CS 423
Operating System Design: Scheduling in Linux

Jongyul Kim

* Thanks for Prof. Adam Bates for the slides.

What We will Learn Today

- Multi-Level Feedback Queue (MLFQ) Scheduler
- Linux Schedulers
  - Early Linux Schedulers
  - O(N), O(1) Schedulers
  - Completely Fair Scheduler (CFS)
- Multi-processor Scheduling

Principles

"CPU scheduling is not planning; there is not an optimal solution. Rather CPU scheduling is about balancing goals and making difficult tradeoffs."

-- Joseph T. Meehean

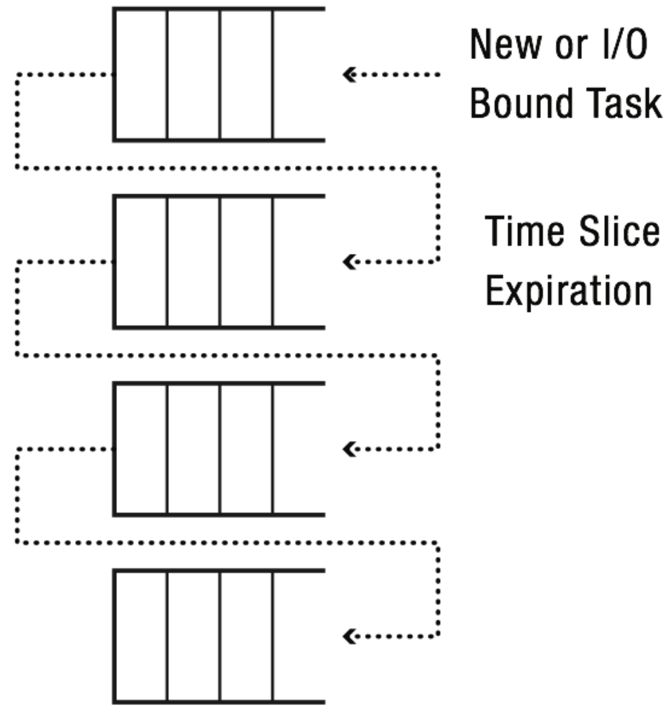
What Are Scheduling Goals?

- What are the goals of a scheduler?
- Linux Scheduler's Goals:
  - Generate illusion of concurrency
  - Maximize resource utilization (e.g., mix CPU and I/O bound processes appropriately)
  - Meet needs of both I/O-bound and CPU-bound processes
    - Give I/O-bound processes better interactive response
    - Do not starve CPU-bound processes
  - Support Real-Time (RT) applications

Multi-Level Feedback Queue

Priority	Time Slice (ms)
1	10
2	20
3	40
4	80

Round Robin Queues



Why is MLFQ a good design?

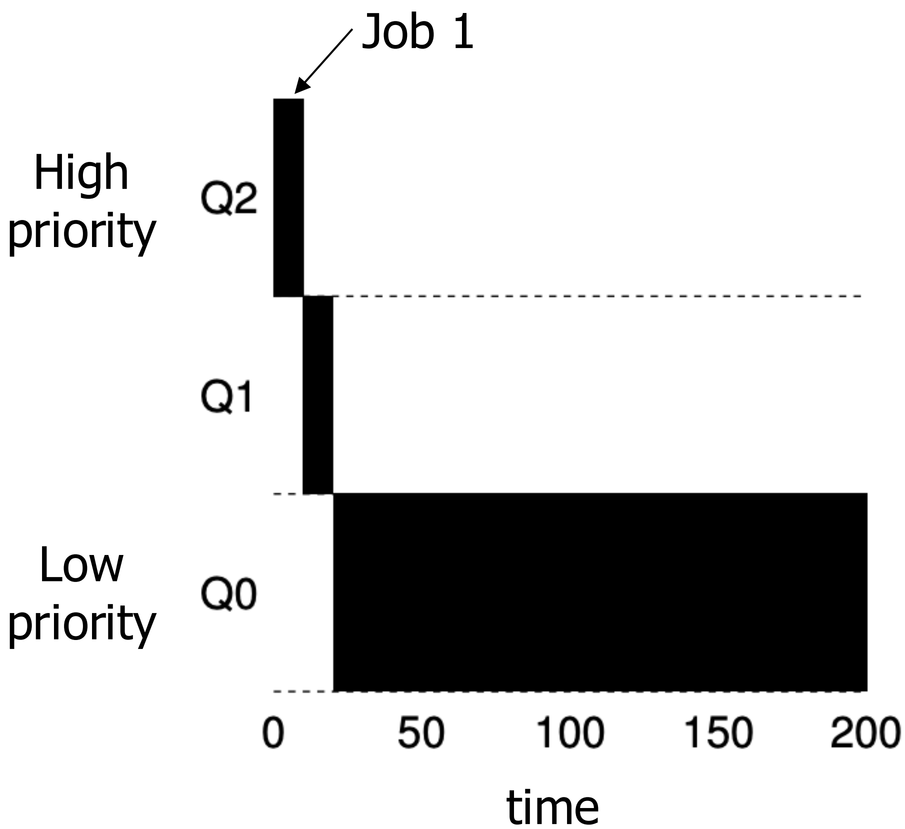
- How to design a scheduler that both minimizes response time for interactive jobs while also minimizing turnaround time without a priori knowledge of job length?

