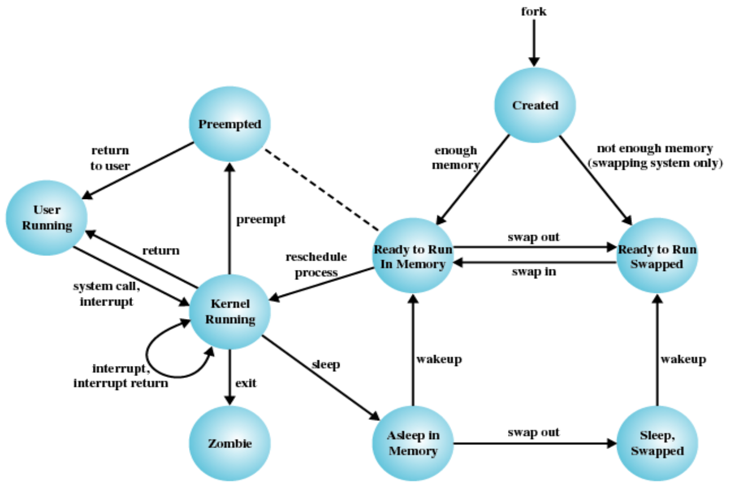
Operating Systems & Computer Networks
Scheduling

Types of Scheduling

Decision Modes

Process Priorities

Scheduling Policies



Content

Definition and Goals

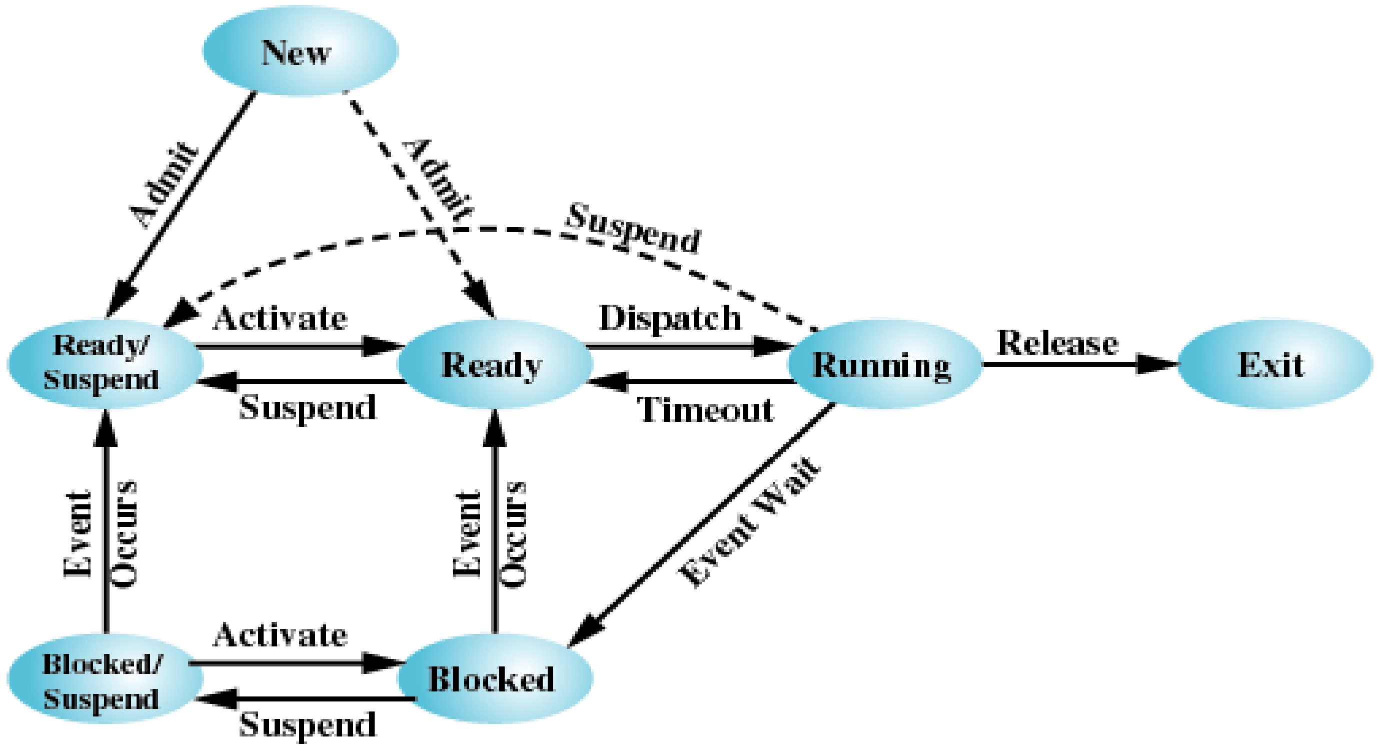
- Assign processes to be executed by the processor(s)
- ➢ More general: Assign consumers to resources
  - Examples: I/O requests ➔ Device-specific queues
    Memory pages ➔ Primary/secondary memory

- Goals:
  - Throughput, i.e., effectively use processing time
  - Response time / fairness, i.e., interactivity of individual processes
  - Processor efficiency, i.e., optimal utilization of CPU (as resource)

➢ Conflicting goals: Maximal throughput means unpredictable response time (and vice versa)

Process States and Scheduling

- Scheduling decisions correspond to state transitions in process state graph



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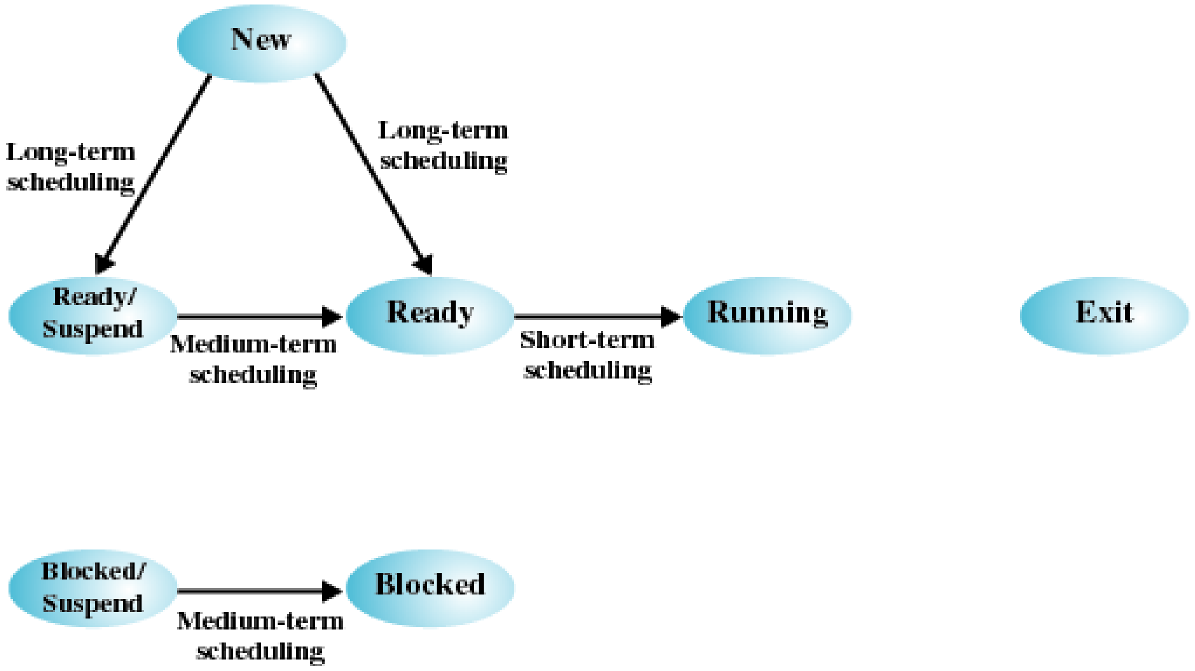
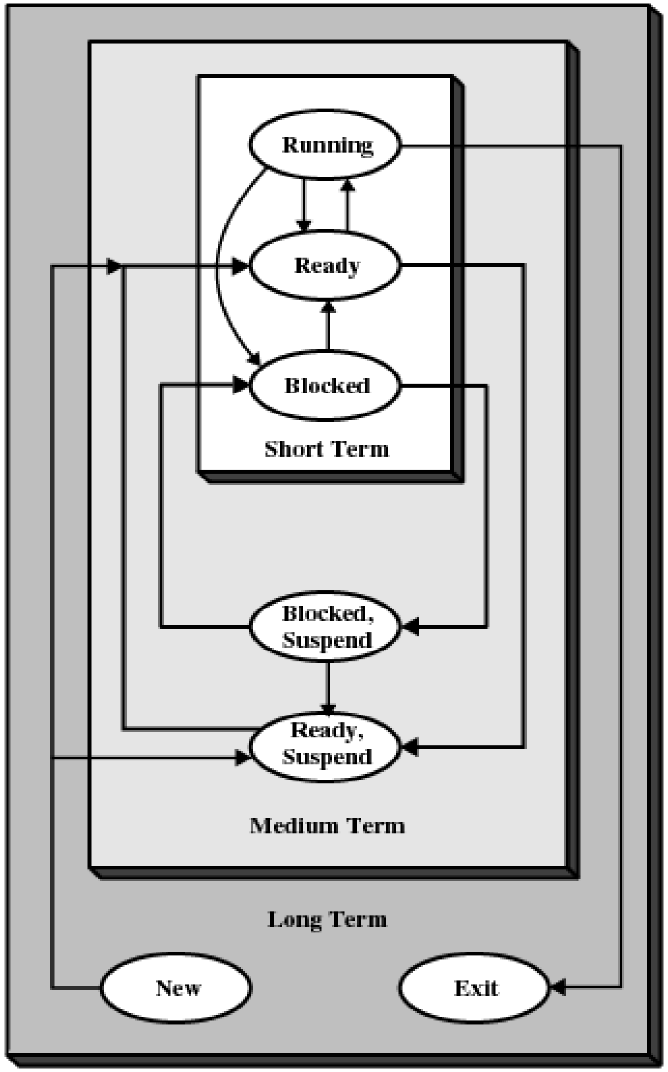
Process States and Scheduling

