Linux Kernel Programming
Process Scheduling

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February 21, 2017

Outline

1. General information
2. Linux Completely Fair Scheduler
3. CFS implementation
4. Preemption and context switching
5. Real-time scheduling policies
6. Scheduling-related syscalls

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1. General information
2. Linux Completely Fair Scheduler
3. CFS implementation
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5. Real-time scheduling policies
6. Scheduling-related syscalls

General information

Scheduling

- **Scheduler**: OS entity that decide which process should run, when, and for how long
- Multiplex processes in time on the processor: enables **multitasking**
    - Gives the user the illusion that processes are executing at the same time
- Scheduler is responsible for making the best use of the resource that is the CPU time
- Basic principle:
    - When in the system there are more ready-to-run processes than the number of cores
        - **The scheduler decides which process should run**

General information

Multitasking

- Single core: gives the illusion that multiple processes are running concurrently
- Multi-cores: enable true parallelism
- 2 types of multitasking OS:
  - **Cooperative multitasking**
    - A process does not stop running until it decides to do so (*yield* the CPU)
    - The operating system cannot enforce fair scheduling
      - For example in the case of a process that never yields
  - **Preemptive multitasking**
    - The OS can interrupt the execution of a process: *preemption*
    - Generally after the process expires its *timeslice*
    - And/or based on tasks priorities

General information

A bit of Linux scheduler history

- From v1.0 to v2.4: simple implementation
  - **But it did not scale to numerous processes and processors**
- V2.5 introduced the `O(1)` scheduler
  - **Constant time scheduling decisions**
    - Scalability and execution time determinism
  - More info in [5]
  - Issues with latency-sensitive applications (Desktop computers)
- O(1) scheduler was replaced in 2.6.23 by what is still now the standard Linux scheduler:
  - **Completely Fair Scheduler (CFS)**
    - Evolution of the *Rotating Staircase Deadline* scheduler [2, 3]

General information

Scheduling policy - I/O vs compute-bound tasks

- Scheduling policy are the set of rules determining the choices made by a given model of scheduler
- **I/O-bound processes**:
  - Spend most of their time *waiting for I/O*: disk, network, but also keyboard, mouse, etc.
    - Filesystem, network intensive, GUI applications, etc.
    - Response time is important
  - Should run ***often and for a small time frame***
- **Compute-bound processes**:
  - *Heavy use of the CPU*
    - SSH key generation, scientific computations, etc.
    - Caches stay hot when they run for a long time
  - Should ***not run often, but for a long time***

General information

Scheduling policy - Priority

- **Priority**
  - Order process according to their ”importance” from the scheduler standpoint
  - A process with a higher priority will execute before a process with a lower one
- **Linux has 2 priority ranges**:
  - **Nice value**: ranges from -20 to +19, default is 0
    - High values of nice means lower priority
    - List process and their nice values with `ps ax -o pid,ni,cmd`
  - **Real-time priority**: range configurable (default 0 to 99)
    - Higher values mean higher priority
    - For processes labeled *real-time*
    - Real-time processes always executes before standard (nice) processes
    - List processes and their real-time priority using `ps ax -o pid,rtprio,cmd`

General information

Scheduling policy - Priority (2)

- User space to kernel priorities mapping:

General information

Scheduling policy - Timeslice

- **Timeslice** (quantum):
  - How much time a process should execute before being preempted
  - Defining the default timeslice in an absolute way is tricky:
    - Too long → bad interactive performance
    - Too short → high context switching overhead
- **Linux CFS does not use an absolute timeslice**
  - The timeslice a process receives is **function of the load of the system**
    - it is *a proportion* of the CPU
  - In addition, that timeslice is **weighted by the process priority**
- When a process P becomes runnable:
  - P will preempt the currently running process C is P consumed a smaller proportion of the CPU than C

