CIS 415: Operating Systems

Scheduling

Spring 2013

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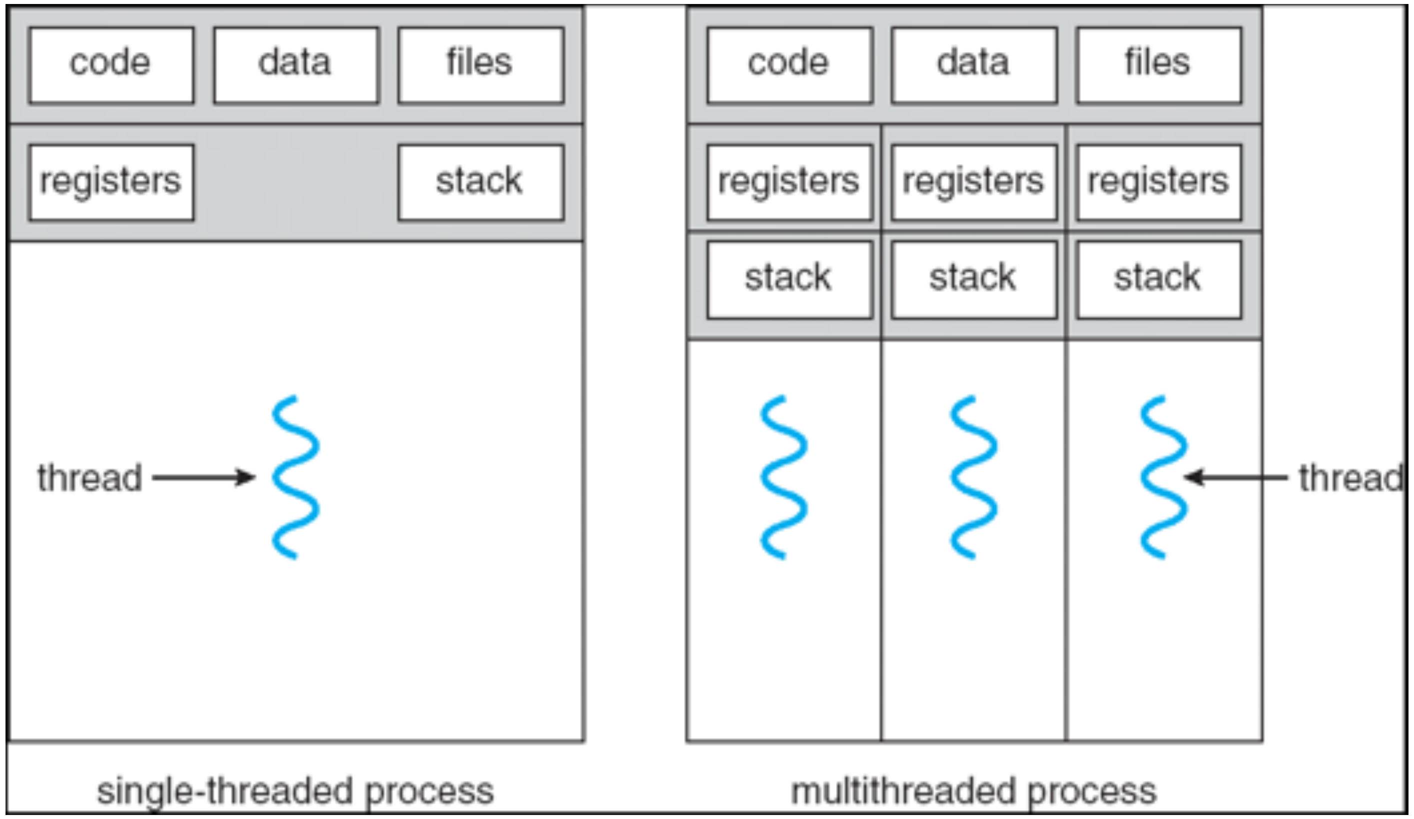
- Last class:
  - Threads
- Today:
  - Intro to Scheduling

- Remember: Project 1 due tonight!

Multi-Threaded vs. Single-Threaded



Regular UNIX process can be thought of as a special case of a multithreaded process: a process that contains just one thread

Reentrance and Thread-Safety

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- Terms that you might hear
- *Reentrant Code*
  - Code that can be run by multiple threads concurrently
- *Thread-safe Libraries*
  - Library code that permits multiple threads to invoke the safe function
- Requirements
  - Rely only on input data
    - Or some thread-specific data
  - Must be careful about locking (later)

Why not threads?

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- Threads can interfere with one another
  - Impact of more threads on caches
  - Impact of more threads on TLB
  - Bug in one thread...
- Executing multiple threads may slow them down
  - Impact of single thread vs. switching among threads
- Harder to program a multithreaded program
  - Multitasking hides context switching
  - Multithreading introduces concurrency issues

Summary of Threads

- Threads
  - Programming systems
  - Multi-threaded design issues
- Useful, but not a panacea
  - Slow down system in some cases
  - Can be difficult to program
- Multiprogramming and multithreading are vital concepts

Resource Allocation

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- In a multiprogramming system, we need to share resources among the running processes
  - What are the types of OS resources?
- Question: Which *process* gets access to which *resources*?
  - To maximize performance

Resource Types

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- Memory: Allocate portion of finite resource
  - Virtual memory tries to make this appear infinite
  - Physical resources are limited
- I/O: Allocate portion of finite resource and time with resource
  - Store information on disk
  - A time slot to store that information
- CPU: Allocate time slot with resource
  - A time slot to run instructions
- We will focus on *CPU scheduling* for now

Types of Scheduling

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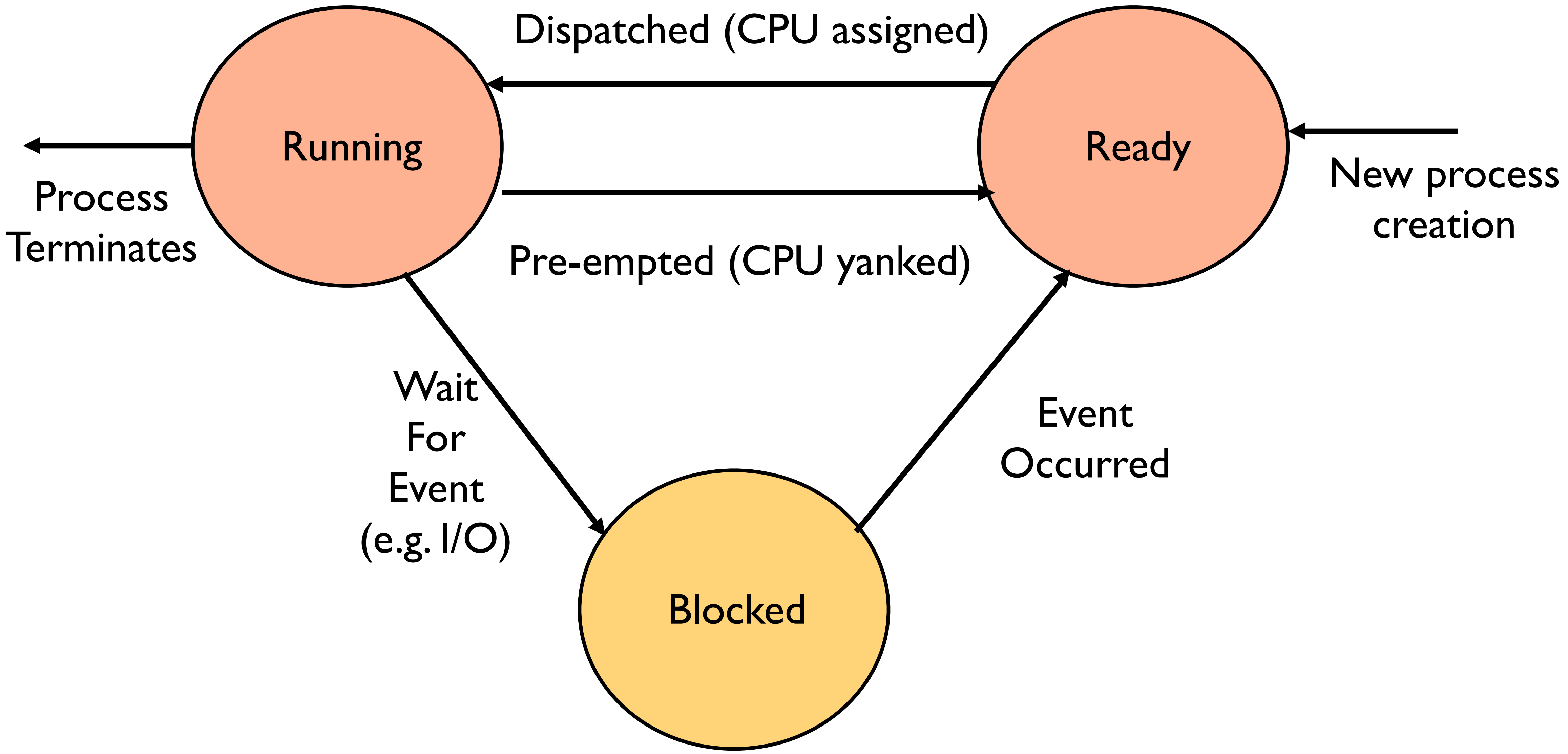
- *Long-term (admission) scheduling:* determining whether to add to the pool of processes to be executed
- *Medium-term scheduling:* determining whether to add to the number of processes partially or fully in memory
- *Short-term scheduling:* determining which process will be executed by the processor
- *I/O scheduling:* determining which process's pending I/O request will be handled by an available I/O device

