

08: Addressing, real-time systems

Microcontrollers

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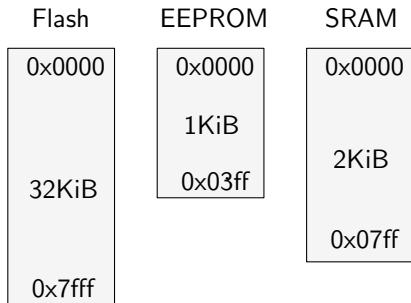
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Addressing

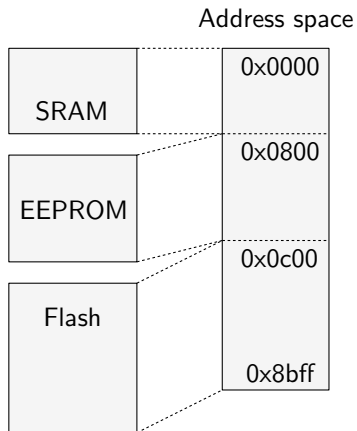
Memory addressing

The ATmega32 uses **separate memory addressing** for its memory:



- ▶ Separate address spaces.
- ▶ Different access methods (instructions, registers) tell which is meant.

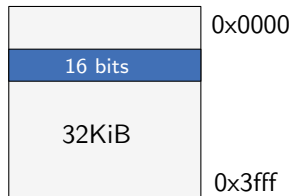
Other systems map them into a common **address space**:



Byte- versus word-addressed

The ATmega32 flash memory is organized as $16\text{ Ki} \times 16$ memory.

- ▶ The Flash is **word-addressed** with a word having 16 bits.
- ▶ The ATmega32 Flash memory addressing actually looks like this:



Rationale behind this design:

- ▶ Most AVR instructions are 16 bits wide: A word per instruction.
- ▶ The PC is 14 bits wide and can therefore address $2^{14} = 16384 = 16\text{ Ki}$ program memory locations.
 - ▶ A PC of $0x13$ translates to a byte address of $0x26$.
 - ▶ The PC cannot address an odd byte address by design!

Byte order: Endianness

There are two possibilities for word-wise access to byte-addressed memory:

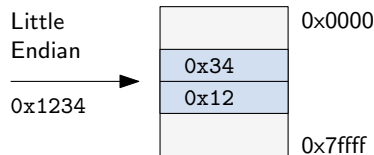
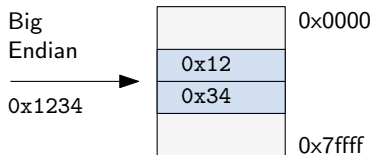
Big Endian High byte first (at the lower address).

Little Endian Low byte first (at the lower address).

Same for putting words on a network.

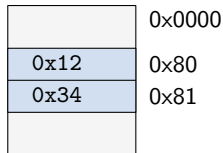
► “Lower address” means first in the byte stream.

Let us put the word `0x1234` in memory or on network:



Byte order: Endianness

Memory (or network):



```
uint16_t* p = 0x80;  
// Prints 0x1234  
printf("%x", *p);
```

Big endian computer

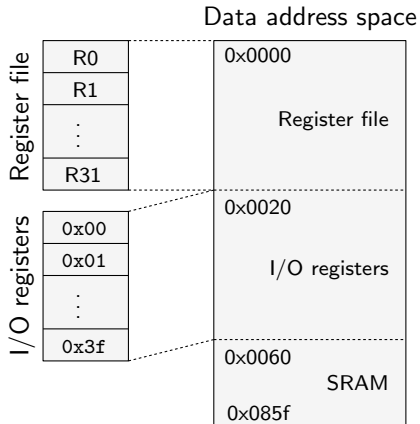
```
uint16_t* p = 0x80;  
// Prints 0x3412  
printf("%x", *p);
```

Little endian computer

Examples

- ▶ Little Endian: Intel x86, ATmega32 with avr-gcc
- ▶ Big Endian: Motorola 68k, Internet protocol suite (see C-functions `htonl()`, ...)
- ▶ ARM (since version 3) support [bi-endianness](#), they can set endianness.

