09: Real-time Linux

Microcontrollers

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Real-Time Linux

Two types of operating systems

GPOS (general-purpose operating system):

- Attempt to cover a broad range of application fields, e.g., desktop, server.
- Optimized for the "average" case, the average throughput, ...
- Linux traditionally is strong in scaling: embedded systems, smart phones, entertainment systems, TV boxes, desktop, servers, high-performance clusters, ...
- Linux also is strong in running on a large variety of architectures, e.g., Alpha, Arm, HPPA, i386, amd64, ia64, m68k, mips, PowerPC, RISC-V, S390, x32, ...

RTOS (real-time operating systems):

- Specialized for real-time operation
- Typically runs on embedded systems

A shift towards COTS and real-time Linux

Proprietary embedded systems[1] traditionally run typically either of two software stacks:

- Bare metal, i.e., without operating system, often on specialized hardware.
- Special-purpose RTOS, e.g., VxWorks or FreeRTOS.

Issues

- Porting software environments (e.g., Python, Qt, or TensorFlow) can be between complex and unachievable.
- Maintaining security updates is troublesome. Having state-of-the-art security mechanisms is virtually unachievable.
- Leveraging complex, contemporary computing platforms is non-trivial. Operating a modern ARM processor bare-metal is unorthodox.[2]
- Product strategy: Costly, longer time-to-market, risky and costly transitions of hardware.

1 Typically the hardware design also also proprietary. This requires hardware-competent software engineers and software-competent hardware engineers to a certain level.

2 Booting a modern ARM processor with proprietary boot loards or setting up the DRAM timing is delicate, especially without vendor support.

A shift towards COTS and real-time Linux

There is a shift towards COTS (commercial off-the-shelf) computing platforms:

- Cheaper and reduced time-to-market
- Increased computational power by complex multi-core processors
- Huge software ecosystem, well established tools in industry and academia
- Contemporary and elaborate security mechanisms

Issue

They are traditionally made for a GPOS (general purpose OS), like Linux. But a GPOS focuses on high average performance but not real time.

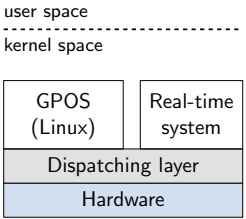
Two general approaches:

- Single kernel approach: Making Linux per se real-time capable.
- Co-kernel approach: Combining a (non-realtime) GPOS (e.g., Linux) with an RTOS.

Co-kernel approach

Combine real-time system with a GPOS is via a co-kernel approach:[3]

- Real-time tasks are executed by an additional RTOS, called the co-kernel.
- An intermediate layer dispatches interrupts from hardware. Sometimes hypervisor techniques are employed here.



[3] Also called pico-kernel, nano-kernel or dual-kernel approach.

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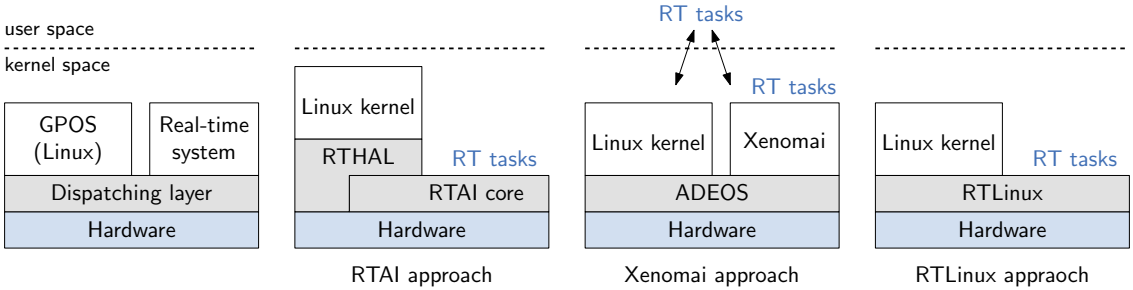
- An intermediate layer dispatches interrupts from hardware. Sometimes hypervisor techniques are employed here.
- This approach is popular in industry and used by a couple of real-time Linux projects [RMF19].



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Co-kernel approach

Advantage:

- Real-time is easier to achieve through special-purpose real-time subsystems.

Disadvantage:

- RT tasks are outside of Linux, so the Linux advantage is partially lost.
- RT tasks often in kernel space rather than user space.
- IPC between kernels needs special care.

Summary

We would wish for a single-kernel approach: a real-time capable Linux kernel. But this is *much* harder to achieve.

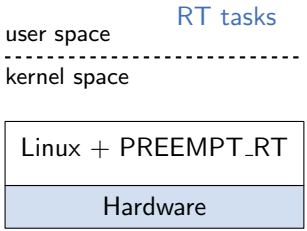
PREEMPT_RT patches

PREEMPT_RT makes the Linux kernel real-time capable.