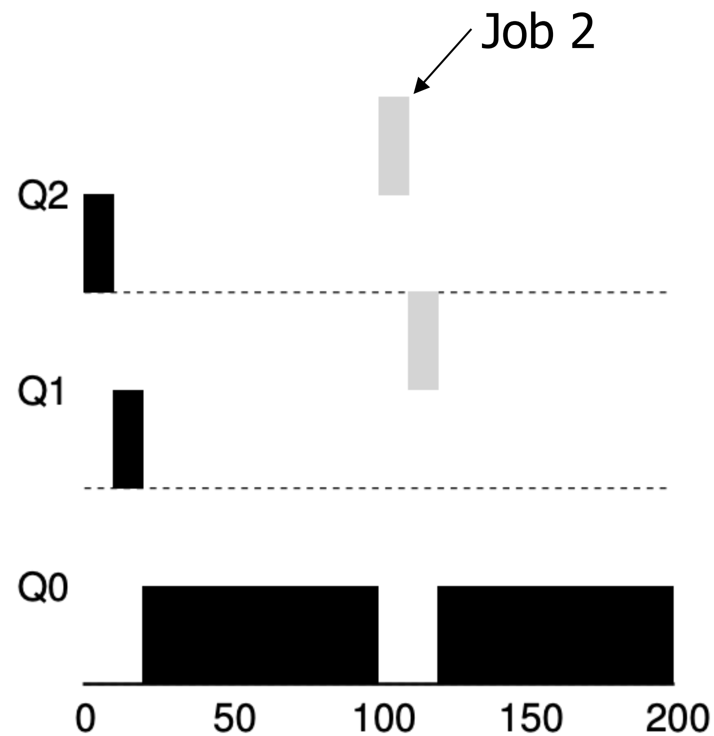
- Yes, SJF – the assumption is to know which is the "shortest.."
  - It's just very hard to know in advance.
  - Sometimes processes/threads could try to game (we will see an example).

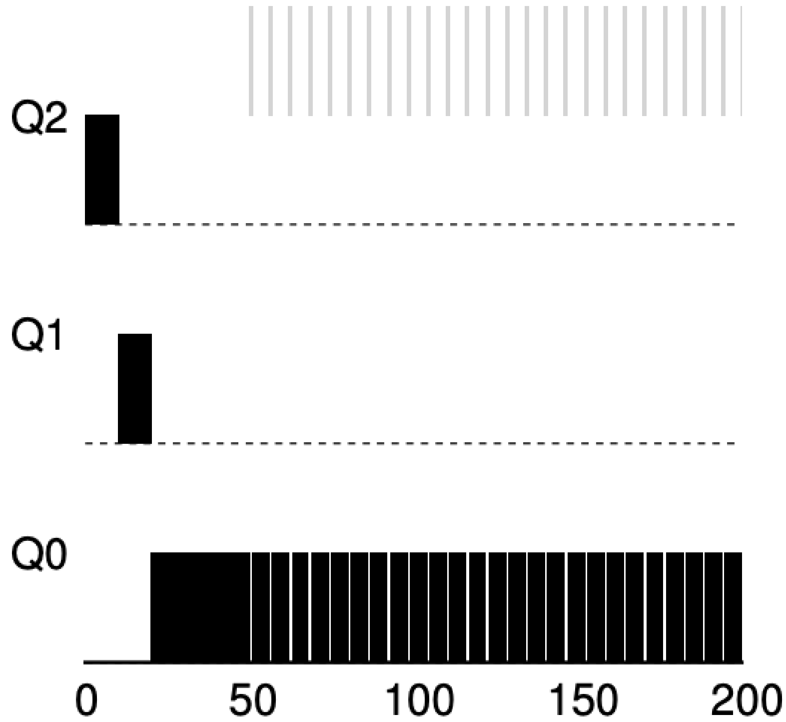
Why is MLFQ a good design?

