Principles of Operating Systems
CS 446/646

4. CPU Scheduling

a. Concepts of Scheduling

b. Scheduling Algorithms

- ✓ Scheduling in batch systems
- ✓ Scheduling in interactive systems

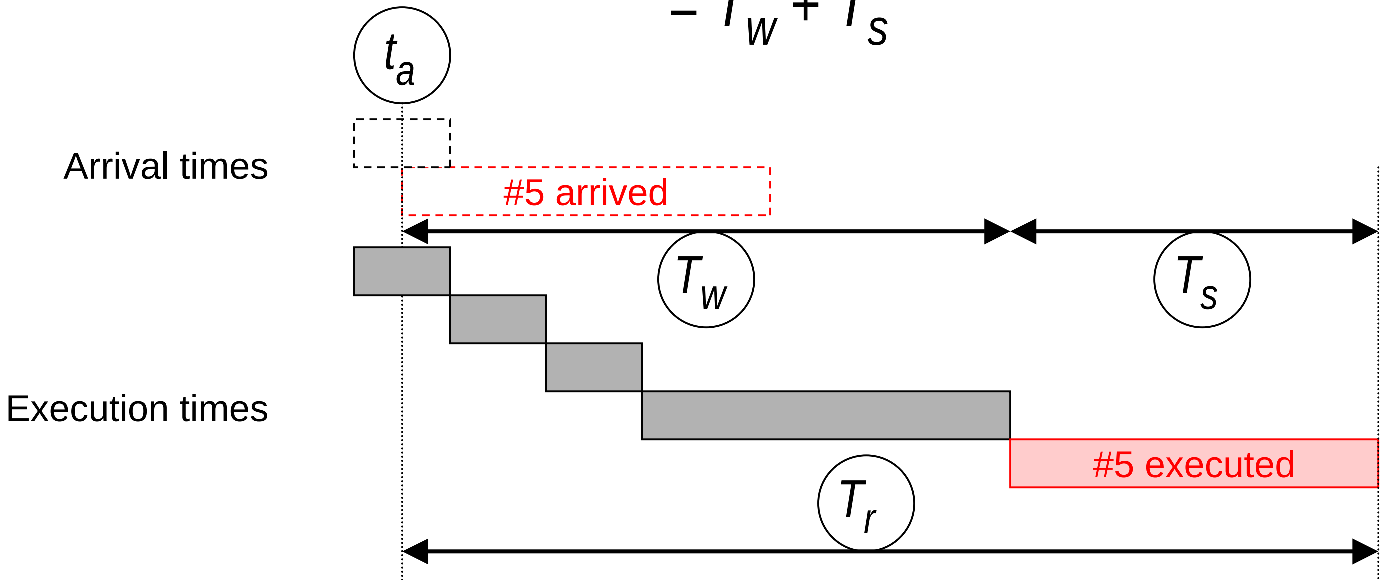
c. Queuing Analysis

d. Thread Scheduling

4.b Scheduling Algorithms

Scheduling in batch systems

- **Scheduling metrics**
  - ✓ arrival time t_a = time the process became "Ready" (again)
  - ✓ wait time T_w = time spent waiting for the CPU
  - ✓ service time T_s = time spent executing in the CPU
  - ✓ <u>turnaround time</u> T_r = total time spent waiting and executing $= T_w + T_s$

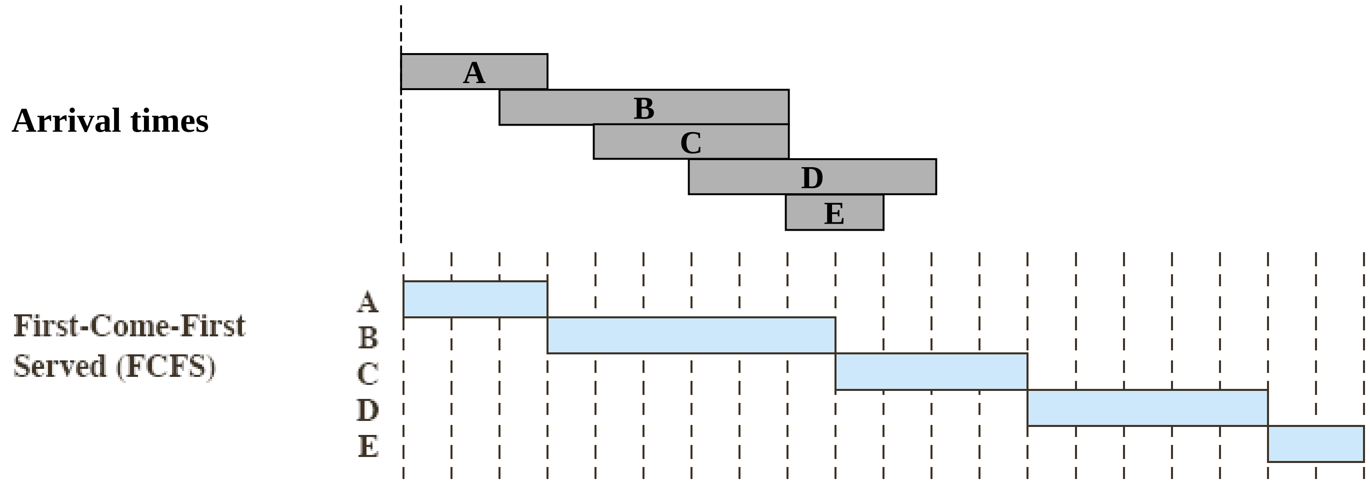


$T_r / T_s = 2.5$

4.b Scheduling Algorithms

Scheduling in batch systems

- ➢ **First-Come-First-Served (FCFS)**
  - ✓ processes are assigned the CPU in the order they request it
  - ✓ when the running process blocks, the first “Ready” is run next
  - ✓ when a process gets “Ready”, it is put at the end of the queue