CPU Scheduling Examples

- Single process view
  - GUI request
    - Click on the mouse
  - Scientific computation
    - Long-running, but want to complete ASAP
- System view
  - Get as many tasks done as quickly as possible
  - Minimize waiting time for processes
  - Get full utilization from the CPU

Process Scheduling



Scheduling Problem

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- Choose the *ready/running* process to run at any time
  - Maximize "performance"
- Model/estimate "performance" as a function
  - System performance of scheduling each process
    - *f(process) = y*
  - What are some choices for *f(process)*?
- Choose the process with the best *y*
  - Estimating overall performance is intractable
    - E.g., scheduling so all tasks are completed as soon as possible is NP-complete, then add in pre-emption...

When Scheduling Occurs

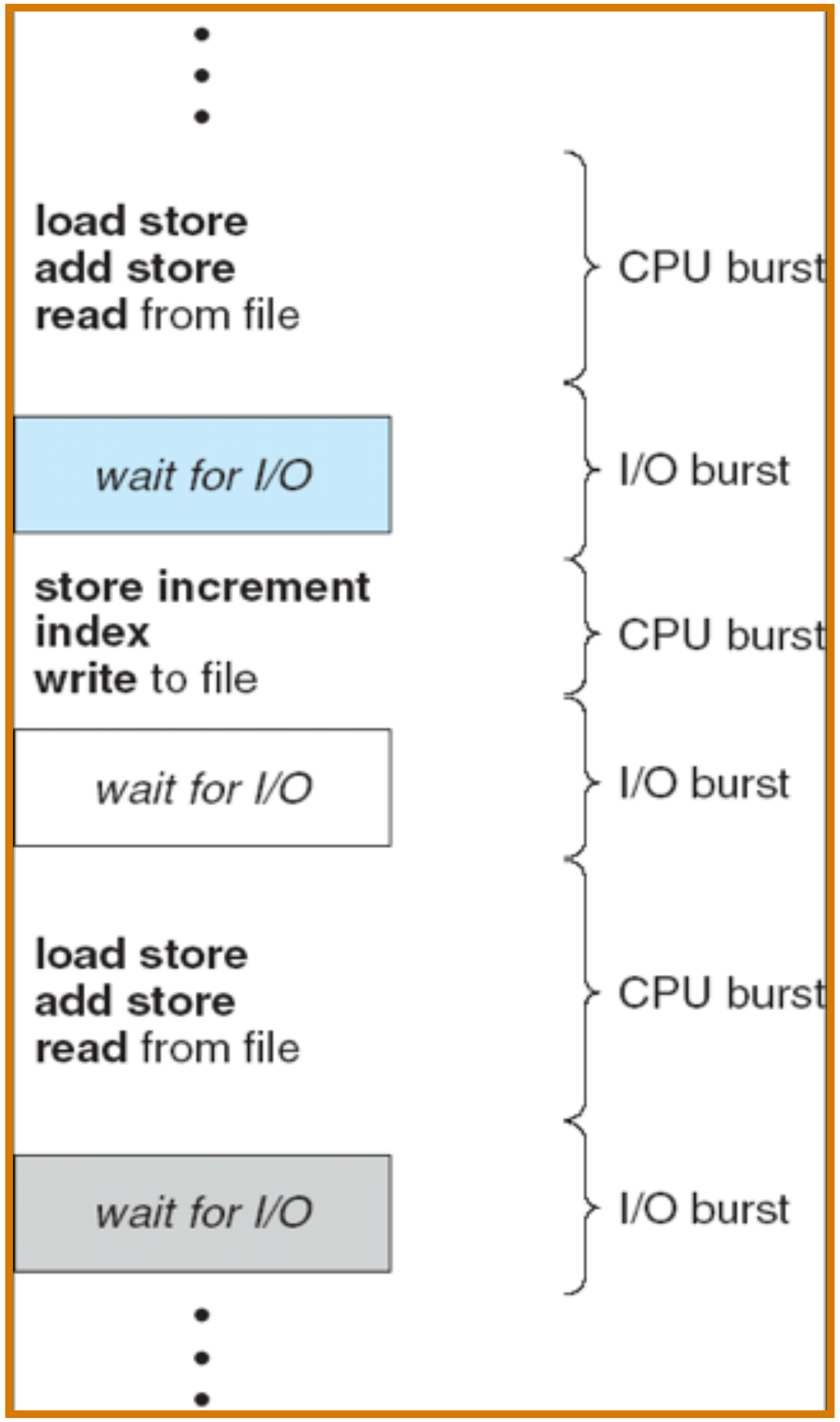
- CPU scheduling decisions may take place when a process:
  - 1. Switches from running to waiting state
  - 2. Switches from running to ready state
  - 3. Switches from waiting to ready
  - 4. Terminates
- Scheduling for events 1 and 4 do not preempt a process
  - Process volunteers to give up the CPU

