CS 5600
Computer Systems

Lecture 6: Process Scheduling

- Scheduling Basics
- Simple Schedulers
- Priority Schedulers
- Fair Share Schedulers
- Multi-CPU Scheduling
- Case Study: The Linux Kernel

Setting the Stage

- Suppose we have:
  - A computer with *N* CPUs
  - *P* process/threads that are ready to run
- Questions we need to address:
  - In what order should the processes be run?
  - On what CPU should each process run?

Factors Influencing Scheduling

- Characteristics of the processes
  - Are they I/O bound or CPU bound?
  - Do we have metadata about the processes?
    - Example: deadlines
  - Is their behavior predictable?
- Characteristics of the machine
  - How many CPUs?
  - Can we preempt processes?
  - How is memory shared by the CPUs?
- Characteristics of the user
  - Are the processes interactive (e.g. desktop apps)…
  - Or are the processes background jobs?

Basic Scheduler Architecture

- Scheduler selects from the *ready* processes, and assigns them to a CPU
  - System may have >1 CPU
  - Various different approaches for selecting processes
- Scheduling decisions are made when a process:
  1. Switches from *running* to *waiting*
  2. Terminates

  No preemption

  3. Switches from *running* to *ready*
  4. Switches from *waiting* to *ready*

  Preemption
- Scheduler may have access to additional information
  - Process deadlines, data in shared memory, etc.

Dispatch Latency

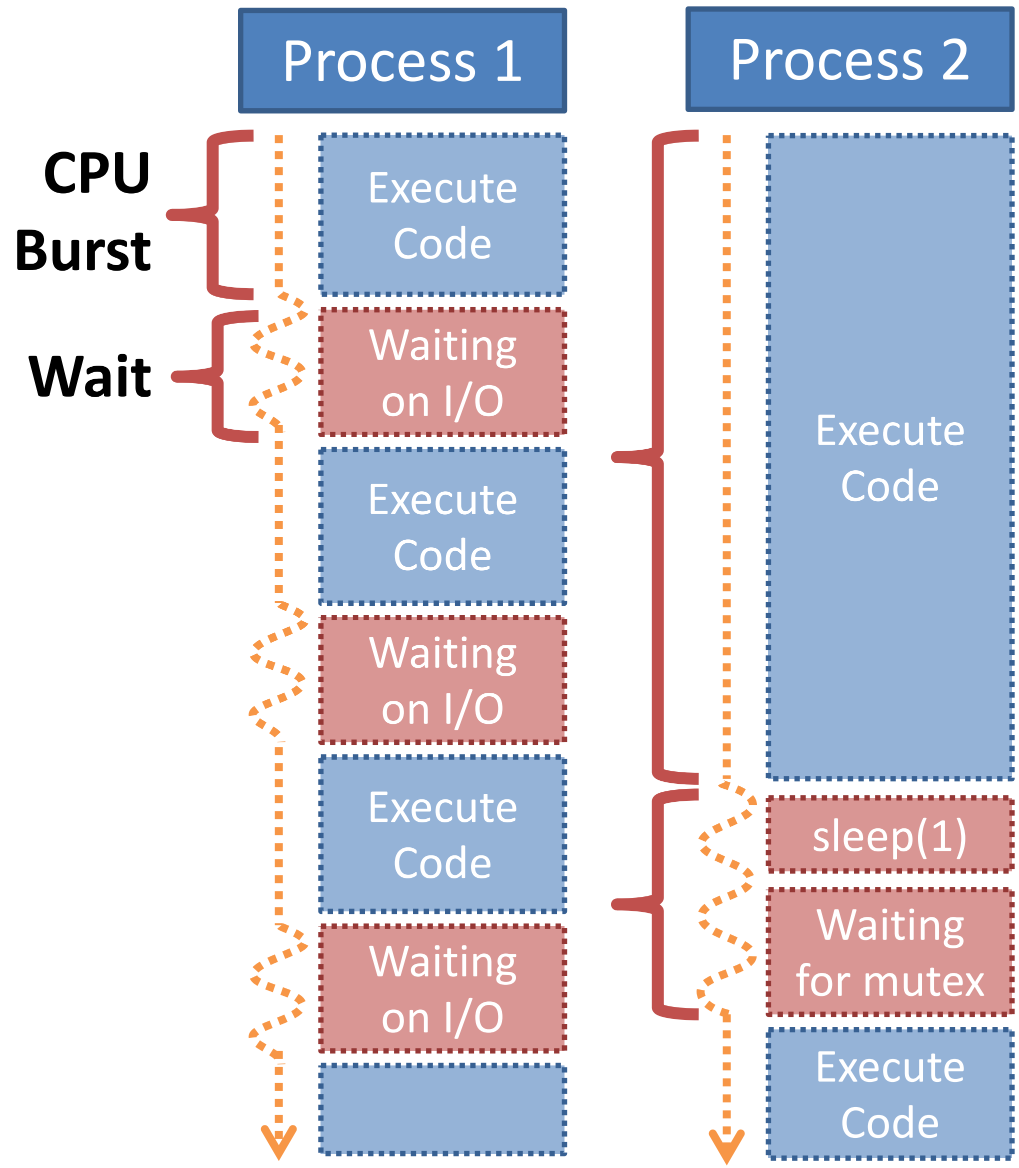
- The dispatcher gives control of the CPU to the process selected by the scheduler
  - Switches context
  - Switching to/from kernel mode/user mode
  - Saving the old EIP, loading the new EIP
- Warning: dispatching incurs a cost
  - Context switching and mode switch are expensive
  - Adds latency to processing times
- It is advantageous to minimize process switching

A Note on Processes & Threads

- Let’s assume that processes and threads are equivalent for scheduling purposes
  - Kernel supports threads
    - System-contention scope (SCS)
  - Each process has >=1 thread
- If kernel does not support threads
  - Each process handles it’s own thread scheduling
  - Process contention scope (PCS)

Basic Process Behavior

- Processes alternate between doing work and waiting
  - Work → CPU Burst
- Process behavior varies
  - I/O bound
  - CPU bound
- Expected CPU burst distribution is important for scheduler design
  - Do you expect more CPU or I/O bound processes?



Scheduling Optimization Criteria

- Max CPU utilization – keep the CPU as busy as possible
- Max throughput – # of processes that finish over time

- **<u>No scheduler can meet all these criteria</u>**
- Which criteria are most important depend on types of processes and expectations of the system
  - E.g. response time is key on the desktop
  - Throughput is more important for MapReduce

  - E.g. time between clicking a button and seeing a response

- Fairness – all processes receive min/max fair CPU resources

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First Come, First Serve (FCFS)

- Simple scheduler
  - Processes stored in a FIFO queue
  - Served in order of arrival

Process	Burst Time	Arrival Time
P1	24	0.000
P2	3	0.001
P3	3	0.002

- Turnaround time = completion time - arrival time
  - P1 = 24; P2 = 27; P3 = 30
  - Average turnaround time: (24 + 27 + 30) / 3 = 27

The Convoy Effect

- FCFS scheduler, but the arrival order has changed

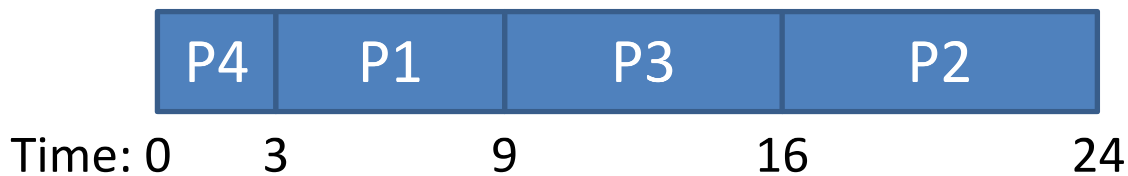
Process	Burst Time	Arrival Time
P1	24	0.002
P2	3	0.000
P3	3	0.001

- Turnaround time: P1 = 30; P2 =3; P3 = 6
  - Average turnaround time: (30 + 3 + 6) / 3 = 13
  - Much better than the previous arrival order!
- Convoy effect (a.k.a. head-of-line blocking)
  - Long process can impede short processes
  - E.g.: CPU bound process followed by I/O bound process

Shortest Job First (SJF)

- Schedule processes based on the length of their next CPU burst time
  - Shortest processes go first

