	150	0	100	
B	40	90	140	100	50	100	
C	30	120	120	60	90	90	
D	20	140	90	30	120	70	
E	10	150	50	10	140	40	
Avg.		110	110	70	80	80	

FCFS vs. RR vs. SJF

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	SJF	FCFS	RR	SJF
A	50	50	150	150	0	100	100
B	40	90	140	100	50	100	60
C	30	120	120	60	90	90	30
D	20	140	90	30	120	70	10
E	10	150	50	10	140	40	0
Avg.		110	110	70	80	80	40

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)

Priority Scheduling: Idea

- More general case of SJF, where each job is assigned a **priority** and the job with the highest priority gets scheduled first

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Priority Scheduling: Idea

- More general case of SJF, where each job is assigned a **priority** and the job with the highest priority gets scheduled first
- SJF is a priority scheduling where priority is the predicted next CPU burst time
- In practice, priorities are implemented using integers within a fixed range
 - No convention on whether "high" priorities use large or small numbers
 - Usually, low numbers for high priorities (0 = the highest possible priority)

Priority Scheduling: Characteristics

- Priorities can be assigned either **internally** or **externally**

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- Priority scheduling can be either **preemptive** or **non-preemptive**

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Priority Scheduling: Issues

- **Indefinite blocking** (or **starvation**): a low-priority task can wait forever because some other jobs have always higher priority
- Stuck jobs may eventually run when the system load is lighter or after a shutdown/crash and a reboot
- **Aging** → solves starvation by increasing the priority of jobs proportionally to the time they wait, until they are eventually scheduled

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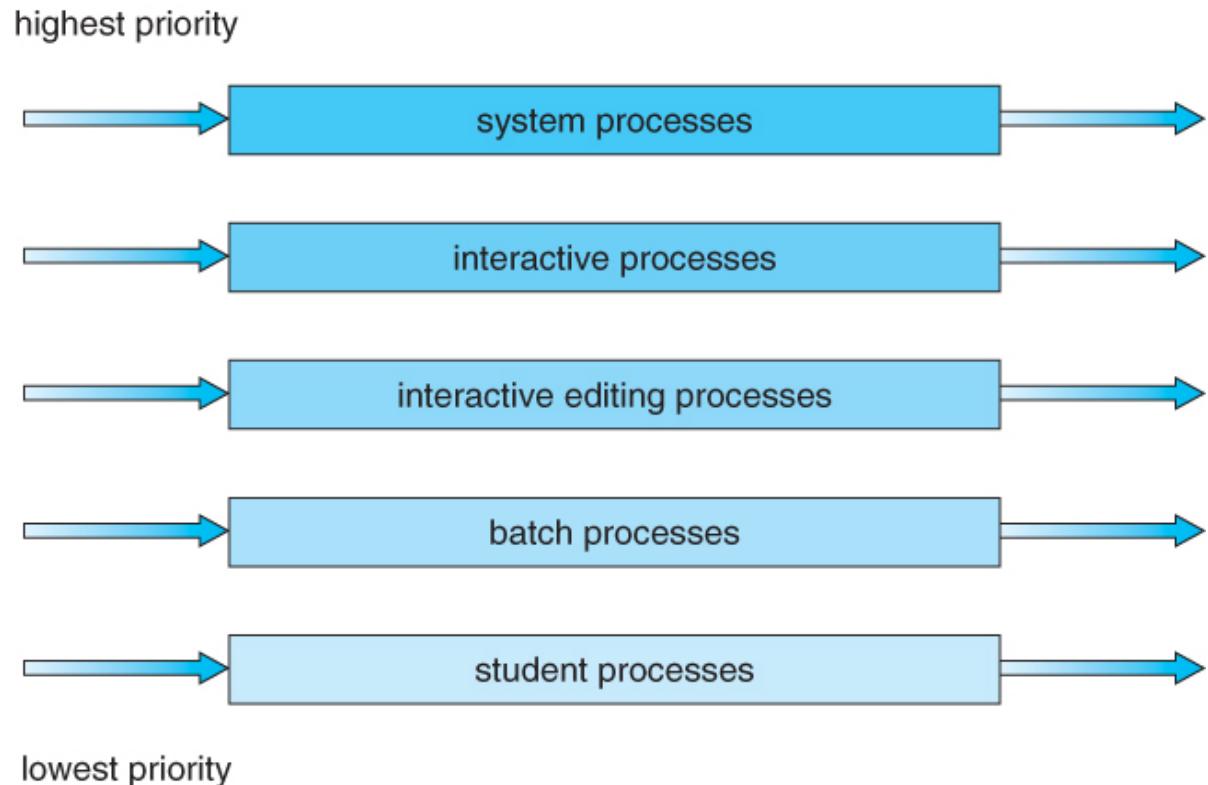
MLQ: Idea

