CS162
Operating Systems and Systems Programming
Lecture 11

Scheduling
Core Concepts and Classic Policies

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https://cs162.org/

Slides based on prior slide decks from David Culler, Ion Stoica, John Kubiatowicz, Alison Norman and Lorenzo Alvisi

Recall: Scheduling Policy Goals/Criteria

Minimize
Latency

Maximize Throughput

While remaining fair and starvation-free

Recall: Useful metrics

Waiting time for P

Total Time spent waiting for *CPU*

Average waiting time

Average of all processes’ wait time

Response Time for P

Time to when process gets first scheduled

Completion time

Waiting time + Run time

Average completion time

Average of all processes' completion time

Recall: Important Performance Metrics

Fairness

Equality in the performance perceived by each task

Starvation

The lack of progress for one task, due to resources being allocated to different tasks

Recall: Assumptions

Threads are independent!

One thread = One User

Unrealistic but simplify the problem so it can be solved

Only look at work-conserving schedulers
=> Never leave processor idle if work to do

Recall: FCFS/FIFO Summary

The good

Simple
Low Overhead
No Starvation*

The bad

Sensitive to arrival order (poor predictability)

The ugly

Convoy Effect.
Bad for Interactive Tasks

Recall: SJF Summary

The good

Optimal Average Completion Time when jobs arrive simultaneously

The bad

Still subject to convoy effect

The ugly

Can lead to starvation!

Requires knowing duration of job

Recall: STCF Summary

<u>The good</u>

Optimal Average Completion Time
Always

<u>The bad</u>

<u>The ugly</u>

Can lead to starvation!

Requires knowing duration of job

Recall: Taking a step back

Property	FCFS	SJF	STCF
Optimizes Average Completion Time		✓	✓
Prevents Starvation	✓ *		
Prevents Convoy Effect			✓
Psychic Skills Not Needed	✓		

* Assuming each job eventually finishes

Goals for Today

- Round-robin scheduling, continued
- Multi-level Feedback Queues (MLFQ)
- What does Linux do?

Round-Robin Scheduling

RR runs a job for a **time slice**

(a scheduling quantum)

Once time slice over,

Switch to next job in ready queue.

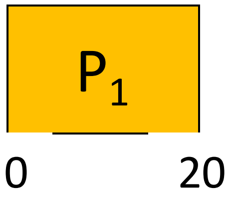
=> Called time-slicing

RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

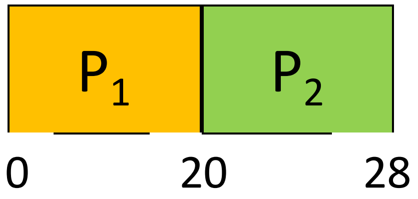
RR with Time Quantum = 20

Process	Burst Time
P_1	53 => 33
P_2	8
P_3	68
P_4	24



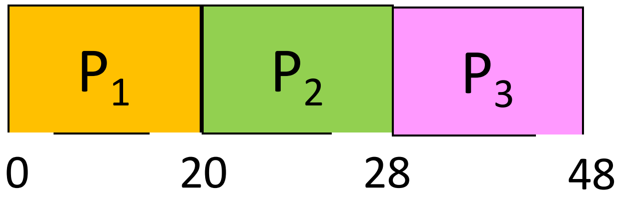
RR with Time Quantum = 20

Process	Burst Time
P_1	33
P_2	8 => 0
P_3	68
P_4	24



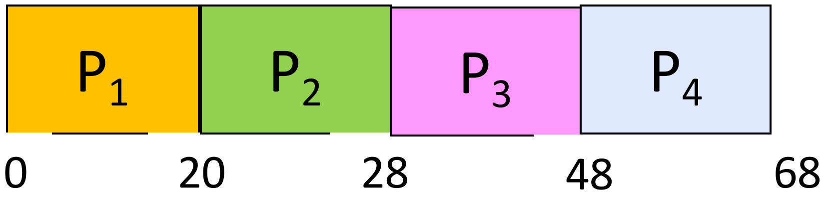
RR with Time Quantum = 20

Process	Burst Time
P_1	33
P_2	0
P_3	68 => 48
P_4	24



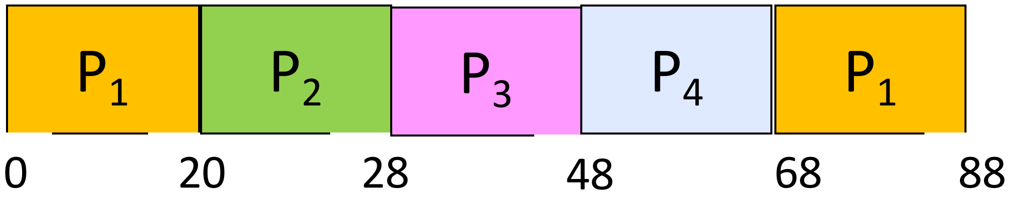
RR with Time Quantum = 20

Process	Burst Time
P_1	33
P_2	0
P_3	48
P_4	24 => 4



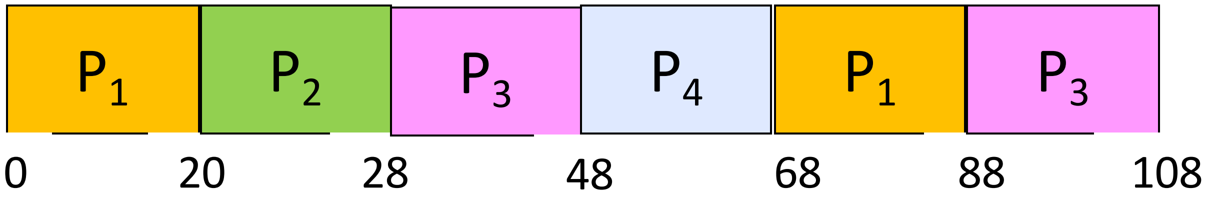
RR with Time Quantum = 20

Process	Burst Time
P_1	33 => 13
P_2	0
P_3	48
P_4	4



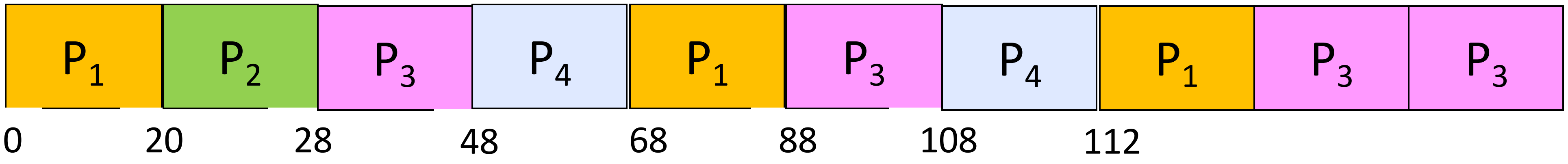
RR with Time Quantum = 20

Process	Burst Time
P_1	13
P_2	0
P_3	48 => 28
P_4	4



RR with Time Quantum = 20

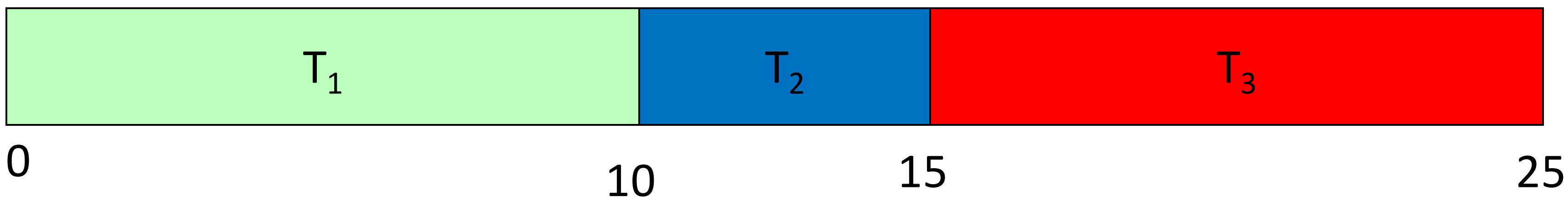
Process	Burst Time
P_1	13
P_2	0
P_3	28
P_4	4 => 0