Process	Burst Time	Arrival Time
P1	6	0
P2	8	0
P3	7	0
P4	3	0

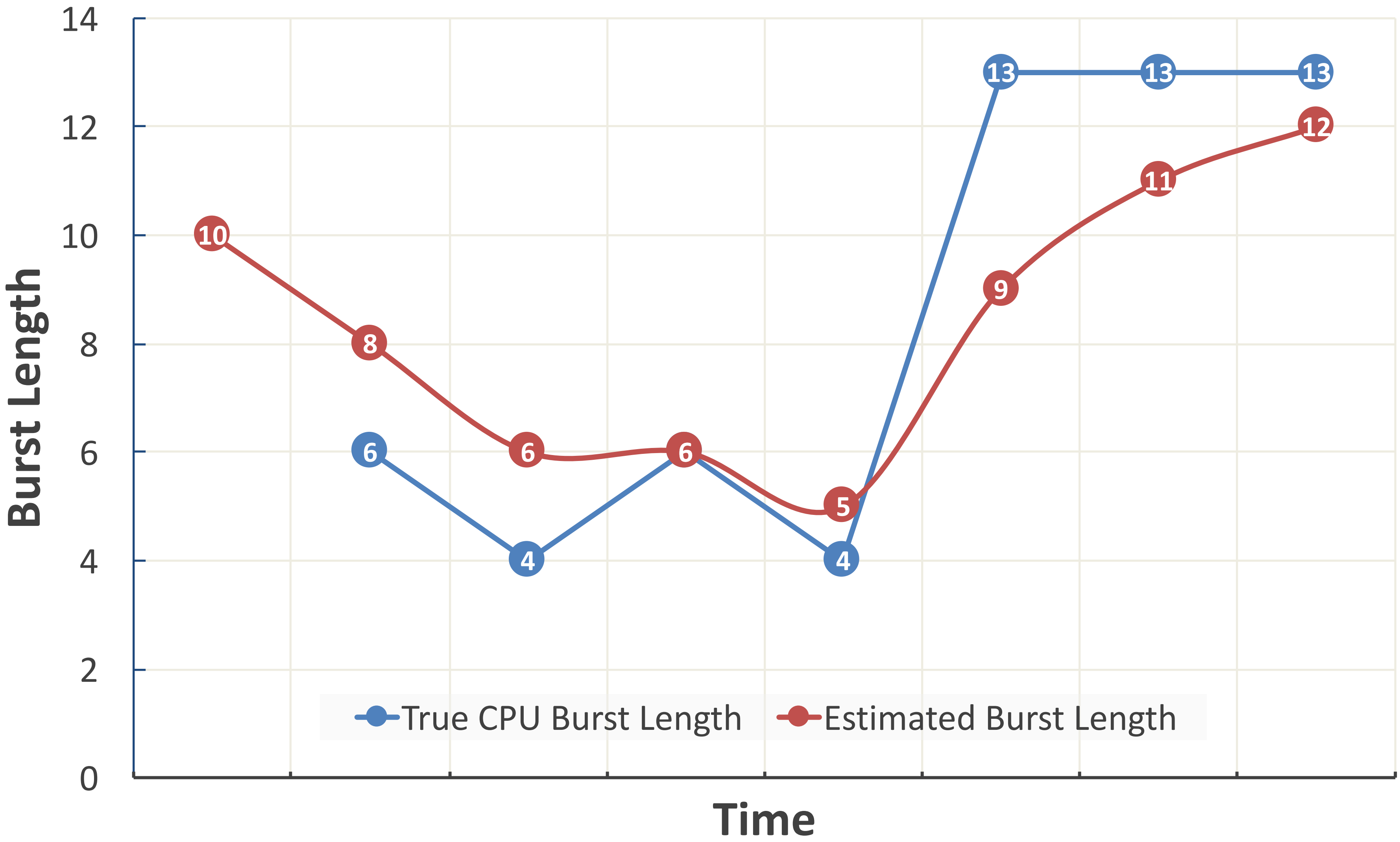


- Average turnaround time: (3 + 16 + 9 + 24) / 4 = 13
- SJF is optimal: guarantees minimum average wait time

Predicting Next CPU Burst Length

- Problem: future CPU burst times may be unknown
- Solution: estimate the next burst time based on previous burst lengths
  - Assumes process behavior is not highly variable
  - Use exponential averaging
    - t_n – measured length of the n^{th} CPU burst
    - τ_{n+1} – predicted value for $n+1^{th}$ CPU burst
    - α – weight of current and previous measurements ($0 \leq \alpha \leq 1$)
    - $\tau_{n+1} = \alpha t_n + (1 - \alpha)\, \tau_n$
  - Typically, $\alpha = 0.5$

Actual and Estimated CPU Burst Times



What About Arrival Time?

- SJF scheduler, CPU burst lengths are known

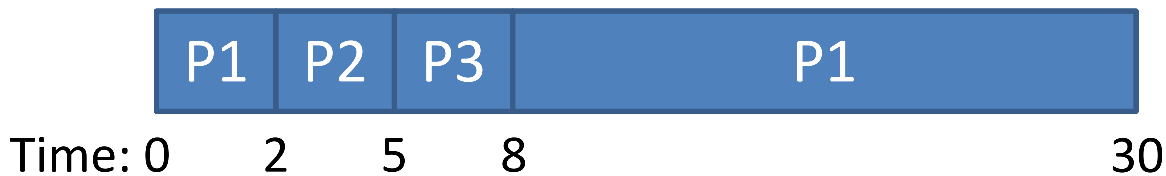
Process	Burst Time	Arrival Time
P1	24	0
P2	3	2
P3	3	3

- Scheduler must choose from available processes
  - Can lead to head-of-line blocking
  - Average turnaround time: (24 + 25 + 27) / 3 = 25.3

Shortest Time-To-Completion First (STCF)

- Also known as Preemptive SJF (PSJF)
  - Processes with long bursts can be context switched out in favor or short processes

Process	Burst Time	Arrival Time
P1	24	0
P2	3	2
P3	3	3



- Turnaround time: P1 = 30; P2 = 3; P3 = 5
  - Average turnaround time: (30 + 3 + 5) / 3 = 12.7
- STCF is also optimal
  - Assuming you know future CPU burst times

Interactive Systems

- Imagine you are typing/clicking in a desktop app
  - You don't care about turnaround time
  - What you care about is responsiveness
    - E.g. if you start typing but the app doesn't show the text for 10 seconds, you'll become frustrated
- Response time = first run time – arrival time

Response vs. Turnaround

- Assume an STCF scheduler

Process	Burst Time	Arrival Time
P1	6	0
P2	8	0
P3	10	0

- Avg. turnaround time: (6 + 14 + 24) / 3 = 14.7
- Avg. response time: (0 + 6 + 14) / 3 = 6.7

Round Robin (RR)

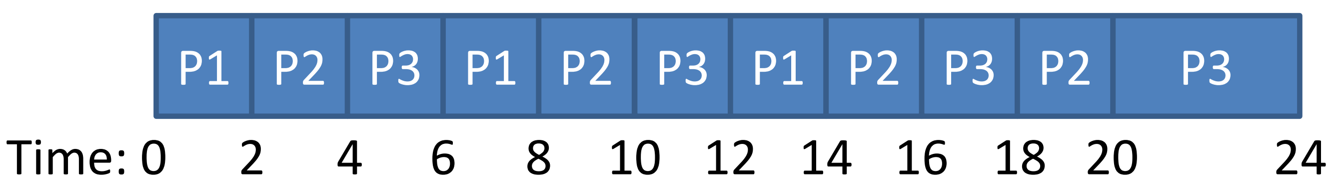
- Round robin (a.k.a time slicing) scheduler is designed to reduce response times
  - RR runs jobs for a time slice (a.k.a. scheduling quantum)
  - Size of time slice is some multiple of the timer-interrupt period

RR vs. STCF

Process	Burst Time	Arrival Time
P1	6	0
P2	8	0
P3	10	0

STCF

- Avg. turnaround time: (6 + 14 + 24) / 3 = **14.7**
- Avg. response time: (0 + 6 + 14) / 3 = **6.7**



RR

- 2 second time slices
- Avg. turnaround time: (14 + 20 + 24) / 3 = **19.3**
- Avg. response time: (0 + 2 + 4) / 3 = **2**

Tradeoffs

RR

+ Excellent response times
  + With *N* process and time slice of *Q*…
  + No process waits more than (*N*-1)/*Q* time slices
+ Achieves fairness
  + Each process receives 1/*N* CPU time
- Worst possible turnaround times
  - If *Q* is large → FIFO behavior

STCF

+ Achieves optimal, low turnaround times
- Bad response times
- Inherently unfair
  - Short jobs finish first

- Optimizing for turnaround or response time is a trade-off
- Achieving both requires more sophisticated algorithms

Selecting the Time Slice

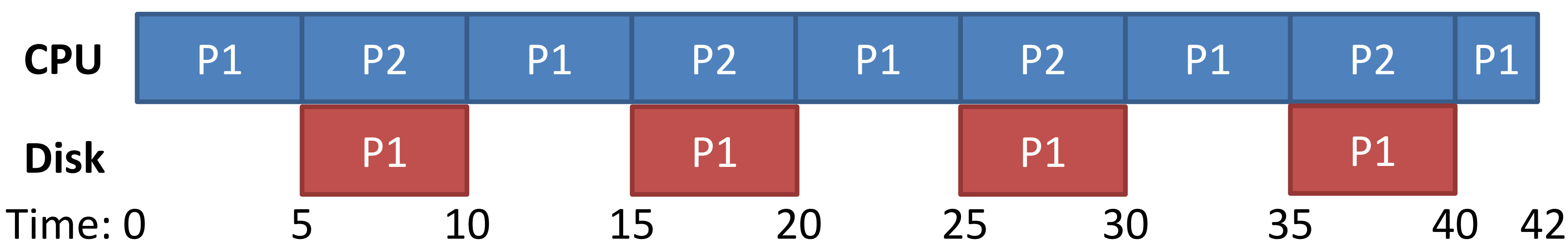
- Smaller time slices = faster response times
- So why not select a very tiny time slice?
  - E.g. 1μs
- Context switching overhead
  - Each context switch wastes CPU time (~10μs)
  - If time slice is too short, context switch overhead will dominate overall performance
- This results in another tradeoff
  - Typical time slices are between 1ms and 100ms

Incorporating I/O

- How do you incorporate I/O waits into the scheduler?
  - Treat time in-between I/O waits as CPU burst time

STCF Scheduler

Process	Total Time	Burst Time	Wait Time	Arrival Time
P1	22	5	5	0
P2	20	20	0	0



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Status Check

- Introduced two different types of schedulers
  - SJF/STCF: optimal turnaround time
  - RR: fast response time
- Open problems:
  - Ideally, we want fast response time and turnaround
    - E.g. a desktop computer can run interactive and CPU bound processes at the same time
  - SJF/STCF require knowledge about burst times
- Both problems can be solved by using prioritization

Priority Scheduling

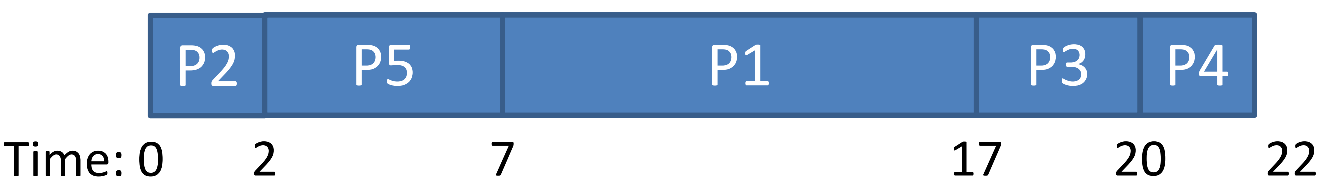
- We have already seen examples of priority schedulers
  - SJF, STCF are both priority schedulers
  - Priority = CPU burst time
- Problem with priority scheduling
  - Starvation: high priority tasks can dominate the CPU
- Possible solution: dynamically vary priorities
  - Vary based on process behavior
  - Vary based on wait time (i.e. length of time spent in the ready queue)

Simple Priority Scheduler

- Associate a priority with each process
  - Schedule high priority tasks first
  - Lower numbers = high priority
  - No preemption

Process	Burst Time	Arrival Time	Priority
P1	10	0	3
P5	5	0	2

- Cannot automatically balance response vs. turnaround time
- Prone to starvation

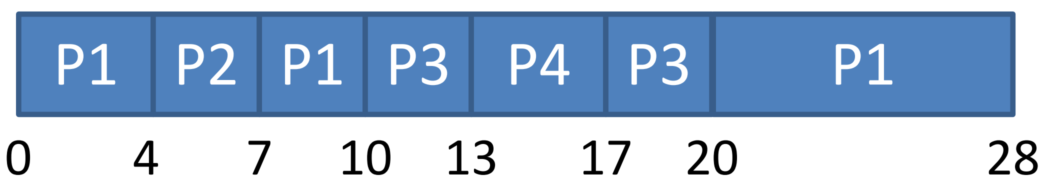


- Avg. turnaround time: (17 + 2 + 20 + 22 + 7) / 5 = 13.6
- Avg. response time: (7 + 0 + 17 + 20 + 2) / 5 = 9.2

