University of Nevada, Reno CSE

Principles of Operating Systems

CS 446/646

4. CPU Scheduling

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Principles of Operating Systems
CS 446/646

0. Course Presentation
1. Introduction to Operating Systems
2. Processes
3. Memory Management
4. CPU Scheduling
5. Input/Output
6. File System
7. Case Studies

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4. CPU Scheduling

a. Concepts of Scheduling

b. Scheduling Algorithms

c. Queuing Analysis

d. Thread Scheduling

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4. CPU Scheduling

a. **Concepts of Scheduling**
   - ✓ Three-level scheduling
   - ✓ Purpose of CPU scheduling

b. **Scheduling Algorithms**

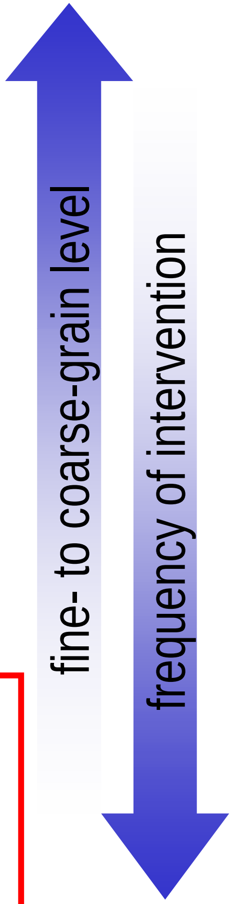
c. **Queuing Analysis**

d. **Thread Scheduling**

4.a Concepts of Scheduling

Three-level scheduling

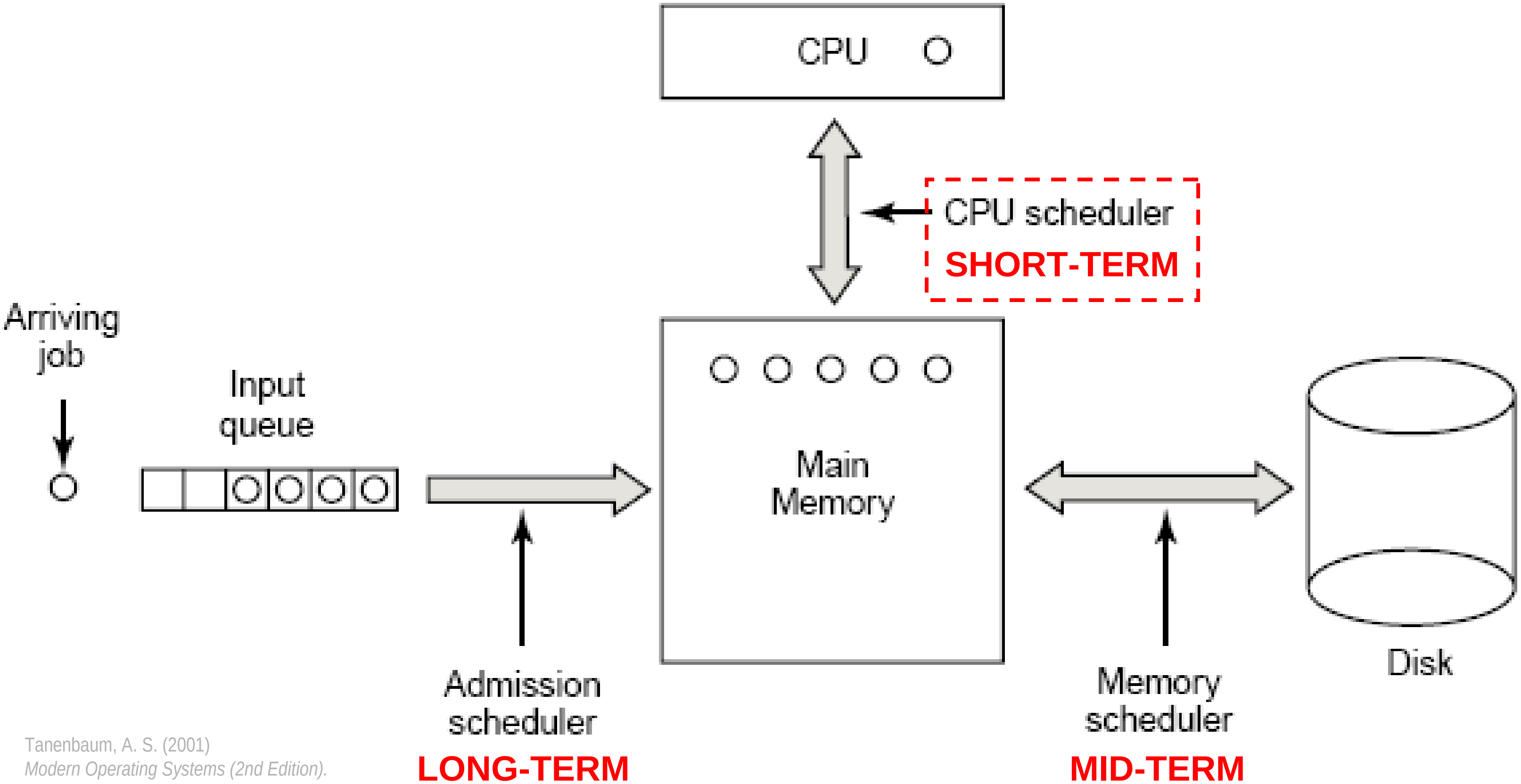
- **Long-term scheduling (mostly in batch)**
  - ✓ the decision to add a program to the pool of processes to be executed: controls the degree of multiprogramming
- **Medium-term scheduling**
  - ✓ the decision to add to the number of processes that are partially or fully in main memory (“swapping”)
  - ✓ *not* the same as paging: swapping out means removing <u>all</u> the pages of a process
- **Short-term scheduling = CPU scheduling**
  - ✓ the decision as to which available processes in memory are to be executed by the processor (“dispatching”)



4.a Concepts of Scheduling

Three-level scheduling

- Three-level scheduling



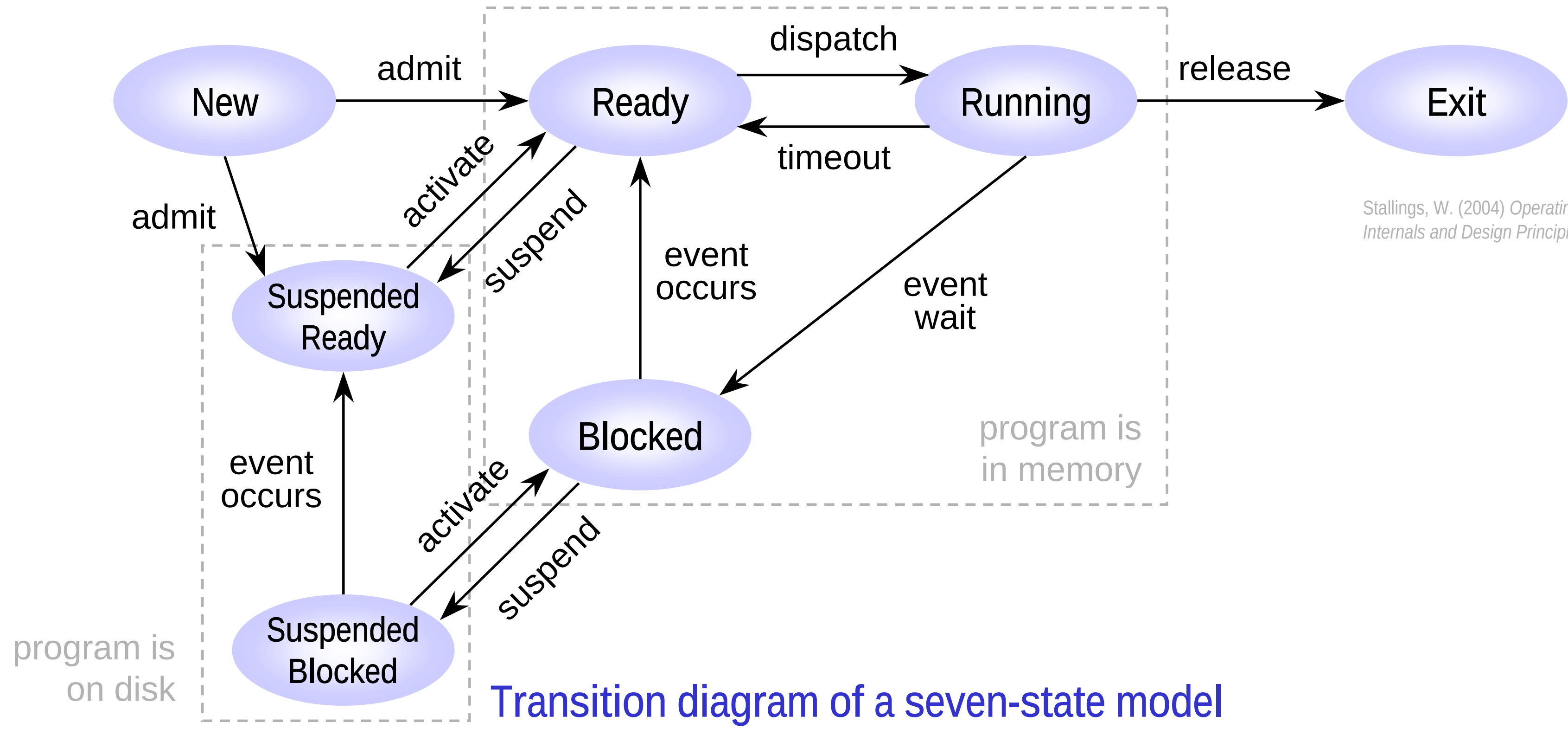
Tanenbaum, A. S. (2001)
Modern Operating Systems (2nd Edition).