- Scheduling decisions correspond to state transitions in process state graph
- States form hierarchy depending on transition frequency
  - ➢ Import to consider when choosing and implementing scheduling algorithms

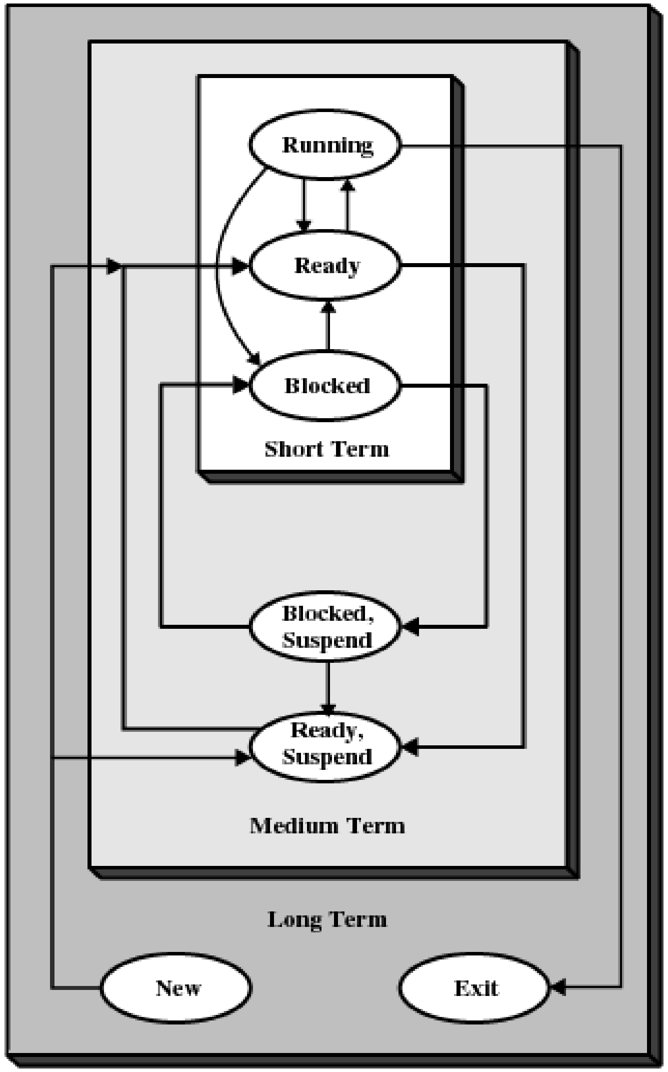




Types of Scheduling

Long-term scheduling

- Whether to add process to running queue and execute it
  - Determines which programs are admitted to system for processing, e.g., based on user
  - Specifies degree of multiprogramming, i.e., maximal number of processes
  - The more processes, the smaller percentage of time each process is executed
- ➢ How many processes should be allowed?



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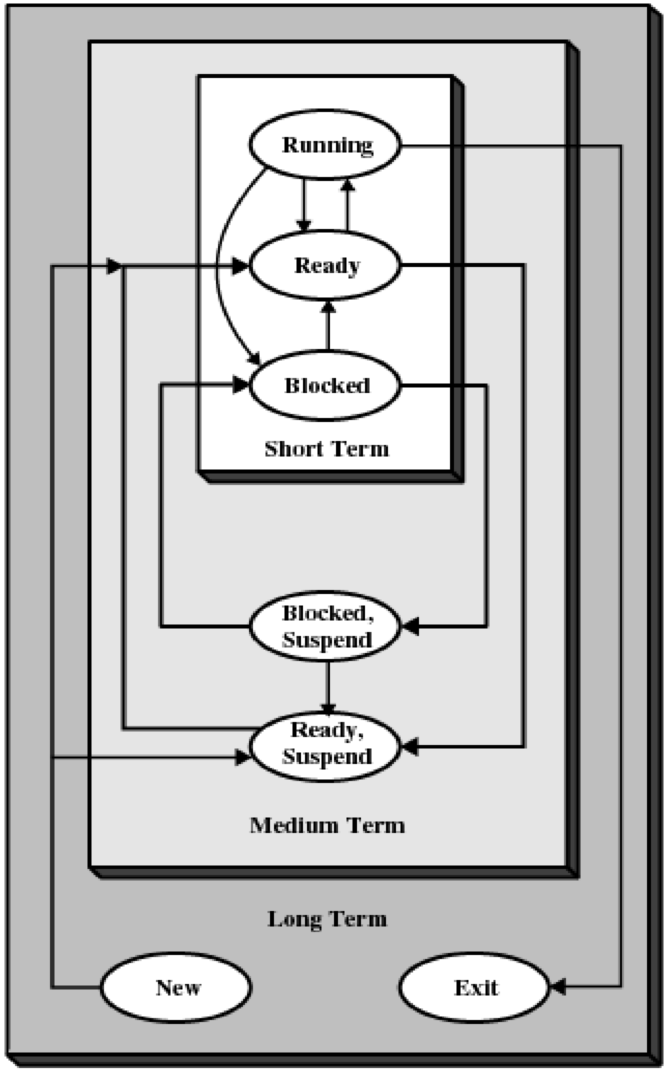
Types of Scheduling

Medium-term scheduling

- Whether to add/remove existing process (that is only partially in primary memory)
  - Part of swapping function
  - Based on need to dynamically manage degree of multiprogramming (considering available resources)

➢ Should processes be swapped in or out? If so, which ones?

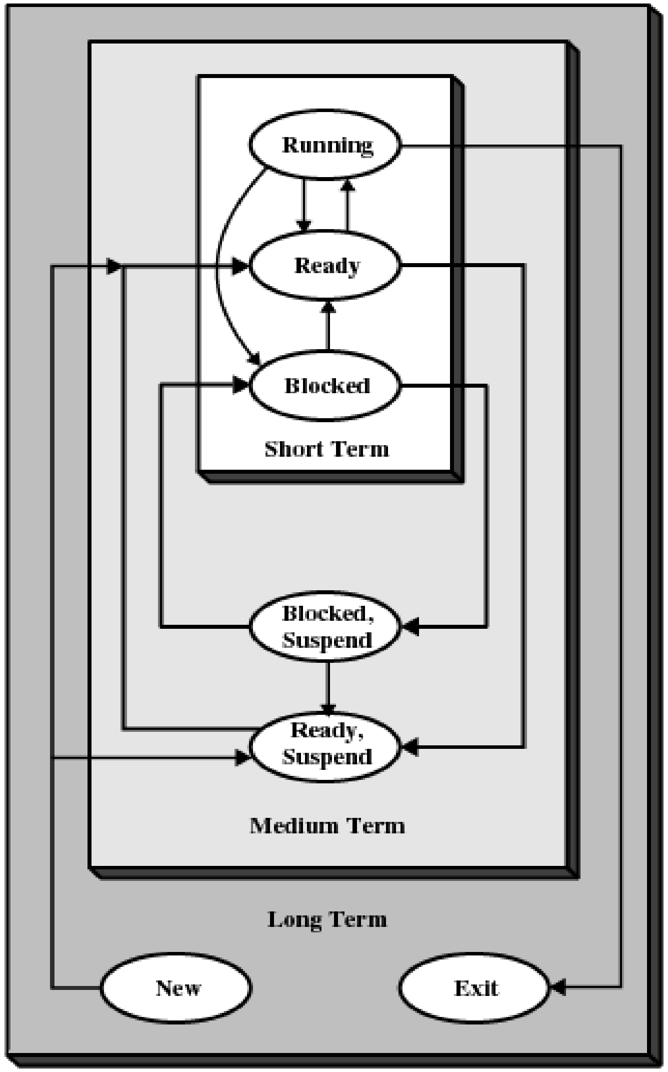


Types of Scheduling

Short-term scheduling

- Which one of fully available processes to run
  - Known as "dispatcher"
  - Executes most frequently
    - ➢ Overhead / algorithmic complexity matters
  - Invoked when event occurs (clock interrupts, I/O interrupts, operating system calls, signals)