Preemption

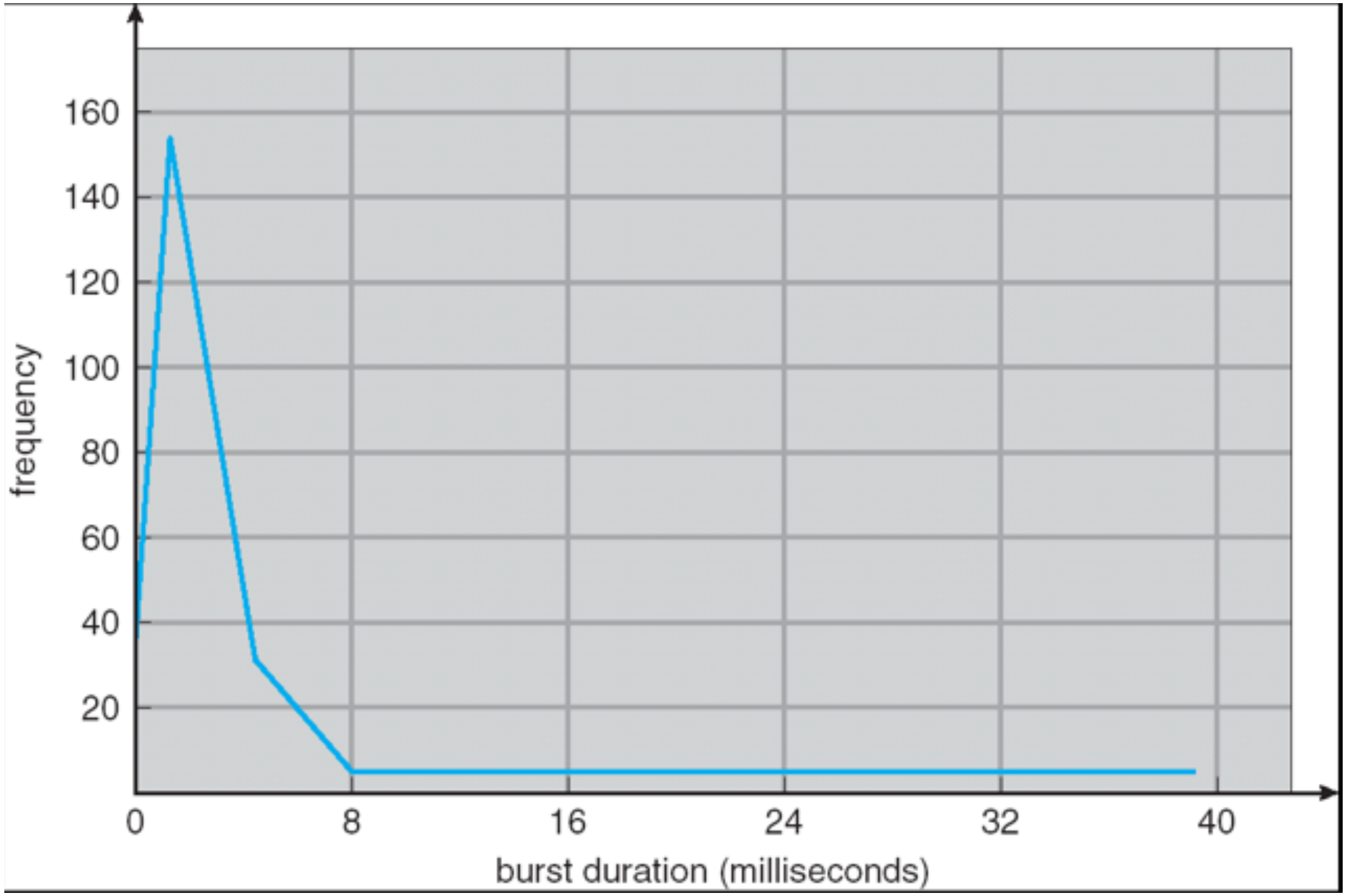
- Can we reschedule a process that is actively running?
  - If so, we have a *preemptive* scheduler
  - If not, we have a *non-preemptive* scheduler
- Suppose a process becomes ready
  - E.g., new process is created or it is no longer waiting
- It may be better to schedule this process
  - So, we preempt the running process
- In what ways could the new process be better?

Bursts

- A process runs in CPU and I/O Bursts
  - Run instructions (CPU Burst)
  - Wait for I/O (I/O Burst)
- Scheduling is aided by knowing the length of these bursts
  - More later…



CPU Burst Duration



Dispatcher

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- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - Switching context
  - Switching to user mode
  - Jumping to the proper location in the user program to restart that program
- *Dispatch latency* – time it takes for the dispatcher to stop one process and start another running

Scheduling Criteria

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- *Utilization/efficiency:* keep the CPU busy 100% of the time with useful work
- *Throughput:* maximize the number of jobs processed per hour.
- *Turnaround time:* from the time of submission to the time of completion.
- *Waiting time:* Sum of time spent (in Ready queue) waiting to be scheduled on the CPU.
- *Response Time:* time from submission until the first response is produced (mainly for interactive jobs)
- *Fairness:* make sure each process gets a fair share of the CPU

Scheduling Algorithms

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- Some may seem intuitively better than others
- But a lot has to do with the type of offered workload to the processor
- Best scheduling comes with best context of the tasks to be completed

FCFS

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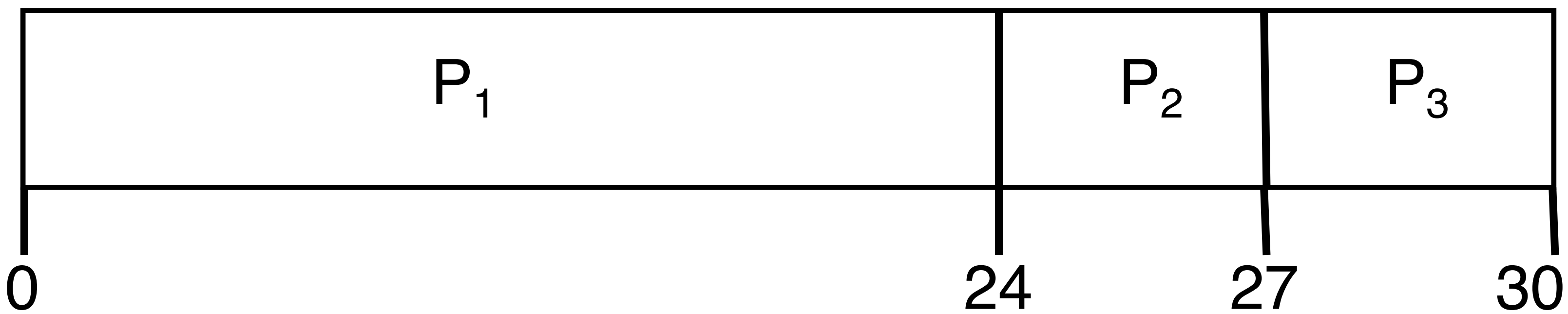
- First-Come, First-Served (FCFS)
  - Serve the jobs in the order they arrive.
  - Non-preemptive
  - Simple and easy to implement: When a process is ready, add it to tail of ready queue, and serve the ready queue in FCFS order.
  - Very fair: No process is starved out, and the service order is immune to job size, etc.

FCFS

Process	Burst Time
P_1	24
P_2	3
P_3	3

- Suppose that the processes arrive in the order: P_1 , P_2 , P_3
  The *Gantt Chart* for the schedule is:



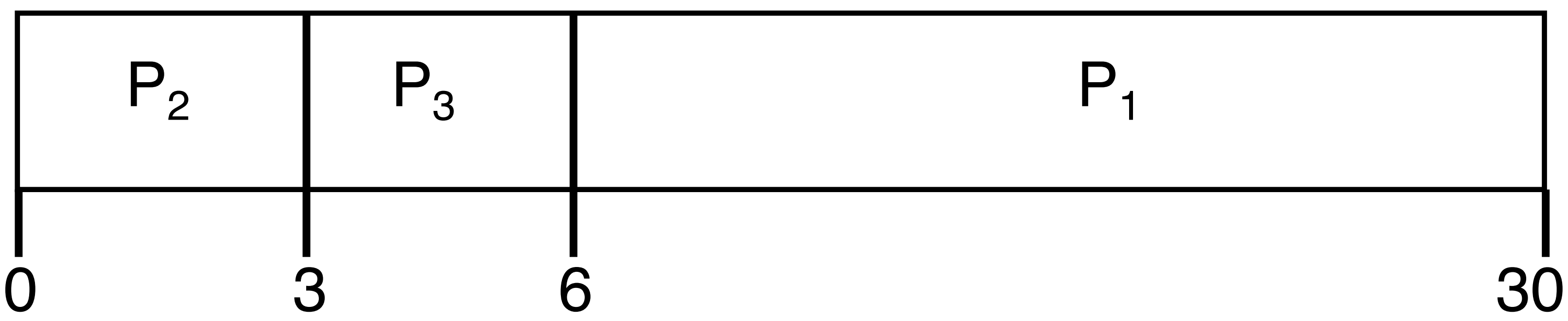
- Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
- Average waiting time: (0 + 24 + 27)/3 = 17

Reducing Waiting Time

Suppose that the processes arrive in the order

P_2 , P_3 , P_1

- The Gantt chart for the schedule is:



- Waiting time for $P_1 = 6$; $P_2 = 0$; $P_3 = 3$
- Average waiting time: (6 + 0 + 3)/3 = 3
- Much better than previous case
- *Convoy effect:* short process behind long process