- Use multiple separate queues, one for each job **category**
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- Two common options are:
 - **strict priority** → no job in a lower priority queue runs until all higher priority queues are empty
 - **round-robin** → each queue gets a time slice in turn, possibly of different sizes

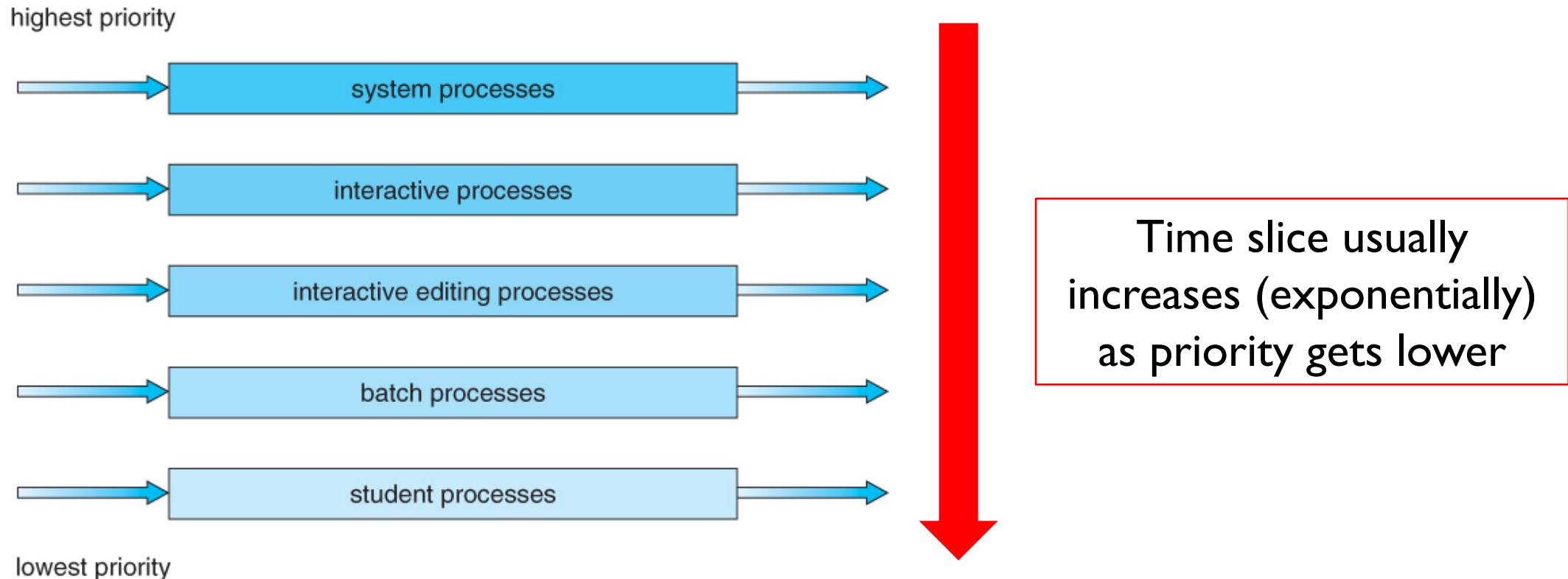
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- **Note:** Jobs cannot switch from queue to queue

MLQ: Overview



MLQ: Overview



Scheduling Algorithms: An Overview

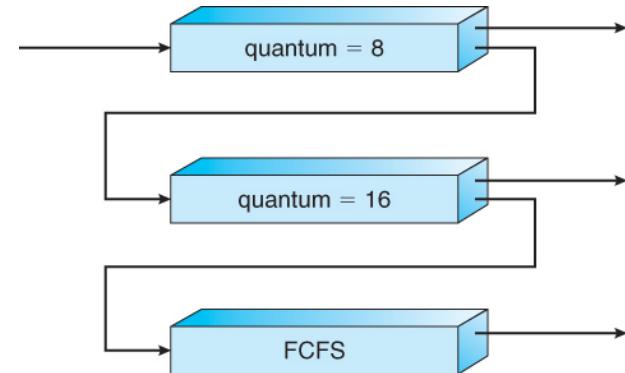
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- Similar to the ordinary MLQ scheduling, except jobs may be moved from one queue to another

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- Similar to the ordinary MLQ scheduling, except jobs may be moved from one queue to another
- Moving jobs may be required when:
 - The characteristics of a job change between CPU-intensive and I/O-intensive
 - A job that has waited for a long time can get bumped up into a higher priority queue for a while (to compensate the aging problem)



MLFQ: Adjusting Job Priority

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MLFQ: Adjusting Job Priority

- Job starts in the highest priority queue (by default)
- If job's time slice expires → drop its priority level by one unit
- If job's time slice does not expire (i.e., the context switch occurs due to an I/O request, instead) → increase its priority level by one unit (up to the top)
- CPU-bound jobs will quickly drop their priority
- I/O-bound jobs will stay at higher priority levels

