Systems and Networking – Unit I

B.Sc. in Applied Computer Science and Artificial Intelligence

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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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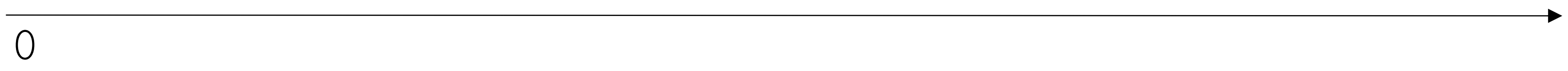

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avg. waiting time =

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avg. waiting time = (3 + 16 + 9 + 0)/4 = 7

SJF: PROs and CONs

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

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  - Works both with preemptive and non-preemptive schedulers

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- PROs:
  - Provably optimal when the goal is to minimize the avg. waiting time
  - Works both with preemptive and non-preemptive schedulers

    (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

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

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$x_t =$ *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

- Predict the length of the next CPU burst, based on some historical measurement of recent burst times (for this process)
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$$x_t = \textit{actual} \text{ length of the } t\text{-th CPU burst}$$

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

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

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

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

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

Exponential Smoothing

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

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

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	…

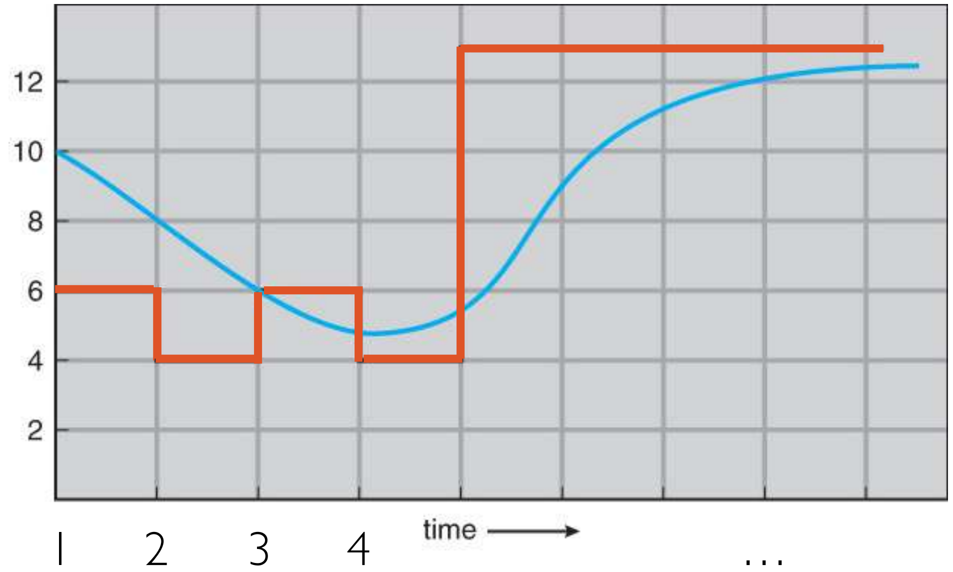
Exponential Smoothing

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

Exponential Smoothing

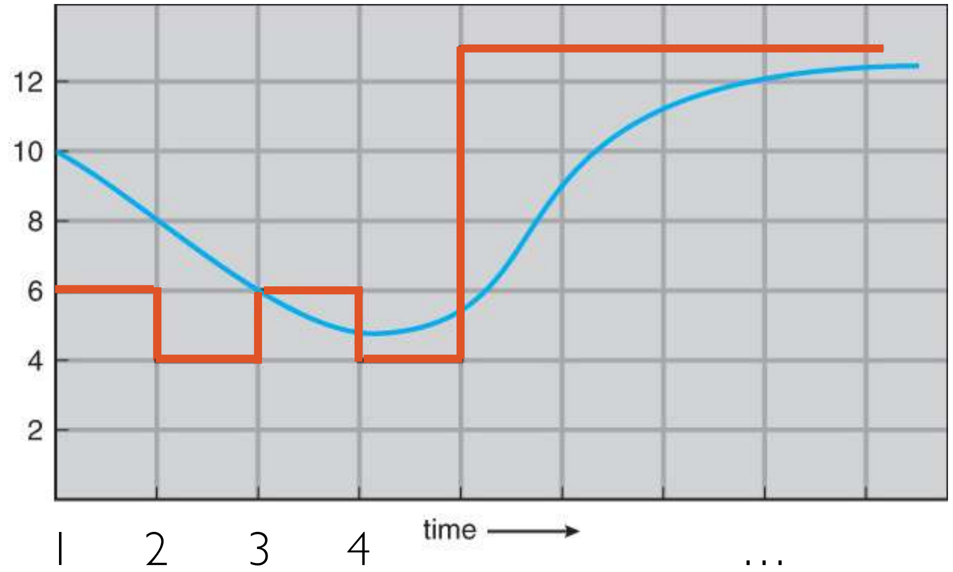
	t	0	1	2	3	4	5	6	7	...
observations	x_t	10	6	4	6	4	13	13	13	...
predictions	s_{t+1}	10	8	6	6	5	9	11	12	...