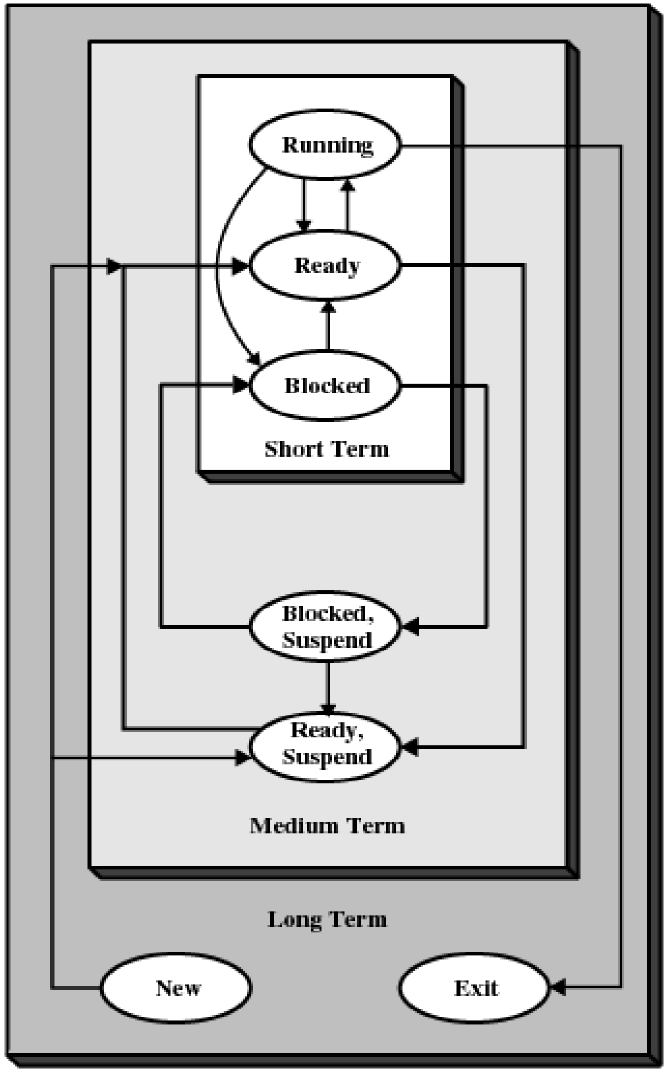
➢ Whose turn is it?



Types of Scheduling

I/O scheduling

- Which I/O request (of which process) to dispatch to I/O device for handling
  - ➢ Consider state of external device

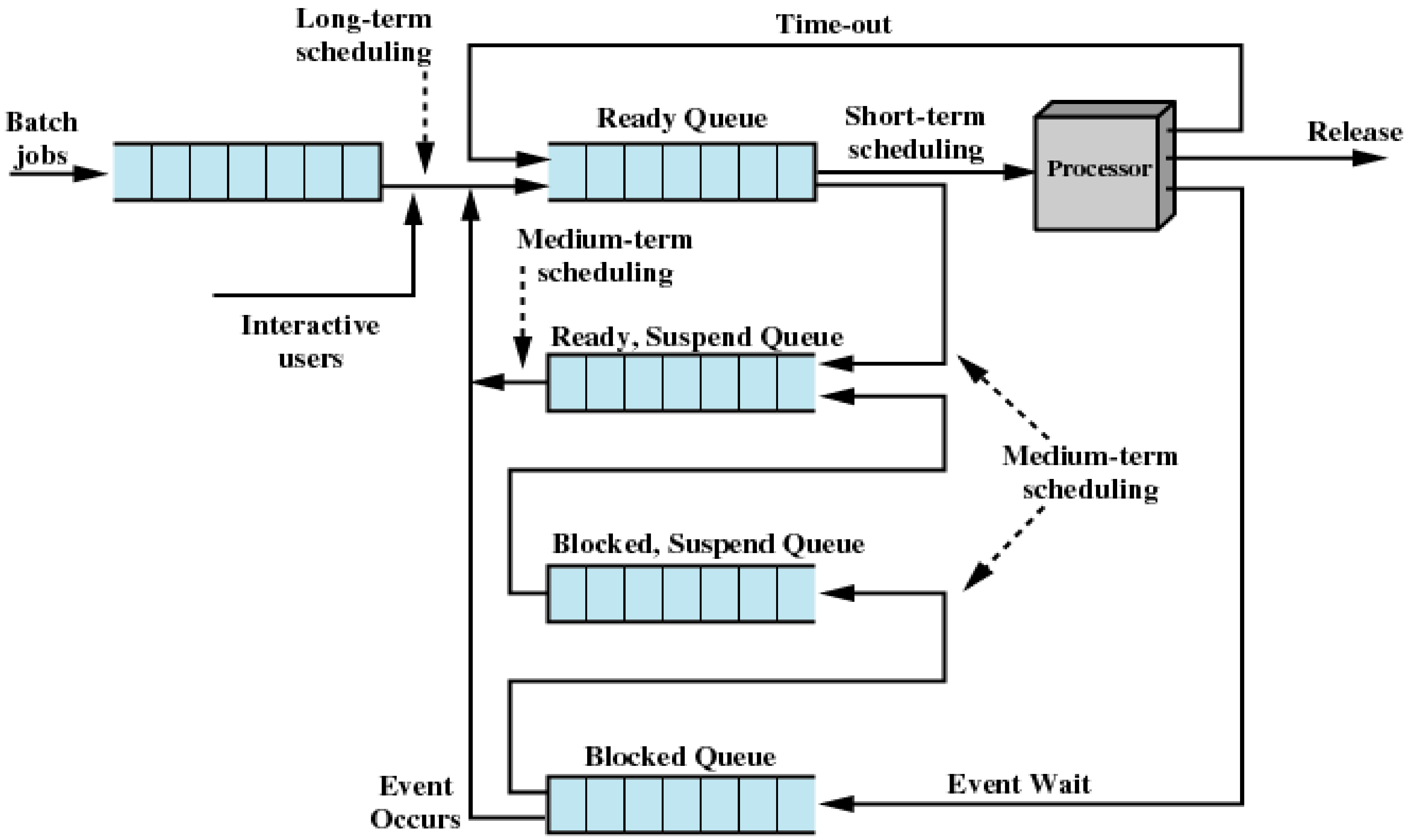


Short-Term Scheduling Criteria

- User-oriented:
  - Response time: elapsed time between submission of a request until there is output
  - ➢ Interactivity: user *perceives* system as "responsive"
- System-oriented (hardware and resources):
  - Effective and efficient utilization of processor
- Performance-related:
  - Quantitative / measurable properties
  - Examples: response time, throughput
- Non-functional:
  - Algorithmic properties
  - Examples: predictability, fairness

	Performance-related	Non-functional
User-oriented	• Turnaround time • Response time • Deadlines	• Predictability
System-oriented	• Throughput • Processor utilization	• Fairness • Enforcing priorities • Balancing resources

Scheduler Implementation: Queuing



Scheduling Decision Modes

- Non-preemptive
  - Current process explicitly yields CPU
    - ➢ Cooperative multitasking, e.g., Windows (<95), Mac OS (<X)
  - Once a process is in running state, it will continue until it terminates or blocks itself for I/O

- Preemptive
  - OS may interrupt current process
    - Transparent to process
    - ➢ Preemptive multitasking, e.g., Windows (≥95), Mac OS X, Unix
  - Allows for better scheduling since no process can monopolize CPU

Priorities

- Some processes are more *important* than other processes, i.e., should get more CPU cycles than others
  - Similar for other resources