- The Key Idea
  - Dynamically adjusting the priority level based on observing the behavior of the processes/threads
- Basic Design
  - When a job enters the system, it is placed at the highest priority (the topmost queue).
  - If a job uses up an entire time slice while running, its priority is reduced (i.e., it moves down one queue).
  - If a job gives up the CPU before the time slice is up, it stays at the same priority level.

Basic Design



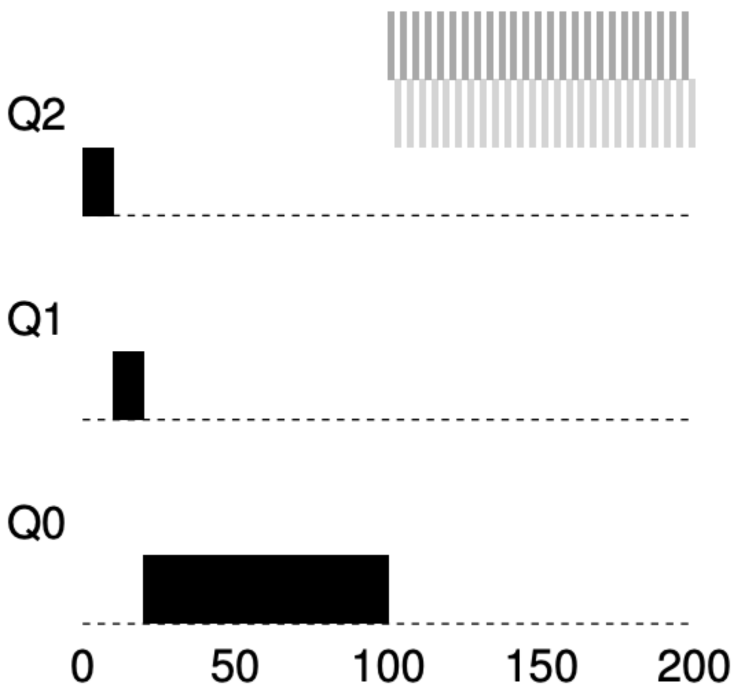


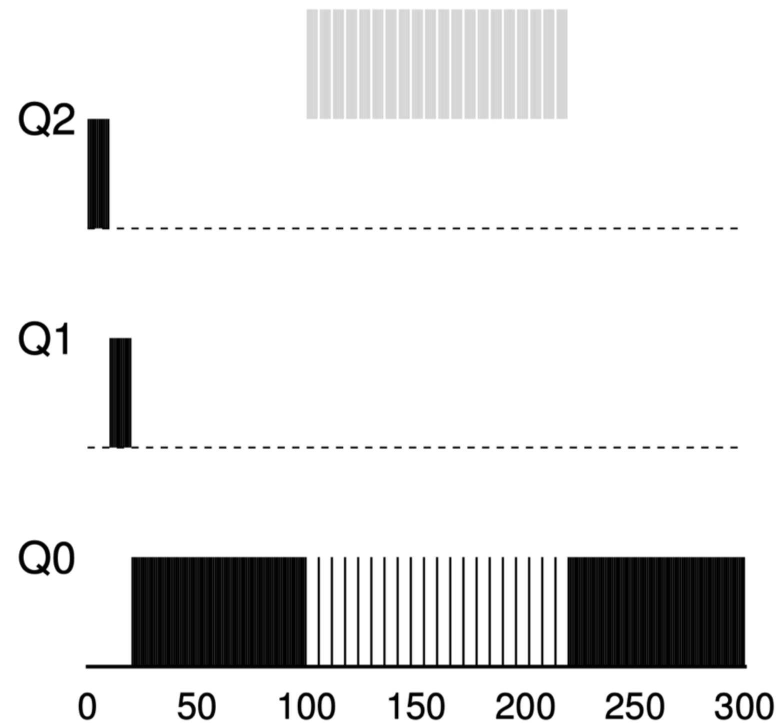


- because it doesn't know whether a job will be a short job or a long-running job, it first assumes it might be a short job, thus giving the job high priority. If it actually is a short job, it will run quickly and complete; if it is not a short job, it will slowly move down the queues, and thus soon prove itself to be a long-running more batch-like process.