Three-level scheduling

4.a Concepts of Scheduling

Three-level scheduling

- Reminder: process states



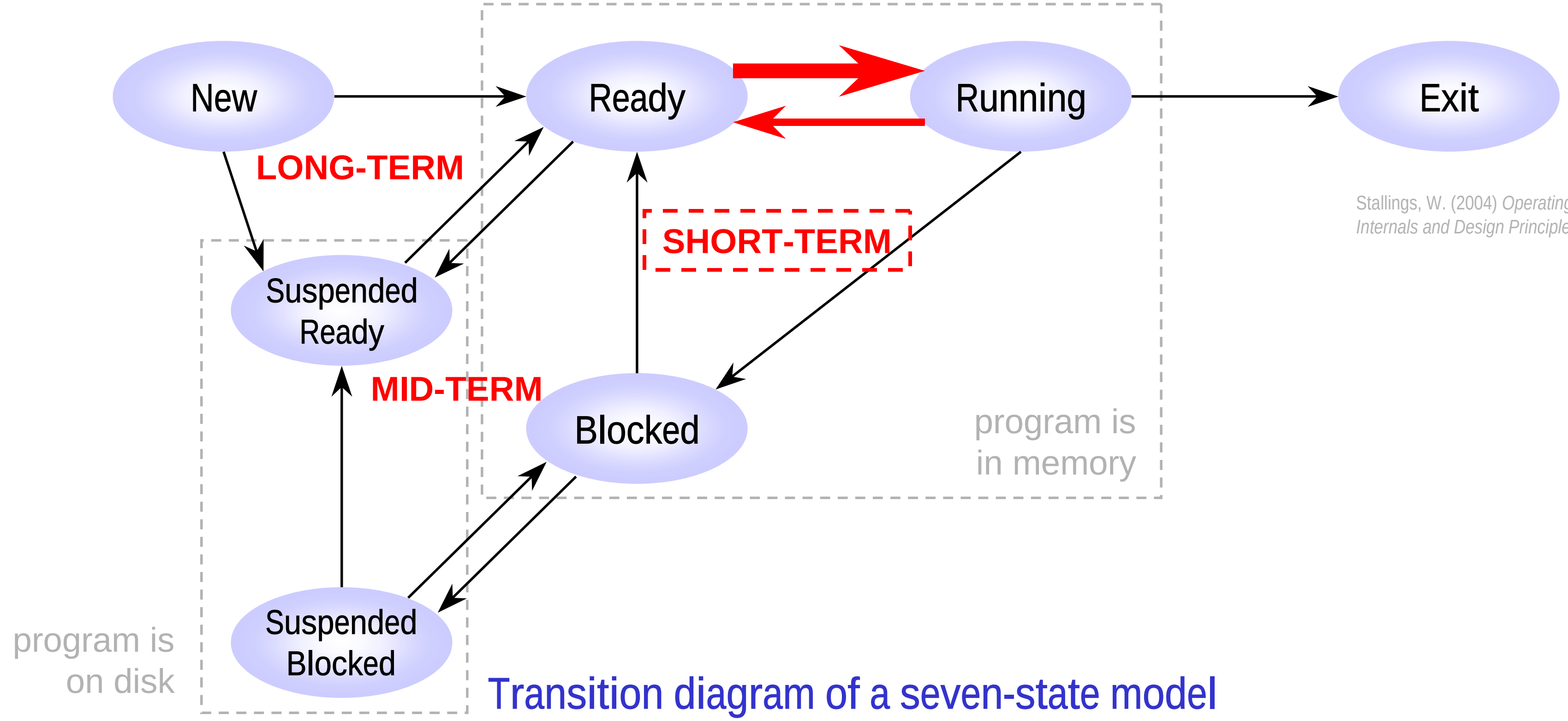
Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Transition diagram of a seven-state model

4.a Concepts of Scheduling

Three-level scheduling

- In the O/S, the CPU scheduler decides which "Ready" process to run next (and to time out the "Running")
  - ✓ the discipline it follows is the **scheduling algorithm**



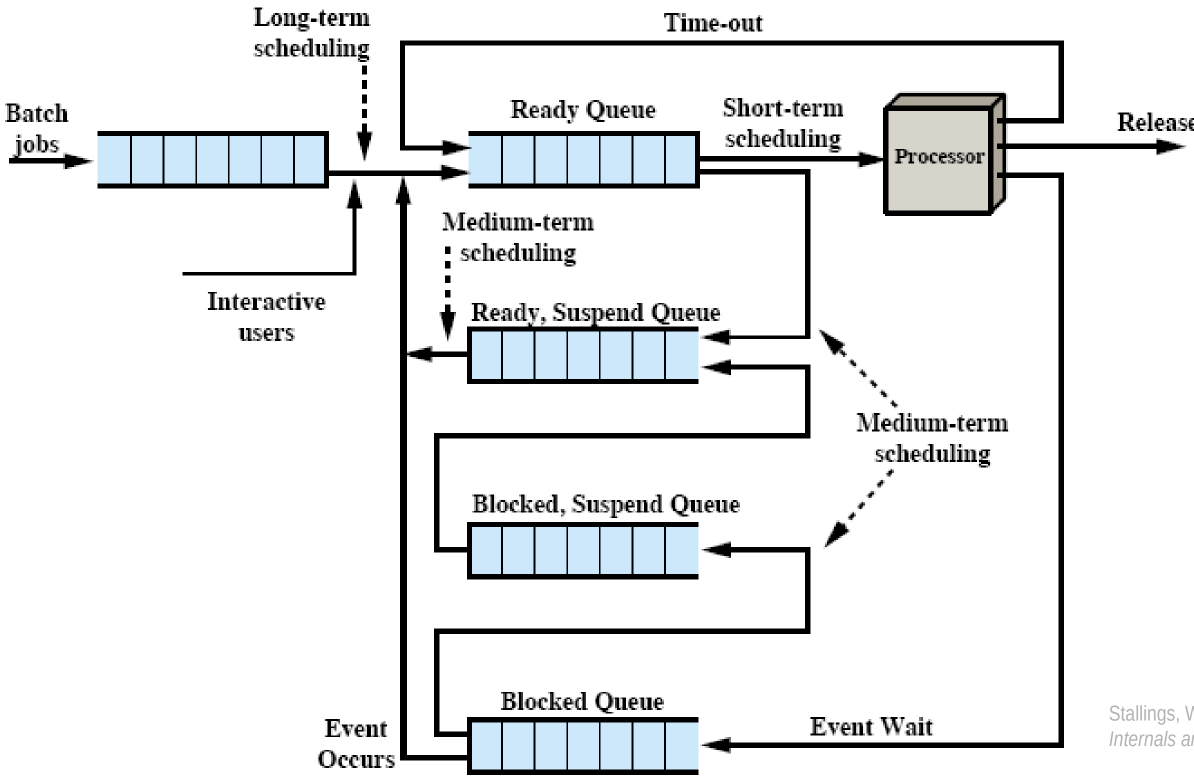
Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Transition diagram of a seven-state model

4.a Concepts of Scheduling

Three-level scheduling

- General queuing system for scheduling
  - ✓ in most algorithms, queues are not strictly FIFO: rather “pools”



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

Queuing diagram for scheduling

4.a Concepts of Scheduling

Purpose of CPU scheduling

- Why scheduling matters: user service response
  - ✓ example: choosing between
    - a process that updates the screen after the user has closed a window
    - a process that sends out queued email
  - ✓ taking 2 seconds to close the window while sending the email would be unacceptable
  - ✓ on the other hand, delaying the email while closing the window would hardly be noticed
  - → *schedule wisely to match user's expectations*