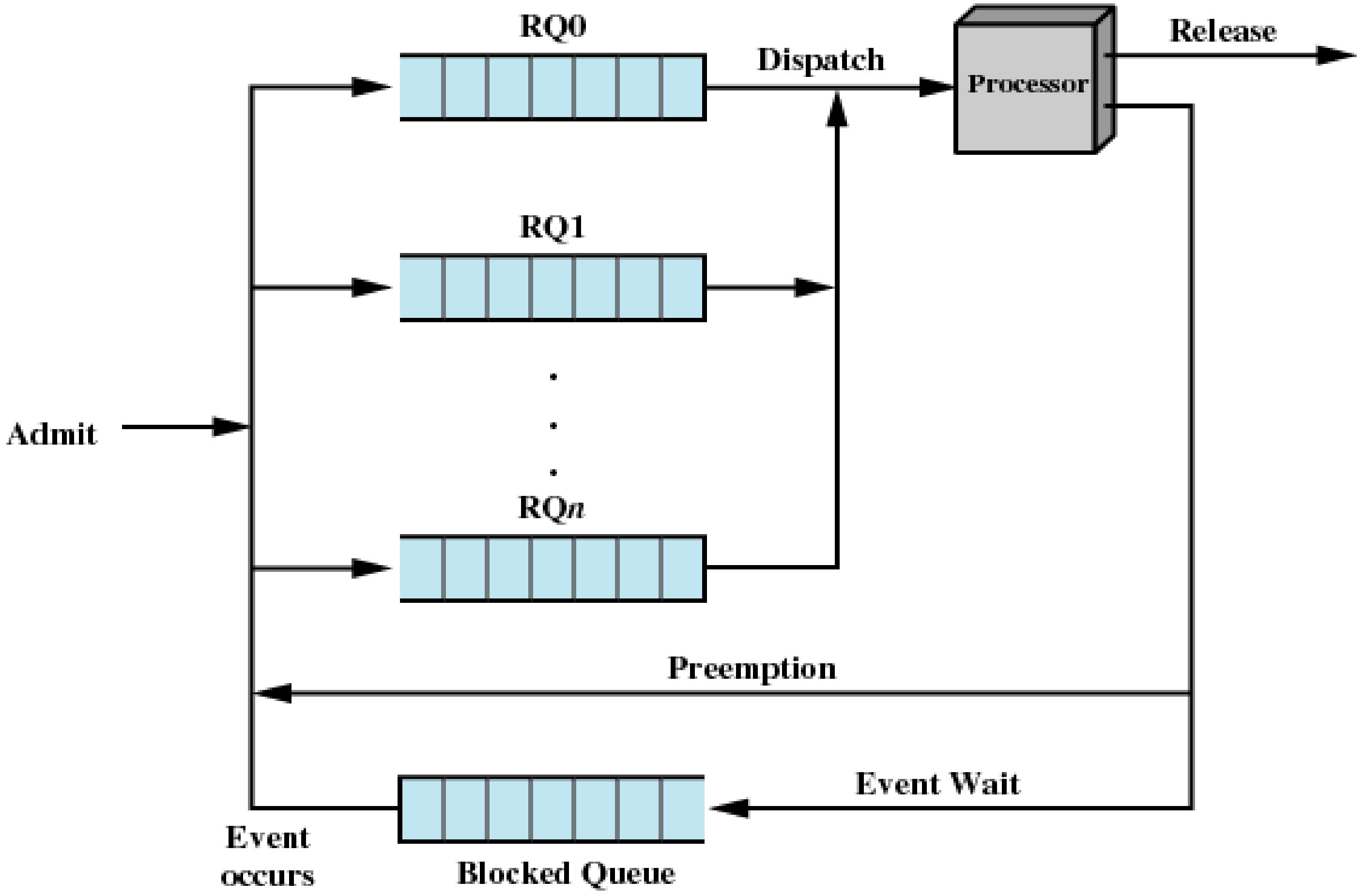
- Scheduling is controlled by per-process priorities
  - OS internal vs. user-visible priorities

- Scheduler will always choose a process of higher priority over one of lower priority

➢ Lower-priority processes may suffer starvation, i.e. are never scheduled and do not make *any* progress

Priority Implementation: Queuing

- Have multiple ready queues to represent each level of priority
- Move process data between queues according to scheduling algorithm



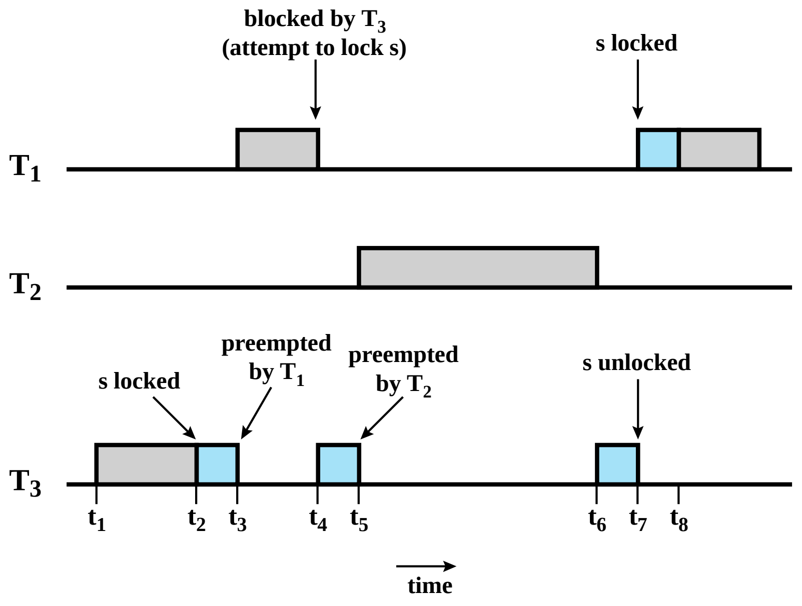
Priority Inversion and Inheritance

Problem: Priority Inversion

- Occurs when circumstances within the system force a higher priority task to wait for a lower priority task

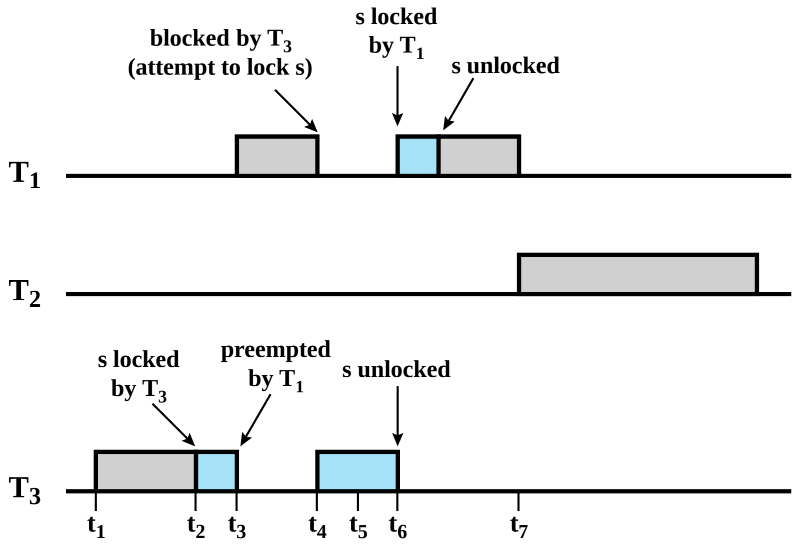
Solution: Priority Inheritance

- Lower-priority task inherits priority of any higher priority task pending on a resource they share



blocked by T_3 (attempt to lock s)
s locked
T_1
T_2
s locked
preempted by T_1
preempted by T_2
s unlocked
T_3
t_1 t_2 t_3 t_4 t_5 t_6 t_7 t_8
time

(a) Unbounded priority inversion



(b) Use of priority inheritance

▨ normal execution 🟦 execution in critical section

Scheduling Algorithm Classes

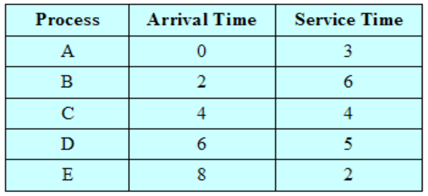
- Non-preemptive
  - First-Come-First-Served (FCFS)
  - Shortest Process Next (SPN)
  - Highest Response Ratio Next (HRRN)
- Preemptive
  - Shortest Remaining Time (SRT)
  - Round-Robin
  - Feedback

Example workload

Process	Arrival Time	Service Time
A	0	3
B	2	6
C	4	4
D	6	5
E	8	2

First-Come-First-Served (FCFS)

- New process placed at end of Ready queue
- When current process ceases to execute, oldest process in the Ready queue is selected



