

Sistemi Operativi I

Corso di Laurea in Informatica
2022-2023



SAPIENZA
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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

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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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avg. waiting time =

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

SJF: PROs and CONs

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- Provably optimal when the goal is to minimize the avg. waiting time

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- PROs:

- Provably optimal when the goal is to minimize the avg. waiting time
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(preemptive SJF is called **SRTF** or **S**hortest **R**emaining **T**ime **F**irst)

- 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

- Predict the length of the next CPU burst, based on some historical measurement of recent burst times (for this process)

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$x_t = \text{actual length of the } t\text{-th CPU burst}$

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

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

$$s_1 = x_0$$

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

SJF: Estimating CPU Time of a Job

- Predict the length of the next CPU burst, based on some historical measurement of recent burst times (for this process)
- One simple, fast, and quite accurate method is the **exponential smoothing**

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

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

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

$$\begin{array}{l} s_1 = x_0 \\ s_{t+1} = \alpha x_t + (1 - \alpha) s_t \end{array}$$

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

Exponential Smoothing

$$s_1 = x_0$$

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

Exponential Smoothing

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

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

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

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

Recent history does not count

Exponential Smoothing

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

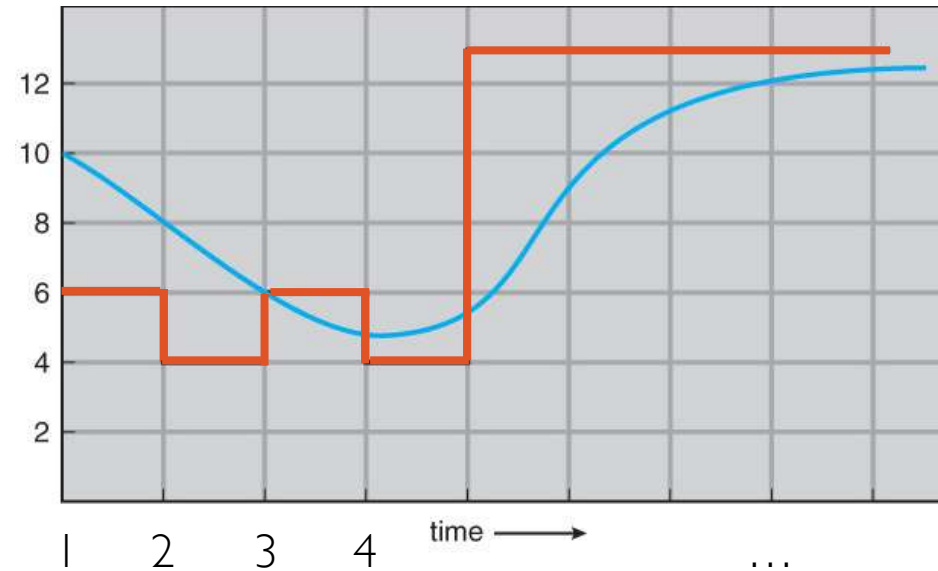
Exponential Smoothing

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

Exponential Smoothing

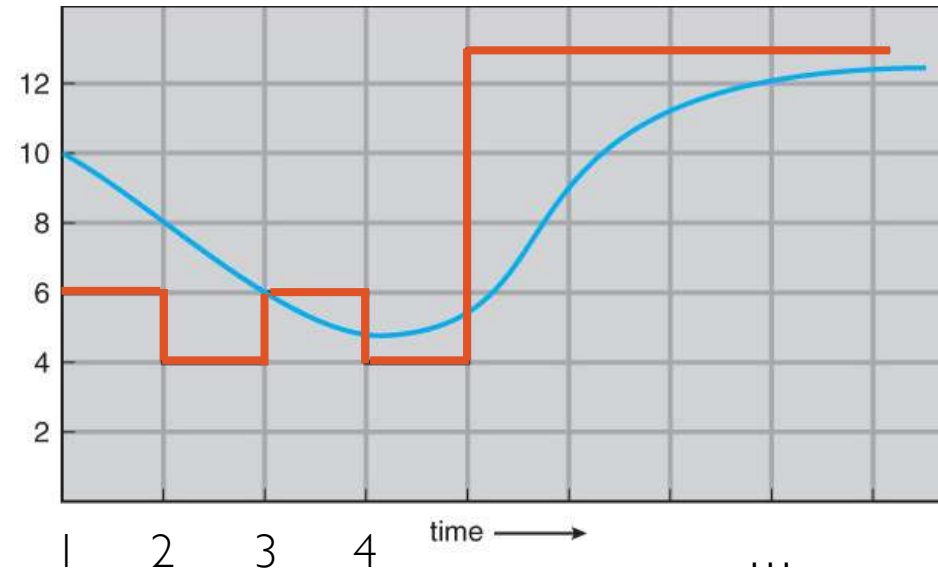
	t	0	1	2	3	4	5	6	7	...
observations	x_t	10	6	4	6	4	13	13	13	...
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

Exponential Smoothing



	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	...

Exponential Smoothing

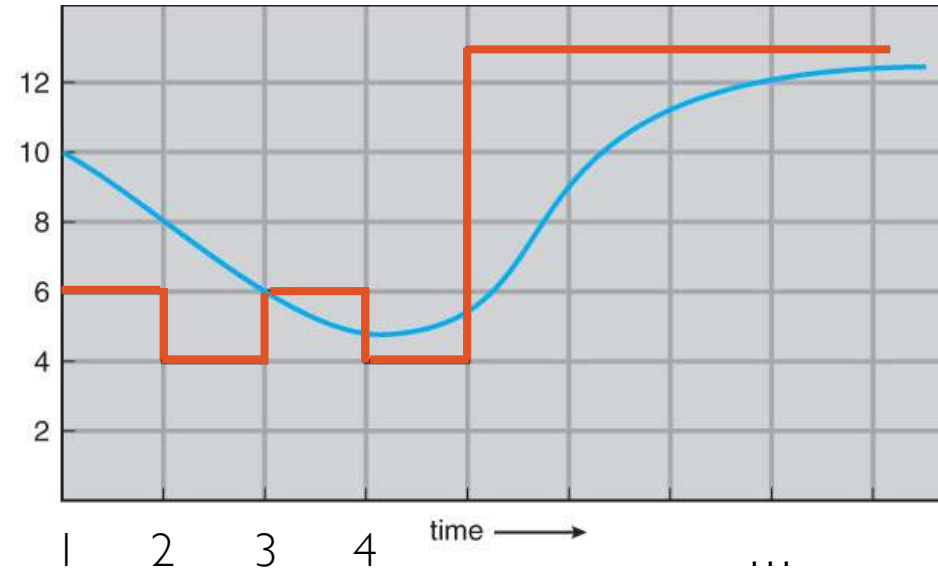


	t	0	1	2	3	4	5	6	7	...
observations	x_t	10	6	4	6	4	13	13	13	...
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