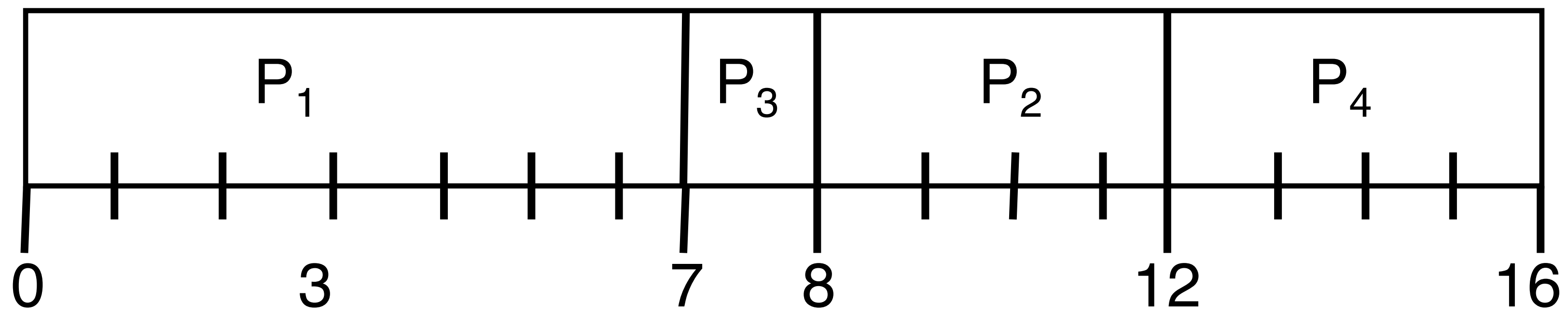
Shortest-Job-First (SJF)

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
- Two schemes:
  - **Non-preemptive** – once CPU given to the process it cannot be preempted until completes its CPU burst
  - **Preemptive** – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is known as the Shortest-Remaining-Time-First (SRTF)
- SJF is *optimal* – gives minimum average waiting time for a given set of processes
  - So we always use it, right?

Non-Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (non-preemptive)

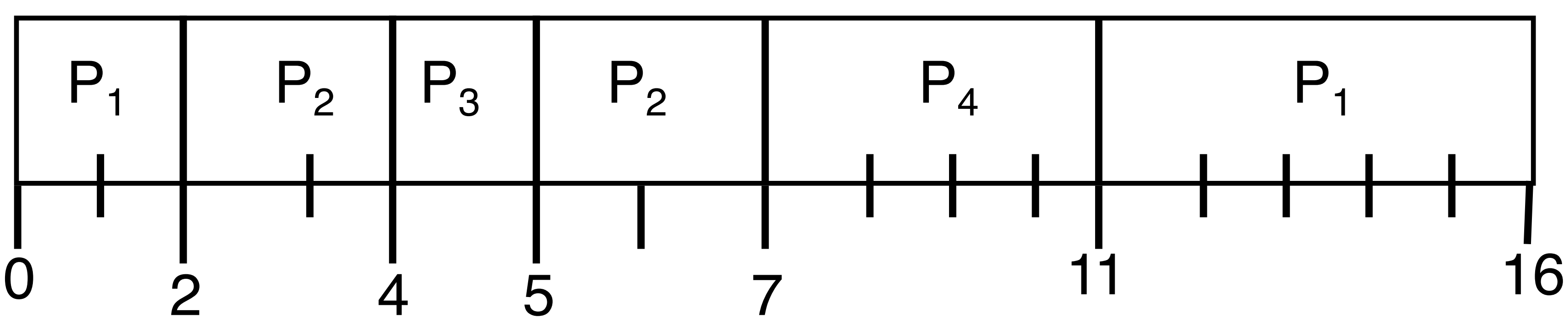


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (preemptive)



- Average waiting time = (9 + 1 + 0 +2)/4 = 3

Determining Next CPU Burst

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- We can only estimate what the duration of the next CPU burst will be
- Use length of previous CPU bursts as a guide, and exponential averaging to predict next burst
  - If t_n is the actual length of the nth CPU burst, and
  - τ_{n+1} is the predicted value of the next CPU burst, then
  - Given some parameter $\alpha, 0 \leq \alpha \leq 1$
  - Define $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$

Determining Next CPU Burst

- If $\alpha = 0$, no weighting to recent history (e.g., current conditions are transient)
- If $\alpha = 1$, no weighting to old history
- Typically, choose $\alpha = 1/2$ which gives equal weighting to recent and past history

1. t_n = actual length of n^{th} CPU burst
2. τ_{n+1} = predicted value for the next CPU burst
3. α, $0 \le \alpha \le 1$
4. Define: $\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\tau_n$.

Exponential Averaging

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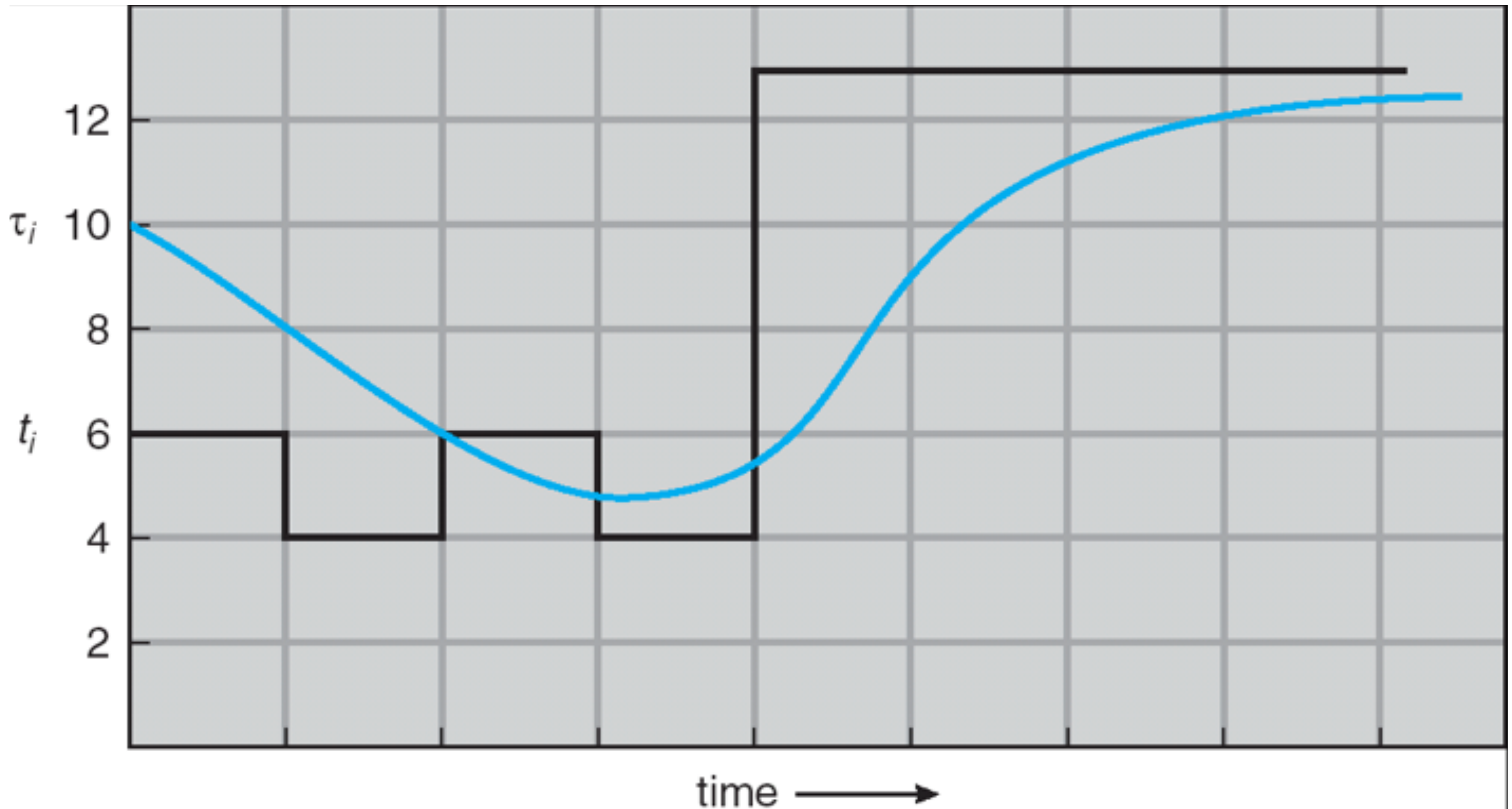
- If we expand the formula, we get:

$$\tau_{n+1} = \alpha\, t_n + (1 - \alpha)\alpha\, t_{n-1} + \ldots$$
$$+ (1 - \alpha)^j \alpha\, t_{n-j} + \ldots$$
$$+ (1 - \alpha)^{n+1} \tau_0$$

- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

CPU Burst Prediction



CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Scheduling Algorithms

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- First-come, First-serve (FCFS)
  - Non-preemptive
  - Does not account for waiting time (or much else)
    - Convoy problem
- Shortest Job First
  - May be preemptive
  - Optimal for minimizing waiting time (how?)
- Lots more… And what do real systems use?