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



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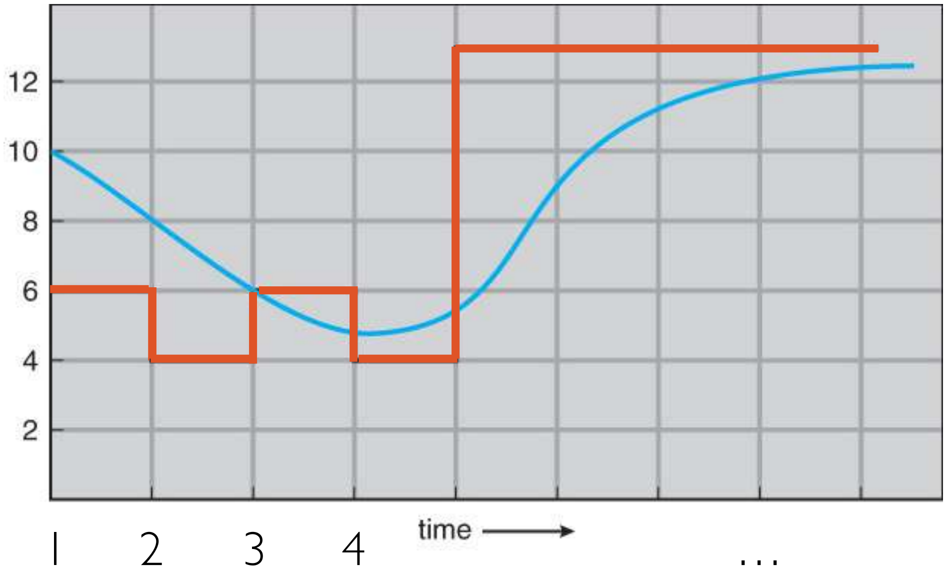
observations x_t	10	6	4	6	4	13	13	13	...
predictions s_{t+1}	10	8	6	6	5	9	11	12	...

$s_1 = x_0$

bootstrap

Exponential Smoothing



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observations x_t	10	6	4	6	4	13	13	13	...
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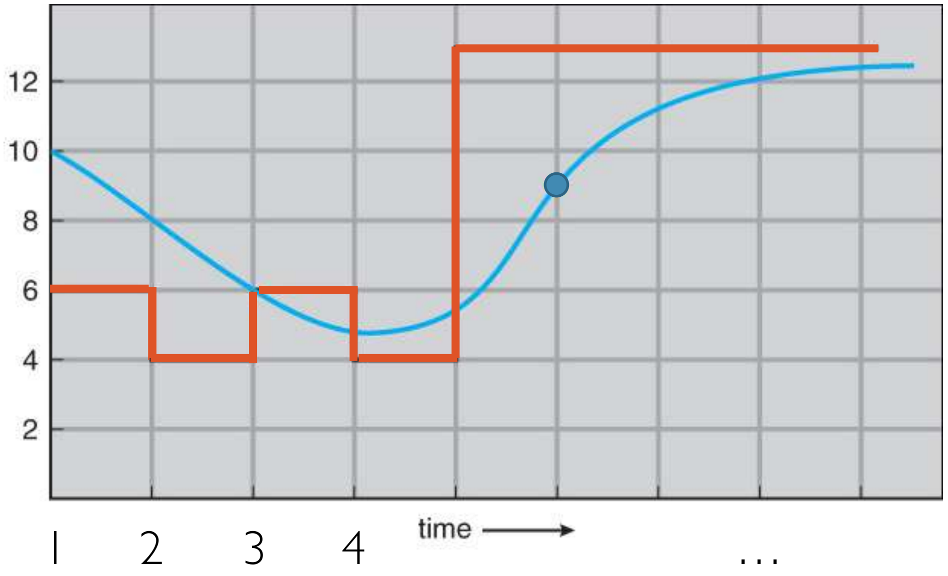
Exponential Smoothing

