Operating Systems
CSCI 3150

Lecture 9: CPU Scheduling

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https://github.com/henryhxu/CSCI3150

Roadmap: CPU Scheduling

- Introduction
- Multi-Level Feedback Queue
- Lottery Scheduling

Introduction

Scheduling: Introduction

- 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** (i.e., they perform no I/O).
  4. The **run-time** of each job is known.

Scheduling Metrics

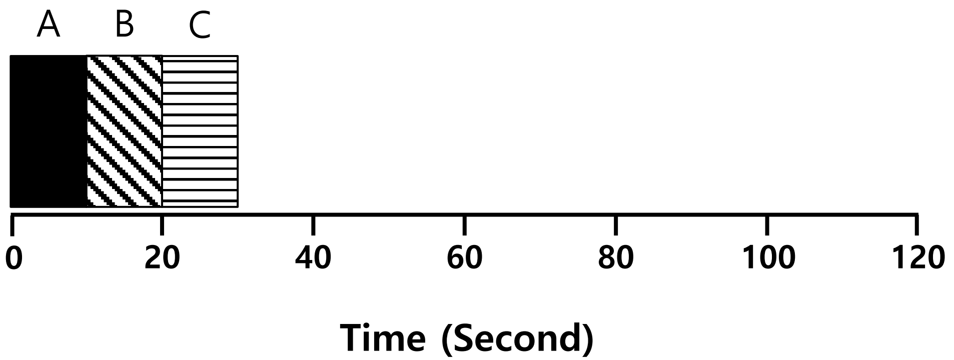
- Performance metric: Turnaround time, or completion time
  - The time at which **the job completes** minus the time at which **the job arrived** in the system.

$$T_{completion} = T_{done} - T_{arrival}$$

- Job completion time, JCT
- Another metric is fairness.
  - Performance and fairness are often at odds in scheduling.

First In, First Out (FIFO)

- First Come, First Served (FCFS)
  - Very simple and easy to implement
- Example:
  - A arrived just before B which arrived just before C.
  - Each job runs for 10 seconds.



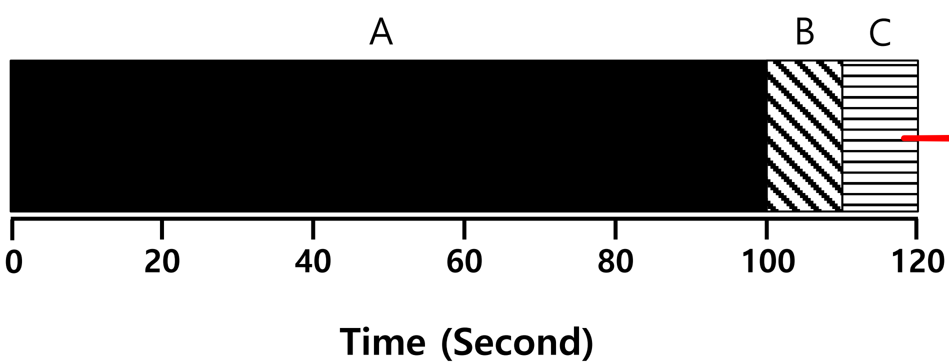
$$Average\ JCT = \frac{10 + 20 + 30}{3} = 20\ sec$$

Why FIFO is not that great? – Convoy effect

- Let's relax assumption 1: Each job **no longer** runs for the same amount of time.
- Example:
  - A arrived just before B which arrived just before C.
  - A runs for 100 seconds, B and C run for 10 each.

HoB

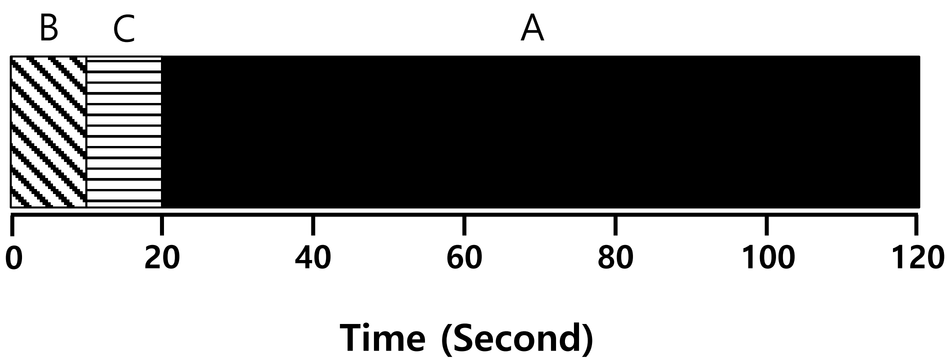
head of line blocking



$$Average\ JCT = \frac{100 + 110 + 120}{3} = 110\ sec$$

Shortest Job First (SJF)

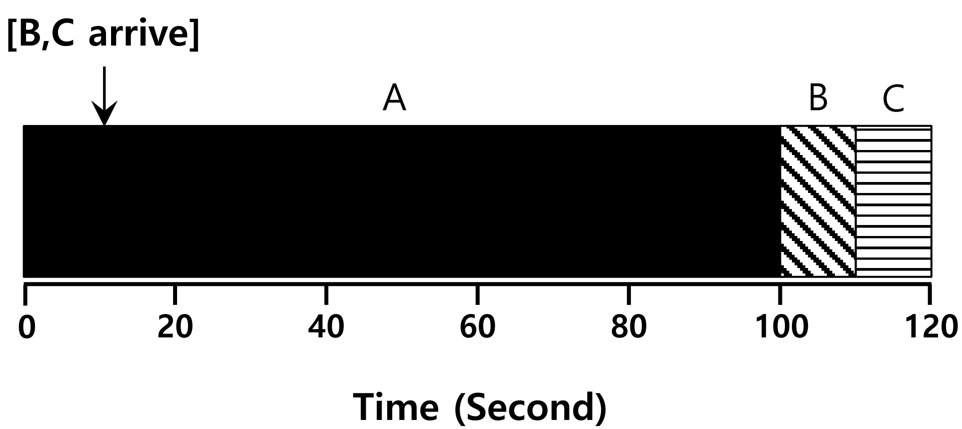
- Run the shortest job first, then the next shortest, and so on
  - Non-preemptive scheduler
- Same example:



$$Average\ JCT = \frac{10 + 20 + 120}{3} = 50\ sec$$

SJF with Late Arrivals from B and C

- Let's relax assumption 2: Jobs can arrive at any time.
- Example:
  - A arrives at t=0 and needs to run for 100 seconds.
  - B and C arrive at t=10 and each needs to run for 10 seconds



$$\boldsymbol{Average\ JCT = \frac{100 + (110 - 10) + (120 - 10)}{3} = 103.33\ sec}$$