Process	Arrival Time	Service Time
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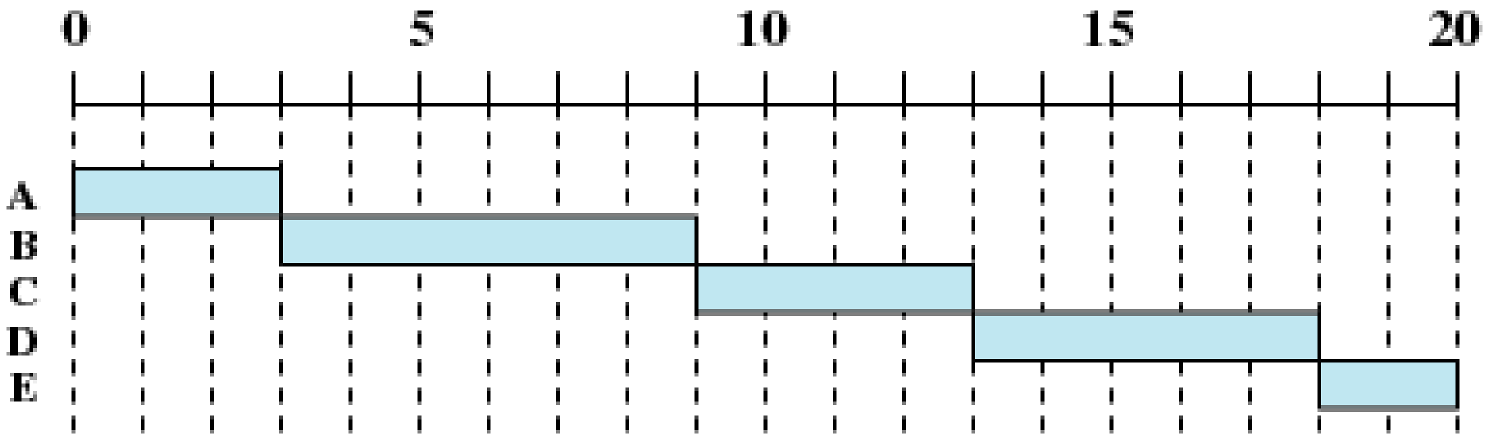
First-Come-First Served (FCFS)



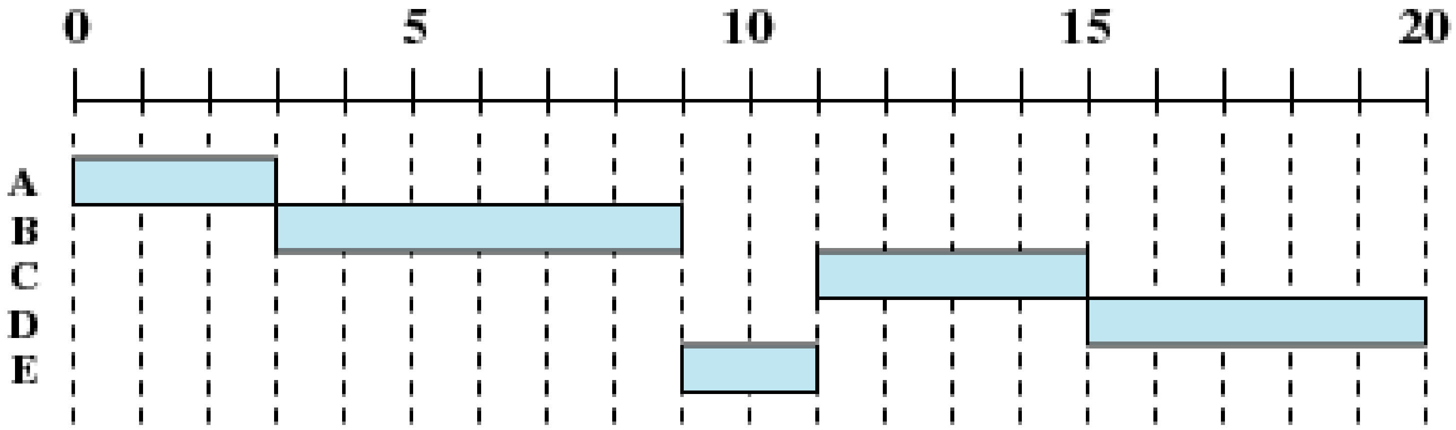
➢ Short process may have to wait a very long time before it can execute
  ➢ Poor response time / interactivity
➢ Favors CPU-bound processes
  - I/O processes have to wait until CPU-bound process completes, since I/O processes frequently call into OS

Shortest Process Next (SPN)

- Process with shortest expected processing time is selected
  - OS may abort processes with incorrect time estimates
- Short processes jump ahead of longer processes

Process	Arrival Time	Service Time
A	0	3
B	2	6
C	4	4
D	6	5
E	8	2

Shortest Process Next (SPN)



➢ Improves interactivity (based on assumption that short processes are due to user interaction)

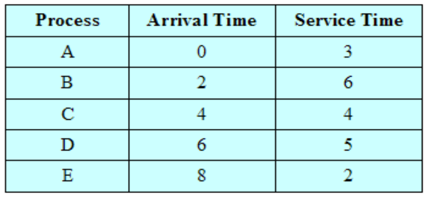
➢ Predictability of longer processes is reduced

➢ Possibility of starvation for longer processes

Highest Response Ratio Next (HRRN)

- Choose next process with the highest ratio

$$\frac{\textit{time spent waiting + expected service time}}{\textit{expected service time}}$$



Process	Arrival Time	Service Time
A	0	3
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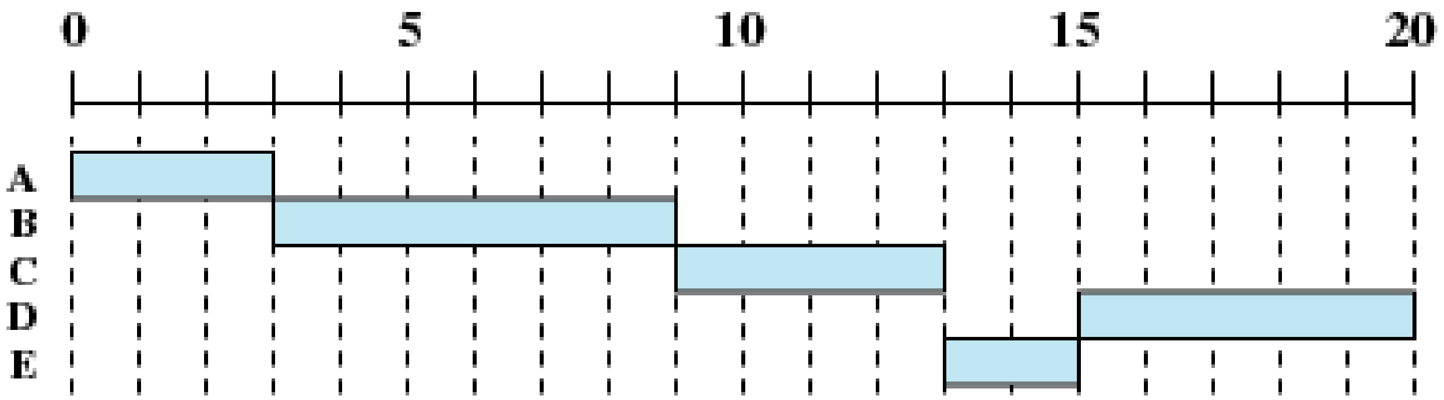
Highest Response Ratio Next (HRRN)

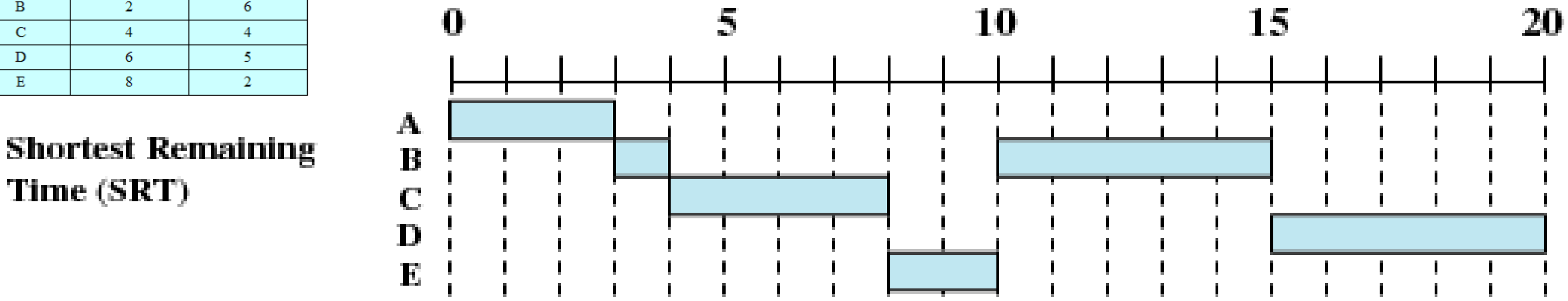


- ➢ Even long process will run eventually
- ➢ Generally, predictable response times not feasible without preemption

