Process Scheduling

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Multitasking

1. Cooperative multitasking

   Yielding a process voluntarily suspends itself

2. Preemptive multitasking

   Preemption involuntarily suspending a running process

   Timeslice the time a process runs before it's preempted

   - usually dynamically calculated
   - used as a configurable system policy

   But Linux's scheduler is different

Linux’s Process Scheduler

up to 2.4: simple, scaled poorly

- $O(n)$
- non-preemptive
- single run queue (cache? SMP?)

from 2.5 on: $O(1)$ scheduler

- 140 priority lists — scaled well
- one run queue per CPU — true SMP support
- preemptive
- ideal for large server workloads
- showed latency on desktop systems

from 2.6.23 on: Completely Fair Scheduler (CFS)

- improved interactive performance

Scheduling Policy

Must attempt to satisfy two conflicting goals:

1. fast process response time (low latency)
2. maximal system utilization (high throughput)

Linux tries

1. favoring I/O-bound processes over CPU-bound processes
2. doesn’t neglect CPU-bound processes

Process Priority

Usually,

- processes with a higher priority run before those with a lower priority
- processes with the same priority are scheduled *round-robin*
- processes with a higher priority receive a longer time-slice

Linux implements two priority ranges:

1. **Nice value**: $-20 \sim +19$ (default 0)
   - large value $\Rightarrow$ lower priority
   - lower value $\Rightarrow$ higher priority $\Rightarrow$ get larger proportion of a CPU

   ~$ `ps -el`

   The *nice value* can be used as
   - a control over the *absolute* time-slice (e.g. MAC OS X), or
   - a control over the *proportion* of time-slice (Linux)
2. **Real-time**: $0 \sim 99$
   - higher value $\Rightarrow$ greater priority

   ~$ `ps -eo state,uid,pid,rtprio,time,comm`

Time-slice

too long: poor interactive performance

too short: context switch overhead

I/O-bound processes: don’t need longer time-slices (prefer short queuing time)

CPU-bound processes: prefer longer time-slices (to keep their caches hot)

Apparently, any long time-slice would result in poor interactive performance.

Problems With Nice Value

`if` two processes A and B

A: $NI = 0, t = 100ms$

B: $NI = 20, t = 5ms$

`then`, the CPU share

A: gets $\frac{100}{105} = 95\%$

B: gets $\frac{5}{105} = 5\%$

What if two $B_{ni=20}$ running?

Good news: Each gets 50%

Bad news: This '50%' is $\frac{5}{10}$, NOT $\frac{52.5}{105}$

Context switch twice every 10ms!

Comparing

$P_{ni=0}$ gets 100ms

$P_{ni=1}$ gets 95ms

With

$P_{ni=19}$ gets 10ms

$P_{ni=20}$ gets 5ms

This behavior means that “nicing down a process by one” has wildly different effects depending on the starting nice value.

Completely Fair Scheduler (CFS)

For a perfect (unreal) multitasking CPU

- n runnable processes can run at the same time
- each process should receive $\frac{1}{n}$ of CPU power

For a real world CPU

- can run only a single task at once — unfair
  - ☺ while one task is running
  - ☹☹ the others have to wait
- `p->wait_runtime` is the amount of time the task should now run on the CPU for it becomes completely fair and balanced.
  - ☺ on ideal CPU, the `p->wait_runtime` value would always be zero
- CFS always tries to run the task with the largest `p->wait_runtime` value

CFS

In practice it works like this:

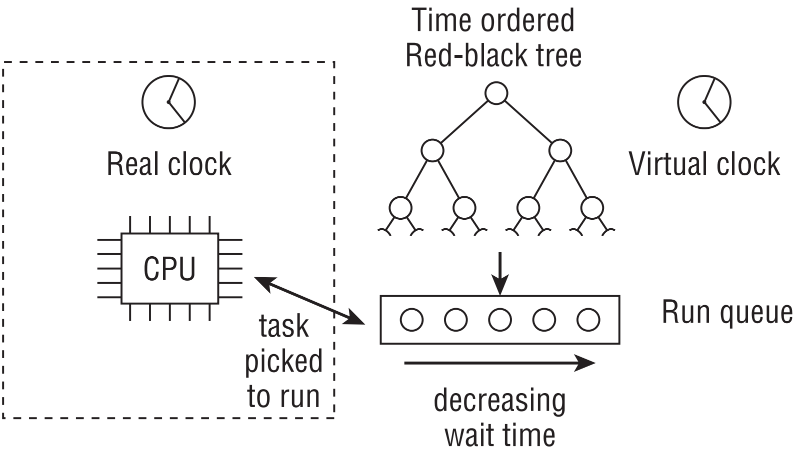
- While a task is using the CPU, its `wait_runtime` decreases

