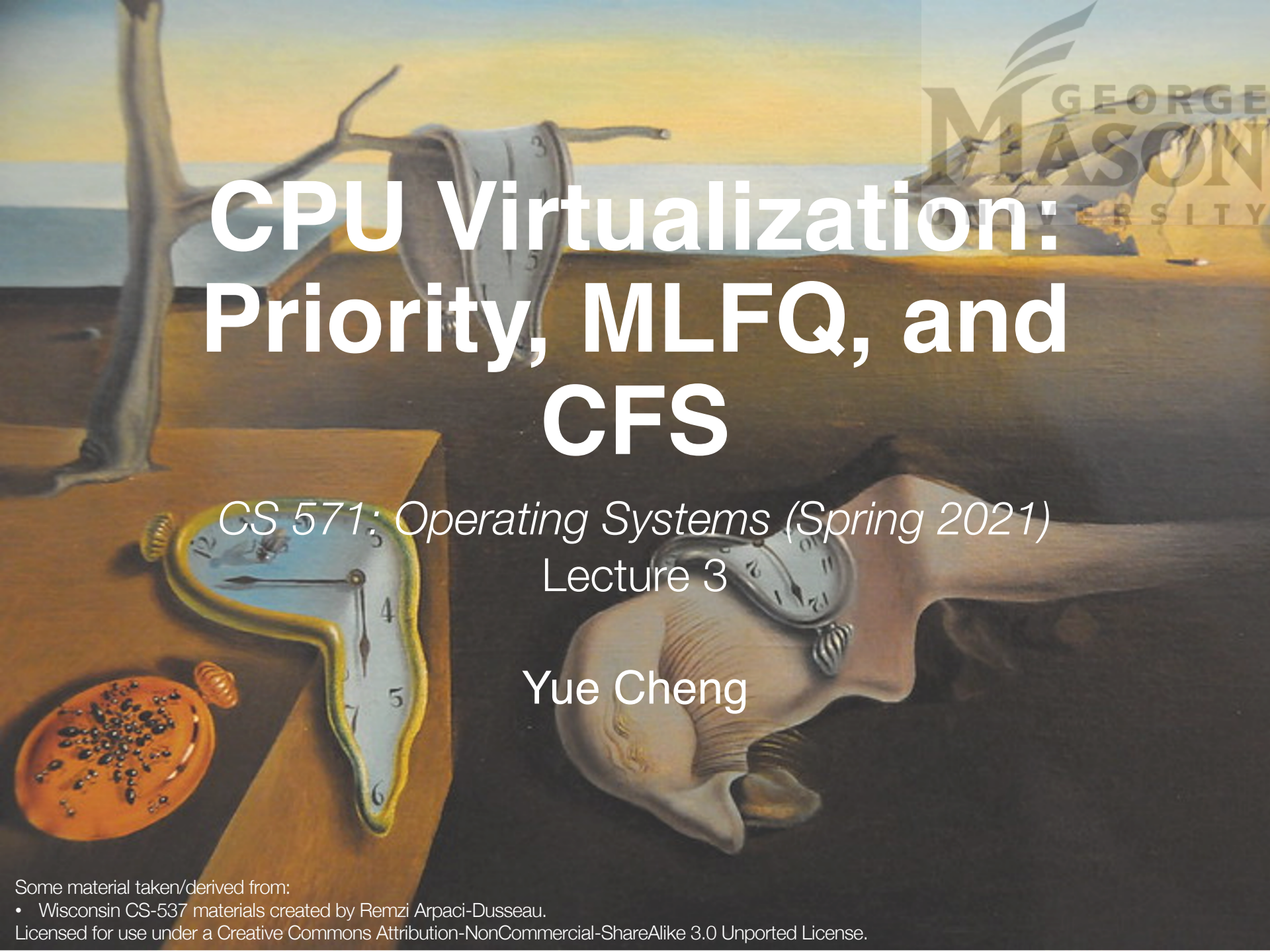

CPU Virtualization: Priority, MLFQ, and CFS

CS 571: Operating Systems (Spring 2021)

Lecture 3

Yue Cheng

Announcement

- Project 0a is graded
- Project 1 is out
  - Please start early!

CPU Scheduling: Outline

- Basic concept
- Scheduling criteria
- Scheduling algorithms
  - First In, First Out (FIFO)
  - Shortest Job First (SFJ)
  - Shortest Time-to-Completion First (STCF)
  - Round Robin (RR)
  - Priority
  - Multi-Level Feedback Queue (MLFQ)
  - (Advanced) Linux scheduling
    - Completely Fair Scheduler (CFS)
    - Lottery Scheduling

Workload Assumptions

1. Each job runs for the same amount of time
2. All jobs arrive at the same time
3. All jobs only use the CPU (no I/O)
4. The run-time of each job is known

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Priority-Based Scheduling

Priority-Based Scheduling

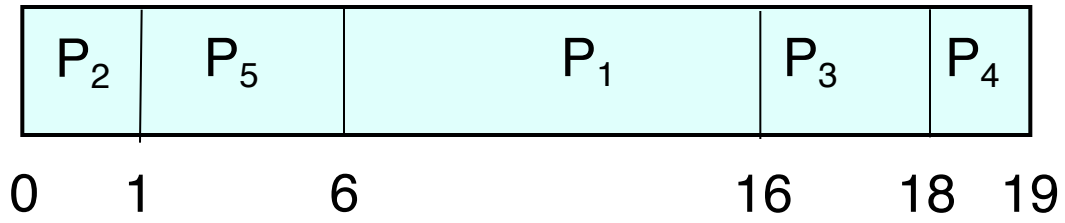
- A priority number (integer) is associated with each process

- The CPU is allocated to the process with the highest priority
  - We assume: smallest integer ≡ highest priority
  - Preemptive
  - Non-preemptive

Example for Priority-Based Scheduling

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	4
P_4	1	5
P_5	5	2

- Priority scheduling Gantt Chart



- Average waiting time = 8.2

Priority-Based Scheduling (cont.)

- Priority Assignment
  - Internal factors: timing constraints, memory requirements, the ratio of average I/O burst to average CPU burst …
  - External factors: Importance of the process, financial considerations, hierarchy among users …
- Problem: Indefinite blocking (or starvation) – low priority processes may never execute
- One solution: Aging
  - As time progresses increase the priority of the processes that wait in the system for a long time

Multi-Level Feedback Queue (MLFQ)

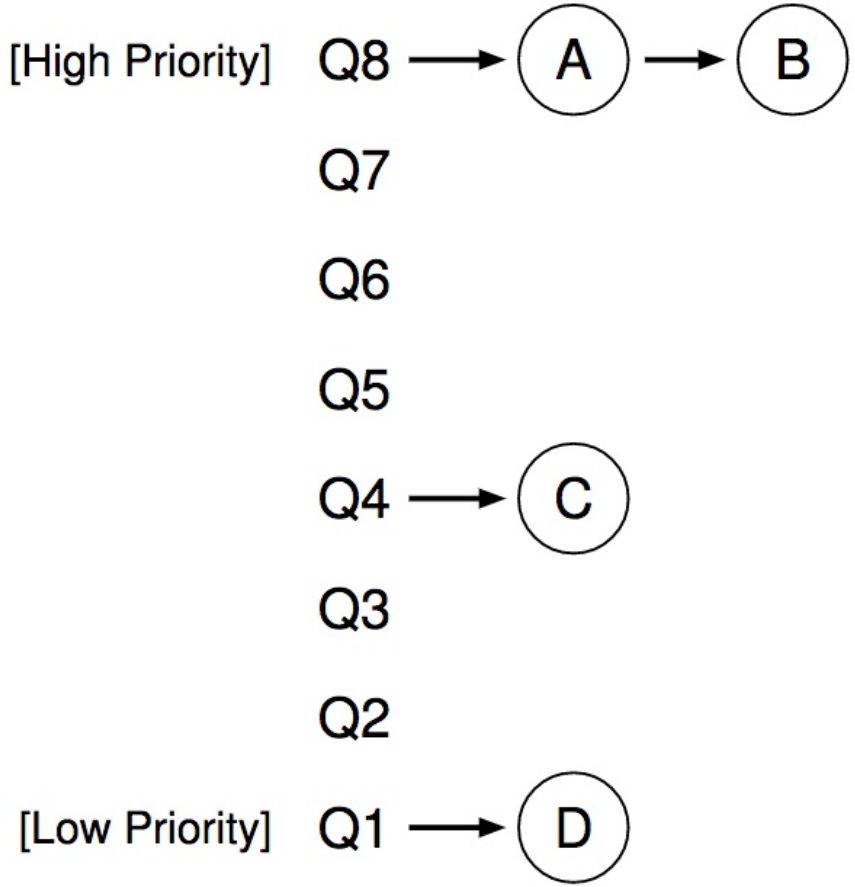
Multi-Level Feedback Queue (MLFQ)

- Goals of MLFQ
  - Optimize turnaround time
    - In reality, SJF does not work since OS does not know how long a process will run
  - Minimize response time
    - Unfortunately, RR is really bad on optimizing turnaround time

MLFQ: Basics

- MLFQ maintains a number of queues (multi-level queue)
  - Each assigned a different priority level
  - Priority decides which process should run at a given time

MLFQ Example



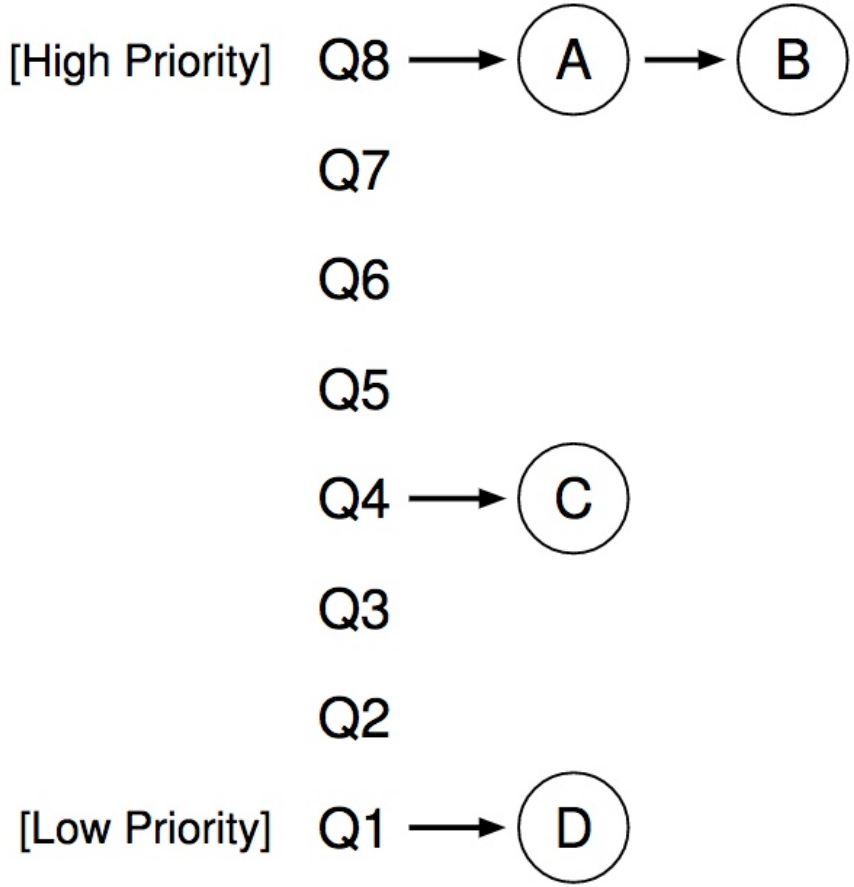
How to know process type to set priority?

1. nice
2. history

How to Check Nice Values in Linux?

- `% ps ax -o pid,ni,cmd`

MLFQ Example



How to know process type to set priority?

