Kernel Data Structures

Completely Fair Scheduling

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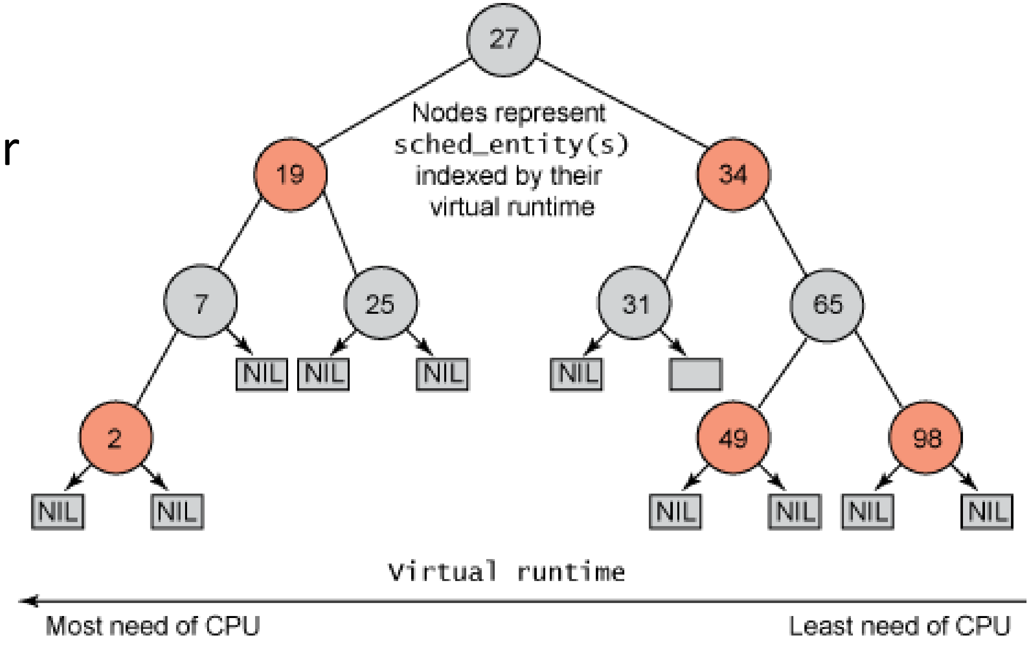
Completely Fair Scheduling (CFS)

References:

1. "Professional Linux Kernel Architecture" by Wolfgang Mauerer (*Chapter 2: Process Management and Scheduling*)

2. "Linux Kernel Development" by Robert Love (*Chapter 4: Process Scheduling*)



Interactive vs Batch Processes

- **Interactive Processes (I/O Bound)**: Needs frequent scheduling but the timeslice duration can be less
  - Example: A text editor – waits for the input from the user, but expects the input to be processed immediately when available

Interactive vs Batch Processes

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- **Batch Processes (CPU Bound)**: Needs longer timeslice to complete the task, but may wait for getting scheduled
  - Example: Video encoding – needs a lot of CPU, but runs in the background – does not have a strong deadline, user does not feel much bad if delayed for 0.5 sec.

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High	-10	110	600ms
Normal	0	120	100ms
Low	+10	130	50ms
Lowest	+19	139	5ms

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Frequent context switching when there are two low priority processes

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Setting an Ideal Timeslice: A Non-trivial Problem

- Large timeslices affect interactivity – two high priority processes in the system -> interactivity will get affected

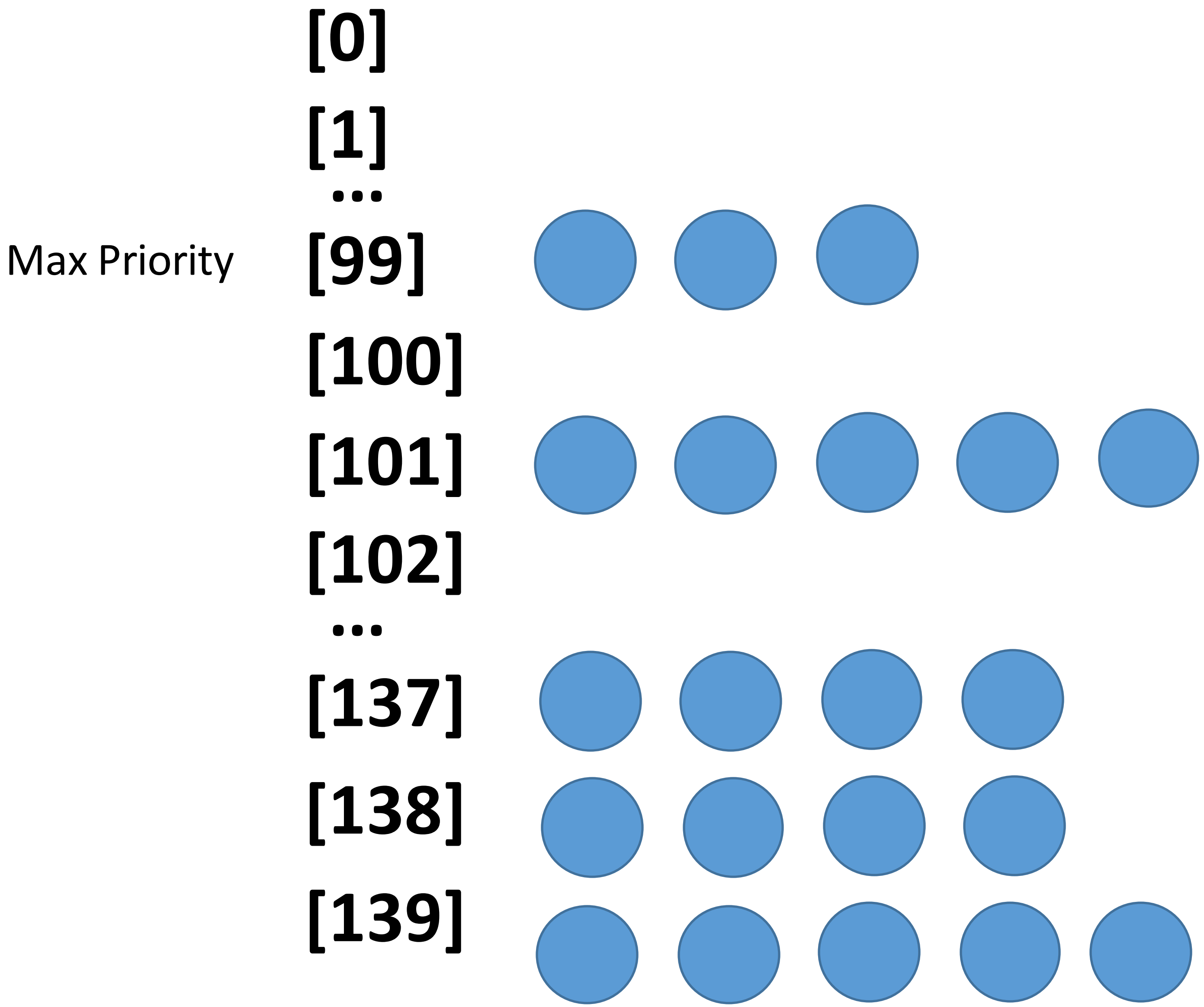
- Small timeslices cause frequent context switching – not desirable

Why a New Scheduler?

- O(1) scheduler failed to demonstrate its promises in practice
  - Implementation is very complicated – difficult to debug
  - The heuristic for interactivity measures did not work – resulting in poor performance in practice
  - Failure of an O(1) algorithm in real environment !

- Various other patches have been applied on the Kernel scheduler
  - **Staircase Scheduler (2004, Kolivas):** Heuristic for interactivity replaced by a rank-based scheme – runqueue as a ranked array
    - Remove the concept of "expired array"
    - The expired process will fall one priority staired down, and will be added back to the same runqueue
    - Once reached at the bottom for the first time, stair up one priority level below the maximum
    - Once reached at the bottom for the second time, stair up two priority levels below the maximum

Staircase Scheduling



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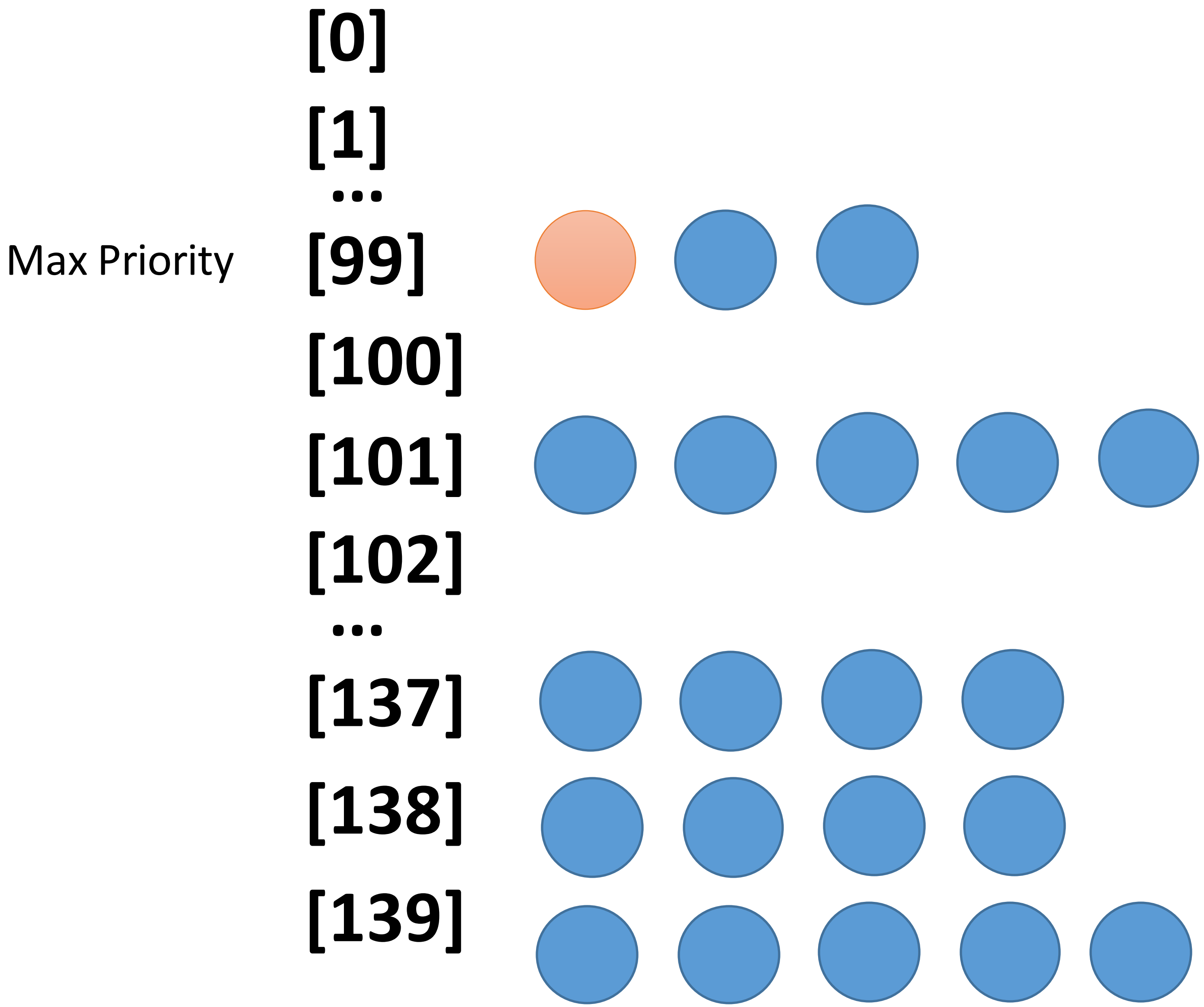


Staircase Scheduling

[0]

[1]

...

Max Priority [99]

[100]

[101]

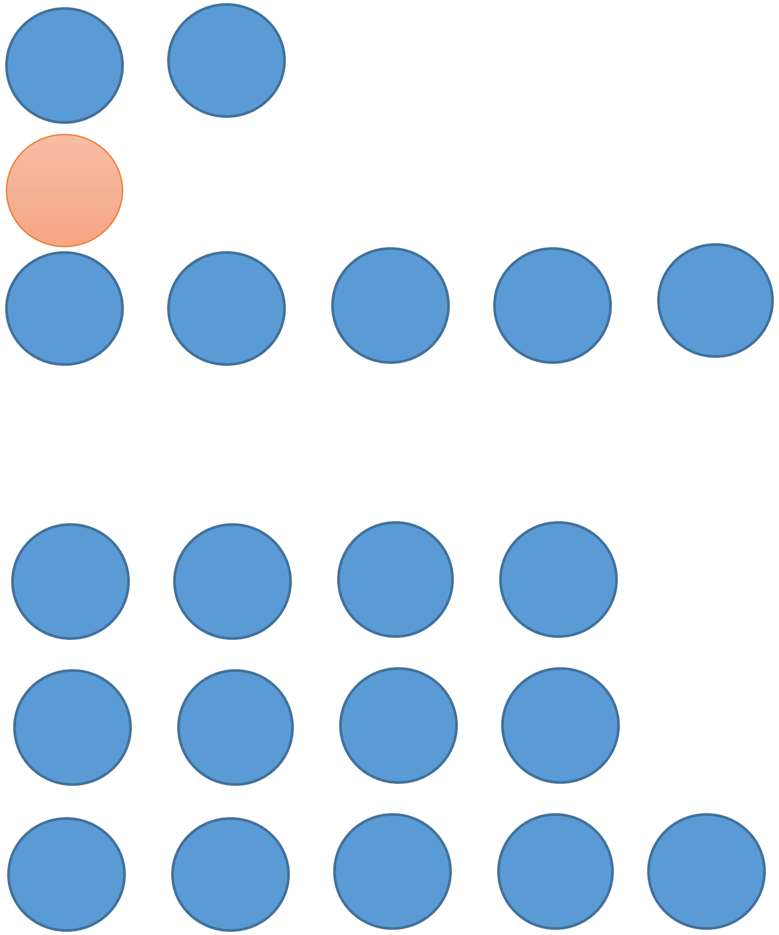
[102]

...

[137]

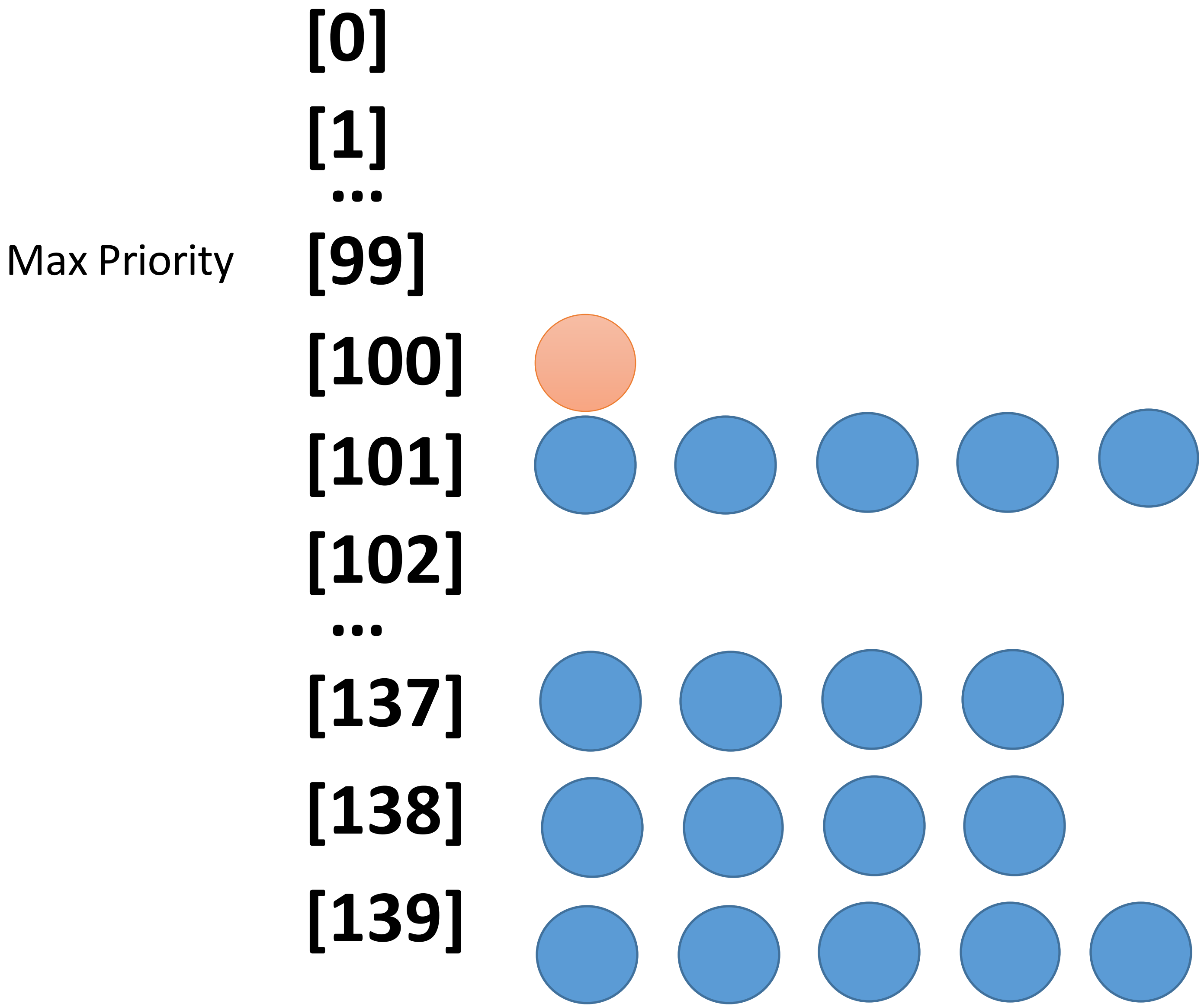
[138]

[139]