Shortest Time-to-Completion First (STCF)

- Add preemption to SJF
  - Also known as Preemptive Shortest Job First (PSJF)

shortest remaining time first

SRTF

- When a new job enters the system:
  - Determine the remaining times of all jobs
  - Schedule the job which has the least time left

Shortest Time-to-Completion First (STCF) SRTF

- Example:
  - A arrives at t=0 and needs to run for 100 seconds.
  - B and C arrive at t=10 and each needs to run for 10 seconds

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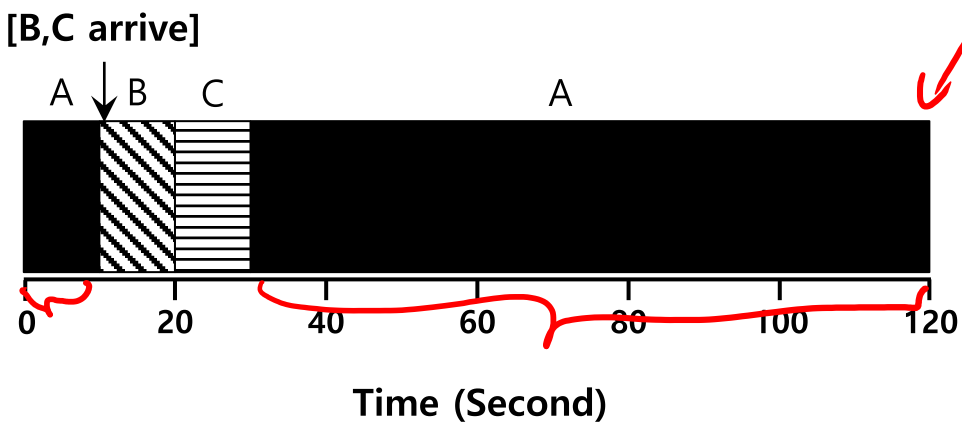


A B C

$$Average\ JCT = \frac{(120 - 0) + (20 - 10) + (30 - 10)}{3} = 50\ sec$$

New scheduling metric: Response time

- The time from **when the job arrives** to the **first time it is scheduled**.

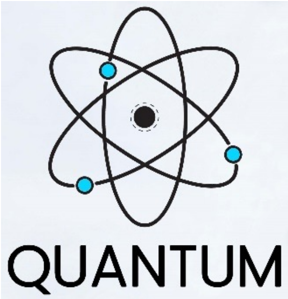
$$T_{response} = T_{firstrun} - T_{arrival}$$

  - STCF and related disciplines are not particularly good for response time.

How can we build a scheduler that is sensitive to response time?

Round Robin (RR) Scheduling

- Time slice:
  - Run a job for a time slice and then switch to the next job in the **run queue** until all jobs are finished.
    - Time slice is sometimes also called a scheduling quantum.



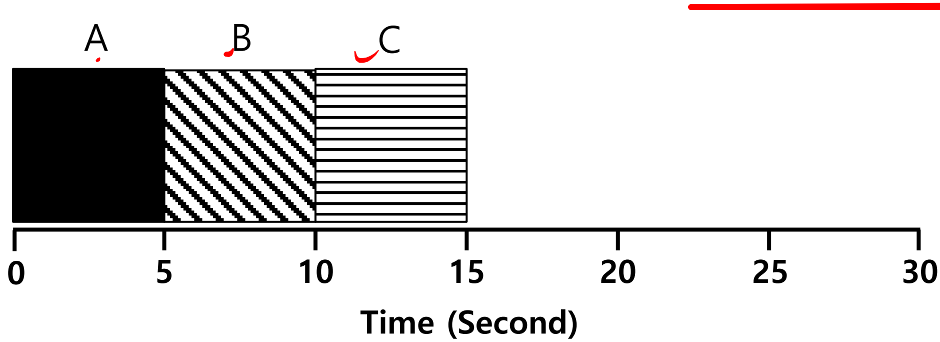
  - The length of a time slice must be *a multiple of* the timer-interrupt period.

RR is fair, but performs poorly on metrics such as JCT

RR Scheduling Example

- A, B and C arrive at the same time.
- They each wishes to run for 5 seconds.

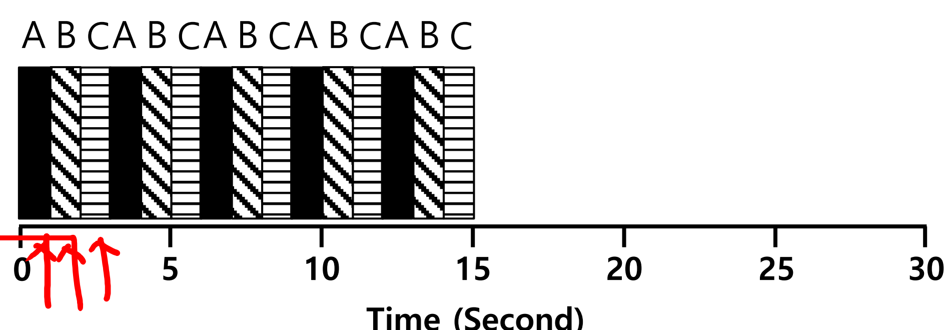
JCT=10S



SJF (Bad for Response Time)

$$T_{average\ response} = \frac{0+5+10}{3} = 5sec$$

What about JCT?



RR with a time-slice of 1sec (Good for Response Time)

$$T_{average\ response} = \frac{0+1+2}{3} = 1sec$$

Length of the time slice is critical

- The shorter time slice
  - Better response time
  - But the cost of context switching will dominate overall performance.

