CPU Scheduling

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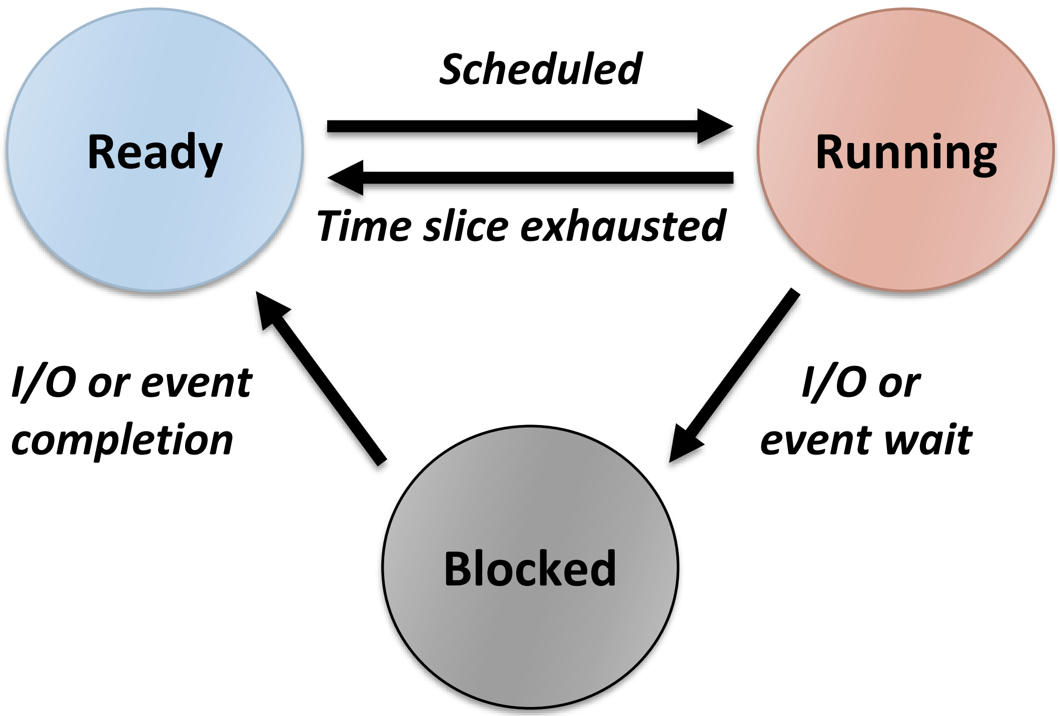
CPU Scheduling

- A policy deciding which process to run next, given a set of runnable tasks (processes or threads)
  - Happens frequently, hence should be fast

- Mechanism
  - ______________________

- Policy
  - ______________________
  - ______________________



Preemptive (or not)

- Non-preemptive scheduler
  - The scheduler waits for the running task to voluntarily yield the CPU
    - cf.) `yield()`
  - Tasks should be ___________

- Preemptive scheduler
  - The scheduler can interrupt a task and force a context switch
  - Implemented using periodic timer interrupts

  - What if a task is preempted in the midst of updating the shared data?
  - What if a process in a system call is preempted?

Work-Conserving (or not)

- Work-conserving scheduler
  - Never leave a resource idle when someone wants it
  - e.g., Linux CPU scheduler (ideally)
- Non-work-conserving scheduler
  - May leave the resource idle despite the presence of jobs
  - e.g., Server waits for short job before starting on a big job
  - e.g., Anticipatory I/O scheduler: waits for a short time after a read operation in anticipation of another close-by read requests to overcome "deceptive idleness"

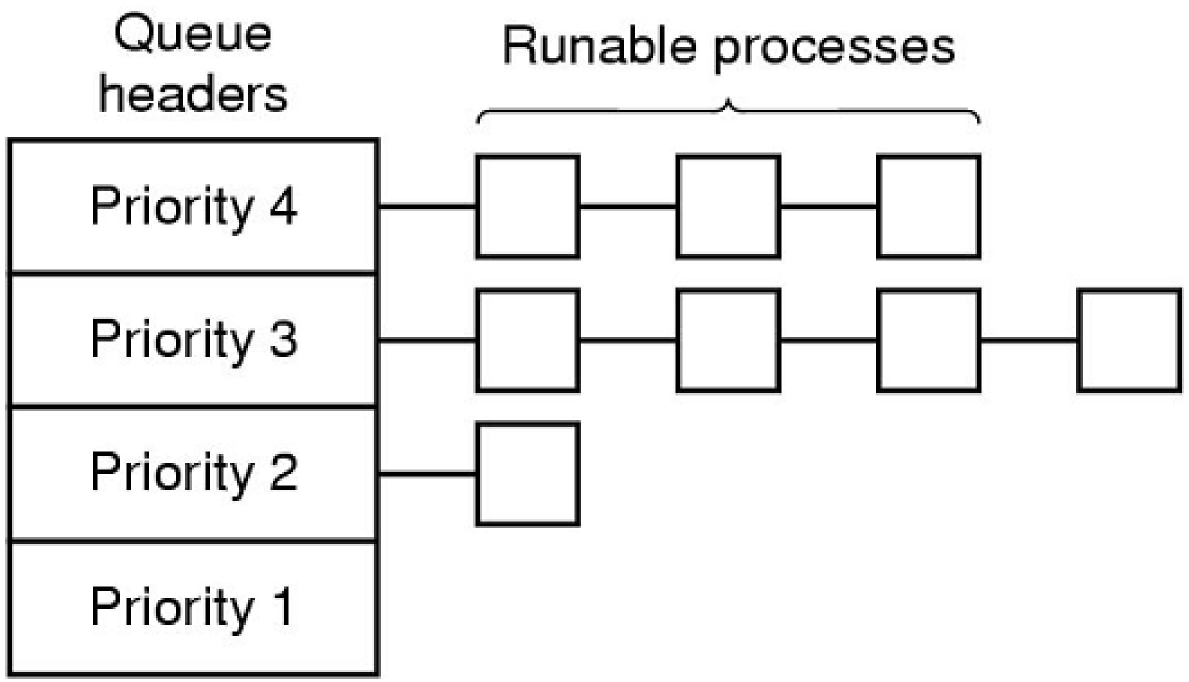
(Static) Priority Scheduling

- Each task has a (static) priority
  - cf.) `nice()`, `renice()`, `setpriority()`, `getpriority()`
- Choose the task with the highest priority to run next
- Round-robin or FIFO within the same priority
- Can be either preemptive or non-preemptive

- Starvation problem
  - If there is an endless supply of high priority tasks, no low priority task will ever run

Priority Scheduling

- Priority is dynamically adjusted at run time
- Modeled as a Multi-level Feedback Queue (MLFQ)
  - A number of distinct queues for each priority level
  - Priority scheduling between queues, round-robin in the same queue



UNIX Scheduler

- MLFQ
  - Preemptive priority scheduling
  - Time-shared based on time slice
  - Tasks dynamically change priority
- Aging for avoiding starvation
  - Increase priority as a function of wait time
  - Decrease priority as a function of CPU time
- Favor interactive tasks over CPU-bound tasks
- Priority vs. time slice?
- Many ugly heuristics have been explored in this area

Linux Scheduler Evolution

Kernel version	CPU Scheduler
Linux 2.4	• Epoch-based priority scheduling • O(*n*) scheduler
Linux 2.6 ~ 2.6.22	• Active / expired arrays with bitmaps • Per-core run queue • O(1) scheduler
Linux 2.6.23 ~	• CFS (Completely Fair Scheduler) by Ingo Molnar
Linux 3.14 ~	• Sporadic task model deadline scheduling (SCHED_DEADLINE)