Effect of Time Quantum on Completion Time

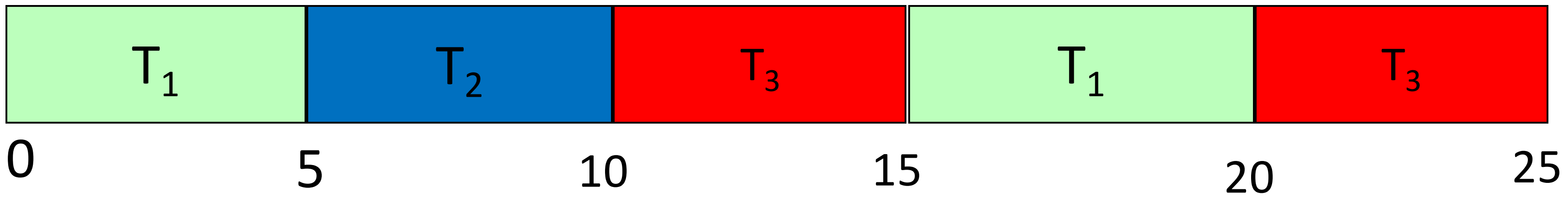
T_1: Burst Length 10 T_2: Burst Length 5 T_3: Burst Length 10

$Q = 10$



Average Completion Time = (10 + 15 + 25)/3 = 16.7

$Q = 5$



Average Completion Time = (20 + 10 + 25)/3 = 18.3

Switching is Also Not Free!

Small scheduling quantas lead to frequent context switches

- Mode switch overhead
- Trash cache-state

Q must be large with respect to context switch,

otherwise overhead is too high

Tuning the Time Quantum

What should the time quantum, Q, be?

If increase the time quantum:

Average Completion Time

Average Response Time

If decrease the time quantum:

Average Completion Time

Average Response Time

FCFS vs Round Robin Showdown

Assuming zero-cost context-switching time,
is RR always better than FCFS?

10 jobs, each take 100s of CPU time
RR scheduler quantum of 1s
All jobs start at the same time

Job #	FIFO	RR
1	100	991
2	200	992
…	…	…
9	900	999
10	1000	1000

Earlier Example with Different Time Quantum

Best FCFS:

P_2 [8]	P_4 [24]	P_1 [53]	P_3 [68]

0 8 32 85 153

Quantum	P1	P2	P3	P4	Average
Best FCFS	85	8	16	32	69.5
Q=1	137	30	153	81	100.5
Q=5	135	28	153	82	99.5
Q=8	133	16	153	80	99,5
Q=10	135	18	153	92	104.5
Q=20	125	28	153	112	104.5
Worst FCFS	121	153	68	145	121.75

Are we done?

Can RR lead to starvation?

No

No process waits more than $(n\text{-}1)q$ time units

Are we done?

Can RR suffer from convoy effect?

No

Only run a time-slice at a time

Taking a step back

Property	FCFS	SJF	STCF	RR
Optimizes Average Completion Time		✓	✓	
Optimizes Average Response Time				✓
Prevents Starvation	✓*			✓
Prevents Convoy Effect			✓	✓
Psychic Skills Not Needed	✓			✓

Recall: Workload Assumptions

A workload is a set of tasks for some system to perform, including how long tasks last and when they arrive

Compute-Bound

Tasks that primarily perform compute

Fully utilise CPU

IO Bound

Mostly wait for IO, limited compute

Often in the Blocked state

RR & IO

RR performs poorly when running mix of
IO and Compute tasks

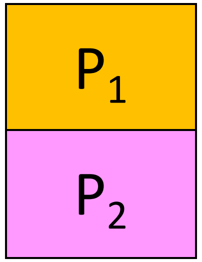
IO tasks need to run "immediately" for a short duration of time (low waiting time).

P_1	Computes for 1 ms. Uses disk for 10 ms
P_2	Computes for 50 ms.

RR & IO

Time Quantum:

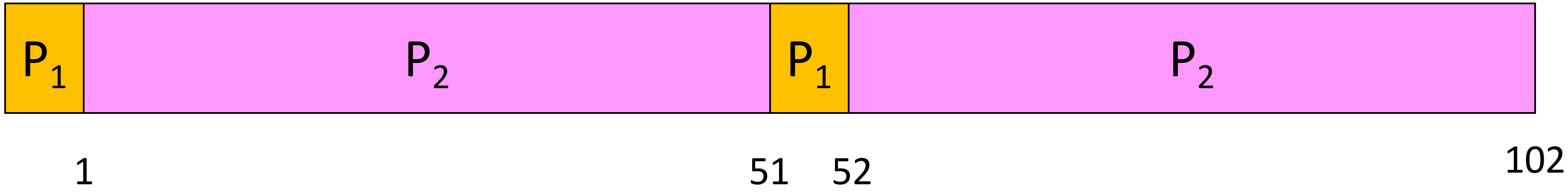
50 ms



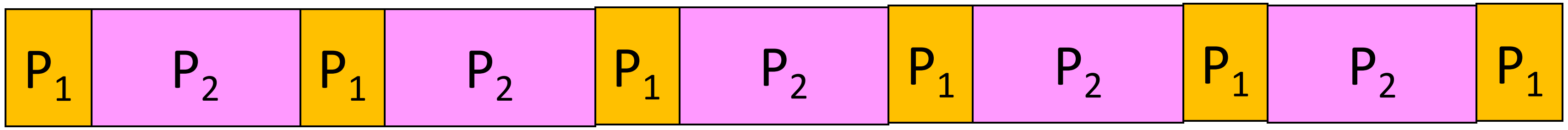
Computes for 1 ms. Uses disk for 10 ms

Computes for 50 ms.