Priority Scheduling

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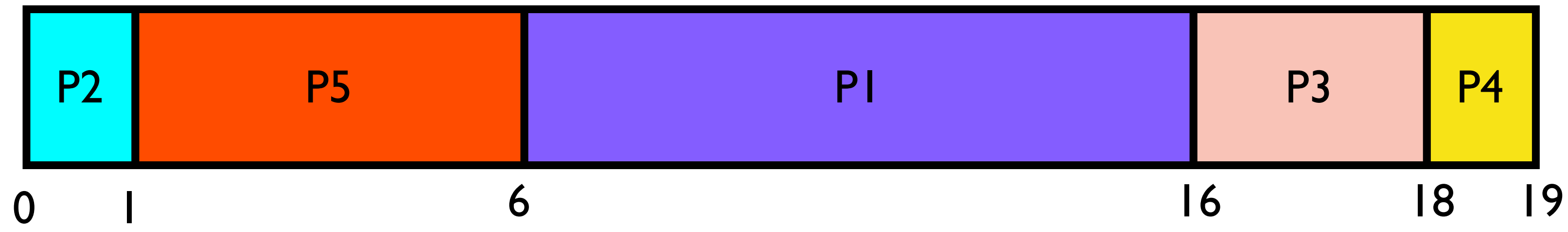
- Each process is given a certain priority "value".
- Always schedule the process with the highest priority.

	Duration(s)	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

Gantt Chart for Priority Scheduling



Priorities

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- Note that FCFS and SJF are specialized versions of Priority Scheduling
  - i.e. there is a way of assigning priorities to the processes so that Priority Scheduling would result in FCFS/SJF.
- *What would examples of those priority functions be?*

Round Robin (RR)

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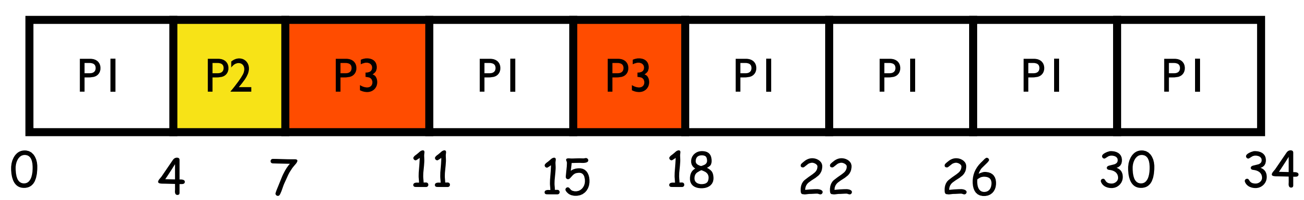
- Each process gets a small unit of CPU time (time quantum)
  - Usually 10-100 milliseconds
  - After this time has elapsed, the process is preempted and added to the end of the ready queue
- Approach
  - If there are n processes in the ready queue and the time quantum is q
  - Then each process gets $1/n$ of the CPU time
  - In chunks of at most q time units at once.
  - No process waits more than $(n-1)q$ time units

Round Robin

	Arrival Time (s)	Job length (s)
P1	**0**	**24**
P2	**0**	**3**
P3	**0**	**7**

Time Quantum = 4 s



RR Time Quantum

- Round robin is virtually sharing the CPU between the processes giving each process the illusion that it is running in isolation (at 1/*n*-th the CPU speed).
- Smaller the time quantum, the more realistic the illusion (note that when time quantum is of the order of job size, it degenerates to FCFS).
- But what is the drawback when time quantum gets smaller?

RR Time Quantum

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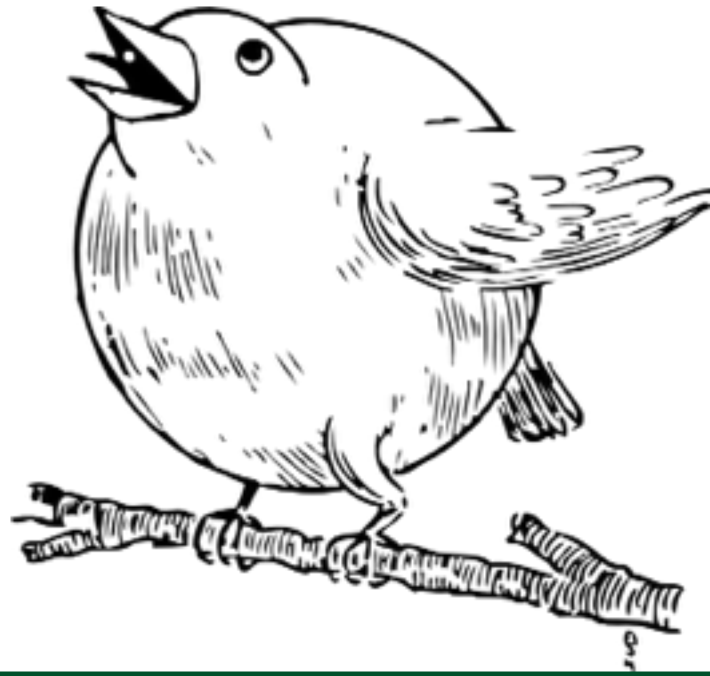
- For the considered example, if time quantum size drops to 2s from 4s, the number of context switches increases to ????
- But context switches are not free!
  - **Saving/restoring registers**
  - **Switching address spaces**
  - **Indirect costs (cache pollution)**

Scheduling Desirables

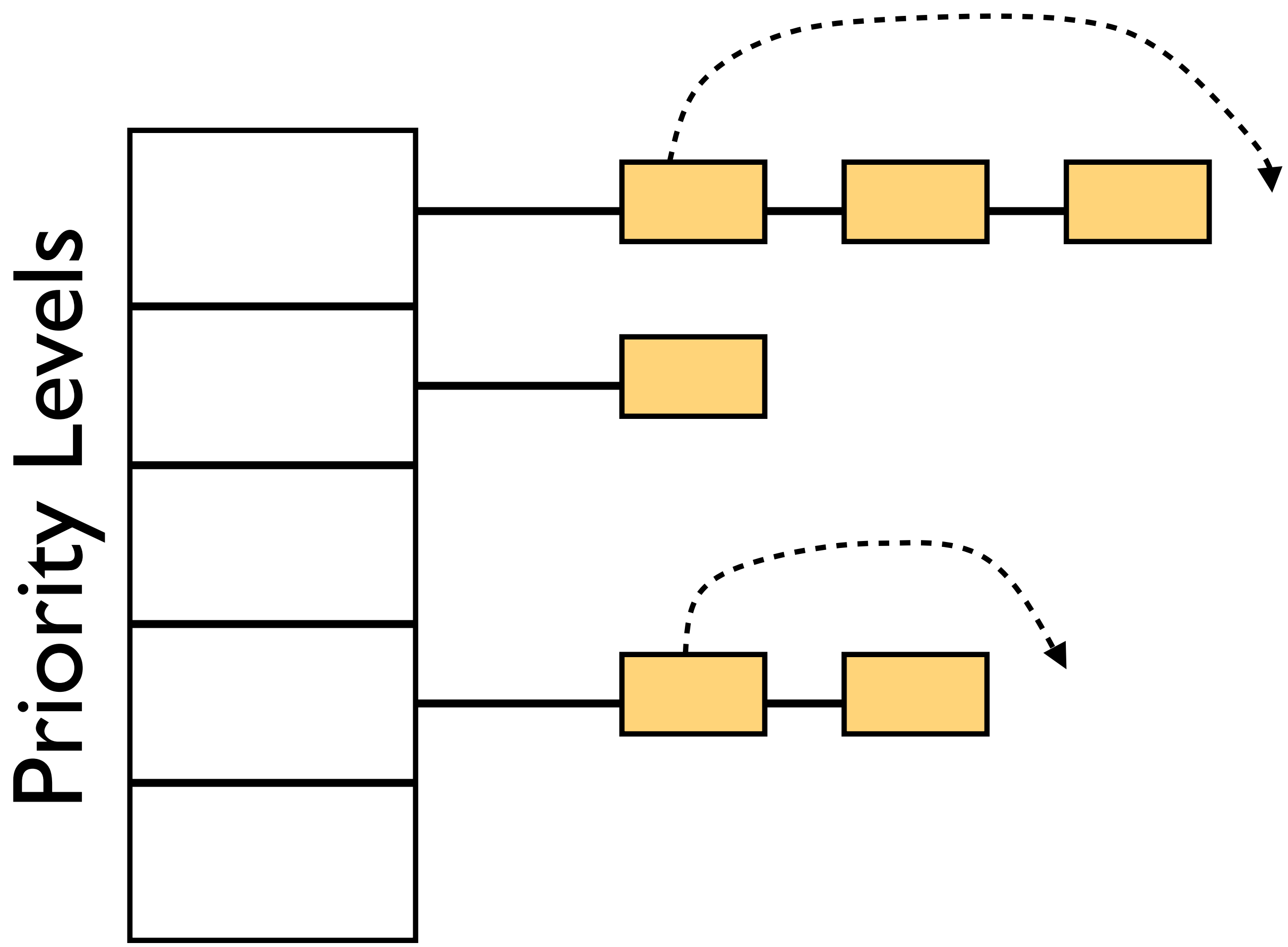
- SJF
  - Minimize waiting time
    - Requires estimate of CPU bursts
- Round robin
  - Share CPU via time quanta
    - If burst turns out to be "too long"
- Priorities
  - Some processes are more important
  - Priorities enable composition of "importance" factors
- No single best approach -- now what?