↑
 $s_1 = x_0$

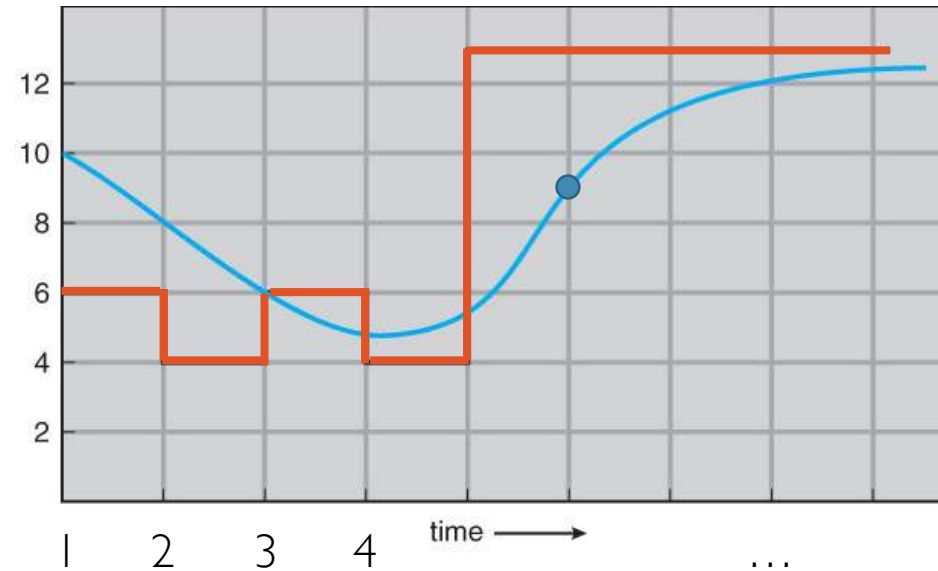
bootstrap

Exponential Smoothing



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

Exponential Smoothing

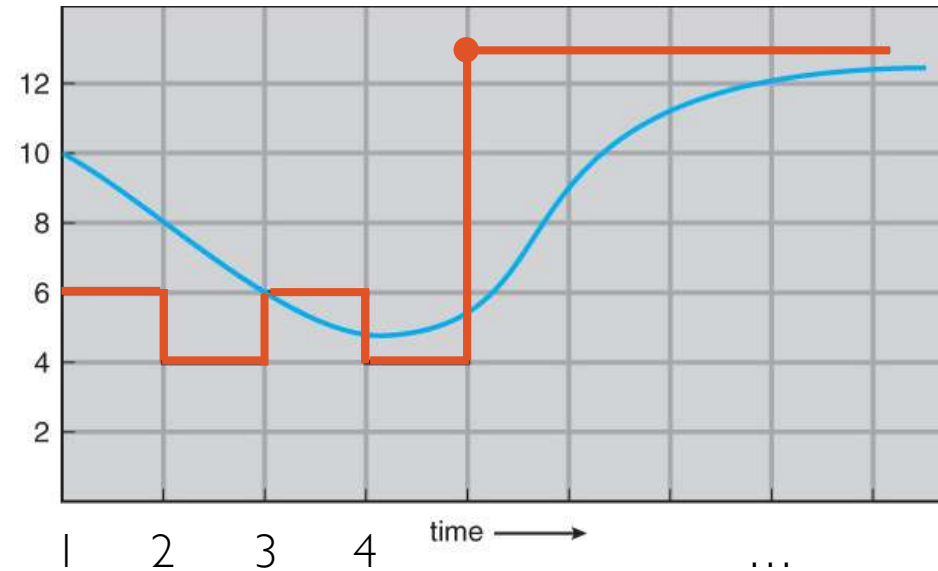


	t	0	1	2	3	4	5	6	7	...
observations	x_t	10	6	4	6	4	13	13	13	...
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