Limitations?

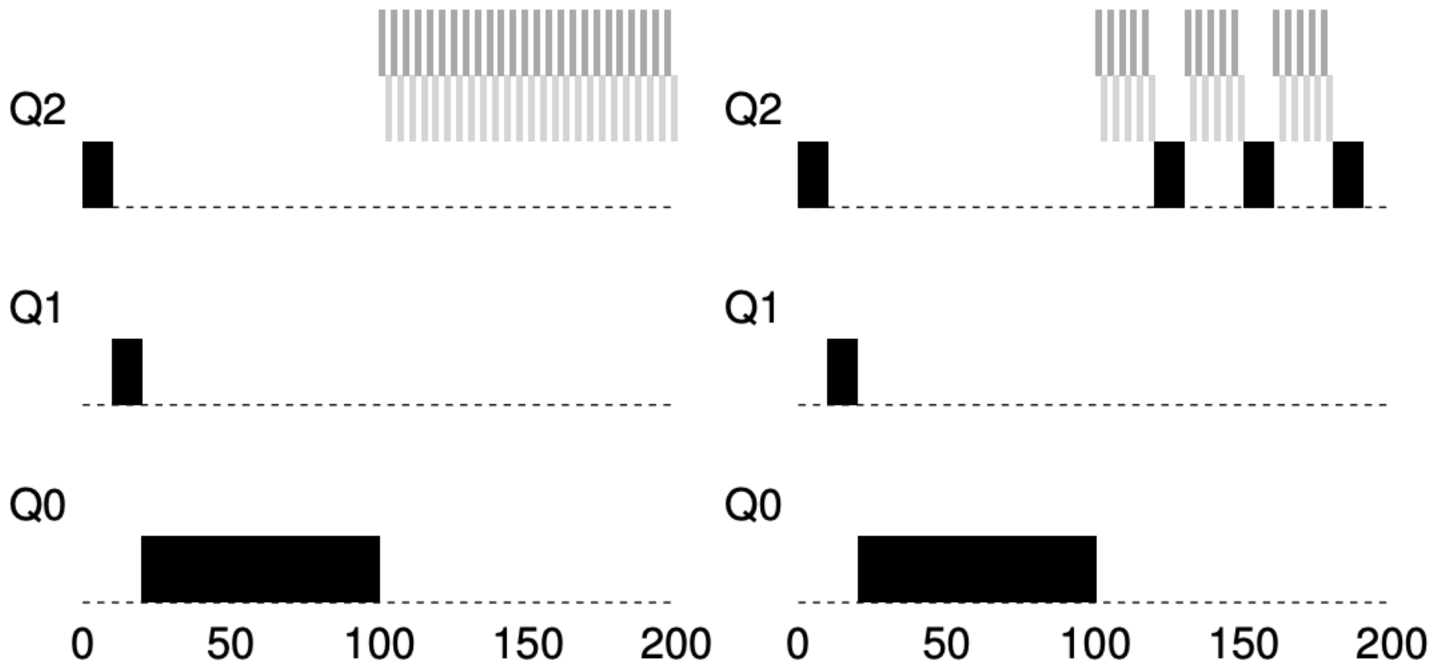
- Starvation
- A process changing its characteristics
- Gaming the scheduler