Current Schedule



Optimal Schedule



What We Want

1) Minimize average waiting time for IO/interactive tasks
(tasks with short CPU bursts)

2) Minimize average completion time

3) Maximize throughput
(includes minimizing context switches)

4) Remain fair/starvation-free

Side Note: Priorities

Some jobs are more important than others

Should be scheduled first.
Should get a larger share of the CPU

Assign each job with a priority

Side Note: Priorities

nice(2) — Linux manual page

NAME | SYNOPSIS | DESCRIPTION | RETURN VALUE | ERRORS | CONFORMING TO | NOTES |
SEE ALSO | COLOPHON

Search online pages

```
NICE(2)                 Linux Programmer's Manual               NICE(2)
```

NAME top

```
       nice - change process priority
```

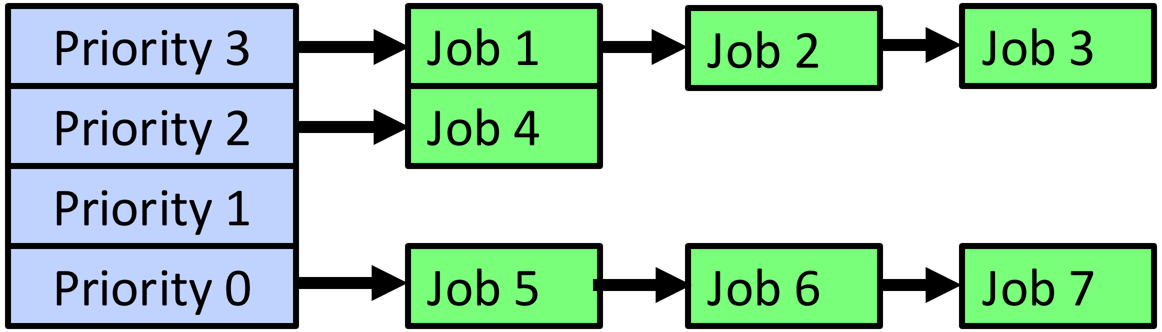
SYNOPSIS top

```
       #include <unistd.h>

       int nice(int inc);

   Feature Test Macro Requirements for glibc (see
   feature_test_macros(7)):

       nice():
           _XOPEN_SOURCE
               || /* Since glibc 2.19: */ _DEFAULT_SOURCE
               || /* Glibc <= 2.19: */ _BSD_SOURCE || _SVID_SOURCE
```

DESCRIPTION top

```
       nice() adds inc to the nice value for the calling thread.  (A
       higher nice value means a lower priority.)
```

Strict Priority Scheduling



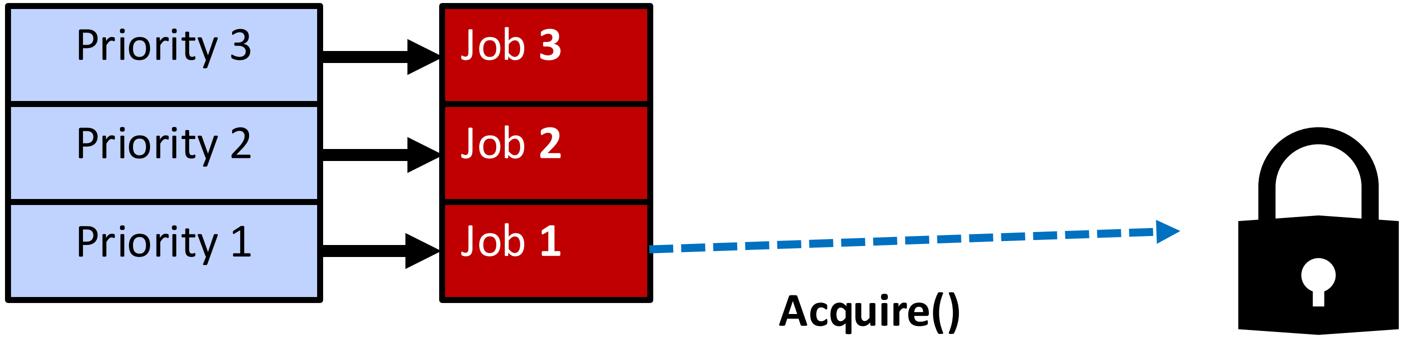
Split jobs by priority into n different queues.

Always process highest-priority queue if not empty. Process each queue round-robin.

Does this lead to starvation?

Priority Inversion

A high–priority thread can become starved by waiting on a low priority thread to release a resource that the high priority thread needs to make progress



Priority Inversion

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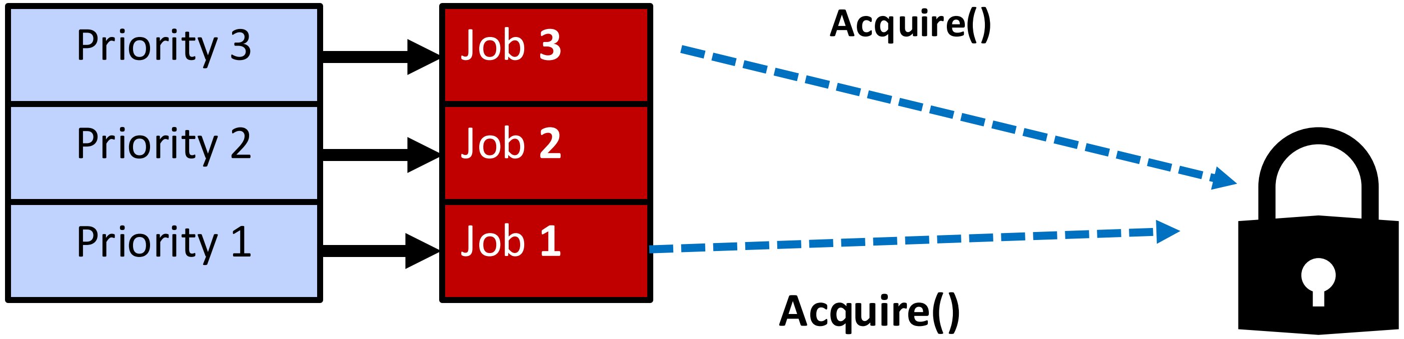
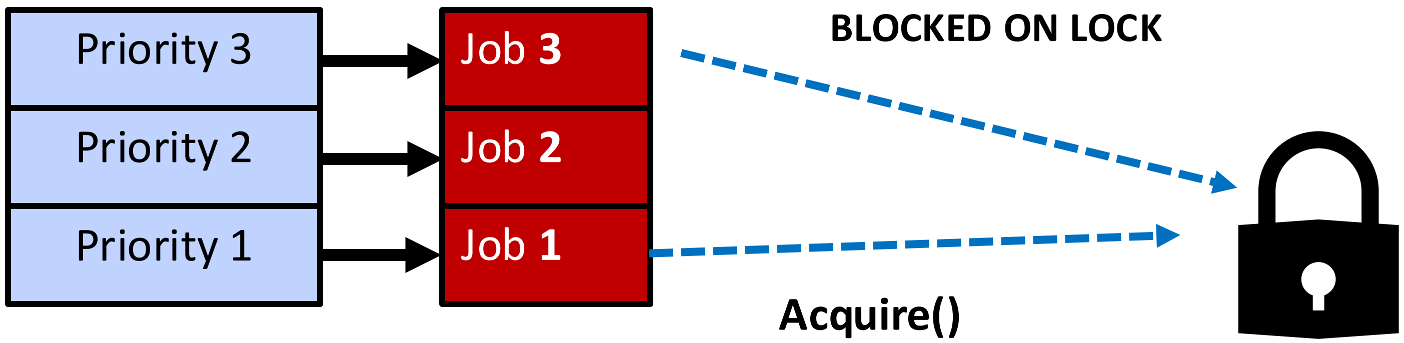