4.a Concepts of Scheduling

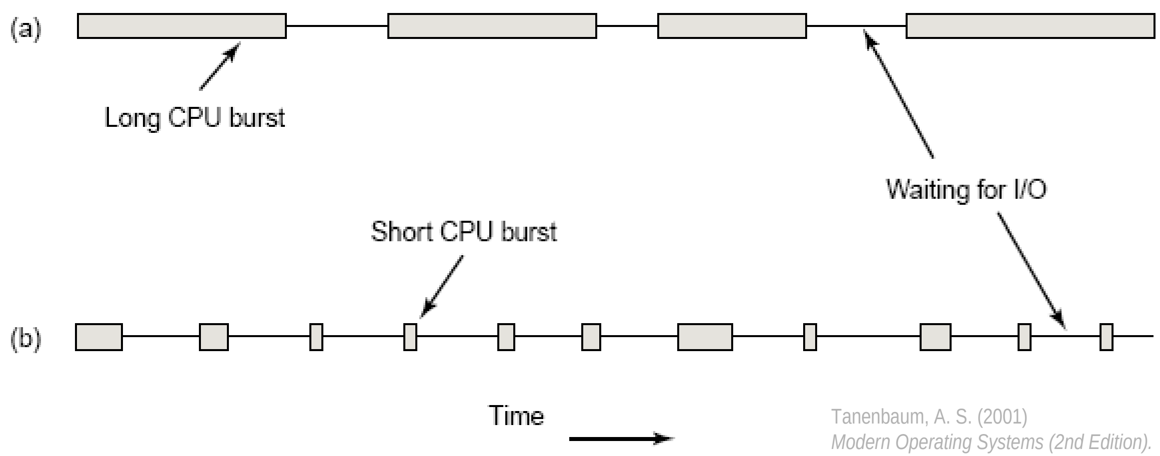
Purpose of CPU scheduling

- Why scheduling matters: CPU usage
  - ✓ switching processes (contexts) is heavy
    - switch from user mode to kernel mode
    - CPU state must be saved
    - process state must be saved
    - pages and page bits must be saved
    - MMU must be reloaded with new page table
    - etc.

  → *to maximize CPU utilization, interleave but at the same time minimize process switches*

4.a Concepts of Scheduling
Purpose of CPU scheduling

- Types of process behavior: CPU-I/O burst cycle
  - processes alternate CPU usage with I/O wait
    - compute-bound processes have long CPU bursts and infrequent I/O
    - I/O-bound processes have short CPU bursts and frequent I/O

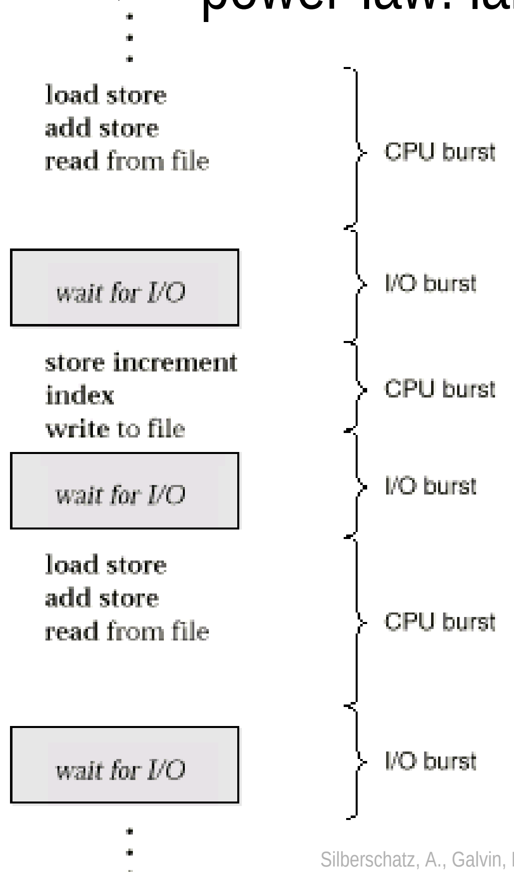


(a) Compute-bound process vs. (b) I/O-bound process

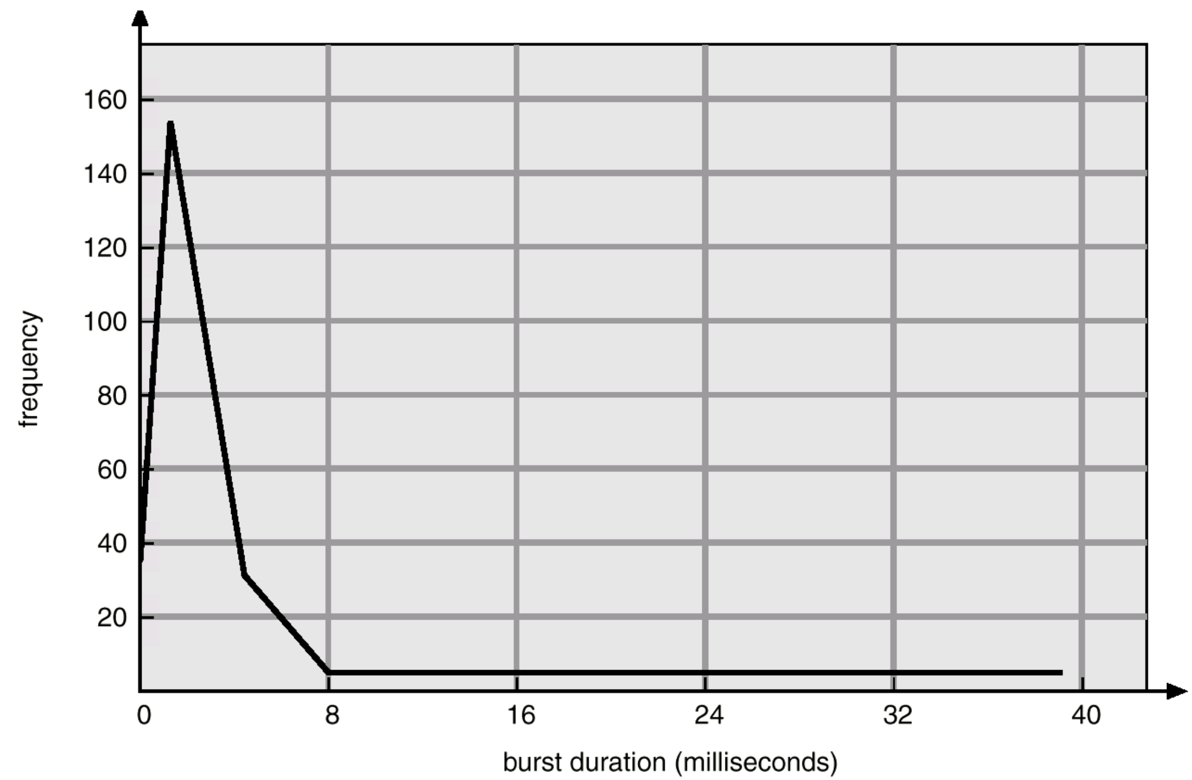
4.a Concepts of Scheduling

Purpose of CPU scheduling

- Types of process behavior: CPU-I/O burst cycle
  - ✓ power-law: large # of short CPU bursts, small # of large bursts



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



Typical histogram of CPU-burst times

4.a Concepts of Scheduling

Purpose of CPU scheduling

- I/O-bound processes
  - ✓ as CPU speeds increase, processes generally tend to become more and more I/O-bound
  - ✓ the scheduling of I/O-bound processes will likely become an important subject in the future
  - → *basic idea: an I/O-bound process that is "Ready" to run should get the CPU quickly so it can keep the disk busy*

4.a Concepts of Scheduling

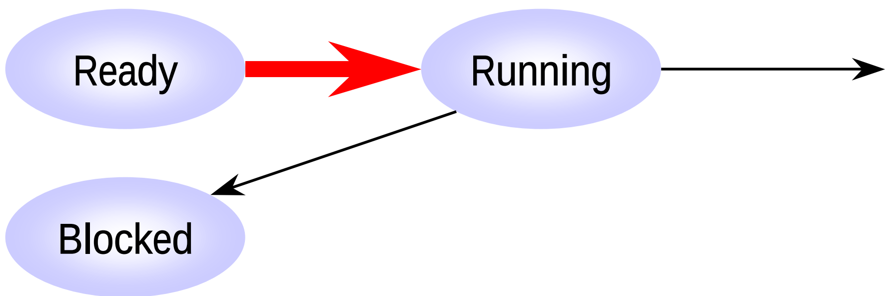
Purpose of CPU scheduling

- When to schedule a new process
  - ✓ when a process is created — run the child or the parent?
  - ✓ when a process exits — who’s next?
  - ✓ when an I/O interrupt occurs upon finishing an I/O task — should the waiting process be rescheduled right away? or let the currently running process continue? or pick another process? etc.