$$9 =$$

$$s_6 =$$

Exponential Smoothing



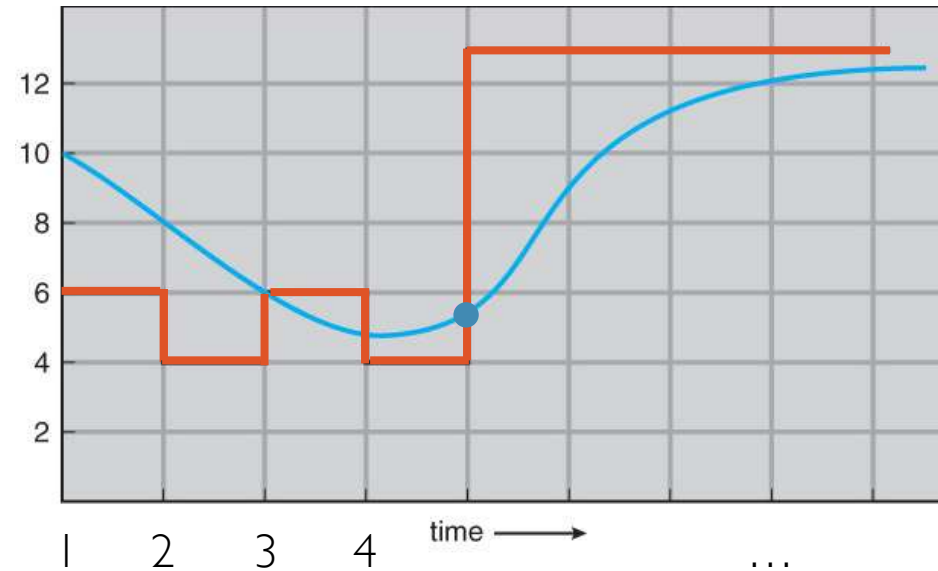
Usually, α is set to 0.5

	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, α 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	...

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

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

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

$$\begin{aligned}s_{t+1} &= \alpha x_t + (1 - \alpha)s_t \\s_t &= \alpha x_{t-1} + (1 - \alpha)s_{t-1} \\&\dots \\s_2 &= \alpha x_1 + (1 - \alpha)s_1 \\s_1 &= x_0\end{aligned}$$

predictions/forecasts

Exponential Smoothing

$$\begin{aligned}s_{t+1} &= \alpha x_t + (1 - \alpha)s_t \\s_t &= \alpha x_{t-1} + (1 - \alpha)s_{t-1} \\&\dots \\s_2 &= \alpha x_1 + (1 - \alpha)s_1 \\s_1 &= x_0\end{aligned}$$

actual observations

Exponential Smoothing

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

Exponential Smoothing

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Exponential Smoothing

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

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Past t observations

Exponential Smoothing

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

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Past t observations

bootstrap

Exponential Smoothing

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$$= \alpha [x_t + (1 - \alpha)x_{t-1} + (1 - \alpha)^2 x_{t-2} + \dots + (1 - \alpha)^{t-1} x_1] + (1 - \alpha)^t x_0$$

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

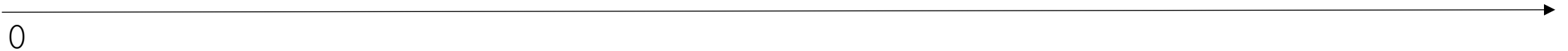
- SJF (non-preemptive) → Once the CPU is given to a process this will execute until it completes its CPU burst

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



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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
B	1	4
C	2	9
D	3	5



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
B	1	4
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

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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

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

SRTF: Example

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A	0	8
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C	2	9
D	3	5



$$\text{avg. waiting time} = [(17-0-8) + (5-1-4) + (26-2-9) + (10-3-5)] / 4 = 26/4 = 6.5$$

FCFS vs. RR vs. SJF

Assumptions:

5 jobs, different CPU burst

Time quantum = 1

Context switch = 0

Arrival time = 0 (for all jobs)

		turnaround time			waiting time		
Job	CPU burst	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	

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Job	CPU burst	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)

		turnaround time			waiting time		
Job	CPU burst	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

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- Round Robin (RR)
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- **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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- 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

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- 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

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)