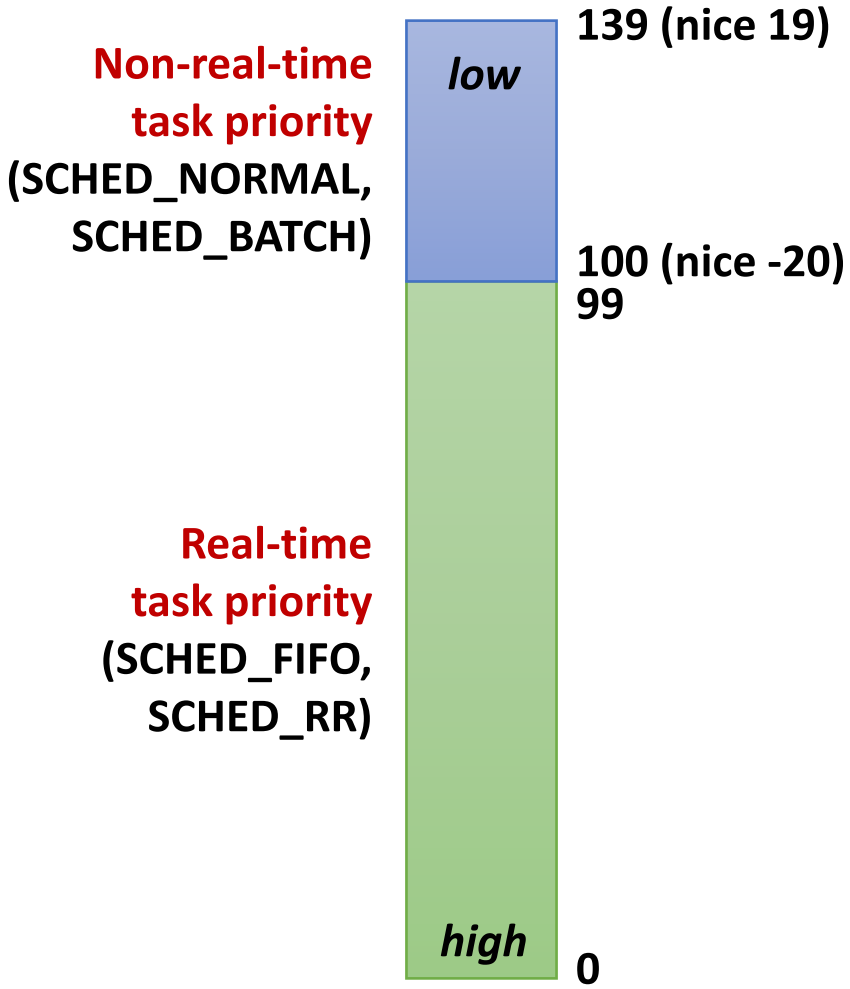
Linux Scheduling Classes

Class	Description	Policy
DL	• For real-time tasks with deadline • Highest priority	SCHED_DEADLINE
RT	• For real-time tasks	SCHED_FIFO SCHED_RR
Fair	• For time-sharing tasks	SCHED_NORMAL SCHED_BATCH
Idle	• For per-CPU idle tasks	SCHED_IDLE

Linux CFS
(Completely Fair Scheduler)

Linux Task Priority

- Total 140 levels (0 ~ 139)
  - A smaller value means higher priority
- Setting priority for non-real-time tasks
  - `nice()`, `setpriority()`
  - -20 ≤ nice value ≤ 19
  - Default nice value = 0 (priority value 120)
- Setting priority for real-time tasks
  - `sched_setattr()`
  - Static priority for SCHED_FIFO & SCHED_RR
  - Runtime, deadline, period for SCHED_DEADLINE



Proportional Share Scheduling

- Basic concept
  - A weight value is associated with each task
  - The CPU is allocated to task in proportion to its weight

Task A (weight 2)

Task B (weight 1)

Task C (weight 4)

Task D (weight 1)

Task A's share = $\frac{weight_A}{\sum weight_i} = \frac{2}{8} = 25.0\%$

Nice to Weight

- How to map nice values to weights?
  - Wants a task to get ~10% less CPU time when it goes from nice i to nice $i+1$
  - This will make another task remained on nice i have ~10% more CPU time
  - weight(i)/weight($i+1$) = 0.55/0.45 = 1.22 (or ≃ 25% increase)
- Examples
  - T_1 (nice 0), T_2 (nice 1)
    - T_1: 1024/(1024+820) = 55.5%
    - T_2: 820/(1024+820) = 44.5%
  - + T_3 (nice 1)
    - T_1: 1024/(1024+820*2) = 38.4%
    - T_2: 820/(1024+820*2) = 30.8%
    - T_3: 820/(1024+820*2) = 30.8%

```
const int sched_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,
};
```

Virtual Runtime

- Approximate the "ideal multitasking" that CFS is modeling
- Normalize the actual runtime to the case with nice value 0

$$VR(T) = \frac{Weight_0}{Weight(T)} \times PR(T) = \left(Weight_0 \times \boxed{\frac{2^{32}}{Weight(T)}} \times PR(T)\right) \gg 32$$

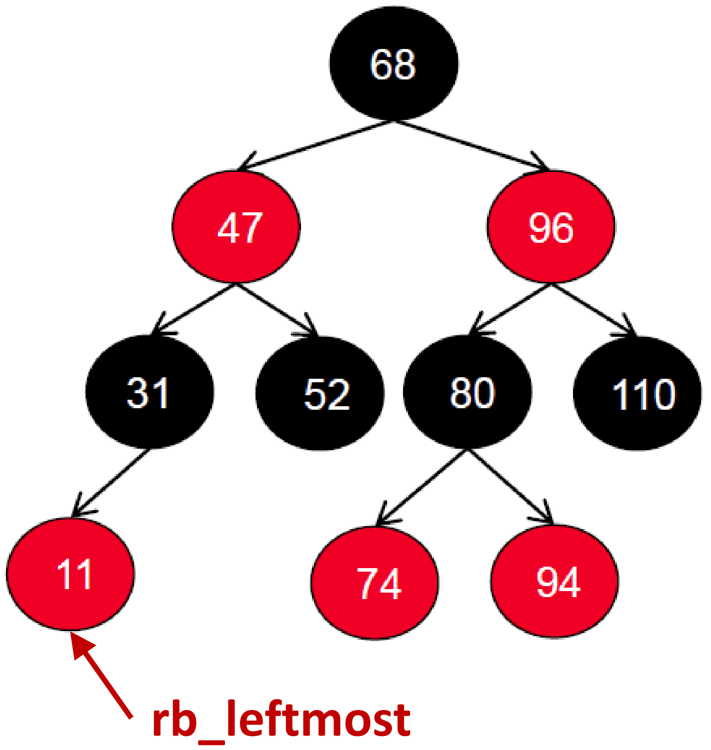
precomputed:
`sched_prio_to_wmult[]`

  - *$Weight_0$*: the weight of nice value 0
  - *Weight(T)*: the weight of the task T
  - *PR(T)*: the actual runtime of the task T
  - *VR(T)*: the virtual runtime (*vruntime*) of the task T

- For a high-priority task, its *vruntime* increases slowly

Runqueue

- CFS maintains a red-black tree where all runnable tasks are sorted by *vruntime*
  - Self-balancing binary search tree
  - The path from the root to the farthest leaf is no more than twice as long as the path to the nearest leaf
  - Tree operations in O(log N) time
  - The leftmost node indicates the smallest *vruntime*



- Choose the task with the smallest virtual runtime (*vruntime*)
  - Small virtual runtime means that the task has received less CPU time than what it should have received