1. nice
2. history

In this example, A and B are given high priority to run, while C and D may starve

MLFQ: Basic Rules

- MLFQ maintains a number of queues (multi-level queue)
  - Each assigned a different priority level
  - Priority decides which process should run at a given time

- **Rule 1:** If Priority(A) > Priority(B), A runs (B doesn't).
- **Rule 2:** If Priority(A) = Priority(B), A & B run in RR.

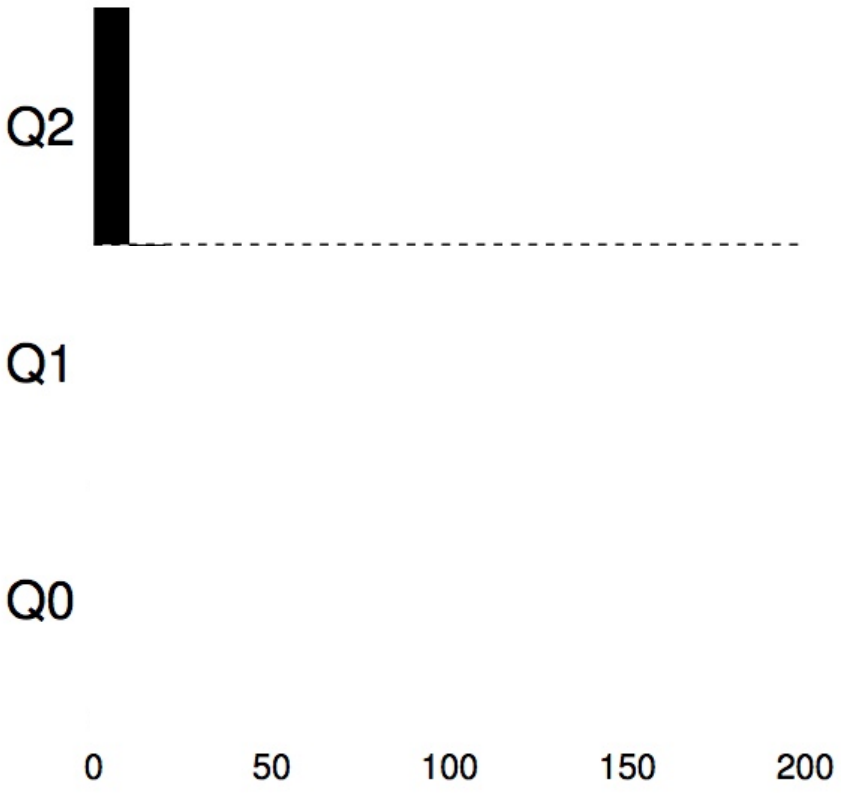
Attempt #1: Change Priority

- Workload
  - Interactive processes (many short-run CPU bursts)
  - Long-running processes (CPU-bound)
- Each time quantum = 10ms

- **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.

Example 1: One Single Long-Running Process

- A process enters at highest priority (time quantum = 10ms)



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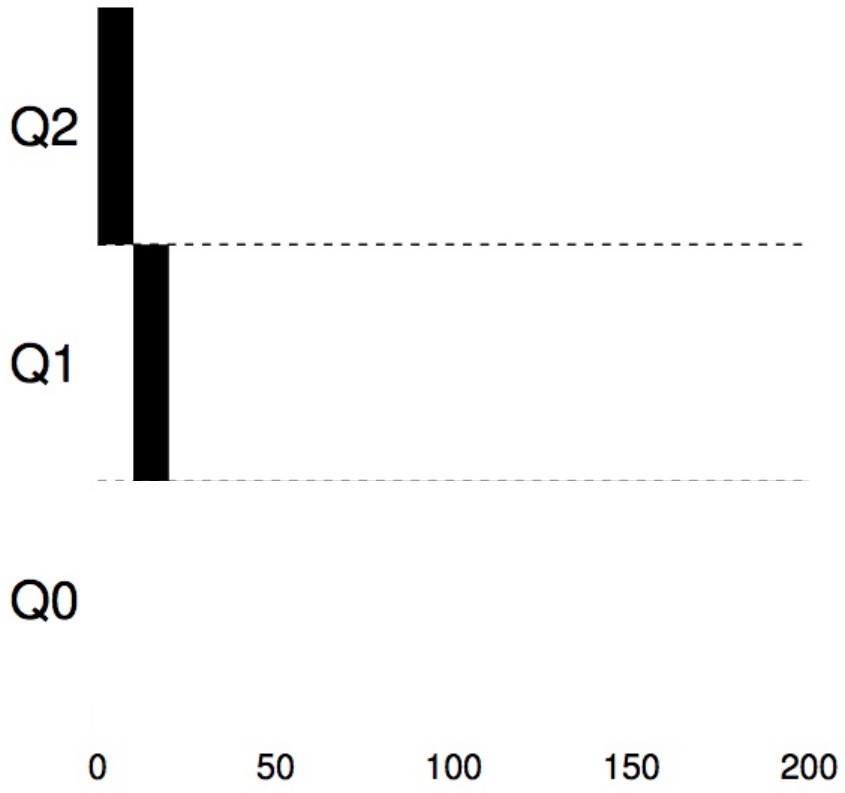

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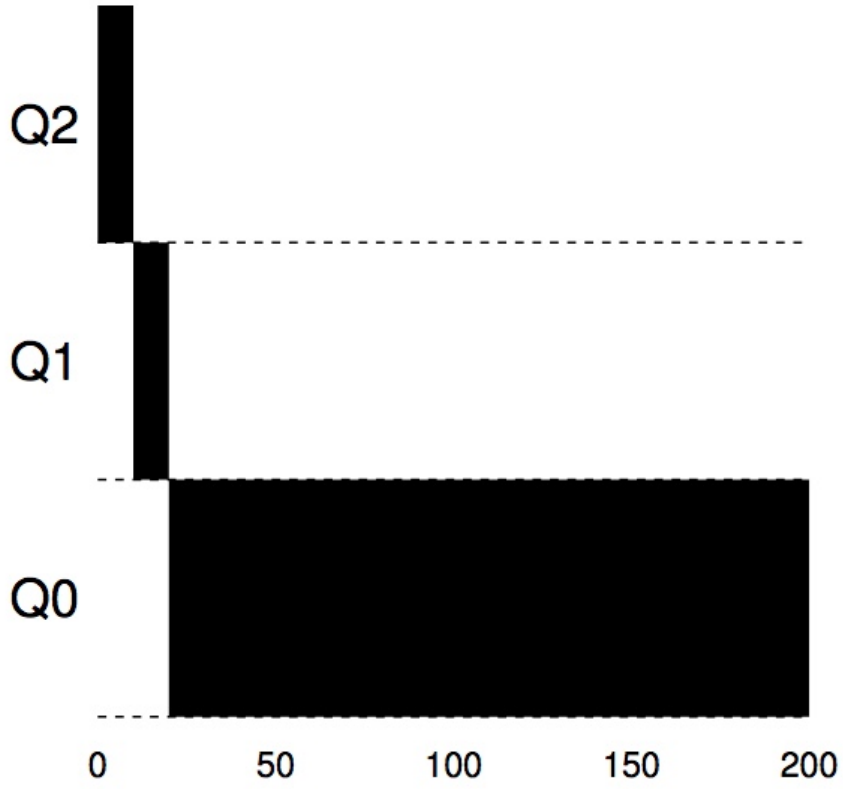
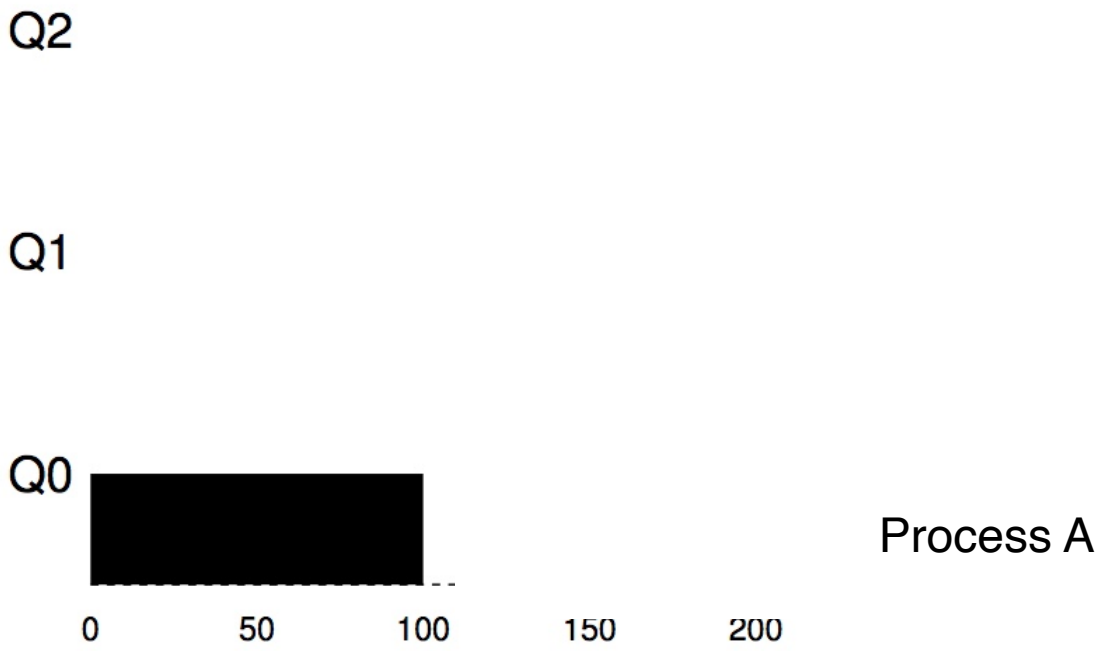


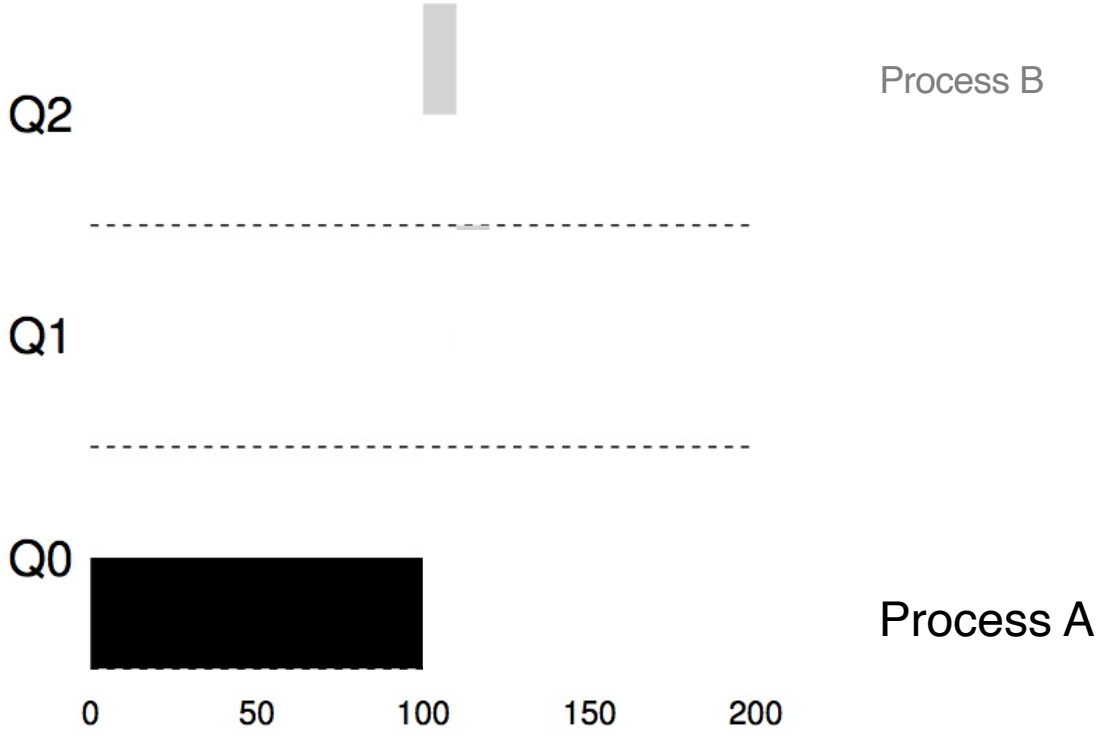
Example 2: Along Came a Short-Running Process