Earliest Deadline First (EDF)

- Each process has a deadline it must finish by
- Priorities are assigned according to deadlines
  - Tighter deadlines are given higher priority

Process	Burst Time	Arrival Time	Deadline
P1	15	0	40



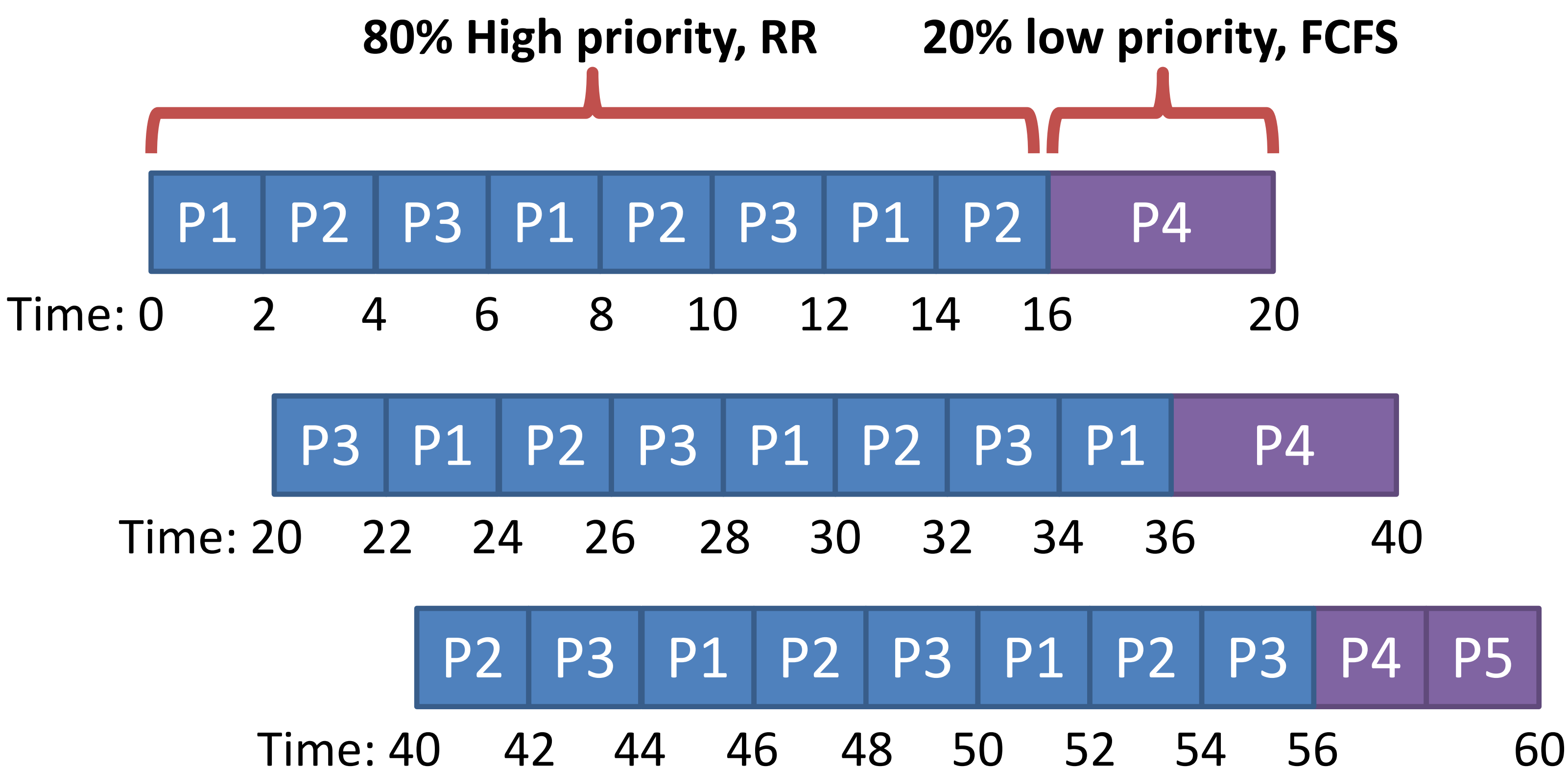
- EDF is optimal (assuming preemption)
- But, it's only useful if processes have known deadlines
  - Typically used in real-time OSes

Multilevel Queue (MLQ)

- Key idea: divide the ready queue in two
  1. High priority queue for interactive processes
     - RR scheduling
  2. Low priority queue for CPU bound processes
     - FCFS scheduling
- Simple, static configuration
  - Each process is assigned a priority on startup
  - Each queue is given a fixed amount of CPU time
    - 80% to processes in the high priority queue
    - 20% to processes in the low priority queue

MLQ Example

Process	Arrival Time	Priority
P1	0	1
P2	0	1
P3	0	1
P4	0	2
P5	1	2



Problems with MLQ

- Assumes you can classify processes into high and low priority
  – How could you actually do this at run time?
  – What of a processes' behavior changes over time?
    - i.e. CPU bound portion, followed by interactive portion
- Highly biased use of CPU time
  – Potentially too much time dedicated to interactive processes
  – Convoy problems for low priority tasks

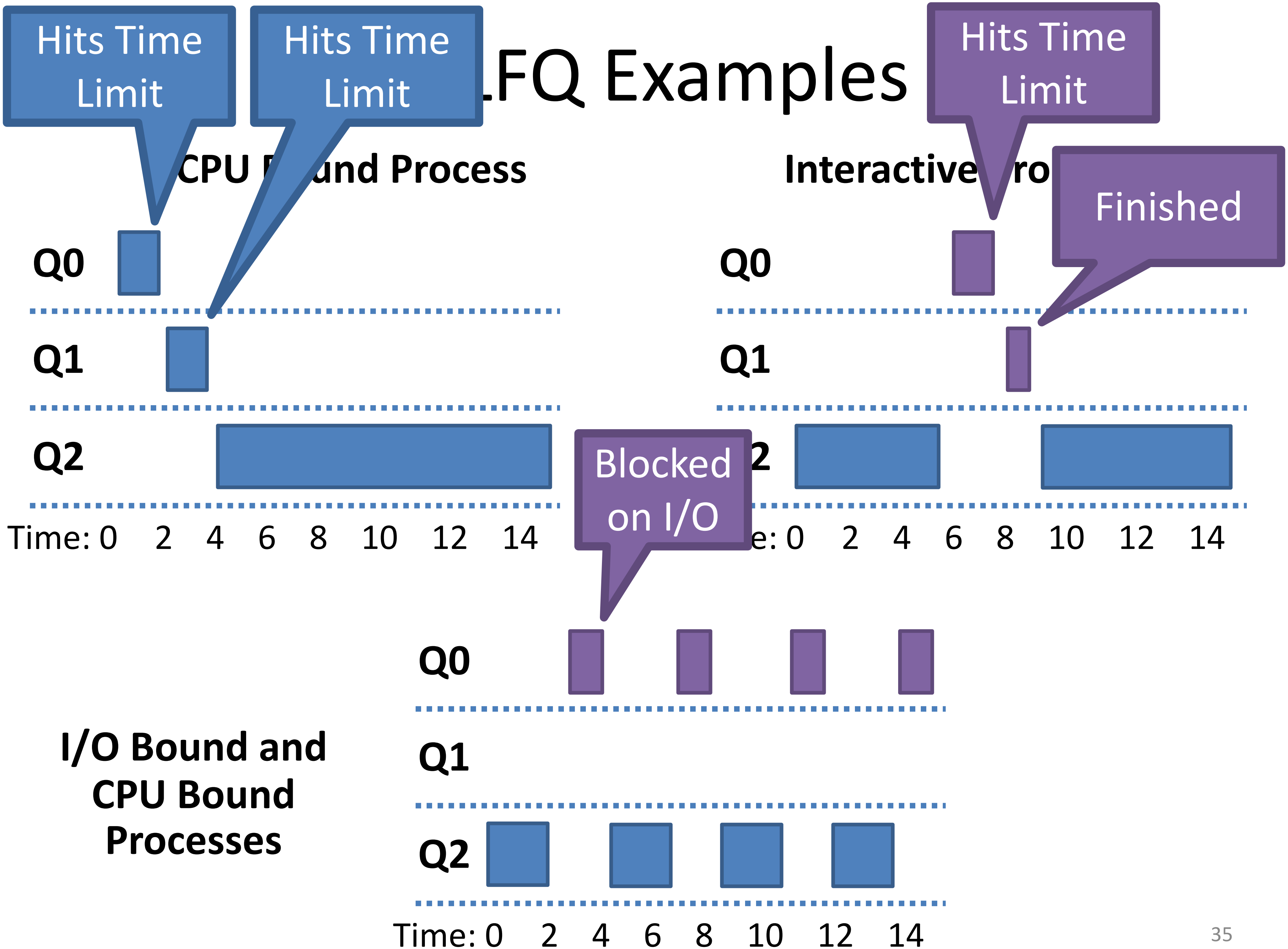
Multilevel Feedback Queue (MLFQ)

- Goals
  - Minimize response time and turnaround time
  - Dynamically adjust process priorities over time
    - No assumptions or prior knowledge about burst times or process behavior
- High level design: generalized MLQ
  - Several priority queues
  - Move processes between queue based on observed behavior (i.e. their history)