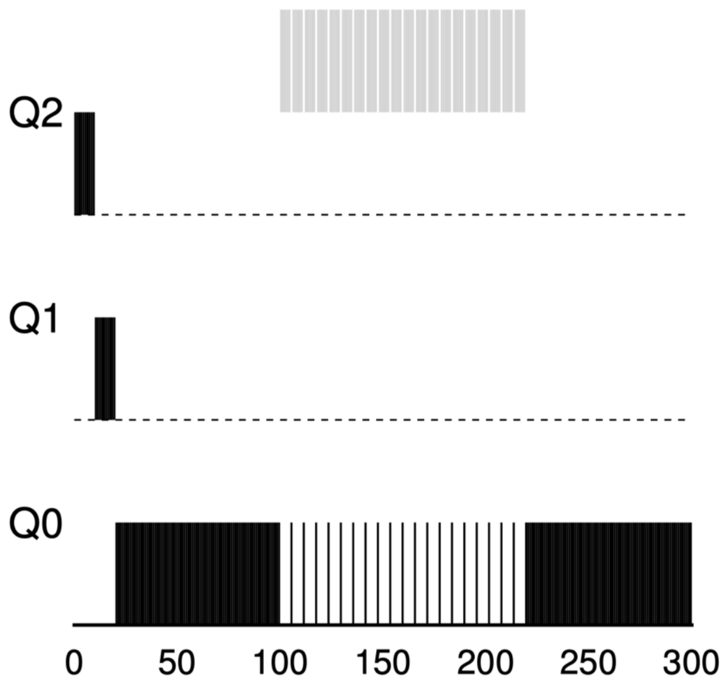
Priority Boost

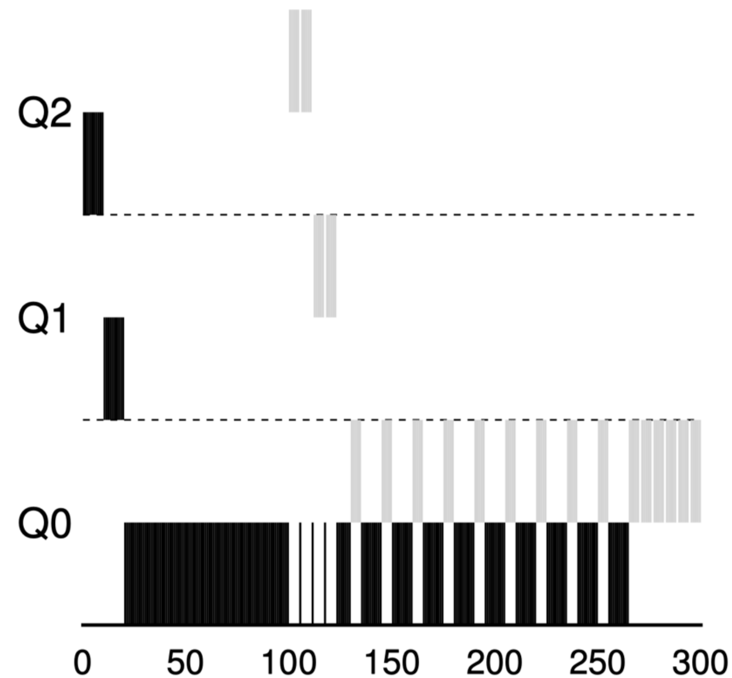
- After some time period S, move all the jobs in the system to the topmost queue



Better Accounting

- 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 (i.e., it moves down one queue).





Sounds perfect?

- How many queues should there be?
- How big should the time slice be per queue?
- How often should priority be boosted in order to avoid starvation and account for changes in behavior?

Early Linux Schedulers

- Linux 1.2: circular queue w/ round-robin policy.
  - Simple and minimal.
  - Did not meet many of the aforementioned goals

- Linux 2.2: introduced scheduling classes (real-time, non-real-time).

```
/* Scheduling Policies
*/
#define SCHED_OTHER  0 // Normal user tasks (default)
#define SCHED_FIFO   1 // RT: Will almost never be preempted
#define SCHED_RR     2 // RT: Prioritized RR queues
```

Why 2 RT mechanisms?

Two Fundamental Mechanisms…

- Prioritization
- Resource partitioning

Prioritization

SCHED_FIFO

- Used for real-time processes
- Conventional preemptive fixed-priority scheduling
  - Current process continues to run until it ends or a higher-priority real-time process becomes runnable
- Same-priority processes are scheduled FIFO

Partitioning

SCHED_RR

- Used for real-time processes
- CPU "partitioning" among same priority processes
  - Current process continues to run until it ends or its time quantum expires
  - Quantum size determines the CPU share
- Processes of a lower priority run when no processes of a higher priority are present

Linux 2.4 Scheduler

- 2.4: O(N) scheduler.
  - Epochs → slices: when blocked before the slice ends, half of the remaining slice is added in the next epoch.
  - Simple.
  - Lacked scalability.
  - Weak for real-time systems.