MLFQ: Idea

- MLFQ is the most flexible but it is also the most complex to implement
- Some of the (many) parameters which define MLFQ systems include:
 - The number of queues
 - The scheduling algorithm for each queue
 - The methods used to upgrade or demote processes from one queue to another
 - The method used to determine which queue a process enters initially

Multilevel Feedback Queue (MLFQ): Example I

New 

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

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No I/O burst

Initial time quantum = 1

Context switch = 0

3 queues

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2	B	20
3	C	10

No I/O burst

Initial time quantum = 1

Context switch = 0

3 queues

$\text{JOB_ID}_{\frac{\text{job_exec_time}}{\text{total_elapsed_time}}} = \text{The job } \text{JOB_ID} \text{ has executed } \text{job_exec_time} \text{ time units after } \text{total_elapsed_time} \text{ time units}$

$A_7^2 = \text{The job } A \text{ has executed 2 time units after 7 time units overall}$

Multilevel Feedback Queue (MLFQ): Example I

New 

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

Queue	Time Slice (time units)	Jobs
1	1	
2	2	
3	4	

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New 

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

Queue	Time Slice (time units)	Jobs
1	1	A^1_1, B^1_2, C^1_3
2	2	
3	4	

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1	A	30
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Queue	Time Slice (time units)	Jobs
1	1	A^1_1, B^1_2, C^1_3
2	2	A^3_5, B^3_7, C^3_9
3	4	

Multilevel Feedback Queue (MLFQ): Example I

New 

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

Queue	Time Slice (time units)	Jobs
1	1	A^1_1, B^1_2, C^1_3
2	2	A^3_5, B^3_7, C^3_9
3	4	$A^7_{13}, B^7_{17}, C^7_{21}$

Multilevel Feedback Queue (MLFQ): Example I

New 

Order	Job	CPU burst (time units)
1	A	30
2	B	20
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Queue	Time Slice (time units)	Jobs
1	1	A^1_1, B^1_2, C^1_3
2	2	A^3_5, B^3_7, C^3_9
3	4	$A^7_{13}, B^7_{17}, C^7_{21}$ $A^{11}_{25}, B^{11}_{29}, C^{10}_{32}$

Multilevel Feedback Queue (MLFQ): Example II

New 

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

Multilevel Feedback Queue (MLFQ): Example II

New A | B | C

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

2 queues and C now alternates 1 time unit of CPU with 1 time unit of I/O

Queue	Time Slice (time units)	Jobs
1	1	
2	2	

Multilevel Feedback Queue (MLFQ): Example II

New

A	B	C
---	---	---

Order	Job	CPU burst (time units)
1	A	30
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2 queues and C now alternates 1 time unit of CPU with 1 time unit of I/O

Queue	Time Slice (time units)	Jobs
1	1	A^1_1, B^1_2, C^1_3
2	2	

Multilevel Feedback Queue (MLFQ): Example II

New

A	B	C
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1	A	30
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2 queues and C now alternates 1 time unit of CPU with 1 time unit of I/O

Queue	Time Slice (time units)	Jobs
1	1	A^1_1, B^1_2, C^1_3
2	2	A^3_5

Multilevel Feedback Queue (MLFQ): Example II

New 

Order	Job	CPU burst (time units)
1	A	30
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3	C	10

2 queues and C now alternates 1 time unit of CPU with 1 time unit of I/O

Queue	Time Slice (time units)	Jobs
1	1	$A^1_1, B^1_2, C^1_3, C^2_6$
2	2	A^3_5

Multilevel Feedback Queue (MLFQ): Example II

New

A	B	C
---	---	---

Order	Job	CPU burst (time units)
1	A	30
2	B	20
3	C	10

2 queues and C now alternates 1 time unit of CPU with 1 time unit of I/O

Queue	Time Slice (time units)	Jobs
1	1	$A^1_1, B^1_2, C^1_3, C^2_6$
2	2	A^3_5, B^3_8

Multilevel Feedback Queue (MLFQ): Example II

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A	B	C
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2 queues and C now alternates 1 time unit of CPU with 1 time unit of I/O

Queue	Time Slice (time units)	Jobs
1	1	$A^1_1, B^1_2, C^1_3, C^2_6, C^3_9$
2	2	A^3_5, B^3_8

Multilevel Feedback Queue (MLFQ): Example II

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A	B	C
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Queue	Time Slice (time units)	Jobs
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Queue	Time Slice (time units)	Jobs
1	1	$A^1_1, B^1_2, C^1_3, C^2_6, C^3_9, C^4_{12}, \dots, C^{10}_{30}$
2	2	$A^3_5, B^3_8, A^5_{11}, B^5_{14}, \dots, B^{12}_{32}, A^{14}_{34}, \dots$