Timeslice

- The time a task runs before it is preempted
  - It gives each runnable task a slice of the CPU's time
  - The length of timeslice of a task is proportional to its weight

$$TS(T) = \frac{Weight(T)}{\sum_{T_i\ in\ RQ} Weight(T_i)} \times P$$

  - *TS(T)*: Ideal runtime for the task *T*
  - *P*: Scheduling period

$$P = \begin{cases} \text{sysctl\_sched\_latency}, & \textit{if } n < \textit{sched\_nr\_latency} \\ \text{sysctl\_sched\_min\_granularity} * n, & \textit{otherwise} \end{cases}$$

sysctl_sched_latency:
Targeted preemption latency for CPU-bound tasks (6ms*(1+log #cores) by default)

sysctl_sched_min_granularity:
Minimal preemption granularity for CPU-bound tasks (0.75ms*(1+log #cores) by default)

sched_nr_latency = **sysctl_sched_latency / sysctl_sched_min_granularity (8 by default)**

Scheduling Flow

- Timer interrupt handler calls the CFS scheduler
- Updates the *vruntime* of the current task
- If preemption is needed, mark the NEED_RESCHED flag
  - When the current task has run beyond its timeslice
  - If the current task's *vruntime* exceeds the *vruntime* of the leftmost task in RB tree
- On exit, `schedule()` is called when NEED_RESCHED flag is set
  - Clear the NEED_RESCHED flag and enqueue the previous task
  - Pick the next task to run
  - Context switch to the next task
- The current task can be also preempted when a higher-priority task is inserted into the runqueue

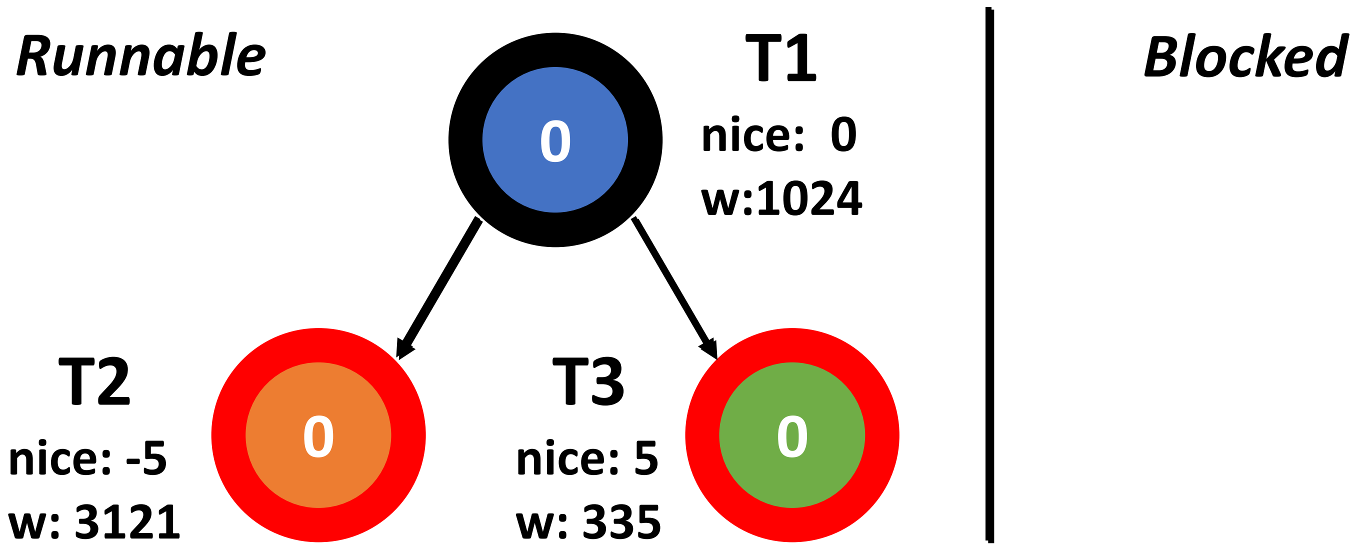
Example:

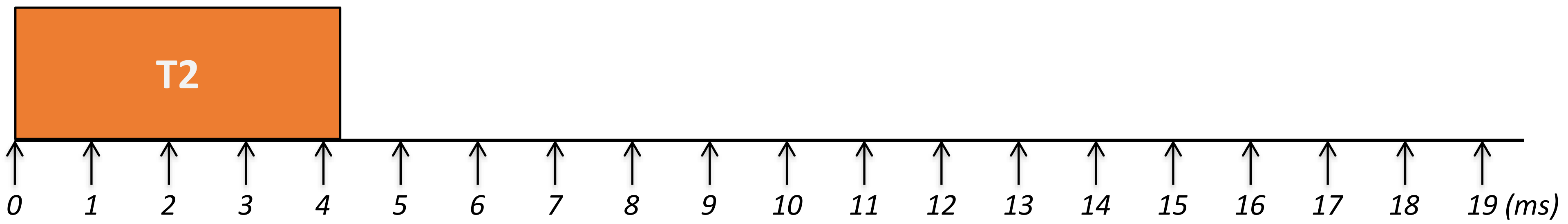
- Initially choose the leftmost task, T2, in this case
- But how long?

$$TS(T2)$$

$$= \frac{3121}{1024 + 3121 + 335} \times P$$

$$= 4.18\,ms$$





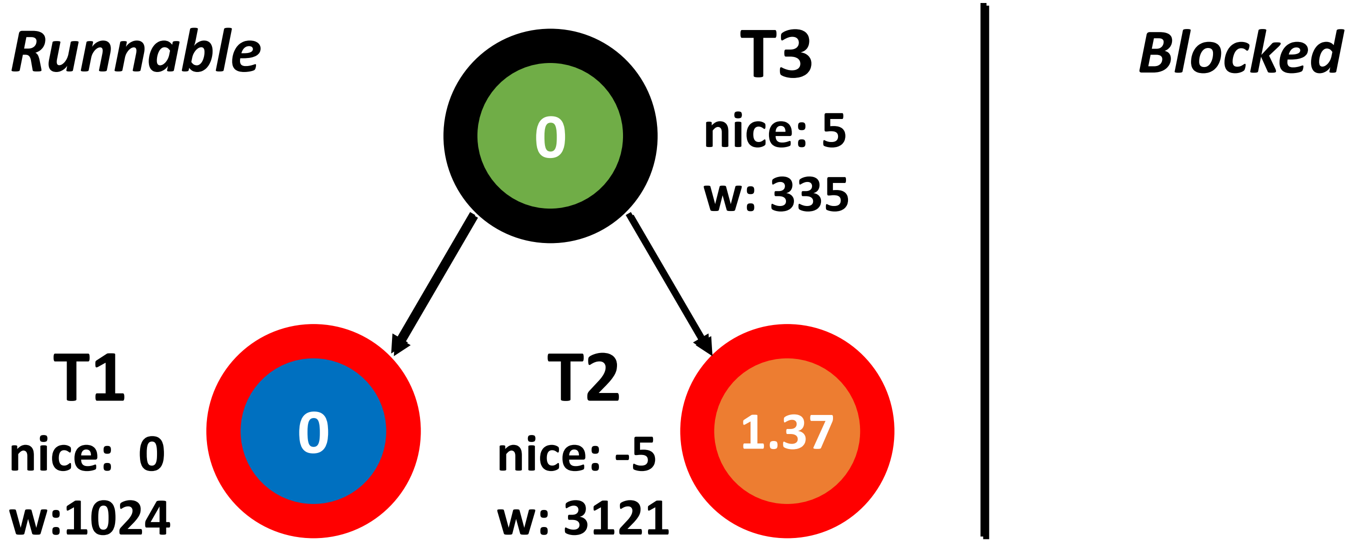
Example:

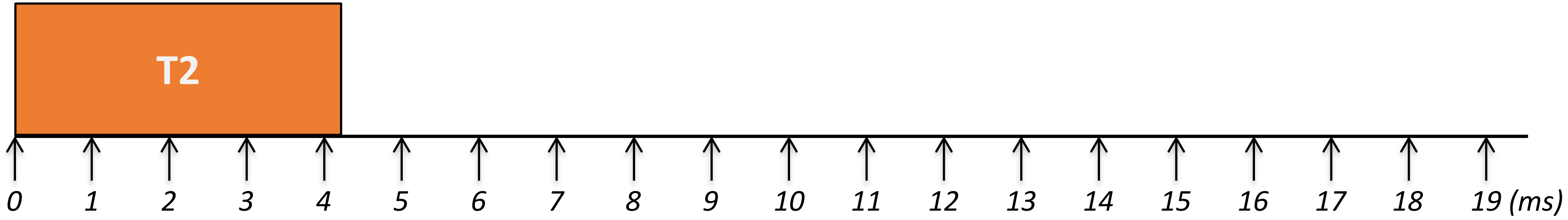
- Update T2's vruntime

$$VR(T2)$$

$$= \frac{1024}{3121} \times 4.18$$

$$= 1.37$$

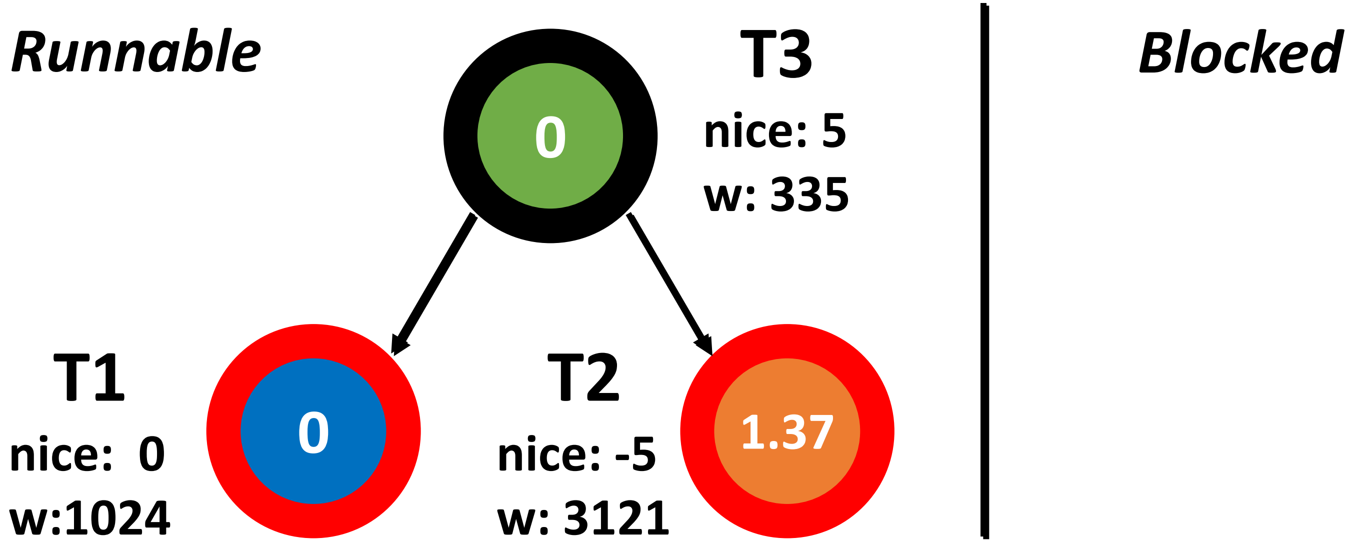


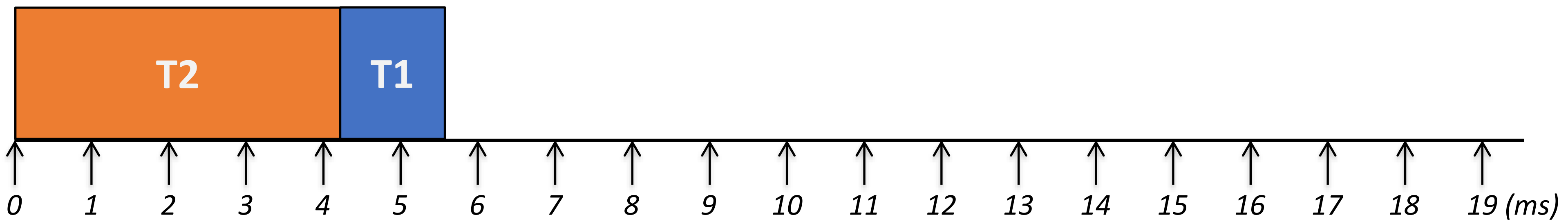


Example:

- Now choose T1

$$TS(T1) = \frac{1024}{1024 + 3121 + 335} \times P = 1.37\ ms$$

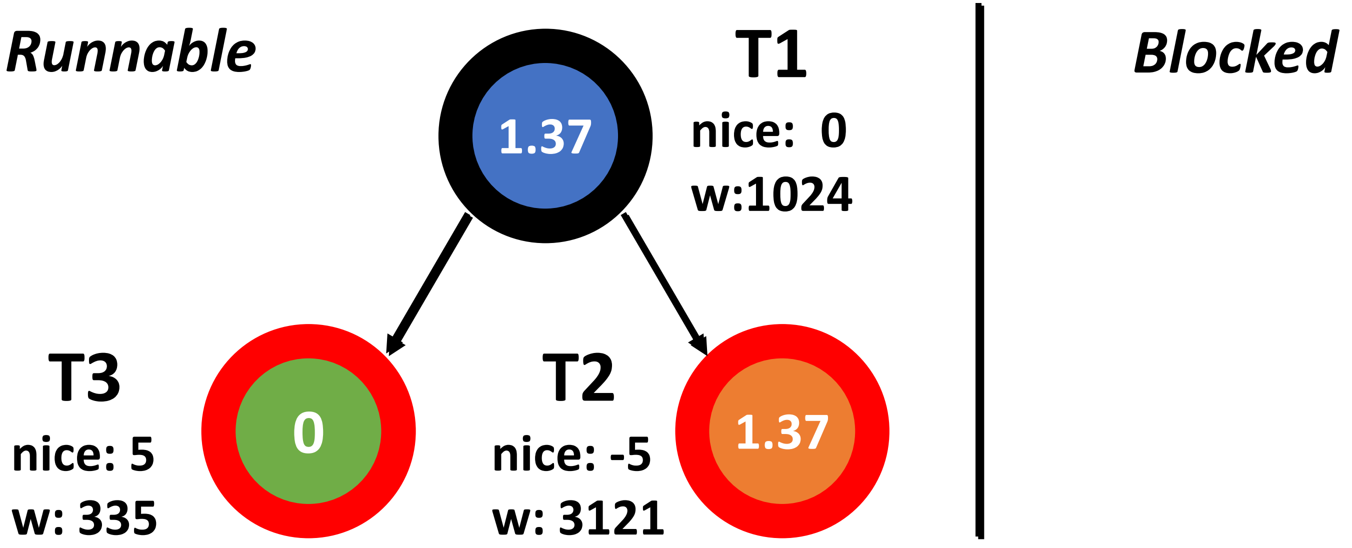


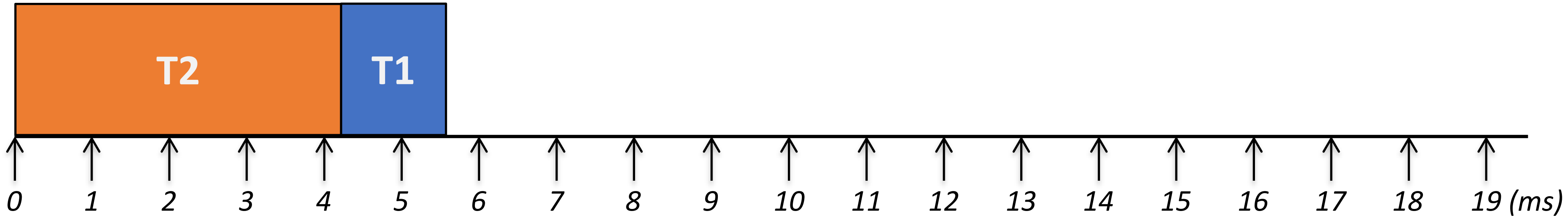


Example:

- Update T1's runtime

$$VR(T1) = \frac{1024}{1024} \times 1.37 = 1.37$$

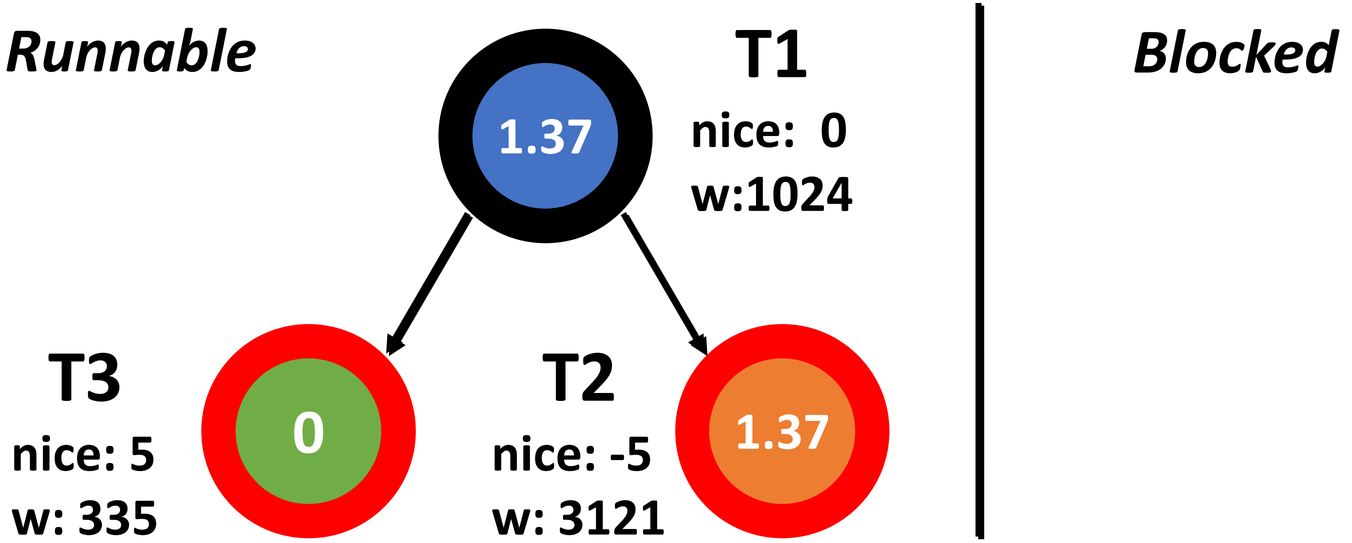


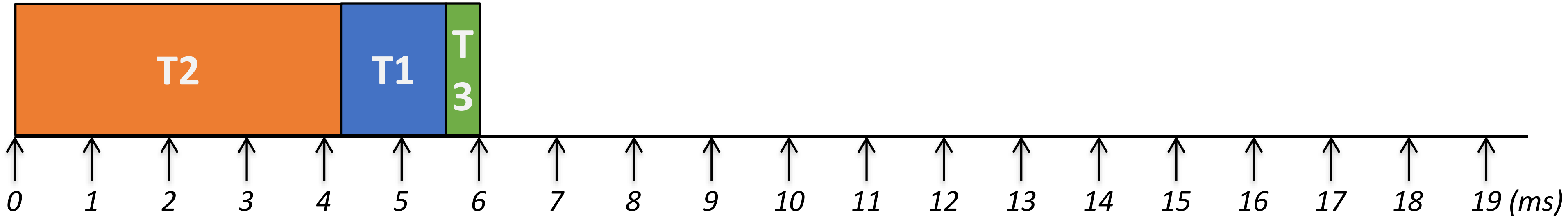


Example:

- Choose T3

$$TS(T3)$$
$$= \frac{335}{1024 + 3121 + 335} \times P$$
$$= 0.45\ ms$$





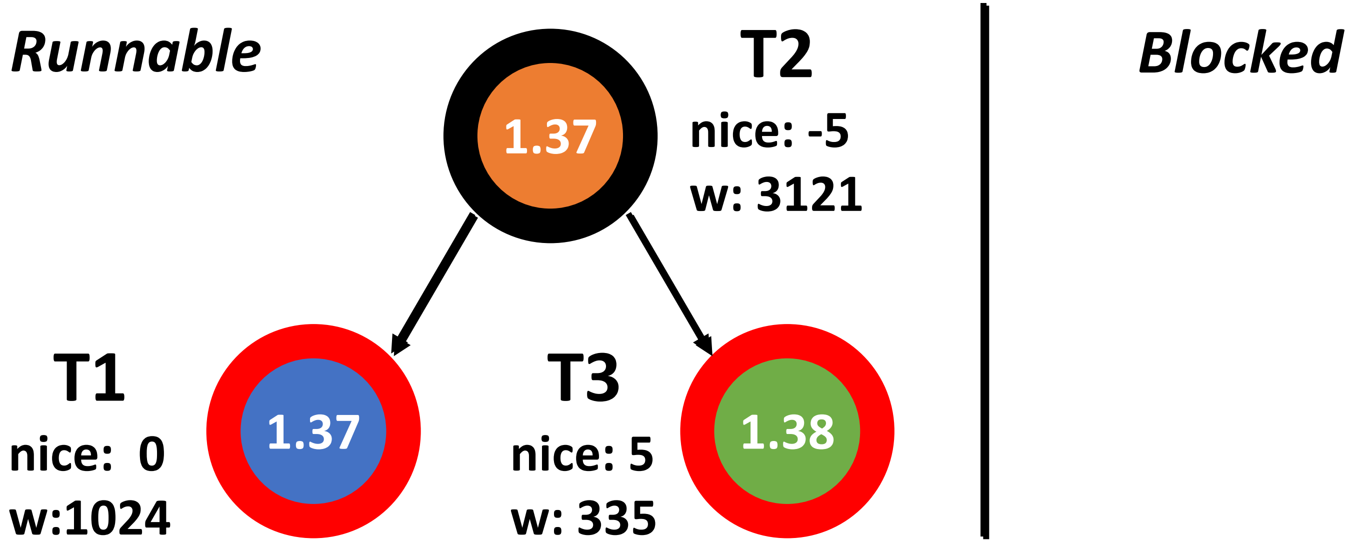
Example:

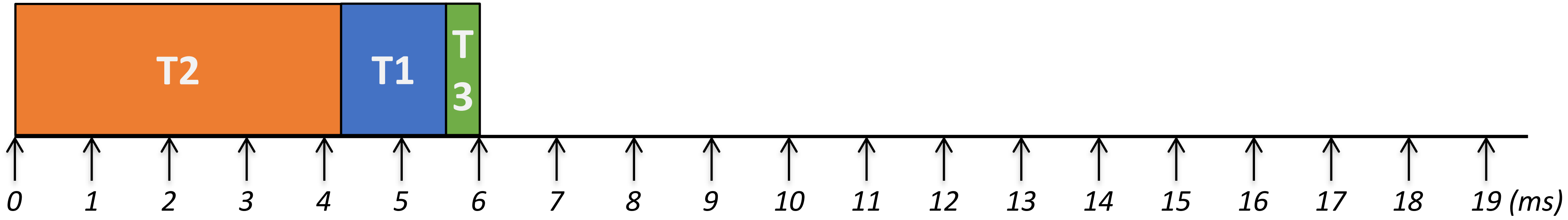
- Update T3's vruntime

$$VR(T3)$$

$$= \frac{1024}{335} \times 0.45$$

$$= 1.38$$

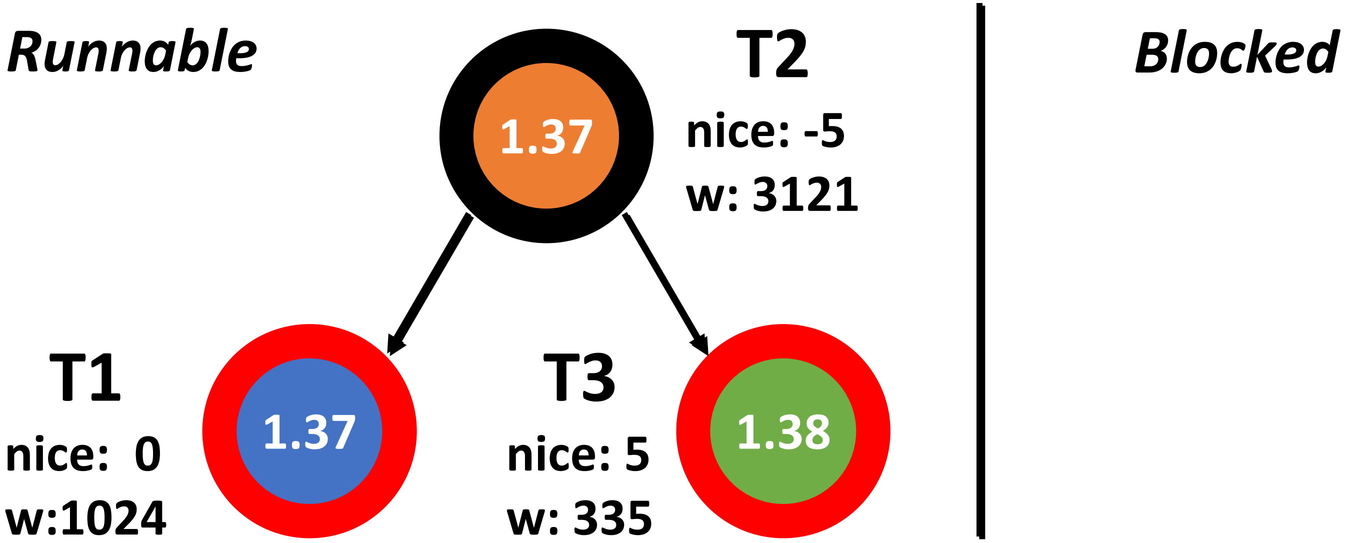


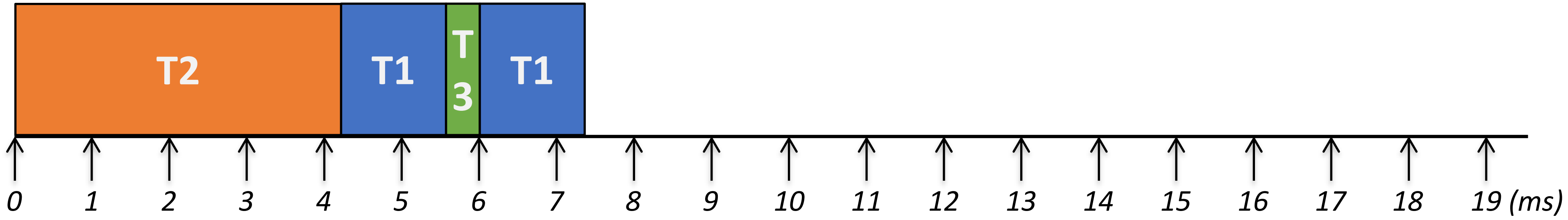


Example:

- Choose T1

$$TS(T1) = \frac{1024}{1024 + 3121 + 335} \times P = 1.37\ ms$$

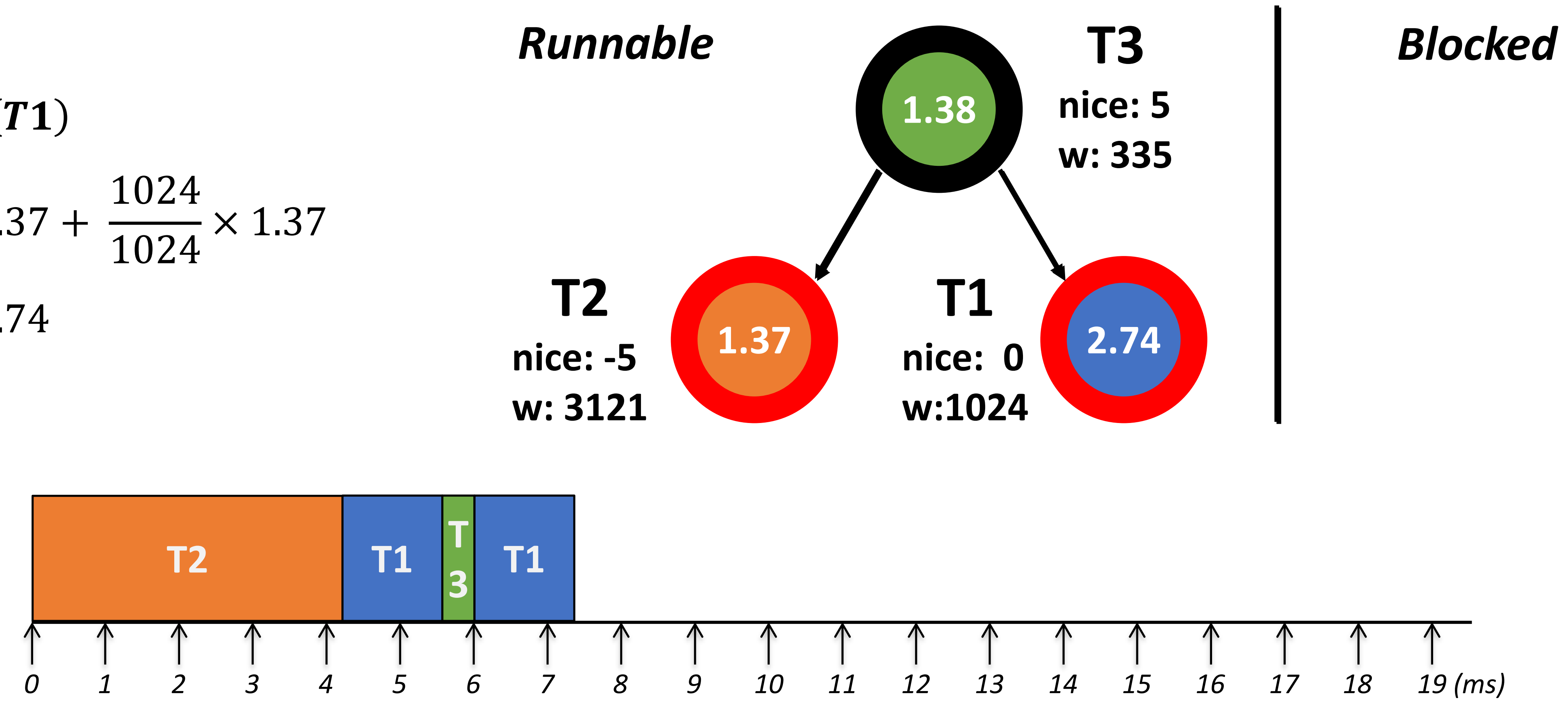




Example:

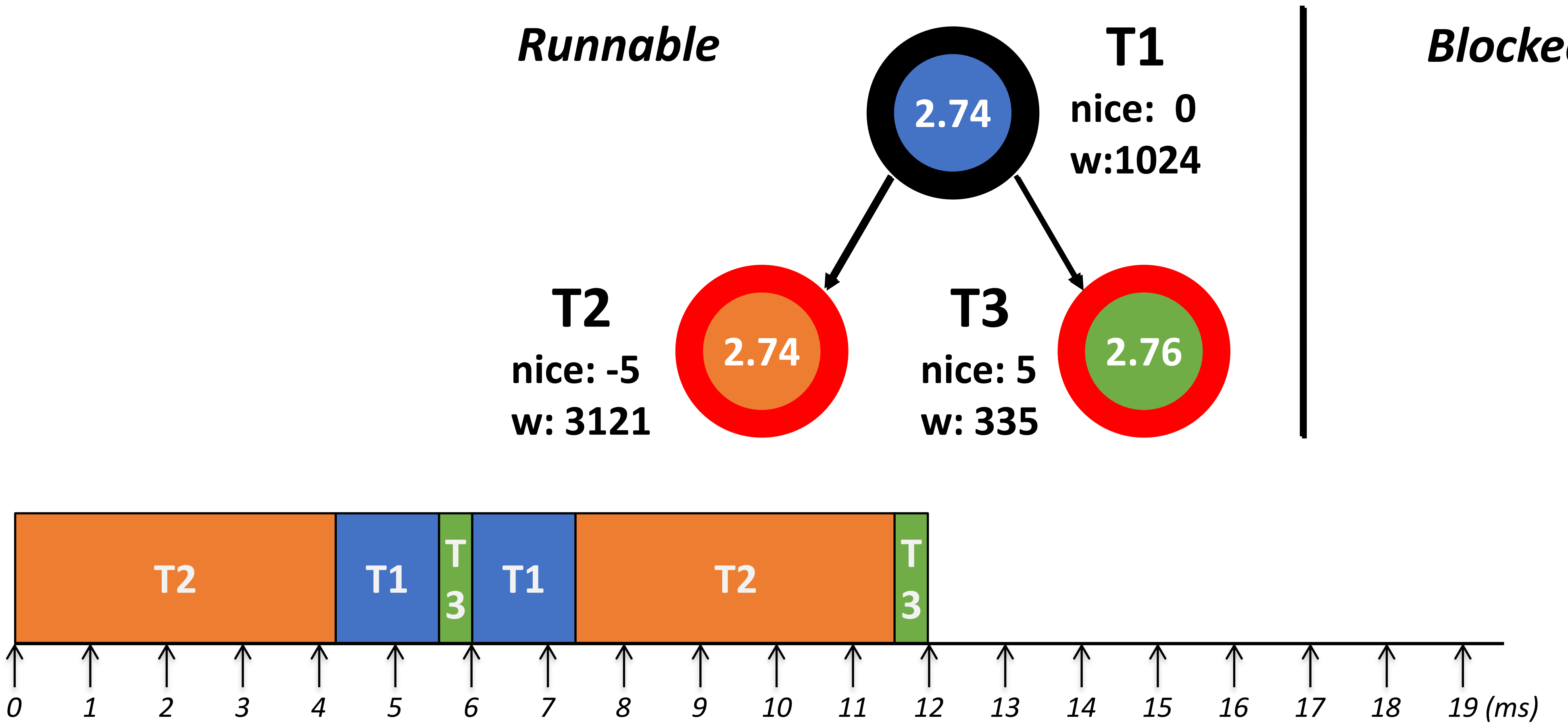
- Update T1's vruntime

$$VR(T1)$$
$$= 1.37 + \frac{1024}{1024} \times 1.37$$
$$= 2.74$$



Example:

- Update T2 for 4.18ms and T3 for 0.45ms



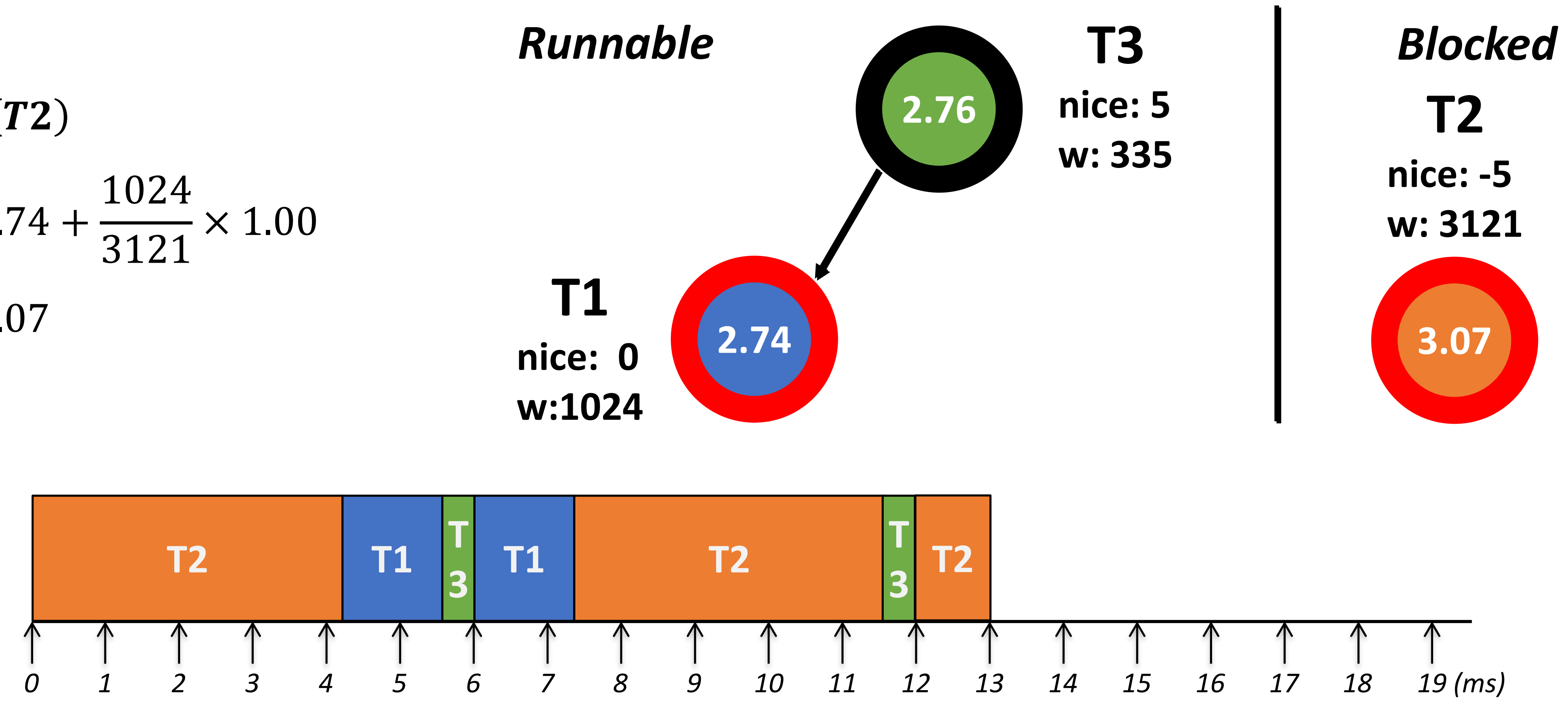
Example:

- Now T2 is scheduled, but it is blocked after running 1ms

$$VR(T2)$$

$$= 2.74 + \frac{1024}{3121} \times 1.00$$

$$= 3.07$$



Example:

- Now T1 runs

$TS(T1)$

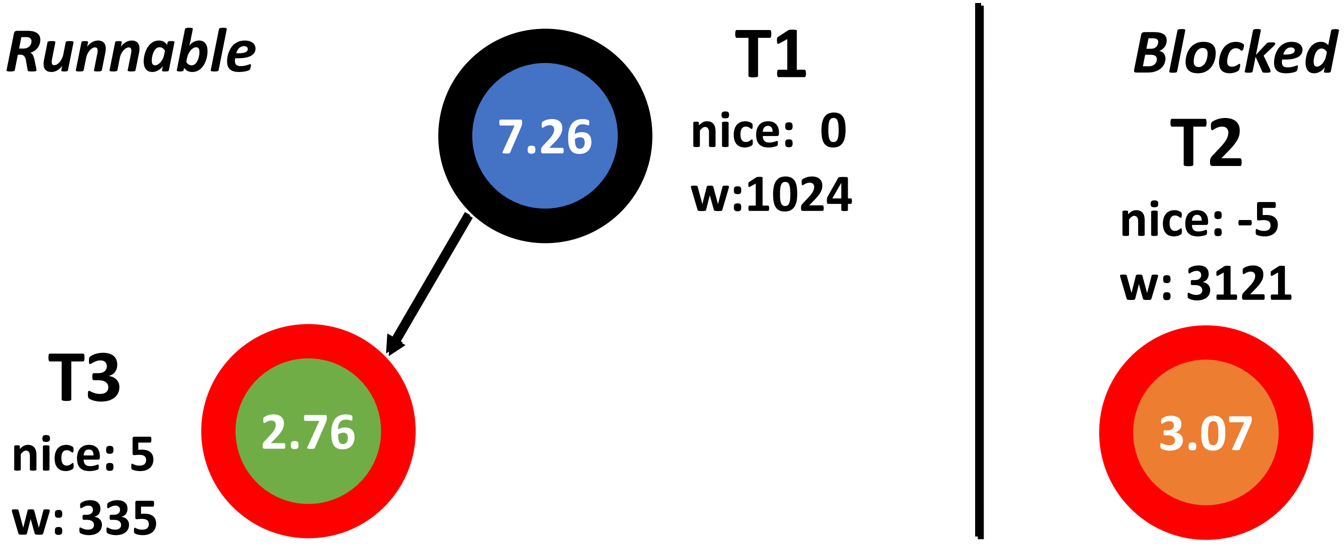
$= \frac{1024}{1024 + 335} \times P$

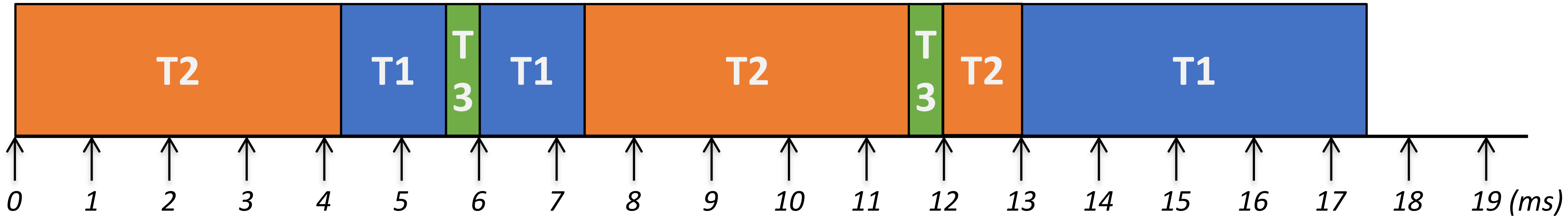
$= 4.52\ ms$

$VR(T1)$

$= 2.74 + \frac{1024}{1024} \times 4.52$

$= 7.26$



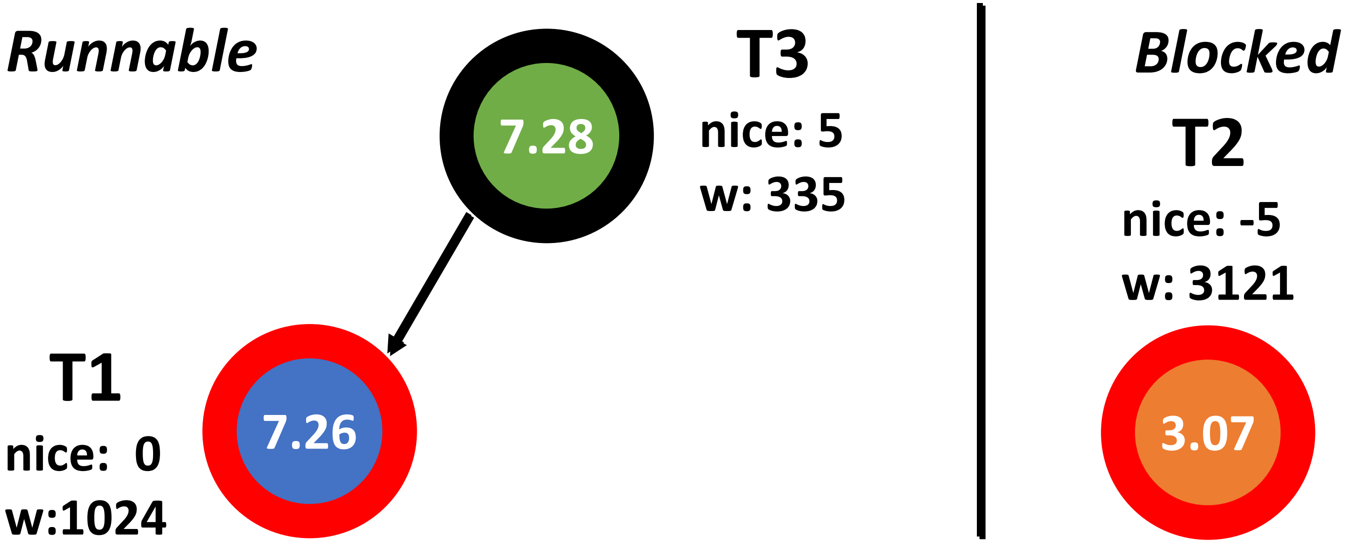


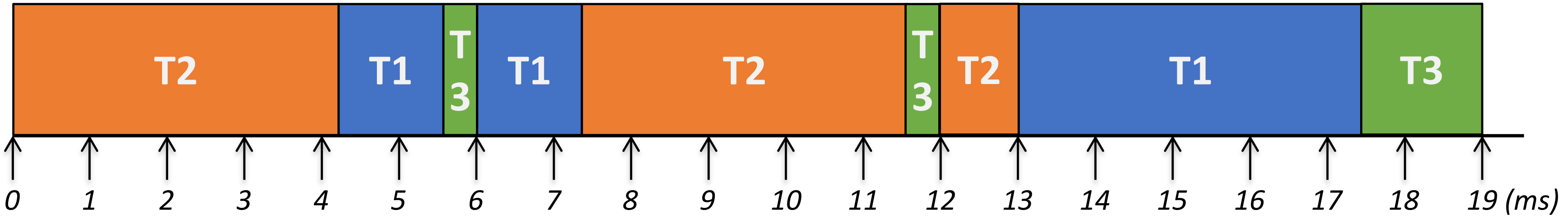
Example:

- T3 runs

$$TS(T3) = \frac{335}{1024 + 335} \times P = 1.48\ ms$$

$$VR(T3) = 2.76 + \frac{1024}{335} \times 1.48 = 7.28$$





Tickless (or DynTick) Kernel

- Full tickless operation introduced in Linux 3.10
  - No need for a periodic tick in the system, particularly when the system is idle
  - Idle CPUs save power
- `CONFIG_HZ_PERIODIC`
  - Old-style mode where the timer tick runs at all times
- `CONFIG_NO_HZ_IDLE` (formerly `CONFIG_NO_HZ`) – default
  - Disable the tick at idle, with re-programming it for the next pending timer
- `CONFIG_NO_HZ_FULL`
  - The CPUs without a timer tick must be designated at boot time
  - At least one CPU needs to receive interrupts and do the necessary housekeeping
  - The timer tick is disabled if there is only a single runnable process on that CPU