Shortest Remaining Time (SRT)

- Ready queue is sorted by remaining processing time
  - Requires estimate of remaining processing time
- New processes may preempt current process upon arrival
  - Preemptive version of shortest process next policy

Process	Arrival Time	Service Time
A	0	3
B	2	6
C	4	4
D	6	5
E	8	2



➢ Improved response time of short processes by using preemption
  - Limited additional overhead due to process switches upon process creation

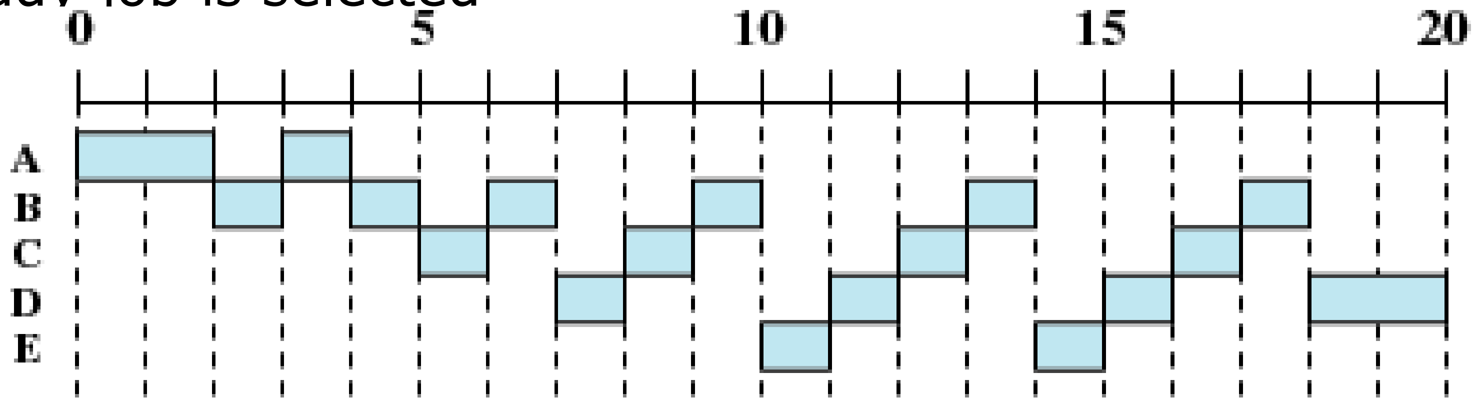
➢ But happens to interactive requests that don’t spawn a new process?

Round-Robin

Process	Arrival Time	Service Time
A	0	3
B	2	6
C	4	4
D	6	5
E	8	2

- Each process may use CPU for given amount of time
  - Process preemption based on clock interrupt generated at intervals, i.e., time slicing
  - Time quantum *q* as tunable parameter
- When interrupt occurs, currently running process is placed in Ready queue, next ready job is selected

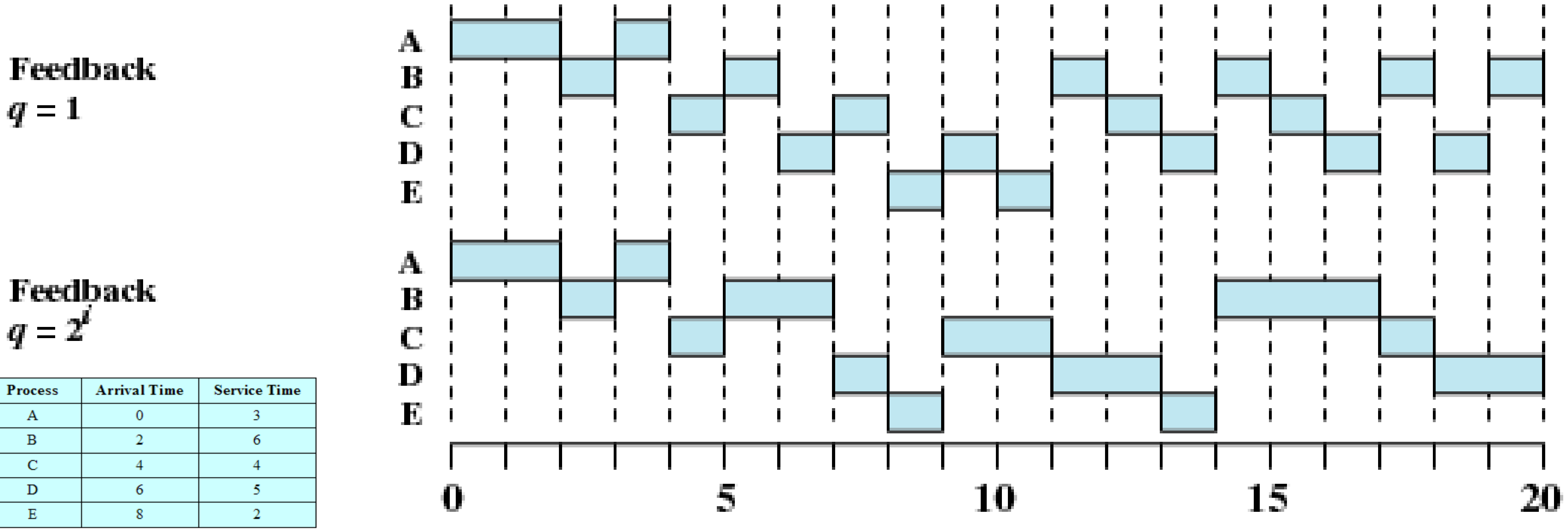
Round-Robin (RR), $q = 1$



- ➢ Initial support for interactivity
- ➢ Scheduling overhead (scheduling decision, process switch)
  - ➢ Tradeoff between interactivity and efficiency, directly tunable by *q*
- ➢ Problematic for I/O processes that hardly ever use full quantum

Feedback

- Processes start in the queue with highest priority RQ0 and move to queues with lower priority after each time slice
  - Multiple queues with different priorities
- For fairness, allow longer time slices *q* for queues RQ*i*



Process	Arrival Time	Service Time
A	0	3
B	2	6
C	4	4
D	6	5
E	8	2

- ➢ Penalize long running processes
- ➢ No need to know remaining execution time of process

Qualitative Comparison of Policies

	Selection Function	Decision Mode	Throughput	Response Time	Overhead	Effect on Processes	Starvation
FCFS	$\max[w]$	Nonpreemptive	Not emphasized	May be high, especially if there is a large variance in process execution times	Minimum	Penalizes short processes; penalizes I/O bound processes	No
Round Robin	constant	Preemptive (at time quantum)	May be low if quantum is too small	Provides good response time for short processes	Minimum	Fair treatment	No
SPN	$\min[s]$	Nonpreemptive	High	Provides good response time for short processes	Can be high	Penalizes long processes	Possible
SRT	$\min[s - e]$	Preemptive (at arrival)	High	Provides good response time	Can be high	Penalizes long processes	Possible
HRRN	$\max\left(\frac{w+s}{s}\right)$	Nonpreemptive	High	Provides good response time	Can be high	Good balance	No
Feedback	(see text)	Preemptive (at time quantum)	Not emphasized	Not emphasized	Can be high	May favor I/O bound processes	Possible

w = time spent waiting, e = time spent in execution so far, s = total service time required by process, including e

Quantitative Comparison of Policies

	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

Multiprocessor and Real-Time Scheduling

Multiprocessor Scheduling

- Assignment of processes to processors
  - ➢ Permanently assign process to a processor
  - ➢ Treat processors as a pooled resource and assign process to processors on demand
    - Possibly move running process between processors (expensive!)
- Architectures
  - Global queue: schedule to any available processor
  - Master/slave: Key kernel functions always run on particular processor, master is responsible for scheduling
  - Peer: Operating system can execute on any processor, each processor does self-scheduling
- Use of multiprogramming on individual processors
- Actual dispatching of processes

Real-Time Scheduling

- Correctness of system depends
  - on logical result of the computation
  - **AND** on time at which the results are produced
- Tasks or processes attempt to control or react to events that take place in outside world
- Examples:
  - Control of laboratory experiments
  - Process control in industrial plants
  - Robotics
  - Air traffic control
  - Telecommunications
  - Military command and control systems
- Real-time applications are *not concerned with speed* but with *completing tasks*