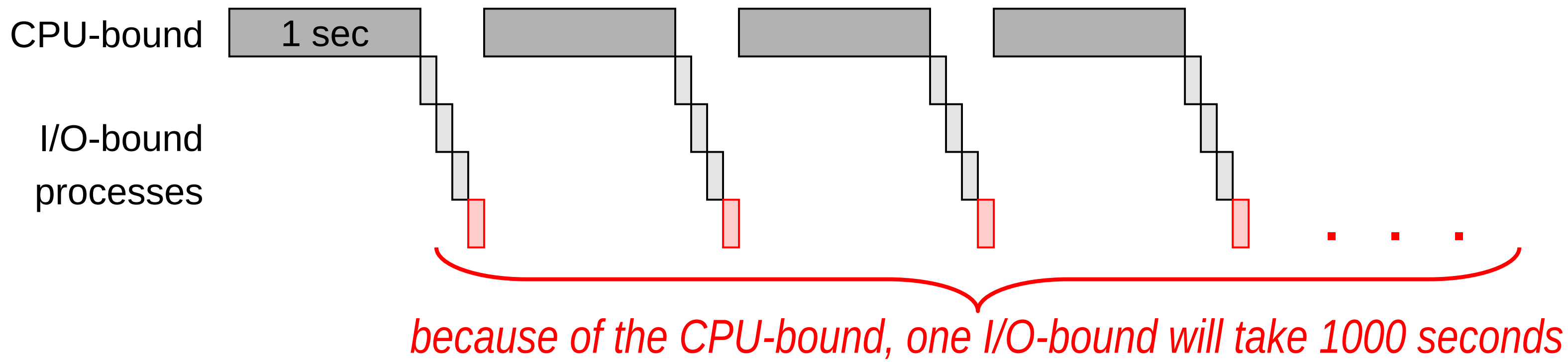
FCFS	Finish Time Turnaround Time (T_r) T_r/T_s	A	B	C	D	E	Mean
	Finish Time	3	9	13	18	20	
	Turnaround Time (T_r)	3	7	9	12	12	8.60
	T_r/T_s	1.00	1.17	2.25	2.40	6.00	2.56

FCFS scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms
Scheduling in batch systems

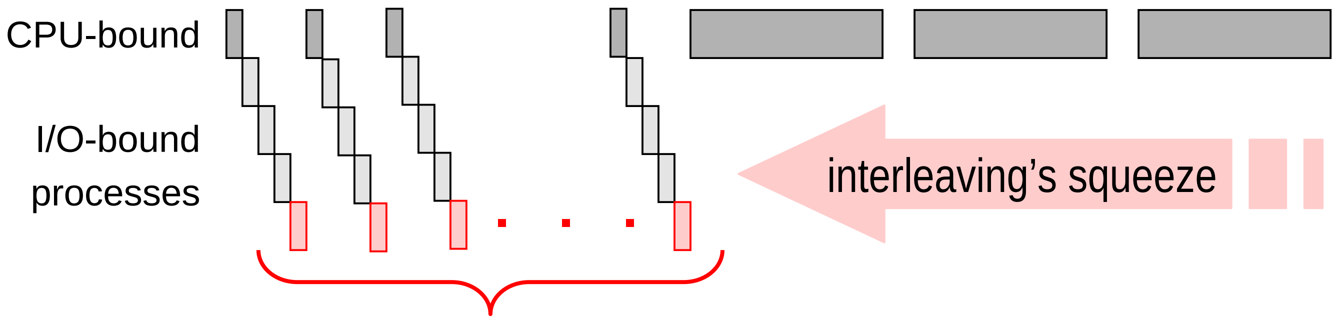
- First-Come-First-Served (FCFS)
  - ✓ nonpreemptive, oldest and simplest to program
  - ✓ apparently “fair” but very inefficient; example:
    - a CPU-bound process runs 1 sec, then reads 1 disk block
    - several I/O-bound processes run little CPU, but must read 1000 disk blocks



→ *preempt the CPU-bound more often to let the I/O-bound progress*

4.b Scheduling Algorithms

Scheduling in batch systems



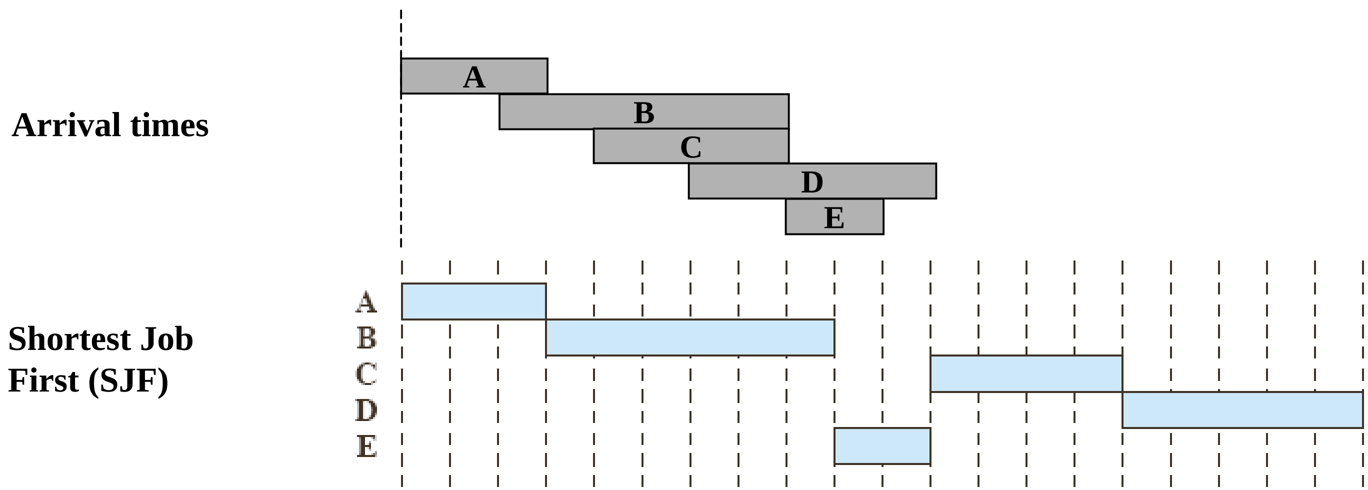
by preempting the CPU-bound every 10ms (100 Hz), each I/O-bound now takes only 10 seconds (without bothering the CPU-bound too much ~10s)