General information

Scheduling policy - Policy application example

- 2 tasks in the system:
  - **Text editor**: I/O-bound, latency sensitive (interactive)
  - **Video encoder**: CPU-bound, background job
- Text editor:
  - A. *Needs a large amount of CPU time*
    - Does not need to run for long, but needs to have CPU time available whenever it needs to run
  - B. *When ready to run, needs to preempt the video encoder*
  - A + B = good interactive performance
- On a classical UNIX system, needs to set a correct combination of priority and timeslice
- Different with Linux: *the OS guarantee the text editor a specific proportion of the CPU time*

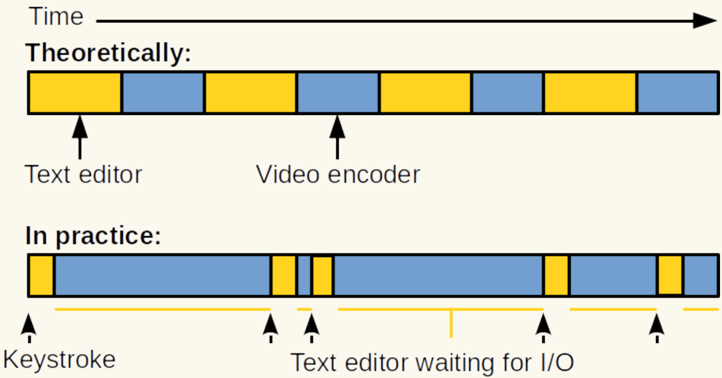
General information

Scheduling policy - Policy application example (2)

- Imagine only the two processes are present in the system and run at the same priority
  - Linux gives 50% of CPU time to each
- Considering an absolute timeframe:
  - **Text editor does not use fully its 50%** as it often blocks waiting for I/O
    - Keyboard key pressed
  - **CFS keeps track of the actual CPU time used by each program**
  - When the text editor wakes up:
    - CFS sees that **it actually used less CPU time than the video encoder**
    - Text editor preempts the video encoder

General information

Scheduling policy - Policy application example (3)



- Good interactive performance
- Good background, CPU-bound performance

Outline

Linux Completely Fair Scheduler

Scheduling classes

- **CPU classes**: coexisting CPU algorithms
  - Each task belongs to a class
- CFS: `SCHED_OTHER`, implemented in `kernel/sched/fair.c`
- Real-time classes: `SCHED_RR`, `SCHED_FIFO`, `SCHED_DEADLINE`
  - For predictable schedule
- `sched_class` data structure:

```
struct sched_class {
  void (*enqueue_task) (/* ... */);
  void (*dequeue_task) (/* ... */);
  void (*yield_task) (/* ... */);
  void (*check_preempt_curr) (/* ... */);
  struct task_struct * (*pick_next_task) (/* ... */);
  void (*set_cur_task) (/* ...*/);
  void (*task_tick) (/* ... */);
  /* ... */
}
```

Linux Completely Fair Scheduler

`sched_class hooks`

- Functions descriptions:
  - `enqueue_task(...)`
    - Called when a task enters a runnable state
  - `dequeue_task(...)`
    - Called when a task becomes unrunnable
  - `yield_task(...)`
    - Yield the processor (dequeue then enqueue back immediatly)
  - `check_preempt_curr(...)`
    - Checks if a task that entered the runnable state should preempt the currently running task
  - `pick_next_task(...)`
    - Chooses the next task to run
  - `set_curr_task(...)`
    - Called when the currentluy running task changes its scheduling class or task group to the related scheduler
  - `task_tick(...)`
    - Called regularly (default: 10 ms) from the system timer tick handler, might lead to context switch

Linux Completely Fair Scheduler

Unix scheduling

- Classical UNIX systems *map priorities (nice values) to absolute timeslices*
- Leads to several issues:
  - **What is the absolute timeslice that should be mapped to a given nice value?**
    - Sub-optimal switching behavior for low priority processes (small timeslices)
  - **Relative nice values and their mapping to timeslices**
    - Nicing down a process by one can have very different effects according to the tasks priorities
  - **Timeslice must be some integer multiple of the timer tick**
    - Minimum timeslice and difference between two consecutive timeslices are bounded by the timer tick frequency