- High-resolution timers, IRQ threads, ...
- Preemptive kernel data structures

A set of patches first released[4] 2006, see [RMF19]

- After many years of finalizing, in mainline kernel since 2024-09-20 released with kernel 6.12.[5]



Fully preemptive kernel

- If a low-priority task ends up in a non-preemptive kernel code then it can delay the execution of real-time tasks, which may then miss its deadline.
- Hence, we would like to minimize all non-preemptive codes in the kernel.
- Also improves responsiveness for desktop applications beyond real-time.

4 On LWN in 2004, but work started in 1999. [Cor23]

5 https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/commit/?id=baeb9a7d8b60b021d907127509c44507539c15e5

Linux scheduling classes

The Linux kernel provides different scheduler classes:

`SCHED_NORMAL` By default a process is scheduled in this non-real-time class. Designed for mixed load, like batch processing, number crunching and desktop interaction.

`SCHED_RR` and `SCHED_FIFO` These are POSIX-compliant real-time classes with static priorities that take precedence over `SCHED_NORMAL`. A running thread is preempted only by a thread of higher priority or by yielding the CPU voluntarily.[6]

`SCHED_DEADLINE` A scheduler for the sporadic task model with deadlines. It implements a global earliest deadline first (GEDF) algorithm (with Constant Bandwidth Server (CBS)).

The `SCHED_RR` and `SCHED_FIFO` classes do not consider deadlines for real-time scheduling, but we have to choose the static priorities and design the tasks in a way to achieve a real-time system.

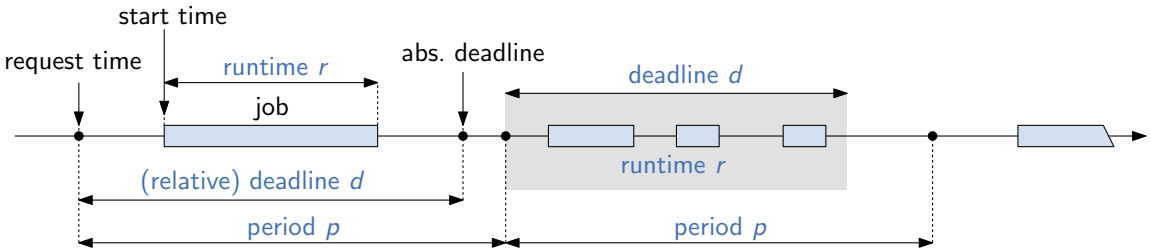
See details in `man sched`, [Oli18a] and [Oli18b].

[6] `SCHED_RR` also implements time-slicing for tasks of equal priority.

The task model of SCHED_DEADLINE

By means of `sched_setattr()` we set runtime r, deadline d and period p.

- Every p ns we spend r ns within the first d ns.
- It models a sequence of jobs with WCET at most r ns.



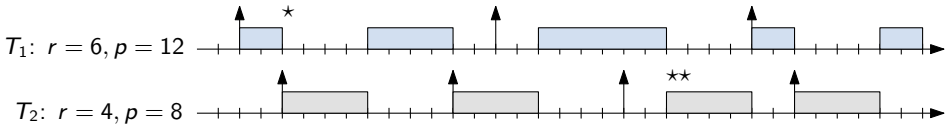
- The kernel performs a schedulability test[7] and requires $0 < r \leq d \leq p$.
- A thread calling `sched_yield()` marks the end of the of the current job and waits for the next period.

[7] On a single-core system it is necessary and sufficient. On a multi-core system it only sufficient.

EDF and bad jobs

Two tasks T_1 and T_2 with deadline equals period.

- At $\star$ we preempt T_1 and schedule T_2, whose deadline is earlier. At $\star\star$ we keep running T_1, whose deadline is earlier.



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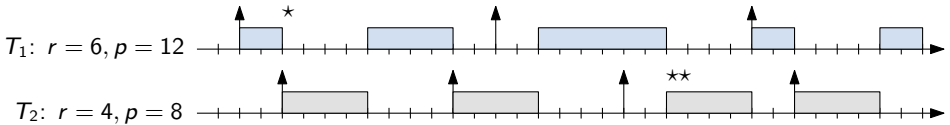
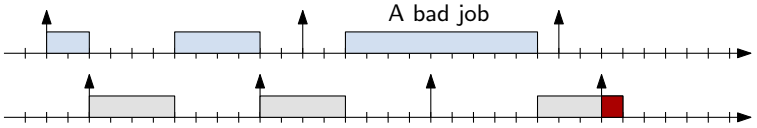


A bad job of T_1 can force T_2 to miss its deadline.

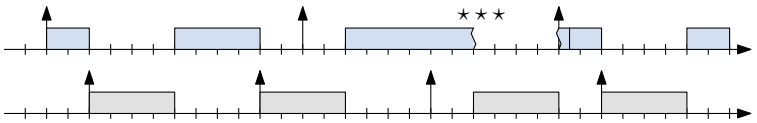
- A plain EDF is lacking temporal isolation between threads!



Constant Bandwidth Server

`SCHED_DEADLINE` implements EDF with Constant Bandwidth Server (CBS) algorithm.

- A job gets a "time budget" equal to its runtime parameter.
- If a job exhausted its budget, it is throtteled. That means, it is not scheduled until next period.
- This provides temporal isolation between threads.