Stair down for one level

Staircase Scheduling



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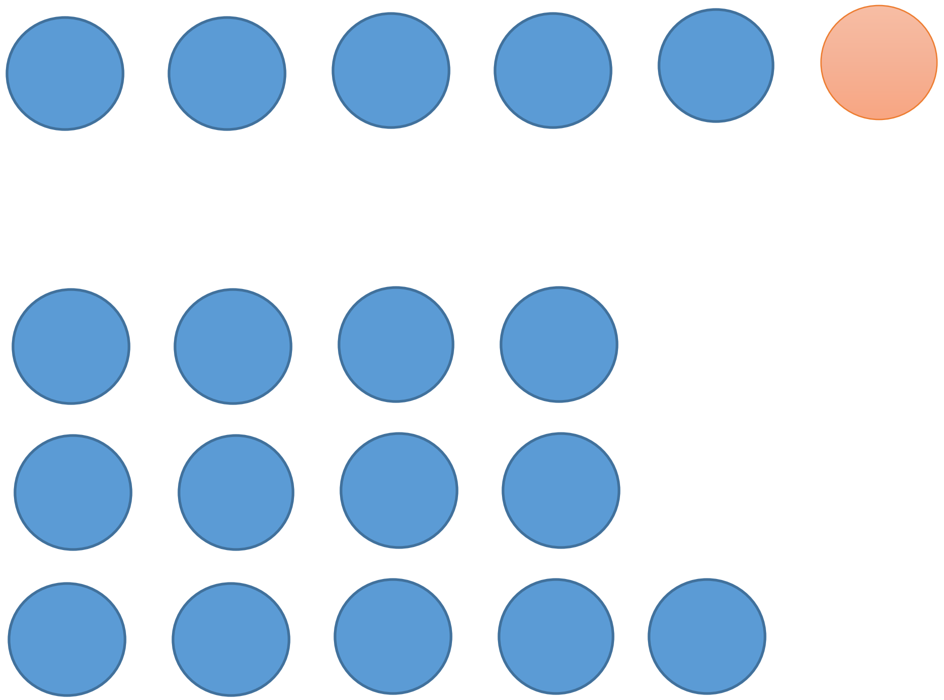
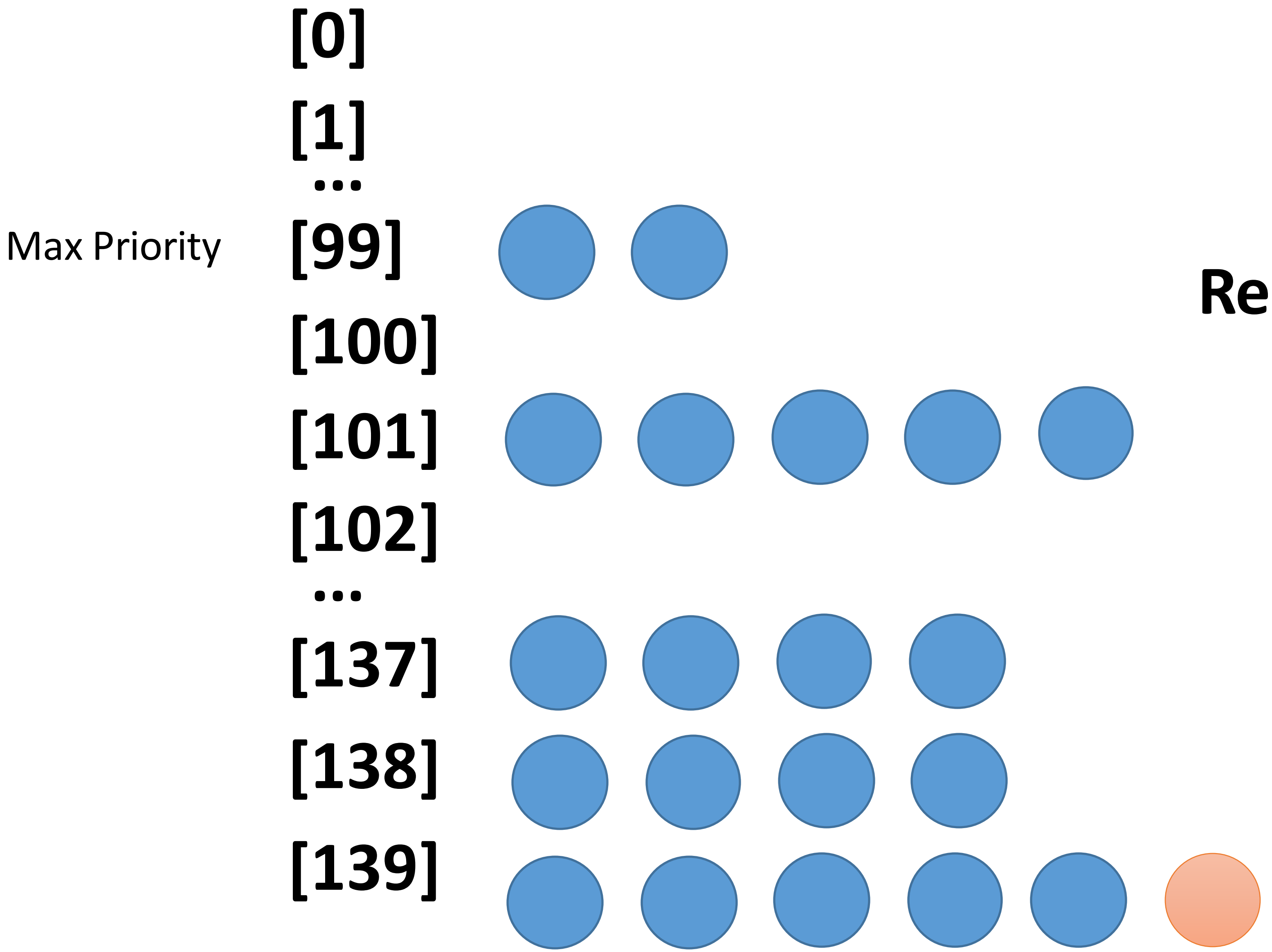


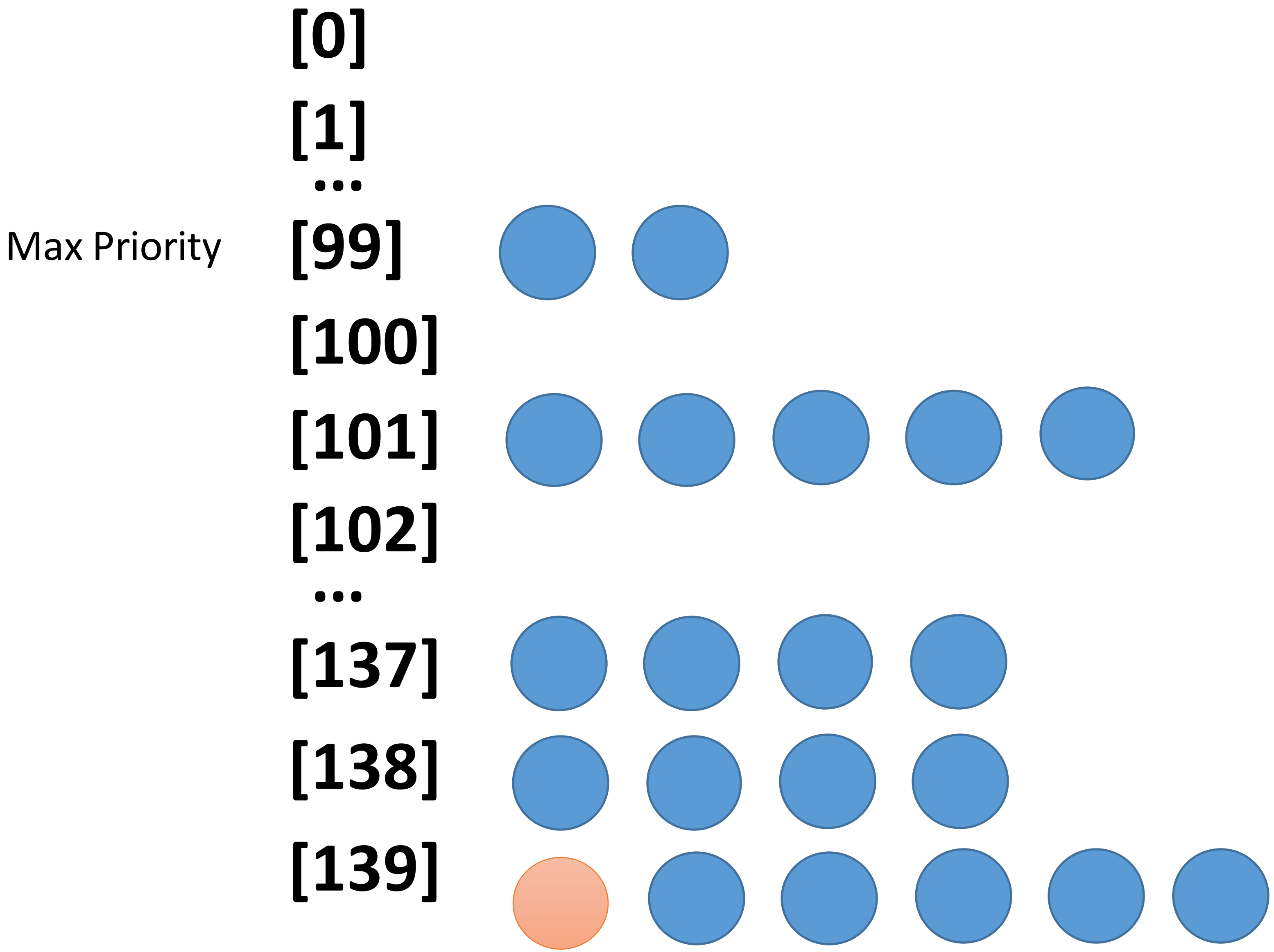
Stair down for one level further

Staircase Scheduling



Reach to the bottom

Staircase Scheduling



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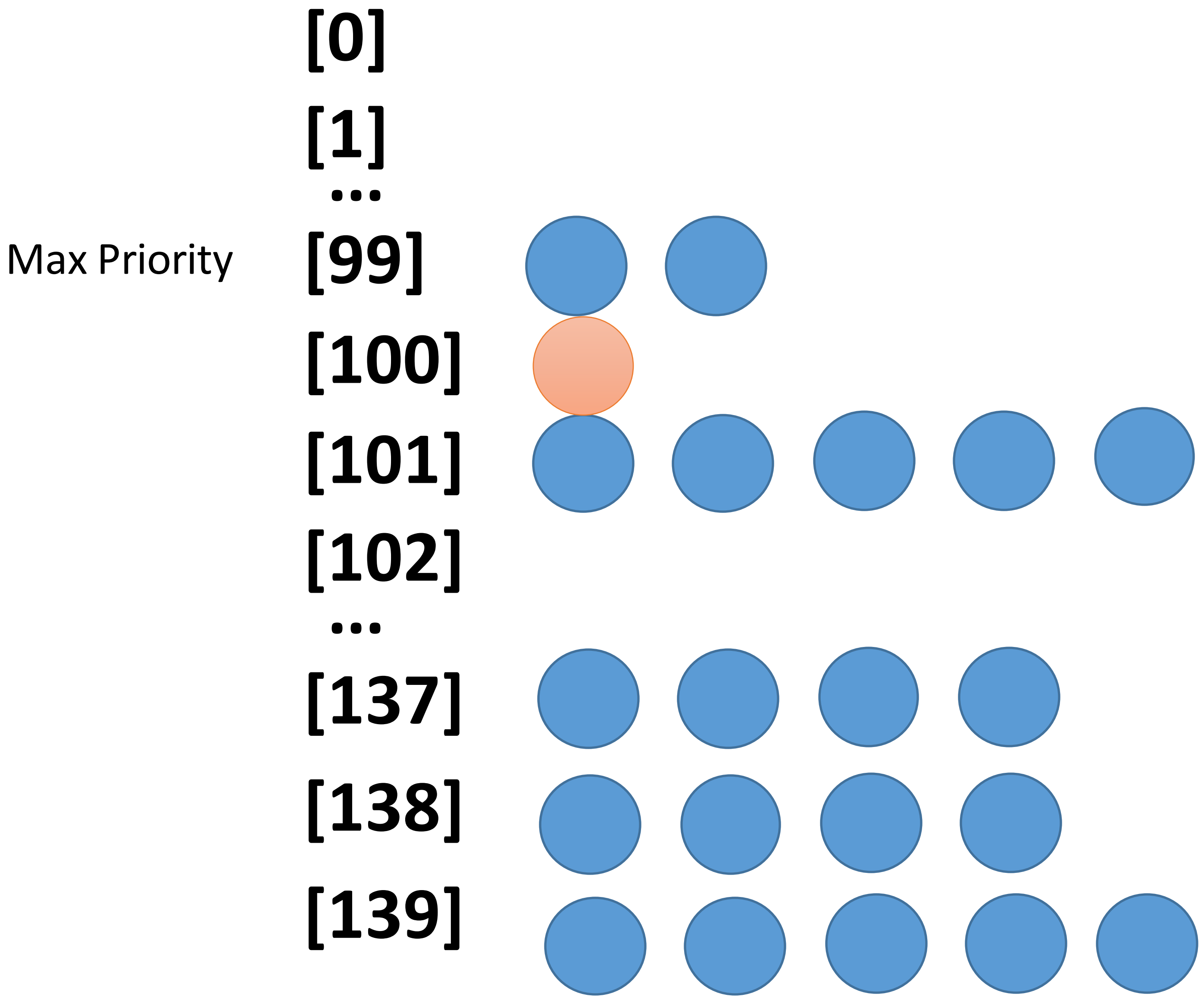
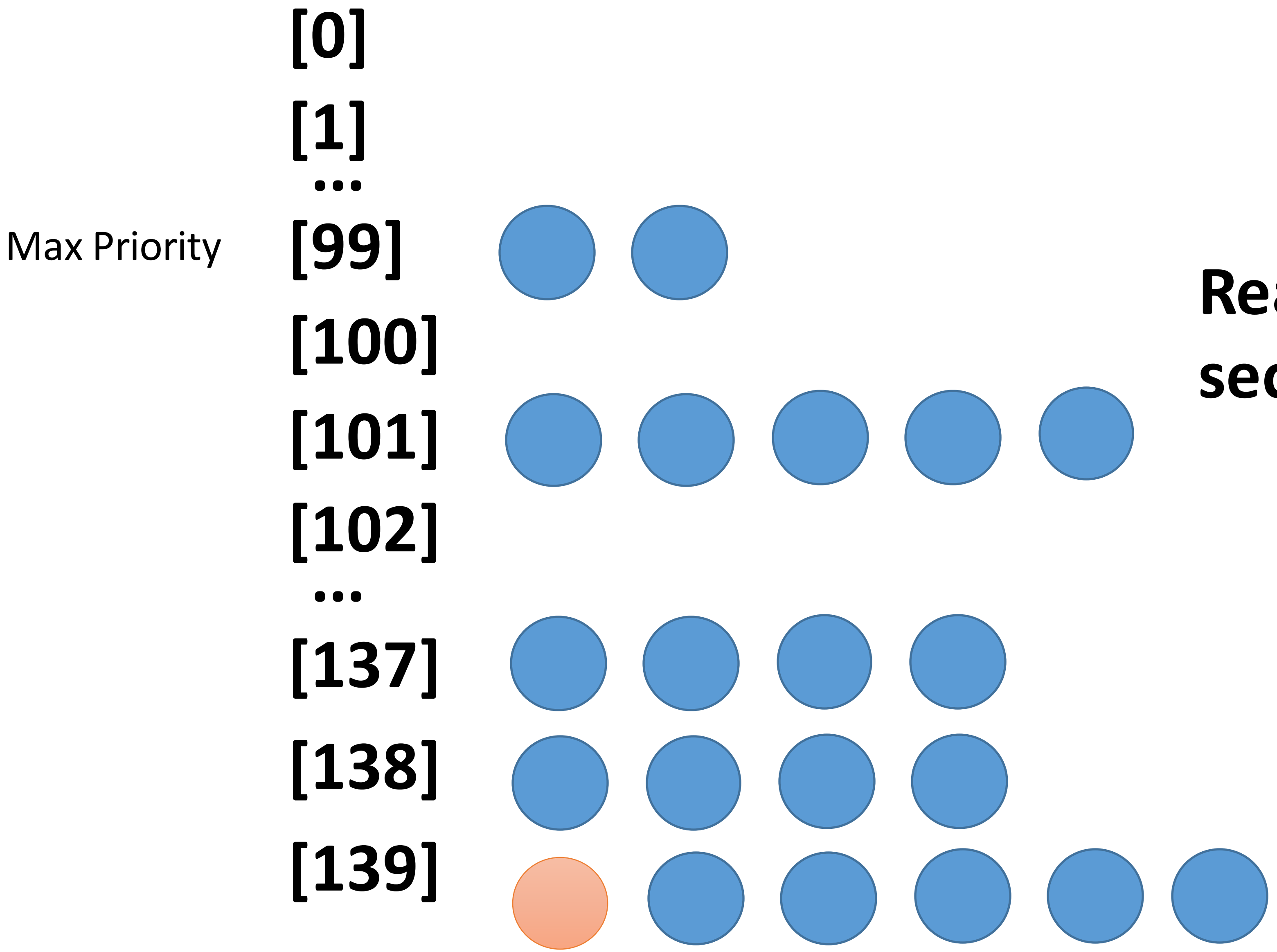