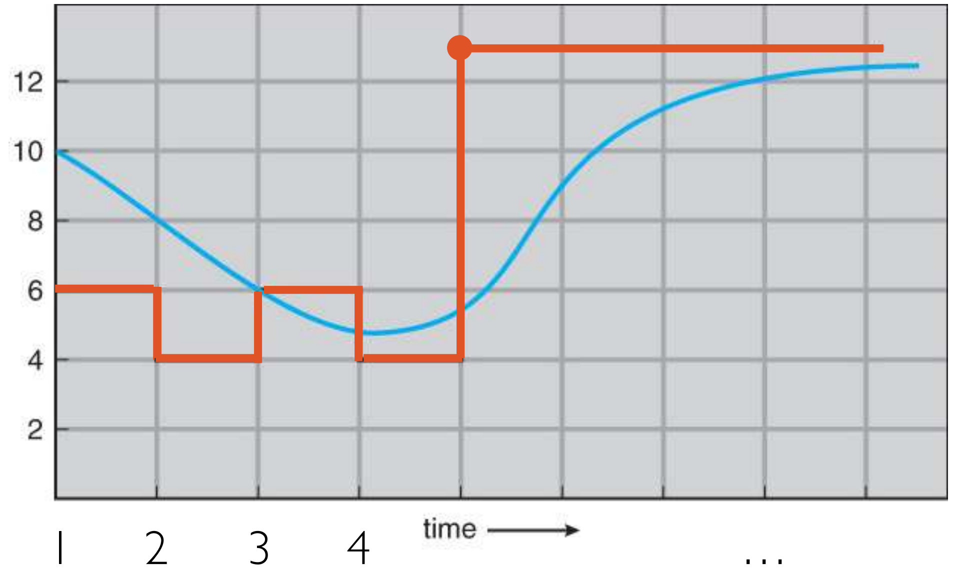


t	0	1	2	3	4	5	6	7	...
observations x_t	10	6	4	6	4	13	13	13	...
predictions s_{t+1}	10	8	6	6	5	$\boxed{9}$	11	12	...

