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ERTS - Embedded real-time systems

ERTS 5 – Process computer HW 2

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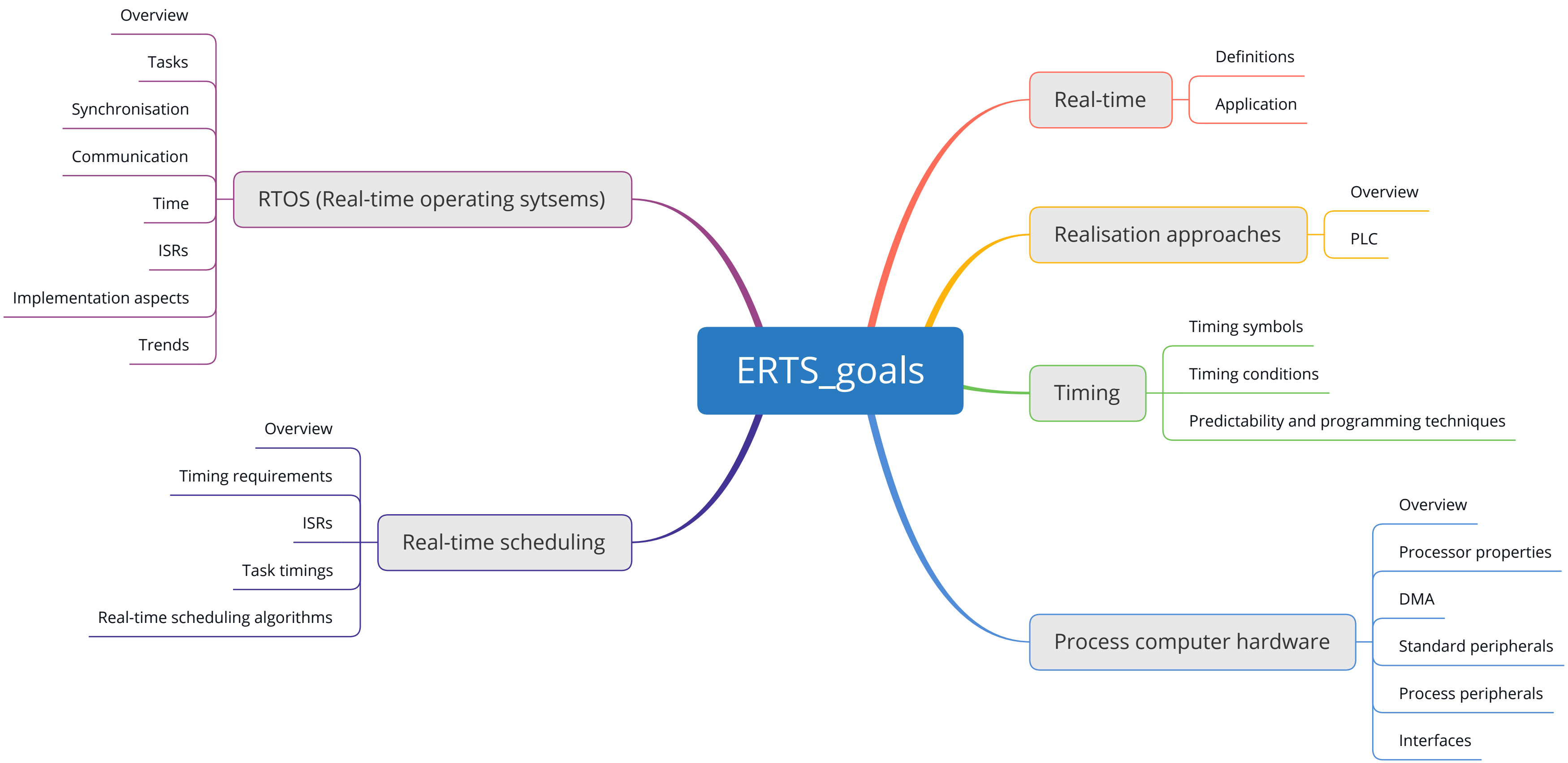
Goal



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Goal

ERTS::Process computer HW 2

- Digital I/O
- Analog I/O
- Real-time clocks
- RTC examples
- Pulse-width modulation

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Digital input

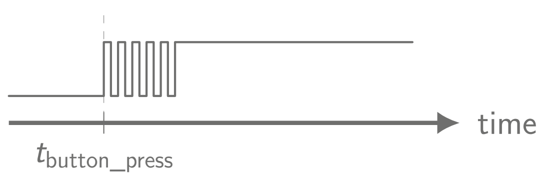
Used for reading binary signals:

- Generating interrupts: on rising or falling edge
- Timer: trigger signal
- On/off detection
- Data transfer (read): UART, SPI, I^2C, RS232, ...

A recurring problem: contact bounce

Hardware switches introduce a contact bouncing, which makes the input go high and low several times, instead of exactly once.