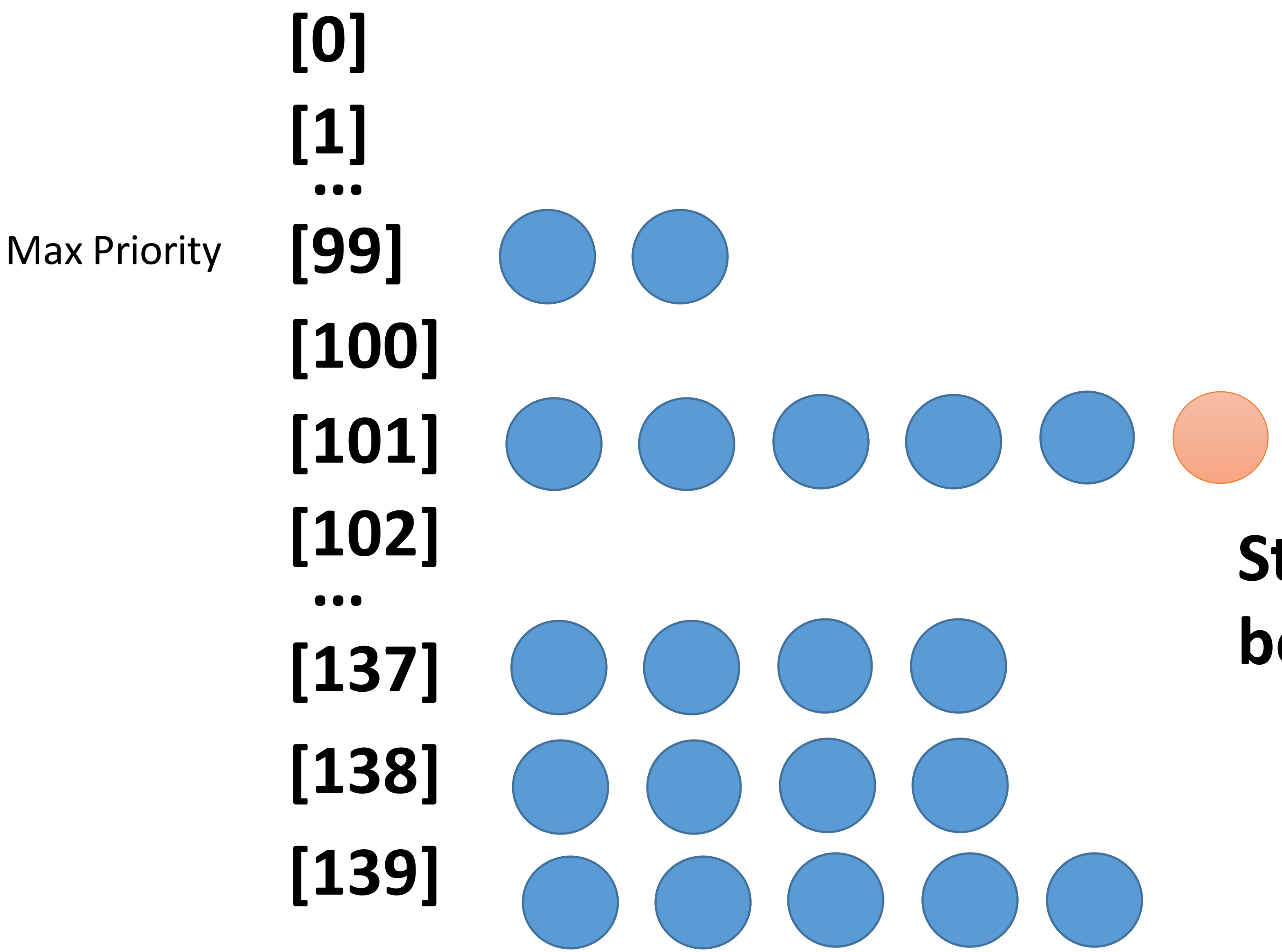
Stair up one level below the maximum

Staircase Scheduling



Reach bottom for the second time

Staircase Scheduling



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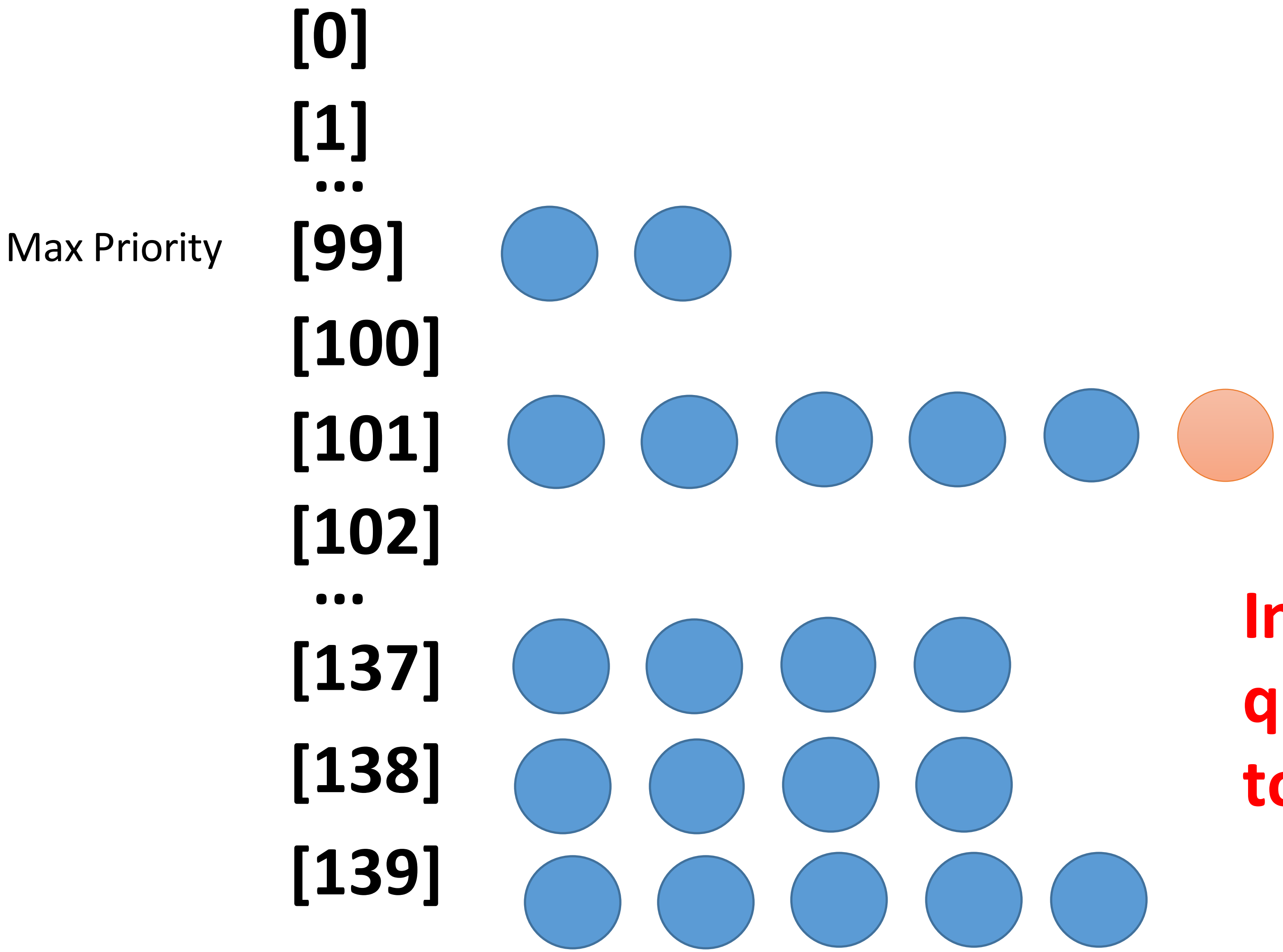

Interactive processes quickly move to the top of the queue

Updating the Scheduler Further

- **Rotating Staircase Deadline Scheduler** (RSDS) -- Kolivas, 2007
  - I/O bound processes can get starved in Staircase Scheduler – Interactive processes quickly jump up and eat all the time slices
  - Bring back the "Expired Array" !!
  - Rotate Staircase scheduling between the active and the expired arrays

- Neither Staircase Scheduler nor RSDS were accepted into the Kernel mainline
  - Too much desktop-oriented !! **Remember the use of Linux in early days**

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- **Completely Fair Scheduler (CFS)**
  - Ingo Molner (developer of O(1) Scheduler), 2007
  - Utilized some of the ideas of fairness from staircase scheduler
  - Merged into Kernel 2.6.23 -- default Linux scheduler since then

Completely Fair Scheduler

- Models an *"ideal, precise multitasking CPU"* on real hardware

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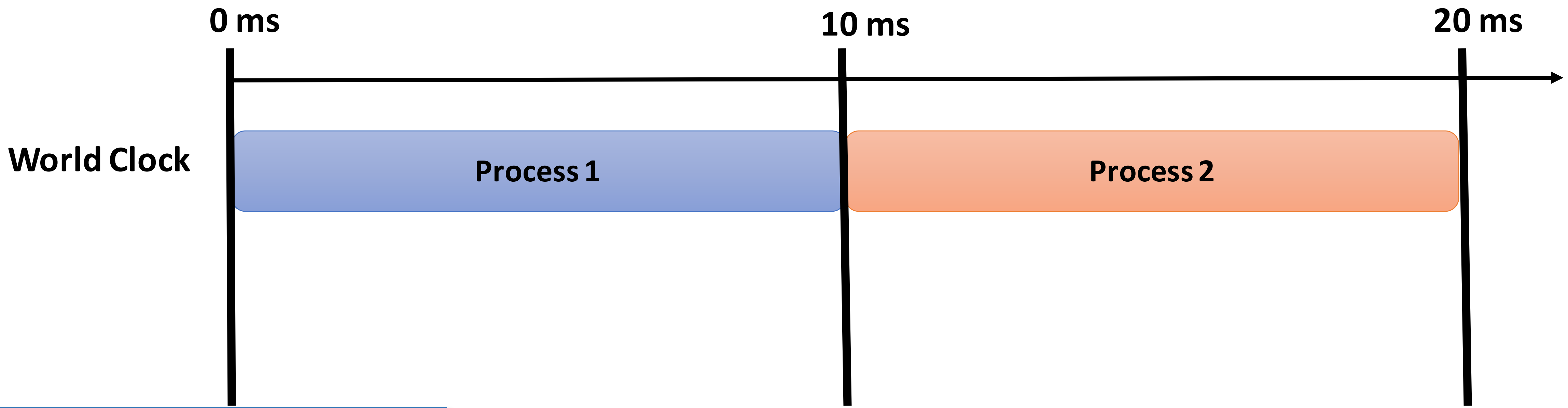
  - Consider two processes – each got executed for 10 ms with 100% CPU utilization



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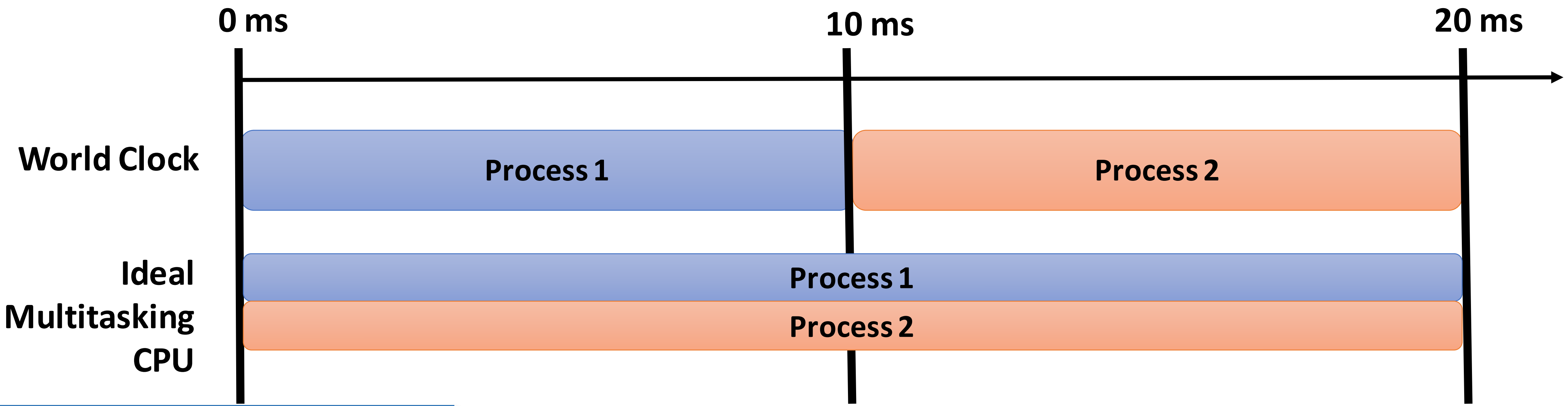
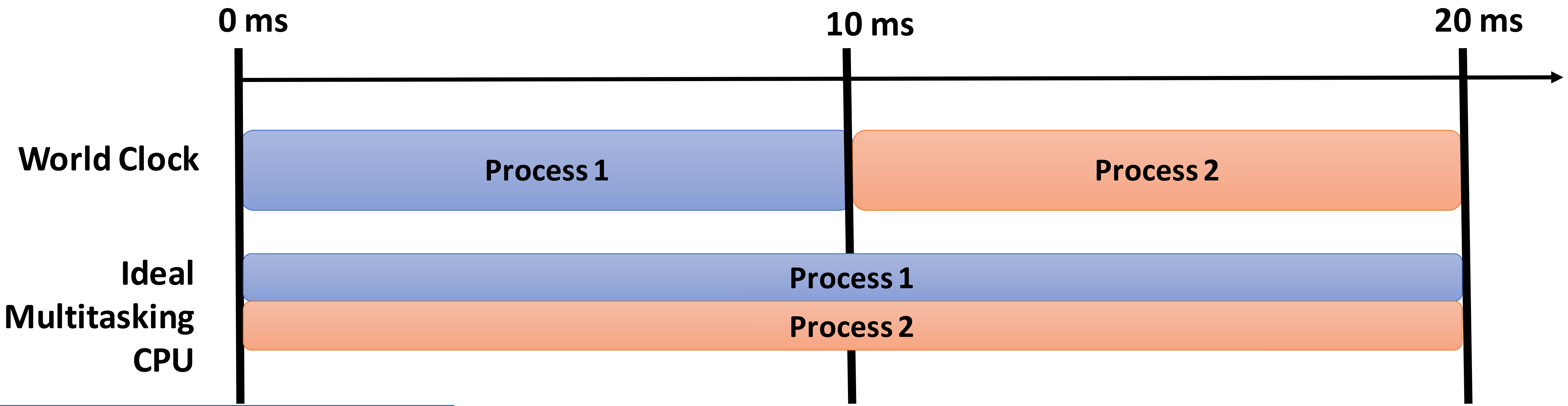
  - With *n* running processes, each process would be having *1/n* amount of CPU time, **when running constantly**
  - Consider two processes – each got executed for 10 ms with 100% CPU utilization
  - **Ideal Multitasking CPU –** each will get executed for 20 ms with 50% CPU utilization



Completely Fair Scheduler

- But, the idea is not practically possible
  - You cannot run two processes on a single CPU !



Completely Fair Scheduler

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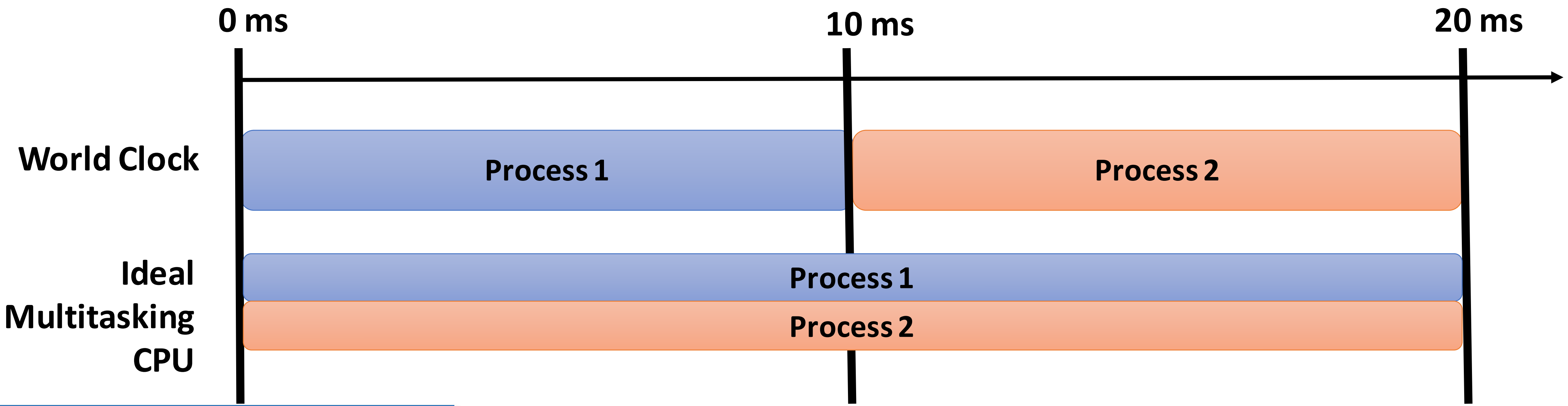
- CFS tries to mimic perfectly fair scheduling



Core Idea

- Calculate how long a task should run as a function of the total number of currently runnable process

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  - Use the priority value to weight a proportion of the CPU the process is to receive – higher priority job should get more CPU time **proportional to the priority of the other processes in the runqueue**

Remember the way we used to set up the time slices earlier:

- Prio < 120; T = (140-Prio) x 20
- Prio ≥ 120; T = (140-Prio) x 5

CFS – Scheduling Algorithm

Case 1: Tasks have the same priority values

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- Set a bounded target (amount of time) *T* within which the scheduler tries to execute all the runnable tasks – if there are *N* runnable tasks, each task will get *T/N* amount of time
  - Let, T = 10ms
    - N = 2, each task will get 5ms
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    - Context switching time should not take over the time for task execution
  - Default target time = 20ms, 4ms chunks are added when each task is likely to get less than 1ms

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- Assign timeslices in proportion to their priority levels
  - Assume two processes having priority values (niceness) 5 and 10, respectively
  - Default target time (period) = 20ms
  - Makes a mapping from niceness to weights:
    - 5 translates to 335
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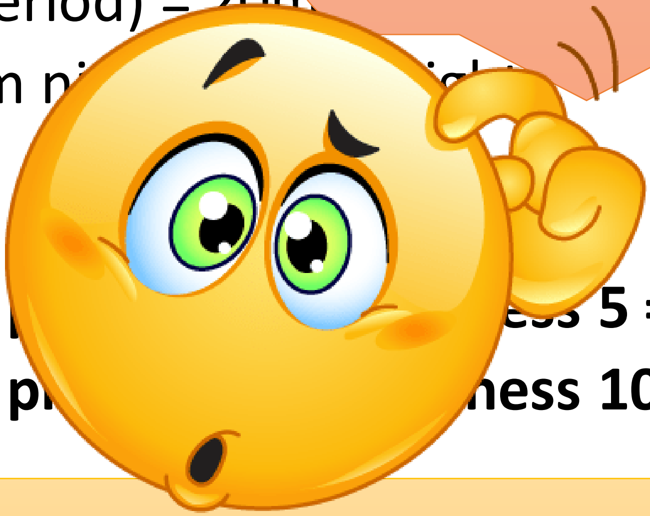
How do we calculate the wall-clock slice?

- ✓ **Number of processes in the runqueue is dynamic**
- ✓ **Needs an iteration over the entire runqueue – O(N)?**



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Red Black (RB) Tree -- A Self-balancing Binary Search Tree

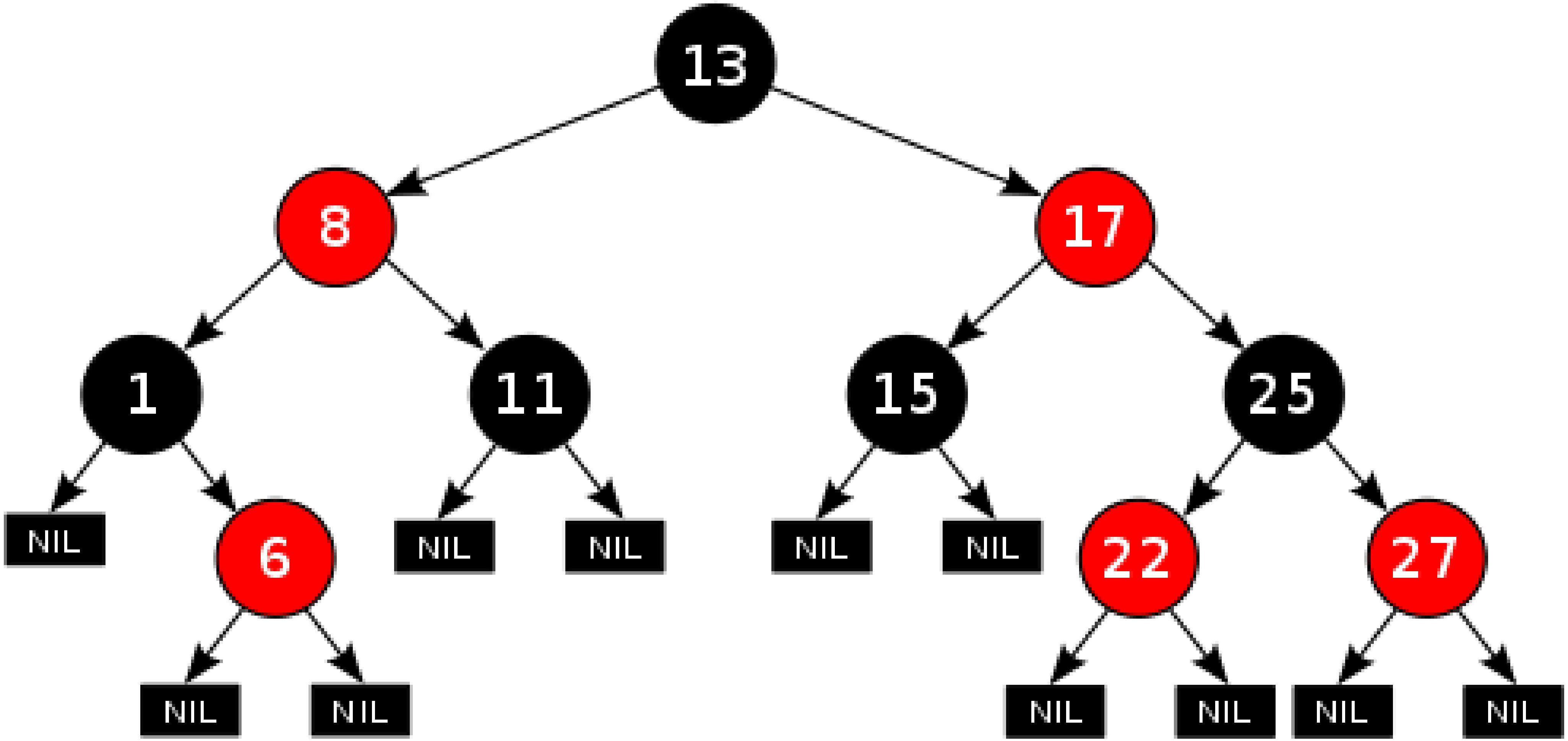


Image source: Wikipedia

CFS Runqueue as a RB Tree

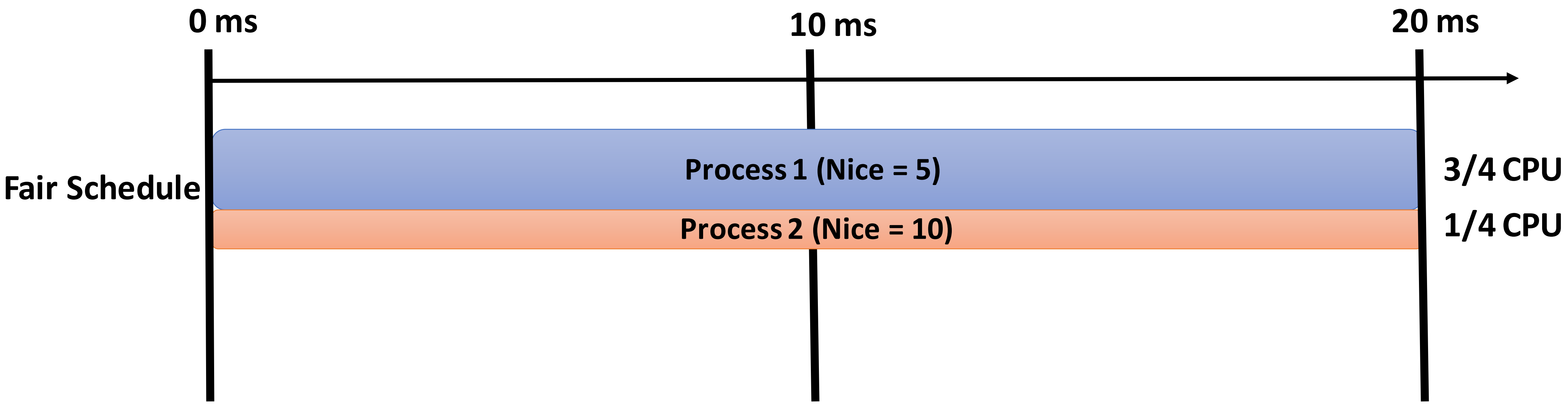
- CFS uses a time-ordered RB tree

- Every processor maintains its own runqueue
  - Each runqueue is implemented as an RB tree