Round Robin with Priority

- Have a ready queue for each priority level.
- Always service the non-null queue at the highest priority level.
- Within each queue, you perform round-robin scheduling between those processes.



Round-Robin with Priority



What is the problem?

- With fixed priorities, processes lower in the priority level can get *starved out!*
- In general, you employ a mechanism to “age” the priority of processes.

Multilevel Queue

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- Ready queue is partitioned into separate queues: foreground (*interactive*) & background (*batch*)
- Each queue has its own scheduling algorithm, foreground – **RR** & background – **FCFS**
- Scheduling must be done between the queues.
  - Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation.
  - Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; i.e., 80% to foreground in RR
  - 20% to background in FCFS

Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way
- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine when to upgrade a process
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service

Multilevel Feedback Queue

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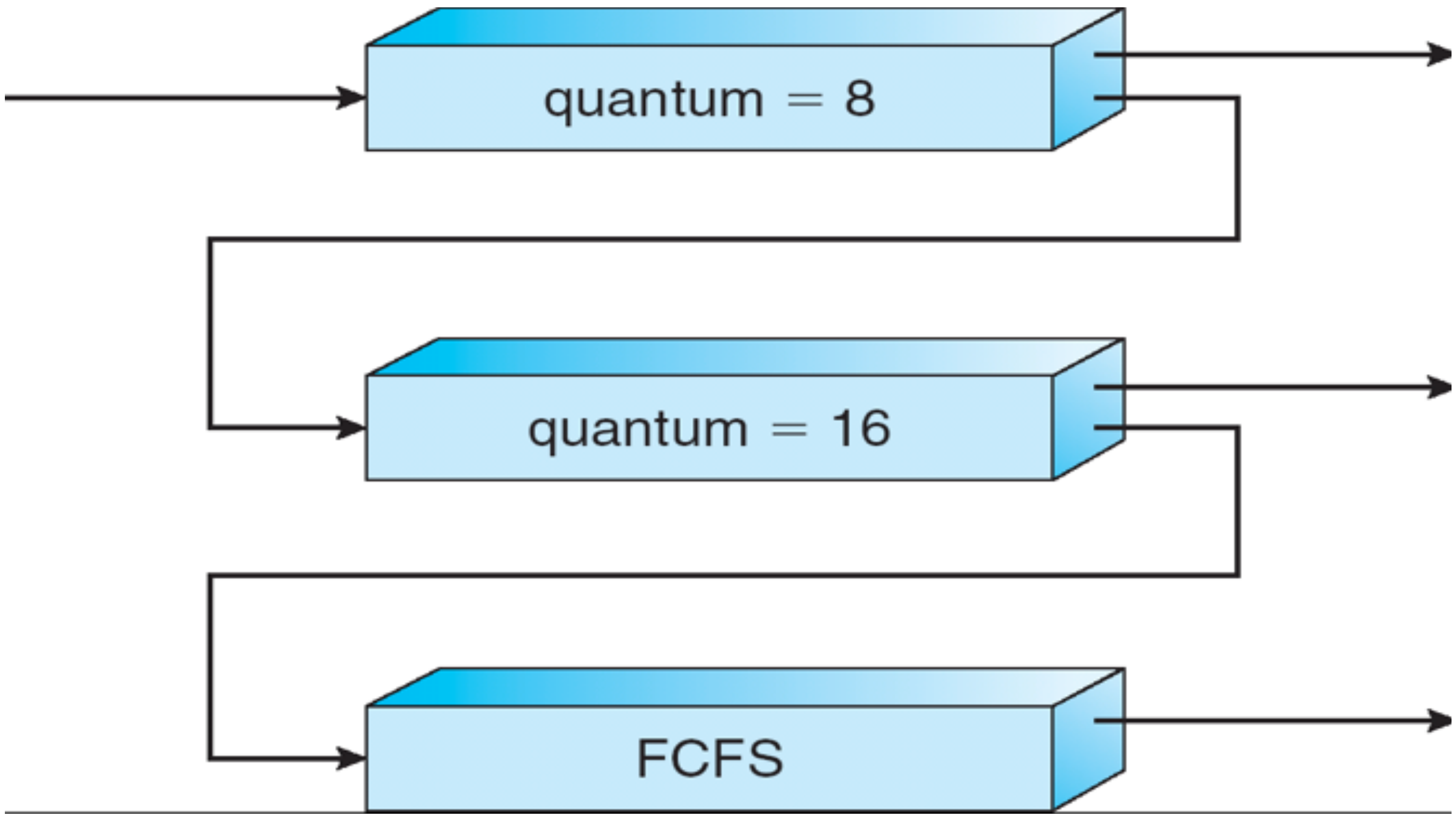
- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS
- Scheduling
  - A new job enters queue Q_0 which is served FCFS. When it gains CPU, job receives 8 milliseconds. If it does not finish in 8 milliseconds, job is moved to queue Q_1.
  - At Q_1 job is again served FCFS and receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.

Multilevel Feedback Queues



Performance for Schedulers

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- *Queueing Theory Analysis* - uses well-established mathematical models and techniques.
- *Simulation* - create a model of the system and simulate its performance using simulation software.
- *Empirical Experiments* - implement and test the algorithms in a real system.