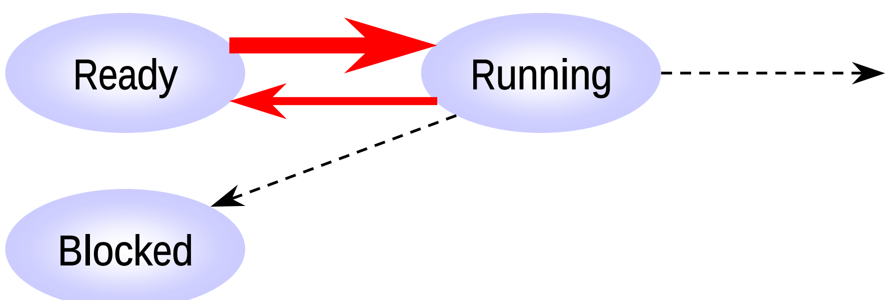
4.a Concepts of Scheduling

Purpose of CPU scheduling

- Two kinds of CPU-scheduling algorithms
  - ✓ **cooperative** scheduling — let a process run until it blocks on I/O, terminates or voluntarily releases the CPU (system call)



  - ✓ **preemptive** scheduling — follow clock interrupts (ex: 50Hz) to forcibly switch processes (demote the “Running” to “Ready”)



4.a Concepts of Scheduling

Purpose of CPU scheduling

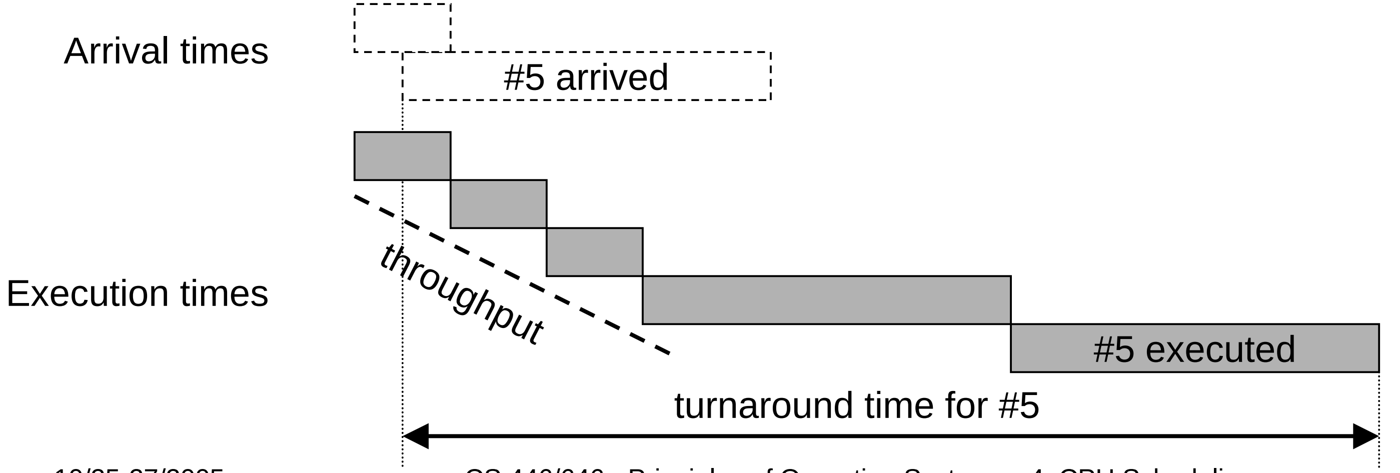
- Scheduling algorithm goals
  - ✓ **fairness** — comparable processes get comparable service
  - ✓ **compliance to system's policy** — ex: high-priority override low-priority processes (ex: safety control vs. payroll in a nuclear plant)
  - ✓ **keep system busy** — CPU and I/O devices should be utilized fully
    - if all CPU-bound were run first: fight for CPU, I/O idle
    - then all I/O-bound were run: fight for I/O, CPU idle

    → keep a well-balanced mix of CPU-bound and I/O-bound processes, so they can fill in for each other

4.a Concepts of Scheduling

Purpose of CPU scheduling

- Scheduling algorithm goals — batch systems
  - ✓ **throughput** — maximize # of completed jobs per time unit
  - ✓ **turnaround time (latency)** — minimize time between submission and termination of job
    - high throughput and low turnaround are rarely compatible
    - for ex: supply of short jobs scheduled in front of long jobs: good throughput, bad turnaround time for long jobs



4.a Concepts of Scheduling

Purpose of CPU scheduling

- Scheduling algorithm goals — interactive systems
  - ✓ **response time** — respond to requests quickly: minimize time between issuing command and getting result
    - ex: a user request to start a new program should take precedence over background work
    - having interactive requests go first will be perceived as good service
  - ✓ **proportionality time** — meet users' expectation, even if irrational
    - ex: 45 seconds to establish a modem connection is commonly *perceived* as acceptable
    - but 45 seconds to hang up is not (although similar task)

4.a Concepts of Scheduling
Purpose of CPU scheduling

- Scheduling algorithm goals — summary

All systems
Fairness - giving each process a fair share of the CPU
Policy enforcement - seeing that stated policy is carried out
Balance - keeping all parts of the system busy

Batch systems
Throughput - maximize jobs per hour
Turnaround time - minimize time between submission and termination
CPU utilization - keep the CPU busy all the time

Interactive systems
Response time - respond to requests quickly
Proportionality - meet users' expectations

Real-time systems
Meeting deadlines - avoid losing data
Predictability - avoid quality degradation in multimedia systems

Tanenbaum, A. S. (2001)
Modern Operating Systems (2nd Edition).

Some goals of CPU scheduling under different circumstances

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4. CPU Scheduling

a. **Concepts of Scheduling**
   - ✓ Three-level scheduling
   - ✓ Purpose of CPU scheduling

b. **Scheduling Algorithms**

c. **Queuing Analysis**

d. **Thread Scheduling**

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4. CPU Scheduling

a. Concepts of Scheduling

b. Scheduling Algorithms

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

c. Queuing Analysis

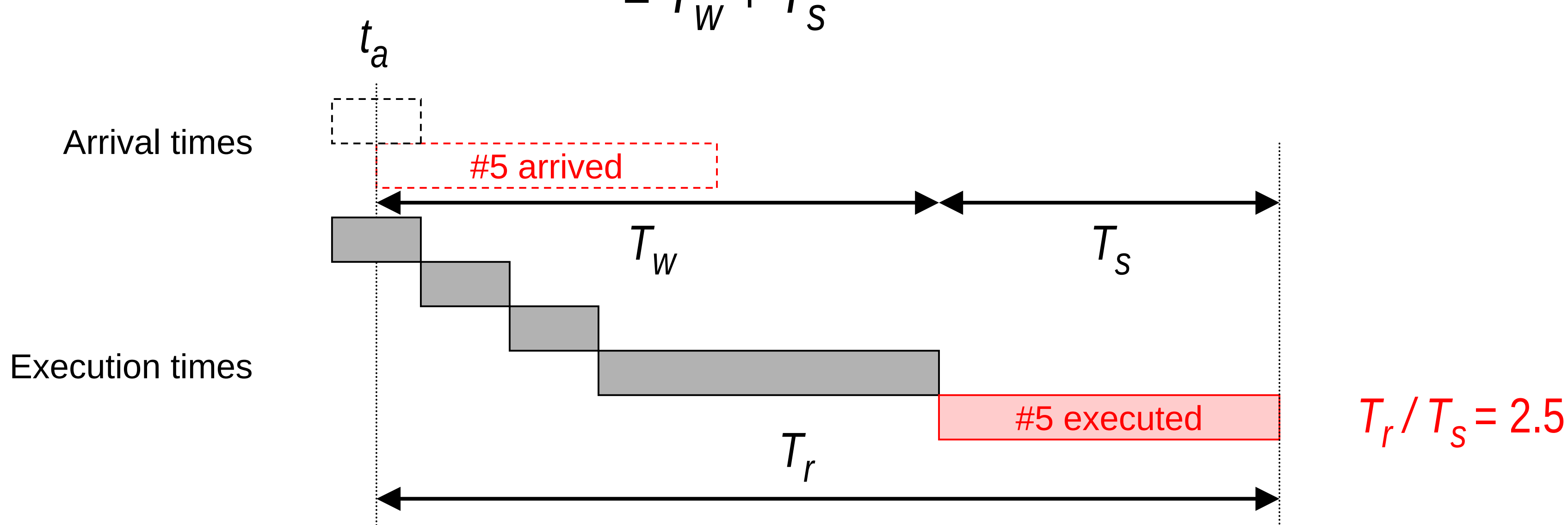
d. Thread Scheduling

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 CPU
  - ✓ service time T_s = time spent executing in CPU
  - ✓ <u>turnaround time</u> T_r = total time spent waiting and executing