ATmega32 data memory map



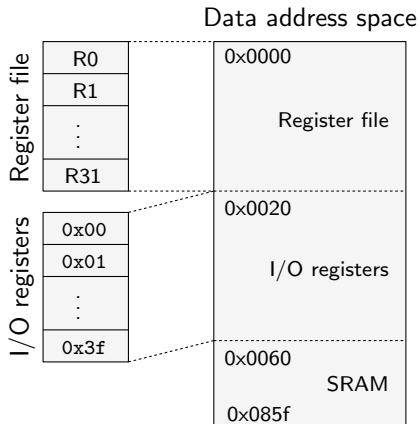
The register file and the I/O registers are mapped into the data address space.¹

- ▶ The I/O registers encompass SREG, SPH, SPL and control registers like PORTA, OCR1, GICR and so on.²
- ▶ The 2 KiB SRAM starts at address 0x0060.

² [ATmega32, p. 17]

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Memory mapped I/O:

- ▶ Ordinary memory access instructions instead of special instructions or additional registers.
- ▶ For avr-gcc, PORTA is just a byte at address 0x003b, or literally: `*(volatile uint8_t *)((0x1B) + 0x20))`

² [ATmega32, p. 17]

² [ATmega32, p. 327]

Real-time systems

A real-time system

A real-time system is a computational system for which the **correct execution** not only depends on the logical correctness of the output, but also whether the output is **computed in time**.

Examples:

- ▶ Fly-by-wire in air planes or obstacle detection in autonomous driving.
- ▶ The control loop in a control system, the cyclic motion planning of a drive or robot.
- ▶ Live audio- and video-processing.

Typical misconceptions

~~A real-time system would be a *fast* system.~~

- ▶ Real-time is about meeting **deadlines**, not about high throughput.
- ▶ Real-time is about computing **always as fast as required** (guaranteed timeliness) and not about as fast as possible on average (best effort).

Achieving **temporal determinism** in a real-time system comes at costs, which typically makes a real-time system achieve less average throughput.

Depending on the context, sometimes “real-time” refers to “live”, e.g., as fast as the physical time.³
This may or may not imply real-time as in real-time systems.⁴

³ E.g., playing a video or running a simulation live.

⁴ And sometimes it is nothing more than advertisement.

Rare events and peak load

A real-time system can be slow, but it must not miss a deadline even at a system's **peak load**.

- ▶ A **rare event** – e.g., failure of a component – can cause many related requests – e.g., an alarm shower – and lead to a peak load.
- ▶ For real-time systems we need to analyze the peak load, including fault scenarios.

Different types of real-time

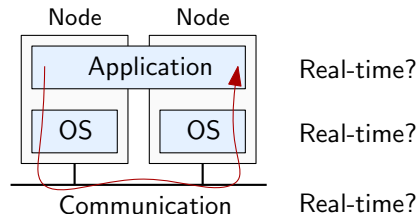
Three categories depending on the **consequence** of missing a deadline:

- Soft** If we miss the deadline the output can still be used. The user experience is degraded, e.g., video streaming. The deadline is a **soft deadline**.
- Firm** The output after the deadline is of no utility, e.g., too late object detection on a moving conveyor line. Infrequent deadline violations degrade quality of service but are tolerable.
- Hard** Missing a **hard deadline** is a system failure and can be catastrophic. Typical for safety critical systems and embedded systems.

Distributed real-time systems

Many embedded systems are actually **distributed**, **cyber-physical**, **real-time systems**:

- ▶ **Distributed**: A collection of autonomous nodes together achieve a common goal, e.g., the ECUs in a car or the drives and controllers that automate an industrial machine.
- ▶ Interacting with the physical world often imposes real-time constraints. E.g., a closed-loop controller for an industrial process must not be late.



The entire signal path (e.g., for a syscall, for a RPC) must be real-time capable.