$$9 =$$

$$s_6 =$$

Exponential Smoothing



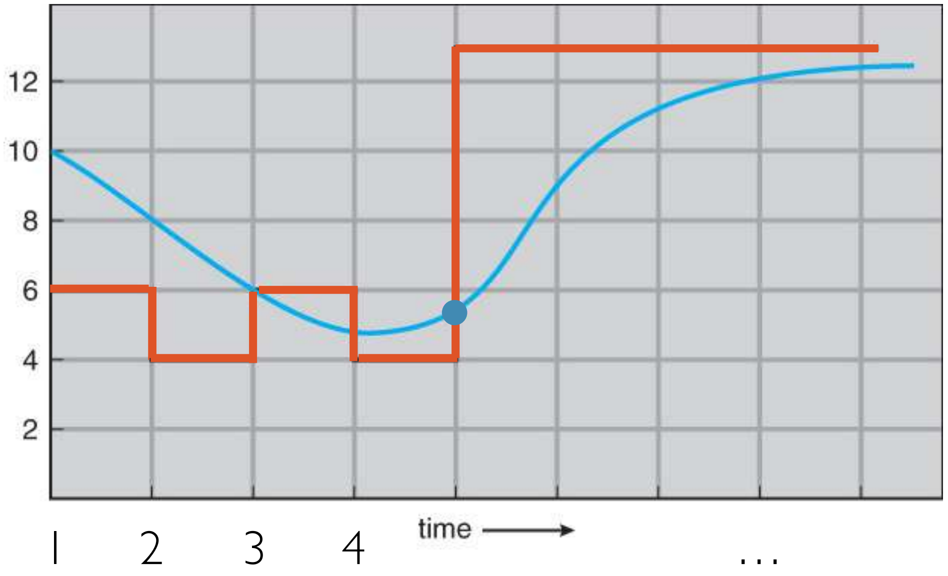
Usually, alpha is set to 0.5

	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



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	t	0	1	2	3	4	5	6	7	...
observations	x_t	10	6	4	6	4	13	13	13	...
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$$9 = 0.5 * 13 + 0.5 * 5$$

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

Exponential Smoothing

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

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

$$\cdots$$

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

$$s_1 = x_0$$

Exponential Smoothing

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

predictions/forecasts

Exponential Smoothing

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

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

$$\ldots$$

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

$$s_1 = \boxed{x_0}$$

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

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

Exponential Smoothing

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$$\ldots$$

$$= \alpha x_t + \alpha(1-\alpha)x_{t-1} + \alpha(1-\alpha)^2 x_{t-2} + \alpha(1-\alpha)^3 x_{t-3} + \ldots + (1-\alpha)^{t-1} s_2$$

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Past t observations

Exponential Smoothing

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

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Past t observations

bootstrap

Exponential Smoothing

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

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 $\{1, (1-\alpha), (1-\alpha)^2, (1-\alpha)^3, \ldots\}$

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

SRTF: Example

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SRTF: Example

Job	Arrival time	CPU burst (time units)
A	0	8
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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

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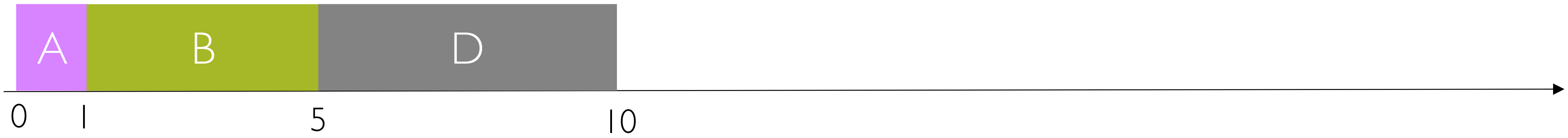

D is scheduled and will execute until it finishes its **5** CPU burst units (no more jobs arrived in the meantime)

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
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C	2	9
D	3	5

avg. waiting time =

SRTF: Example

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

SRTF: Example

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A	0	8
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D	3	5

avg. waiting time = [(17-0-8) + (5-1-4)]/4

SRTF: Example

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

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
B	1	4
C	2	9
D	3	5

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	

FCFS vs. RR vs. SJF

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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	
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

- 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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- 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)