First 4 Rules of MFLQ

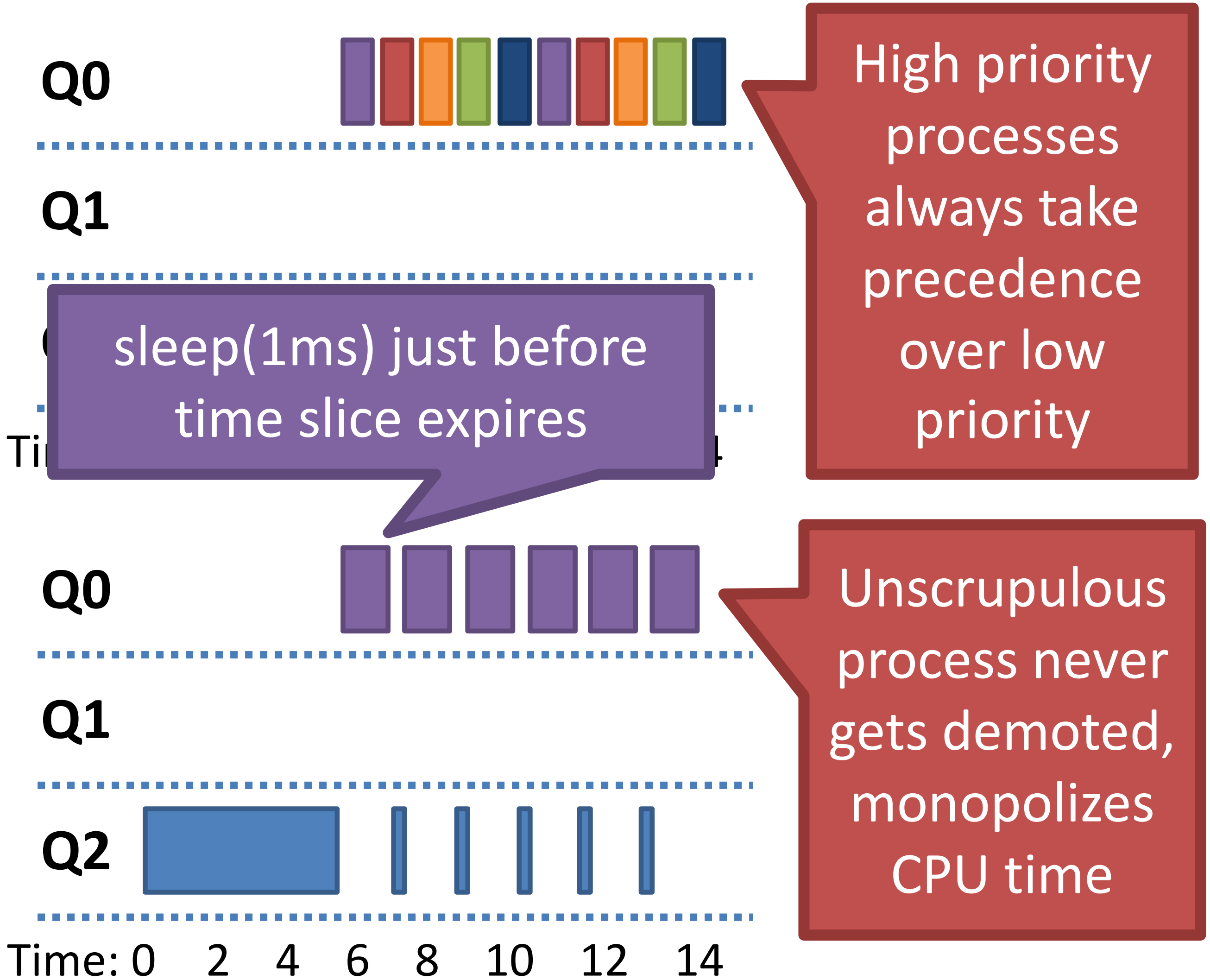
- **Rule 1**: If Priority(A) > Priority(B), A runs, B doesn't
- **Rule 2**: If Priority(A) = Priority(B), A & B run in RR
- **Rule 3**: Processes start at the highest priority
- **Rule 4**:
  - **Rule 4a**: If a process uses an entire time slice while running, its priority is *reduced*
  - **Rule 4b**: If a process gives up the CPU before its time slice is up, it remains at the *same* priority level

LFQ Examples



Problems With MLFQ So Far…

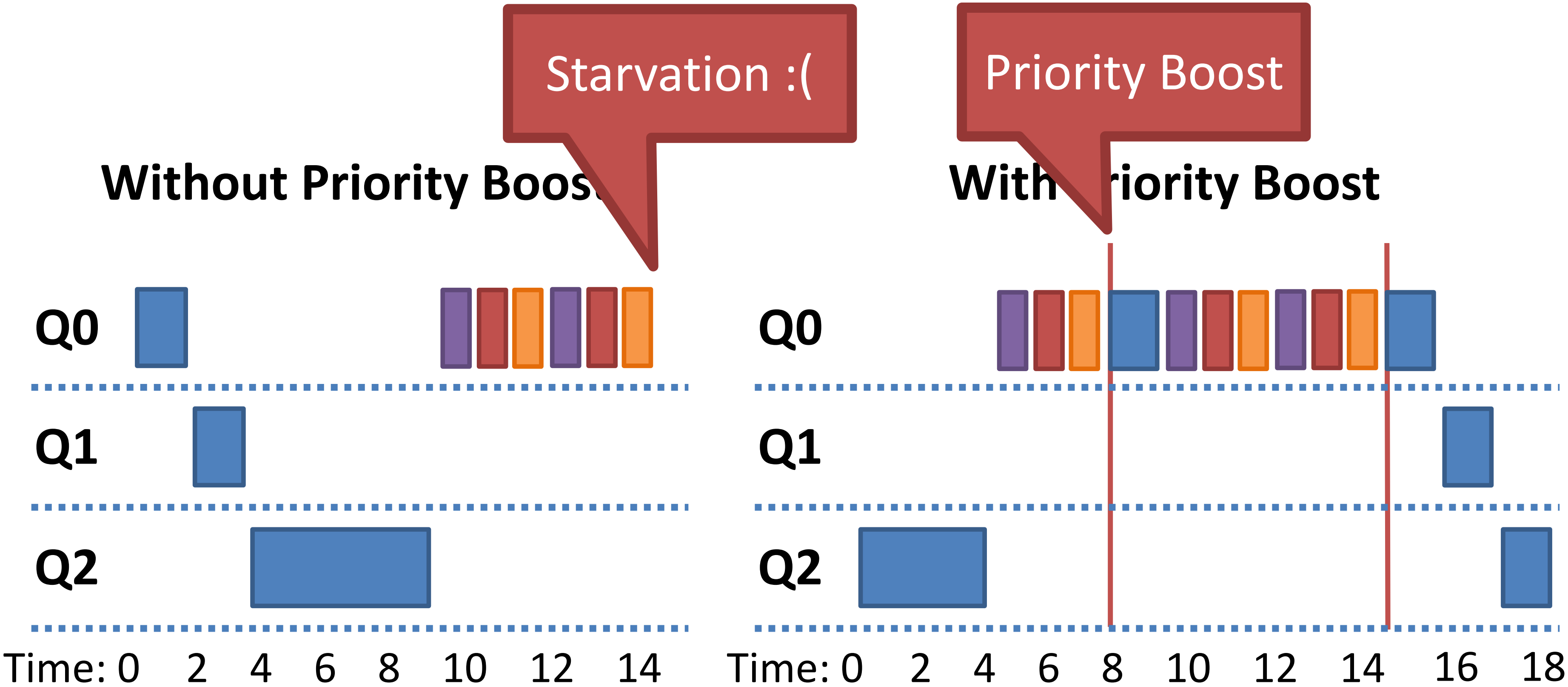
- Starvation
- Cheating



MLFQ Rule 5: Priority Boost

- **Rule 5**: After some time period *S*, move all processes to the highest priority queue
- Solves two problems:
  - Starvation: low priority processes will eventually become high priority, acquire CPU time
  - Dynamic behavior: a CPU bound process that has become interactive will now be high priority

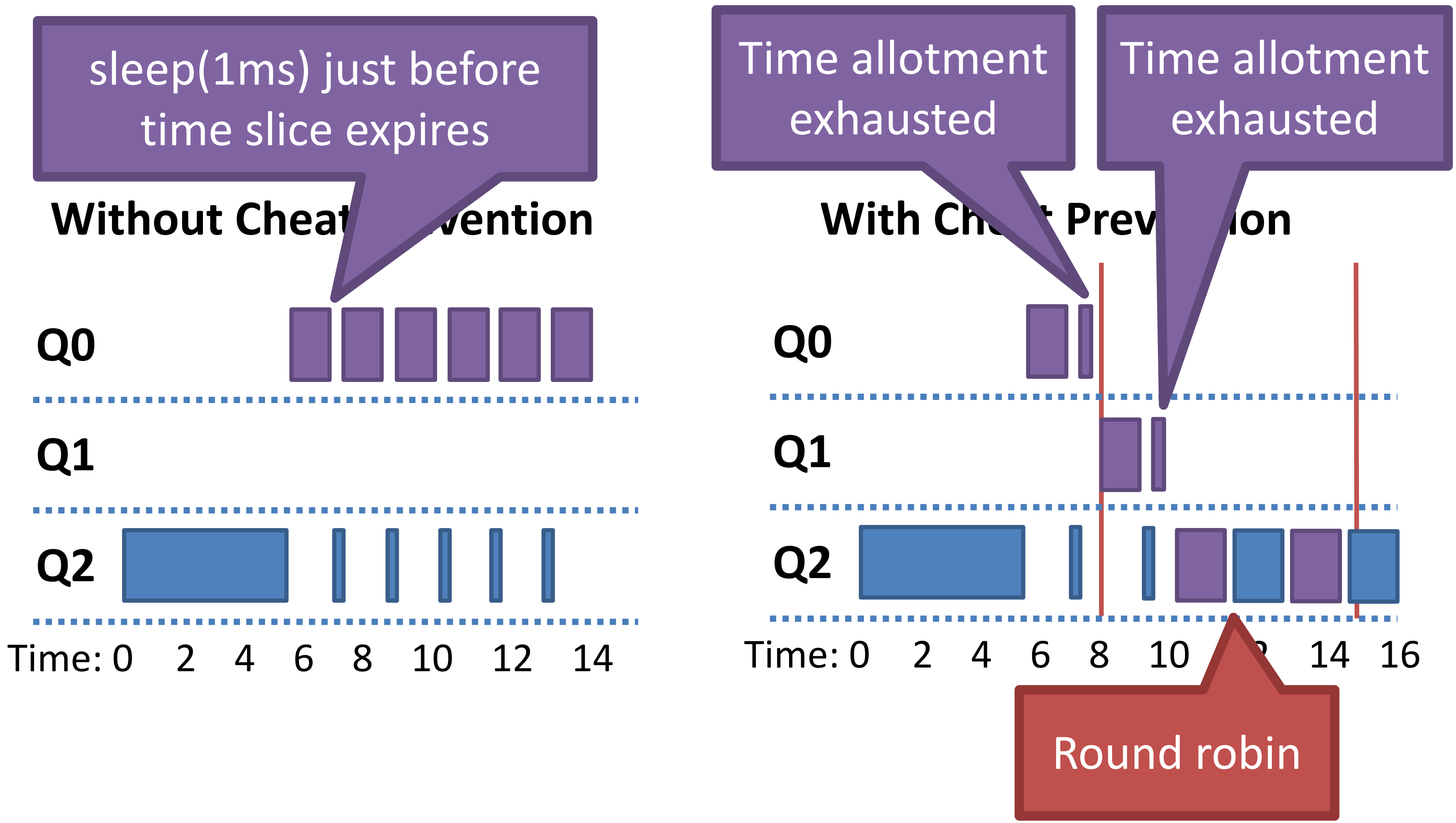
Priority Boost Example



Revised Rule 4: Cheat Prevention

- **Rule 4a** and **4b** let a process game the scheduler
  - Repeatedly yield just before the time limit expires
- Solution: better accounting
  - **Rule 4**: Once a process uses up its time allotment at a given priority (regardless of whether it gave up the CPU), demote its priority
  - Basically, keep track of total CPU time used by each process during each time interval *S*
    - Instead of just looking at continuous CPU time