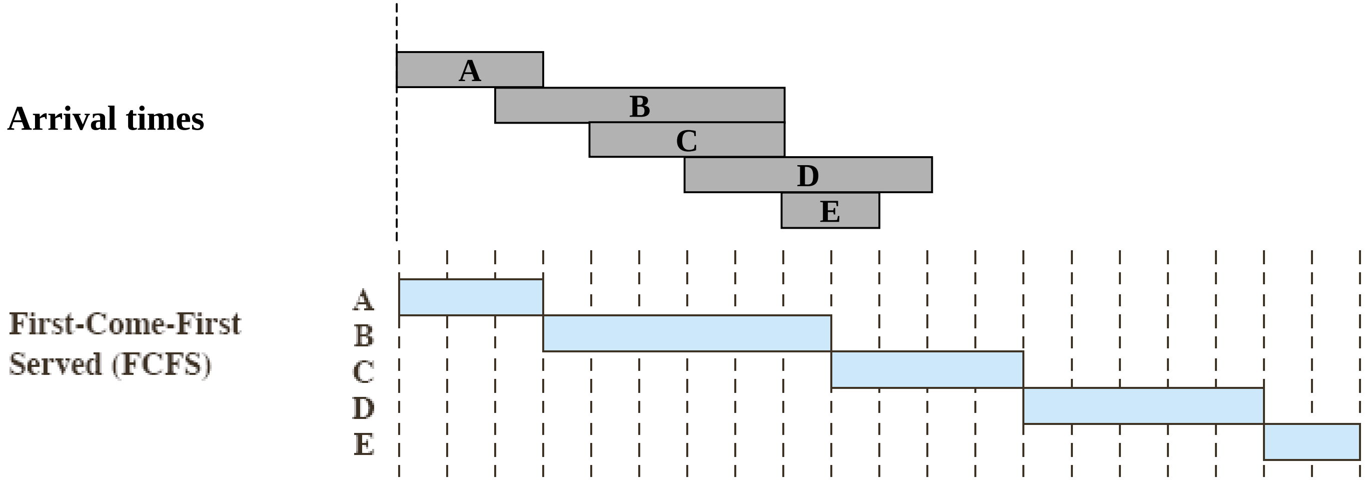
$$= T_w + T_s$$



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



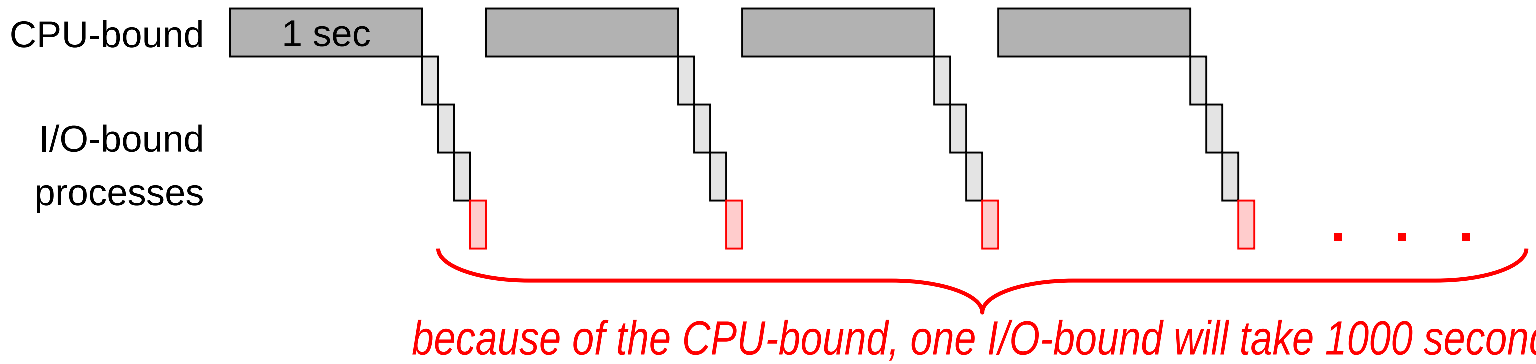
FCFS		A	B	C	D	E	Mean
	Finish Time	3	9	13	18	20	
	Turnaround Time (T_r)	3	7	9	12	12	8.60
	T_r/T_s	1.00	1.17	2.25	2.40	6.00	2.56

FCFS scheduling policy

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

4.b Scheduling Algorithms
Scheduling in batch systems

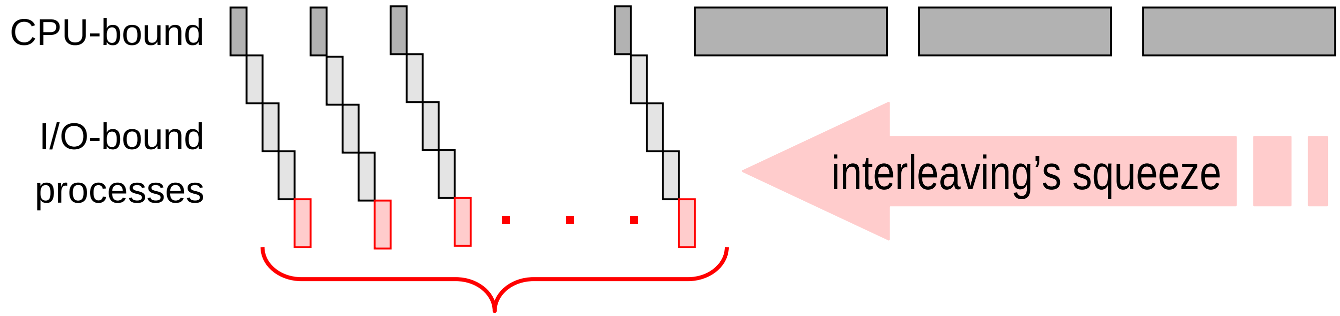
- First-Come-First-Served (FCFS)
  - ✓ nonpreemptive, oldest and simplest to program
  - ✓ apparently “fair” but very inefficient; example:
    - a CPU-bound process runs 1 sec, then reads 1 disk block
    - several I/O-bound processes run little CPU, but must read 1000 disk blocks



→ *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)

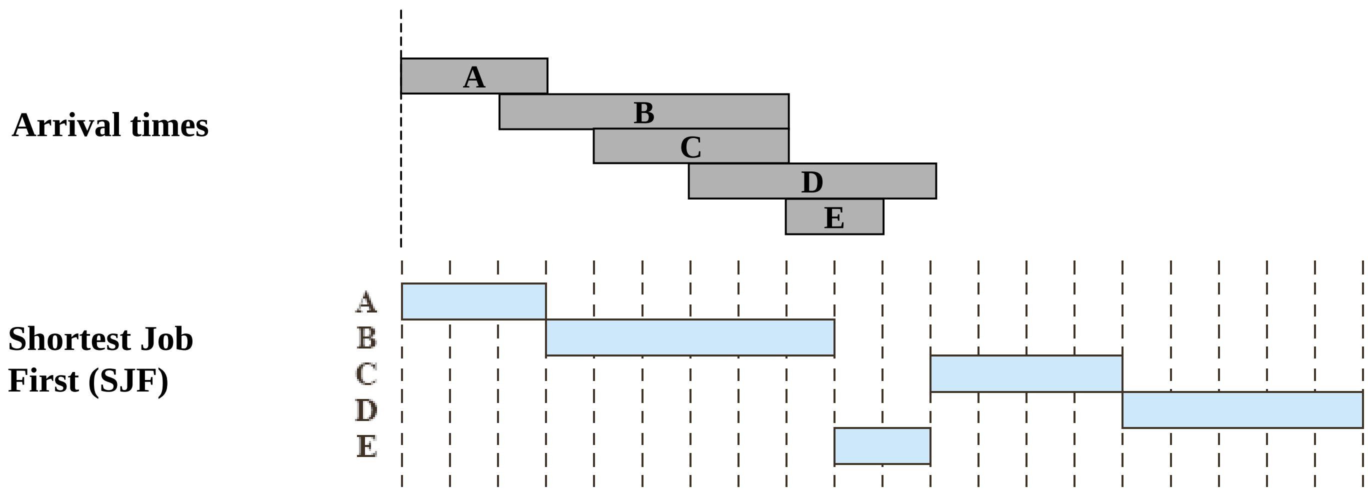
→ *see preemptive algorithms (Round-Robin, etc.) in later sections*

4.b Scheduling Algorithms

Scheduling in batch systems

➢ Shortest Job First (SJF)

- ✓ nonpreemptive, 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	Finish Time	A 3	B 9	C 15	D 20	E 11	Mean
	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) turnaround times T_r = 8, 12, 16, 20 $\rightarrow$ mean T_r = 14