- Process A: long-running process (start at 0)



Example 2: Along Came a Short-Running Process

- Process A: long-running process (start at 0)
- Process B: short-running interactive process (start at 100)



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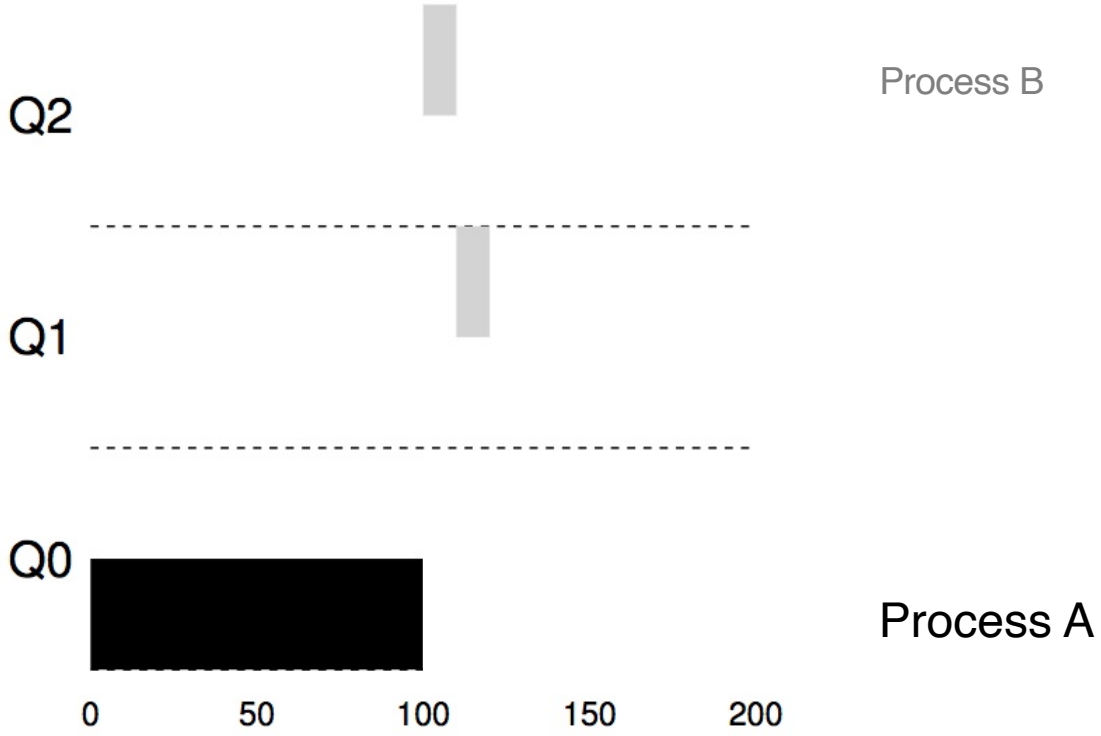

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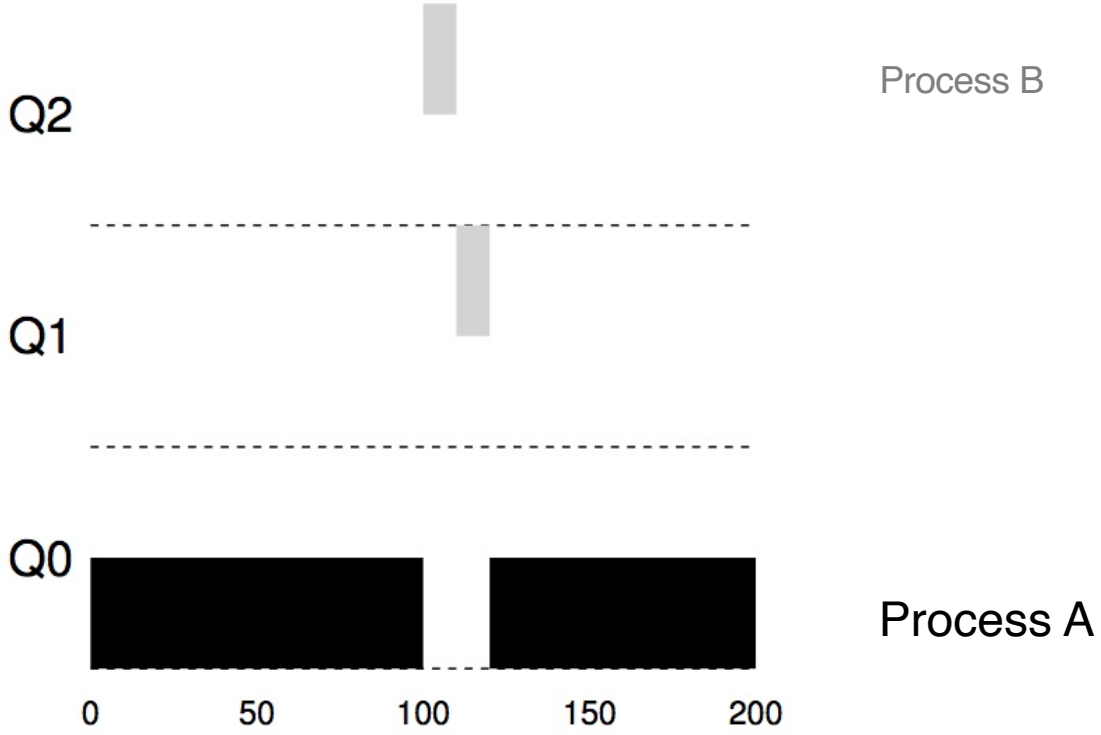
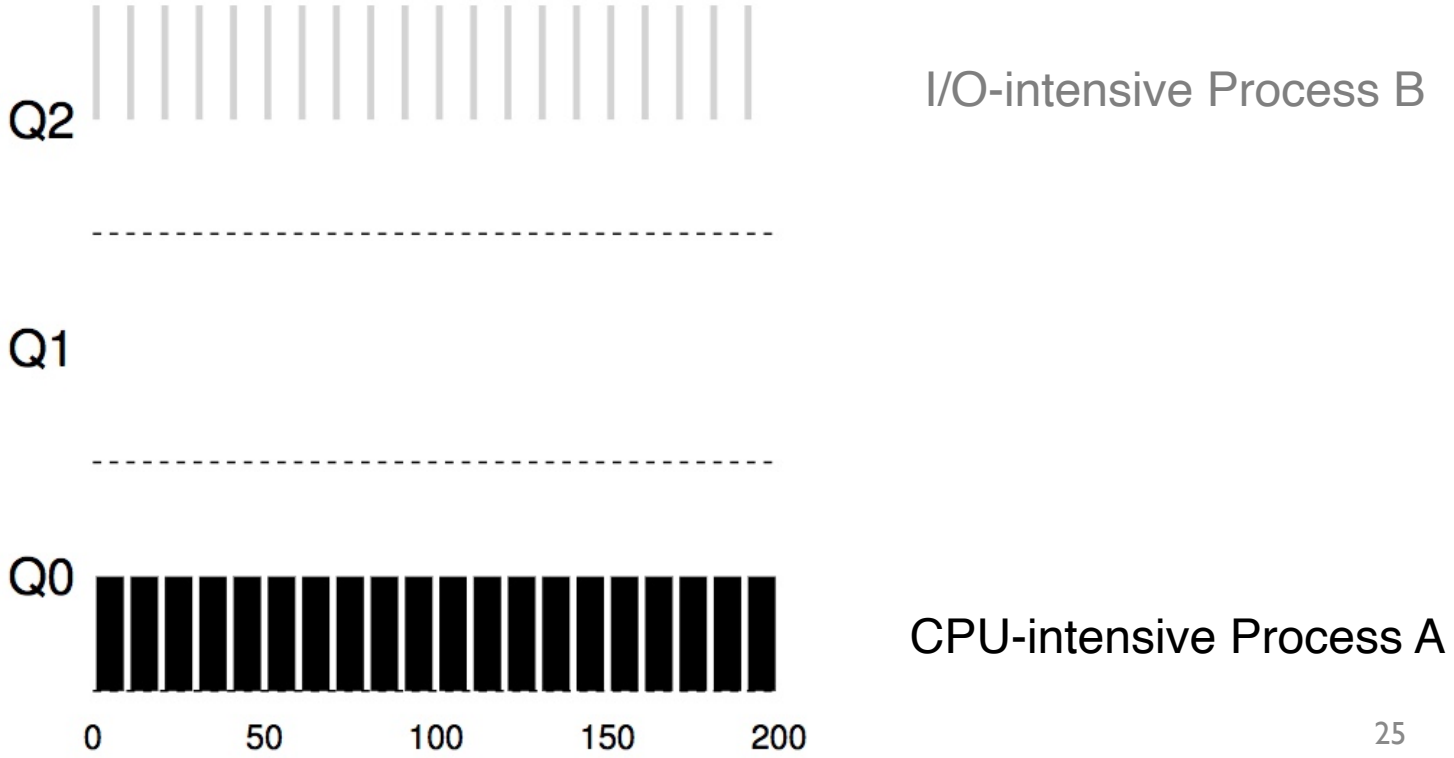


Example 3: What about I/O?

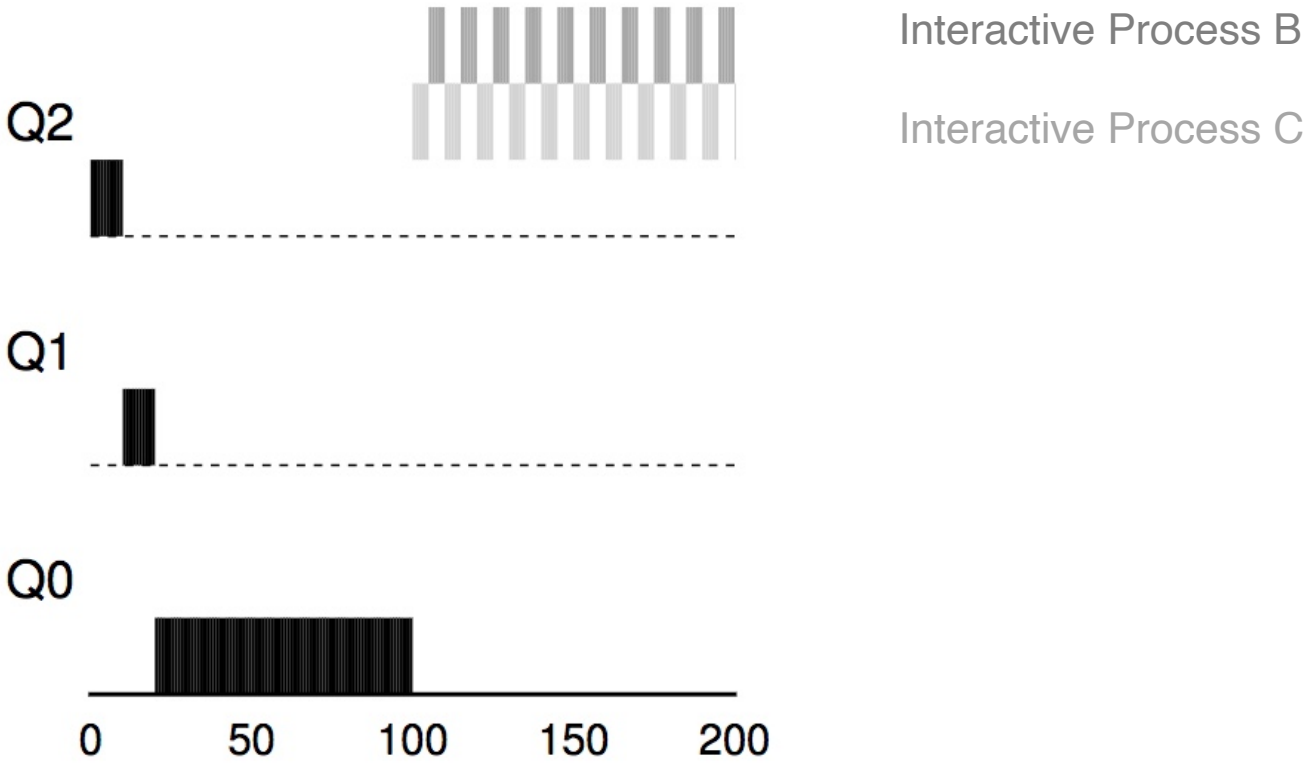
- Process A: long-running process
- Process B: I/O-intensive interactive process (each CPU burst = 1ms)