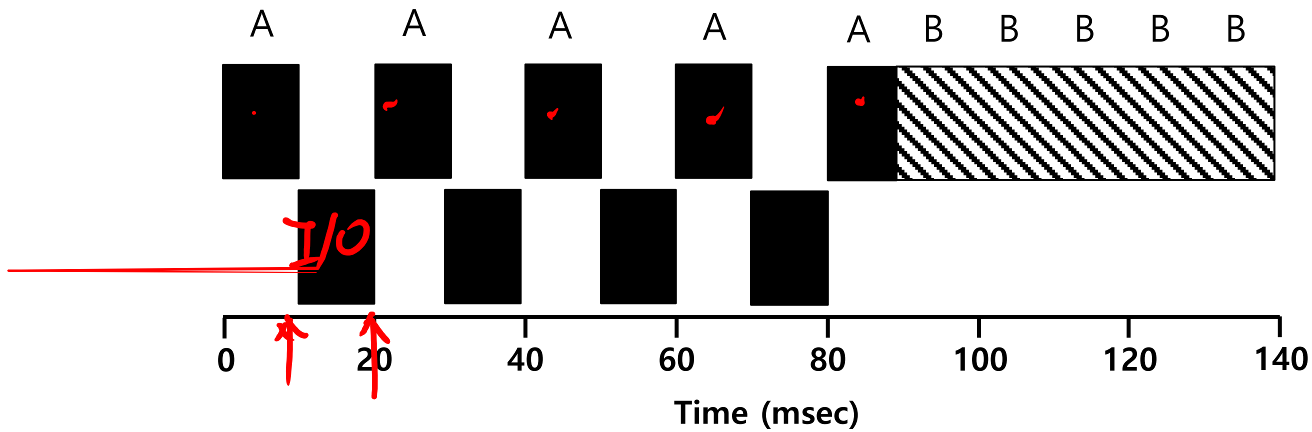
- The longer time slice
  - Amortize the cost of switching
  - Worse response time

Deciding on the length of the time slice presents a trade-off to a system designer

Incorporating I/O

- Let's relax assumption 3: All programs perform I/O
- Example:
  - A and B need 50ms of CPU time each.
  - A runs for 10ms and then issues an I/O request
    - I/Os takes 10ms each
  - B simply uses the CPU for 50ms and performs no I/O
  - The scheduler runs A first, then B

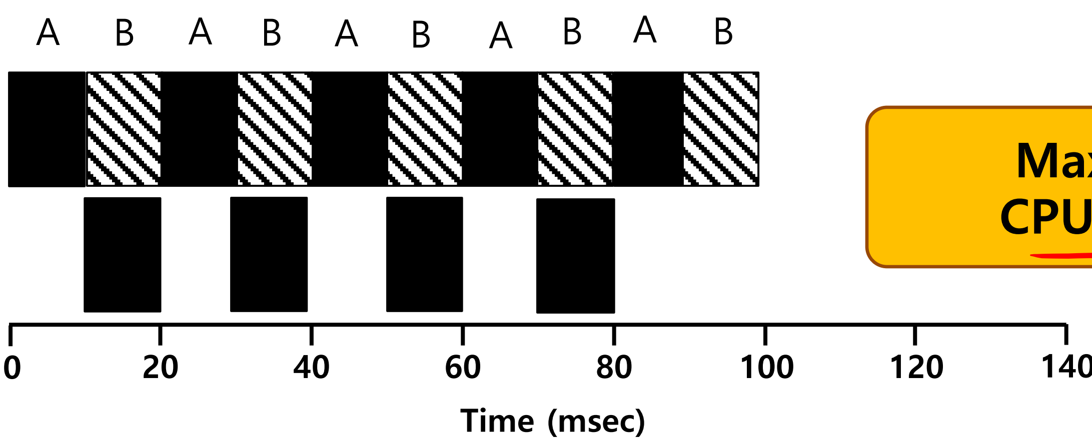
Incorporating I/O (Cont.)



Poor Use of Resources

CPU

I/O →



Overlap Allows Better Use of Resources

Maximize the CPU utilization

Incorporating I/O (Cont.)

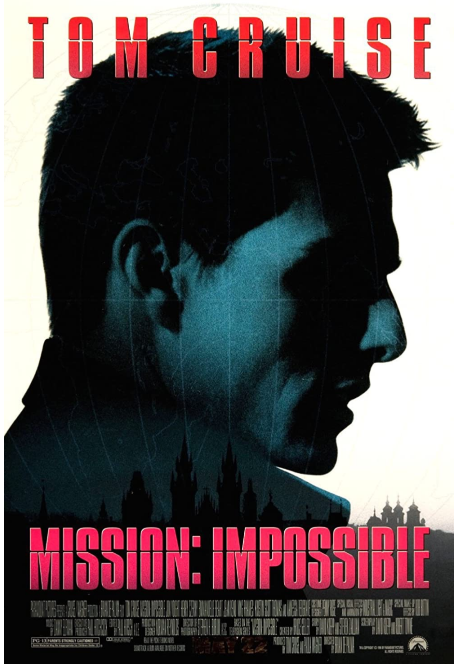
- When a job initiates an I/O request
  - The job is blocked waiting for I/O completion.
  - The scheduler should schedule jobs on the CPU.

- When the I/O completes
  - An interrupt is raised.
  - The OS moves the process from the wait to the ready state.

Multi-Level Feedback Queue

Motivation

- In reality, an OS does not know how long a job needs to run for!
  - Do you know how long you'll use the Web browser or game for?
- But we still want to schedule jobs well!
- Is it possible to still design a good scheduler without any prior knowledge of job's running time?
  - Optimize **JCT** → Run shorter jobs first
  - Also **response time**
  - **"huh?"**



MLFQ: Key idea

- Upon arrival, each job is assumed to be a short, latency-sensitive job
  - Thus it should be scheduled right away with the highest priority for better response time.
- If the job keeps running
  - It's obvious that it's not a short job anymore, and more likely to be a long or loong or looong job
  - Decrease its priority level, so other (shorter) jobs can run first for better JCT

We can be wrong at the beginning, but that's a necessary small price to pay for practicality

MLFQ: Basic Rules

- MLFQ has a number of distinct **queues**.
  - Each queues is assigned a different priority level.