Preventing Cheating



MLFQ Rule Review

- **Rule 1**: If Priority(A) > Priority(B), A runs, B doesn't
- **Rule 2**: If Priority(A) = Priority(B), A & B run in RR
- **Rule 3**: Processes start at the highest priority
- **Rule 4**: Once a process uses up its time allotment at a given priority, demote it
- **Rule 5**: After some time period *S*, move all processes to the highest priority queue

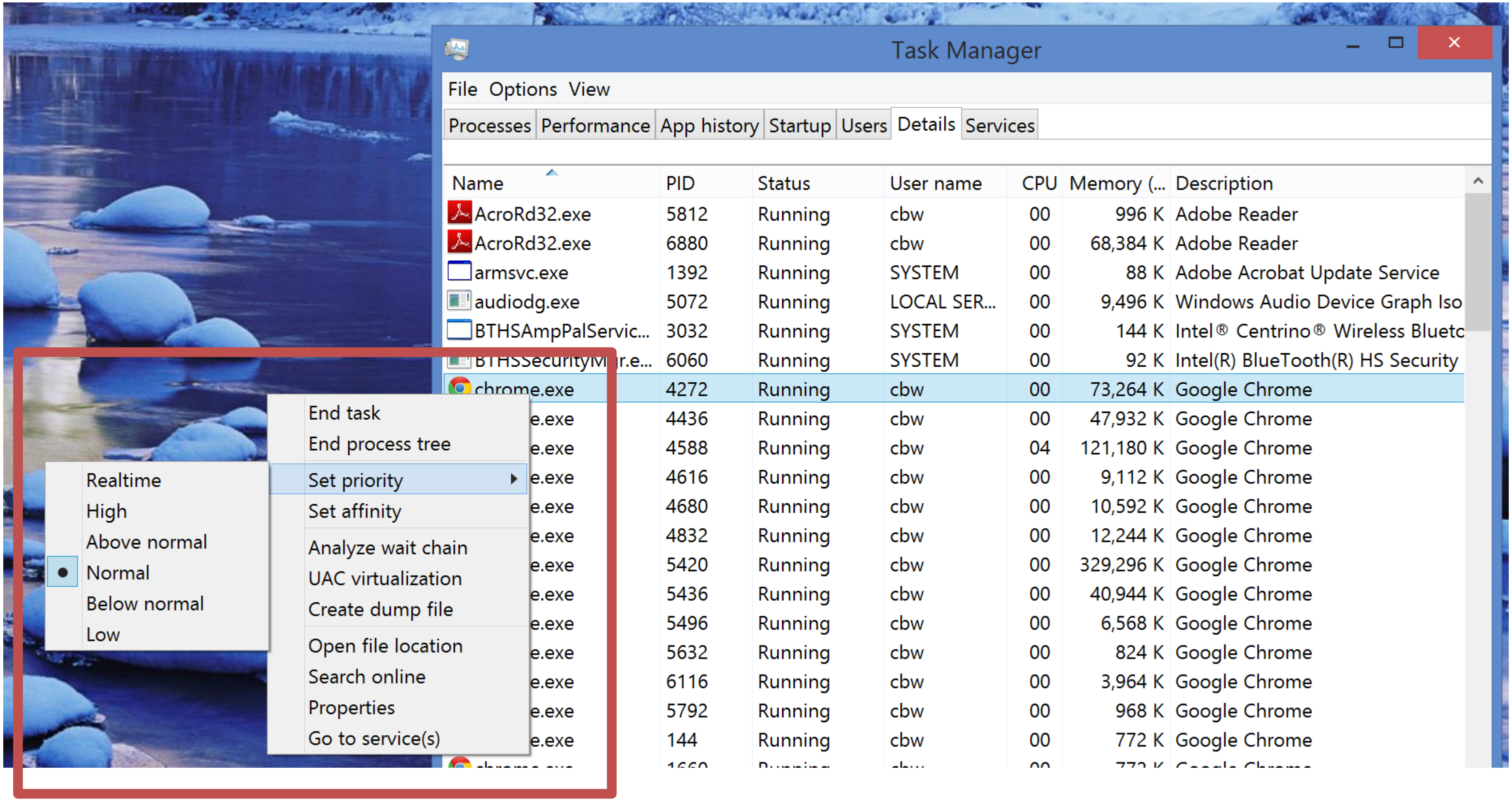
Parameterizing MLFQ

- MLFQ meets our goals
  - Balances response time and turnaround time
  - Does not require prior knowledge about processes
- But, it has many knobs to tune
  - Number of queues?
  - How to divide CPU time between the queues?
  - For each queue:
    - Which scheduling regime to use?
    - Time slice/quantum?
  - Method for demoting priorities?
  - Method for boosting priorities?

MLFQ In Practice

- Many OSes use MLFQ-like schedulers
  - Example: Windows NT/2000/XP/Vista, Solaris, FreeBSD
- OSes ship with “reasonable” MLFQ parameters
  - Variable length time slices
    - High priority queues – short time slices
    - Low priority queues – long time slices
  - Priority 0 sometimes reserved for OS processes

Giving Advice



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Status Check

- Thus far, we have examined schedulers designed to optimize performance
  - Minimum response times
  - Minimum turnaround times
- MLFQ achieves these goals, but it's complicated
  - Non-trivial to implement
  - Challenging to parameterize and tune
- What about a simple algorithm that achieves fairness?

Lottery Scheduling

- Key idea: give each process a bunch of tickets
  - Each time slice, scheduler holds a lottery
  - Process holding the winning ticket gets to run

Process	Arrival Time	Ticket Range
P1	0	0-74 (75 total)
P2	0	75-99 (25 total)

- **P1 ran 8 of 11 slices – 72%**
- **P2 ran 3 of 11 slices – 27%**

P1	P2	P1	P1	P1	P2	P2	P1	P1	P1	P1

Time: 0 2 4 6 8 10 12 14 16 18 20 22

- Probabilistic scheduling
  - Over time, run time for each process converges to the correct value (i.e. the # of tickets it holds)

Implementation Advantages

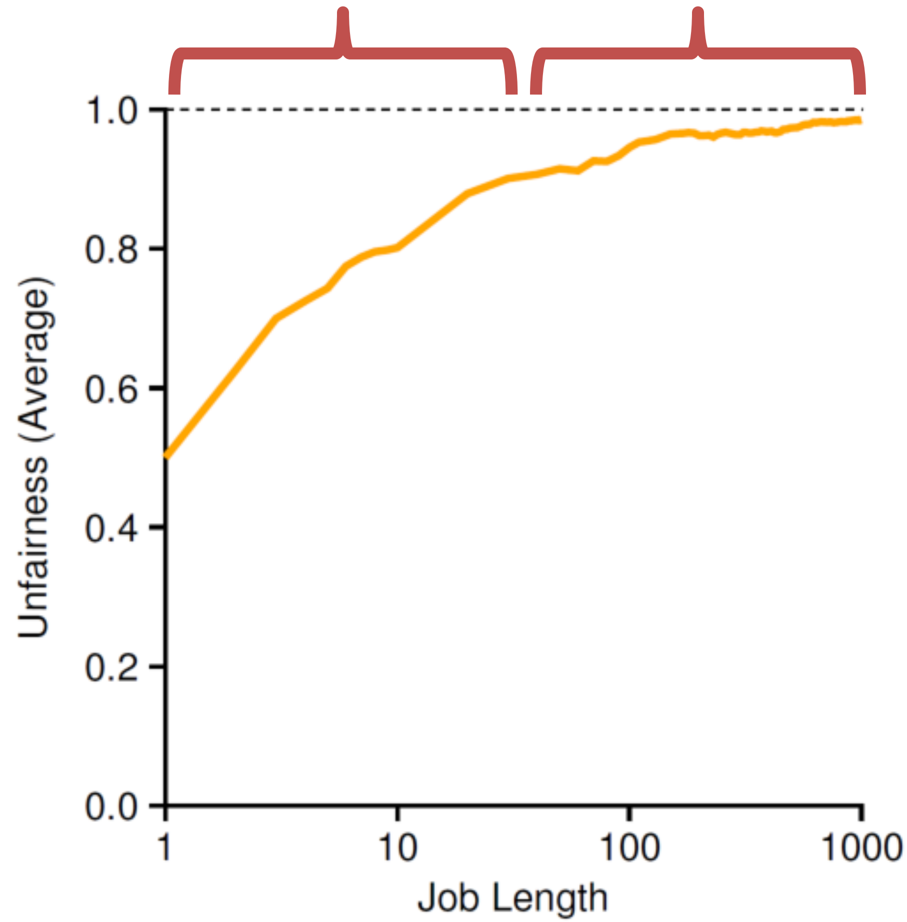
- Very fast scheduler execution
  - All the scheduler needs to do is run *random()*
  - No need to manage *O(log N)* priority queues
- No need to store lots of state
  - Scheduler needs to know the total number of tickets
  - No need to track process behavior or history
- Automatically balances CPU time across processes
  - New processes get some tickets, adjust the overall size of the ticket pool
- Easy to prioritize processes
  - Give high priority processes many tickets
  - Give low priority processes a few tickets
  - Priorities can change via ticket inflation (i.e. minting tickets)

Is Lotte

Unfair to short job due to randomness

Randomness is amortized over long time scales

- Does lottery scheduling achieve fairness?
  - Assume two processes with equal tickets
  - Runtime of processes varies
  - Unfairness ratio = 1 if both processes finish at the same time



Stride Scheduling

- Randomness lets us build a simple and approximately fair scheduler
  - But fairness is not guaranteed
- Why not build a deterministic, fair scheduler?
- Stride scheduling
  - Each process is given some tickets
  - Each process has a stride = a big # / # of tickets
  - Each time a process runs, its pass += stride
  - Scheduler chooses process with the lowest pass to run next

Stride Scheduling Example

Process	Arrival Time	Tickets	Stride (K = 10000)
P1	0	100	100
P2	0	50	200
P3	0	250	40

- P1: 100 of 400 tickets – 25%
- P2: 50 of 400 tickets – 12.5%
- P3: 250 of 400 tickets – 62.5%

P1 pass	P2 pass	P3 pass	Who runs?