Rule 4b



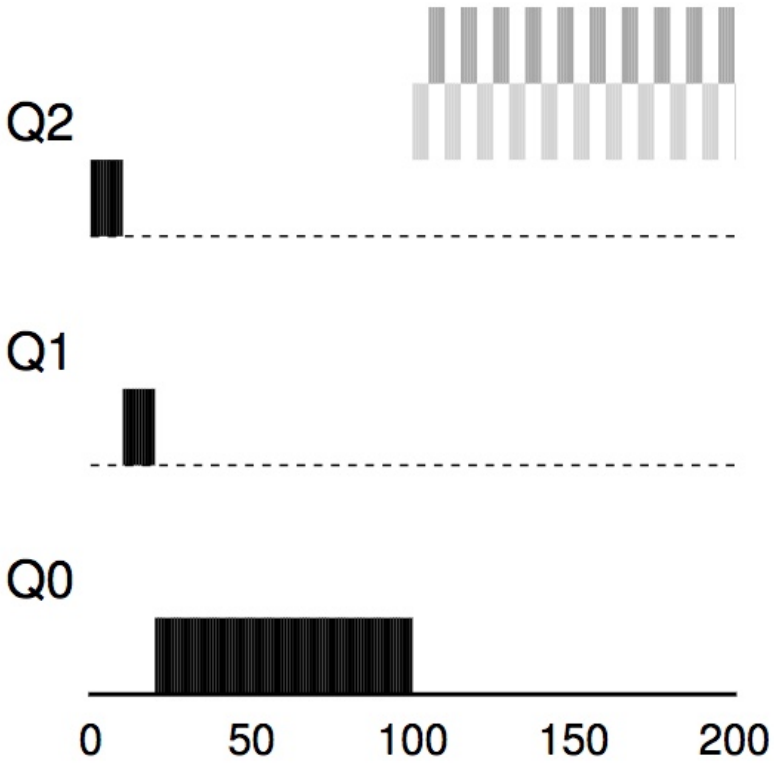
Example 4: What's the Problem?

- Process A: long-running process
- Process B + C: Interactive process



Example 4: What's the Problem?

- Process A: long-running process
- Process B + C: Interactive process



Interactive Process B

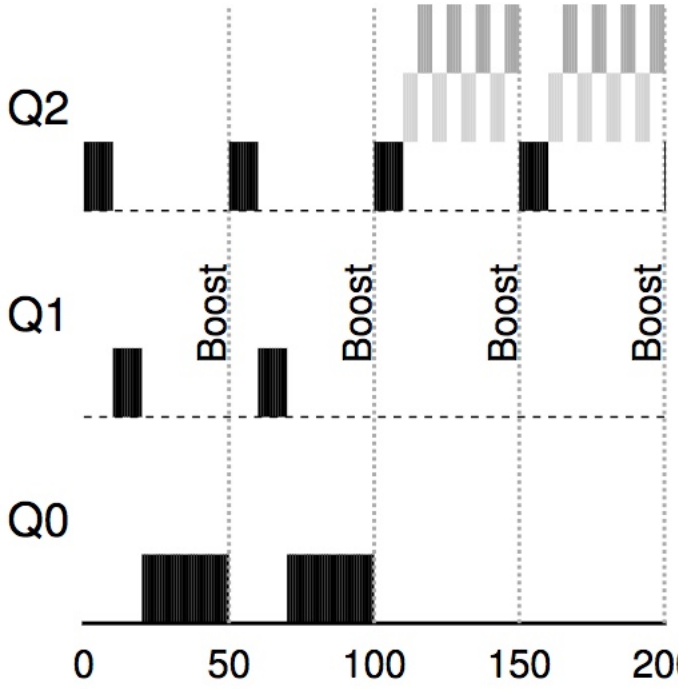
Interactive Process C

CPU-intensive Process A starves!

Attempt #2: Priority Boost

- Simple idea: Periodically boost the priority of all processes

- **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue.



Interactive Process B

Interactive Process C

CPU-intensive Process A proceeds!

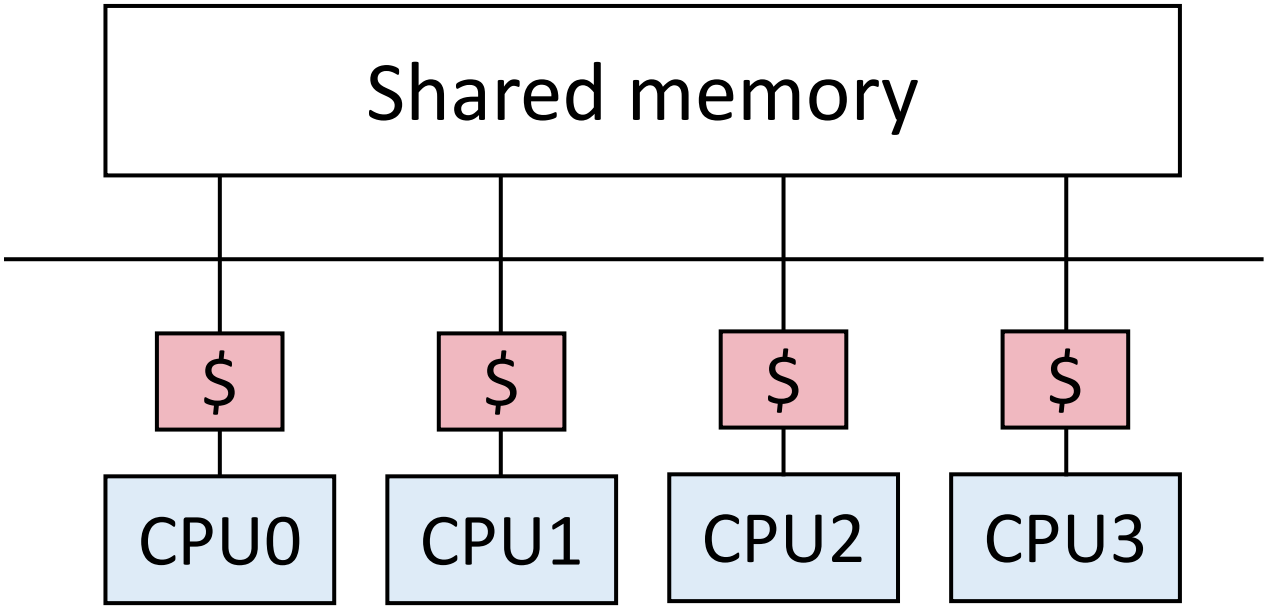
Tuning MLFQ

- MLFQ scheduler is defined by many parameters:
  - Number of queues
  - Time quantum of each queue
  - How often should priority be boosted?
  - A lot more…

- The scheduler can be configured to match the requirements of a specific system
  - Challenging and requires experience

(Advanced) Linux Scheduling

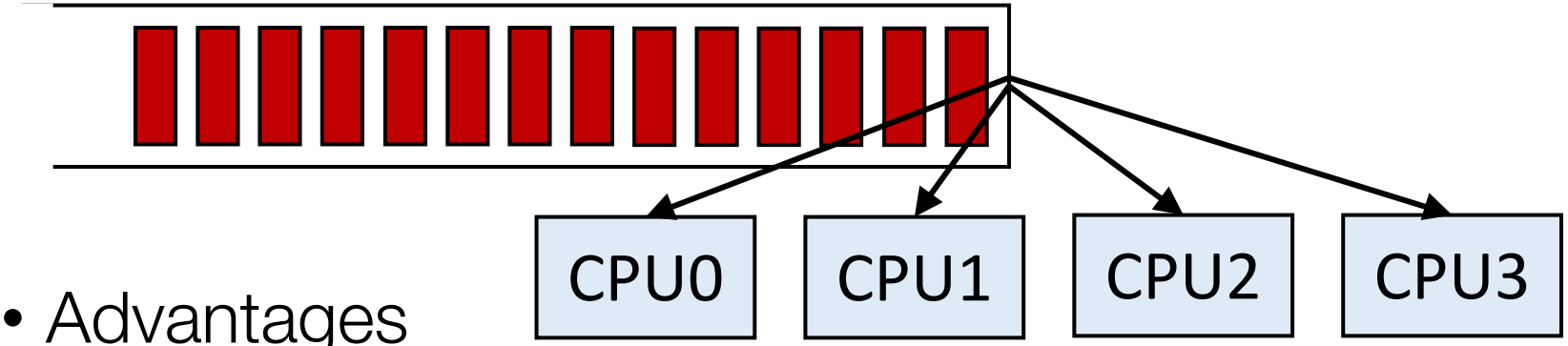
Symmetric Multiprocessing (SMP)



- Multiple CPUs
- Same access time to main memory (DRAM)
- Private CPU cache

Global Queue of Processes

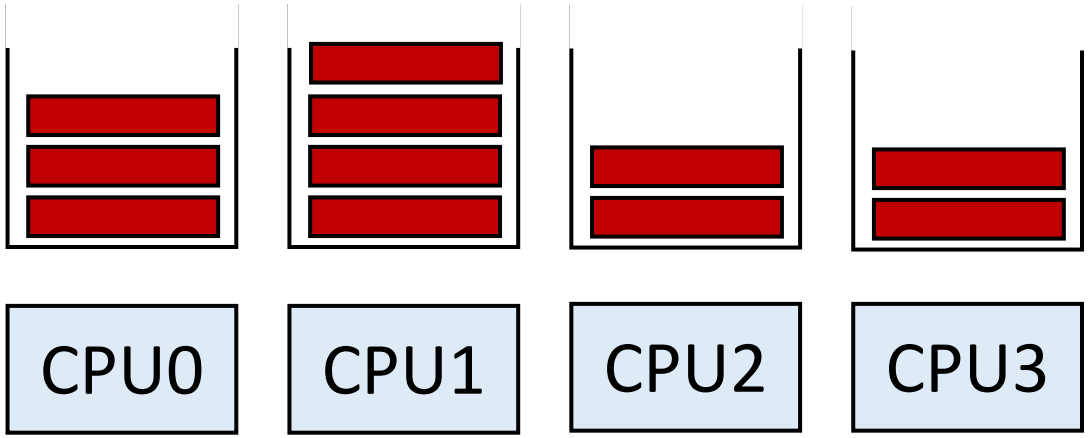
- One ready queue shared across all CPUs



- Advantages
  - Good CPU utilization
  - Fair to all processes
- Disadvantages
  - Not scalable (contention for global queue lock)
  - Poor cache locality
- Linux 2.4 uses global queue