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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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- Two common options are:
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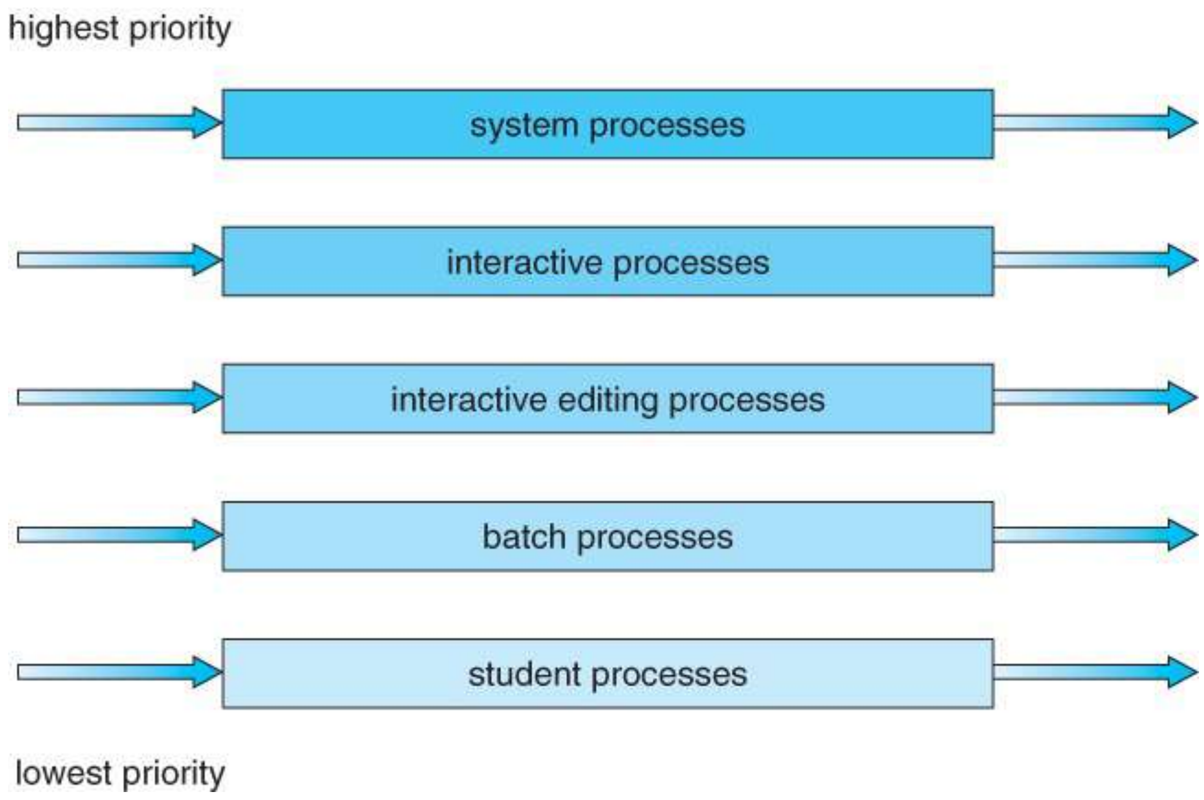
- Note: Jobs cannot switch from queue to queue

MLQ: Overview



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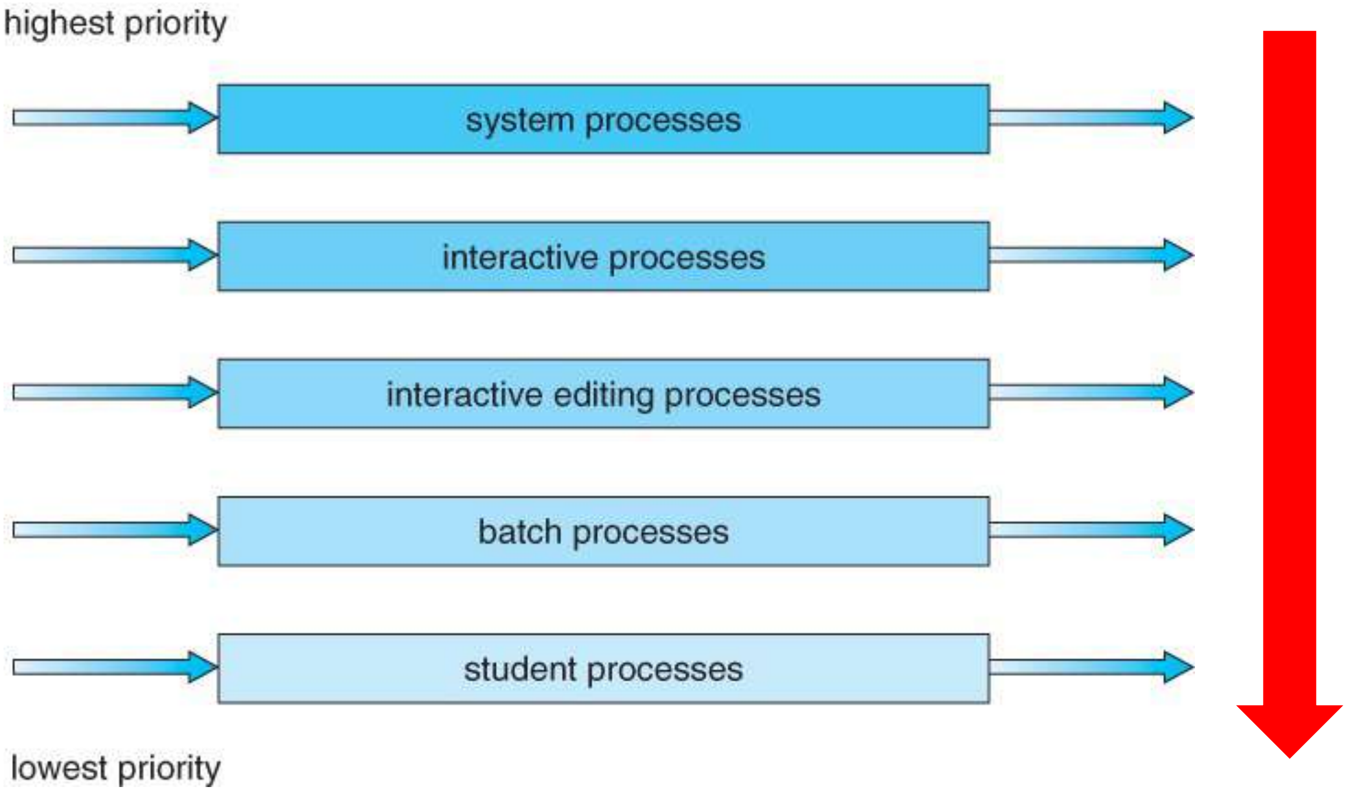