Linux 2.6 Scheduler

- O(1) scheduler
- Tasks are indexed according to their priority [0,139]
  - Real-time [0, 99]
  - Non-real-time [100, 139]

SCHED_NORMAL

- Used for non real-time processes
- Complex heuristic to balance the needs of I/O and CPU centric applications
- Processes start at 120 by default
  - Static priority
    - A “nice” value: 19 to -20.
    - Inherited from the parent process
    - Altered by user (negative values require special permission)
  - Dynamic priority
    - Based on static priority and applications characteristics (interactive or CPU-bound)
    - Favor interactive applications over CPU-bound ones
  - Timeslice is mapped from priority

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Static Priority: Handles assigned task priorities

Dynamic Priority: Favors interactive tasks

Combined, these mechanisms govern CPU access in the SCHED_NORMAL scheduler.

SCHED_NORMAL Heuristic

How does a static priority translate to real CPU access?

if (static priority < 120)

    Quantum = 20 × (140 – static priority)

else

    Quantum = 5 × (140 – static priority)

(in ms)

Higher priority → Larger quantum

SCHED_NORMAL Heuristic

How does a static priority translate to CPU access?

Description	Static priority	Nice value	Base time quantum
Highest static priority	100	-20	800 ms
High static priority	110	-10	600 ms
Default static priority	120	0	100 ms
Low static priority	130	+10	50 ms
Lowest static priority	139	+19	5 ms

SCHED_NORMAL Heuristic

How does a dynamic priority adjust CPU access?

bonus = min (10, (avg. sleep time / 100) ms)

- avg. sleep time is 0 => bonus is 0
- avg. sleep time is 100 ms => bonus is 1
- avg. sleep time is 1000 ms => bonus is 10
- avg. sleep time is 1500 ms => bonus is 10
- Your bonus increases as you sleep more.

Max priority # is still 139

dynamic priority =

max (100, min (static priority – bonus + 5, 139))

Min priority # is still 100

(Bonus is subtracted to increase priority)

SCHED_NORMAL Heuristic

How does a dynamic priority adjust CPU access?

bo

What's the problem with this (or any) heuristic?

- Your bonus increases as you sleep more.

Max priority # is still 139

dynamic priority =

max (100, min (static priority – bonus + 5, 139))

Min priority # is still 100

(Bonus is subtracted to increase priority)

Completely Fair Scheduler

- **Goal:** Fairly divide a CPU evenly among all competing processes with a clean implementation
- Merged into the 2.6.23 release of the Linux kernel and is the default scheduler.
- Created by Ingo Molnar in a short burst of creativity which led to a 100K kernel patch developed in 62 hours.

Basic Idea:

- **Virtual Runtime (vruntime):** When a process runs it accumulates "virtual time." If priority is high, virtual time accumulates slowly. If priority is low, virtual time accumulates quickly.
- It is a "catch up" policy — task with smallest amount of virtual time gets to run next.

Completely Fair Scheduler

- Scheduler maintains a red-black tree where nodes are ordered according to received virtual execution time
- Node with smallest virtual received execution time is picked next
- Priorities determine accumulation rate of virtual execution time
  - Higher priority → slower accumulation rate

Completely Fair Scheduler

- Sc ... are
  or ... ne
- N ... is
  pi
- Pr
  execution time
  - Higher priority → slower accumulation rate

Property of CFS: If all task's virtual clocks run at exactly the same speed, they will all get the same amount of time on the CPU.

How does CFS account for I/O-intensive tasks?

Example

- Three tasks A, B, C accumulate virtual time at a rate of 1, 2, and 3, respectively.
- What is the expected share of the CPU that each gets?

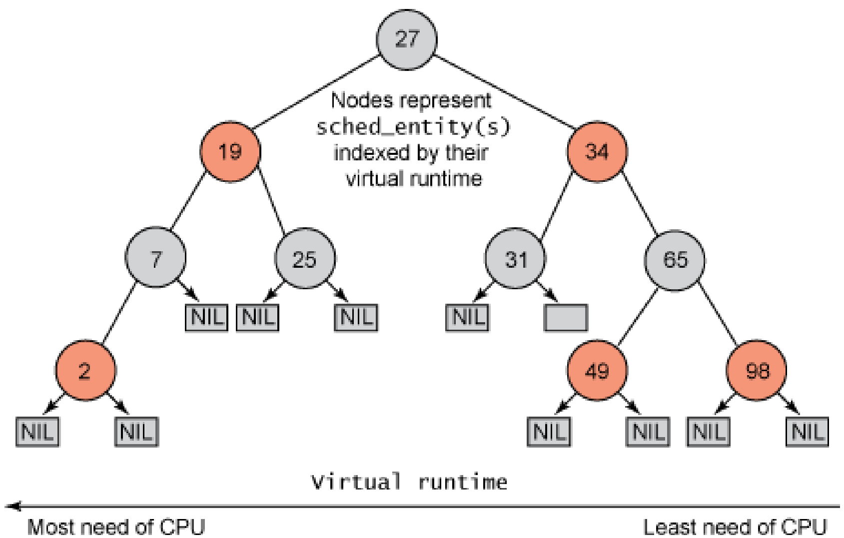
Strategy: **How many quantums required for all clocks to be equal?**