Priority Inversion

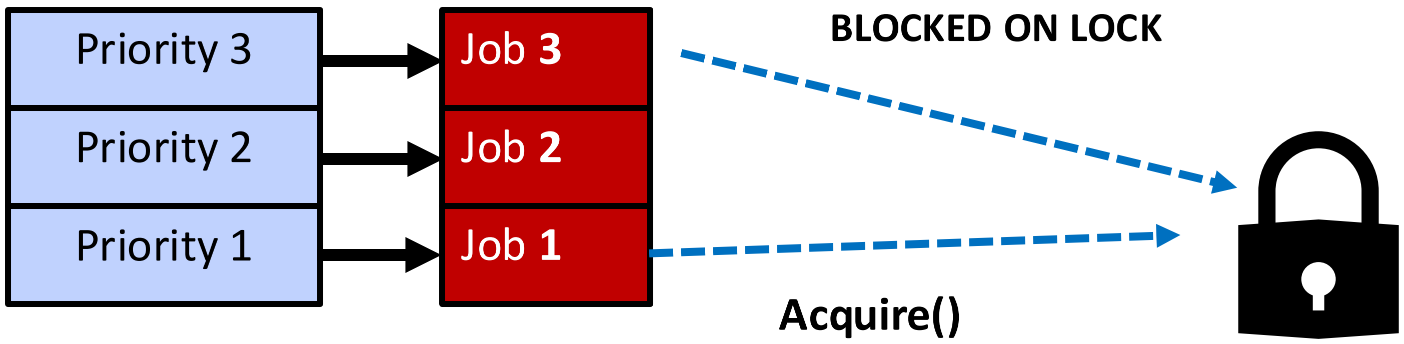
A high–priority thread can become starved by waiting on a low priority thread to release a resource that the high priority thread needs to make progress



Schedule Job 2 instead.

Priority Inversion

A high–priority thread can become starved by waiting on a low priority thread to release a resource that the high priority thread needs to make progress



Keeps scheduling Job 2 over Job 1, Job 3 never runs!

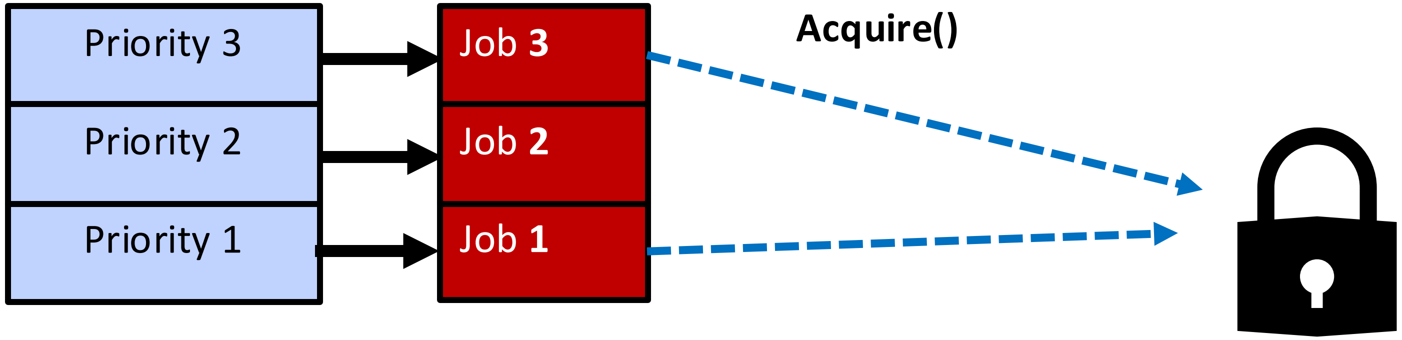
Priority Inversion

Where high priority task is blocked waiting
on low priority task

Low priority one ***must*** run for high priority to make progress

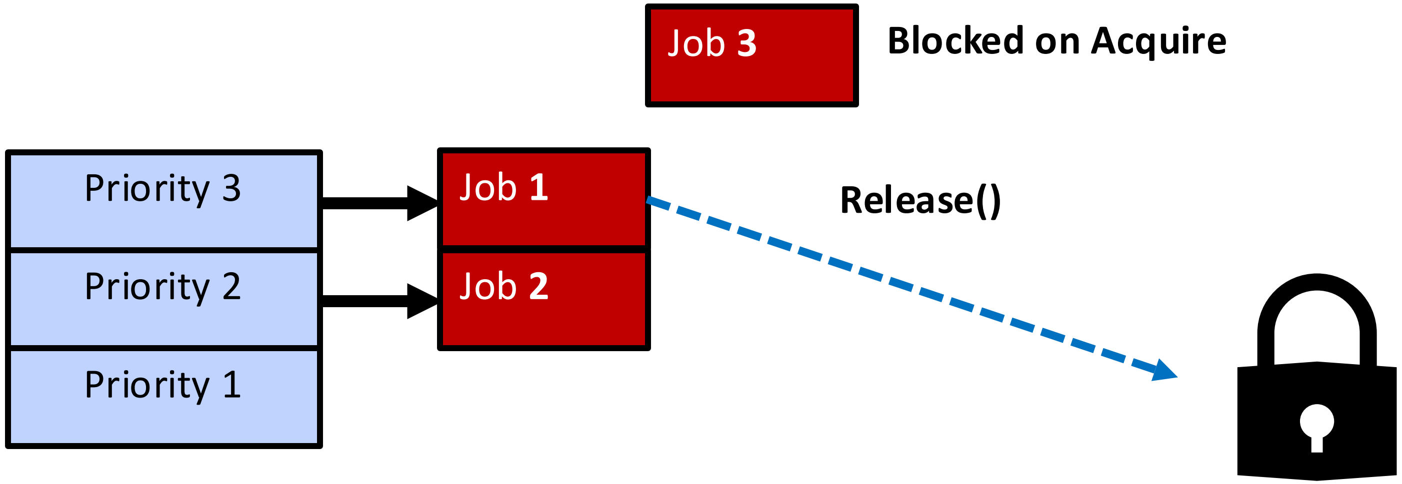
Medium priority task can starve a high priority one

One Solution: Priority Donation/Inheritance



Job 3 temporarily grants Job 1 its "high priority" to run on its behalf

One Solution: Priority Donation/Inheritance



Job 3 temporarily grants Job 1 its "high priority" to run on its behalf

Case Study: Martian Pathfinder Rover

July 4, 1997 – Pathfinder lands on Mars
- First US Mars landing since Vikings in 1976; first rover

And then…a few days into mission…:
- System would reboot randomly, losing valuable time and progress

Problem? Priority Inversion!
- Low priority task grabs mutex trying to communicate with high priority task:
- Realtime watchdog detected lack of forward progress and invoked reset to safe state

Recall: What We Want

1) Minimize average waiting time for IO/interactive tasks
(tasks with short CPU bursts)

2) Minimize average completion time

3) Maximize throughput
(includes minimizing context switches)

4) Remain fair/starvation-free

Recall: STCF

Schedule jobs in order of shortest completion time

Requires knowledge of job completion time

⇩

Approximate duration of CPU burst; encode it in priorities

Subject to Starvation

⇩

Dynamically adapt priorities

Introducing the Multi-level Feedback Queue

Create distinct **queues for ready jobs**, each assigned a different **priority level**.