Per-CPU queue of processes

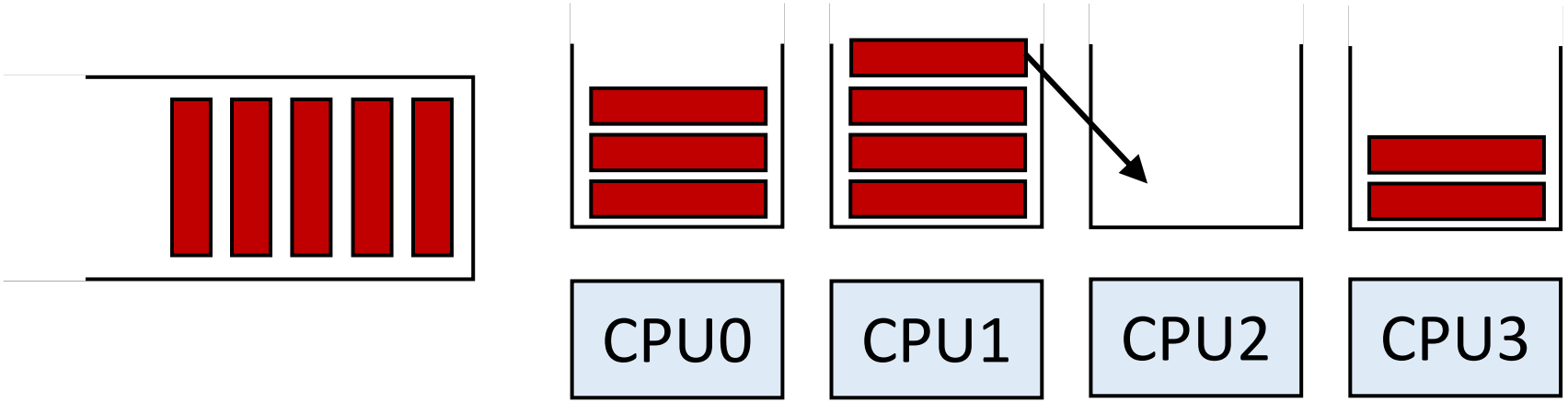
- Static partition of processes to CPUs



- Advantages
  - Easy to implement
  - Scalable (no contention on ready queue)
  - Better cache locality
- Disadvantages
  - Load imbalance (some CPUs have more processes)
    - Unfair to processes and lower CPU utilizations

Modern OSes Take Hybrid Approaches

- Use both global and per-CPU queues
- Migrate processes across per-CPU queues



- Processor affinity
  - Add process to a CPU's queue if recently run on that CPU
    - Cache state may still present

Real-Time Scheduling

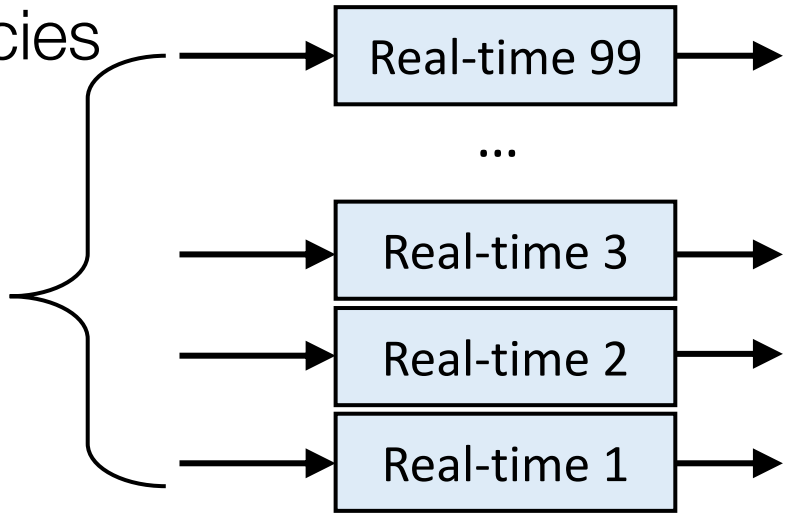
- Real-time processes have timing constraints
  - Expressed as deadlines or rate requirements
  - E.g., gaming, video/music player, autopilot

- Hard real-time systems – required to complete a critical task within a guaranteed amount of time
- Soft real-time computing – requires that critical processes receive priority over others

- Linux supports soft real-time

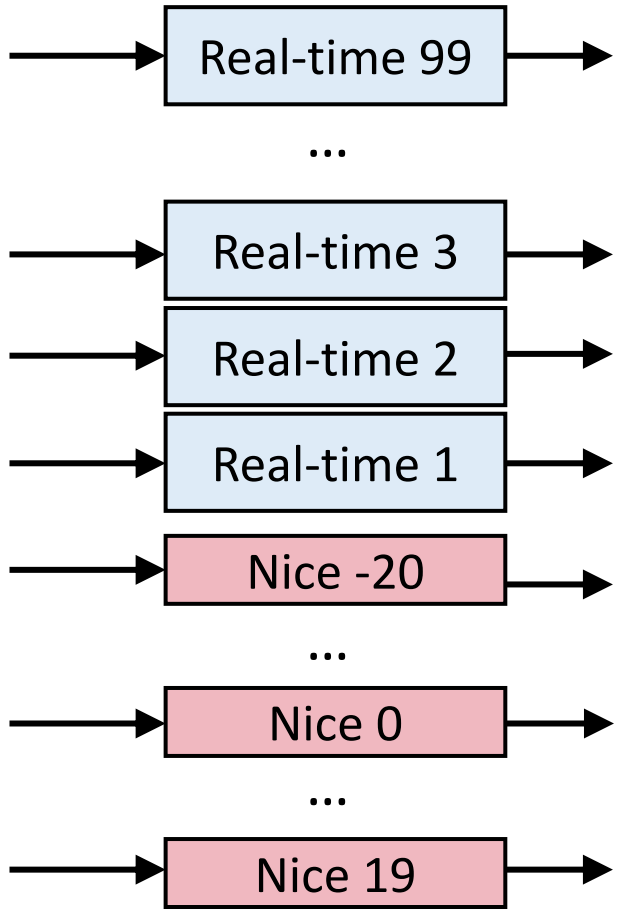
Linux: Multi-Level Queue with Priorities

- Soft real-time scheduling policies
  - `SCHED_FIFO` (FIFO)
  - `SCHED_RR` (round robin)
  - Priority over normal tasks
  - 100 static priority levels (1–99)



Linux: Multi-Level Queue with Priorities

- Soft real-time scheduling policies
  - `SCHED_FIFO` (FIFO)
  - `SCHED_RR` (round robin)
  - Priority over normal tasks
  - 100 static priority levels (1–99)
- Normal scheduling policies
  - `SCHED_NORMAL`: standard
    - `SCHED_OTHER` in POSIX
  - `SCHED_BATCH`: CPU-bound tasks
  - `SCHED_IDLE`: lower priority tasks
  - Static priority is 0
    - 40 dynamic priority levels
    - "Nice" values
- `sched_setscheduler()`, `nice()`
- See "`man 7 sched`" for detailed overview



Linux Scheduler History

- `O(N)` scheduler up to 2.4
  - Simple: global run queue
  - Poor performance on multiprocessor and large N
- `O(1)` scheduler in 2.5 & 2.6
  - Good performance: per-CPU run queue
  - Complex and error-pone logic to boost interactivity
  - No fairness guarantee
- Completely Fair Scheduler (CFS) in 2.6 and later
  - Currently default scheduler for `SCHED_NORMAL`
  - Processes get fair share of CPU
  - Naturally boosts interactivity

O(N) Scheduler (Linux 2.4)

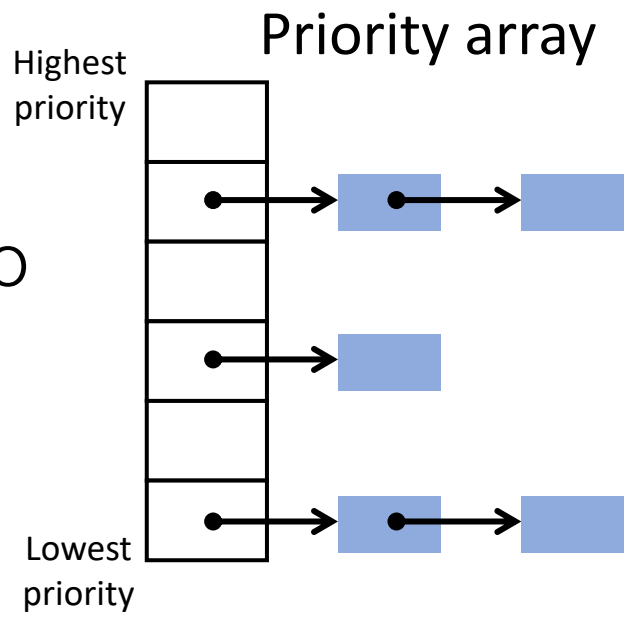
- Time is divided into epochs
- At the start of each epoch, scheduler assigns a priority to every process based on its behavior
  - Real-time processes have an absolute priority assigned to them, and are highest priority
  - Interactive processes have a dynamic priority assigned to them based on behavior in the previous epoch
  - Batch processes are given the lowest priority
- Each process' priority is used to compute a time quantum
  - Different processes can have different quantum lengths
  - Higher-priority processes generally get larger time quantums
  - When a process has completely used up its quantum, it is preempted and another process runs

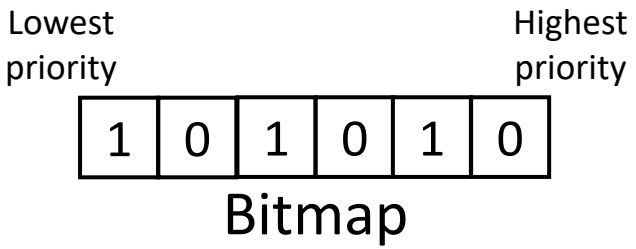
O(N) Scheduler (Linux 2.4)

- When scheduler is invoked or at start of an epoch, scheduler iterates thru all processes
  - Compute a new priority for each process
- Higher-priority processes preempt lower-priority ones
- The current epoch ends when all runnable processes have consumed their entire time quantum
- Several `O(N)` computations in the scheduler makes it scale terribly to large numbers of processes

O(1) Scheduler (Linux 2.6)

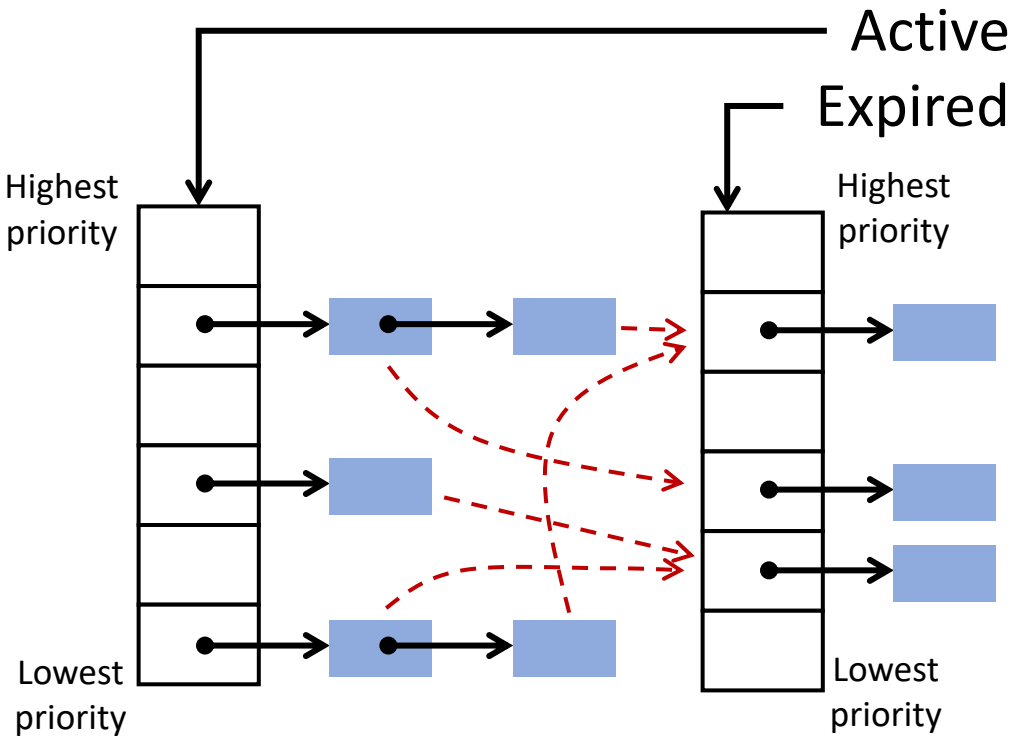
- Linux `O(1)` scheduler still includes the notion of epochs, but only informally
- Priority array + bitmap
- Find the highest-priority process to run is a constant-time operation
  - Find index of lowest 1-bit in bitmap
  - Use that index to access the priority array