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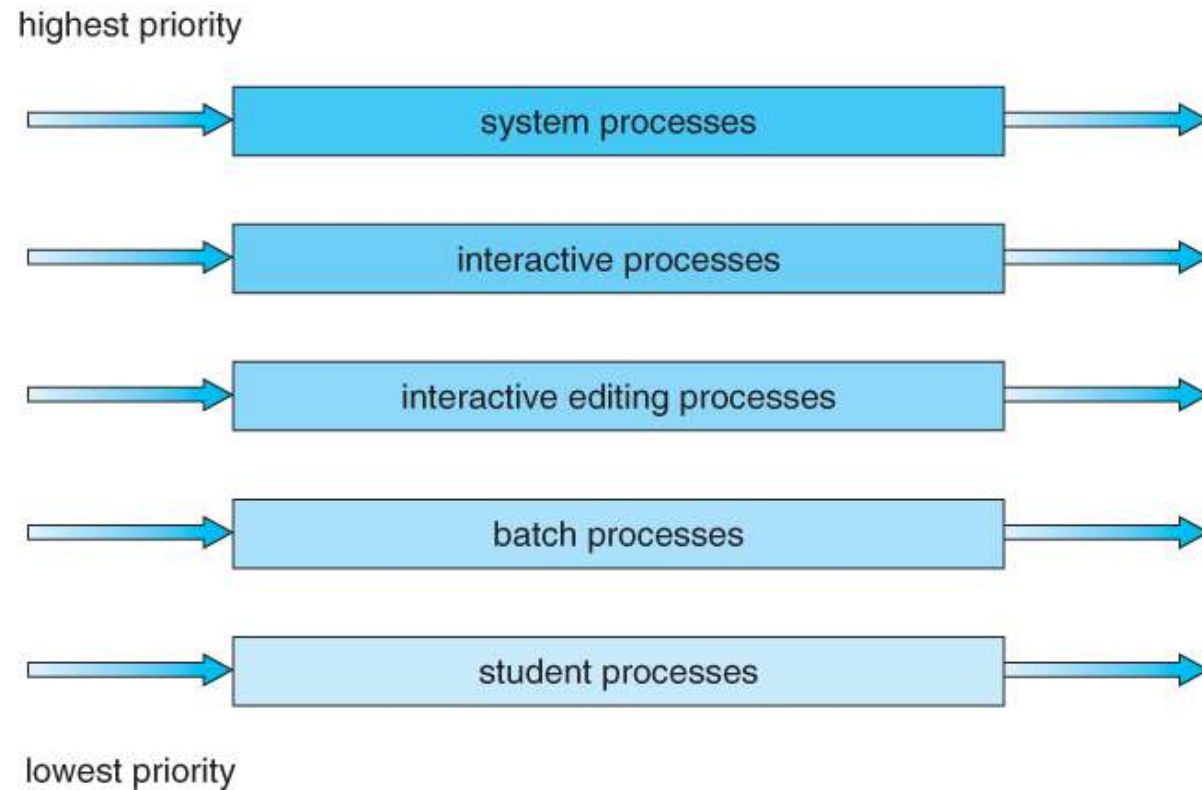
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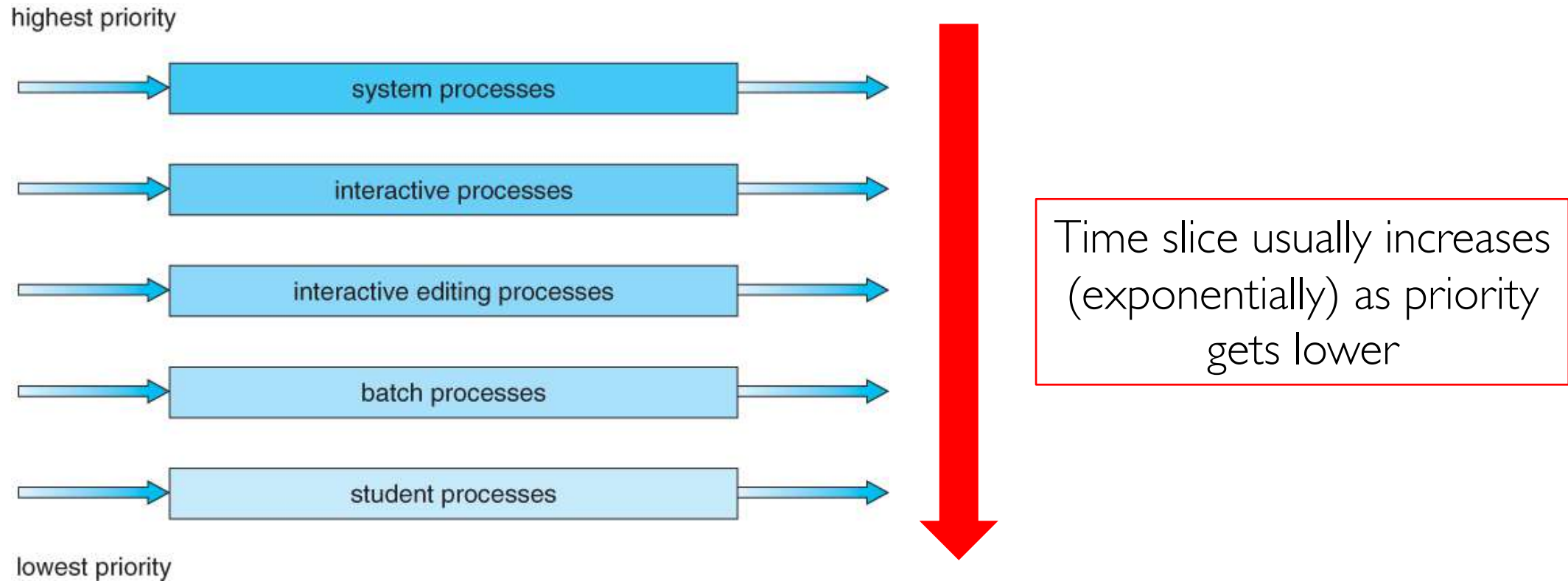
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- **Note:** Jobs cannot switch from queue to queue