All jobs belong to one queue at a time. Jobs can move between queues.

MLFQ uses priorities to decide from which queue it should pick next job.

Individual queues run RR with increasing time quantas

MLFQ (V 1.0)

Rule 1

If Priority(A) > Priority(B) (different queues)

A runs (B doesn't).

Rule 2

If Priority(A) = Priority(B), A & B run in RR.

Key question:

How do you set the priorities?

Vary the priority of a job based on its *observed behavior*

Use the *history* of the job to predict its *future* behavior

Learning behavior

Rule 3

When a job enters the system, it is placed at the highest priority (the topmost queue).

Rule 4a

If a job uses up an entire time slice while running, its priority is *reduced* (i.e., it moves down one queue).

Rule 4b

If a job gives up the CPU before the time slice is up, it stays at the *same* priority level.

Learning behavior

Where do IO-bound/interactive jobs end up?

a) Top Queue b) Bottom Queue

MLQF emulates STCF: short jobs given higher priorities than long jobs.

First assumes all jobs are short. If jobs finish < time quanta, assume IO-bound, otherwise CPU bound

Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.

q= 2 ms

q= 10 ms

q= 100 ms

Schedule

Learning behavior

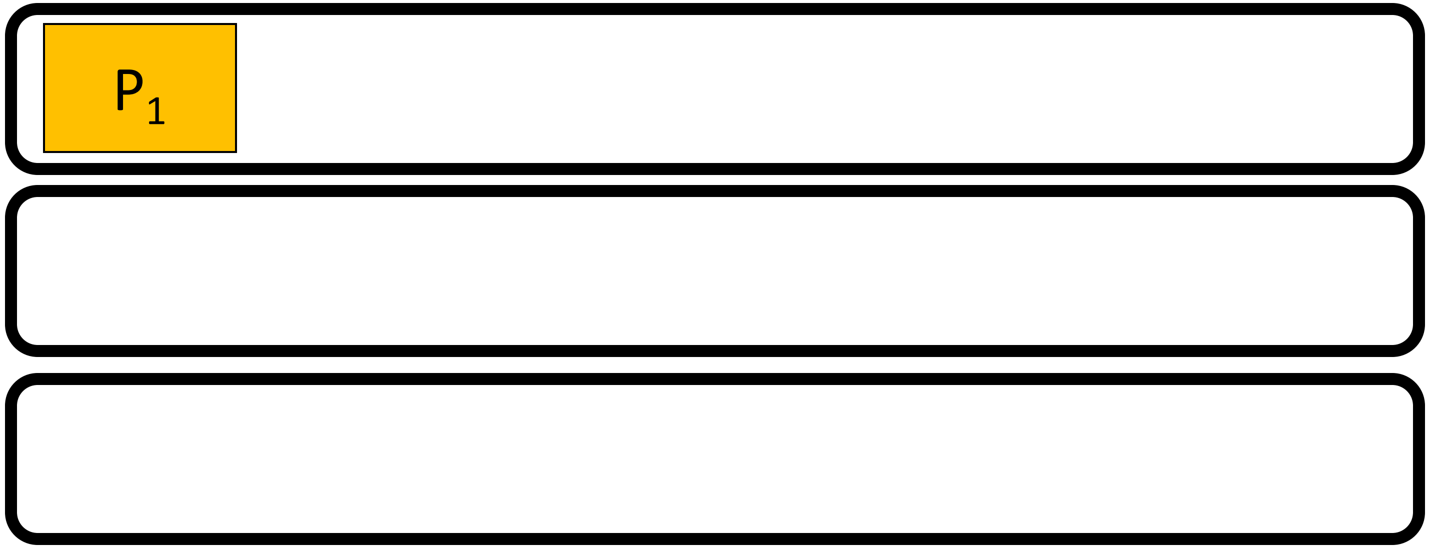
P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.

q= 2 ms

q= 10 ms

q= 100 ms



Schedule

Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.

q= 2 ms

q= 10 ms

q= 100 ms

Schedule P_1

Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.