Linux Completely Fair Scheduler

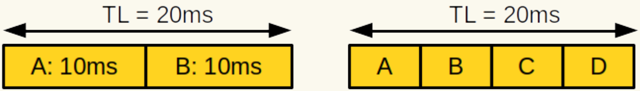
Fair scheduling

- **Perfect multitasking**:
  - From a single core standpoint
    - At each moment, each process of the same priority has received an exact amount of the CPU time
    - What we would get if we could ***run*** n ***tasks in parallel on the CPU while giving them 1/***n ***of the CPU processing power*** → not possible in reality
    - Or if we could ***schedule tasks for infinitely small amounts of time*** → context switch overhead issue
- **3 main (high-level) CFS concepts:**
  1. CFS runs a process for some times, then swaps it for the runnable process that has run the least
  2. No default timeslice, CFS calculates how long a process should run according to the number of runnable processes
  3. That dynamic timeslice is weighted by the process priority (nice)

Linux Completely Fair Scheduler

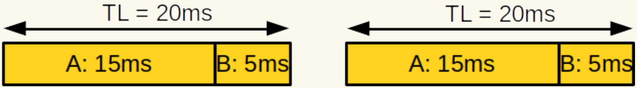
Fair scheduling (2)

- ***Targeted latency***: period during which all runnable processes should be scheduled at least once
- Example: processes with the same priority



$(A_{nice} = B_{nice} = C_{nice} = D_{nice})$

- Example: processes with different priorities



$(A_{nice} = 0 \; ; \; B_{nice} = 5)$ $(A_{nice} = 10 \; ; \; B_{nice} = 15)$

- ***Minimum granularity***: floor at 1 ms (default)

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CFS implementation

- **4 main components:**
  1. Time accounting
  2. Process selection
  3. Scheduler entry point (calling the scheduler)
  4. Sleeping & waking up

CFS implementation

Time accounting

- `sched_entity` structure in the `task_struct` (`se` field)

```
struct sched_entity
{
  struct load_weight  load;
  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;

  /* additional statistics not shown here */
}
```

- **Virtual runtime**
  - How much time a process has been executed (ns)

CFS implementation

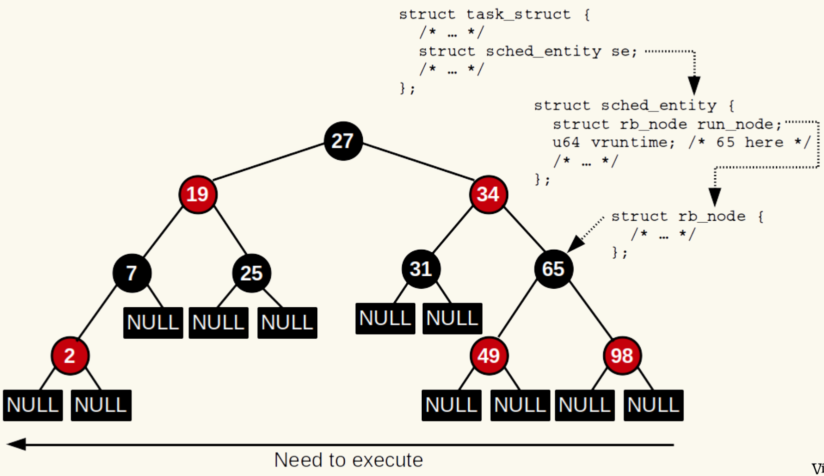
Time accounting (2)

```c
static void update_curr(struct cfs_rq * cfs_rq)
{
  struct sched_entity *curr =
    cfs_rq->curr;
  u64 now = rq_clock_task(rq_of(cfs_rq));
  u64 delta_exec;

  if (unlikely(!curr))
    return;

  delta_exec = now - curr->exec_start;
  if (unlikely((s64)delta_exec <= 0))
    return;

  curr->exec_start = now;

  schedstat_set(curr->statistics.exec_max,
          max(delta_exec, curr->statistics.exec_max));
  curr->sum_exec_runtime += delta_exec;
  schedstat_add(cfs_rq->exec_clock, delta_exec);

  curr->vruntime += calc_delta_fair(delta_exec, curr);
  update_min_vruntime(cfs_rq);

  if (entity_is_task(curr)) {
    struct task_struct *curtask
      = task_of(curr);

    trace_sched_stat_runtime(curtask, delta_exec, curr->vruntime);
    cpuacct_charge(curtask, delta_exec);
    account_group_exec_runtime(curtask, delta_exec);
  }

  account_cfs_rq_runtime(cfs_rq, delta_exec);
}
```