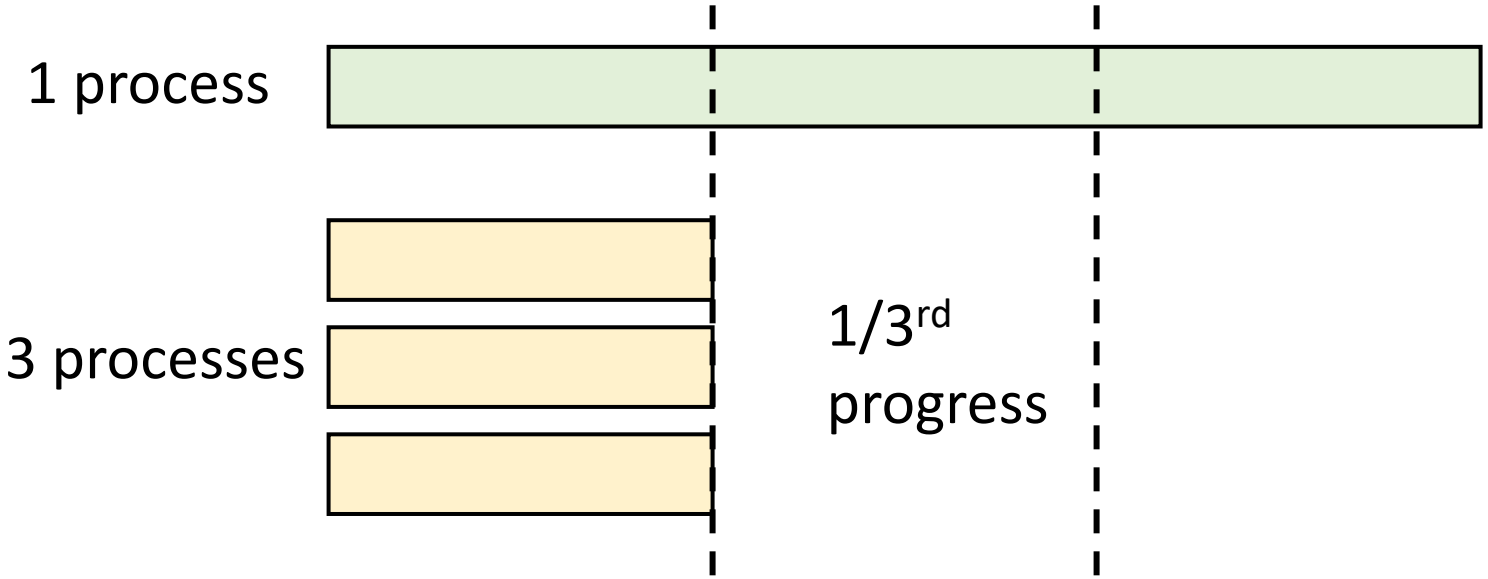
O(1) Scheduler (Linux 2.6)

- Maintains two priority arrays
  - Active array contains processes w/ remaining time
  - Expired array holds processes that have used up their quantums
- When an active process uses entire quantum, it is moved to the expired array
  - A new priority is given to that process
- When the active array is empty, the epoch is over
  - `O(1)` scheduler switches the active and expired pointers and starts over again



Ideal Fair Scheduling

- Infinitesimally small time slice
- N processes: each runs uniformly at 1/Nth rate



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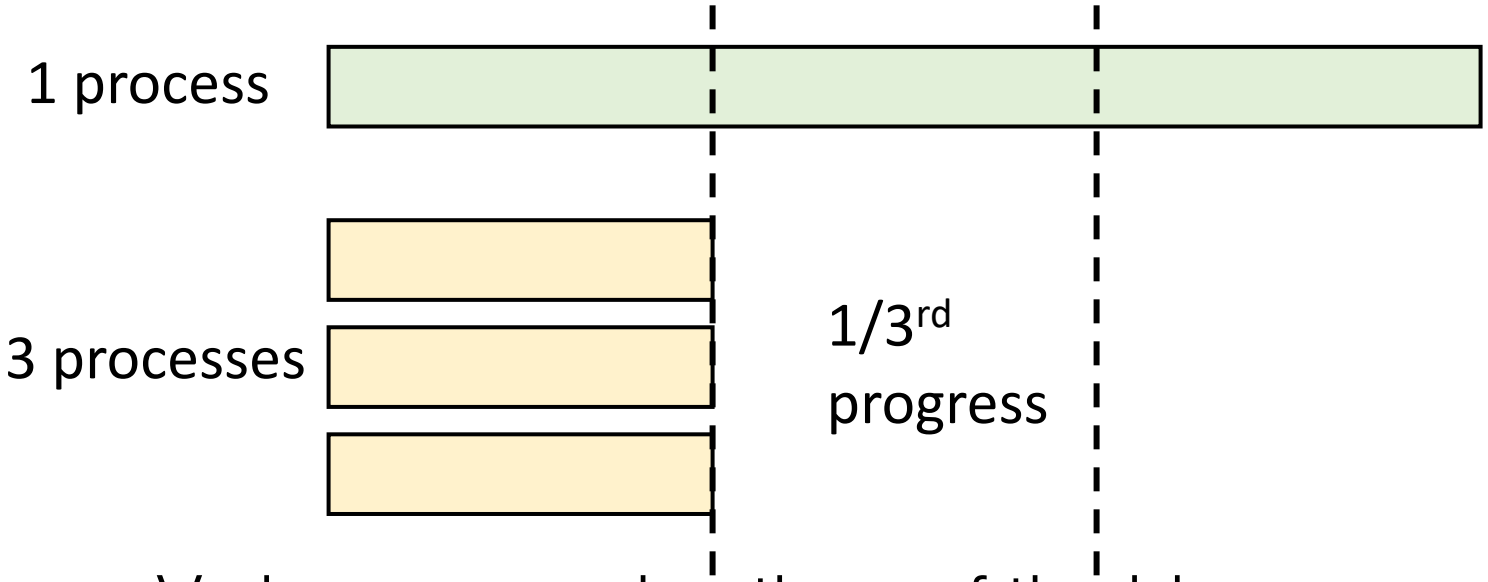


- Various approximations of the idea
  - Linux CFS
  - Lottery scheduling

Completely Fair Scheduler (Linux 2.6.23 till now)

- CFS approximates fair scheduling
  - Run each process once per schedule period T
    - `sysctl_sched_latency`
  - Time slice for process Pi: T * Wi/(Sum of all Wi)
    - `sched_slice()`

- Too many processes?
  - Lower bound on smallest time slice
    - `sysctl_sched_min_granularity`
  - Schedule latency T = lower bound * number of procs

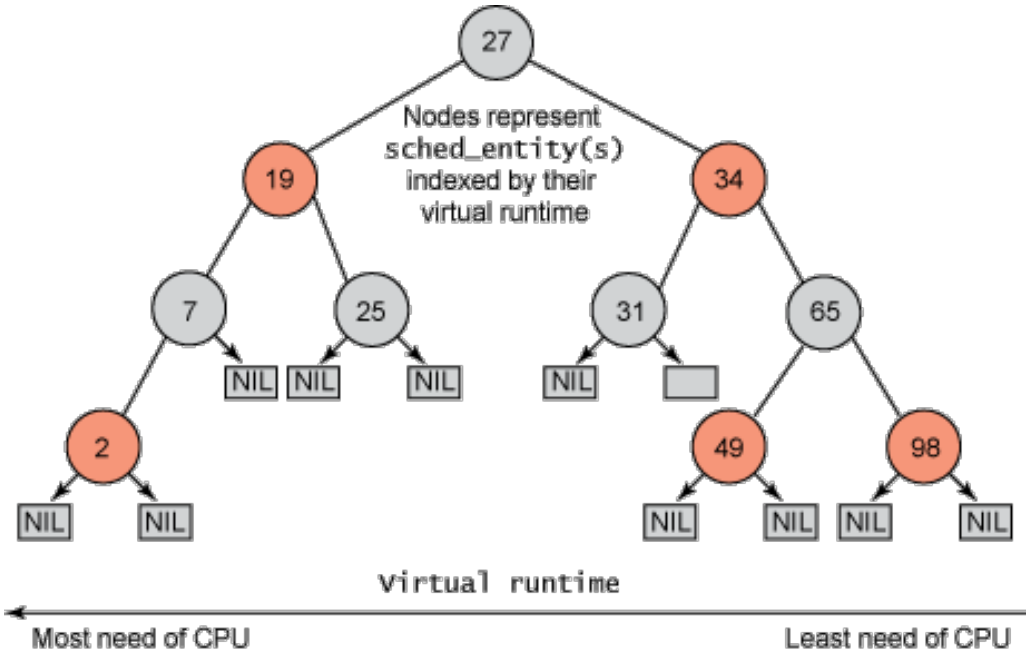
CFS: Picking the Next Process

- Pick process w/ minimum weighted vruntime so far
  - Virtual runtime:

```
task->vruntime += executed time / Wi
```

CFS: Picking the Next Process

- CFS uses a red-black tree (RB tree)
  - Balanced binary search tree (BST)
  - Ordered by `vruntime` as key
  - `O(logN)` insertion, deletion, update; `O(1)`: find min



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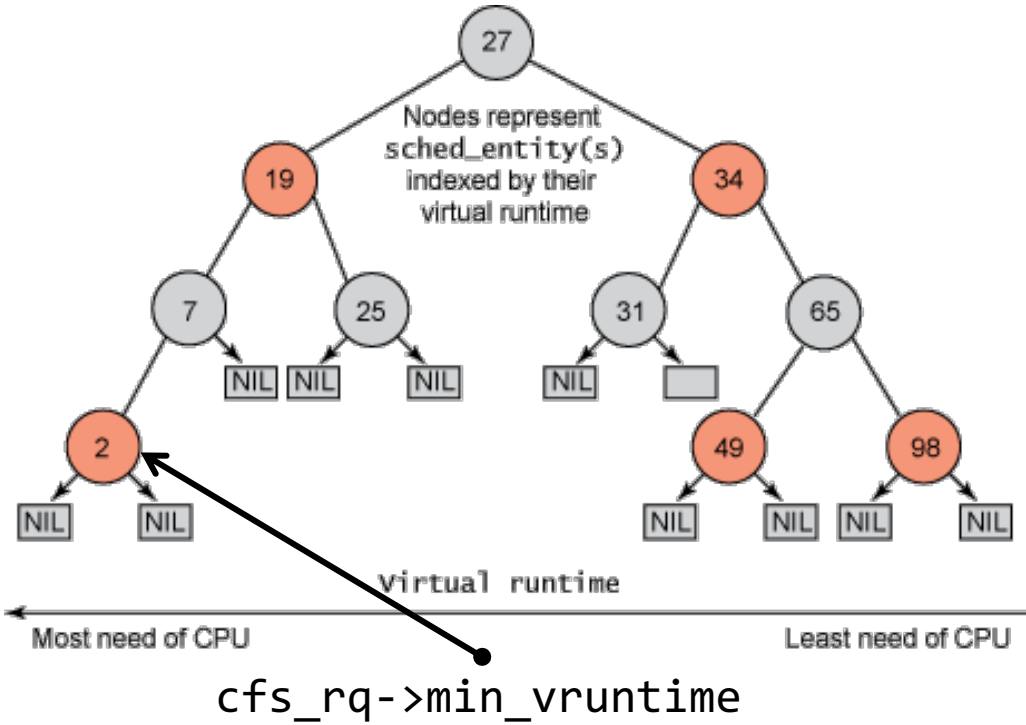
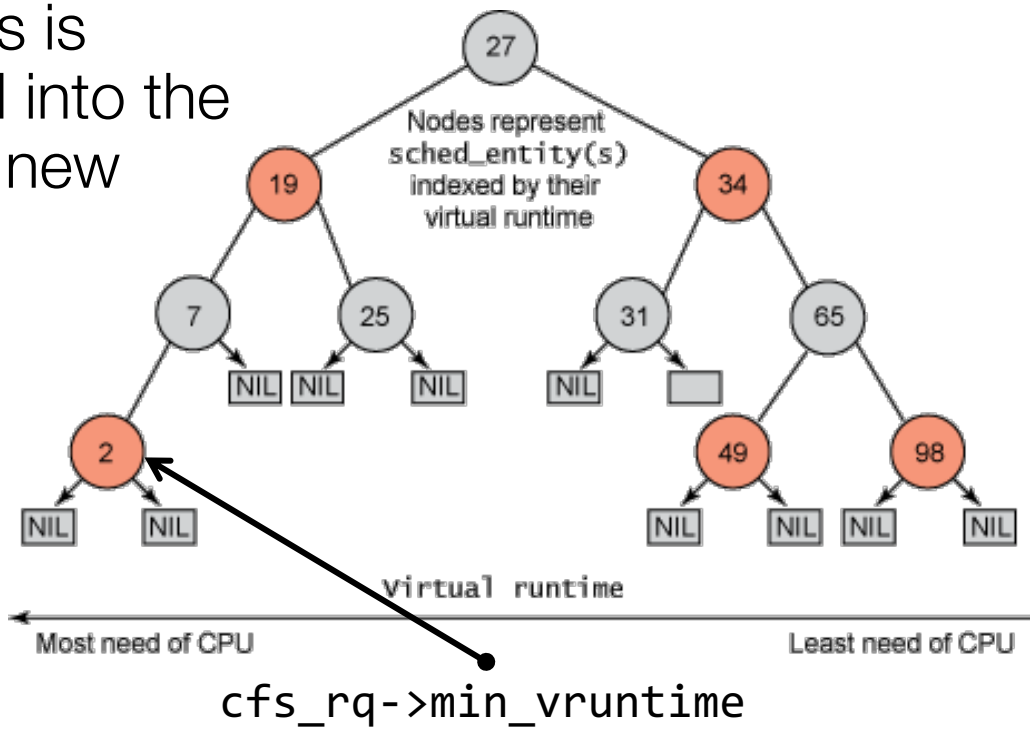
- Tasks move from left of tree to the right
- `min_vruntime` caches smallest value
- Update `vruntime` and `min_vruntime`
  - When task is added or removed
  - On every timer tick, context switch