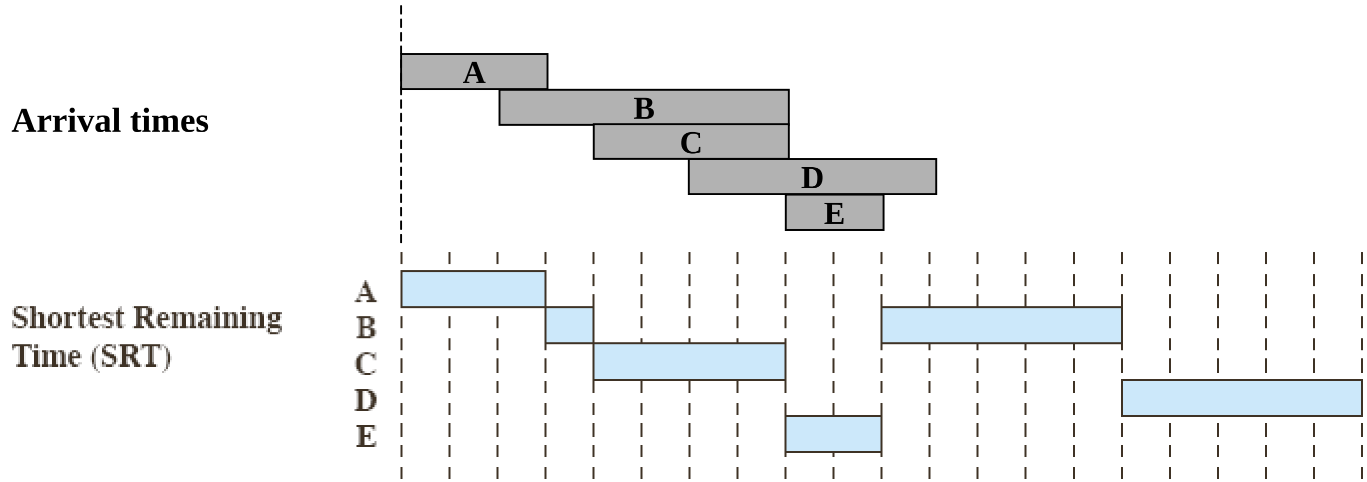
b) turnaround times T_r = 4, 8, 12, 20 $\rightarrow$ mean T_r = 11

  - ✓ 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, because of no-preemption, SJF is not dealing well with jobs arriving subsequently

4.b Scheduling Algorithms

Scheduling in batch systems

- Shortest Remaining Time (SRT)
  - ✓ <u>preemptive</u> version of SJF, also assumes known run time
  - ✓ choose the process whose <u>remaining</u> 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

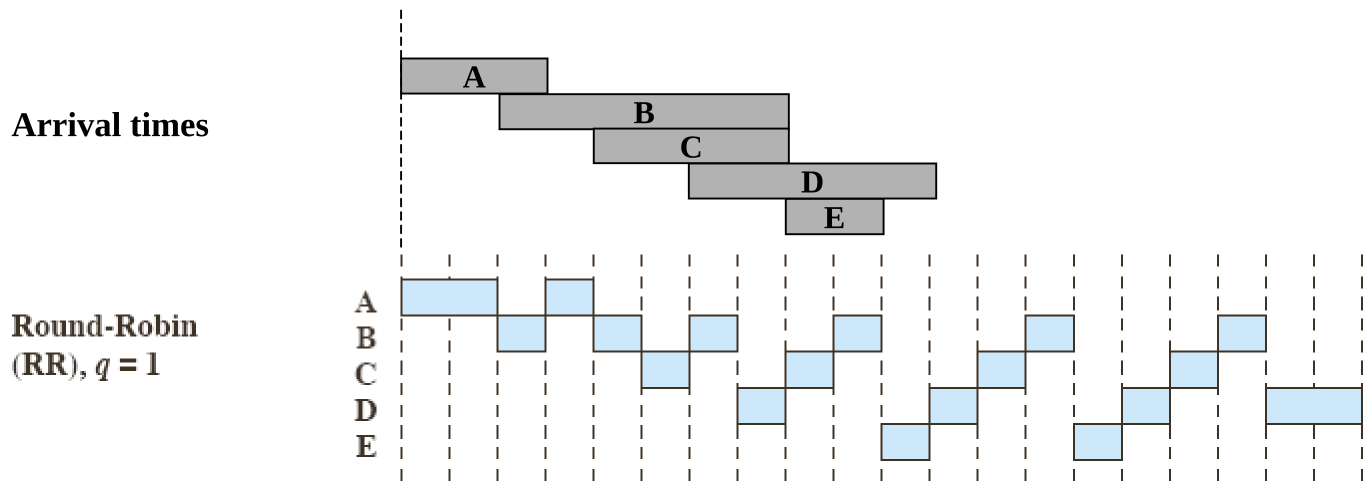
SRT scheduling policy

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 time interval, the **quantum** *q*
  - ✓ a running process is interrupted by the clock (timed out) and transitioned to the “Ready” state; another “Ready” process is run



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

RR ($q = 1$) scheduling policy

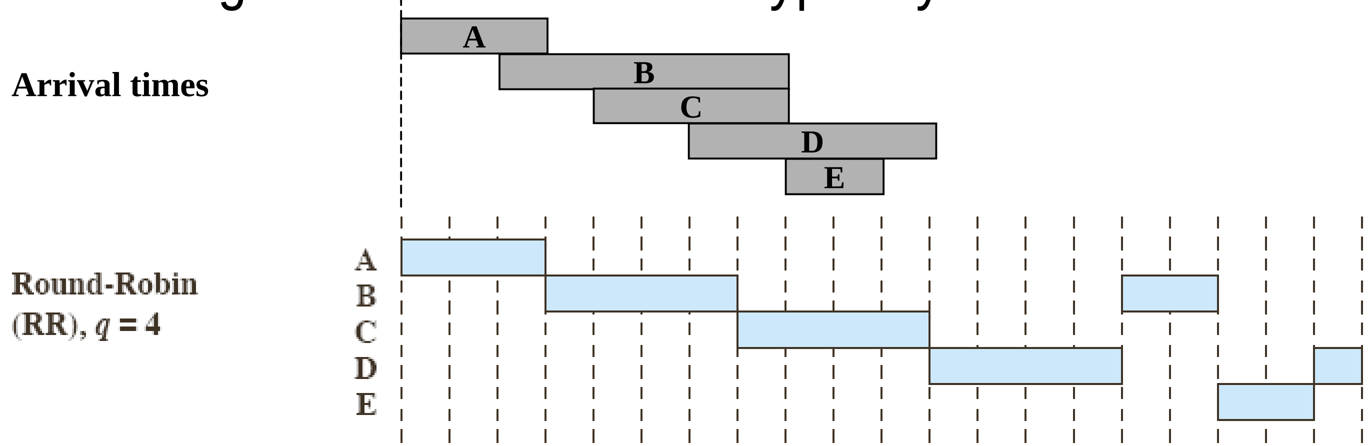
Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

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

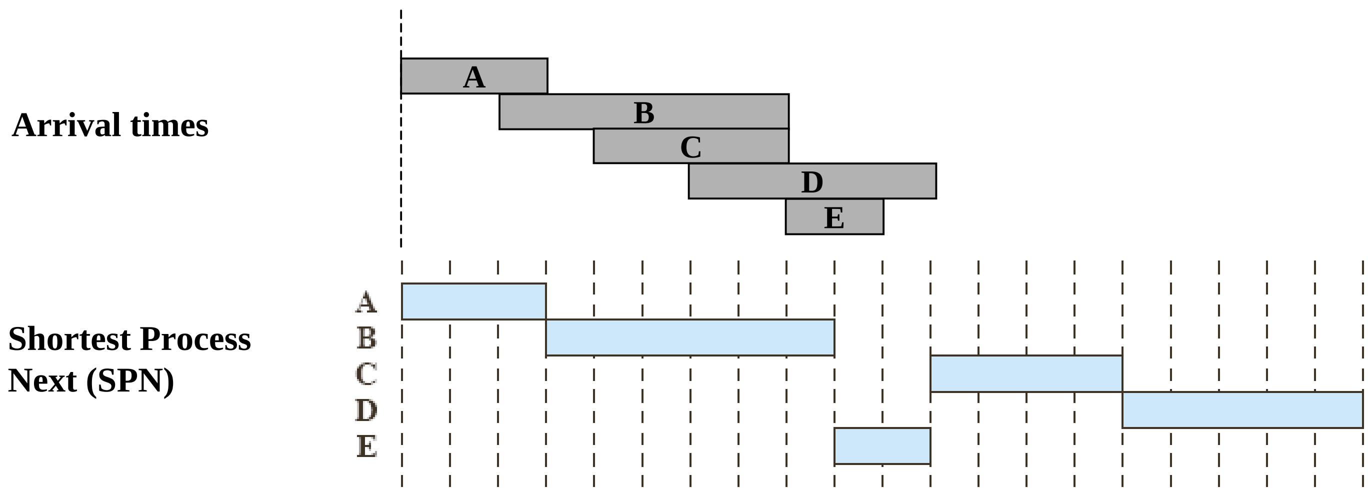
RR ($q = 4$) scheduling policy

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

4.b Scheduling Algorithms

Scheduling in interactive systems

- **Shortest Process Next (SPN)**
  - ✓ equivalent to SJF: pick the one that should finish the earliest
  - → *difference in an interactive system: base the prediction about future duration upon the past durations*