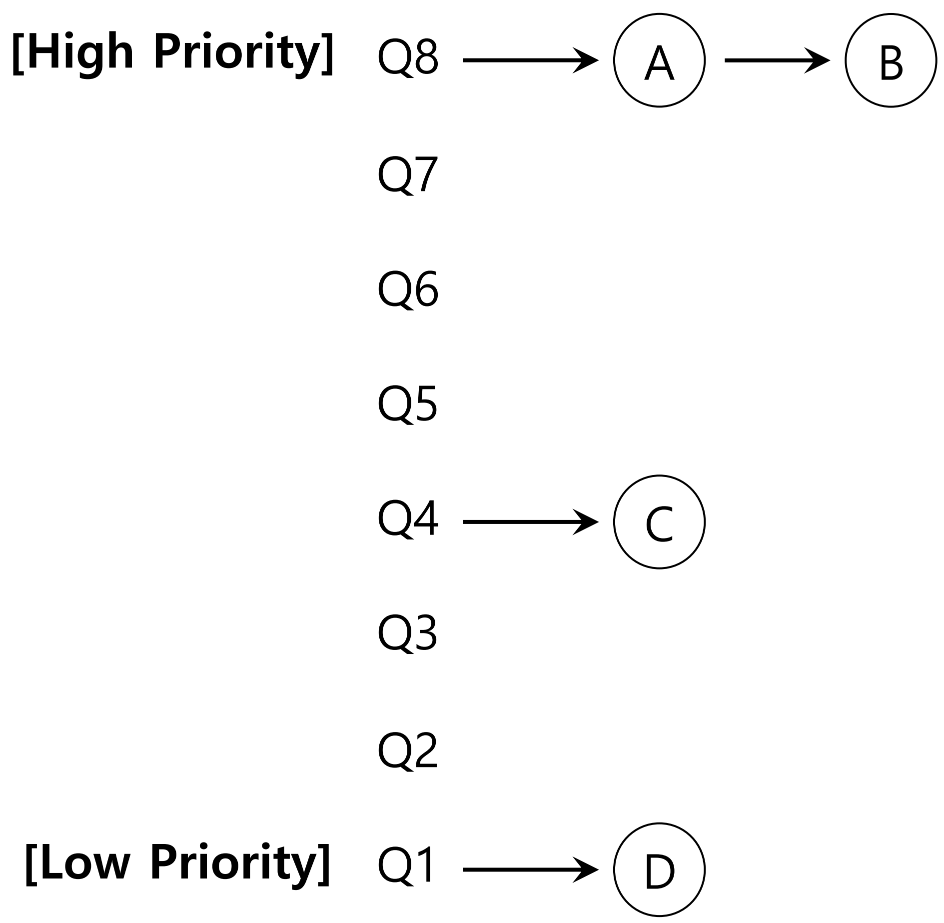
- A job that is ready to run is on a single queue.
  - A job **on a higher queue** is chosen to run.
  - Use round-robin scheduling among jobs in the same queue

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

MLFQ: Basic Rules (Cont.)

- MLFQ varies the priority of a job based on its observed behavior.
- Example:
  - A job repeatedly relinquishes the CPU while waiting IOs → Keep its priority high
  - A job uses the CPU intensively for long periods of time → Reduce its priority.

MLFQ Example



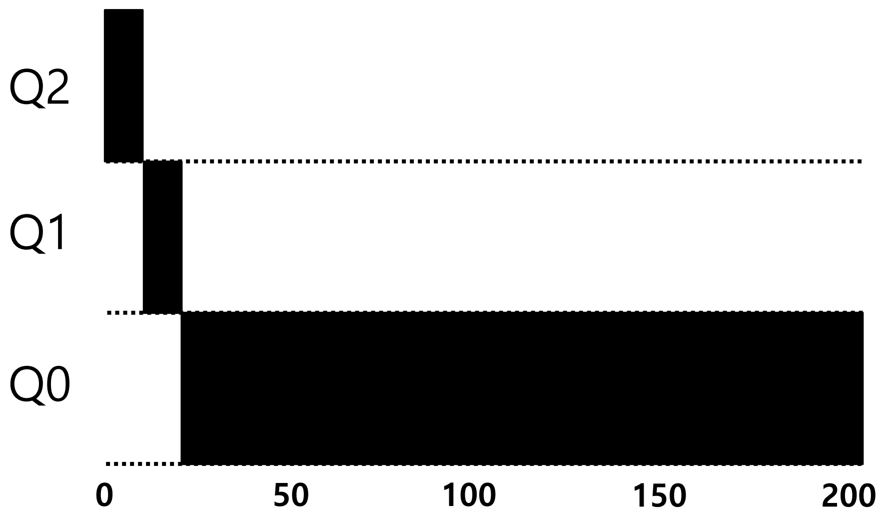
MLFQ: How to Change Priority

- MLFQ priority adjustment:
  - **Rule 3**: When a job enters the system, it is placed at the highest priority
  - **Rule 4a**: If a job uses up an entire time slice while running, its priority is reduced (i.e., it moves down on queue).
  - **Rule 4b**: If a job gives up the CPU before the time slice is up, it stays at the same priority level