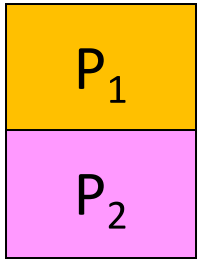
q= 2 ms P_1

q= 10 ms

q= 100 ms

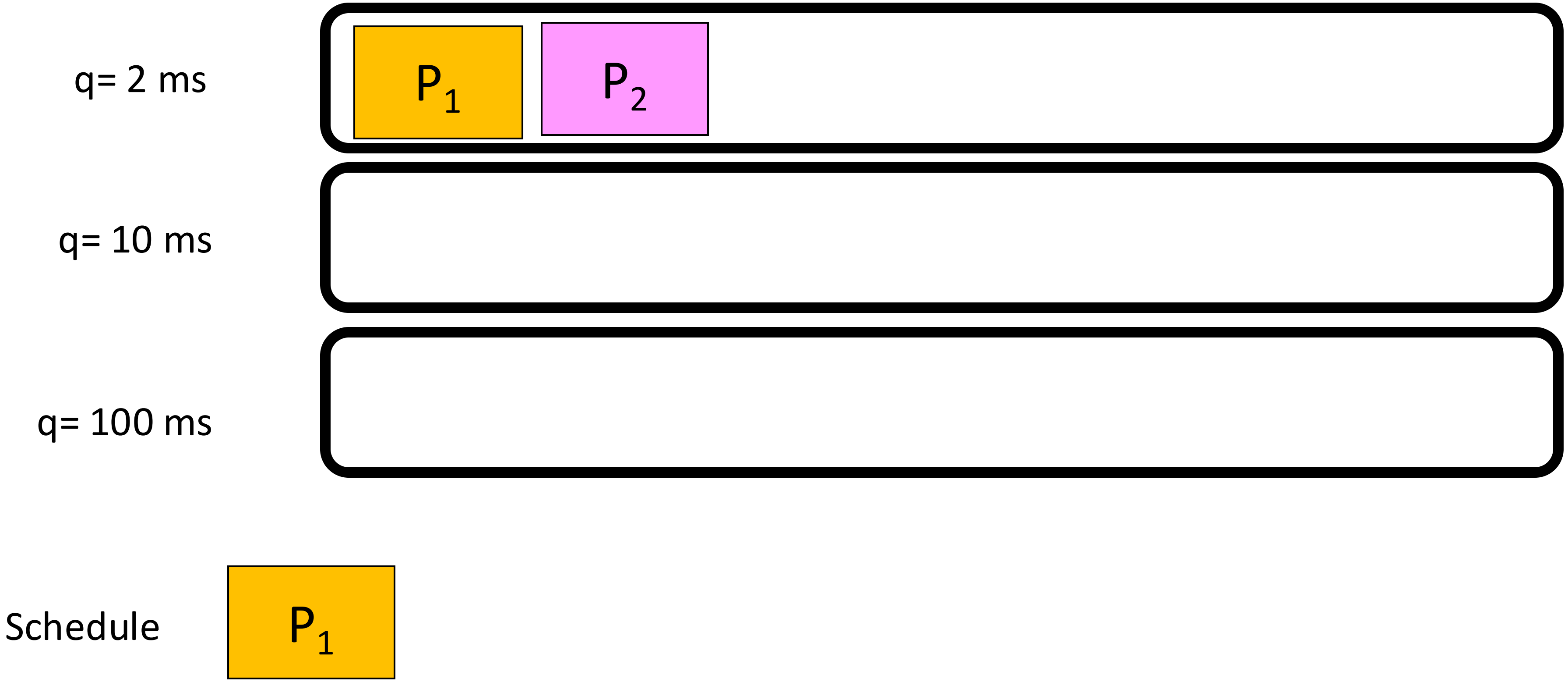
Schedule P_1

Learning behavior



Computes for 1 ms. Uses disk for 10 ms

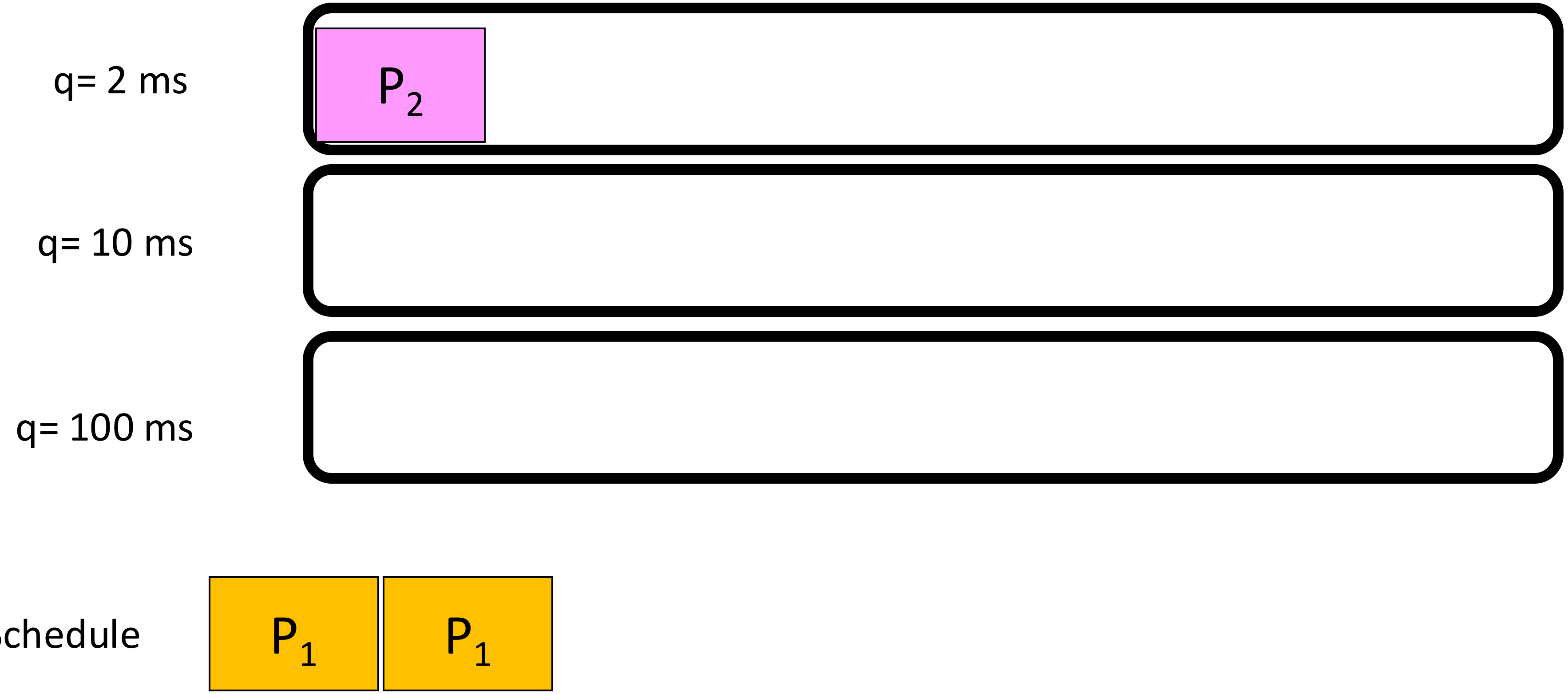
Computes for 50 ms.



Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.



Learning behavior

P$_1$ Computes for 1 ms. Uses disk for 10 ms

P$_2$ Computes for 50 ms.

q= 2 ms

q= 10 ms

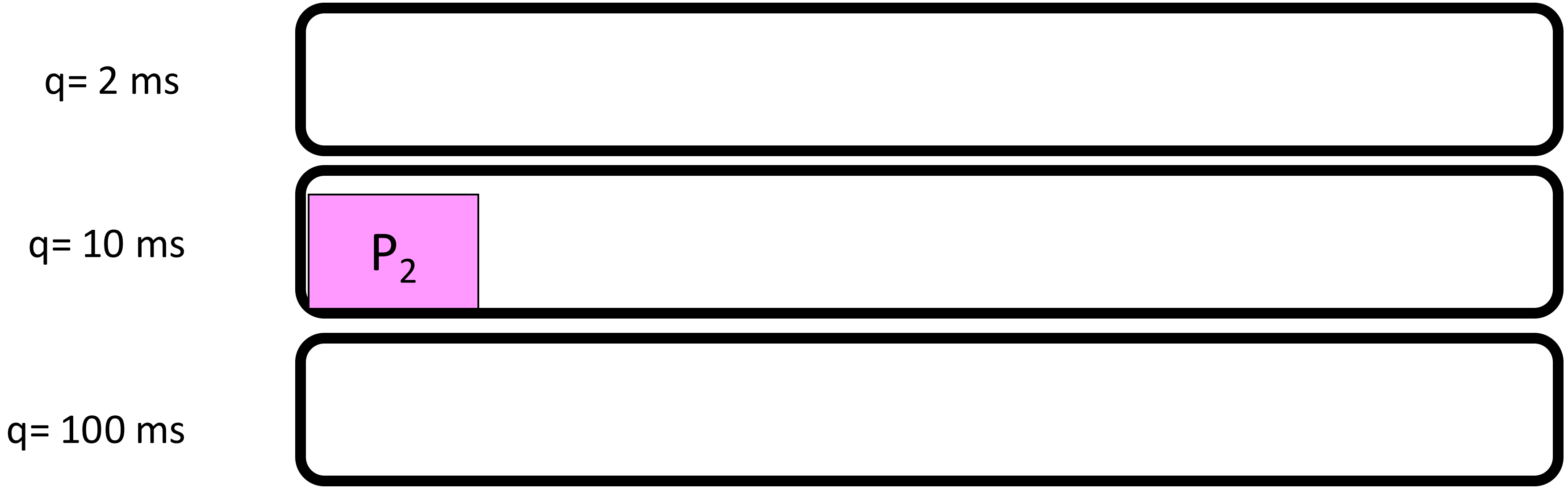
q= 100 ms

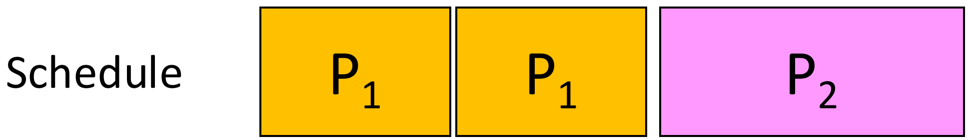
Schedule P$_1$ P$_1$ P$_2$

Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.





Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.

q= 2 ms

q= 10 ms

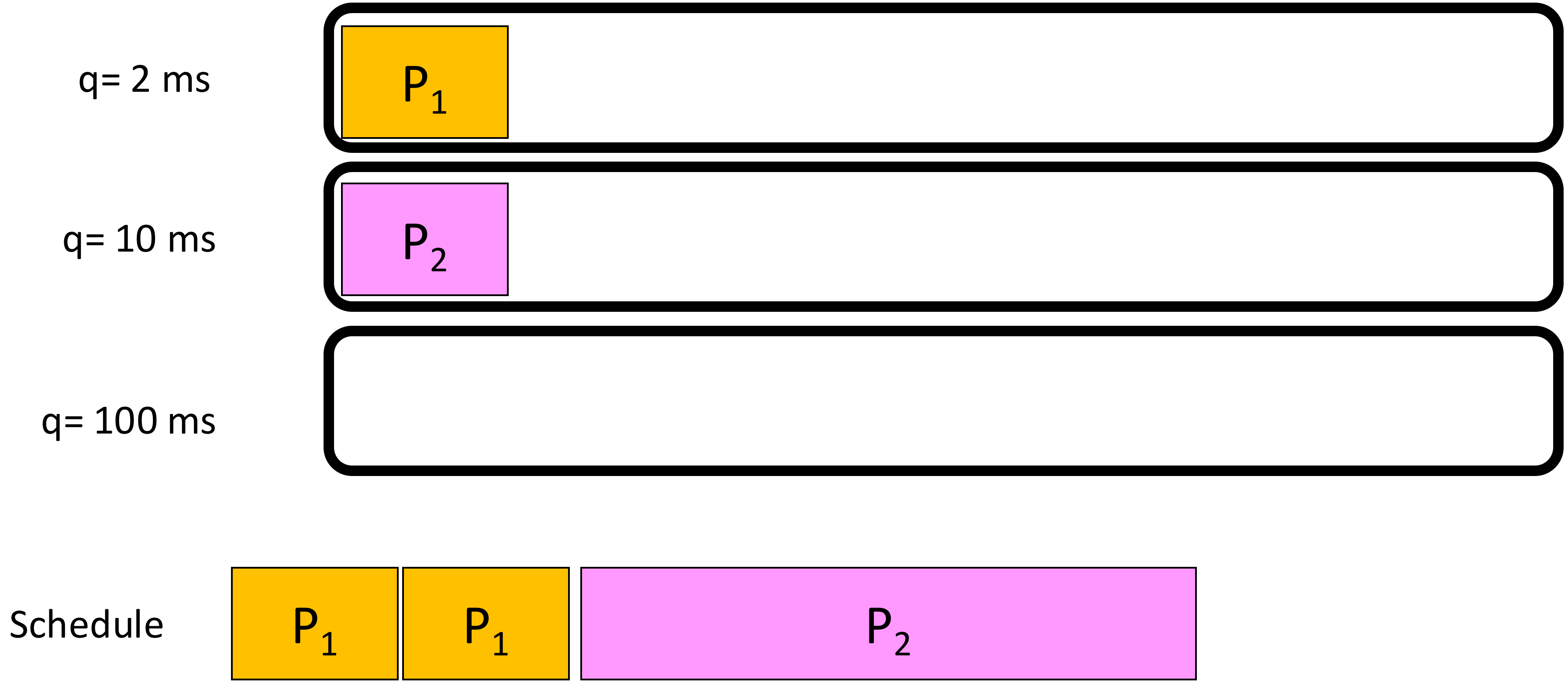
q= 100 ms

Schedule P_1 P_1 P_2

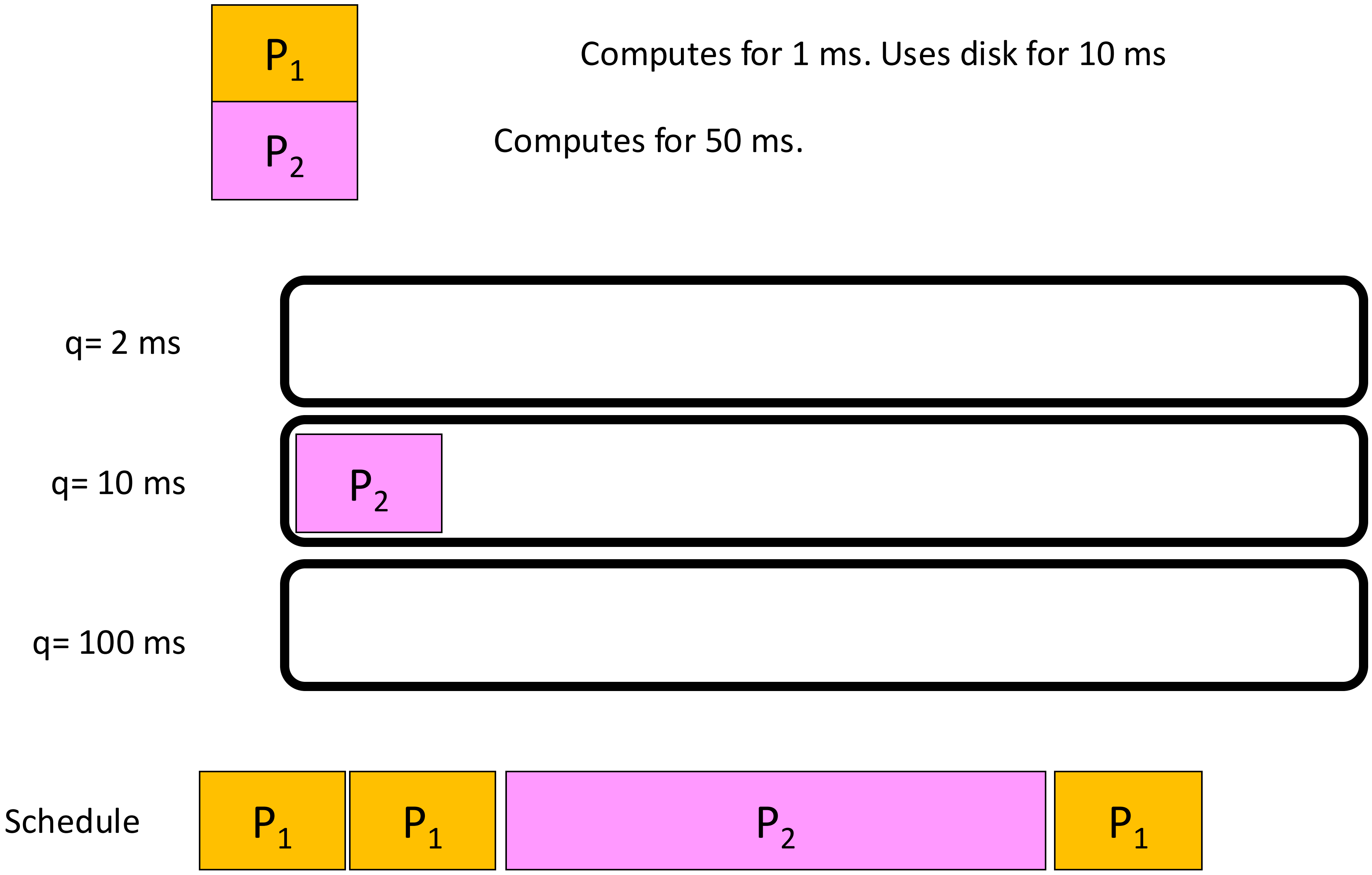
Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.