  `wait_runtime = wait_runtime - time_running`

if: its `wait_runtime` $\neq$ $\mathtt{MIN}_{wait\_runtime}$ (among all processes)

then: it gets preempted

- Newly woken tasks (`wait_runtime = 0`) are put into the tree more and more to the right
- slowly but surely giving a chance for every task to become the 'leftmost task' and thus get on the CPU within a deterministic amount of time



- the run queue is sorted by waiting time with a red-black tree
- the leftmost node in the tree is picked by the scheduler

The virtual clock

Time passes slower on this clock than in real time

more processes waiting $\Rightarrow$ more slower

Example

if: 4 processes in run queue

then: the virtual clock speed is $\frac{1}{4}$ of the real clock

if: a process sitting in the queue for 20s in real time

then: resulting to 5s in virtual time

if: the 4 processes executing for 5s each

then: the CPU will be busy for 20s in real time

To sort tasks on the red-black tree

$$\boxed{\texttt{fair\_clock - wait\_runtime}}$$

`fair_clock` The virtual time, e.g. 5s in the previous example

`wait_runtime` Fairness imbalance measure

To move a node rightward in the red-black tree

$$\boxed{\texttt{wait\_runtime = wait\_runtime - time\_running}}$$

`time_running` When a task is allowed to run, the interval during which it has been running

CFS

Example:

Assuming *targeted latency* is 20ms. If we have

2 processes: each gets 10ms

4 processes: each gets 5ms

20 processes: each gets 1ms

∞ processes: each gets 1ms (to avoid unacceptable context switching costs)

Example

A system with two processes running:

1. a text editor, say, Emacs (I/O-bound)
2. gcc is compiling the kernel source (CPU-bound)

if: they both have the same nice value
then: the proportion they get would be 50%-50%

Consequence:

- Emacs uses far less than 50% of CPU
- gcc can enjoy more than 50% of CPU freely

When Emacs wakes up

1. CFS notes that it has 50% of CPU, but uses very little of it (far less than gcc)
2. CFS preempts gcc and enables Emacs to run immediately

Thus, better interactive performance.

Scheduler Classes

Different, pluggable algorithms coexist

- Each algorithm schedules its own type of processes
- Each scheduler class has a priority

`SCHED_FIFO`

`SCHED_RR`

`SCHED_NORMAL`

Example: nice value difference

Assume:

1. nice value 5 pts up results in a $\frac{1}{3}$ penalty
2. targeted latency is again 20ms
3. 2 processes in the system

Then:

- $P_{ni=0}$ gets 15ms; $P_{ni=5}$ gets 5ms
- $P_{ni=10}$ gets 15ms; $P_{ni=15}$ gets 5ms

- Absolute nice values no longer affect scheduling decision
- Relative nice values does

Base Time Quantum

$O(1)$ scheduler

$$\begin{array}{c}\text{base time quantum}\\ \text{(ms)}\end{array} = \begin{cases} (140 - \text{static priority}) \times 20 & \textit{if } \text{static priority} < 120, \\ (140 - \text{static priority}) \times 5 & \textit{if } \text{static priority} \geq 120. \end{cases}$$

Major Components of CFS

- Time Accounting
- Process Selection
- The Scheduler Entry Point
- Sleeping and Waking Up

Time accounting

`sched_entity` keeps track of process accounting
(`task_struct -> se`)

```
struct sched_entity {
  struct load_weight        load;           /* for load-balancing */
  struct rb_node            run_node;
  struct list_head          group_node;
  unsigned int              on_rq;

  u64                       exec_start;
  u64                       sum_exec_runtime;
  u64                       vruntime;
  u64                       prev_sum_exec_runtime;

  u64                       last_wakeup;
  u64                       avg_overlap;

  u64                       nr_migrations;

  u64                       start_runtime;
  u64                       avg_wakeup;

  /* many state variables elided, enabled only if CONFIG_SCHEDSTATS is set */
};
```

The Virtual Runtime

`vruntime` stores the *virtual runtime* of a process. On an ideal processor, all tasks' `vruntime` would be identical.

Accounting is done in `update_curr()` and `__update_curr()`

Process Selection

The core of CFS algorithm Pick the process with the smallest `vruntime`

- run the process represented by the leftmost node in the `rbtree`

```
static struct sched_entity *__pick_next_entity(struct cfs_rq *cfs_rq)
{
  struct rb_node *left = cfs_rq->rb_leftmost;
  if (!left)
    return NULL;
  return rb_entry(left, struct sched_entity, run_node);
}
```

Adding Processes to the Tree

- Happens when a process wakes up or is created
- `enqueue_entity()` and `__enqueue_entity()`

Removing Processes from the Tree

- Happens when a process blocks or terminates
- `dequeue_entity()` and `__dequeue_entity()`

The Scheduler Entry Point

Sleeping and Waking Up