In this manner, MLFQ approximates SJF

Example 1: A Single Long-Running Job

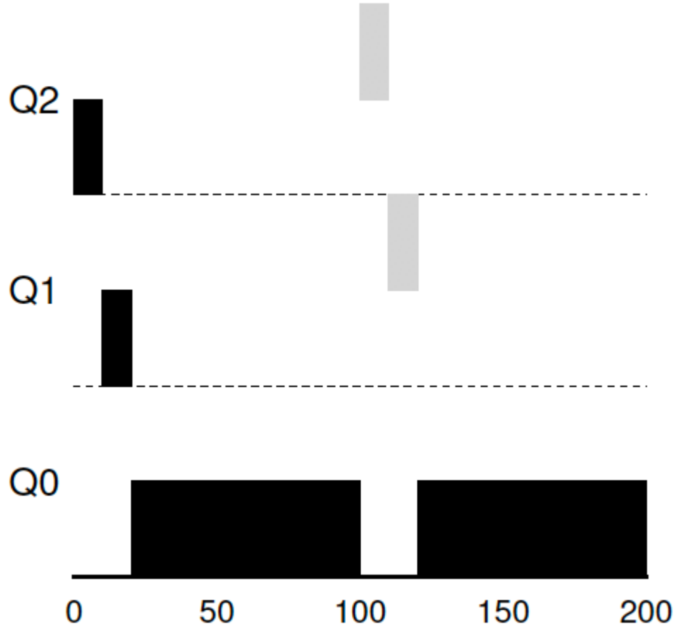
- A three-queue scheduler with time slice 10ms



Long-running Job Over Time (ms)

Example 2: Along Came a Short Job

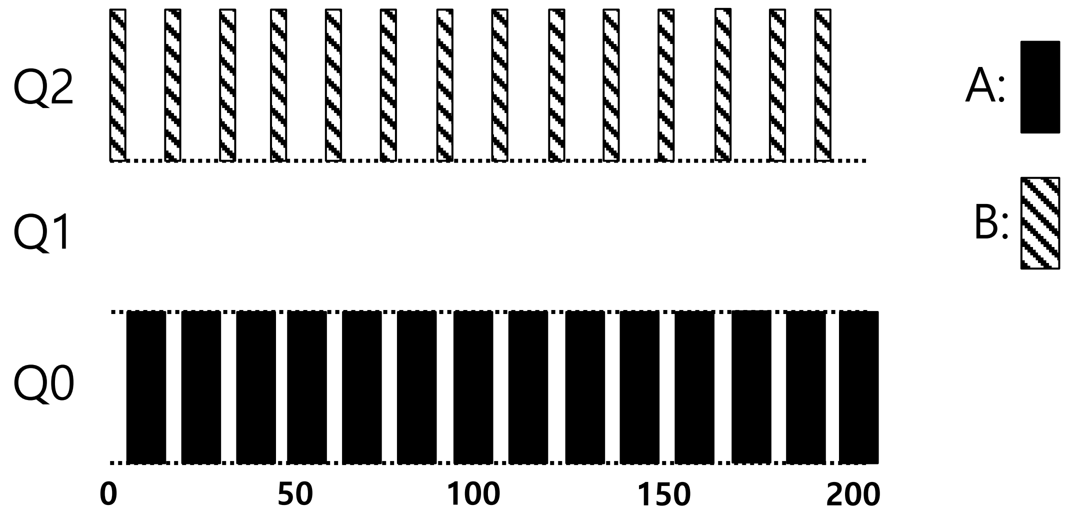
- Assumption:
  - **Job A**: A long-running CPU-intensive job
  - **Job B**: A short-running interactive job (20ms runtime)
  - A has been running for some time, and then B arrives at time T=100.



Along Came An Interactive Job (ms)

Example 3: What About I/O?

- Assumption:
  - **Job A**: A long-running CPU-intensive job
  - **Job B**: An interactive job that needs CPU only for 1ms before performing an I/O



A Mixed I/O-intensive and CPU-intensive Workload (msec)

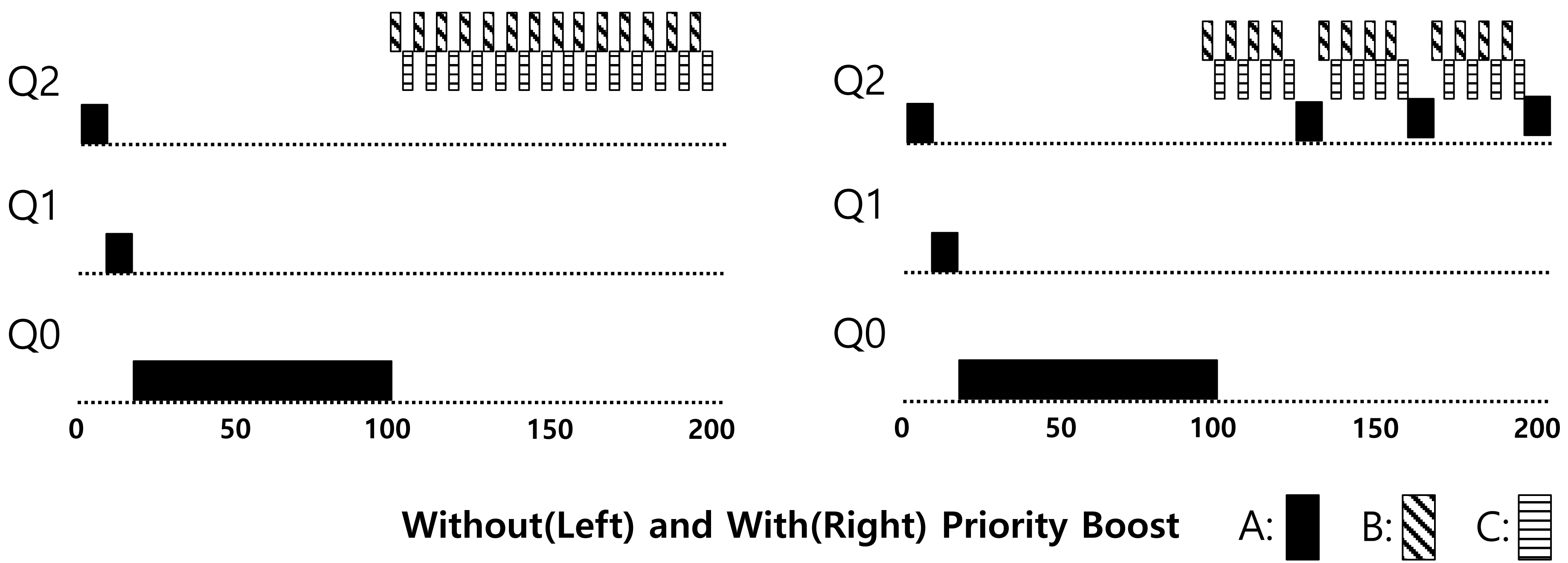
The MLFQ approach keeps an interactive job at the highest priority