- Least common multiple is 6
- To reach VT=6…
  - A is scheduled 6 times
  - B is scheduled 3 times
  - C is scheduled 2 times.
- 6+3+2 = 11
- A => 6/11 of CPU time
- B => 3/11 of CPU time
- C => 2/11 of CPU time

```
Q01: A => {A:1, B:0, C:0}
Q02: B => {A:1, B:2, C:0}
Q03: C => {A:1, B:2, C:3}
Q04: A => {A:2, B:2, C:3}
Q05: B => {A:2, B:4, C:3}
Q06: A => {A:3, B:4, C:3}
Q07: A => {A:4, B:4, C:3}
Q08: C => {A:4, B:4, C:6}
Q09: A => {A:5, B:4, C:6}
Q10: B => {A:5, B:6, C:6}
Q11: A => {A:6, B:6, C:6}
```

Red-Black Trees

- CFS dispenses with a run queue and instead maintains a time-ordered **red-black tree**. Why?



An RB tree is a BST w/ the constraints:

1. Each node is red or black
2. Root node is black
3. All leaves (NIL) are black
4. If node is red, both children are black
5. Every path from a given node to its descendent NIL leaves contains the same number of black nodes

Red-Black Trees

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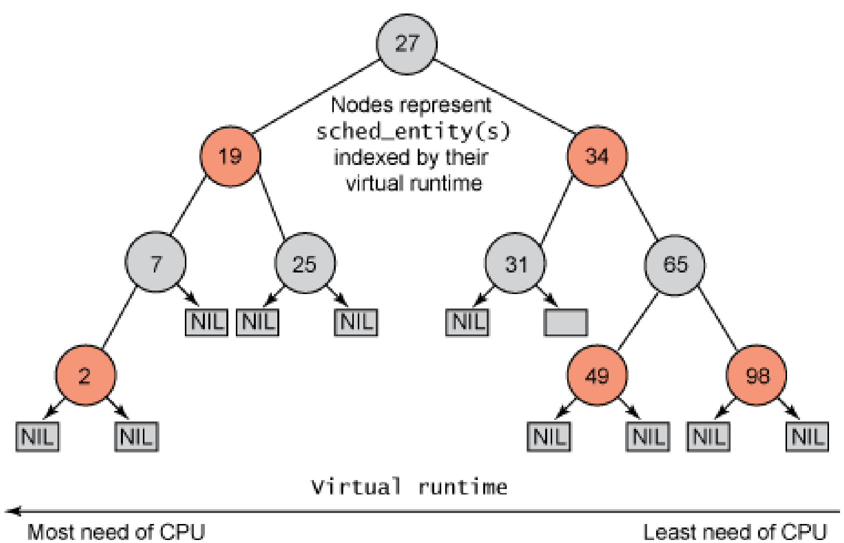

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Takeaway: In an RB Tree, the path from the root to the farthest leaf is no more than twice as long as the path from the root to the nearest leaf.