- The nodes of a runqueue is either a task or a task-group (`sched_entity`)
  - **Task group:** A group of tasks (processes) having the same/similar functionalities; ex. An HTTP server having multiple threads / processes for parallelization

- The nodes are indexed by their virtual runtimes (vruntime) -- **amount of time a waiting process would have been allowed to spend on the CPU on a completely fair system**

Conceptualizing the Virtual Runtime using a Virtual Clock



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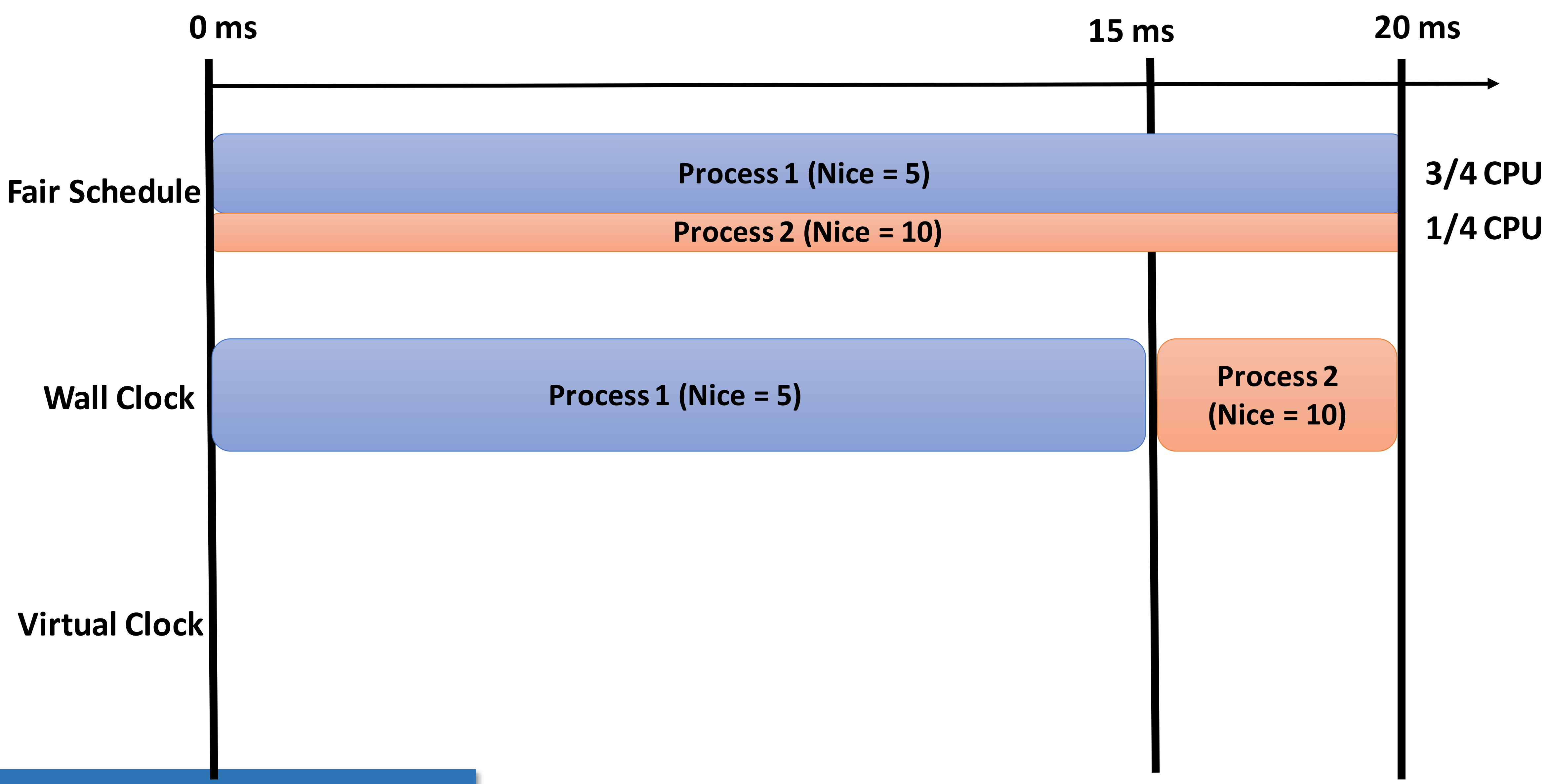

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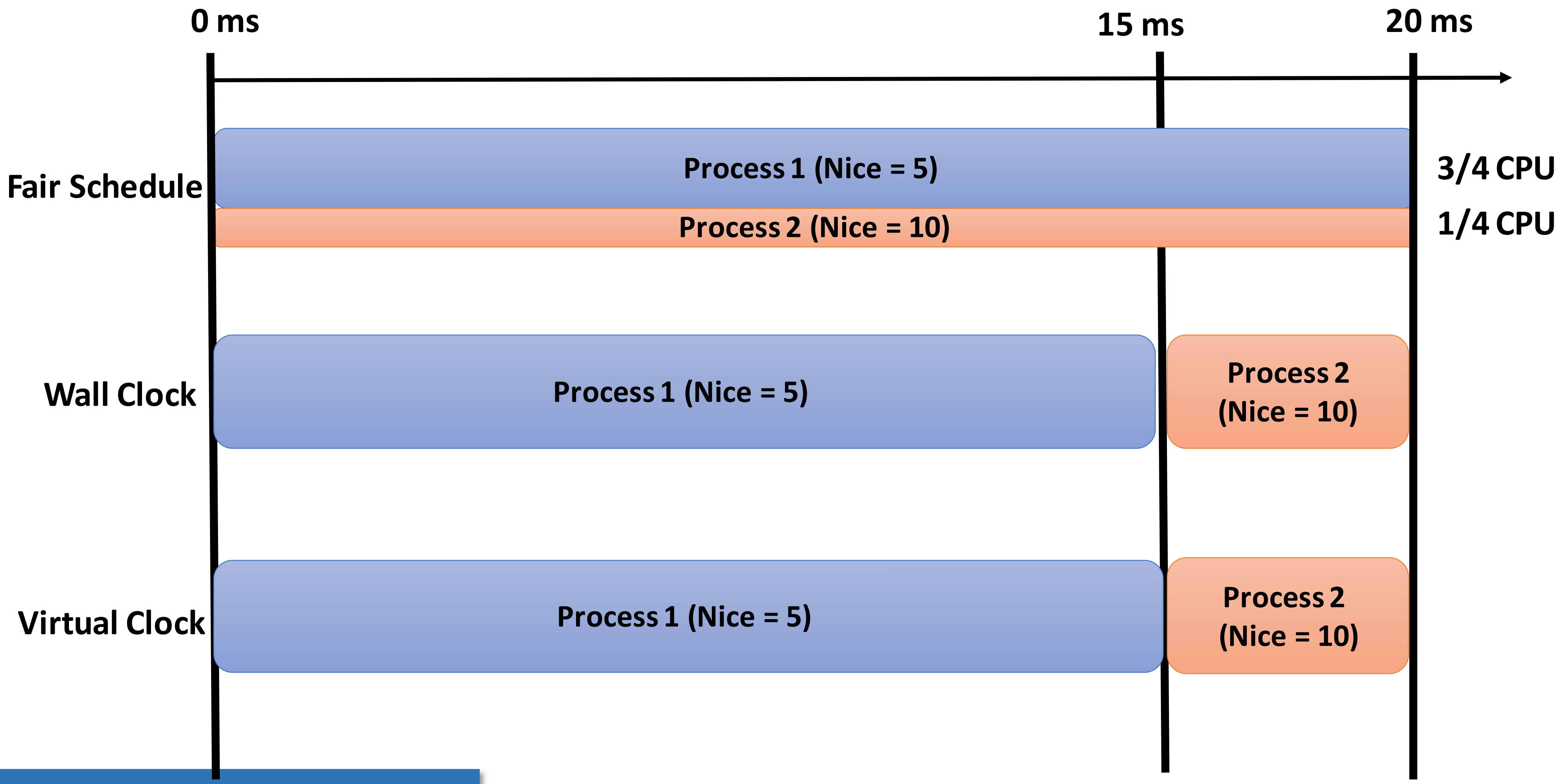

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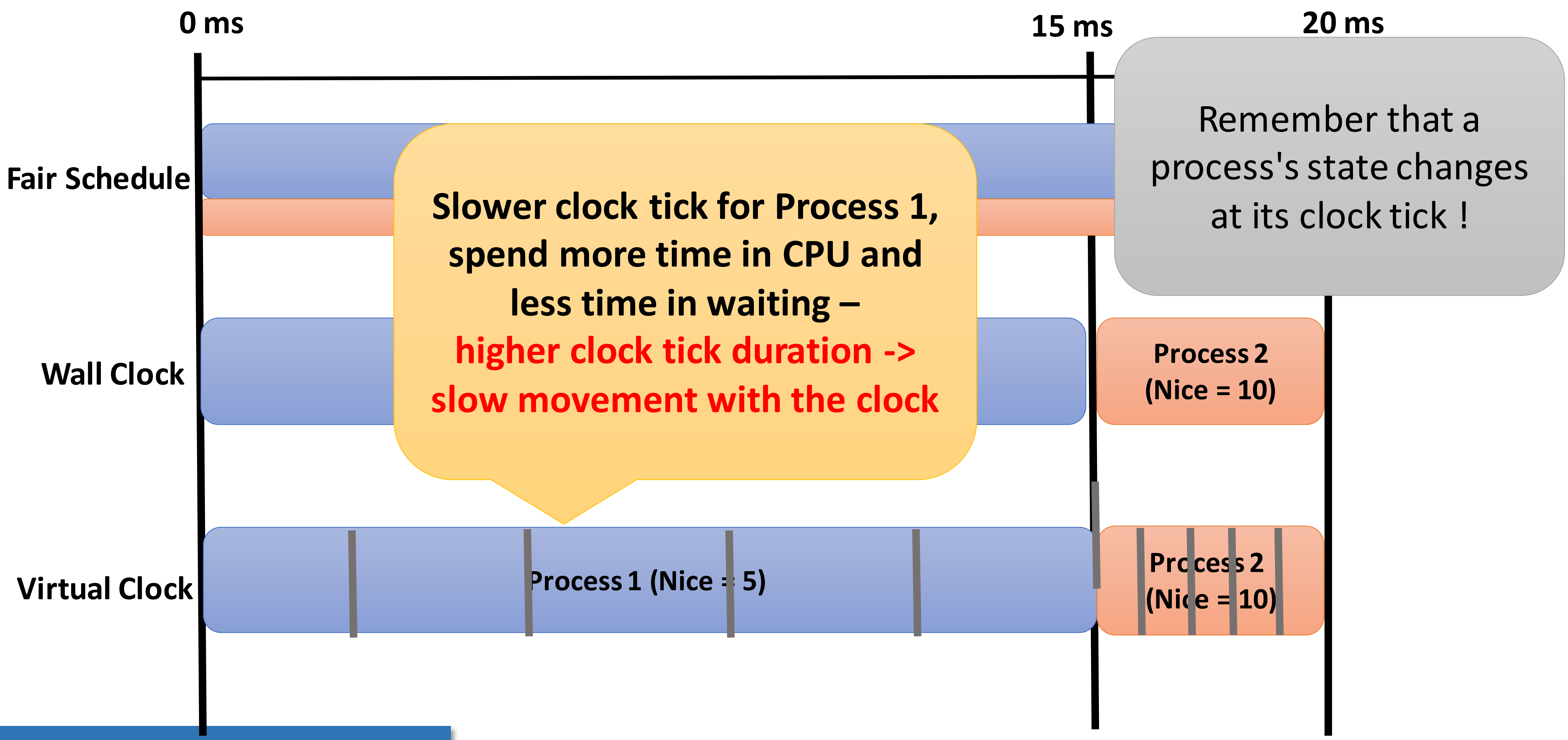

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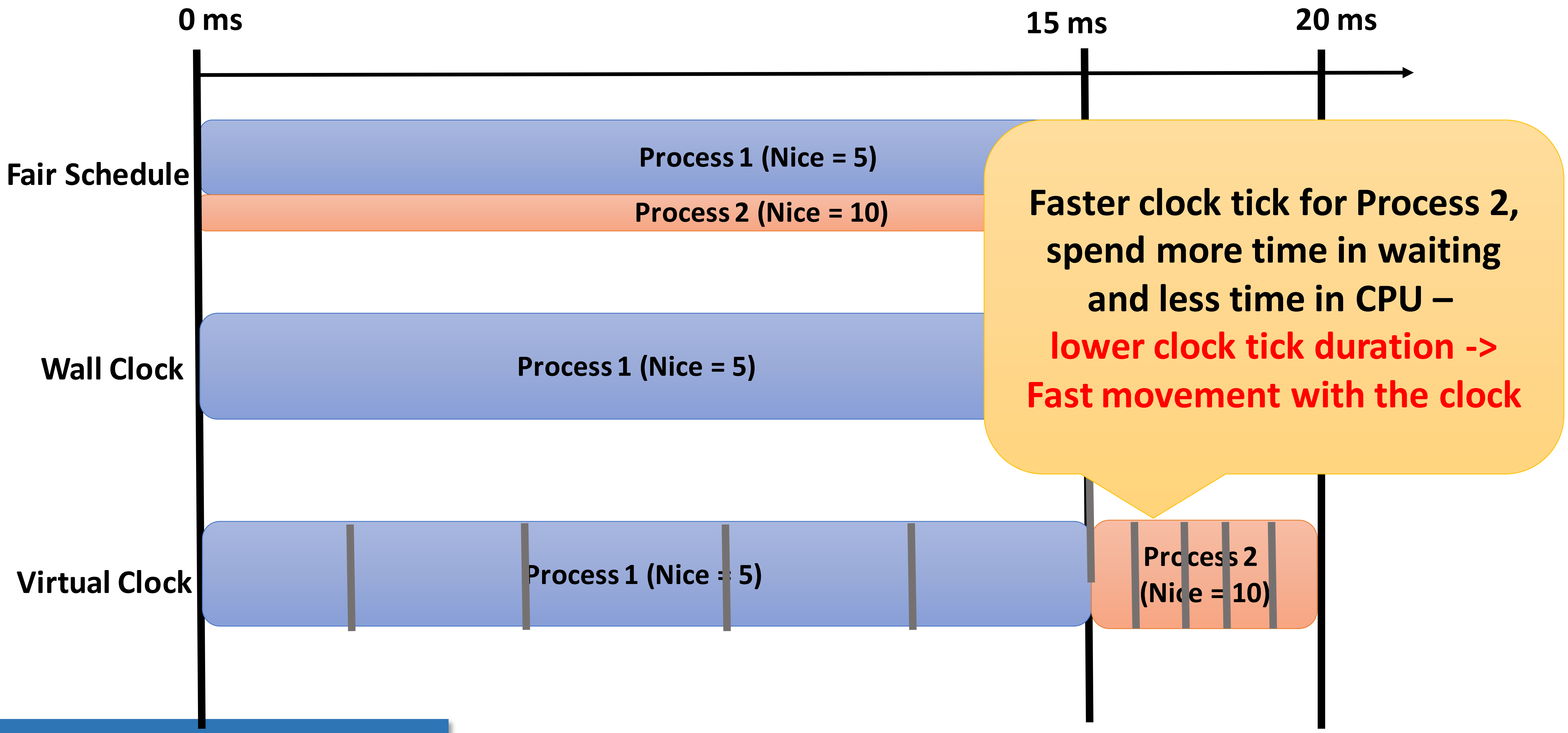

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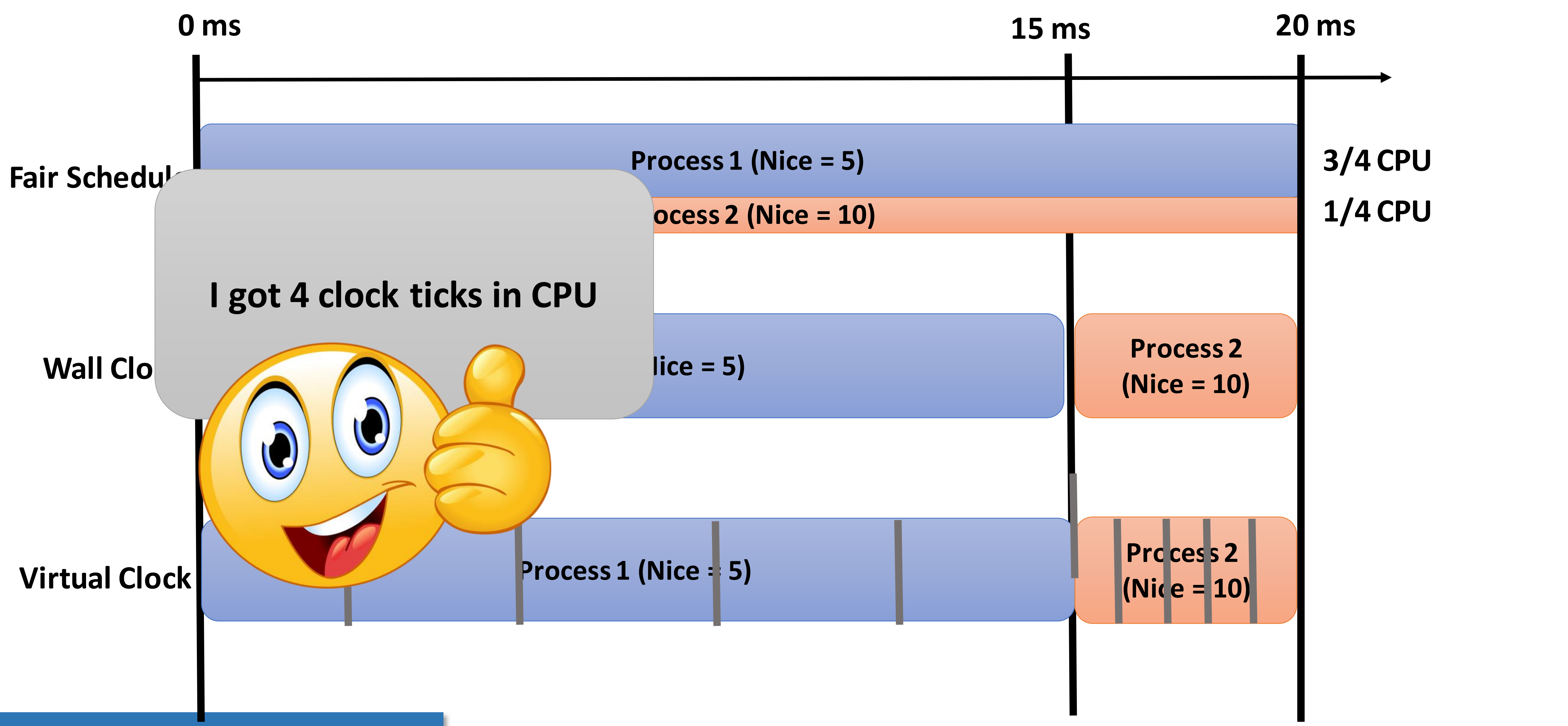