Literature:

- ▶ **Hermann Kopetz**. *Real-Time Systems: Design Principles for Distributed Embedded Applications*. 2nd. Springer Publishing Company, Incorporated, 2011. ISBN: 9781441982360

A distributed system requires (network) communication.

- ▶ Hence, a distributed real-time system requires **real-time communication**.
- ▶ In industry, time-triggered Ethernet-based networking protocols became standard, e.g., TTEthernet, Powerlink, Varan, Ethercat, TSN.
- ▶ On the host, we need network interfaces that are real-time capable. For instance, we need ethernet controllers⁵ that allows for scheduled packet transmission. In Linux, there is the socket option `SO_TXTIME` which allows for scheduled packet transmission.

Not in the focus of this lecture.

⁵ Like the Intel i210.

Real-time operating systems

A real-time operating system has the following requirements:

- ▶ Predictable temporal behavior of system calls, e.g., concerning scheduling and memory management.
- ▶ Predictable response time upon events, e.g., when a GPIO toggles, a network packet arrived, a timer is due.
- ▶ Temporal isolation between processes, i.e., preemptive multitasking

Worst-case execution time

For a given task, function or piece of code we define the **worst-case execution time** (WCET) as the maximum length of *physical* time required.

A deadline for a task can only be met if the WCET of the task is bound.

- ▶ Real-time algorithms are therefore $O(1)$ algorithms (or the input size is bound).
- ▶ For instance, if we do dynamic memory allocation in real-time code then we need a constant-time memory allocator, such as TLSF [TLSF].

How to find the WCET?

Unpredictability of contemporary processors

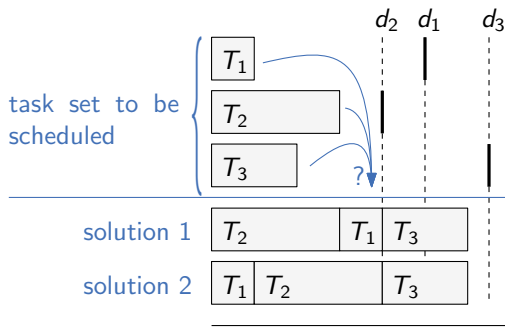
- ▶ Processors caches, including simultaneous access from multiple cores
- ▶ Virtual memory management, prefetching and speculative execution, instruction reordering
- ▶ Shared access to I/O and memory buses
- ▶ Power-saving strategies and system-management mode (SMM)

Hence, predicting the physical time spent on a LOC in C, or even a single machine instruction, is virtually impossible.

- ▶ Even if we could, WCET would be hopelessly pessimistic.
- ▶ This is an unsolved problem and makes engineering of real-time systems a delicate endeavor; a clean WCET analysis is typically not performed. Instead, margins – like 20 % – are added to measurements, although this is theoretically unjustified.
- ▶ **Cache locking** improves predictability and somewhat simplifies WCET analysis.

Real-time scheduling

- ▶ A **real-time scheduler** schedules real-time tasks T_i in a way such that they all meet their respective **deadlines** d_i .
- ▶ Multi-core real-time scheduling is *much* harder than single-core real-time scheduling.

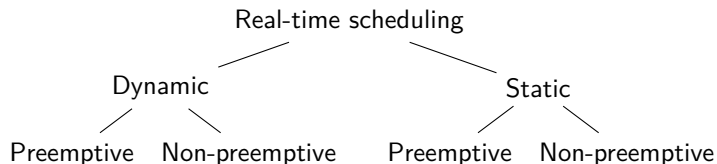


In this example, T_1 and T_2 cannot be scheduled last, because either of them will miss its deadline. Hence, T_3 needs to be last, and we are left with two possibilities.

But how does an algorithm look like to solve the problem in general?

Figure: Two possible single-core schedules for tasks T_i with deadlines d_i .

Classification of scheduling algorithms



Dynamic A dynamic scheduler is an online scheduler: Scheduling decisions are made during runtime. It is flexible, adaptable, but more complex. Making a scheduling decision can be computationally costly.