Queuing Theory Analysis

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Single-server Queue:

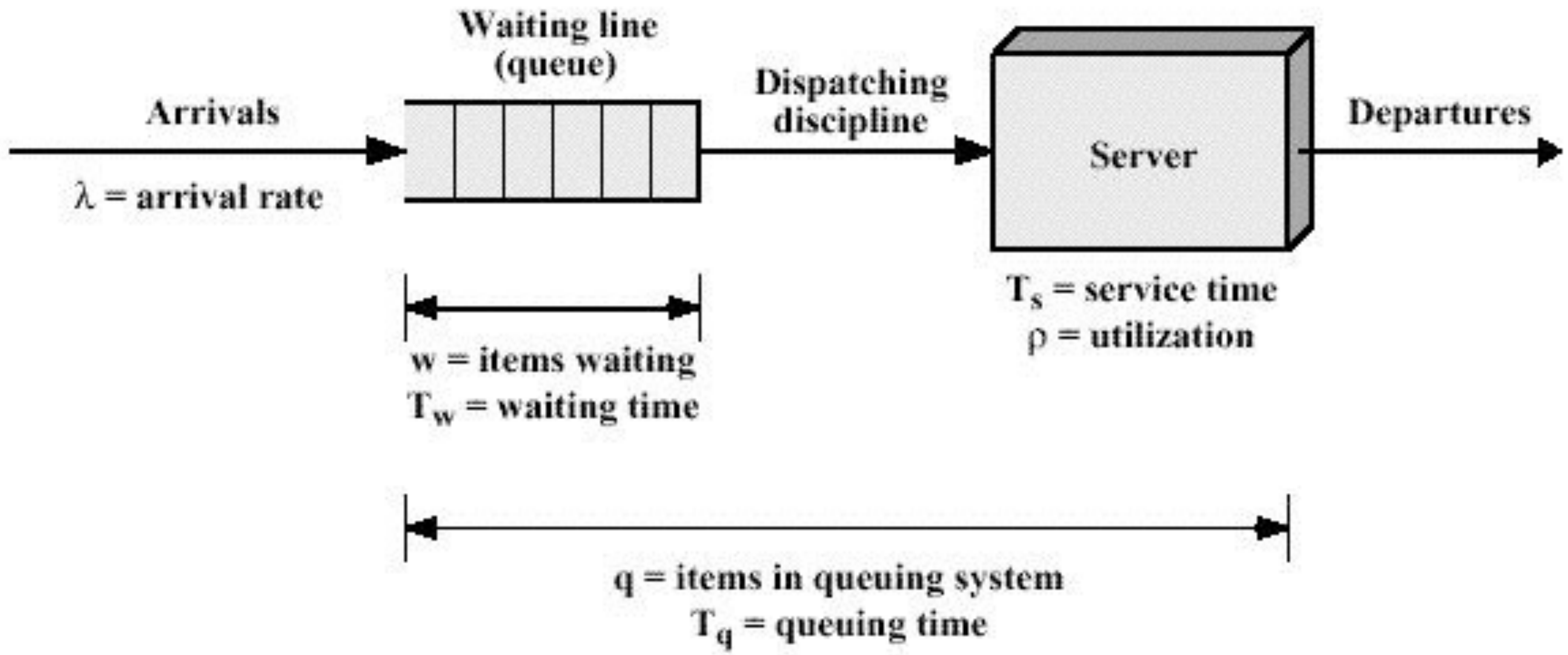

Figure A.2 Queuing System Structure and Parameters for Single-Server Queue

Queuing Theory Analysis

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- Inputs:
  - *arrival rate* - from a probability distribution (usually Poisson which implies random arrivals)
  - *service time* - from a probability distribution (often exponential)
  - *scheduling discipline/algorithm*

Queuing Theory Analysis

- Outputs:
  - Items waiting
  - Waiting time
  - Items queued
  - Queuing time

Queuing Theory Analysis

Single-server Queue:

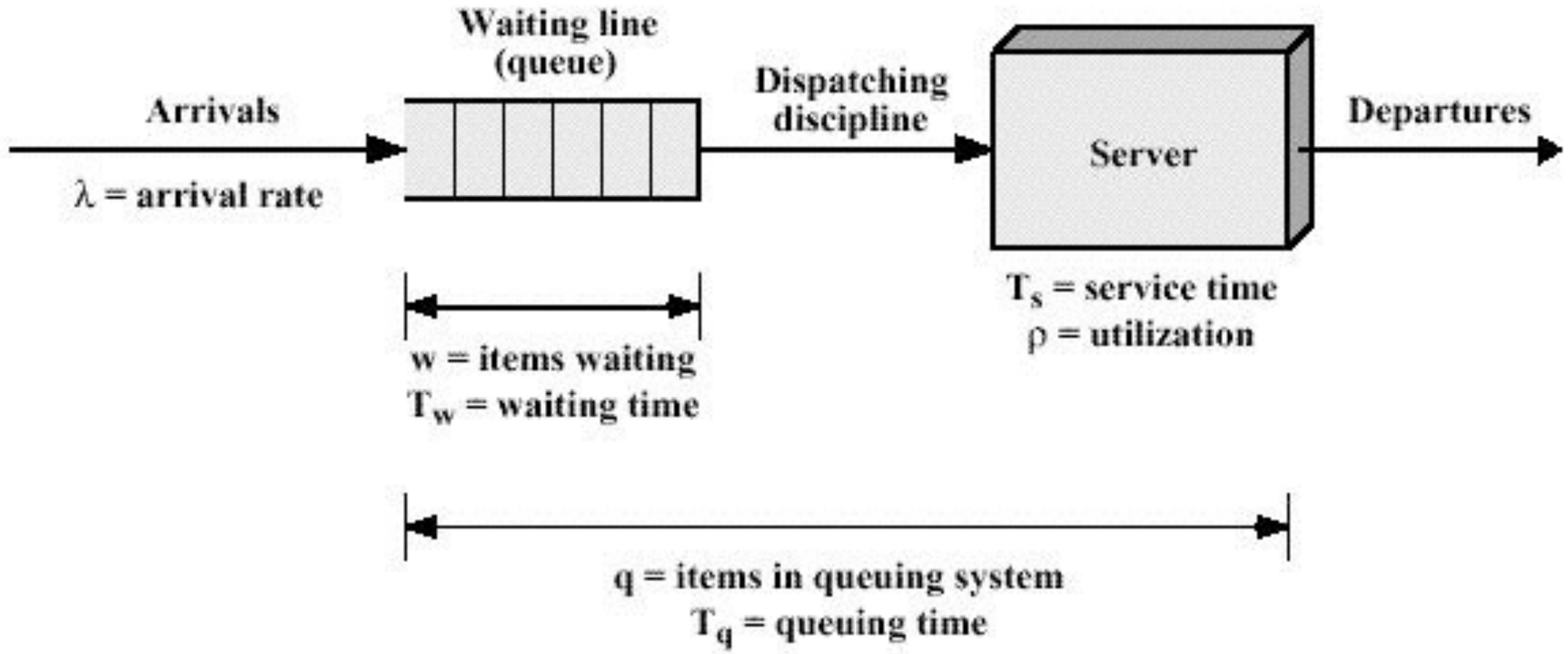

Figure A.2 Queuing System Structure and Parameters for Single-Server Queue

Little's Formula: $n = \lambda W$ (n = queue length)

Simulation Analysis

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- Discrete-event Simulation
  - Often uses models similar to queueing analysis
  - More detailed or more realistic parameters (e.g. trace driven)
  - Simulates events step by step and gathers statistics rather than using mathematical formulas

Empirical Experiments

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- Run experiments on live system

- Properties:
  - Costly and time-consuming
  - Sometimes not possible
  - More realistic

Traditional UNIX Scheduling

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- Multilevel feedback queues
- 128 priorities possible (-64 to +63)
- 1 Round Robin queue per priority
- Every scheduling event the scheduler picks the highest priority (lowest number) non-empty queue and runs jobs in round-robin

UNIX Process Scheduling

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- Negative numbers reserved for processes waiting in kernel mode (just woken up by interrupt handlers) (why do they have a higher priority?)
- Time quantum = 1/10 sec (empirically found to be the longest quantum that could be used without loss of the desired response for interactive jobs such as editors)
  - short time quantum means better interactive response
  - long time quantum means higher overall system throughput since less context switch overhead and less processor cache flush.
- Priority dynamically adjusted to reflect
  - resource requirement (e.g., blocked awaiting an event)
  - resource consumption (e.g., CPU time)

Linux Scheduler

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- Kernel 2.4 and earlier: essentially the same as the traditional UNIX scheduler
- Kernel 2.6: *O(1)* scheduler
  - time to select process is constant regardless of system load or the number of processors
  - separate queue for each priority level
  - CPU affinity (keeps processes on same CPU)
- More recently (kernel 2.6.23 and up): CFS
  - Completely fair scheduler (runs O(log N))
    - uses red-black trees rather than runqueues