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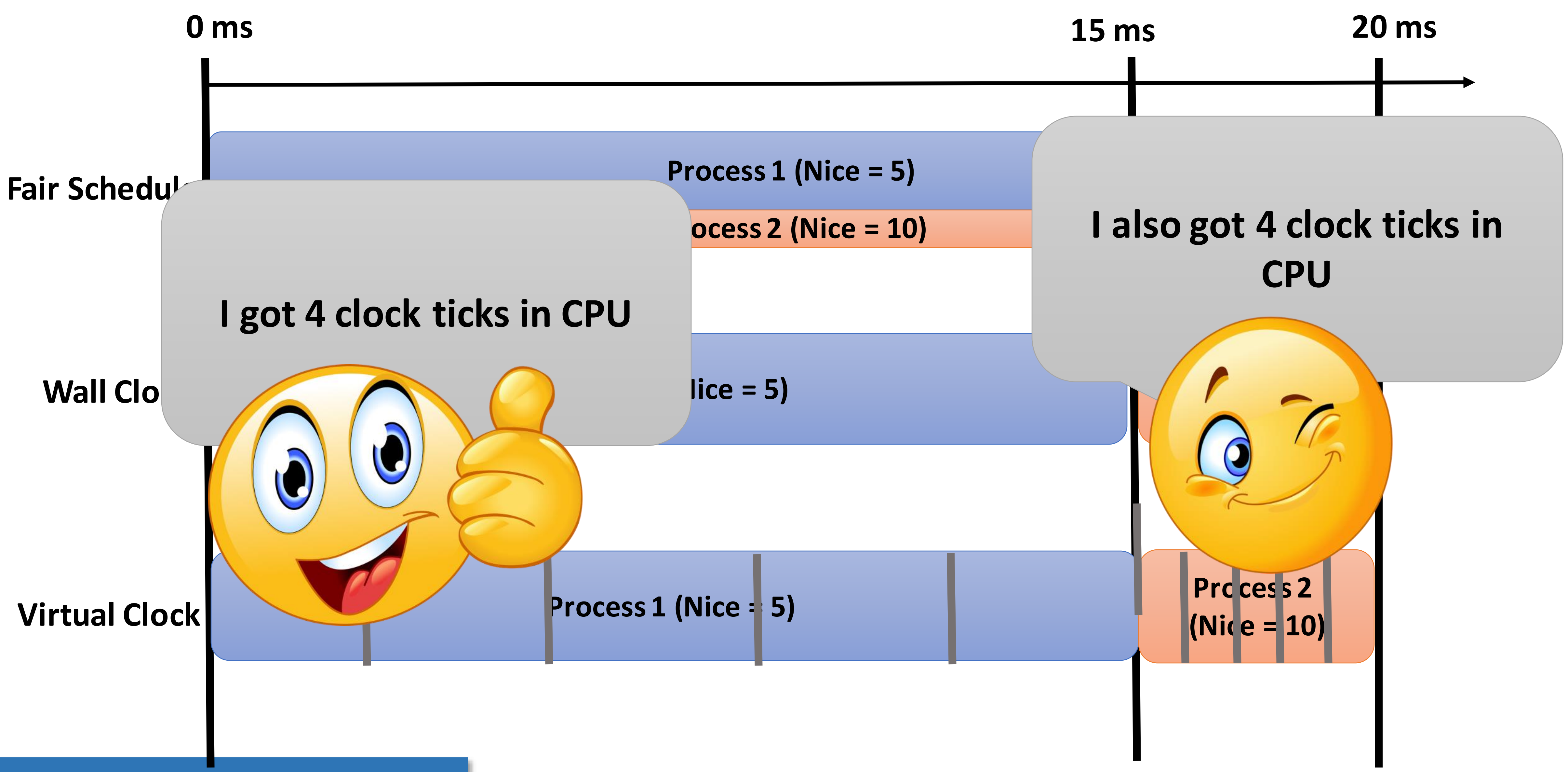
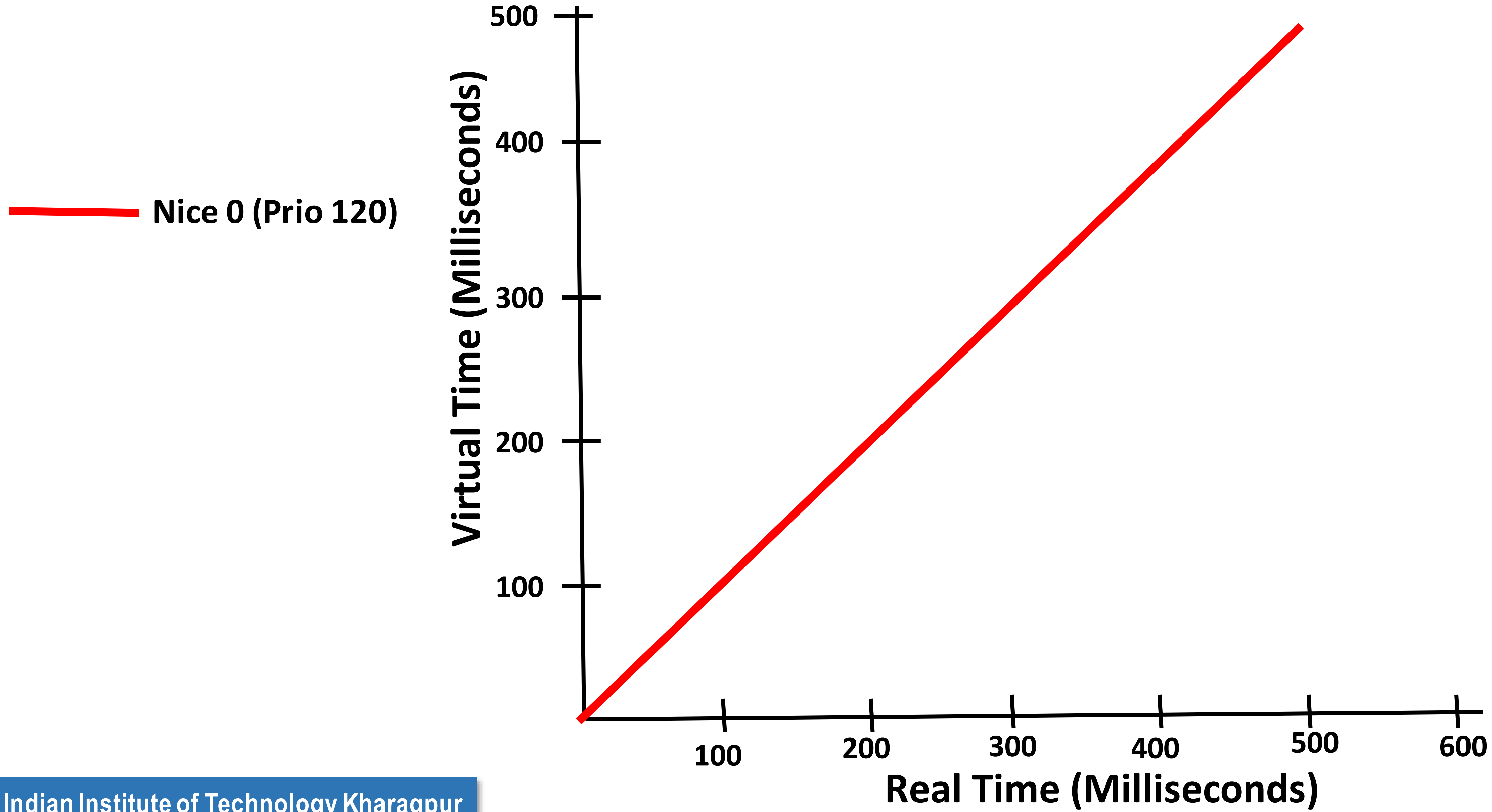


Real Time (Wall Clock) vs Virtual Time



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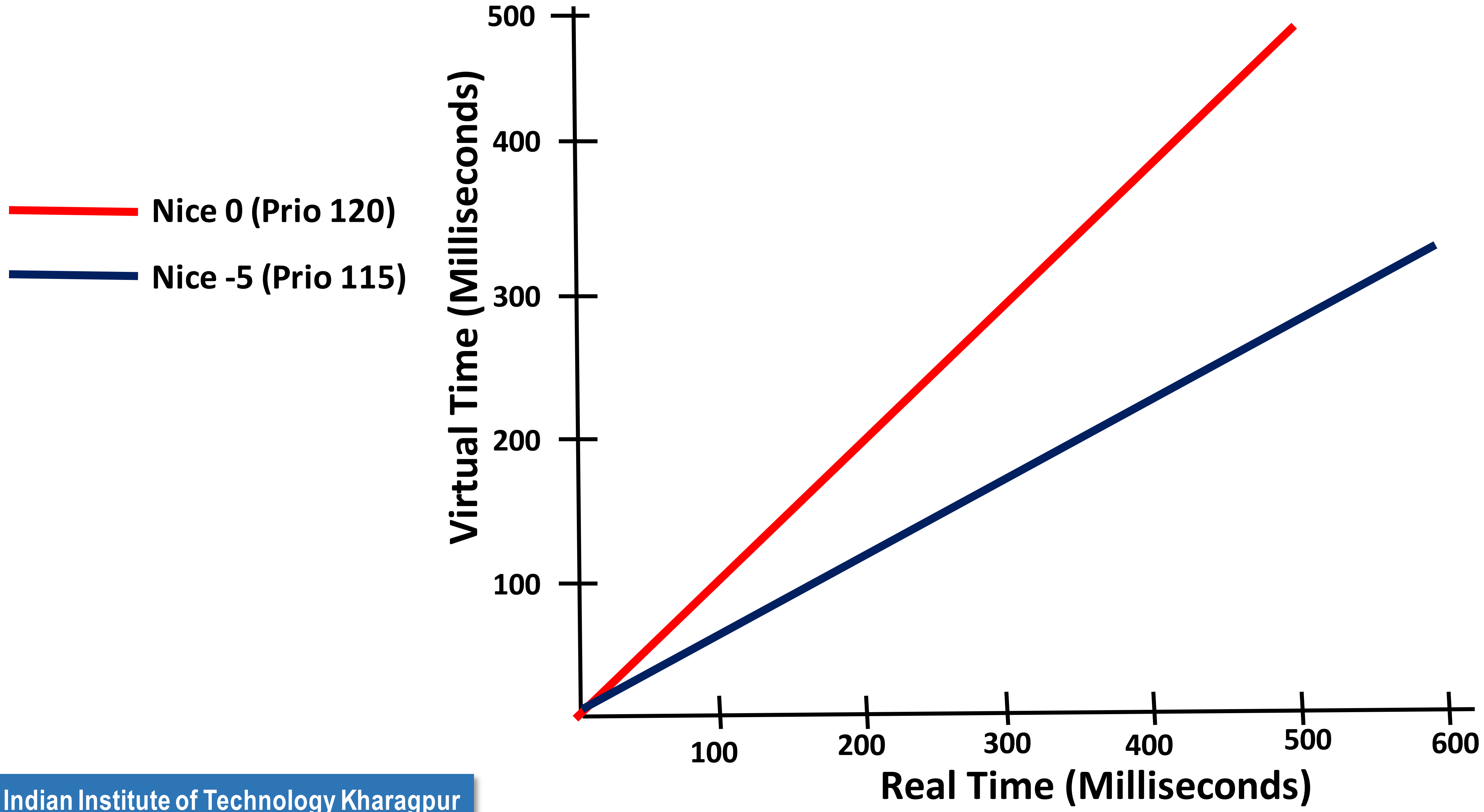

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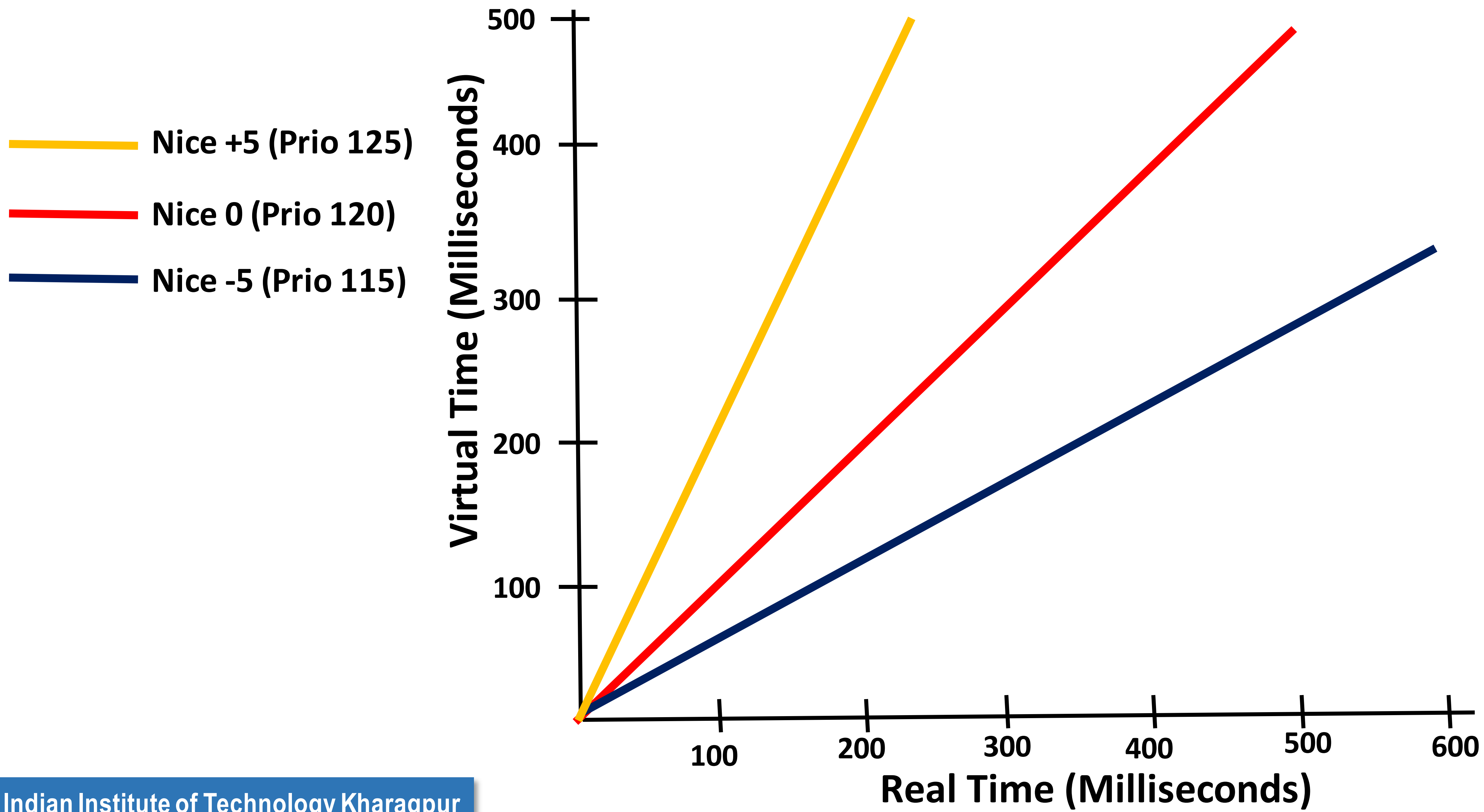


Implementing the Virtual Runtime

- CFS uses a virtual clock to implement vruntime.
- For a runnable task (or task group), the vruntime is updated as the task executes in the CPU, as follows:

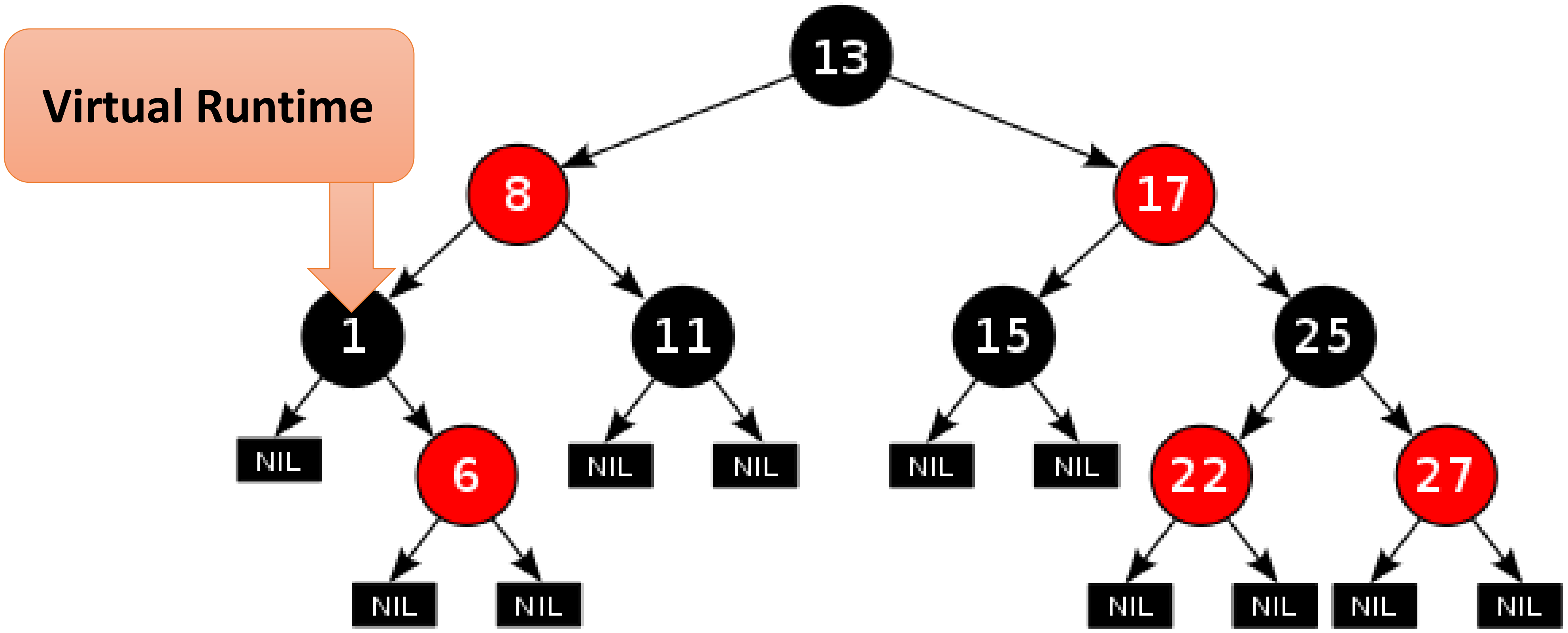
```
vruntime += delta_exec x (NICE_0_LOAD / se->load.weight)
```