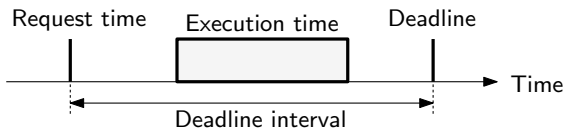
Static A static scheduler makes the schedule during compile time. It needs to know the task characteristics (WCET, interdependencies, mutex, deadlines) a priori. It is simple but not flexible. Typical for industrial control systems.

- ▶ Non-preemptive schedulers are simpler and might be used in constrained systems, but they do not provide temporal isolation.
- ▶ Linux provides a dynamic, preemptive real-time scheduler.

Real-time tasks

The time when we request the execution of a task is called **task request time**.

- ▶ The difference between deadline and request time is called **deadline interval**.
- ▶ The **laxity** is the difference between deadline interval and the execution time. For schedulability the laxity must be non-negative.
- ▶ For analysis purposes, we have to assume that the execution time is the WCET.



Two types of tasks:

Periodic The initial request time determines all future request times a priori by adding multiples of a **period**.

Sporadic The task request times are not known a priori.

Dynamic real-time scheduling

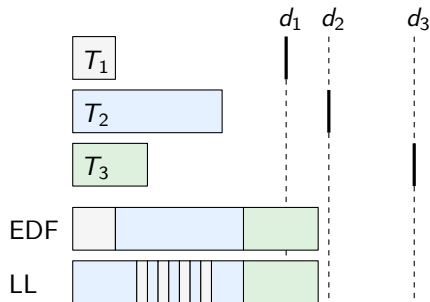
Both are based on **dynamic priorities**, i.e., scheduling priorities that change over time.

EDF The earliest deadline first (EDF) algorithm gives the task with the earliest deadline the highest priority. Note that we do not need to know the execution time for EDF.

LL The least laxity (LL) algorithm gives the task with the shortest laxity the highest priority.

Assumptions:

- ▶ Tasks are independent of each other; no precedence constraints.



- ▶ Laxity stays constant for the task that is scheduled and declines for those not being scheduled.
- ▶ Least laxity leads to frequent context switches when two tasks reach the same laxity, as they repeatedly relieve each other.
- ▶ This makes least laxity impractical.

Optimality

A scheduler is called optimal when it can find a schedule (given one exists).⁶

One can prove that on uni-processor systems and with periodic tasks both, EDF and LL, are optimal.

- ▶ On multi-core systems they are both not optimal. But LL can find schedules where EDF fails.
- ▶ Real-time scheduling on multi-core systems is *very* hard.

Can we test whether a task set is schedulable?

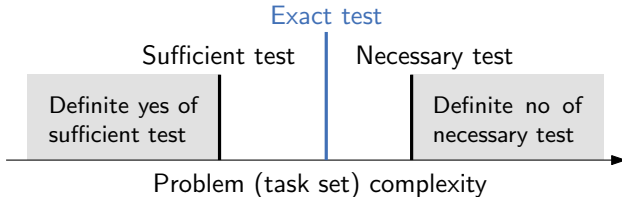
- ▶ We would like to test whether we can accept a new task to be scheduled.

⁶

To be precise, they find a schedule if a so-called clairvoyant scheduler – which knows all future request times – can find one.

Schedulability tests

- ▶ An **exact schedulability test** answers “yes” if there exists a schedule and “no” if not. Depending on setups this problem can easily be NP-complete, so no polynomial time algorithms exist.⁷



- ▶ A **sufficient schedulability test** is simpler: It answers “yes” if there definitely exists a schedule. Otherwise a schedule may or may not exist.
- ▶ A **necessary schedulability test** is the opposite: It answers “no” if there definitely does not exist a schedule. Otherwise a schedule may or may not exist.

⁷

Unless the most famous open problem “P vs. NP” in computer science turns out to be $P=NP$.

Utilization

We consider a set of **periodic tasks** T_1, \dots, T_n , where T_i has a period p_i and execution time c_i .