Time slice usually increases (exponentially) as priority gets lower

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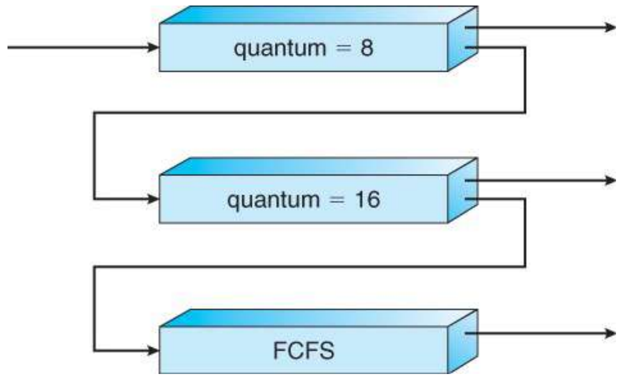
- Similar to the ordinary MLQ scheduling, except jobs may be moved from one queue to another
- Moving jobs may be required when:
  - The characteristics of a job change between CPU-intensive and I/O-intensive
  - A job that has waited for a long time can get bumped up into a higher priority queue for 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 1

New | A | B | C

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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strict priority between queues

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$$\text{JOB\_ID}^{job\_exec\_time}_{total\_elapsed\_time} = \text{The job JOB\_ID has executed } job\_exec\_time \text{ time units after } total\_elapsed\_time \text{ time units}$$

$$A^2_7 = \text{The job } A \text{ has executed 2 time units after 7 time units overall}$$

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Queue	Time Slice (time units)	Jobs
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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 alternates 1 time unit of CPU with 1 time unit of I/O

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Queue	Time Slice (time units)	Jobs
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2	2	A^{3}_{5}, B^{3}_{8}, A^{5}_{11}, B^{5}_{14}, …, B^{12}_{32}, A^{14}_{34}, …

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- 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

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  - This is fair only if jobs are evenly distributed (i.e., uniformly) across queues

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- Adjust dinamically 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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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

- 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

Lottery Scheduling vs. All

Question:

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

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What is the main difference between lottery scheduling and any other algorithgm 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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2/0	50% (10/20)	-
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

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

$$m_{short} = \text{number of tickets assigned to each } short \text{ job}$$
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$$\boxed{\begin{aligned} \text{CPU}_{short} &= \frac{m_{short}}{M} \\ \text{CPU}_{long} &= \frac{m_{long}}{M} \end{aligned}}$$

Lottery Scheduling: CPU Assignment Probability

$$m_i = \text{number of tickets assigned to job } i$$

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

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

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

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