- Invoked regularly by the system timer, and when a process becomes runnable/unrunnable

CFS implementation

Process selection



```
struct task_struct {
  /* … */
  struct sched_entity se;
  /* … */
};
```

```
struct sched_entity {
  struct rb_node run_node;
  u64 vruntime; /* 65 here */
  /* … */
};
```

```
struct rb_node {
  /* … */
};
```

- Adapted from [1]

CFS implementation

Process selection (2)

- When CFS needs to choose which runnable process to run next:
  - **The process with the smallest `vruntime` is selected**
  - It is the leftmost node in the tree

```
struct sched_entity *__pick_first_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);
}
```

CFS implementation

Process selection: adding a process to the tree

- A process is added through `enqueue_entity`:

```c
static void
enqueue_entity(struct cfs_rq *cfs_rq,
      struct sched_entity *se, int flags)
{
  bool renorm = !(flags & ENQUEUE_WAKEUP)
      || (flags & ENQUEUE_MIGRATED);
  bool curr = cfs_rq->curr == se;

  if (renorm && curr)
    se->vruntime += cfs_rq->min_vruntime;

  update_curr(cfs_rq);

  if (renorm && !curr)
    se->vruntime += cfs_rq->min_vruntime;

  update_load_avg(se, UPDATE_TG);
  enqueue_entity_load_avg(cfs_rq, se);
  account_entity_enqueue(cfs_rq, se);
  update_cfs_shares(cfs_rq);
```

```c
  if (flags & ENQUEUE_WAKEUP)
    place_entity(cfs_rq, se, 0);

  check_schedstat_required();
  update_stats_enqueue(cfs_rq, se, flags);
  check_spread(cfs_rq, se);
  if (!curr)
    __enqueue_entity(cfs_rq, se);
  se->on_rq = 1;

  if (cfs_rq->nr_running == 1) {
    list_add_leaf_cfs_rq(cfs_rq);
    check_enqueue_throttle(cfs_rq);
  }
}
```

CFS implementation

Process selection: adding a process to the tree (2)

- `__enqueue_entity`:

```c
static void __enqueue_entity(struct cfs_rq
      *cfs_rq, struct sched_entity *se)
{
  struct rb_node **link = &cfs_rq->
     tasks_timeline.rb_node;
  struct rb_node *parent = NULL;
  struct sched_entity *entry;
  int leftmost = 1;

  /*
   * Find the right place in the rbtree:
   */
  while (*link) {
    parent = *link;
    entry = rb_entry(parent, struct
      sched_entity, run_node);
    /*
     * We dont care about collisions.
      Nodes with
     * the same key stay together.
     */
    if (entity_before(se, entry)) {
      link = &parent->rb_left;
    } else {
      link = &parent->rb_right;
      leftmost = 0;
    }
  }
  /*
   * Maintain a cache of leftmost tree
      entries (it is frequently
   * used):
   */
  if (leftmost)
    cfs_rq->rb_leftmost = &se->run_node;

  rb_link_node(&se->run_node, parent, link
     );
  rb_insert_color(&se->run_node, &cfs_rq->
     tasks_timeline);
}
```