→ *see preemptive algorithms (Round-Robin, etc.) in later sections*

4.b Scheduling Algorithms

Scheduling in batch systems

- **Shortest Job First (SJF)**
  - ✓ <u>nonpreemptive</u>, assumes the run times are known in advance
  - ✓ among several equally important "Ready" jobs (or CPU bursts), the scheduler picks the one that will finish the earliest



SJF		A	B	C	D	E	Mean
	Finish Time	3	9	15	20	11	
	Turnaround Time (T_r)	3	7	11	14	3	7.60
	T_r/T_s	1.00	1.17	2.75	2.80	1.50	1.84

SJF scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in batch systems

- Shortest Job First (SJF)
  - ✓ example:

(a) no SJF   (b) SJF

a) turnaround times T_r = 8, 12, 16, 20 $\rightarrow$ mean T_r = 14

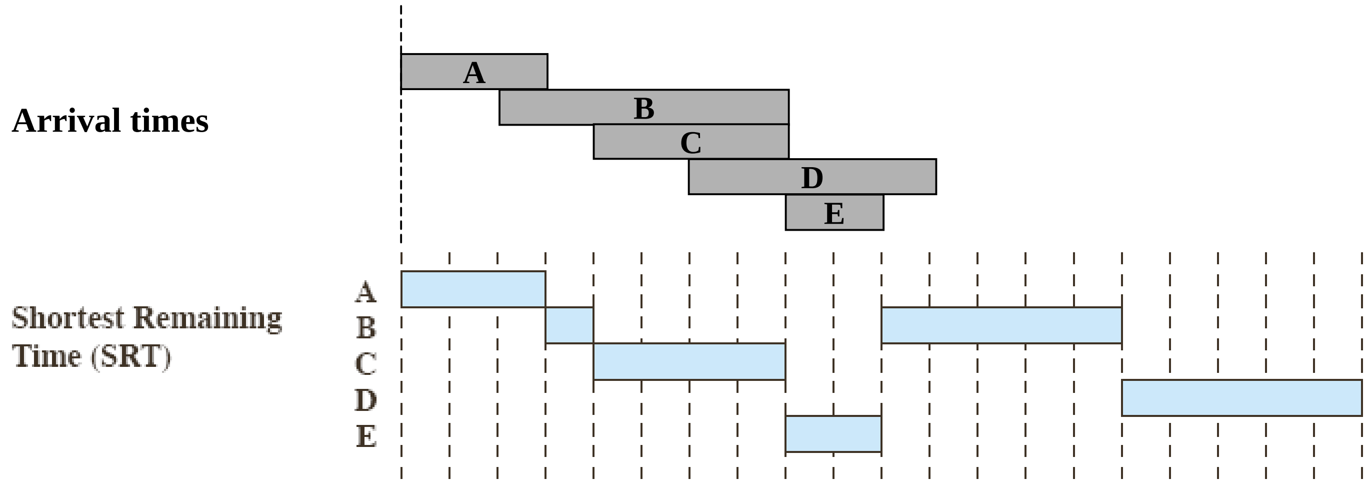
b) turnaround times T_r = 4, 8, 12, 20 $\rightarrow$ mean T_r = 11

- ✓ SJF is optimal among jobs available immediately; proof:
  - generally, with service times $T_s = a, b, c, d$ the mean turnaround time is: $T_r = (4a + 3b + 2c + d) / 4$, therefore it is always better to schedule the longest process (d) last
- ✓ however, being non-preemptive, SJF does not deal well with jobs arriving subsequently (ex: 2,4,1,1,1 arriving at 0,0,3,3,3)

4.b Scheduling Algorithms

Scheduling in batch systems

- **Shortest Remaining Time (SRT)**
  - ✓ preemptive version of SJF, also assumes known run time
  - ✓ choose the process whose remaining run time is shortest
  - ✓ allows new short jobs to get good service



SRT		A	B	C	D	E	Mean
	Finish Time	3	15	8	20	10	
	Turnaround Time (T_r)	3	13	4	14	2	7.20
	T_r/T_s	1.00	2.17	1.00	2.80	1.00	1.59