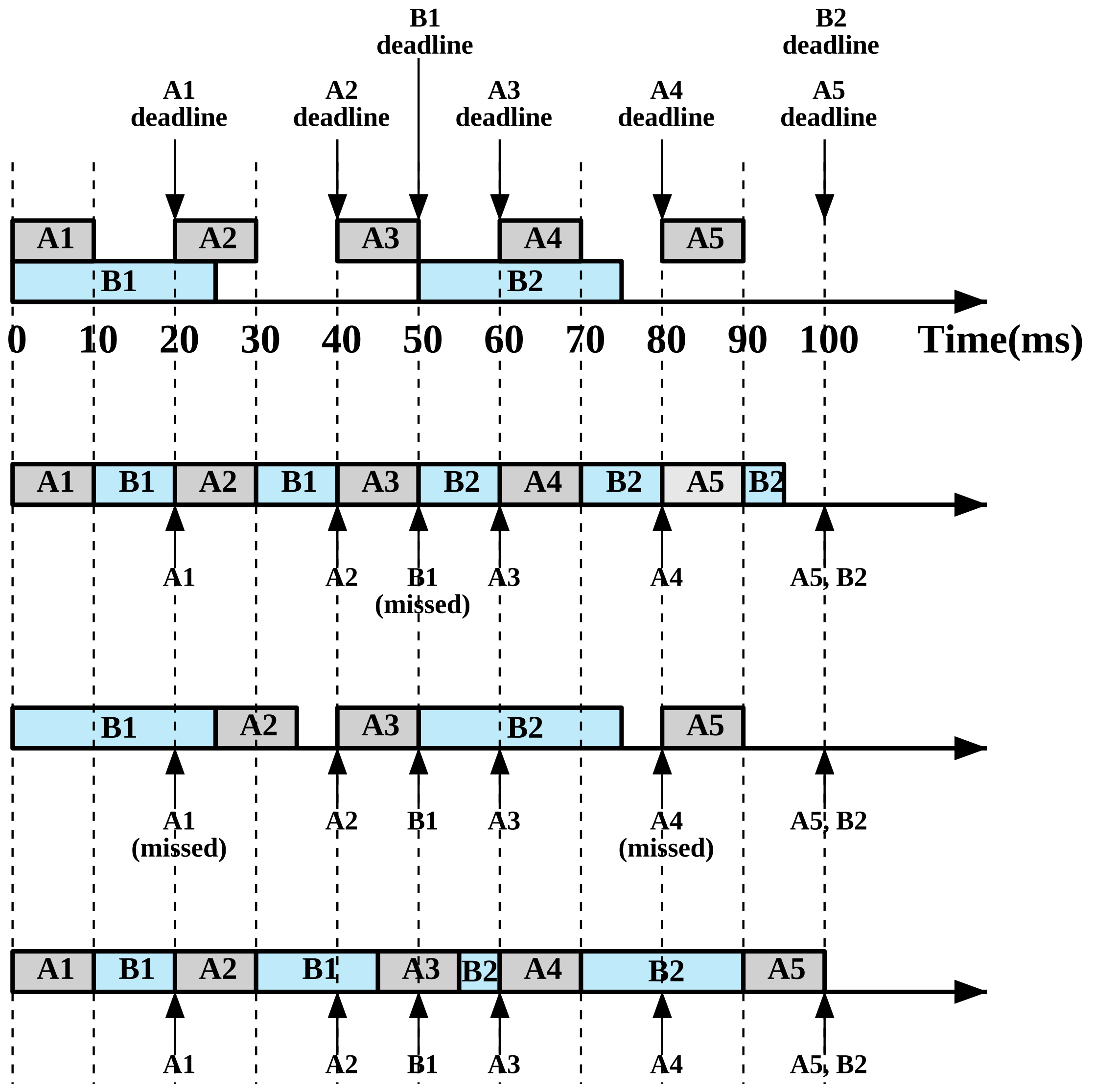
Real-Time Scheduling: Examples

Arrival times, execution times, and deadlines

Fixed-priority scheduling; A has priority

Fixed-priority scheduling; B has priority

Earliest deadline scheduling using completion deadlines



Examples

Examples: Traditional UNIX Scheduling

- Multilevel feedback using round robin within each priority queue
- If running process does not block or complete within one second, it is preempted
- Priorities are recomputed once per second
- Base priority (set upon process creation) divides all processes into fixed bands of priority levels

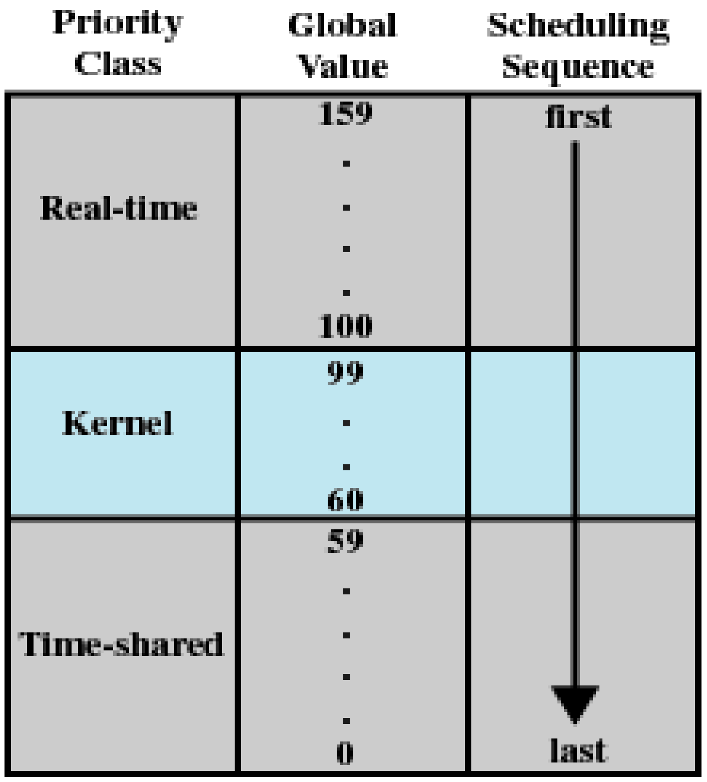
Examples: UNIX SVR4 Scheduling

- Preemptable static priority scheduler

- Introduces set of 160 priority levels divided into three priority classes
  - Highest preference to real-time processes
  - Next-highest to kernel-mode processes
  - Lowest preference to other user-mode processes

- In-kernel preemption points, i.e. long running kernel operations may be preempted

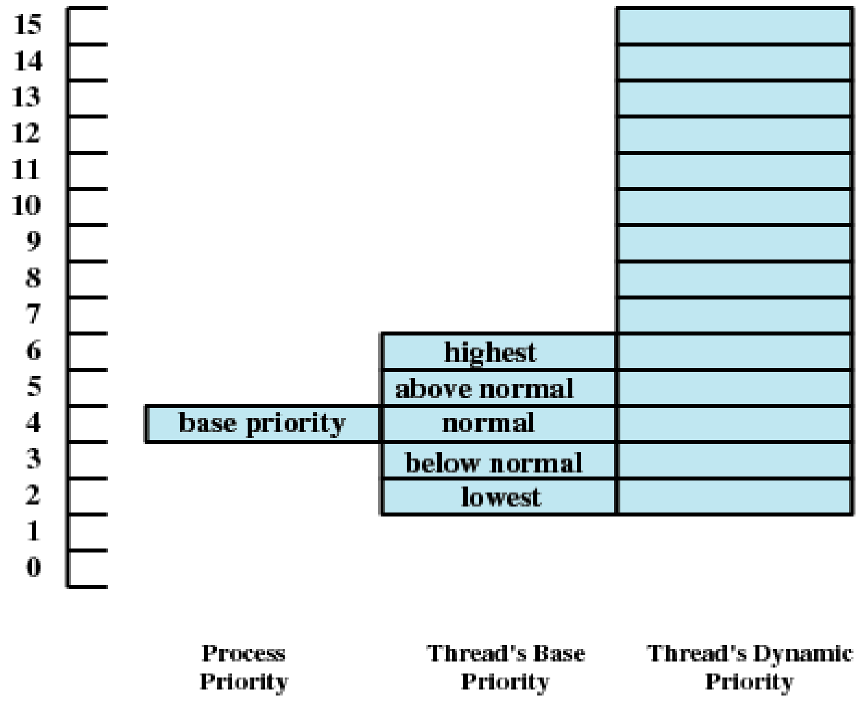
- SVR4 Priority Classes:
  - Real time (159 – 100)
  - Kernel (99 – 60)
  - Time-shared (59-0)