The **utilization** μ is defined by

$$\mu = \sum_{i=1}^n \frac{c_i}{p_i}.$$

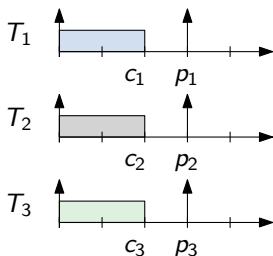
Interpretation: A single task T_i utilizes a single core for a fraction of $\frac{c_i}{p_i}$. All tasks together utilize a single core for a fraction of μ of its time.

A necessary schedulability test

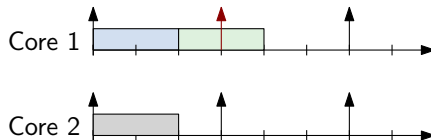
A **necessary schedulability test** for a m -core system is

$$\mu \leq m.$$

This test is **not sufficient**. Here we have tasks T_1, T_2, T_3 with period $p_i = 3$ and $c_i = 2$ for $1 \leq i \leq 3$. Although $\mu = 3 \cdot 2/3 = 2$, we cannot schedule them on a 2-core machine:⁸



Some task violates its deadline.



⁸

If we could parallelize tasks, we could utilize all cores. But this would mean we split T_3 into two tasks with execution time of 1 each, and we only changed our counter example to fix it.

Dhall's effect

Dhall's effect

Choose an arbitrarily large number m of cores. Then there is a set of tasks with $\mu \approx 1$ that is non-schedulable with EDF. Even if deadlines equal periods.

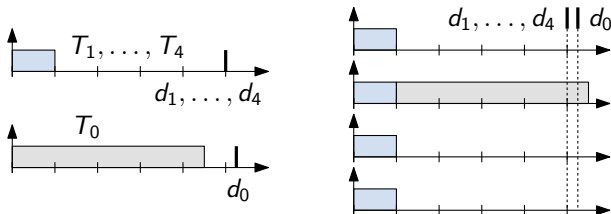
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Example:

- ▶ A task T_0 with deadline $d_0 = 1 + \epsilon$, with $\epsilon > 0$ arbitrarily small and an execution time $c_0 = 1 - 2\epsilon$.
- ▶ Tasks T_1, \dots, T_m with deadline $d_i = 1$ and $c_i = 4\epsilon$. So we have $\mu = 4\epsilon m + \frac{1-2\epsilon}{1+\epsilon} \approx 1$.



- ▶ EDF schedules T_1, \dots, T_m first. Hence, T_0 ends at time $1 + 2\epsilon$, after its deadline.

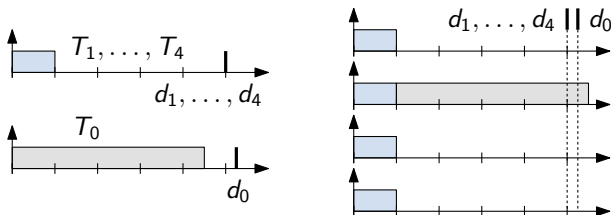
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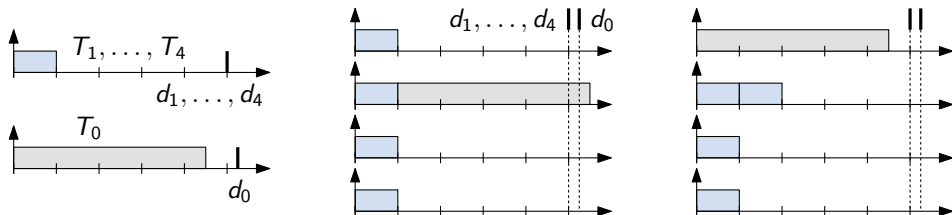
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- [ATmega32] *ATmega32: 8-bit AVR Microcontroller with 32KBytes In-System Programmable Flash.* Atmel Corporation. Feb. 2011.
- [Kop11] *Hermann Kopetz. Real-Time Systems: Design Principles for Distributed Embedded Applications.* 2nd. Springer Publishing Company, Incorporated, 2011. ISBN: 9781441982360.
- [TLSF] *Two Level Segregate Fit.* URL: <http://www.gii.upv.es/tlsf/>.