Problems with the Basic MLFQ

- Starvation
  - If there are “too many” interactive jobs in the system.
  - Lon-running jobs will never receive any CPU time.
- Game the scheduler, or “cheat”
  - After running 99% of a time slice, issue an I/O operation.
  - The job gain a higher percentage of CPU time.
- A program may change its behavior over time
  - CPU bound → I/O process

The Priority Boost

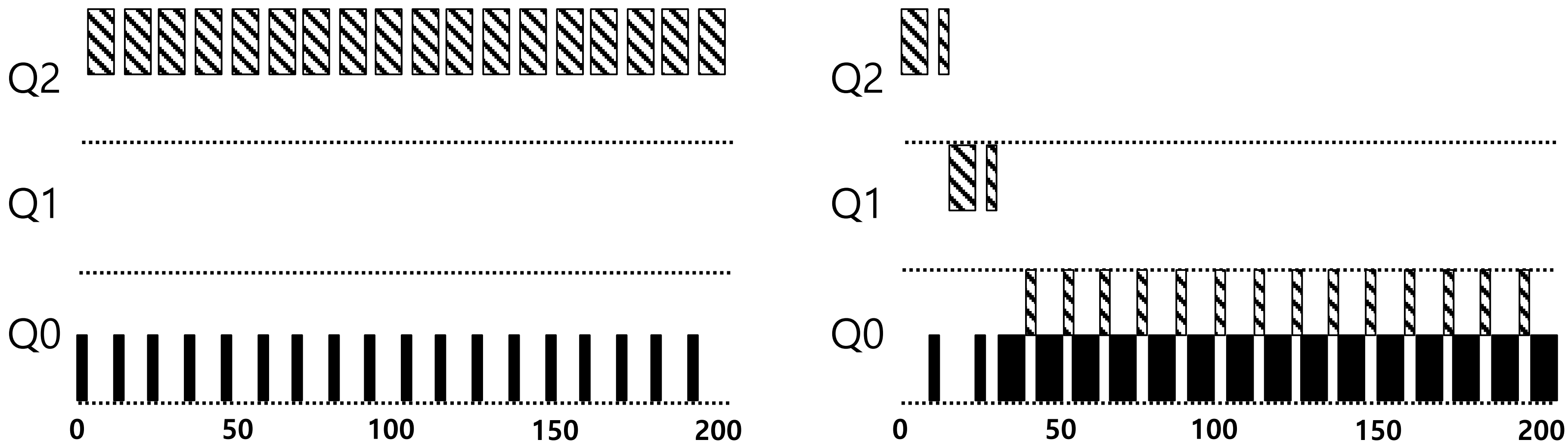
- **Rule 5:** After some time period S, move all jobs in the system to the top queue.
  - Example:
    - A long-running job (A) with two short-running interactive jobs (B, C)



Without(Left) and With(Right) Priority Boost

Better Accounting

- How to prevent jobs from gaming our scheduler?
- Solution:
  - **Rule 4** (Rewrite Rules 4a and 4b): 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 on queue).

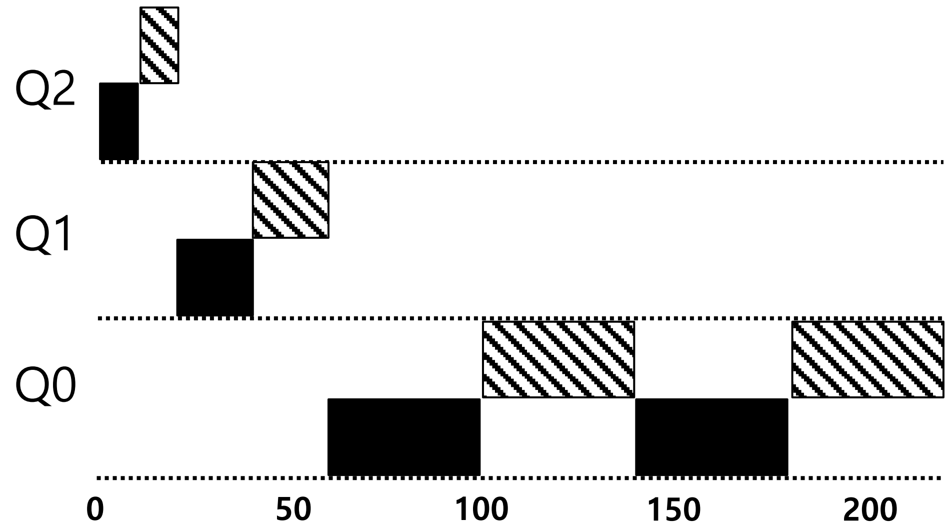


Without(Left) and With(Right) Gaming Tolerance

Tuning MLFQ And Other Issues

Lower Priority, Longer Quanta

- High-priority queues → Short time slices
  - E.g., 10 or fewer milliseconds
- Low-priority queue → Long time slices
  - E.g., 100 milliseconds



Example) 10ms for the highest queue, 20ms for the middle, 40ms for the lowest

MLFQ implementation: on Solaris

- For the Time-Sharing scheduling class (TS)
  - 60 Queues
  - Slowly increasing time-slice length
    - The highest priority: 20msec
    - The lowest priority: A few hundred milliseconds
  - Priorities boosted around every 1 second or so.

MLFQ: Summary

- The refined set of MLFQ rules:
  - **Rule 1:** If Priority(A) > Priority(B), A runs (and B doesn't).
  - **Rule 2:** If Priority(A) = Priority(B), A and B run in RR.
  - **Rule 3:** When a job enters the system, it is placed at the highest priority.
  - **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 (i.e., it moves down one queue).
  - **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue.
- Beauty of MLFQ
  - It does not require prior knowledge on the CPU usage of a process.