SPN		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

SPN scheduling policy

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

4.b Scheduling Algorithms

Scheduling in interactive systems

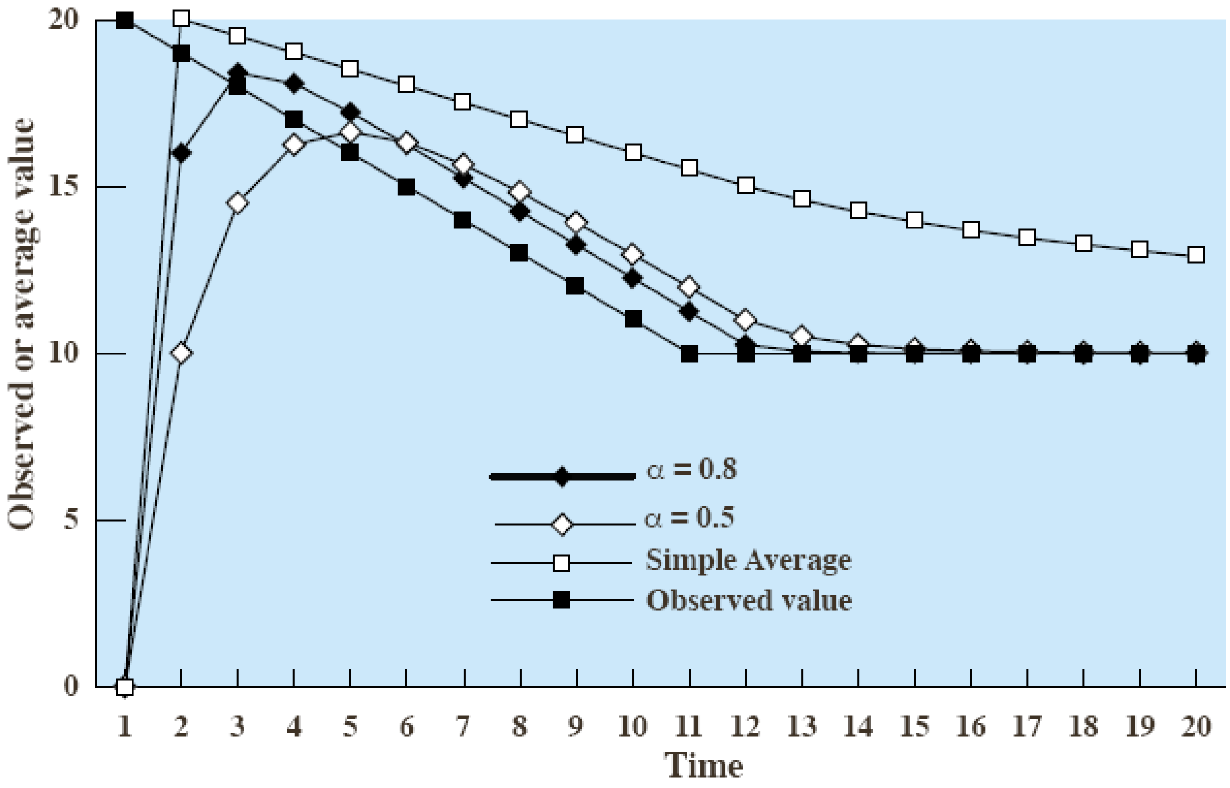
- **Estimation of processing time from past**
  - simple averaging
    - $S(n+1) = (1/n) \sum T(i)$

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



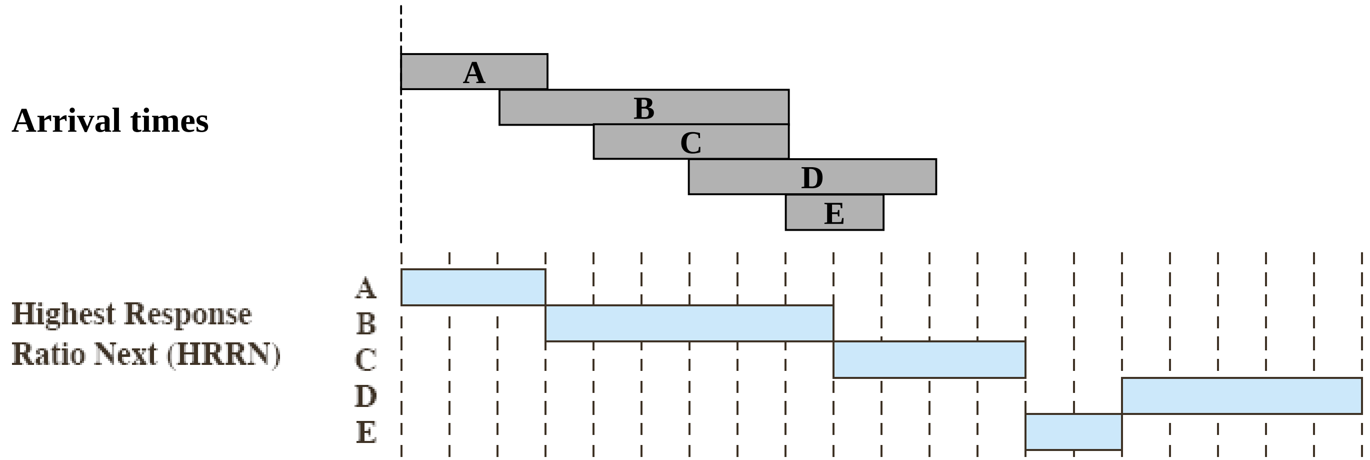
Example of exponential averaging in duration estimation