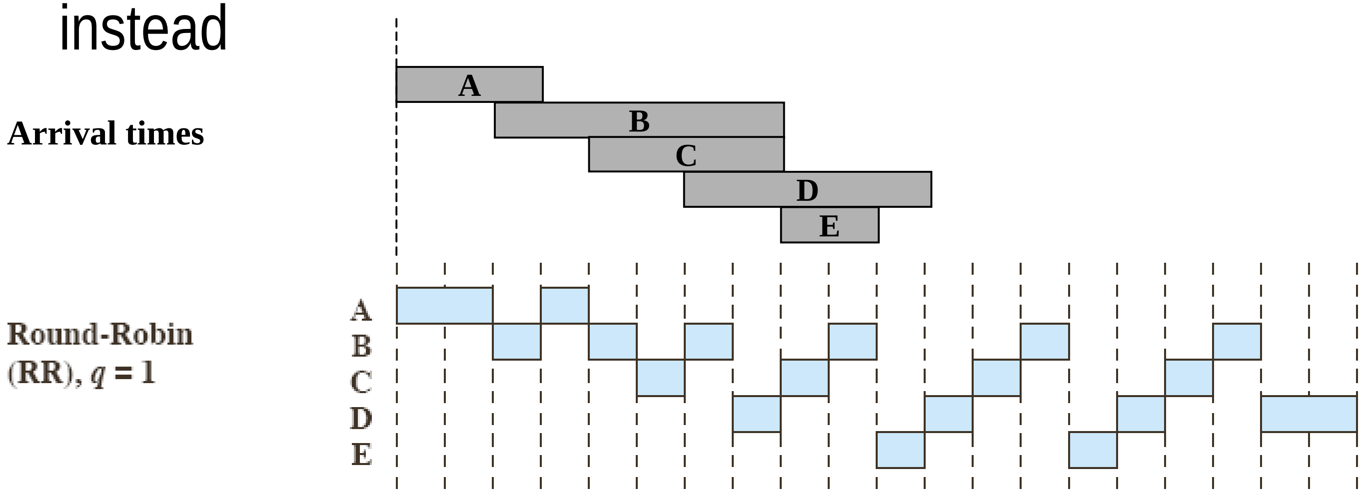
SRT scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Round-Robin (RR)**
  - ✓ <u>preemptive</u> FCFS, based on a timeout interval, the **quantum** *q*
  - ✓ the running process is interrupted by the clock and put last in a FIFO "Ready" queue; then, the first "Ready" process is run instead



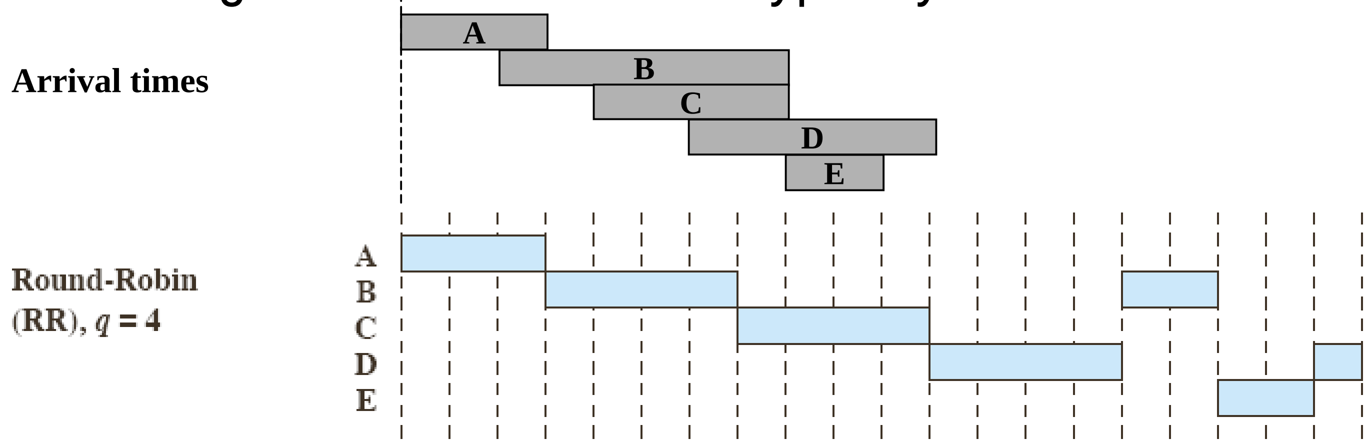
RR $q = 1$		A	B	C	D	E	Mean
	Finish Time	4	18	17	20	15	
	Turnaround Time (T_r)	4	16	13	14	7	10.80
	T_r/T_s	1.33	2.67	3.25	2.80	3.50	2.71

RR (q = 1) scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms
Scheduling in interactive systems

- **Round-Robin (RR)**
  - ✓ a crucial parameter is the quantum *q* (generally ~10–100ms)
    - *q* should be big compared to context switch latency (~10μs)
    - *q* should be less than the longest CPU bursts, otherwise RR degenerates to FCFS → typically at 80% of the distrib. tail



RR $q = 4$							
	Finish Time	A 3	B 17	C 11	D 20	E 19	Mean
	Turnaround Time (T_r)	3	15	7	14	11	10.00
	T_r/T_s	1.00	2.5	1.75	2.80	5.50	2.71