Here, `delta_exec` is the real-time elapsed for the currently running process, `NICE_0_LOAD` is 1024 and the `load.weight` for a process is computed from its nice value

From Nice Value to Weight

```
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,
};
```

CFS Runqueue



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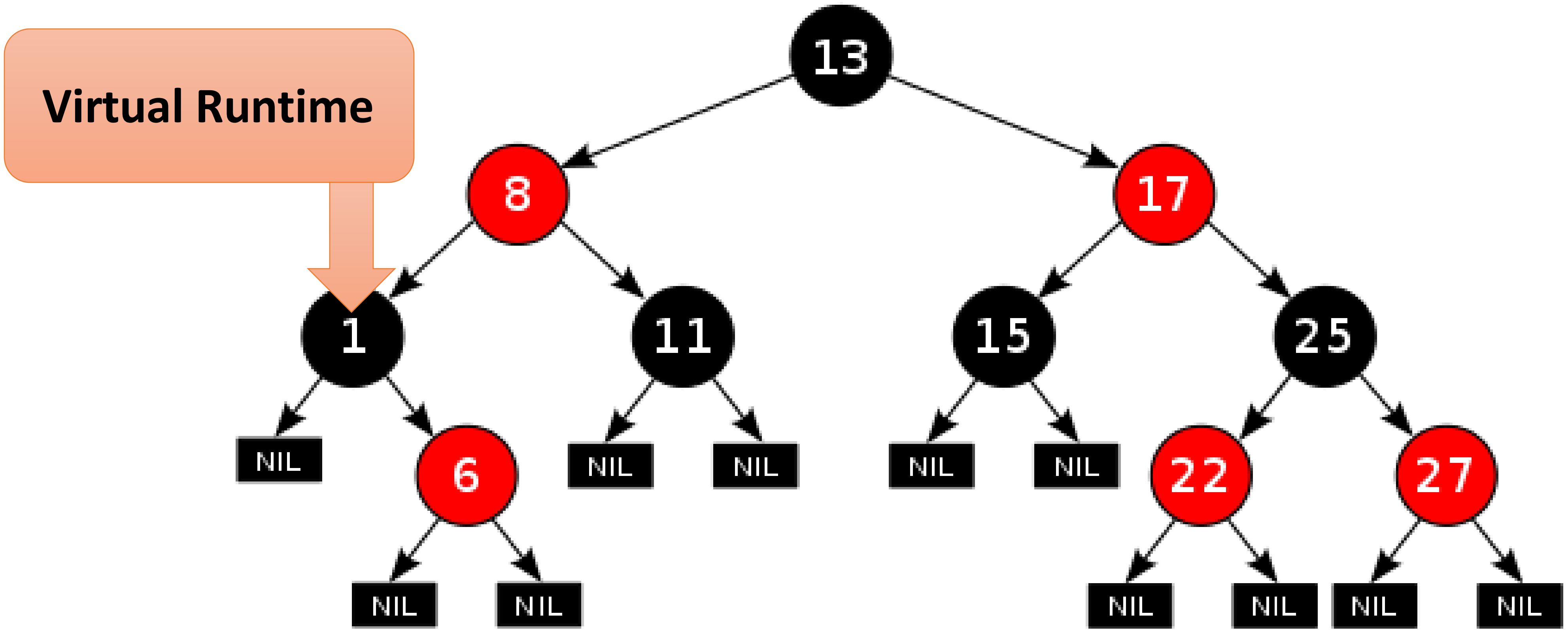

Less CPU-time
More need of the CPU

More CPU-time
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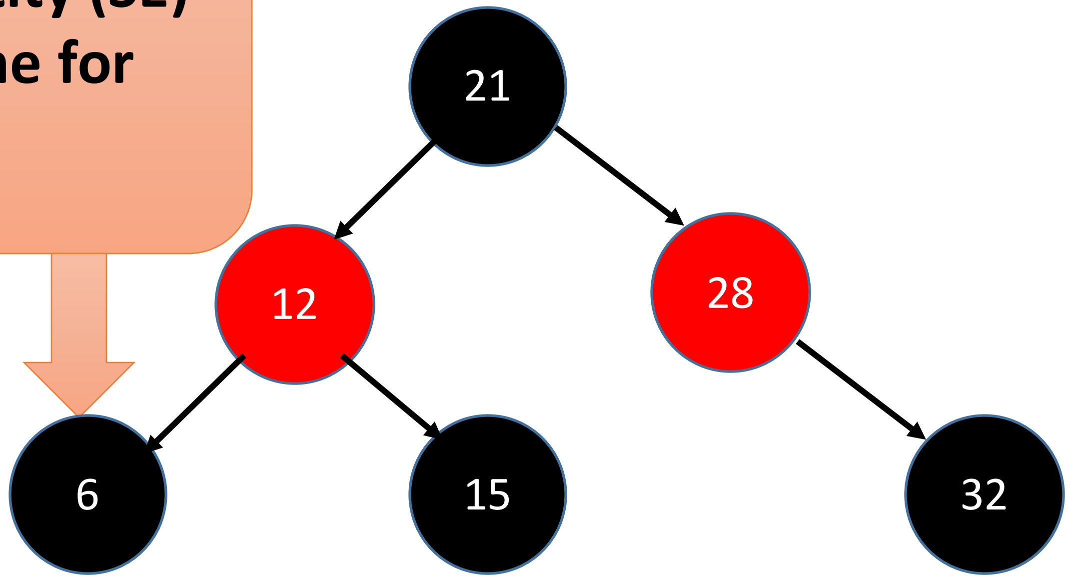
CFS in Action

Select the Scheduling Entity (SE) with minimum vruntime for execution



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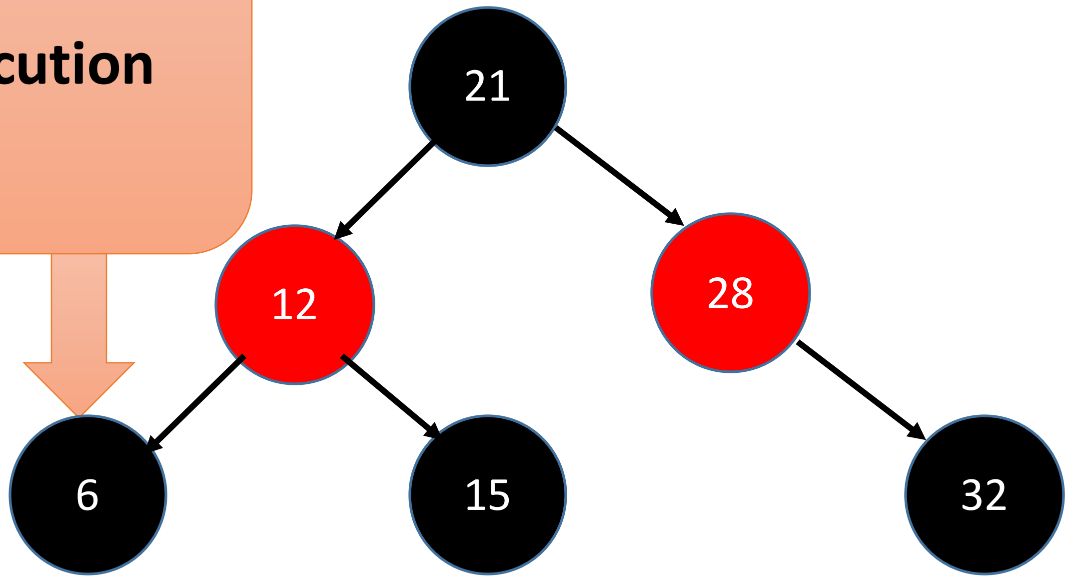
CFS in Action

Dequeue the SE for execution



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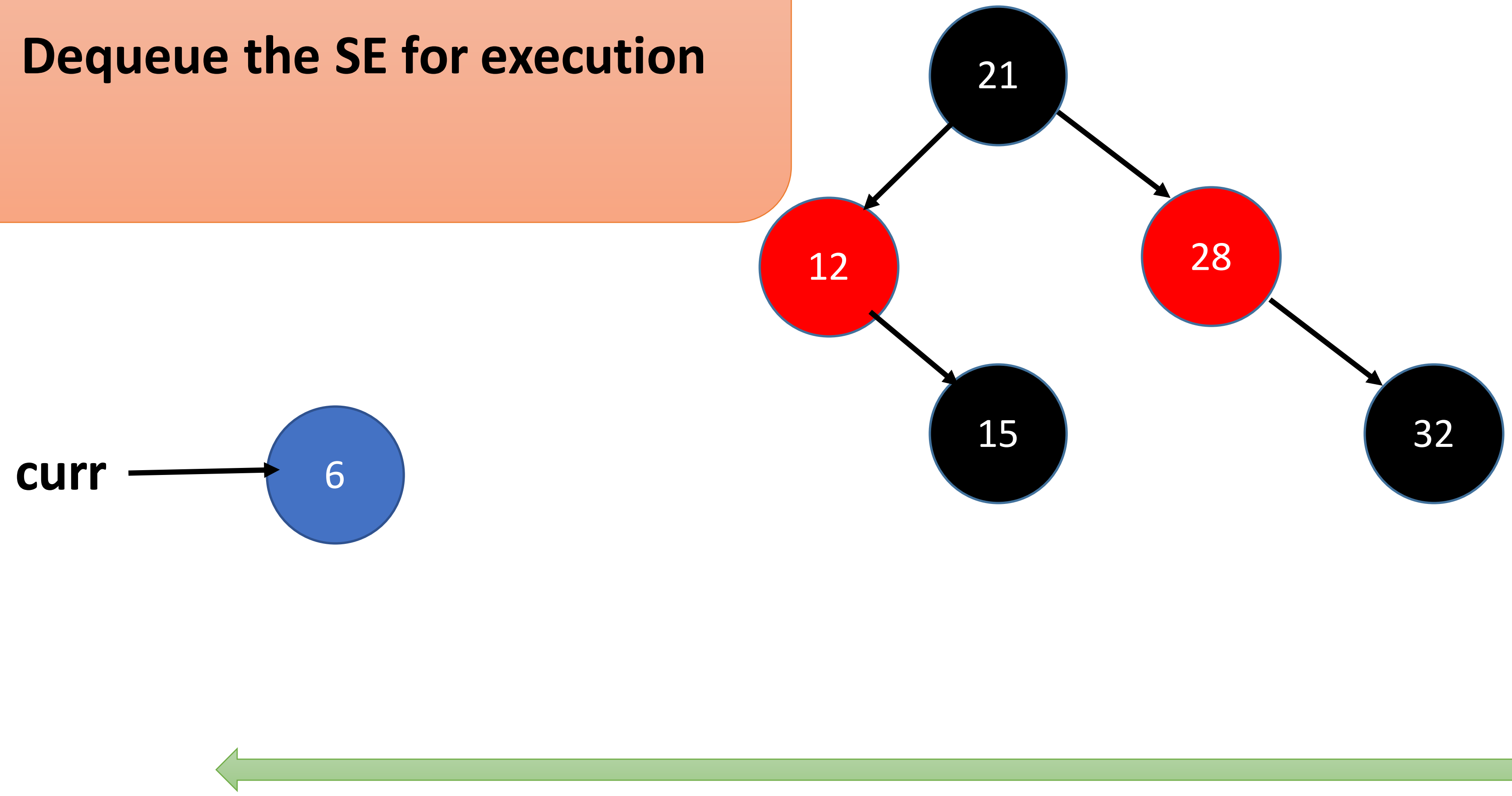

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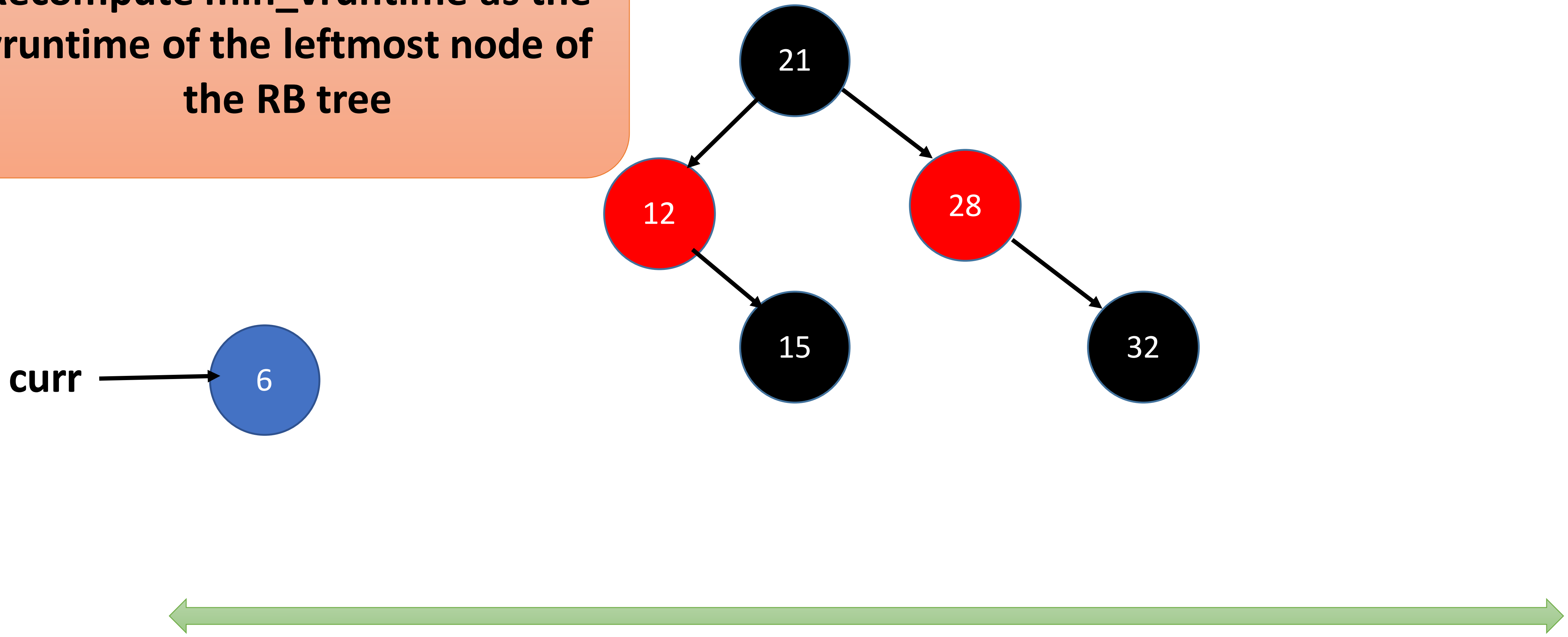
CFS in Action