Linux Scheduling

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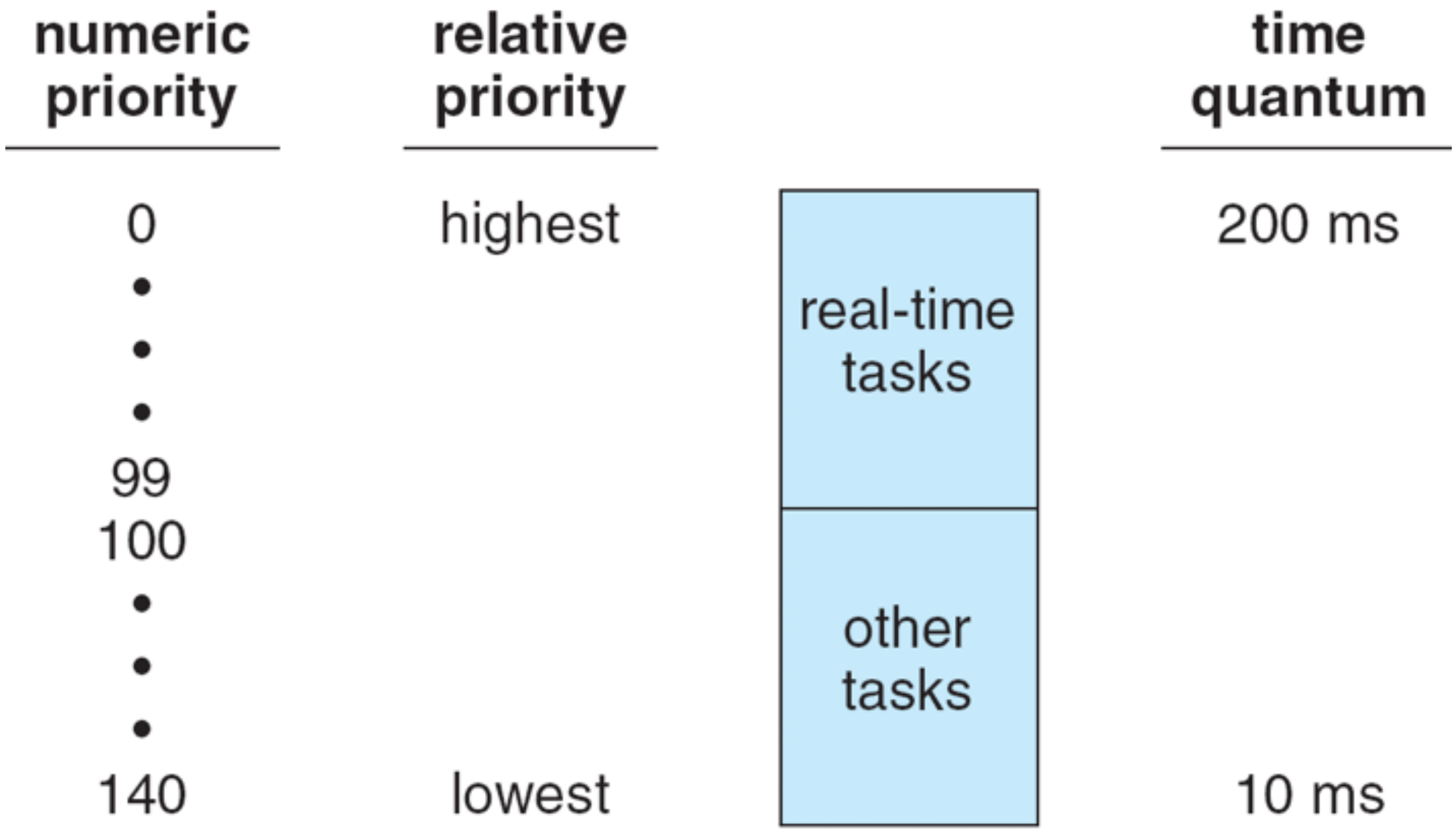
- Two algorithms: time-sharing and real-time
- Time-sharing (still abstracted)
  - Two queues: *active* and *expired*
  - In active, until you use your entire time slice (*quantum*), then expired
    - Once in expired, Wait for all others to finish (*fairness*)
  - Priority recalculation -- based on waiting vs. running time
    - From 0-10 milliseconds
    - Add waiting time to value, subtract running time
    - Adjust the static priority
- Real-time
  - Soft real-time
  - Posix.1b compliant – two classes
    - FCFS and RR; Highest priority process always runs first

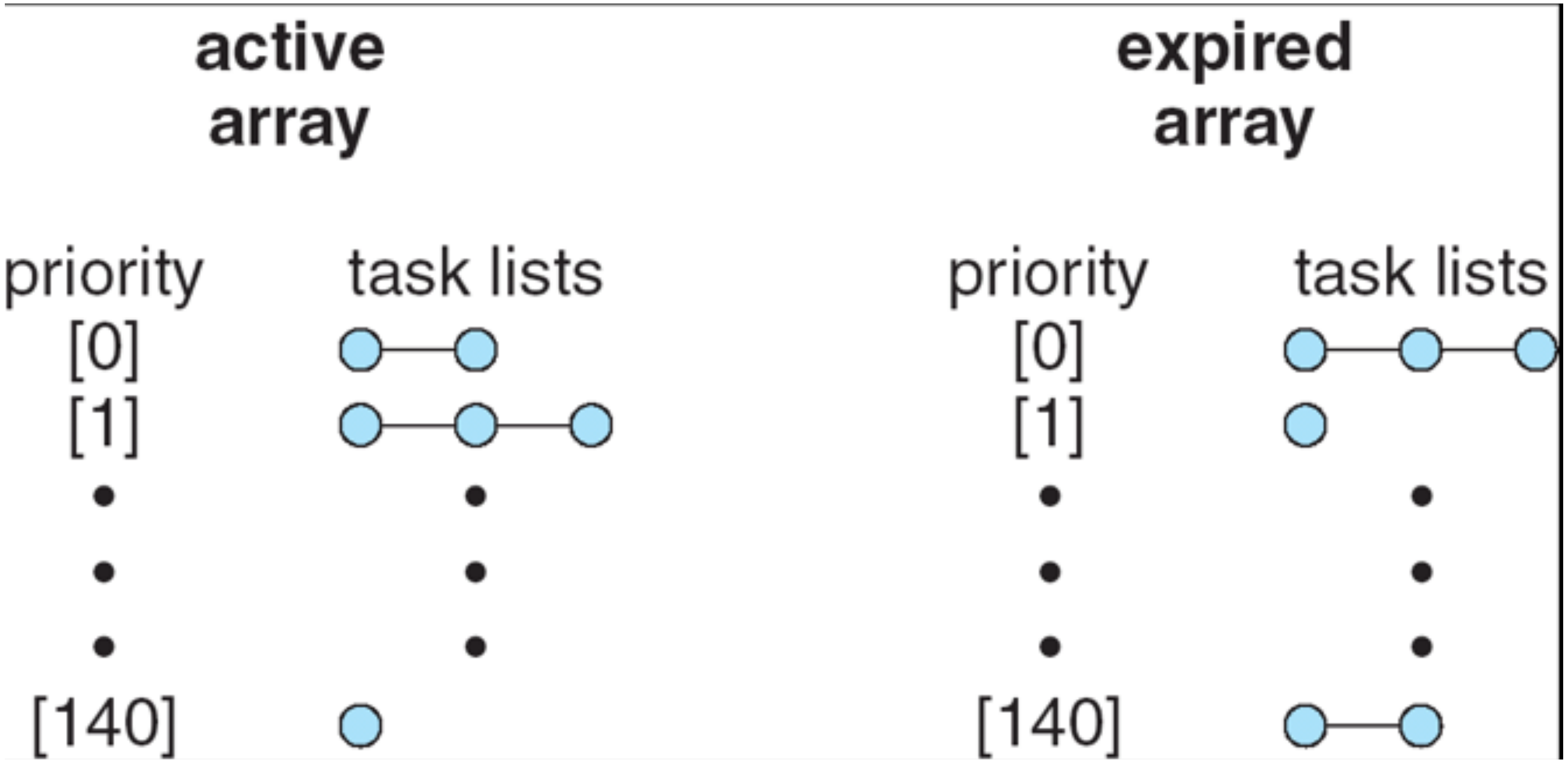
Time-Slice length

The Relationship Between Priorities and Time-Slice length



Priorities

List of Tasks Indexed According to Priorities



Summary

- CPU Scheduling
  - Algorithms
  - Combination of algorithms
    - Multi-level Feedback Queues

- Scheduling Systems
  - UNIX
  - Linux

- Next time: Synchronization