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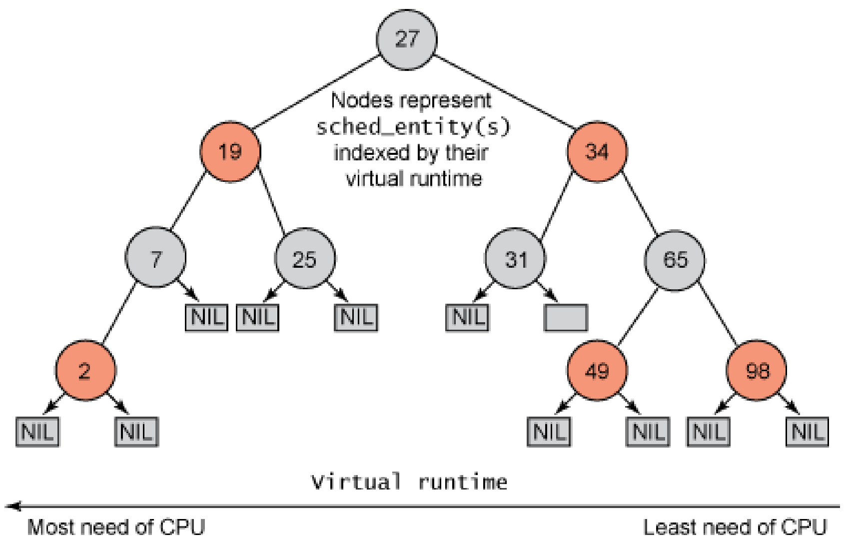

Benefits over run queue:
- O(1) access to leftmost node (lowest virtual time).
- O(log n) insert
- O(log n) delete
- self-balancing

Account for I/O

One problem with picking the lowest vruntime to run next arises with jobs that have gone to sleep for a long period of time. Imagine two processes, A and B, one of which (A) runs continuously, and the other (B) which has gone to sleep for a long period of time (say, 10 seconds). When B wakes up, its vruntime will be 10 seconds behind A's, and thus (if we're not careful), B will now monopolize the CPU for the next 10 seconds while it catches up, effectively starving A.

What's the solution? ☺

How/when to preempt?

- Kernel sets the `need_resched` flag (per-process var) at various locations
  - `scheduler_tick()`, a process used up its timeslice
  - `try_to_wake_up()`, higher-priority process awaken
- Kernel checks `need_resched` at certain points, if safe, `schedule()` will be invoked
- User preemption
  - Return to user space from a system call or an interrupt handler
- Kernel preemption
  - A task in the kernel explicitly calls `schedule()`
  - A task in the kernel blocks (which results in a call to `schedule()`)

A Note on CPU Affinity

We've had lots of great (abstraction-violating) questions about how multiprocessor scheduling works in practice…

- To answer, consider *CPU Affinity* — scheduling a process to stay on the same CPU as long as possible
  - Benefits?
- Soft Affinity — Natural occurs through efficient scheduling
  - Present in O(1) onward, absent in O(N)
- Hard Affinity — Explicit request to scheduler made through system calls (Linux 2.5+)

Multi-Processor Scheduling

- CPU affinity would seem to necessitate a multi-queue approach to scheduling… but how?
- Asymmetric Multiprocessing (AMP): One processor (e.g., CPU 0) handles all scheduling decisions and I/O processing, other processes execute only user code.
- Symmetric Multiprocessing (SMP): Each processor is self-scheduling. Could work with a single queue, but also works with private queues.
    - Potential problems?

SMP Load Balancing

- SMP systems require load balancing to keep the workload evenly distributed across all processors.
- Two general approaches:
  - Push Migration: Task routinely checks the load on each processor and redistributes tasks between processors if imbalance is detected.
  - Pull Migration: Idle processor can actively pull waiting tasks from a busy processor.

Other scheduling policies

- What if you want to maximize throughput?

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  - Earliest deadline first!
  - Problem?

Other scheduling policies

- What if you want to maximize throughput?
  - Shortest job first!
- What if you want to meet all deadlines?
  - Earliest deadline first!
  - Problem?
  - Works only if you are not "overloaded". If the total amount of work is more than capacity, a domino effect occurs as you always choose the task with the nearest deadline (that you have the least chance of finishing by the deadline), so you may miss a lot of deadlines!

EDF Domino Effect

- Problem:
  - It is Monday. You have a homework due tomorrow (Tuesday), a homework due Wednesday, and a homework due Thursday
  - It takes on average 1.5 days to finish a homework.
- Question: What is your best (scheduling) policy?

EDF Domino Effect

- Problem:
  - It is Monday. You have:
    - a homework (A) due tomorrow (Tuesday),
    - a homework (B) due Wednesday,
    - and a homework (C) due Thursday.
  - It takes on average 1.5 days to finish a homework.
- Question: What is your best (scheduling) policy?
  - You could instead skip tomorrow's homework and work on the next two, finishing them by their deadlines
  - Note that EDF is bad: It always forces you to work on the next deadline, but you have only one day between deadlines which is not enough to finish a 1.5 day homework – you might not complete any of the three homeworks!