Recompute min_vruntime as the vruntime of the leftmost node of the RB tree



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More need of the CPU

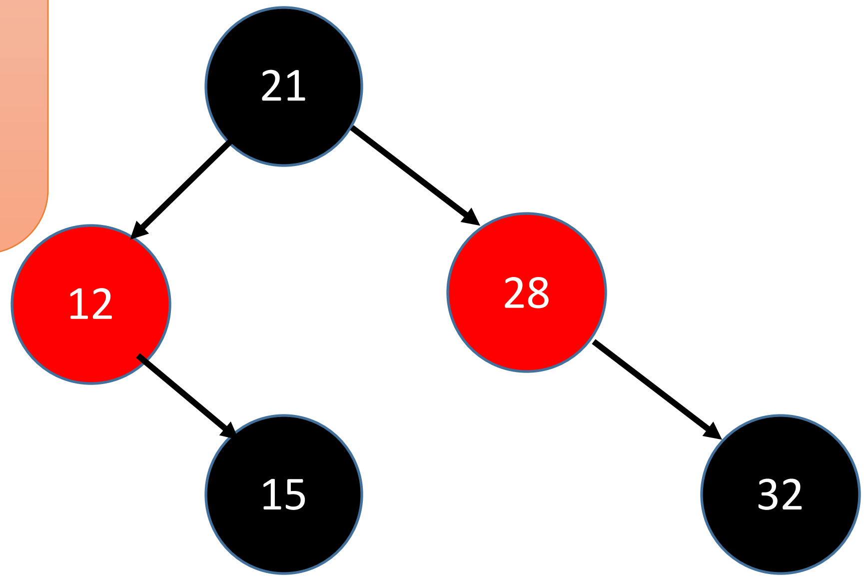
More CPU-time

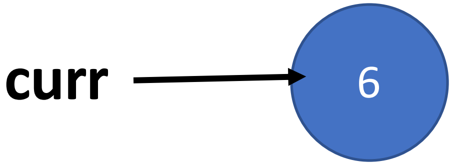
Less need of the CPU

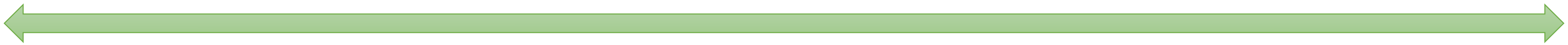
CFS in Action

Recompute min_vruntime as the vruntime of the leftmost node of the RB tree

min_vruntime = 12





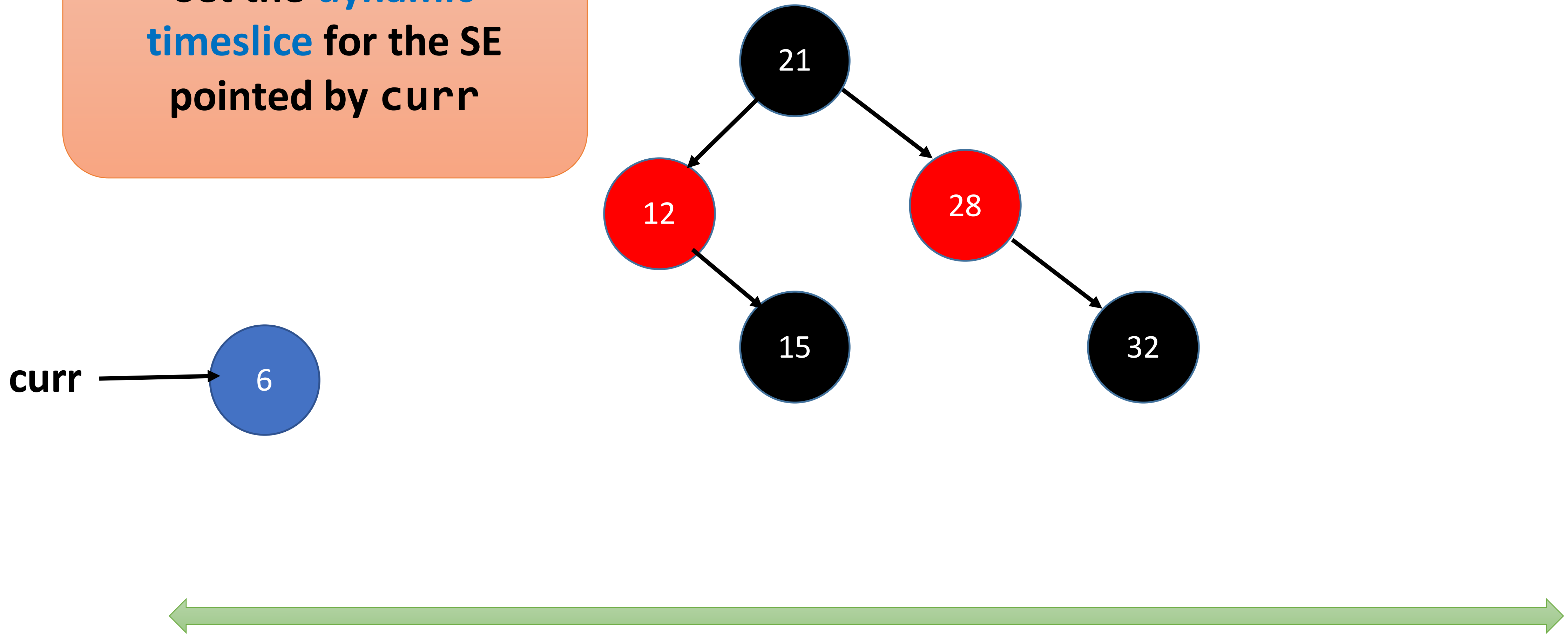


Less CPU-time
More need of the CPU

More CPU-time
Less need of the CPU

CFS in Action

Set the **dynamic timeslice** for the SE pointed by `curr`

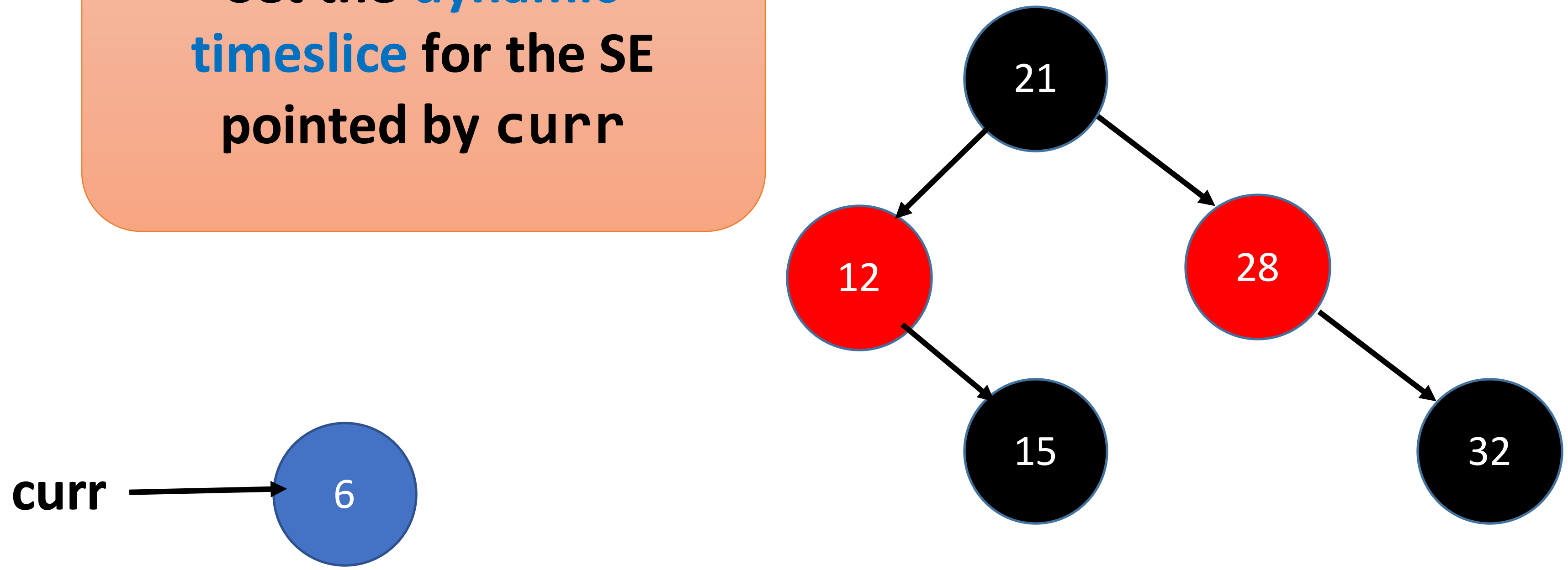


Less CPU-time
More need of the CPU

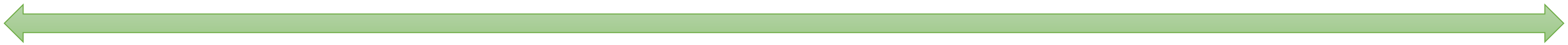
More CPU-time
Less need of the CPU

CFS in Action

Set the dynamic timeslice for the SE pointed by `curr`




```
slice = sched_period x (se->load.weight / cfs_rq->load)
```

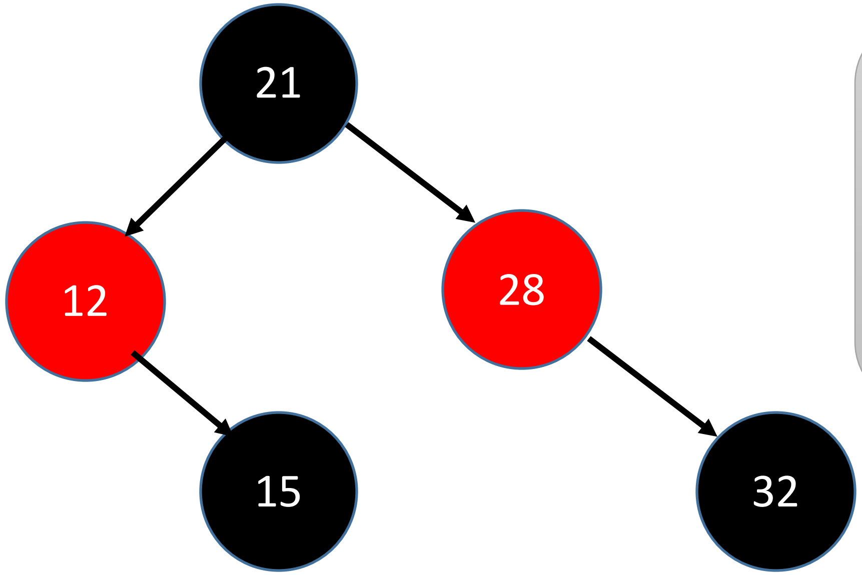


Less CPU-time
More need of the CPU

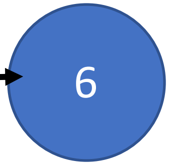
More CPU-time
Less need of the CPU

CFS in Action

Set the **dynamic timeslice** for the SE pointed by `curr`



curr



Remember, that the `sched_period` is dynamic

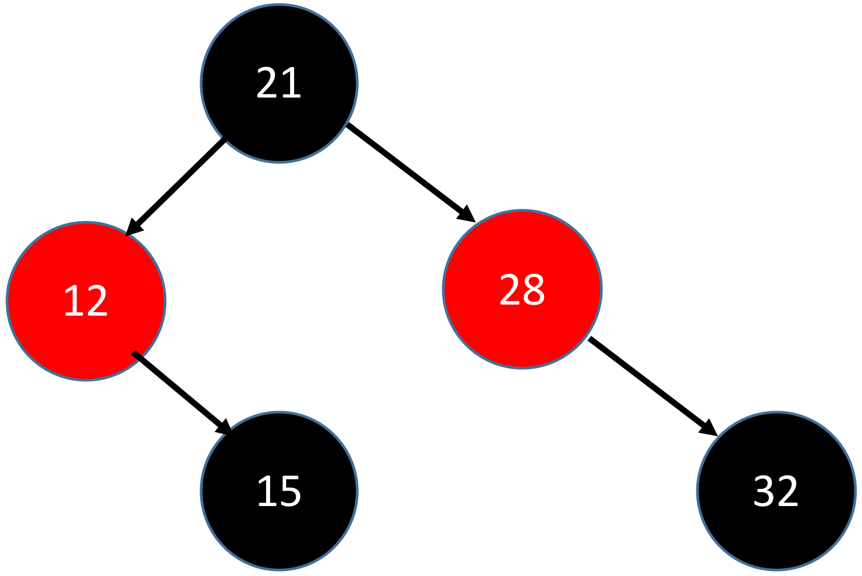
```
slice = sched_period x (se->load.weight / cfs_rq->load)
```

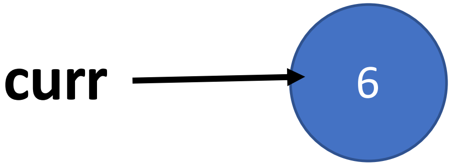
Less CPU-time
More need of the CPU

More CPU-time
Less need of the CPU

CFS in Action

Set the dynamic timeslice for the SE pointed by `curr`





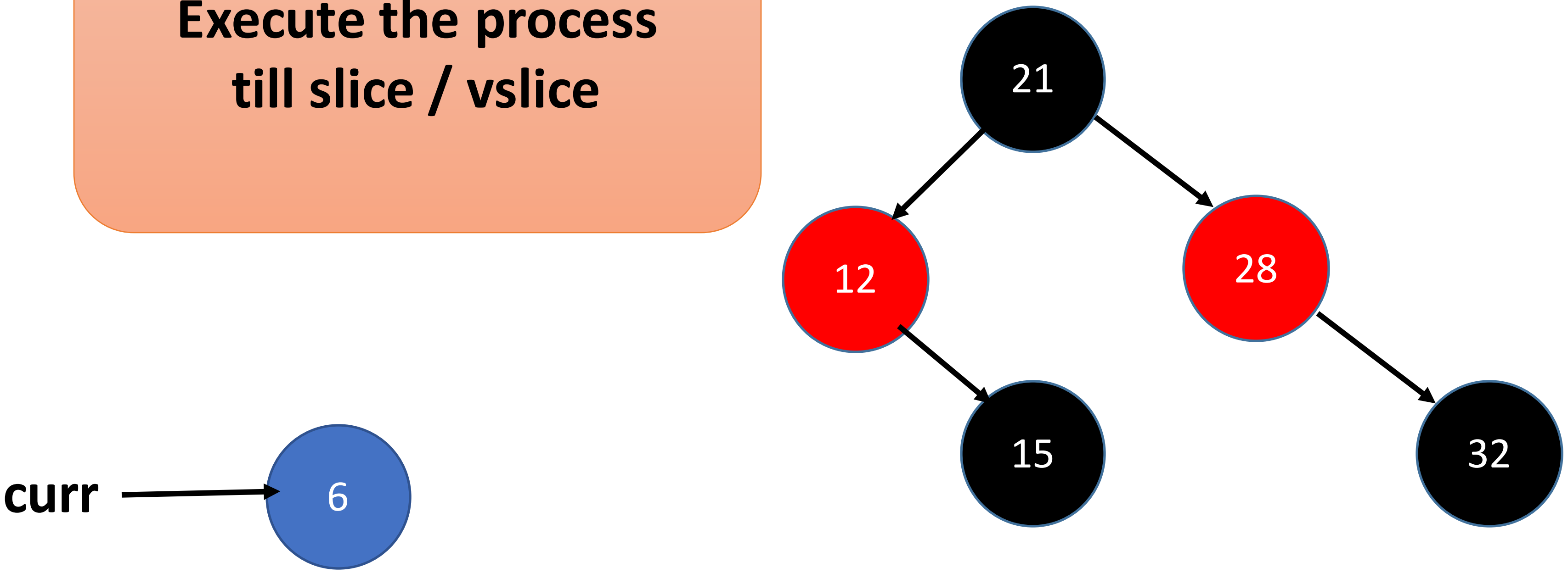

```
vslice = slice x (NICE_0_LOAD / se->load.weight)
```

Less CPU-time
More need of the CPU

More CPU-time
Less need of the CPU

CFS in Action

Execute the process till slice / vslice

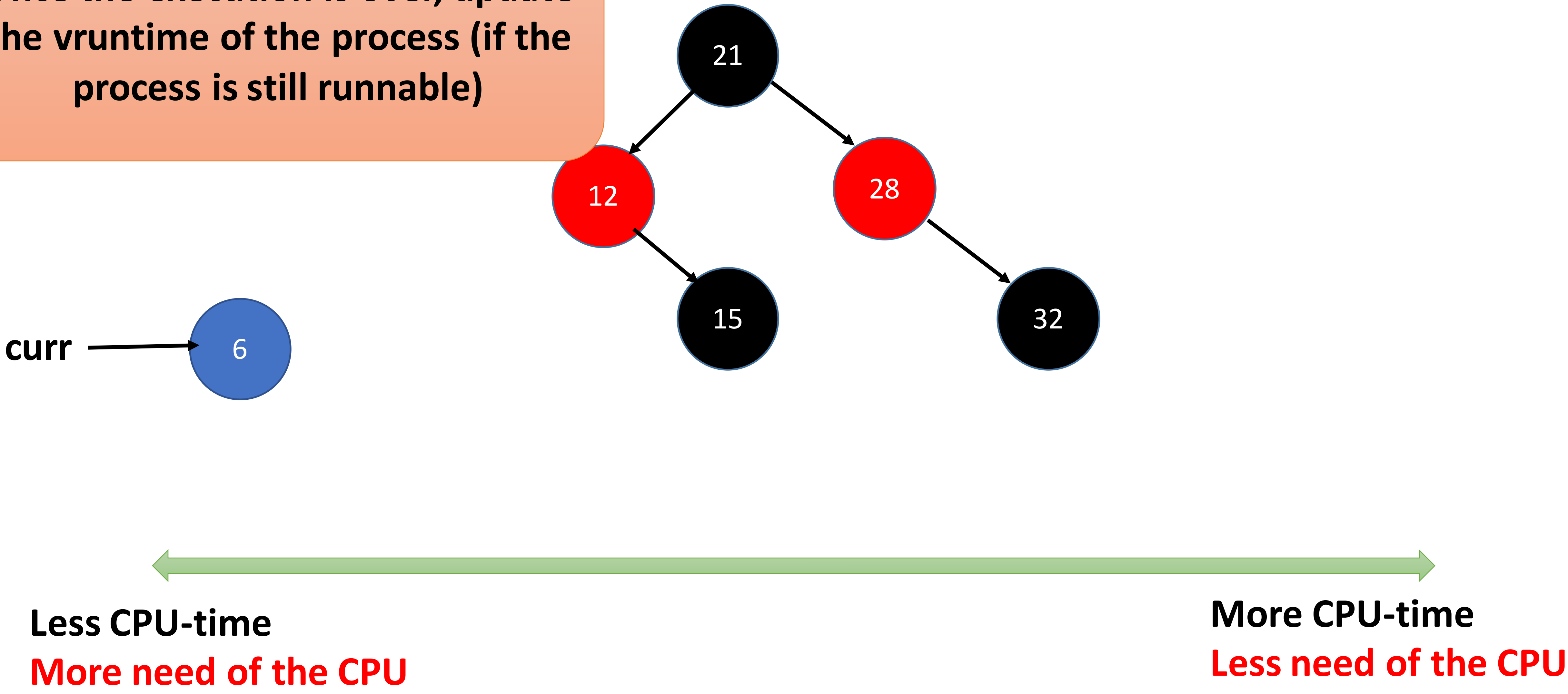


Less CPU-time
More need of the CPU

More CPU-time
Less need of the CPU

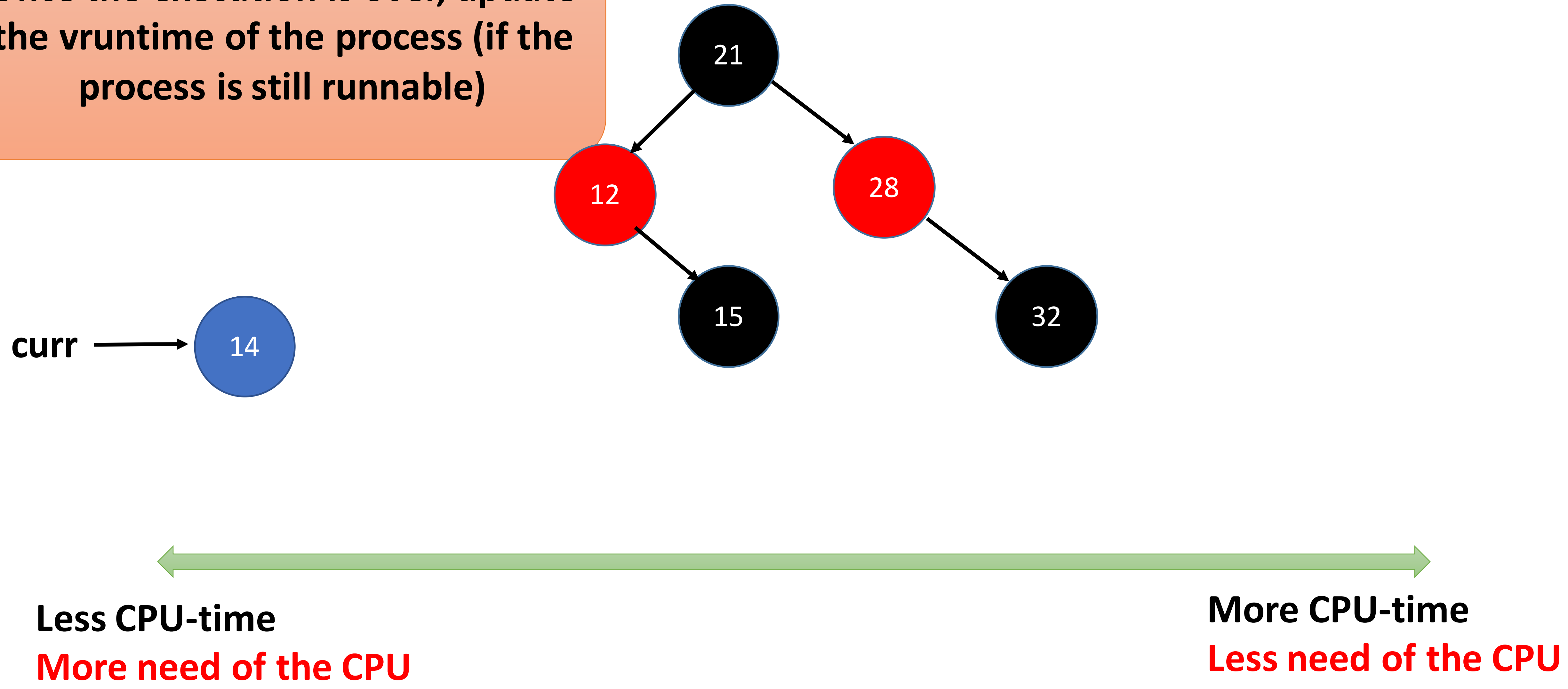
CFS in Action

Once the execution is over, update the vruntime of the process (if the process is still runnable)



CFS in Action

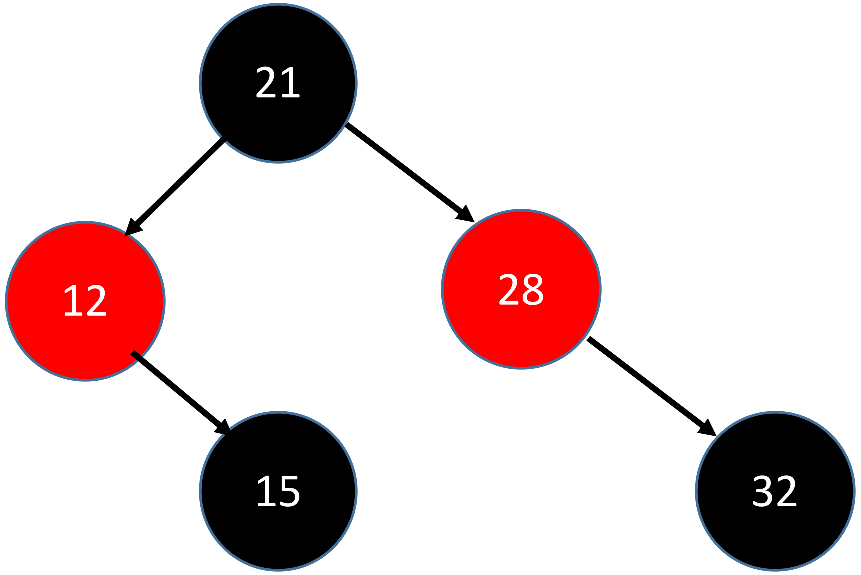
Once the execution is over, update the vruntime of the process (if the process is still runnable)