- P1 ran 2 of 8 slices – 25%
- P2 ran 1 of 8 slices – 12.5%
- P3 ran 5 of 8 slices – 62.5%

Lingering Issues

- Why choose lottery over stride scheduling?
  - Stride schedulers need to store a lot more state
  - How does a stride scheduler deal with new processes?
    - Pass = 0, will dominate CPU until it catches up
- Both schedulers require tickets assignment
  - How do you know how many tickets to assign to each process?
  - This is an open problem

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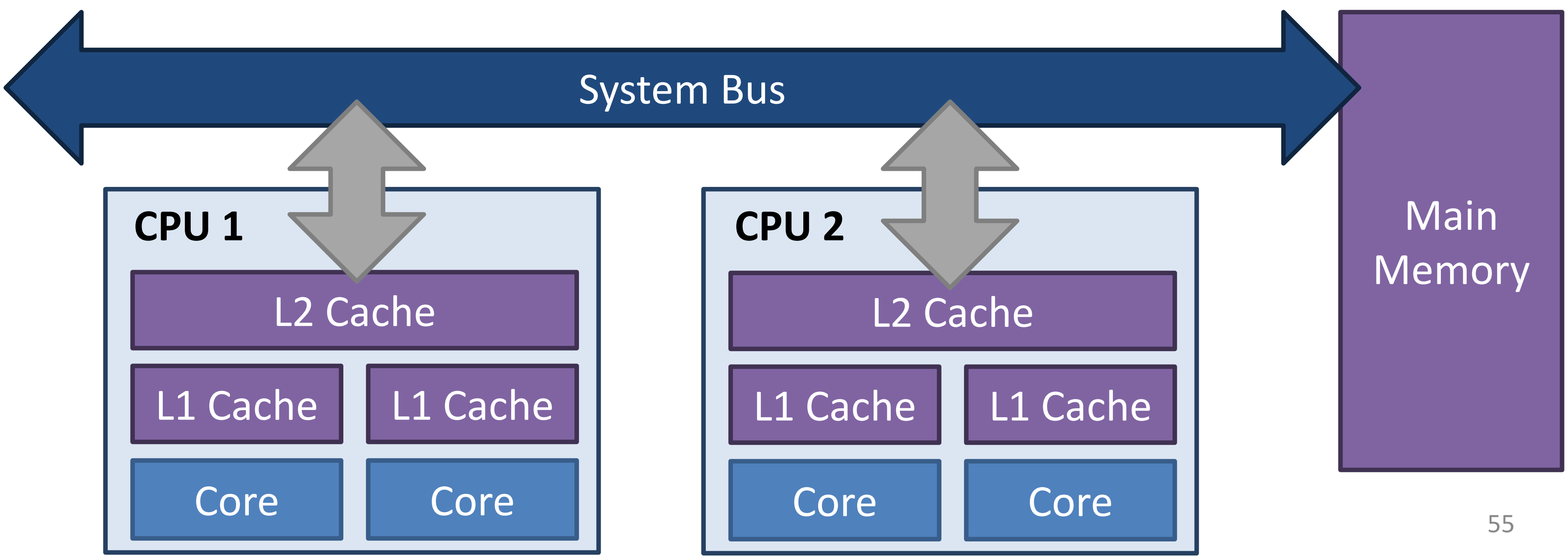
Status Check

- Thus far, all of our schedulers have assumed a single CPU core
- What about systems with multiple CPUs?
  - Things get a lot more complicated when the number of CPUs > 1

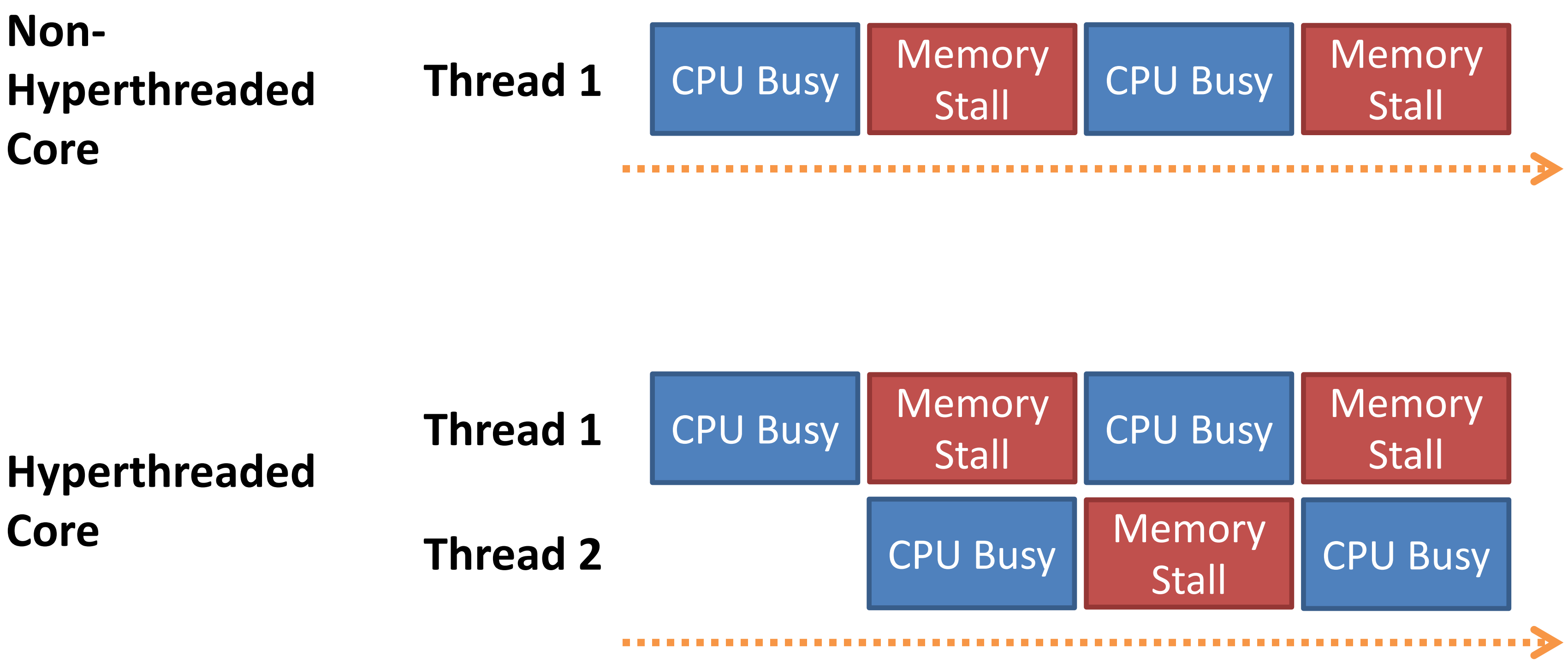
Symmetric Multiprocessing (SMP)

- ≥2 homogeneous processors
  - May be in separate physical packages
- Shared main memory and system bus
- Single OS that treats all processors equally