MLFQ: Fairness Issue

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- It explicitly promotes short jobs (i.e., I/O-bound ones) by design

MLFQ: Fairness Issue

- MFLQ tries to mimic the optimal behavior of SJF in terms of average waiting time
- It explicitly promotes short jobs (i.e., I/O-bound ones) by design
- **Problem:** SJF (and MFLQ) might be unfair (as opposed to RR)

Any increase in fairness by giving long jobs a fraction of the CPU when shorter jobs could be instead selected will increase waiting time

MLFQ: Improving Fairness

- Give each queue a fraction of the CPU time
 - This is fair only if jobs are evenly distributed (i.e., uniformly) across queues

MLFQ: Improving Fairness

- Give each queue a fraction of the CPU time
 - This is fair only if jobs are evenly distributed (i.e., uniformly) across queues
- Adjust dynamically the priority of jobs as they don't get scheduled
 - This avoids starvation but average waiting time might increase when the system is overloaded (all jobs get to the higher priority queue, eventually)

Advanced Topics: Lottery Scheduling

- Give every job a certain number of lottery tickets

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As the number of time slices (i.e., the number of random picks) goes to infinity

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Law of Large Numbers

Lottery Scheduling: Policy

- Assign tickets to jobs as follows:
 - Give more tickets to short running jobs
 - Give few tickets to long running jobs

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- simulating SJF

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 - Give few tickets to long running jobs
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simulating SJF

Lottery Scheduling: Policy

- Assign tickets to jobs as follows:
 - Give more tickets to short running jobs
 - Give few tickets to long running jobs
- To avoid starvation, each job gets at least one ticket
- Degrades gracefully as system load changes
 - Adding/deleting a job affects all the other jobs proportionally

simulating SJF

Lottery Scheduling vs. All

Question:

What is the main difference between lottery scheduling and any other algorithm we have seen so far?

Lottery Scheduling vs. All

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What is the main difference between lottery scheduling and any other algorithm we have seen so far?

Answer:

This is the only example of **randomized** scheduler
(rather than deterministic one)

Lottery Scheduling: Example

#short jobs / #long jobs	% of CPU for each short job	% of CPU for each long job

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1 / 1		

Lottery Scheduling: Example

short jobs get **10** tickets each

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# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)
0/2		

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)
0/2	-	

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)
0/2	-	50% (1/2)

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)
0/2	-	50% (1/2)
2/0	50% (10/20)	-

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)
0/2	-	50% (1/2)
2/0	50% (10/20)	-
10/1	~9.9% (10/101)	~0.99% (1/101)

Lottery Scheduling: Example

short jobs get **10** tickets each

long jobs get **1** ticket each

# short jobs / # long jobs	% of CPU for each short job	% of CPU for each long job
1/1	~91% (10/11)	~9% (1/11)
0/2	-	50% (1/2)
2/0	50% (10/20)	-
10/1	~9.9% (10/101)	~0.99% (1/101)
1/10	50% (10/20)	5% (1/20)

Lottery Scheduling: CPU Assignment

n_{short} = total number of *short* jobs

n_{long} = total number of *long* jobs

$N = n_{short} + n_{long}$ = total number of jobs

m_{short} = number of tickets assigned to each *short* job

m_{long} = number of tickets assigned to each *long* job

$M = m_{short} * n_{short} + m_{long} * n_{long}$ = total number of tickets

Lottery Scheduling: CPU Assignment

n_{short} = total number of *short* jobs

n_{long} = total number of *long* jobs

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m_{short} = number of tickets assigned to each *short* job

m_{long} = number of tickets assigned to each *long* job

$M = m_{short} * n_{short} + m_{long} * n_{long}$ = total number of tickets

$$\text{CPU}_{short} = \frac{m_{short}}{M}$$

$$\text{CPU}_{long} = \frac{m_{long}}{M}$$

Lottery Scheduling: CPU Assignment Probability

m_i = number of tickets assigned to job i

N = total number of jobs

$$M = \sum_{i=1}^N m_i = \text{total number of tickets}$$

$$P(i) = \frac{m_i}{M} = \text{probability of job } i \text{ being scheduled}$$

Summary of CPU Scheduling Algorithms

- **First-Come-First-Serve (FCFS)**: Very simple, non-preemptive, generally unfair, and highly variant waiting time
- **Round Robin (RR)**: Fair but average waiting time may be long
- **Shortest Job First (SJF)**: Generally unfair and possible starvation, but provably optimal in terms of average waiting time (assuming we are able to correctly predict the length of the next CPU burst)
- **Multilevel Queuing (MLQ/MLFQ)**: An approximation of SJF
- **Lottery**: Fairer with a low average waiting time yet less predictable due to randomization