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

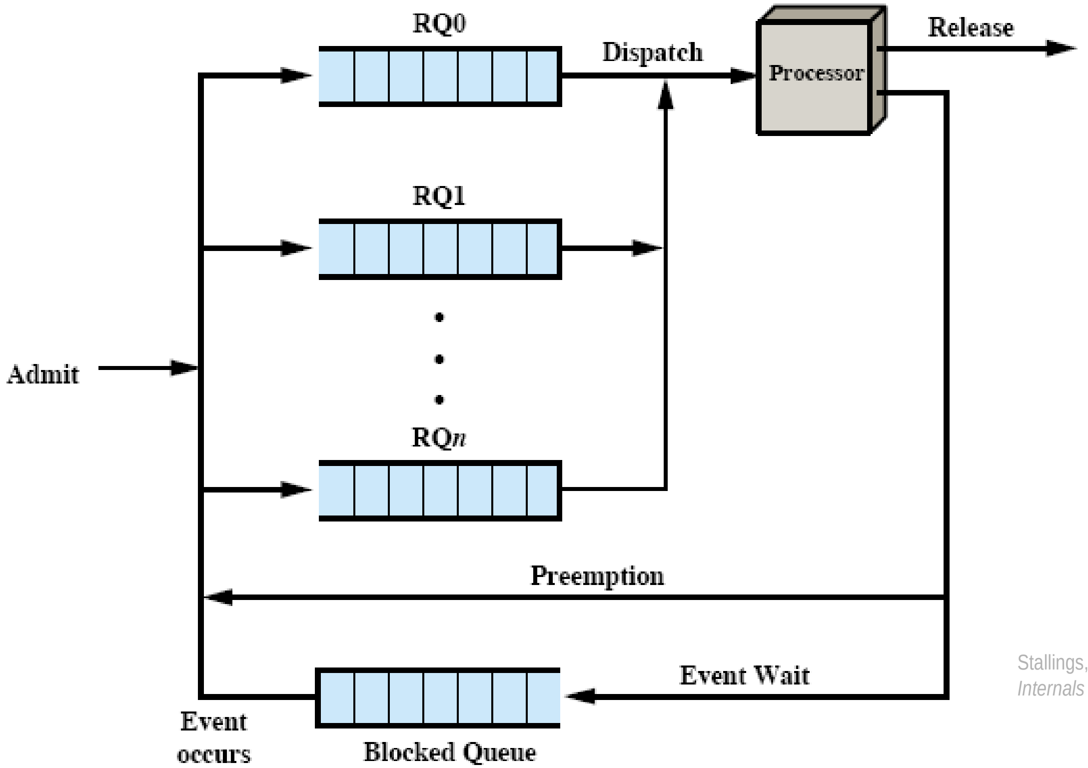
HRRN scheduling policy

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

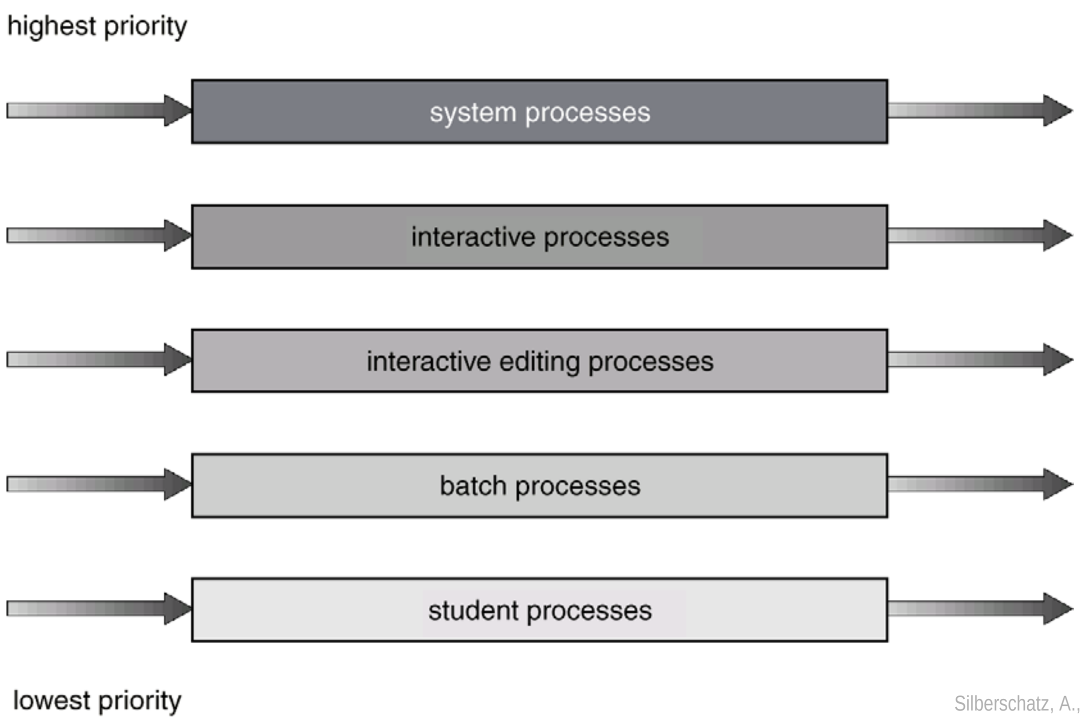


Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

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.)



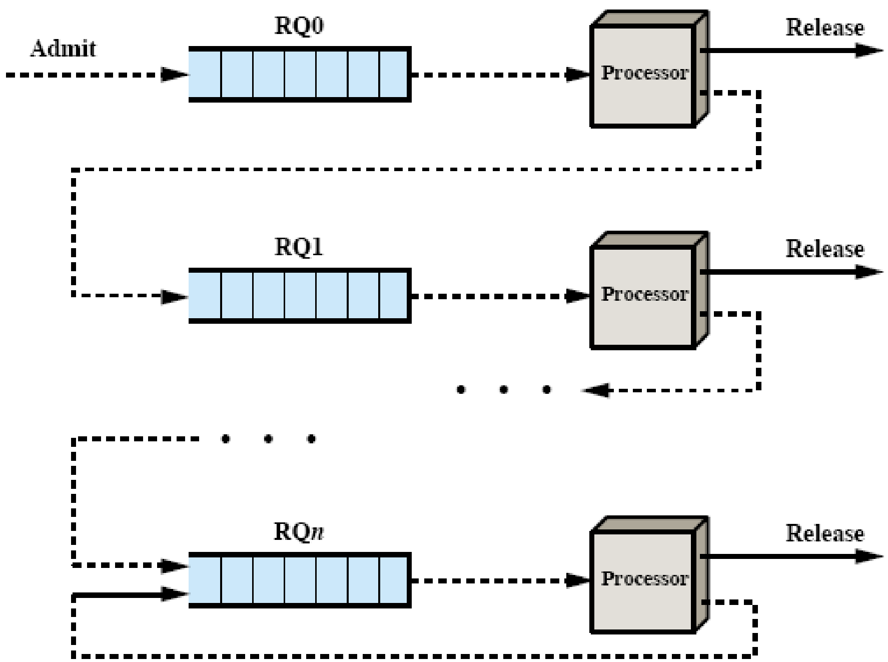
Multilevel queue scheduling

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).*

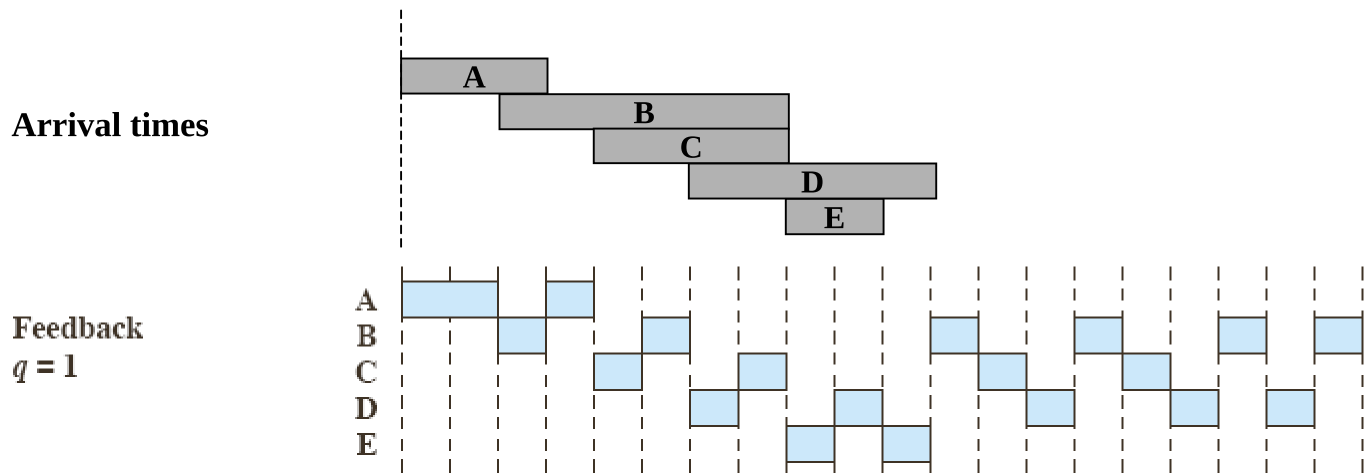
Priority queuing

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

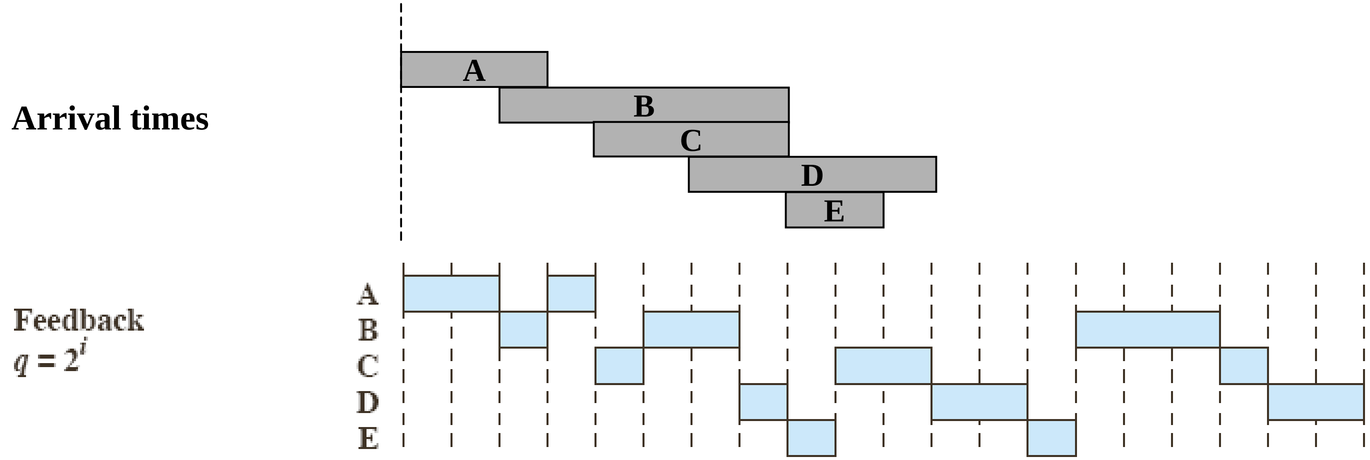
FB (q = 1) scheduling policy

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 $q = 2^i$



FB $q = 2^i$											
	Finish Time	**A**	4	**B**	17	**C**	18	**D**	20	**E**	14	**Mean**
	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
RR $q = 1$	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 $q = 4$	Finish Time	3	17	11	20	19	
	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
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

Principles of Operating Systems

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4. CPU Scheduling

a. Concepts of Scheduling

b. **Scheduling Algorithms**

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

c. **Queuing Analysis**

d. **Thread Scheduling**