RR (q = 4) scheduling policy

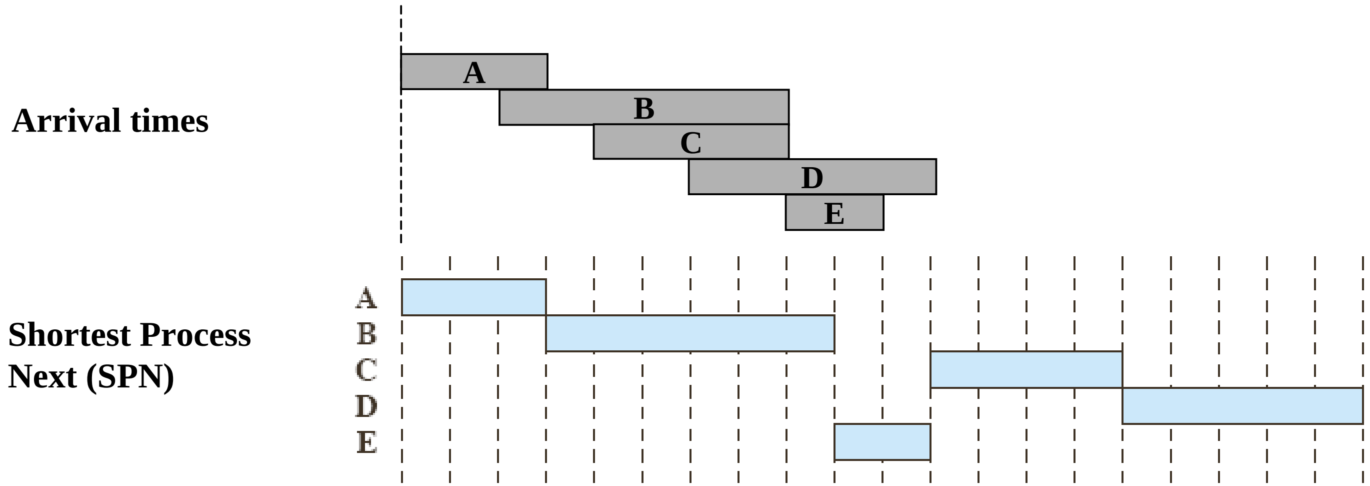
Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

➢ Shortest Process Next (SPN)

- ✓ same as SJF: pick the one that should finish the earliest
- → *difference in the interactive system: the prediction about future duration is not known but estimated from past durations*



SPN	Finish Time Turnaround Time (T_r) T_r/T_s	**A** 3 3 1.00	**B** 9 7 1.17	**C** 15 11 2.75	**D** 20 14 2.80	**E** 11 3 1.50	**Mean** 7.60 1.84

SPN scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Estimation of processing time from past**
  - ✓ predicted service time = simple averaging of past run times
    - $S(n+1) = (1/n) \sum T(i)$

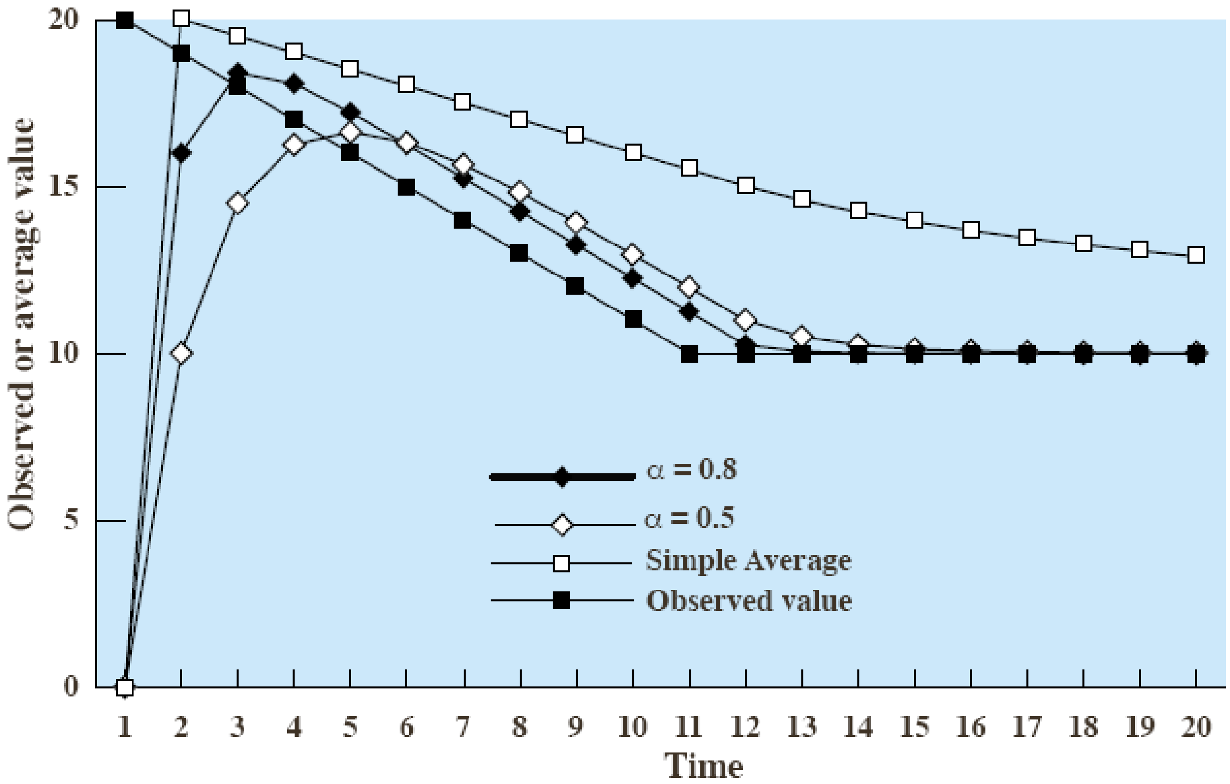
    $\Leftrightarrow S(n+1) = T(n)/n + (1 - 1/n)\, S(n)$

  - ✓ exponential averaging, also called "aging"
    - $S(n+1) = \alpha\, T(n) + (1-\alpha)\, S(n), \quad 0 < \alpha \leq 1$
    - high α forgets past runs quickly
    - low α remembers past runs for a long time

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Estimation of processing time from past**
  - ✓ "aging" tracks changes in process behavior faster than the mean