CFS: Picking the Next Process

- Sched is invoked at context switch or at timer tick
  - Pick the left-most node w/ the lowest `vruntime`
  - If the previous process is runnable, it is inserted into the tree depending on its new `vruntime`



How CFS Handles I/O-bound Processes?

- Ideally:
  - An I/O-bound process should get higher priority and thus should get the CPU more easily (after being blocked for a while waiting for I/O)

- How CFS boosts interactivity:
  - I/O-bound processes typically have shorter CPU bursts and thus will have a low `vruntime` – higher priority

Lottery Scheduling

If time permits…

Lottery Scheduling

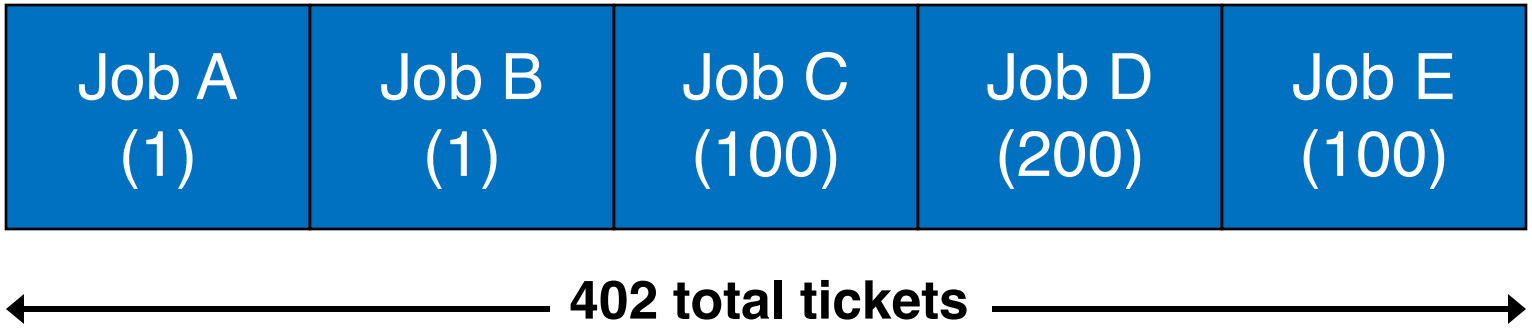
- Goal: Proportional share
  - One of the fair-share schedulers

- Approach
  - Gives processes lottery tickets
  - Whoever wins runs
  - Higher priority → more tickets

Lottery Code

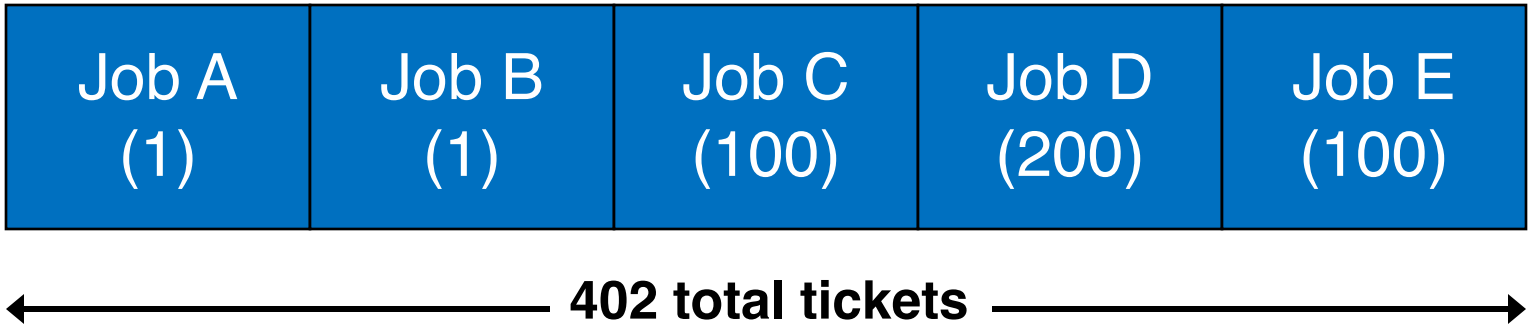
```
1   // counter: used to track if we've found the winner yet
2   int counter = 0;
3
4   // winner: use some call to a random number generator to
5   //         get a value, between 0 and the total # of tickets
6   int winner = getrandom(0, totaltickets);
7
8   // current: use this to walk through the list of jobs
9   node_t *current = head;
10
11  // loop until the sum of ticket values is > the winner
12  while (current) {
13      counter = counter + current->tickets;
14      if (counter > winner)
15          break; // found the winner
16      current = current->next;
17  }
18  // 'current' is the winner: schedule it...
```

Lottery Scheduling Example



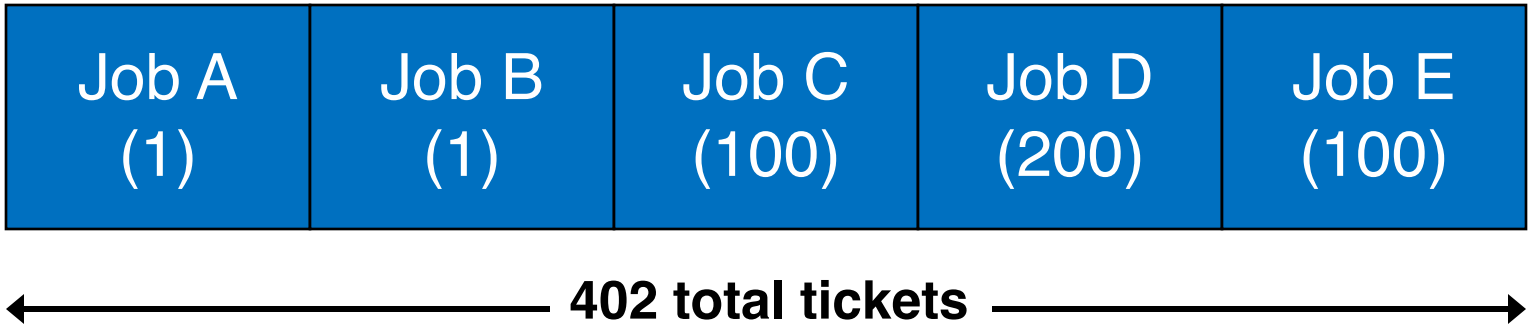
Lottery Scheduling Example

winner = random(402)