CFS implementation

Process selection: removing a process from the tree

- `dequeue_entity`:

```
static void
dequeue_entity(struct cfs_rq *cfs_rq,
     struct sched_entity *se, int flags)
{
    update_curr(cfs_rq);
    dequeue_entity_load_avg(cfs_rq, se);

    update_stats_dequeue(cfs_rq, se, flags
      );

    clear_buddies(cfs_rq, se);

    if (se != cfs_rq->curr)
        __dequeue_entity(cfs_rq, se);
    se->on_rq = 0;
    account_entity_dequeue(cfs_rq, se);
```

```
    if (!(flags & DEQUEUE_SLEEP))
        se->vruntime -= cfs_rq->
      min_vruntime;

    return_cfs_rq_runtime(cfs_rq);

    update_cfs_shares(cfs_rq);

    if ((flags & (DEQUEUE_SAVE |
      DEQUEUE_MOVE)) == DEQUEUE_SAVE)
        update_min_vruntime(cfs_rq);
}
```

CFS implementation

Process selection: removing a process from the tree (2)

- `__dequeue_entity`:

```
static void __dequeue_entity(struct cfs_rq *cfs_rq, struct sched_entity *se)
{
    if (cfs_rq->rb_leftmost == &se->run_node) {
        struct rb_node *next_node;

        next_node = rb_next(&se->run_node);
        cfs_rq->rb_leftmost = next_node;
    }

    rb_erase(&se->run_node, &cfs_rq->tasks_timeline);
}
```

CFS implementation

Entry point: `schedule()`

- The kernel calls **`schedule()`** anytime it wants to invoke the scheduler
  - Calls `pick_next_task()`

```
static inline struct task_struct *
pick_next_task(struct rq *rq, struct task_struct *prev, struct pin_cookie cookie)
{
  const struct sched_class *class = &fair_sched_class;
  struct task_struct *p;

  if (likely(prev->sched_class == class &&
       rq->nr_running == rq->cfs.h_nr_running)) {
    p = fair_sched_class.pick_next_task(rq, prev, cookie);
    if (unlikely(p == RETRY_TASK))
      goto again;

    if (unlikely(!p))
      p = idle_sched_class.pick_next_task(rq, prev, cookie);
    return p;
  }
```

```
again:
  for_each_class(class) {
    p = class->pick_next_task(rq, prev, cookie);
    if (p) {
      if (unlikely(p == RETRY_TASK))
        goto again;
      return p;
    }
  }

  BUG(); /* the idle class will always have a runnable task */
}
```

CFS implementation

Sleeping and waking up

- Multiple reasons for a task to sleep:
  - Specified amount of time, waiting for I/O, blocking on a mutex, etc.
- Going to sleep - steps:
  1. Task marks itself as sleeping
  2. Task enters a *waitqueue*
  3. Task leaves the rbtree of runnable processes
  4. Task calls `schedule()` to select a new process to run
- Inverse steps for waking up
- Two states associated with sleeping:
  - `TASK_INTERRUPTIBLE`
    - Will be awaken on signal reception
  - `TASK_UNINTERRUPTIBLE`
    - Ignore signals

CFS implementation

Sleeping and waking up: wait queues

- **Wait queue**:
  - List of processes waiting for an event to occur

```
typedef struct __wait_queue_head wait_queue_head_t
struct wait_queue_head {
  spinlock_t lock;
  struct list_head task_list;}
```

- Some simple interfaces used to go to sleep have races:
  - It is possible to go to sleep *after* the event we are waiting for has occurred
  - Recommended way:

```
/* We assume the wait queue we want to wait on is accessible through a variable q */

DEFINE_WAIT(wait); /* initialize a wait queue entry */

add_wait_queue(q, &wait);
while (!condition) { /* event we are waiting for */
  prepare_to_wait(&q, &wait, TASK_INTERRUPTIBLE);
  if(signal_pending(current))
    /* handle signal */
  schedule();
}
finish_wait(&q, &wait);
```

CFS implementation

Sleeping and waking up: wait queues (2)

- **Steps for waiting on a waitqueue:**
  1. Create a waitqueue entry (`DEFINE_WAIT()`)
  2. Add the calling process to a wait queue (`add_wait_queue()`)
  3. Call `prepare_to_wait()` to change the process state
  4. If the state is `TASK_INTERRUPTIBLE`, a signal can wake the task up → need to check
  5. Executes another process with `schedule()`
  6. When the task awakens, check the condition
  7. When the condition is true, get out of the wait queue and set the state accordingly using `finish_wait()`