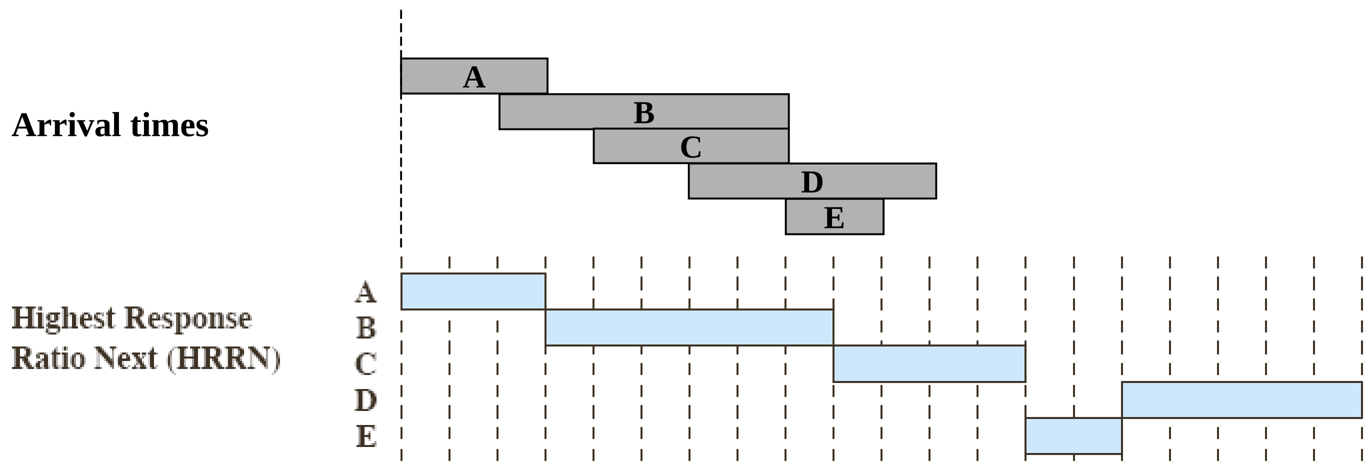
Example of exponential averaging in duration estimation

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Highest Response Ratio Next (HRRN)**
  - ✓ minimize the normalized turnaround time T_r / T_s
  - → *compromise between FCFS, which favors long processes, and SPN, which favors short processes*



HRRN	Finish Time Turnaround Time (T_r) T_r/T_s	A 3 3 1.00	B 9 7 1.17	C 13 9 2.25	D 20 14 2.80	E 15 7 3.5	Mean 8.00 2.14

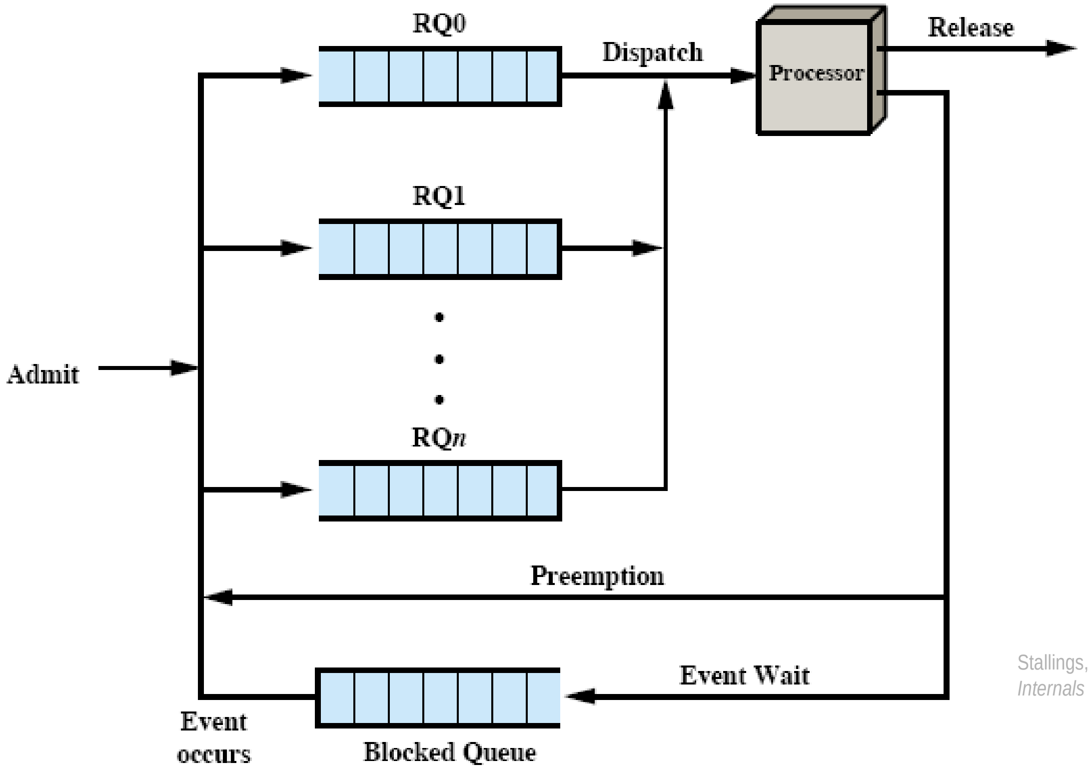
HRRN scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Priority Scheduling**
  - ✓ several "Ready" process queues, with different priorities