SCHED_DEADLINE: Three application models

```c
int main (int argc, char **argv) {

    /* A task that runs 20ms within 100ms periods. */
    struct sched_attr attr;
    memset(&attr, 0, sizeof(attr));
    attr.size = sizeof(attr);
    attr.sched_policy = SCHED_DEADLINE;
    attr.sched_runtime = 20000000;
    attr.sched_deadline = attr.sched_period = 100000000;

    int flags = 0;
    if (sched_setattr(0, &attr, flags) < 0) {
        perror("sched_setattr() failed");
        return EXIT_FAILURE;
    }

    /* The actual work... */
    work();
    return EXIT_SUCCESS;
}
```

SCHED_DEADLINE: Three application models

```c
/* Model: Periodic tasks */
void work() {
    while(1) {
        /* Cylic work. WCET of 20ms. */
        periodic_job();
        /* Notify scheduler about end of
         * job. Only for real-time
         * scheduling! */
        sched_yield();
    }
}
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```c
/* Model: Sporadic event-handling task. */
void work() {
    while(1) {
        /* Sleep until next event. */
        blocking_wait_for_event();
        /* After wakeup: React on event,
         * e.g., process data, produce
         * result. */
        sporadic_job();
    }
}
```

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    }
}
```

```c
/* Model: Aperiodic, bandwidth-guaranteed computing. */
void work() {
    /* Just compute, without blocking or calls or yield. The CBS will throttle
     * the thread after 20ms per period. */
    while(1);
}
```

Linux commands and tools

chrt

Can change real-time attributes of processes, e.g., scheduling policies and their attributes.

cyclictest

Performs timer latency tests with various different modes of operation.

- Part of the rt-tests suite [rt-tests], which also includes signaltest, fwlatdetect, and many more.
- Can set processor affinity or mlockall
- For different scheduling policies and priorities, with different timers, like nanosleep or POSIX timers.

latencytop

For visualizing and debugging system latencies and their causes

- For kernel and user space

Dependent tasks

In practice, real-time tasks are often dependent:

- Precedence of tasks: Task A's job needs to be done before task B's job can run, e.g., because it depends on A's result.
- Mutual exclusion: Two or more tasks access the same mutual-exclusive resource.
  - A high-priority task is indirectly delayed by a low-priority task.
  - This can make a real-time task miss its deadline.

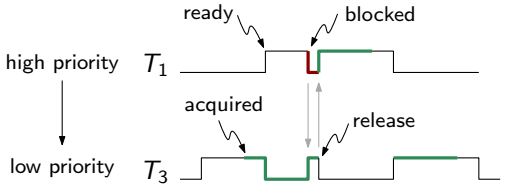
Priority inversion

Mutual exclusion can lead to the phenomenon called priority inversion:

- A task of lower priority can effectively make a task of higher priority to wait.

Example:

- Tasks T_1, T_2, T_3 with decreasing priority on a single processor.
- T_3 acquires a lock on a mutex first. T_1 is blocked when acquiring the same mutex. T_3 quickly releases the lock in favor of T_1 in a well-designed system.



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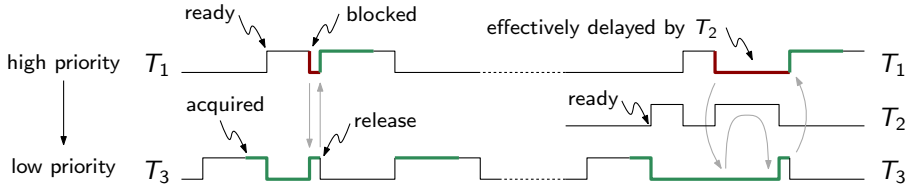
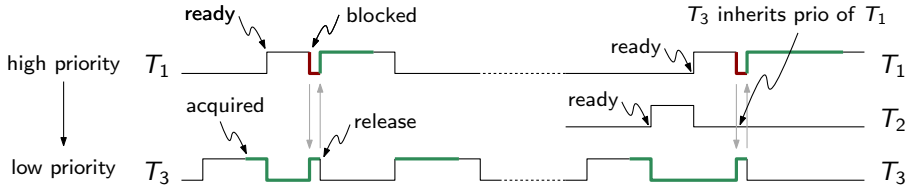
- T_3 acquires a lock on a mutex first. T_1 is blocked when acquiring the same mutex. T_3 quickly releases the lock in favor of T_1 in a well-designed system.
- T_2 delays T_3 from giving up the lock, which makes T_1 to wait despite its priority: Priority inversion.



Priority inheritance

The Linux kernel implements priority inheritance to avoid priority inversion:

- T_1 is blocked because T_3 holds the lock. Then T_3 temporarily inherits the higher priority of T_1.
- So a mid-priority task T_2 cannot delay T_3 from releasing the lock.



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[Oli18b] Daniel Bristot de Oliveira. "Deadline scheduling part 2 — details and usage". In: *LWN.net* (Jan. 2018). URL: https://lwn.net/Articles/743946/.

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