CFS implementation

Sleeping and waking up: `wake_up()`

- **Waking up** is taken care of by `wake_up()`
  - **Awakes all the processes on a waitqueue** by default

```
#define wake_up(x) __wake_up(x, TASK_NORMAL, 1, NULL)
/* type of x is wait_queue_head_t */
```

- `__wake_up()` calls `__wake_up_common()`:

```
static void __wake_up_common(wait_queue_head_t *q, unsigned int mode,
      int nr_exclusive, int wake_flags, void *key)
{
  wait_queue_t *curr, *next;

  list_for_each_entry_safe(curr, next, &q->task_list, task_list) {
    unsigned flags = curr->flags;

    if (curr->func(curr, mode, wake_flags, key) &&
        (flags & WQ_FLAG_EXCLUSIVE) && !--nr_exclusive)
      break; /* wakes up only a subset of 'exclusive' tasks */
  }
}
```

- Exclusive tasks are added through `prepare_to_wait_exclusive()`

CFS implementation

Sleeping and waking up: `wake_up()` (2)

- A wait queue entry contains a pointer to a wake-up function
    - `include/linux/wait.h`:

```c
typedef struct __wait_queue wait_queue_t;
typedef int (*wait_queue_func_t)(wait_queue_t *wait, unsigned mode, int flags, void *key);
int default_wake_function(*wait_queue_func_t)(wait_queue_t *wait, unsigned mode,
                                              int flags, void *key);

/* ... */

struct __wait_queue {
  /* ... */
  wait_queue_func_t func;
  /* ... */
}
```

- `default_wake_function()` calls `try_to_wake_up()` ...
    - ... which calls `ttwu_queue()` ...
    - ... which calls `ttwu_do_activate()` (put the task back on runqueue) ...
    - ... which calls `ttwu_do_wakeup` ...
    - ... which **sets the task state to `TASK_RUNNING`**

CFS implementation

CFS on multicores: brief, high-level overview

- **Per-CPU runqueues** (rbtrees)
  - To avoid costly accesses to shared data structures
- **Runqueues must be kept balanced**
  - Ex: dual-core with one large runqueue of high-priority processes, and a small one with low-priority processes
    - High-priority processes get less CPU time than low-priority ones
  - A load balancing algorithm is run periodically
    - Balances the queues based on processes priorities and their actual CPU usage
- More info: [6]

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Preemption and context switching

Context switch

- A **context switch** is the action of swapping the process currently running on the CPU to another one
  - **Performed by the `context_switch()` function**
    - Called by `schedule()`

    1. Switch the address space through `switch_mm()`
    2. Switch the CPU state (registers) through `switch_to()`
- A task can voluntarily relinquish the CPU by calling `schedule()`
  - **But when does the kernel check if there is a need of preemption?**
    - `need_resched` flag (per-process, in the `thread_info` of `current`)
  - `need_resched` is set by:
    1. `scheduler_tick()` when the currently running task needs to be preempted
    2. `try_to_wake_up()` when a process with higher priority wakes up

Preemption and context switching

`need_resched`, user preemption

- The `need_resched` flag is checked:
  1. Upon returning to user space (from a syscall or an interrupt)
  2. Upon returning from an interrupt
- If the flag is set, `schedule()` is called
- **User preemption happens:**
  1. When returning to user space from a syscall
  2. When returning to user space from an interrupt
- With Linux, **the kernel is also subject to preemption**

Preemption and context switching

Kernel preemption

- In most of Unix-like, kernel code is non-preemptive:
  - It runs until it finishes
- **Linux kernel code is preemptive**
  - A task can be preempted in the kernel as long as execution is **in a safe state**
    - *Not holding any lock* (kernel is SMP safe)
- `preempt_count` in the `thread_info` structure
  - Indicates the current lock depth
- If `need_resched && !preempt_count` → safe to preempt
  - Checked when returning to the kernel from interrupt
  - `need_resched` is also checked when releasing a lock and `preempt_count` is 0
- Kernel code can also call directly `schedule()`