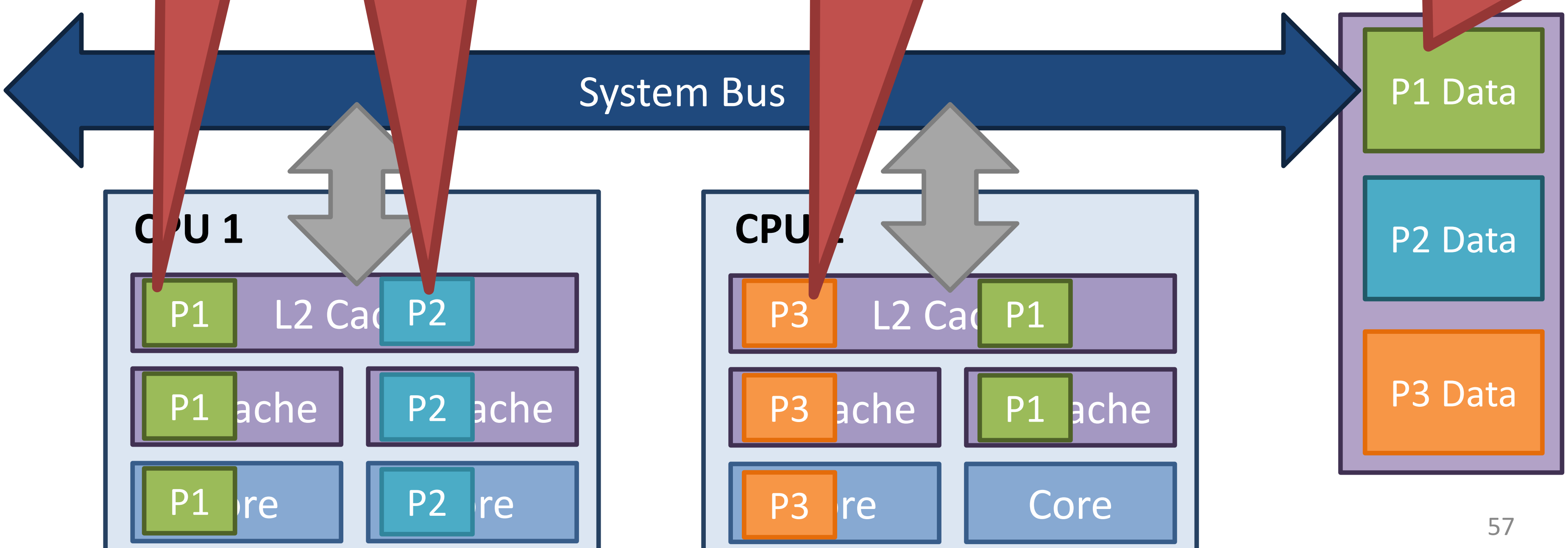
Hyperthreading

- Two threads on a single CPU core



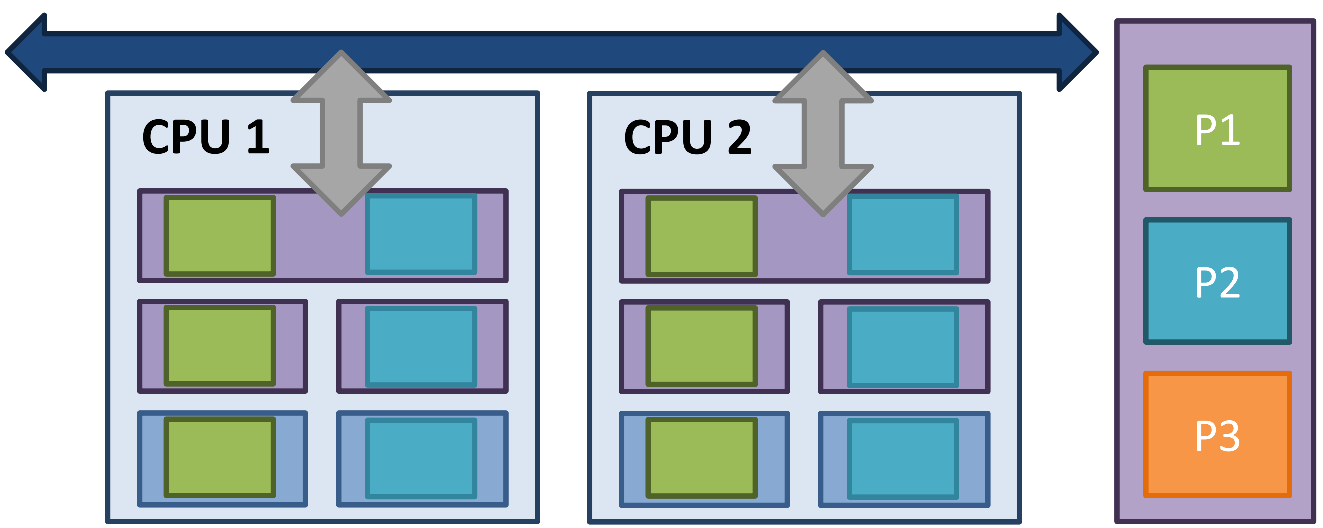
Brief Intro to CPU Caches

- Process performance is linked to locality
  - Ideally, a process should be placed close to its data
- Shared data is problematic due to cache coherency
  - P3 writes variable *x*, new value is cached in CPU 2
  - P2 in CPU 1 reads *x*, but value in main memory is stale



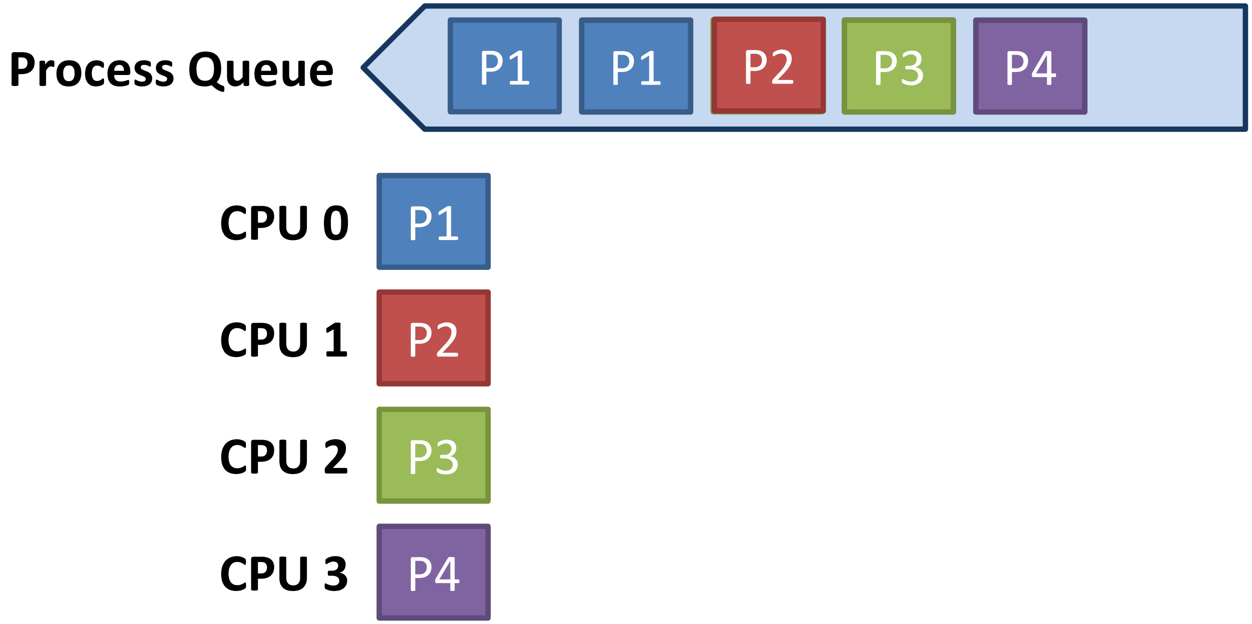
NUMA and Affinity

- Non-Uniform Memory Access (NUMA) architecture
  - Memory access time depends on the location of the data relative to the requesting process
- Leads to cache affinity
  - Ideally, processes want to stay close to their cached data



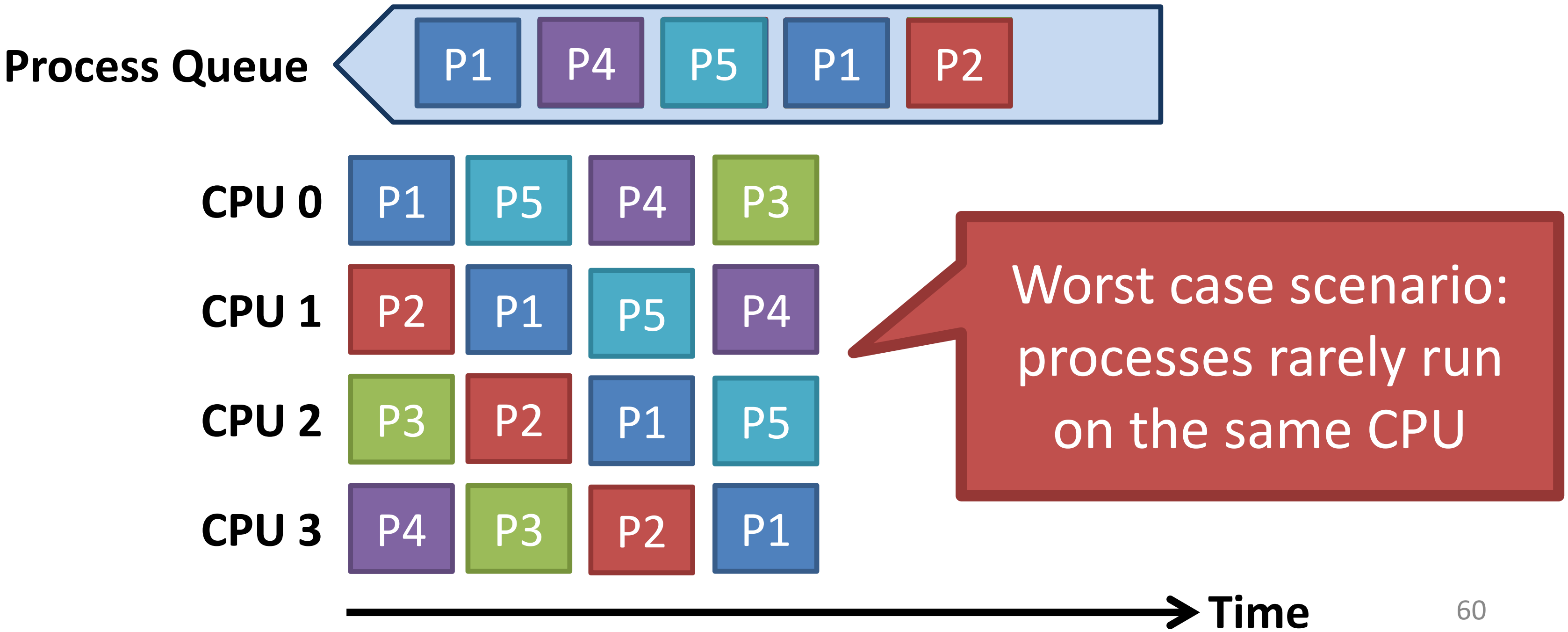
Single Queue Scheduling

- Single Queue Multiprocessor Scheduling (SQMS)
  - Most basic design: all processes go into a single queue
  - CPUs pull tasks from the queue as needed
  - Good for load balancing (CPUs pull processes on demand)



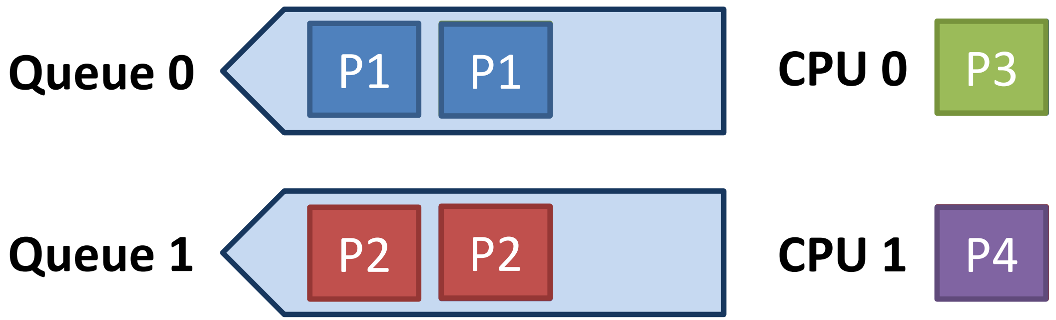
Problems with SQMS

- The process queue is a shared data structure
  - Necessitates locking, or careful lock-free design
- SQMS does not respect cache affinity



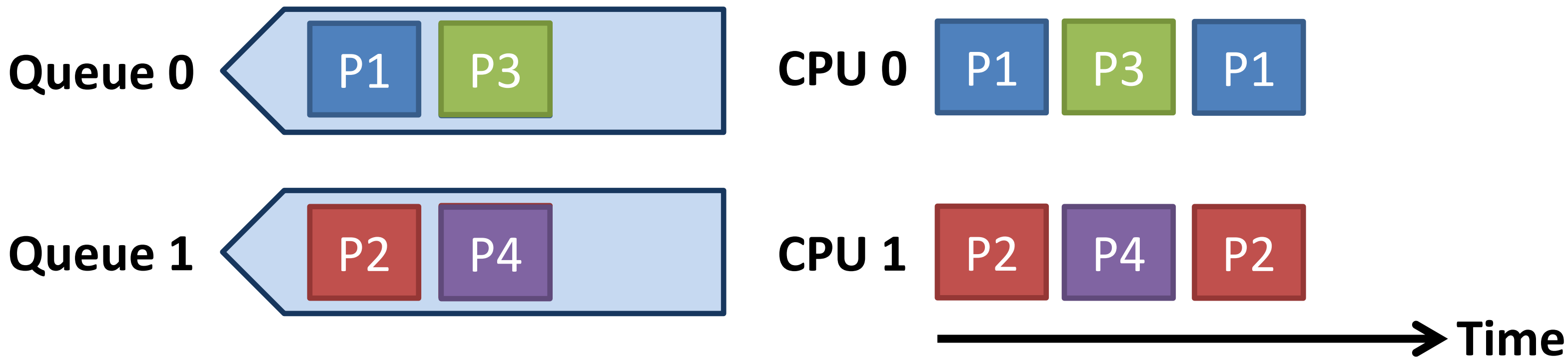
Multi-Queue Scheduling

- SQMS can be modified to preserve affinity
- Multiple Queue Multiprocessor Scheduling (MQMS)
  - Each CPU maintains it's own queue of processes
  - CPUs schedule their processes independently