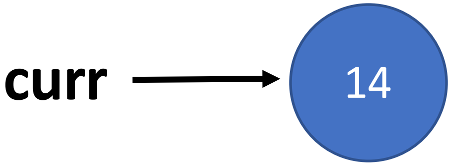


CFS in Action

Check with the cached value of min_vruntime

min_vruntime = 12





Less CPU-time

More need of the CPU

More CPU-time

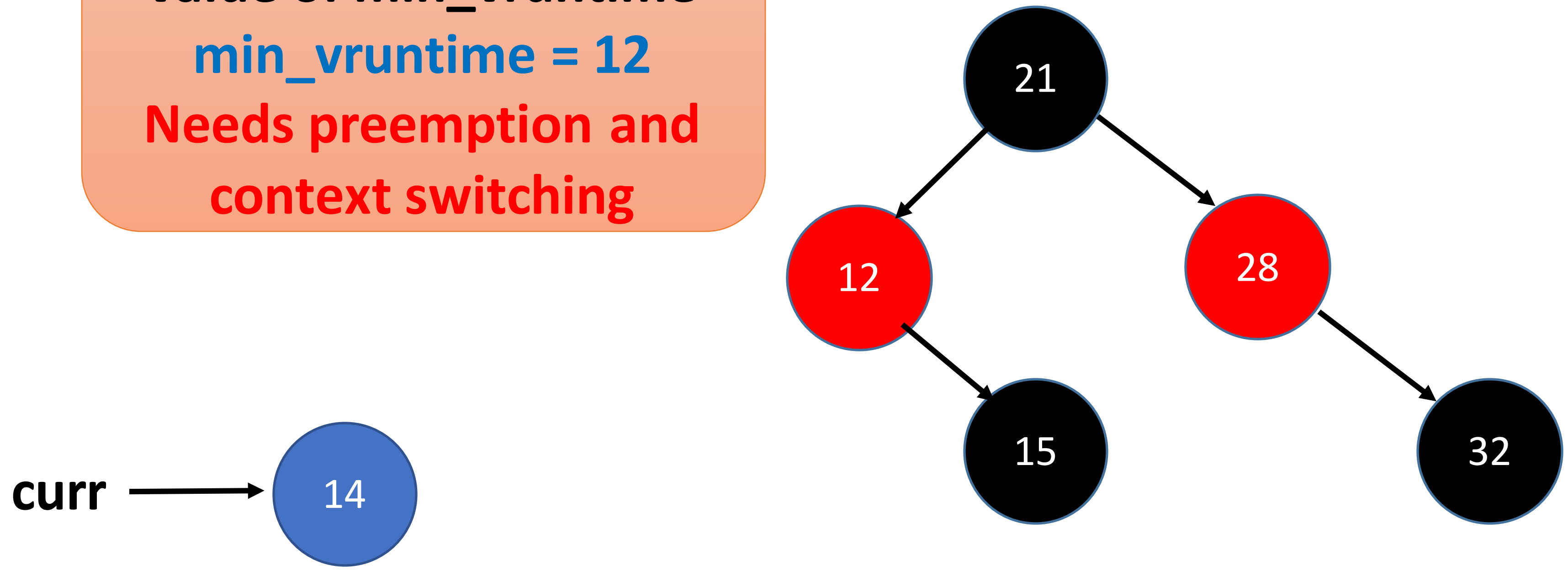
Less need of the CPU

CFS in Action

Check with the cached value of min_vruntime

min_vruntime = 12

Needs preemption and context switching



Less CPU-time

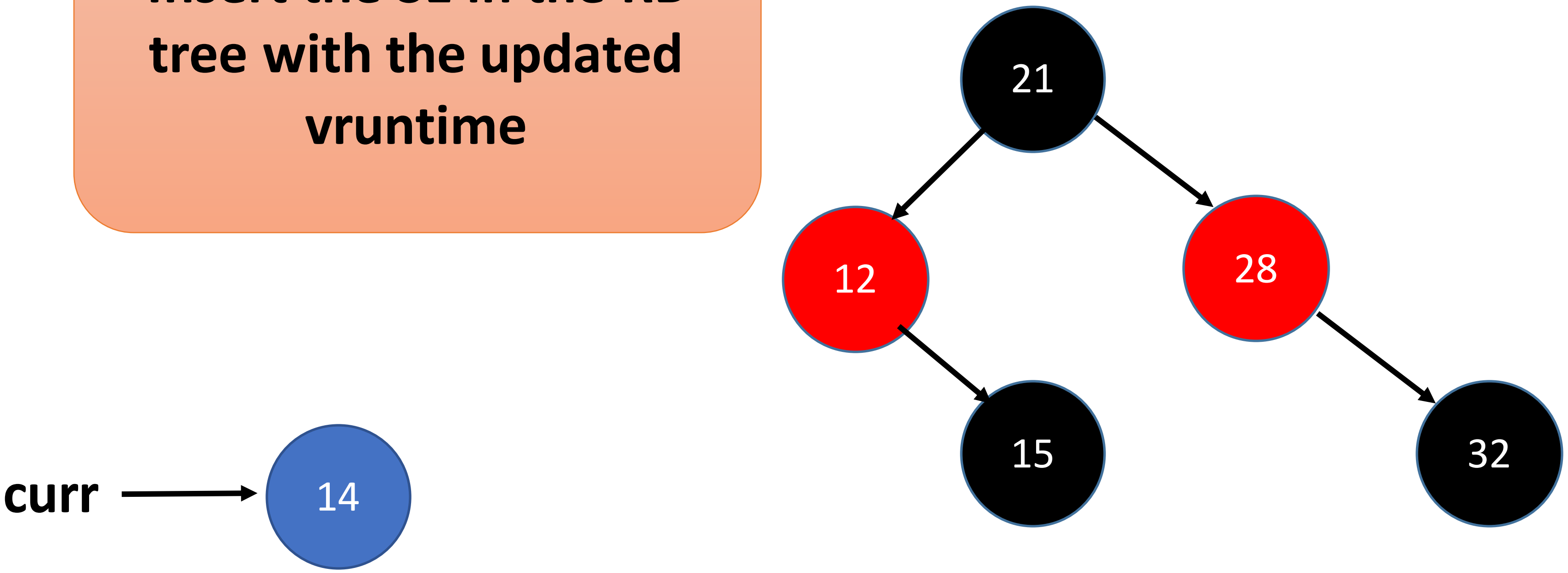
More need of the CPU

More CPU-time

Less need of the CPU

CFS in Action

Insert the SE in the RB tree with the updated vruntime



Less CPU-time
More need of the CPU

More CPU-time
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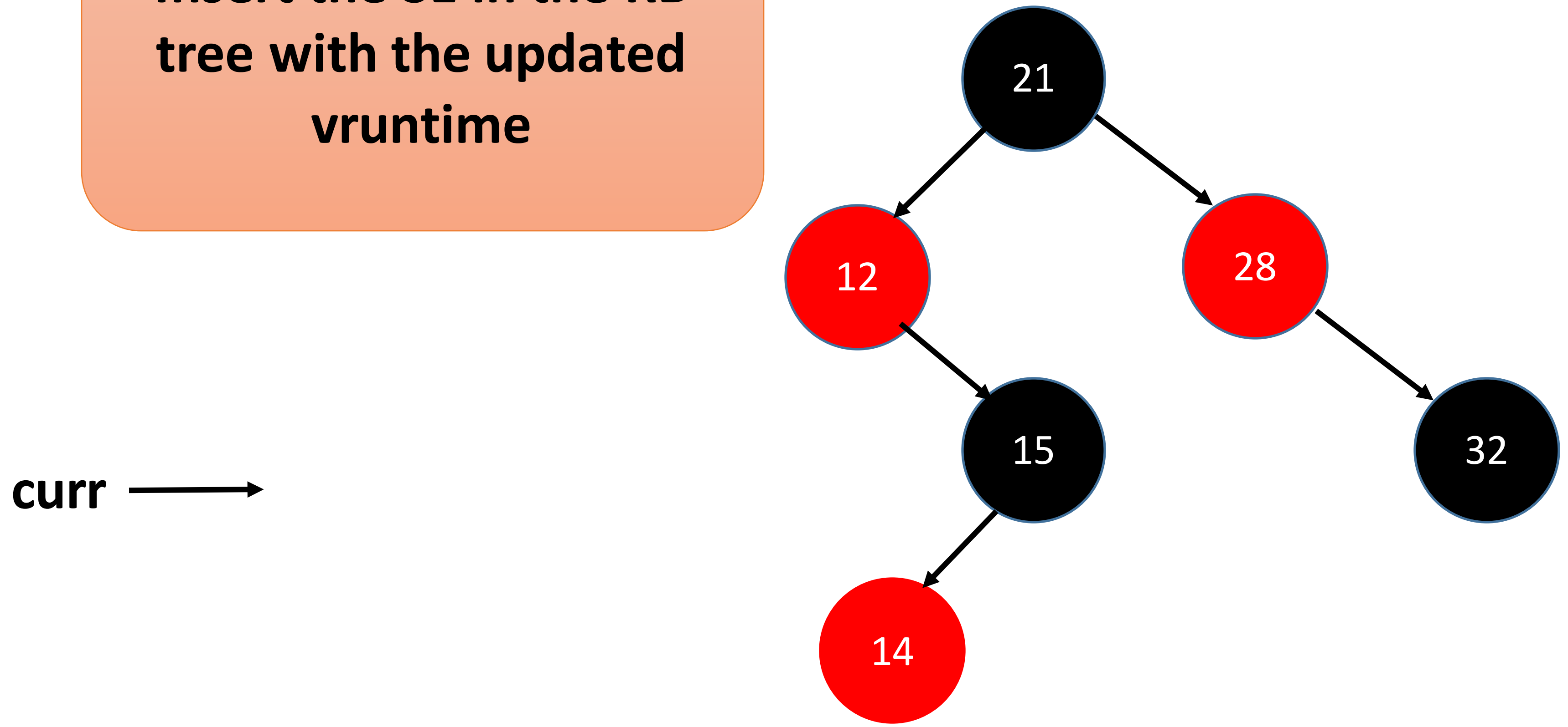
CFS in Action

Insert the SE in the RB tree with the updated vruntime



Less CPU-time

More need of the CPU

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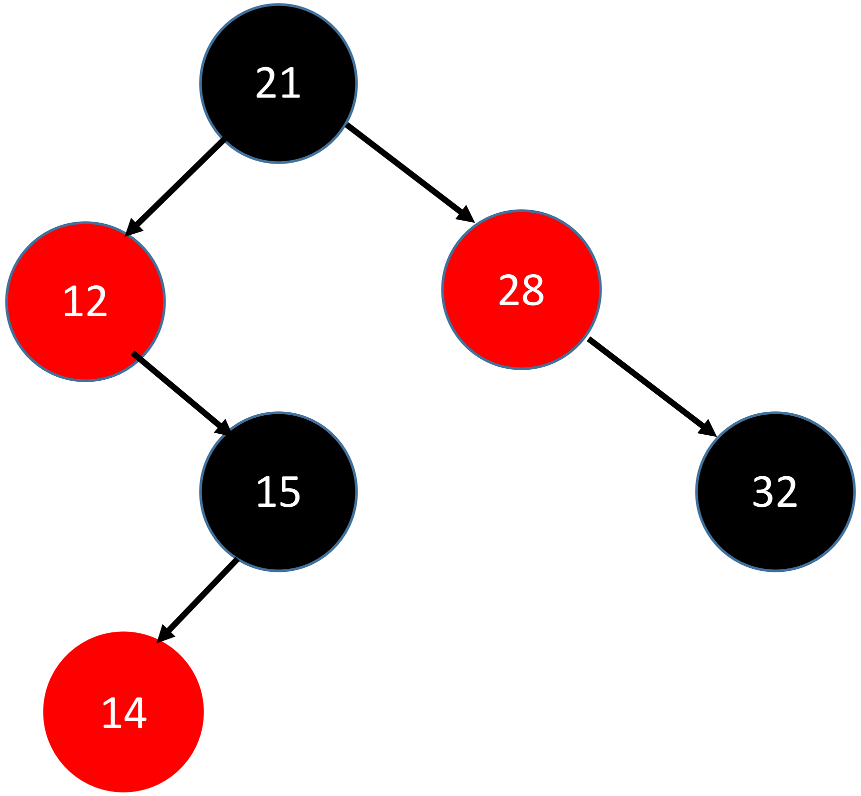
CFS in Action

Insert the SE in the RB tree with the updated vruntime



An AVL tree could result a better hight balancing – Why don't we use that?

curr →

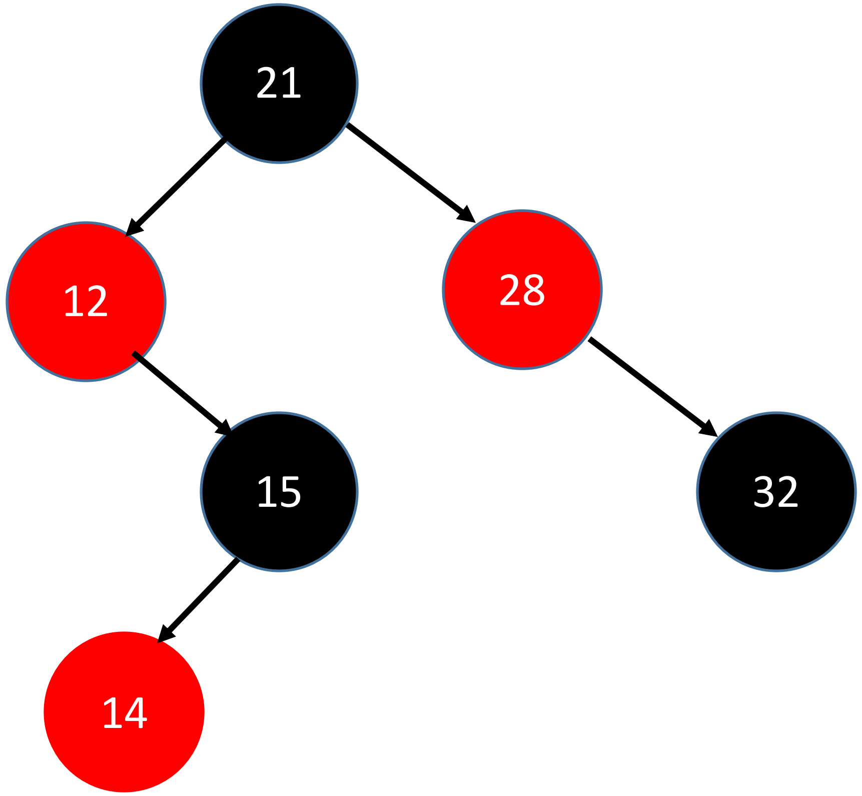
Less CPU-time
More need of the CPU

More CPU-time
Less need of the CPU

CFS in Action

Extract the leftmost node for scheduling, update min_vruntime , rebalance the tree

curr



Less CPU-time

More need of the CPU

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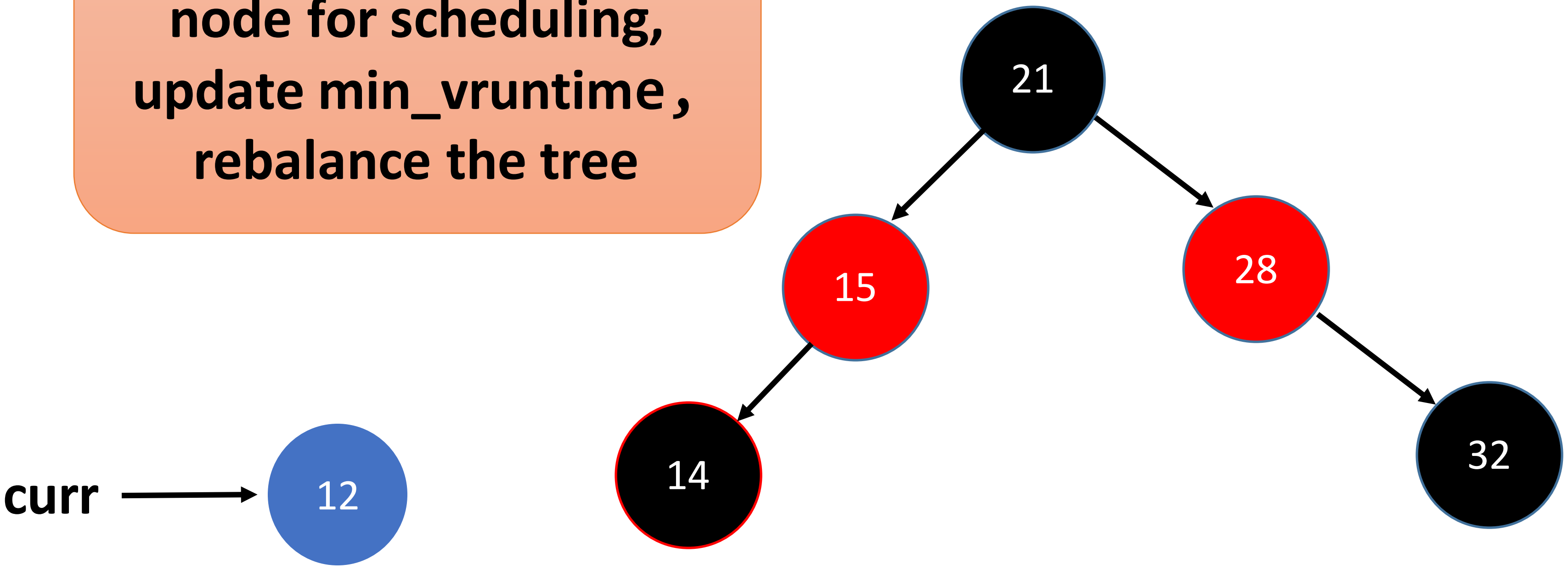
CFS in Action

Extract the leftmost node for scheduling, update min_vruntime , rebalance the tree



Less CPU-time
More need of the CPU

More CPU-time
Less need of the CPU

CFS in Action – Core Premitives

- When a task is executing, its vruntime increases, so it moves to the right in the red-black tree

CFS in Action – Core Premitives

- When a task is executing, its vruntime increases, so it moves to the right in the red-black tree
  - **Interactive processes**: Have small CPU burst -> low vruntime
    - Remains at the left side of the RB tree, gets scheduled quickly
    - Have higher priority, virtual clock ticks slowly – spends more time in the CPU whenever needed

CFS in Action – Core Premitives

- When a task is executing, its vruntime increases, so it moves to the right in the red-black tree

- Virtual clock ticks slowly for higher priority tasks, so they move slower to the right of the RB tree, and their chance to be scheduled again soon is bigger than lower priority tasks

CFS in Action – Core Premitives

- When a task is executing, its vruntime increases, so it moves to the right in the red-black tree
- Virtual clock ticks more slowly for higher priority tasks, so they move slower to the right of the RB tree, and their chance to be scheduled again soon is bigger than lower priority tasks
- When a process sleeps, its vruntime remains unchanged.

CFS in Action – Core Primitives

- When a task is executing, its vruntime increases, so it moves to the right in the red-black tree
- Virtual clock ticks more slowly for higher priority tasks, so they move slower to the right of the RB tree, and their chance to be scheduled again soon is bigger than lower priority tasks
- When a process sleeps, its vruntime remains unchanged
- New processes start with `min_vruntime` of the RB tree, to allow them to get scheduled quickly

Happy Learning