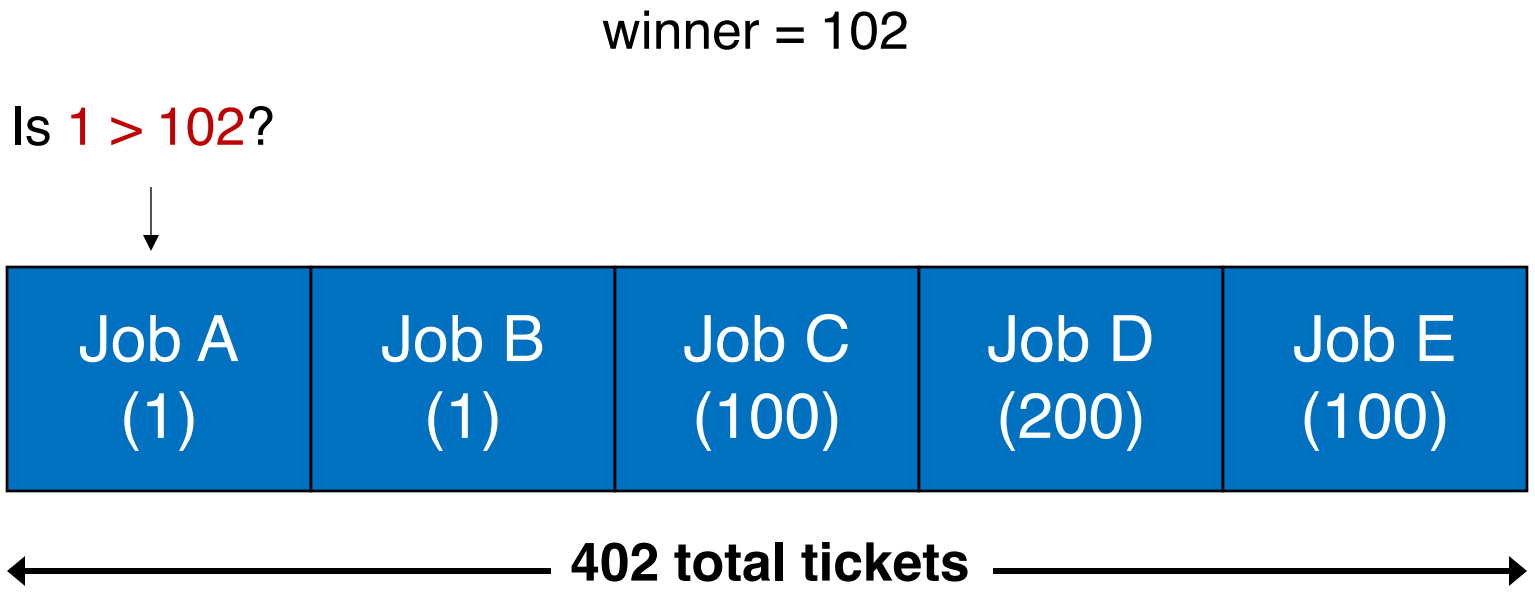


Lottery Scheduling Example

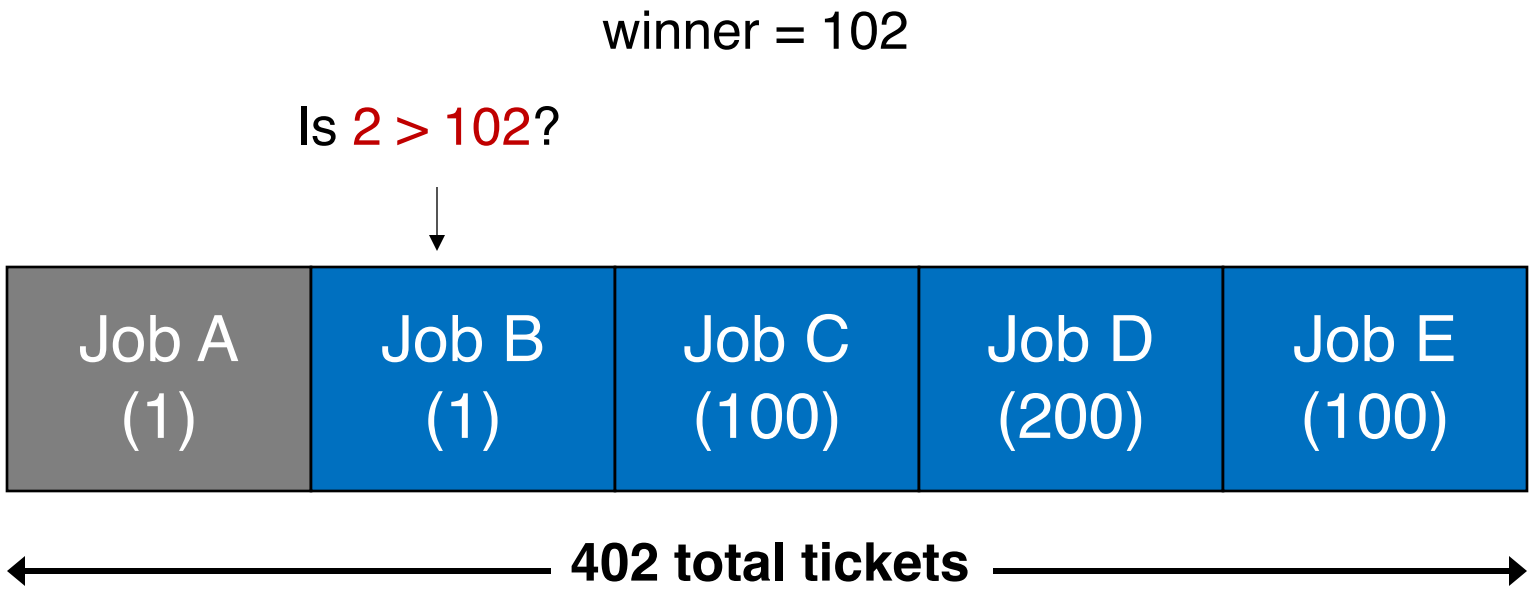
winner = 102



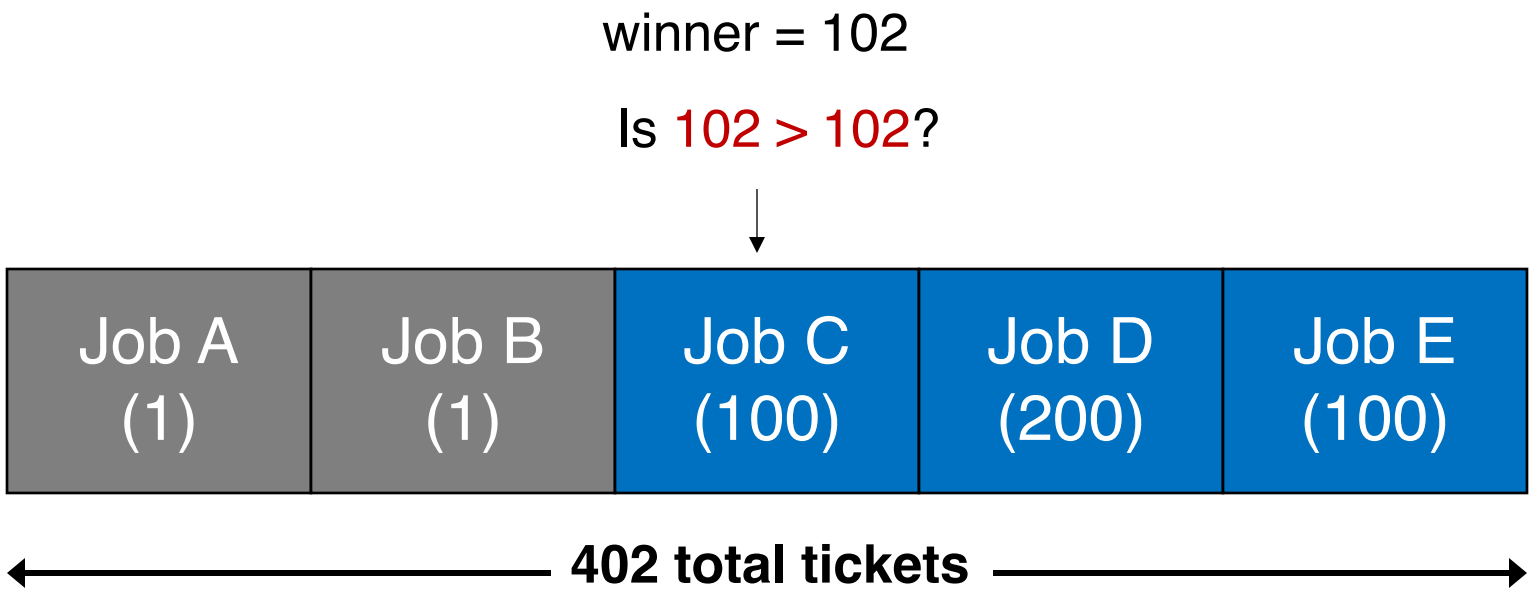
Lottery Scheduling Example



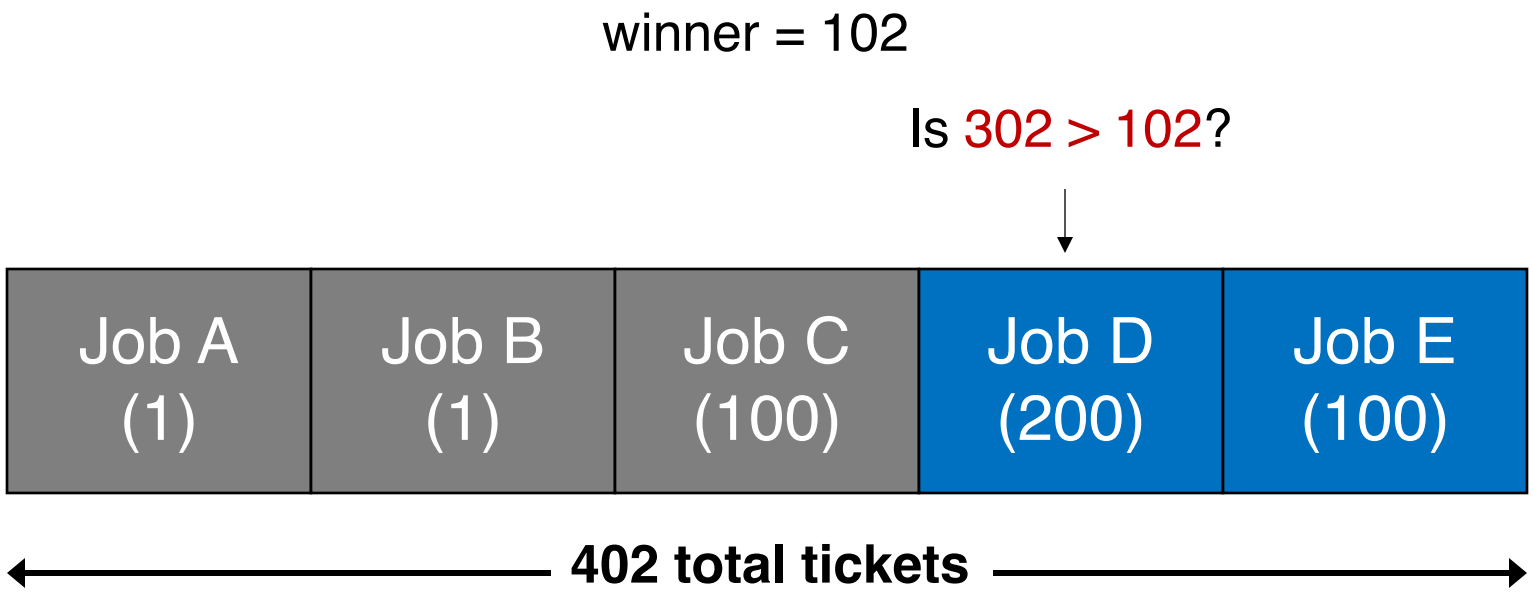
Lottery Scheduling Example



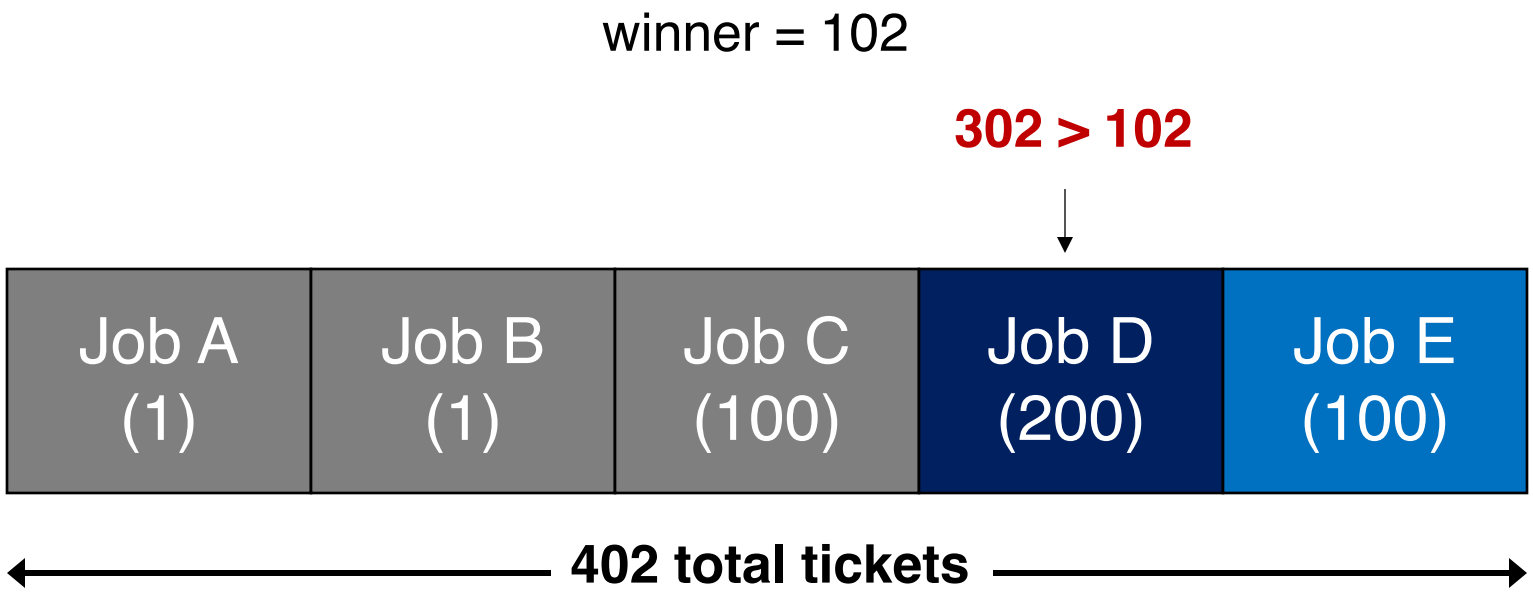
Lottery Scheduling Example



Lottery Scheduling Example



Lottery Scheduling Example



OS picks Job D to run!

Other Lottery Ideas

- Ticket transfers
- Ticket currencies
- Ticket inflation
- Read more in OSTEP
- The original lottery scheduling paper:
  - Lottery scheduling: flexible proportional-share resource management. Carl A. Waldspurger and William E. Weihl. USENIX OSDI'94