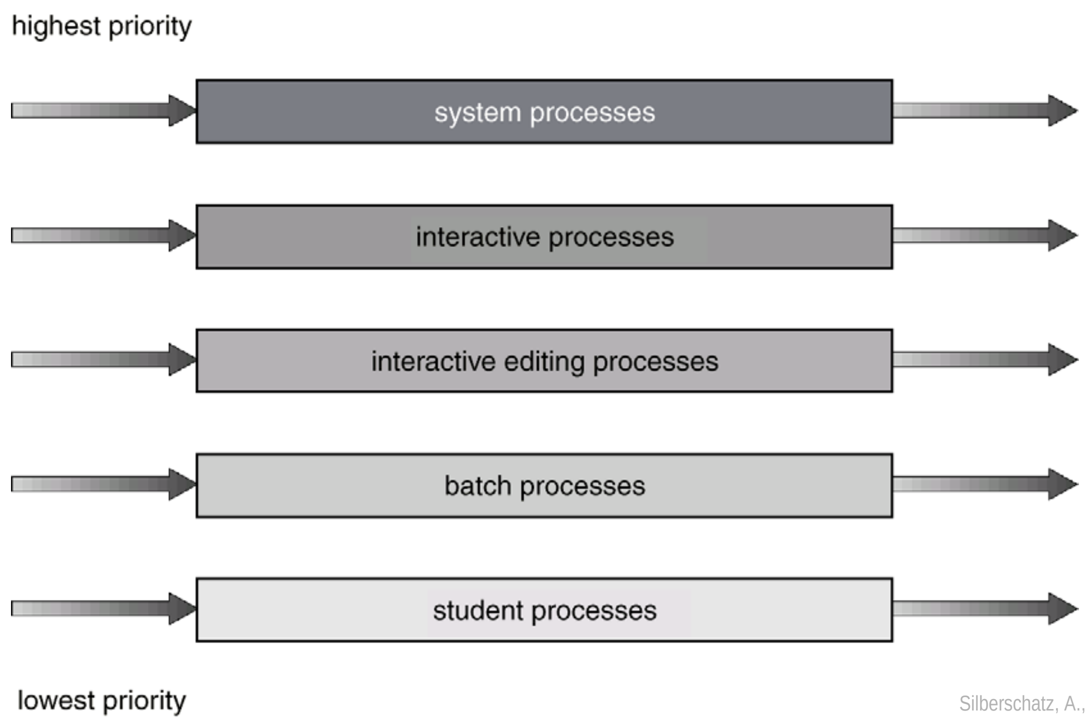


Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Priority queuing

4.b Scheduling Algorithms
Scheduling in interactive systems

- **Priority Scheduling**
  - ✓ processes are assigned to queues based on their properties (memory size, priority, bound type, etc.)



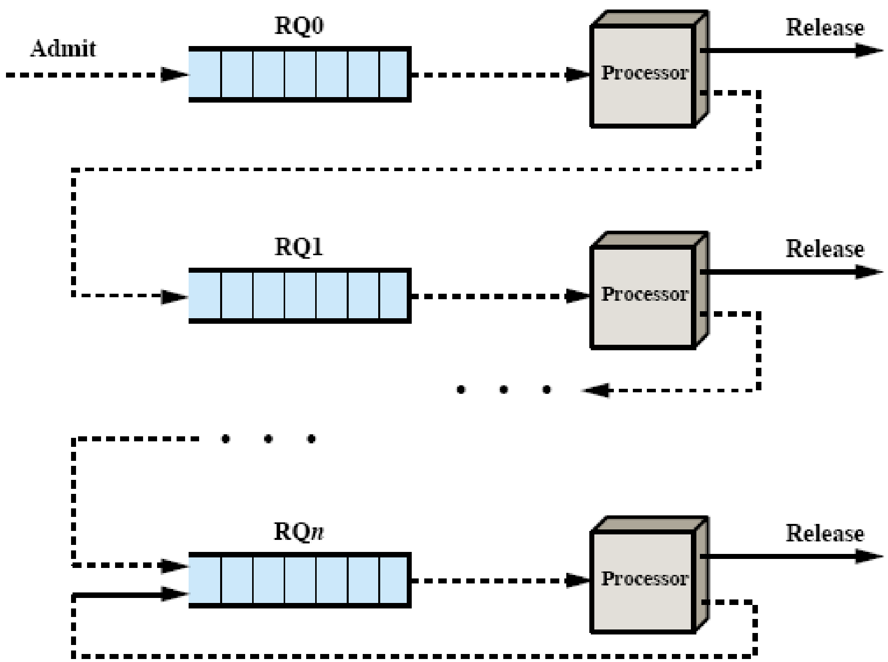
Multilevel queue scheduling

Silberschatz, A., Galvin, P. B. and Gagne. G. (2003)
Operating Systems Concepts with Java (6th Edition).

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Priority Scheduling with Feedback (FB)**
  - ✓ processes can be moved among queues
  - ✓ each queue has its own policy, generally RR with variable $q(Q_i)$



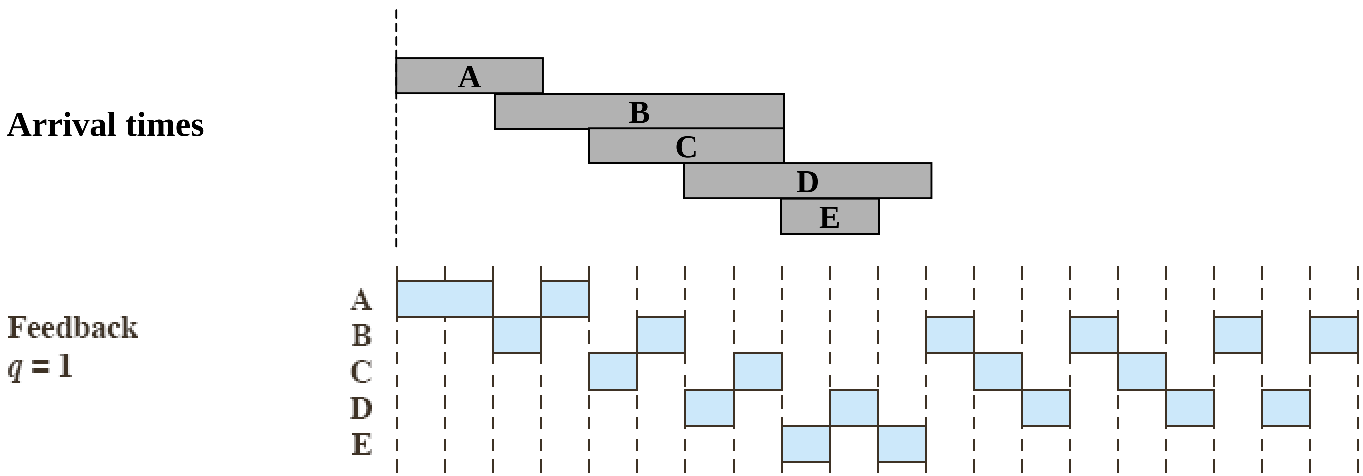
Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Priority queuing