Lottery Scheduling, Fair-share

Proportional Share Scheduler

- Fair-share scheduler
  - Guarantee that each job obtain *a certain percentage* of CPU time.
  - Not optimized for JCT or response time

Basic Concept

- Tickets
  - Represents a scheduling opportunity
  - The percentage of tickets represents a process's share of the system resource in question.

- Example
  - There are two processes, A and B.
    - Process A has 75 tickets → receive 75% of the CPU
    - Process B has 25 tickets → receive 25% of the CPU

Lottery scheduling

- The scheduler picks <u>a winning ticket</u>
  - Load the state of that *winning process* and runs it.
- Example
  - There are 100 tickets
    - Process A has 75 tickets: 0 ~ 74
    - Process B has 25 tickets: 75 ~ 99

Scheduler's winning tickets:	63	85	70	39	76	17	29	41	36	39	10	99	68	83	63
Resulting scheduler:	A	B	A	A	B	A	A	A	A	A	A	B	A	B	A

The longer these two jobs compete,
The more likely they are to achieve the desired percentages.

Ticket Mechanisms

- Ticket currency
  - A user allocates tickets among their own jobs in whatever currency they would like.
  - The system converts the currency into the correct global value.
  - Example
    - There are 200 tickets (Global currency)
    - Process A has 100 tickets
    - Process B has 100 tickets

User A → *500* (A's currency) to A1 → *50* (global currency)
→ *500* (A's currency) to A2 → *50* (global currency)

User B → *10* (B's currency) to B1 → *100* (global currency)

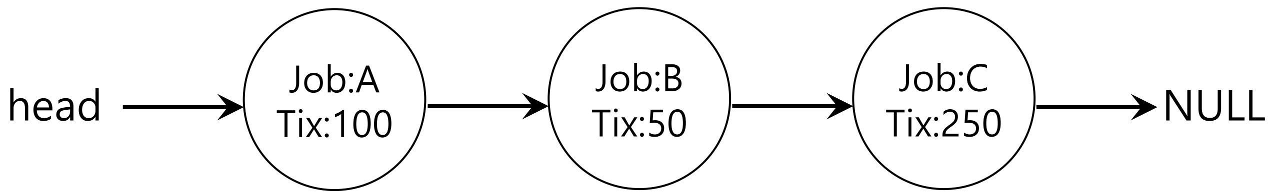
Ticket Mechanisms (Cont.)

- Ticket transfer
  - A process can temporarily hand off *its tickets* to another process.

- Ticket inflation
  - A process can temporarily raise or lower the number of tickets it owns.
  - If any one process needs *more CPU time*, it can boost its tickets.

Implementation

- Example: There are three processes, A, B, and C.
  - Keep the processes in a list sorted by the ticket number



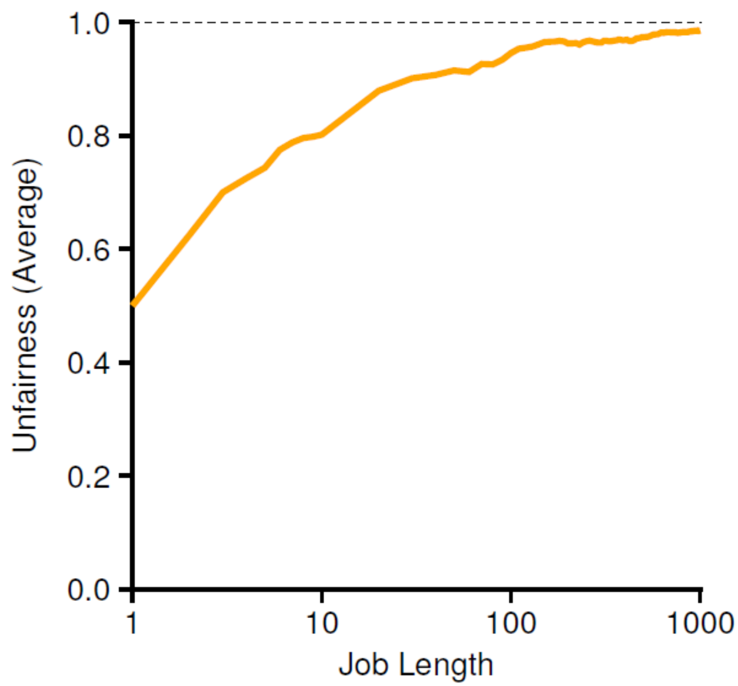

```c
// counter: used to track if we've found the winner yet
int counter = 0;

// winner: use some call to a random number generator to
// get a value, between 0 and the total # of tickets
int winner = getrandom(0, totaltickets);

// current: use this to walk through the list of jobs
node_t *current = head;

// loop until the sum of ticket values is > the winner
while (current) {
        counter = counter + current->tickets;
        if (counter > winner)
                break; // found the winner
        current = current->next;
}
// 'current' is the winner: schedule it...
```

Implementation (Cont.)

- Random can be much more difficult than you thought!
  - https://stackoverflow.com/questions/2509679/how-to-generate-a-random-integer-number-from-within-a-range
- U: unfairness metric
  - The time the first job completes divided by the time that the second job completes.
- Example:
  - There are two jobs, each jobs has runtime 10.
    - First job finishes at time 10; Second job finishes at time 20
  - $U = \frac{10}{20} = 0.5$
  - U will be close to 1 when both jobs finish at nearly the same time.

Lottery Fairness Study

- There are two jobs.
  - Each jobs has the same number of tickets (100).



When the job length is not very long,
average unfairness can be quite severe.

Deterministic Approach: Stride Scheduling

- Stride of each process
  - A large number / number of tickets of the process
  - Example: A large number = 10,000
    - Process A has 100 tickets → stride of A is 100
    - Process B has 50 tickets → stride of B is 200

- A process runs, increments a counter (pass value) for it by its stride
  - Pick the process that has the lowest pass value to run

```
current = remove_min(queue);          // pick client with minimum pass
schedule(current);                    // use resource for quantum
current->pass += current->stride;     // compute next pass using stride
insert(queue, current);               // put back into the queue
```

A pseudo code implementation

Stride Scheduling Example

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	…

Stride scheduling needs to maintain the per process pass value.
If new job enters with pass value 0 it will monopolize the CPU!