Learning behavior



Learning behavior

P_1	Computes for 1 ms. Uses disk for 10 ms
P_2	Computes for 50 ms.

q= 2 ms

q= 10 ms

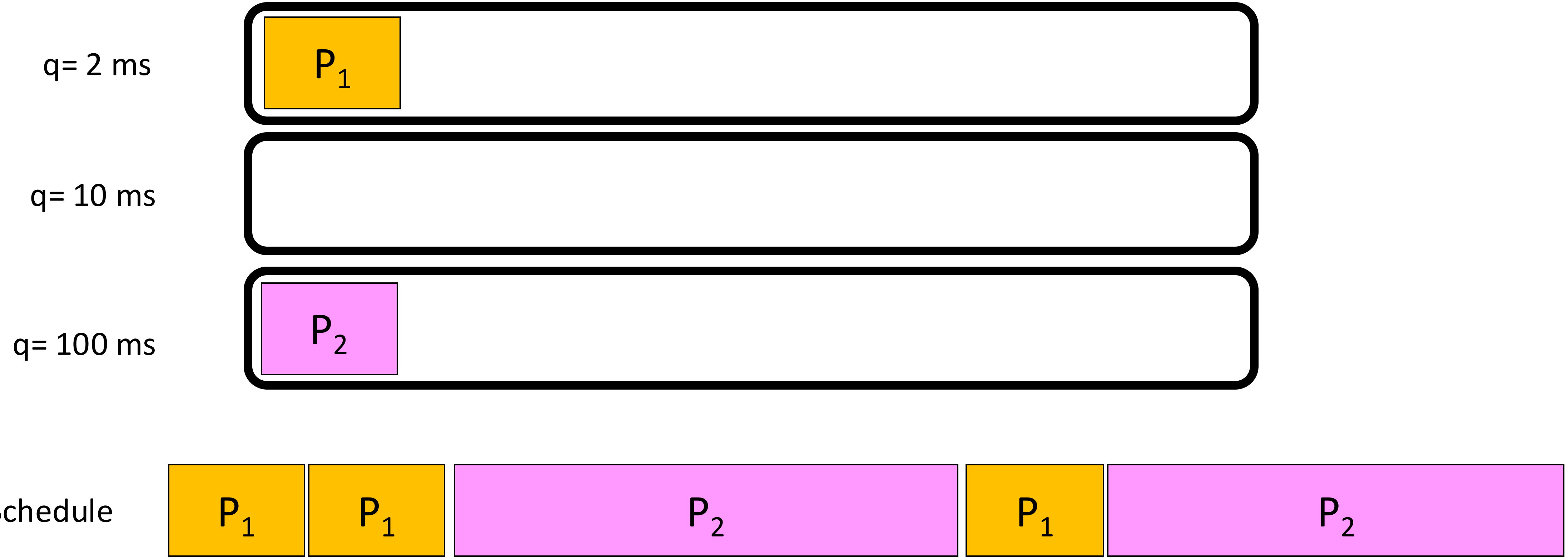
q= 100 ms

Schedule	P_1	P_1	P_2	P_1	P_2

Learning behavior

P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.



Are we done?

MLQF can be gamed:

Intentionally insert IO request just before time quanta to stay on queue.

The “Othello” strategy

MLQF is subject to starvation:

Systematically prioritizes higher-priority queues

Are we done?

MLQF can be gamed:

Intentionally insert IO request just before time quanta to stay on queue.

The “Othello” strategy

Rule 4

Once a job uses up its time allotment at a given levels (regardless of how many times it gave up the CPU), reduce priority

MLQF is subject to starvation:

Systematically prioritise higher-priority queues

Rule 5

After some time period S, move all jobs in system to the topmost queue.

MLFQ

Rule 1

If Priority(A) > Priority(B), A runs (B doesn't).

Rule 2

If Priority(A) = Priority(B), A & B run RR using quantum of queue.

Rule 3

A new job is placed in the topmost queue.

Rule 4

Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced.

Rule 5

After some time period S, move all the jobs in the system to the topmost queue.

Many many different variants of MLQF

Change how prevent starvation

Change constants

Change scheduling policies within each queue

Most modern schedulers are variants of MLQF queues

History of Schedulers in Linux

O(n) scheduler

Linux 2.4 to Linux 2.6

O(1) scheduler

Linux 2.6 to 2.6.22

Completely Fair Scheduler (CFS)

Linux 2.6.23 to 6.6

EEVDF scheduler

Linux 6.6 onwards

Case Study: Linux O(n) Scheduler

At every context switch:

- Scan full list of processes in the ready queue
- Compute relevant priorities
- Select the best process to run

Scalability issues:

- Context switch cost increases as number of processes increase
- Single queue even in multicore systems

Case Study: Linux O(1) Scheduler

Next process to run is chosen in constant time

Priority-based scheduler with 140 different priorities

Real-time/kernel tasks assigned priorities 0 to 99 (0 is highest priority)

User tasks (interactive/batch) assigned priorities 100 to 139 (100 is highest priority)

Case Study: O(1) Scheduler – User tasks

Per priority-level, each CPU has **two ready queues**

An active queue, for processes which have not used up their time quanta

An expired queue, for processes who have

Timeslices/priorities/interactivity credits all computed when jobs finishes timeslice

Timeslice depends on priority

User tasks – Priority Adjustment

User-task priority adjusted ± 5 based on heuristics

» p->sleep_avg = sleep_time – run_time

» Higher sleep_avg $\Rightarrow$ more I/O bound the task, more reward (and vice versa)

Interactive Credit

» Earned when a task sleeps for a "long" time

» Spend when a task runs for a "long" time

» IC is used to provide hysteresis to avoid changing interactivity for temporary changes in behavior

However, "interactive tasks" get special dispensation

» To try to maintain interactivity

» Placed back into active queue, unless some other task has been starved for too long…

O(1) Scheduler – Real tasks

Real-Time Tasks always preempt non-RT tasks

No dynamic adjustment of priorities

Scheduling schemes:

» SCHED_FIFO: preempts other tasks, no timeslice limit

» SCHED_RR: preempts normal tasks, RR scheduling amongst tasks of same priority

An aside: Real-Time Scheduling

Goal

Predictability of Performance!

We need to predict with confidence worst case response times for systems!

Real-time is about enforcing predictability,

and does not equal fast computing.