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Priority Scheduling with Feedback (FB)**
  - ✓ each time a process is preempted, it is demoted to a lower-level queue
  - ✓ tends to leave I/O-bound in higher priority queues, as desired



FB $q = 1$							
		A	**B**	**C**	**D**	**E**	**Mean**
	Finish Time	4	20	16	19	11	
	Turnaround Time (T_r)	4	18	12	13	3	10.00
	T_r/T_s	1.33	3.00	3.00	2.60	1.5	2.29

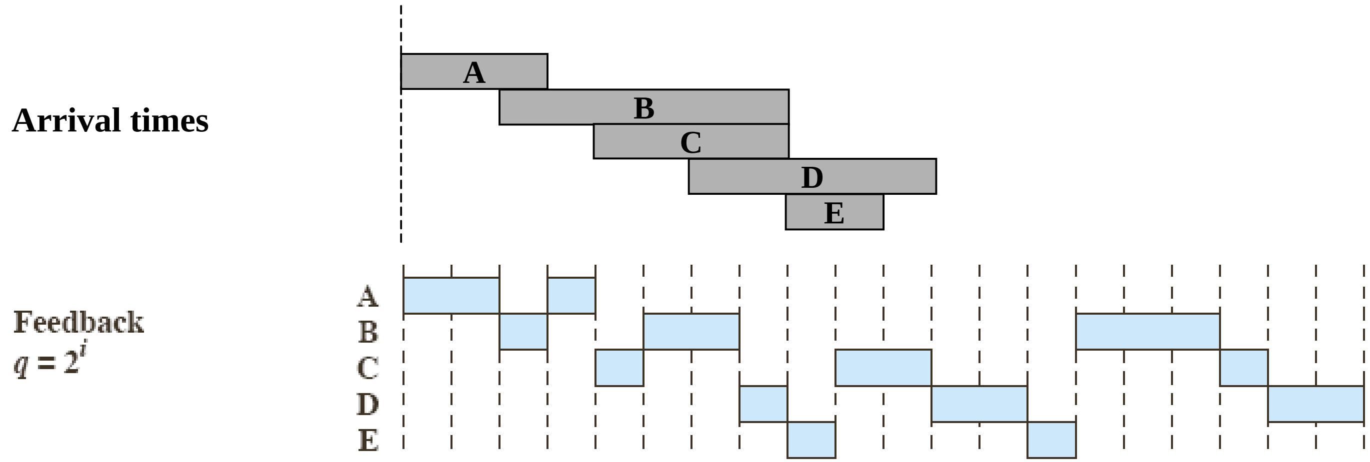
FB ($q = 1$) scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Priority Scheduling with Feedback (FB)**
  - ✓ a uniform RR quantum for all queues might create starvation
  - ✓ to compensate for increasing wait times in lower queue, increase q, too; for example $q = 2^i$



		A	B	C	D	E	Mean
FB $q = 2^i$	Finish Time	4	17	18	20	14	
	Turnaround Time (T_r)	4	15	14	14	6	10.60
	T_r/T_s	1.33	2.50	3.50	2.80	3.00	2.63

FB ($q = 2^i$) scheduling policy

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

	Process	A	B	C	D	E	
	Arrival Time	0	2	4	6	8	
	Service Time (T_s)	3	6	4	5	2	Mean
FCFS	Finish Time	3	9	13	18	20	
	Turnaround Time (T_r)	3	7	9	12	12	8.60
	T_r/T_s	1.00	1.17	2.25	2.40	6.00	2.56
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RR $q = 4$	Finish Time	3	17	11	20	19	
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SPN	Finish Time	3	9	15	20	11	
	Turnaround Time (T_r)	3	7	11	14	3	7.60
	T_r/T_s	1.00	1.17	2.75	2.80	1.50	1.84
SRT	Finish Time	3	15	8	20	10	
	Turnaround Time (T_r)	3	13	4	14	2	7.20
	T_r/T_s	1.00	2.17	1.00	2.80	1.00	1.59
HRRN	Finish Time	3	9	13	20	15	
	Turnaround Time (T_r)	3	7	9	14	7	8.00
	T_r/T_s	1.00	1.17	2.25	2.80	3.5	2.14
FB $q = 1$	Finish Time	4	20	16	19	11	
	Turnaround Time (T_r)	4	18	12	13	3	10.00
	T_r/T_s	1.33	3.00	3.00	2.60	1.5	2.29
FB $q = 2^i$	Finish Time	4	17	18	20	14	
	Turnaround Time (T_r)	4	15	14	14	6	10.60
	T_r/T_s	1.33	2.50	3.50	2.80	3.00	2.63

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

4.b Scheduling Algorithms

Scheduling in interactive systems

- Traditional UNIX scheduling
  - ✓ multilevel feedback using RR within each of the priority queues
  - ✓ typically 1-second preemption timeout
  - ✓ system of integer priorities recomputed once per second
  - ✓ a base priority divides processes into fixed bands of priority levels; in decreasing order:
    - swapper
    - block I/O device control
    - file manipulation
    - character I/O device control
    - user processes

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