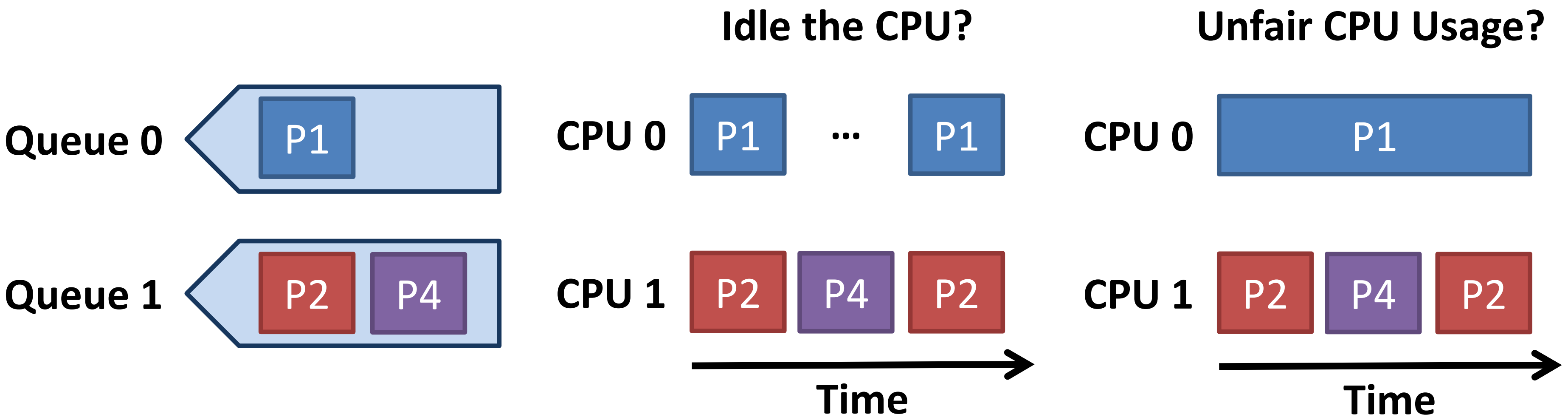


Advantages of MQMS

- Very little shared data
  - Queues are (mostly) independent
- Respects cache affinity



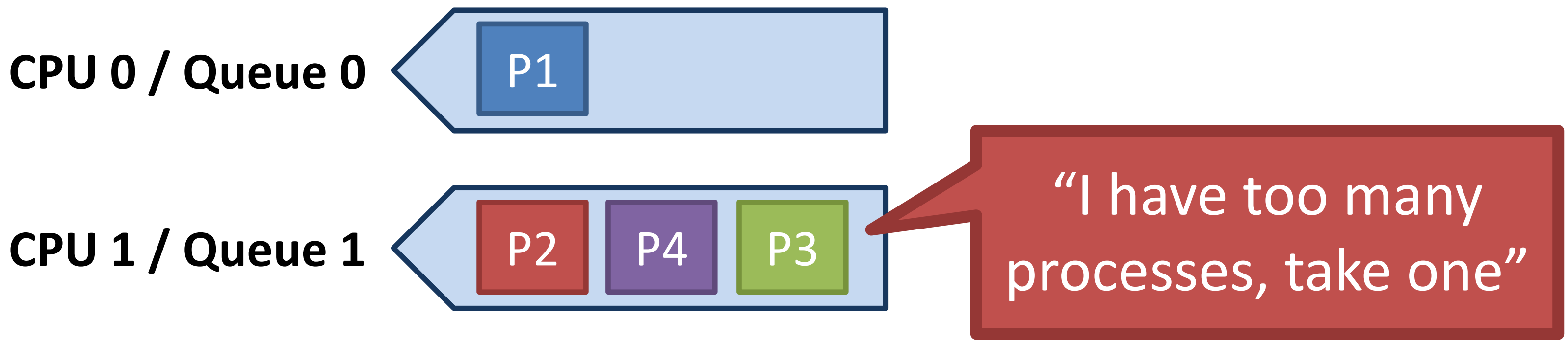
Shortcoming of MQMS



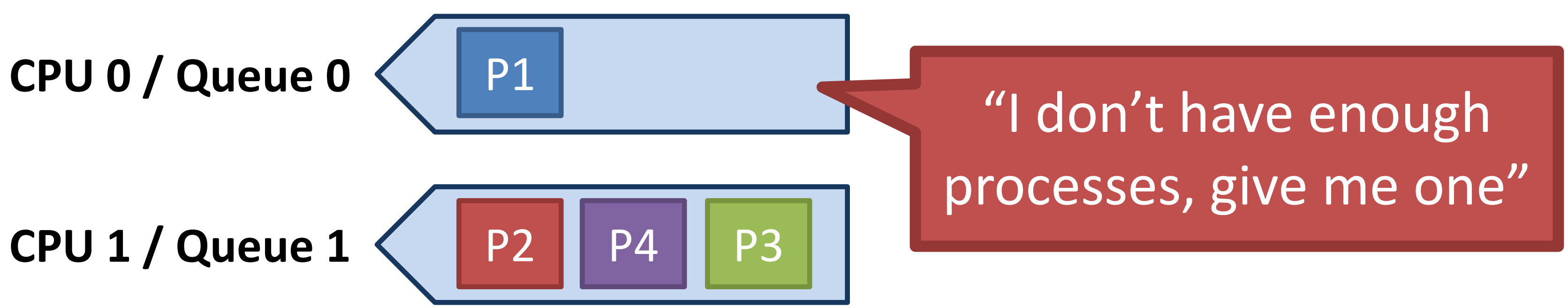
- MQMS is prone to load imbalance due to:
  - Different number of processes per CPU
  - Variable behavior across processes
- Must be dealt with through process migration

Strategies for Process Migration

- Push migration



- Pull migration, a.k.a. work stealing



- Scheduling Basics
- Simple Schedulers
- Priority Schedulers
- Fair Share Schedulers
- Multi-CPU Scheduling
- Case Study: The Linux Kernel

Final Status Check

- At this point, we have looked at many:
  - Scheduling algorithms
  - Types of processes (CPU vs. I/O bound)
  - Hardware configurations (SMP)
- What do real OSes do?
- Case study on the Linux kernel
  - Old scheduler: O(1)
  - Current scheduler: Completely Fair Scheduler (CFS)
  - Alternative scheduler: BF Scheduler (BFS)

O(1) Scheduler

- Replaced the very old O(n) scheduler
  - Designed to reduce the cost of context switching
  - Used in kernels prior to 2.6.23
- Implements MLFQ
  - 140 priority levels, 2 queues per priority
    - Active and inactive queue
    - Process are scheduled from the active queue
    - When the active queue is empty, refill from inactive queue
  - RR within each priority level

Priority Assignment

- Static priorities – *nice* values [-20,19]
  - Default = 0
  - Used for time slice calculation
- Dynamic priorities [0, 139]
  - Used to demote CPU bound processes
  - Maintain high priorities for interactive processes
  - *sleep()* time for each process is measured
    - High sleep time → interactive or I/O bound → high priority

SNP / NUMA Support

- Processes are placed into a virtual hierarchy
  - Groups are scheduled onto a physical CPU
  - Processes are preferentially pinned to individual cores
- Work stealing used for load balancing

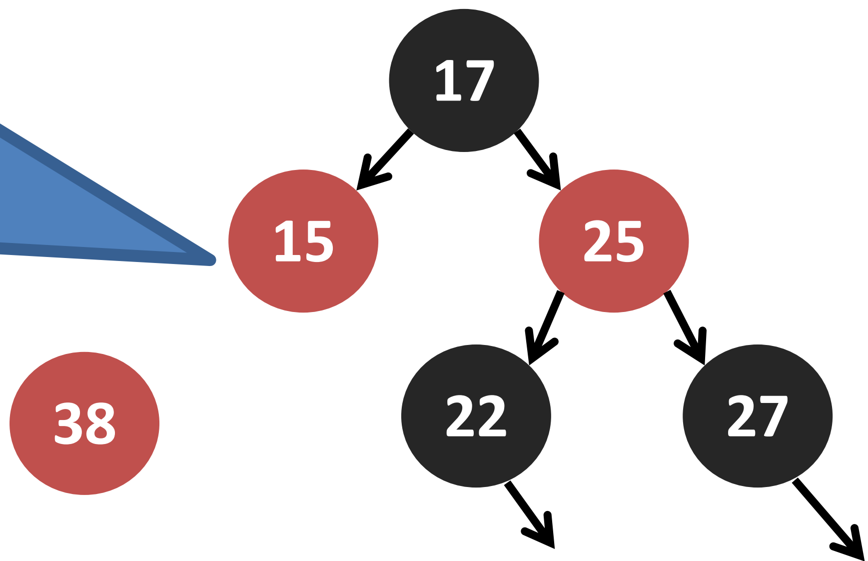
Completely Fair Scheduler (CFS)

- Replaced the O(1) scheduler
  - In use since 2.6.23, has O(log N) runtime
- Moves from MLFQ to Weighted Fair Queuing
  - First major OS to use a fair scheduling algorithm
  - Very similar to stride scheduling
  - Processes ordered by the amount of CPU time they use
- Gets rid of active/inactive run queues in favor of a red-black tree of processes
- CFS isn't actually "completely fair"
  - Unfairness is bounded O(N)

Red-Black Process Tree

- Tree organized according to amount of CPU time used by each process
  - Measured in nanoseconds, obviates the need for time slices

- **Left-most process has always used the least time**
- **Scheduled next**



- **Add the process back to the tree**
- **Rebalance the tree**

BF Scheduler

- What does BF stand for?
  - Look it up yourself
- Alternative to CFS, introduced in 2009
  - O(n) runtime, single run queue
  - Dead simple implementation
- Goal: a simple scheduling algorithm with fewer parameters that need manual tuning
  - Designed for light NUMA workloads
  - Doesn’t scale to cores > 16
- For the adventurous: download the BFS patches and build yourself a custom kernel