Advantage of Lottery scheduling: no per-process state

The Linux Completely Fair Scheduling (CFS)

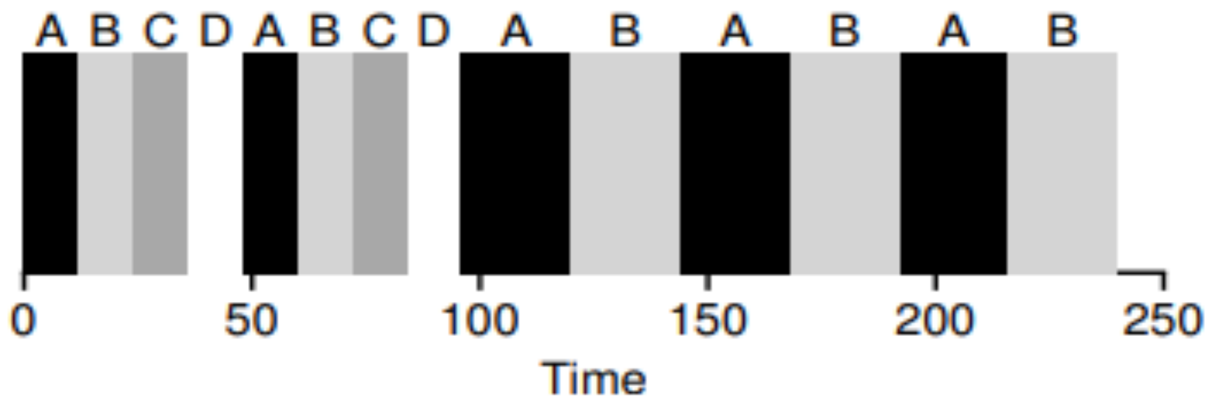
- Completely Fair Scheduling (CFS)
  - The current CPU scheduler in Linux
  - Non-fixed timeslice
    - CFS assigns process's timeslice a proportion of the processor.
  - Priority
    - Enables control over priority by using nice value.
  - Efficient data structures
    - Use red-black tree for efficient search, insertion and deletion of a process.

Basic

- Virtual runtime (vruntime)
  - Denote how long the process has been executing.
  - Per-process variable
  - Increase in **proportion with physical (real) time** when it runs.
  - CFS will pick the process with the **lowest vruntime** to run next.
- sched_latency
  - A typical value is 48 (milliseconds)
  - Process's timeslice = sched_latency / (the number of process)

Example

- Simple Example
  - 4 processes (A,B,C,D) and then 2 processes(C,D) complete.



- min_granularity
  - The minimum timeslice (6ms)
  - Ensure that not too much time is spent in scheduling overhead, When there are too many processes running.

Weight

- Nice value
  - CFS enables control over process priority
  - Nice parameter is an integer value and can be set from -20 to +19
  - The nice value is mapped to a weight (value is not important)

```
static const int prio_to_weight[40] = {
 /* -20 */     88761,     71755,     56483,     46273,     36291,
 /* -15 */     29154,     23254,     18705,     14949,     11916,
 /* -10 */      9548,      7620,      6100,      4904,      3906,
 /*  -5 */      3121,      2501,      1991,      1586,      1277,
 /*   0 */      1024,       820,       655,       526,       423,
 /*   5 */       335,       272,       215,       172,       137,
 /*  10 */       110,        87,        70,        56,        45,
 /*  15 */        36,        29,        23,        18,        15,
};
```

Weighting (Niceness)

- New timeslice formula

$$time\_slice_k = \frac{weight_k}{\sum_{n=0}^{n-1} weight_i} \cdot sched\_latency$$

- Simple Example
  - Assign Process A a nice value of -5 and process B a nice value of 0.

Process	nice value	weight	Time slice
A	-5	3121	36 ms
B	0	1024	12 ms

vruntime with weight

- Weighting (Niceness)
  - vruntime formula
    - Calculate the actual run time; scale it inversely by the weight

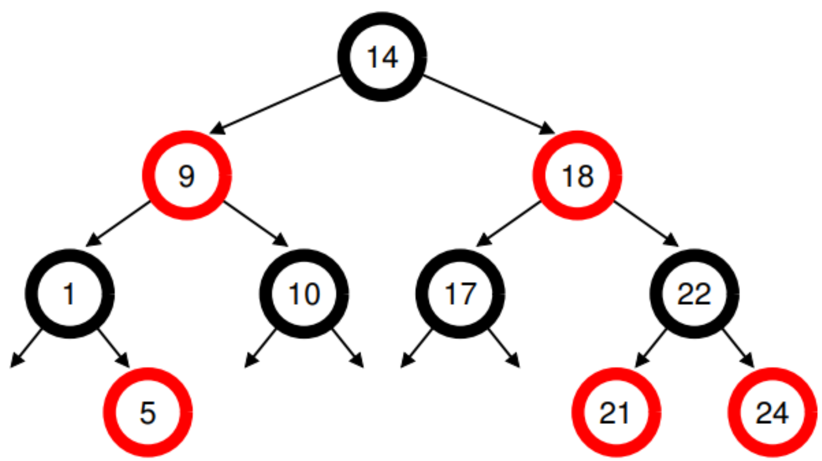
$$vruntime_i = vruntime_i + \frac{weight_0}{weight_i} \cdot runtime_i$$

    - $weight_0$ is the default weight, 1024
  - Example

Process	nice value	weight	Accumulated value
A	-5	3121	1/3 * runtime
B	0	1024	1 * runtime

Structure of ready queue

- Red-Black Tree
  - Balanced binary tree (can address worst-case insertion)
  - Ordering of Red-Black Tree: O(log n)
  - Efficiently find the process with minimum virtual runtime.
  - Only running (or runnable) processes are kept therein.



IO and sleeping process

- Dealing with I/O and sleeping processes
  - Avoid the situation where some process monopolizes CPU, if it has significantly small vruntime after sleeping
  - Set the vruntime of process to the minimum value found in tree when it wakes up.
  - Cost: Process that sleeps for short periods of time frequently do not ever get their fair share of the CPU