Preemption and context switching

Kernel preemption (2)

- **Kernel preemption can occur:**
  1. On return from interrupt to kernel space
  2. When kernel code becomes preemptible again
  3. If a task explicitly calls `schedule()` from the kernel
  4. If a task in the kernel blocks (ex: mutex, result in a call to `schedule()`)

Outline

Real-time scheduling policies

`SCHED_FIFO` and `SCHED_RR`

- *Soft real-time* scheduling classes:
  - Best effort, no guarantees
- **Real-time task of any scheduling class will always run before non-real time ones** (CFS, **`SCHED_OTHER`**)
  - `schedule()` → `pick_next_task()` → `for_each_class()`
- 2 ”classical” RT scheduling policies (`kernel/sched/rt.c`):
  - **`SCHED_FIFO`**
    - Tasks run until it blocks/yield, only a higher priority RT task can preempt it
    - Round-robin for tasks of same priority
  - **`SCHED_RR`**
    - Same as `SCHED_FIFO`, but with a fixed timeslice

Real-time scheduling policies

Other scheduling policies

- **`SCHED_DEADLINE`**:
    - Real-time policies mainlined in v3.14 enabling *predictable RT scheduling*
    - EDF implementation based on a period of activation and a worst case execution time (WCET) for each task
    - More info: `Documentation/sched-deadline.txt`, [4], etc.
- **`SCHED_BATCH`**: non-real-time, low priority background jobs
- **`SCHED_IDLE`**: non-real-time, *very* low priority background jobs

Outline

Scheduling-related syscalls

Scheduling syscalls list

- `sched_getscheduler`, `sched_setscheduler`
- `nice`
- `sched_getparam`, `sched_setparam`
- `sched_get_priority_max`, `sched_get_priority_min`
- `sched_getaffinity`, `sched_setaffinity`
- `sched_yield`

Scheduling-related syscalls

Usage example

```c
#define _GNU_SOURCE

#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <unistd.h>
#include <sched.h>
#include <assert.h>

void handle_err(int ret, char *func)
{
  perror(func);
  exit(EXIT_FAILURE);
}

int main(void)
{
  pid_t pid = -1;
  int ret = -1;
  struct sched_param sp;
  int max_rr_prio, min_rr_prio = -42;
  size_t cpu_set_size = 0;
  cpu_set_t cs;
/* Get the PID of the calling process */
  pid = getpid();
  printf("My pid is: %d\n", pid);

  /* Get the scheduling class */
  ret = sched_getscheduler(pid);
  if(ret == -1)
    handle_err(ret, "sched_getscheduler");
  printf("sched_getscheduler returns: "
    "%d\n", ret);
  assert(ret == SCHED_OTHER);

  /* Get the priority (nice/RT) */
  sp.sched_priority = -1;
  ret = sched_getparam(pid, &sp);
  if(ret == -1)
    handle_err(ret, "sched_getparam");
  printf("My priority is: %d\n",
    sp.sched_priority);

  /* Set the priority (nice value) */
  ret = nice(1);
  if(ret == -1)
    handle_err(ret, "nice");
```