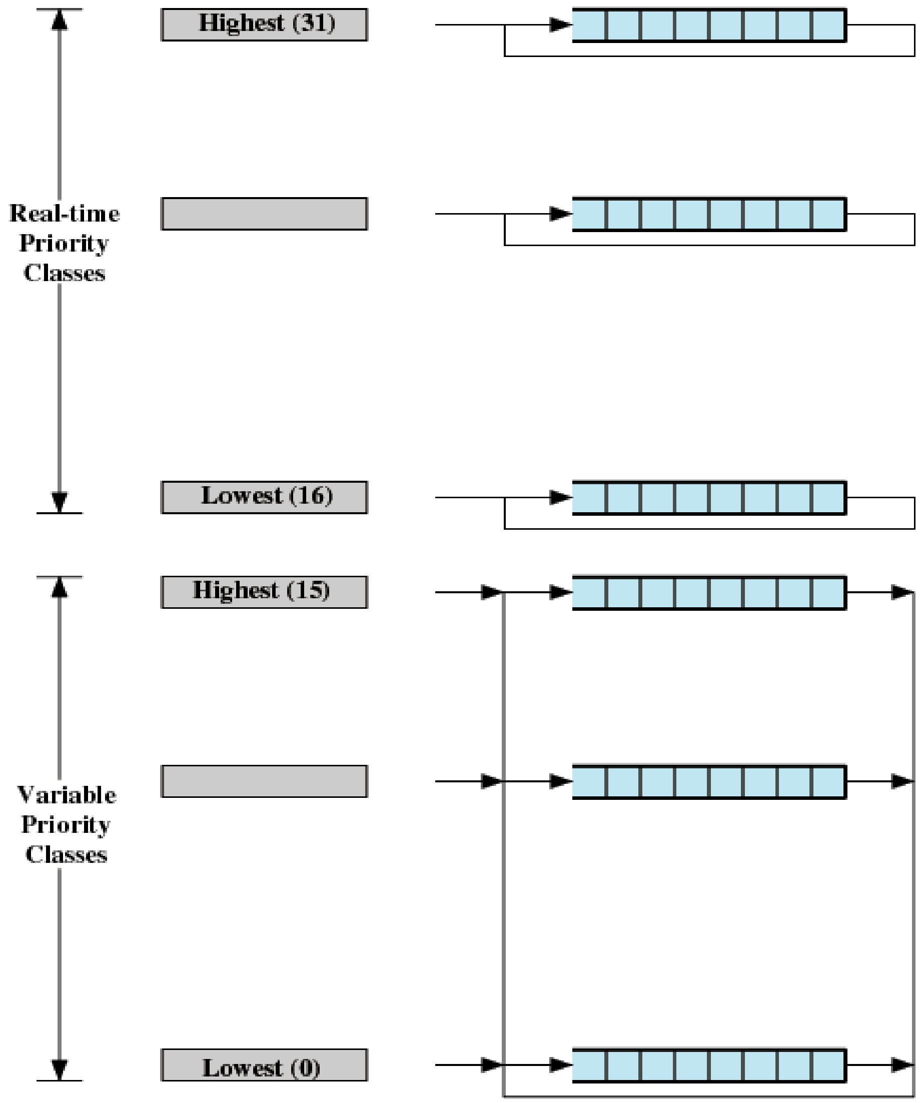


Priority Class	Global Value	Scheduling Sequence
Real-time	159 100	first
Kernel	99 . . 60	
Time-shared	59 0	last

Examples: Windows Scheduling

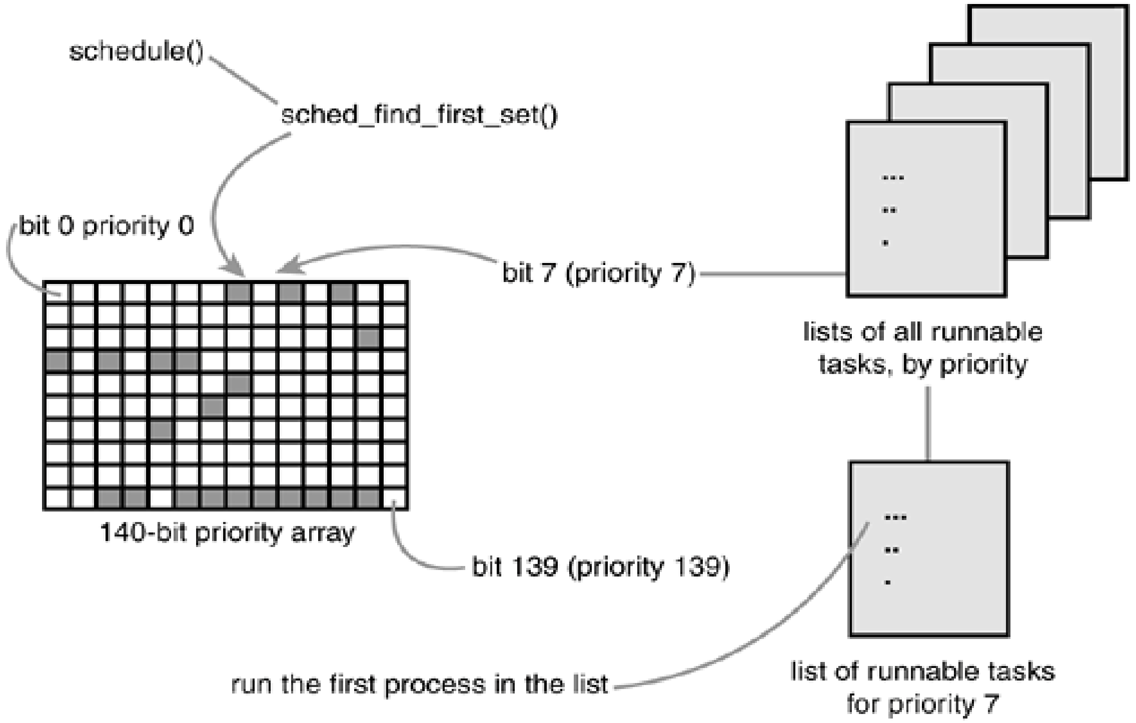
- Priorities organized into two bands or classes
  - Real time
  - Variable
- Priority-driven preemptive scheduler within each class





Example: Linux O(1) Scheduling

- Scheduling algorithm needs to scale with number of processes
  - Variable overhead unacceptable for real-time systems



schedule()
sched_find_first_set()
bit 0 priority 0
bit 7 (priority 7)
140-bit priority array
bit 139 (priority 139)
lists of all runnable tasks, by priority
list of runnable tasks for priority 7
run the first process in the list

➢ Linux O(1) scheduler

- Active/expired bit arrays for priorities; one list per priority
- Priority assigned based on
  - Static (process) priority
  - Heuristics to determine interactivity requirements, e.g. CPU- vs. I/O-bound
- Process timeslice (i.e. runtime in relation to other processes) calculated when process moves from active to expired state
- Switch from active to expired bit array when all processes have used their timeslice

➢ Scheduling decision in constant time

Related System Calls

Related System Calls (Linux)

- **`int sched_yield(void)`**
  - Voluntarily yield processor, e.g. when waiting for input

- **`int getpriority(int which, int who)`**
- **`int setpriority(int which, int who, int prio)`**
  - Get/set priority of user, group or process (**`which`**) with ID **`who`**
  - Library interface: **`int nice(int inc)`**
    - Increment how nice you are; only root is allow not to be nice

- **`int sched_get_priority_max(int policy)`**
- **`int sched_get_priority_min(int policy)`**
  - Returns max/min priority values for given scheduling **`policy`**

Related System Calls (Linux, cont.)

- **`int sched_setscheduler(pid_t pid, int policy, conststruct sched_param *param)`**
- **`int sched_getscheduler(pid_t pid)`**
  - Controls which scheduling policy to use for a process
  - Policies are **`SCHED_BATCH`**, **`SCHED_FIFO`**, **`SCHED_RR`** and **`SCHED_OTHER`**

- **`int sched_setparam(pid_t pid, const struct sched_param *param)`**
- **`int sched_getparam(pid_t pid, struct sched_param *param)`**
  - Get/set policy specific scheduling parameters

- **`int sched_setaffinity(pid_t pid, unsigned int cpusetsize, cpu_set_t *mask)`**
- **`int sched_getaffinity(pid_t pid, unsigned int cpusetsize, cpu_set_t *mask)`**
  - Controls on which CPU in multi-processor system a process can/should run

Content