MLQ: Overview



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Scheduling Algorithms: An Overview

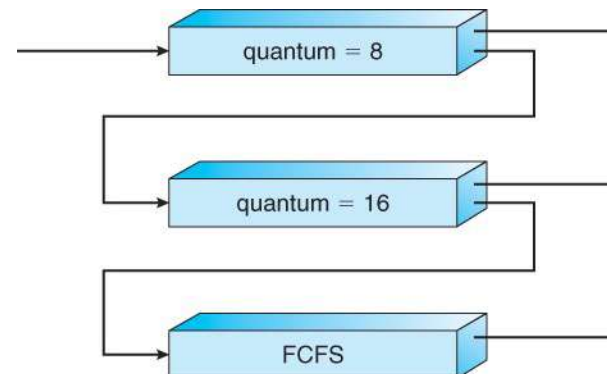
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- Similar to the ordinary MLQ scheduling, except jobs may be moved from one queue to another
- Moving jobs may be required when:
 - The characteristics of a job change between CPU-intensive and I/O-intensive
 - A job that has waited for a long time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



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- 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 A B C

Order	Job	CPU burst (time units)
1	A	30
2	B	20
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Context switch = 0

3 queues

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

A_7^2 = The job A has executed 2 time units after 7 time units overall

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3	4	

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Multilevel Feedback Queue (MLFQ): Example II

New

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

Order	Job	CPU burst (time units)
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Multilevel Feedback Queue (MLFQ): Example II

New A B C

Order	Job	CPU burst (time units)
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2 queues and C now
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2	2	$A^3_5, B^3_8, A^5_{11}, B^5_{14}, \dots, B^{12}_{32}, A^{14}_{34}, \dots$

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- MLFQ 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 MLFQ) 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

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- 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 highest priority queue, eventually)

Advanced Topics: Lottery Scheduling

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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
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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?

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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

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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)	

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#short jobs / #long jobs	% of CPU for each short job	% of CPU for each long job
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0/2		

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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)	~9% (1/11)
0/2	-	50% (1/2)

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10/1	~9.9% (10/101)	~0.99% (1/101)

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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

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

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

$$\begin{aligned} \text{CPU}_{short} &= \frac{m_{short}}{M} \\ \text{CPU}_{long} &= \frac{m_{long}}{M} \end{aligned}$$

Lottery Scheduling: CPU Assignment Probability

m_i = number of tickets assigned to job i

N = total number of jobs

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

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

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