Scheduling-related syscalls

Usage example (2)

```
  /* Get the priority */
  sp.sched_priority = -1;
  ret = sched_getparam(pid, &sp);
  if(ret == -1)
    handle_err(ret, "sched_getparam");
  printf("My priority is: %d\n",
    sp.sched_priority);

  /* Switch scheduling class to FIFO and
   * the priority to 99 */
  sp.sched_priority = 99;
  ret = sched_setscheduler(pid,
    SCHED_FIFO, &sp);
  if(ret == -1)
    handle_err(ret, "sched_setscheduler");

  /* Get the scheduling class */
  ret = sched_getscheduler(pid);
  if(ret == -1)
    handle_err(ret, "sched_getscheduler");
  printf("sched_getscheduler returns:"
    " %d\n", ret);
  assert(ret == SCHED_FIFO);
```

```
  /* Get the priority */
  sp.sched_priority = -1;
  ret = sched_getparam(pid, &sp);
  if(ret == -1)
    handle_err(ret, "sched_getparam");
  printf("My priority is: %d\n",
    sp.sched_priority);

  /* Set the RT priority */
  sp.sched_priority = 42;
  ret = sched_setparam(pid, &sp);
  if(ret == -1)
    handle_err(ret, "sched_setparam");
  printf("Priority changed to %d\n",
    sp.sched_priority);

  /* Get the priority */
  sp.sched_priority = -1;
  ret = sched_getparam(pid, &sp);
  if(ret == -1)
    handle_err(ret, "sched_getparam");
  printf("My priority is: %d\n",
    sp.sched_priority);
```

Scheduling-related syscalls

Usage example (2)

```c
  /* Get the max priority value for SCHED_RR */
  max_rr_prio = sched_get_priority_max(SCHED_RR);
  if(max_rr_prio == -1)
    handle_err(max_rr_prio, "sched_get_priority_max");
  printf("Max RR prio: %d\n", max_rr_prio);

  /* Get the min priority value for SCHED_RR */
  min_rr_prio = sched_get_priority_min(SCHED_RR);
  if(min_rr_prio == -1)
    handle_err(min_rr_prio, "sched_get_priority_min");
  printf("Min RR prio: %d\n", min_rr_prio);

  cpu_set_size = sizeof(cpu_set_t);
  CPU_ZERO(&cs);  /* clear the mask */
  CPU_SET(0, &cs);
  CPU_SET(1, &cs);
  /* Set the affinity to CPUs 0 and 1 only */
  ret = sched_setaffinity(pid, cpu_set_size, &cs);
  if(ret == -1)
    handle_err(ret, "sched_setaffinity");
```

```c
  /* Get the CPU affinity */
  CPU_ZERO(&cs);
  ret = sched_getaffinity(pid,
    cpu_set_size, &cs);
  if(ret == -1)
    handle_err(ret,
      "sched_getaffinity");
  assert(CPU_ISSET(0, &cs));
  assert(CPU_ISSET(1, &cs));
  printf("Affinity tests OK\n");

  /* Yield the CPU */
  ret = sched_yield();
  if(ret == -1)
    handle_err(ret,
      "sched_yield");

  return EXIT_SUCCESS;
}
```

Additional documentation

- **CFS:**
  - `http://www.ibm.com/developerworks/library/l-completely-fair-scheduler/`
  - `http://elinux.org/images/d/dc/Elc2013_Na.pdf`
- **Linux scheduling:**
  - `https://www.cs.columbia.edu/~smb/classes/s06-4118/l13.pdf`

Bibliography I

[1] Inside the linux 2.6 completely fair scheduler.
`https://www.ibm.com/developerworks/library/l-completely-fair-scheduler/.`
Accessed: 2017-02-01.

[2] The rotating staircase deadline scheduler.
`https://lwn.net/Articles/224865/.`
Accessed: 2017-01-29.

[3] Rsdl completely fair starvation free interactive cpu scheduler.
`https://lwn.net/Articles/224654/.`
Accessed: 2017-01-29.

[4] Sched_deadline: a status update.
`http://events.linuxfoundation.org/sites/events/files/slides/SCHED_DEADLINE-20160404.pdf.`
Accessed: 2017-02-06.

[5] Understanding the linux 2.6.8.1 cpu scheduler.
`https://web.archive.org/web/20131231085709/http://joshaas.net/linux/linux_cpu_scheduler.pdf.`

Accessed: 2017-01-28.

[6] LOZI, J.-P., LEPERS, B., FUNSTON, J., GAUD, F., QUÉMA, V., AND FEDOROVA, A.
The linux scheduler: A decade of wasted cores.
In *Proceedings of the Eleventh European Conference on Computer Systems* (2016), EuroSys '16, ACM, pp. 1:1–1:16.