HW switch



Possible solutions:

- Hardware solution based on electrical parts
- Software solution

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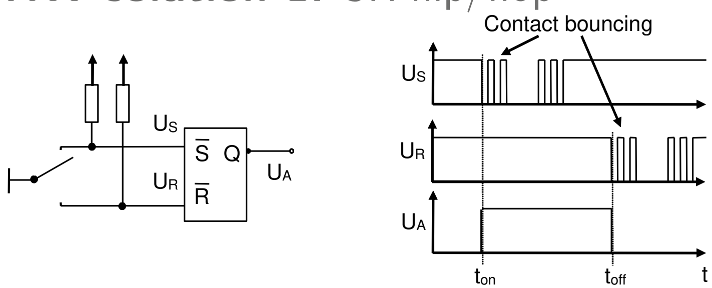
Digital input

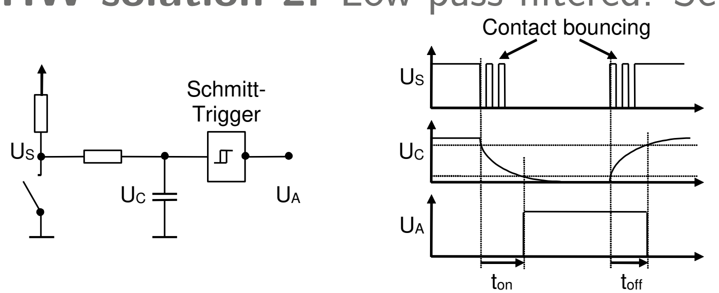
Possible hardware solutions for contact de-bounce:

- **HW solution 1:** SR flip/flop



⇒ Only possible for switches

- **HW solution 2:** Low pass filtered: Schmitt trigger



⇒ Can introduce a switch-on and switch-off delay

⇒ Also possible for push buttons

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Digital input

Possible software solutions for contact de-bounce:

- **SW solution 1:** Read input multiple times in a defined time period

$\Rightarrow$ Introduces an additional CPU load and an additional delay (read time)

- **SW solution 2:** Introduce a waiting timer after an impuls

```
//init
bool old_state = false;

//cyclic application
while(true) {
  bool io_state = read_io_port();
  if(io_state != old_state) {
    //perform some action

    delay(WAIT_TIME);
    old_state = io_state;
  }
}
```

$\Rightarrow$ Usually not suitable for real-time systems

Digital input

Possible software solutions for contact de-bounce:

- **SW solution 3:** Remember last switch time

```c
//init
const uint32_t DEBOUNCE_DELAY = /*HERE SOME APPROPRIATE TIME*/;
uint32_t last_switch_time = 0;
uint32_t current_time = 0;
bool old_state = false;

//cyclic application
while(true){
  bool io_state = read_io_port();
  current_time = get_time();
  if(io_state != old_state &&
     (current_time - last_switch_time) > DEBOUNCE_DELAY)
  {
    //perform some action

    old_state = io_state;
    last_switch_time = current_time
  }
}
```

⇒ `get_time();` may be expensive and relying on a SysTick

⇒ Additional variables (e.g. `last_switch_time`) required

Digital output

Used for writing binary signals:

- On/off: relais, engine, state information, ...
- Pulse-width modulation (PWM)
- Timer
- LCD
- Data transfer (send): UART, SPI, I^2C, RS232, ...
- ...

Usually, transistors are used for powering/switching relais, engines, ..., to not overload the digital output pin, connected to the processor.

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Analog input

Analog do digital converter (ADC)

The analog value (voltage) is converted into a number of bits in a register.

Details:

- Sample- and hold amplifier (remembers value)
- Converting into bits
- For multiple channels: each has its own sample- and hold amplifier

Types:

Class	Principle	Converting time	Resolution	Example
Counting method	1 Value/step	0.1 . . . 1000 ms	8 - 20 Bit	Dual-slope (integrating) ADC
Successive method	1 Bit/step	0.1 . . . 100 μs	8 - 16 Bit	Successive approximation ADC using a binary search
Parallel method	1 Conversion/step	1 . . . 100 ns	4 - 10 Bit	Time-interleaved ADC with m parallel ADCs

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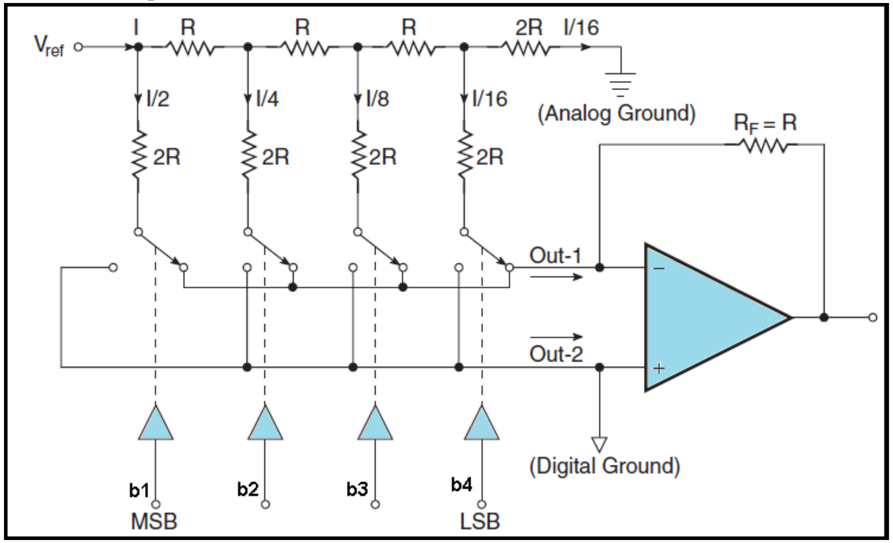
Analog output

Digital to analog converter (DAC)

The bits of a register are converted into an analog value (voltage).

- Number of bits ⇒ resolution of accuracy
- Modes
  - unipolar: 0 to $+x$ V
  - bipolar: $-x$ to $+x$ V
- Current range: e.g. 0 mA to 20 mA

Example: 4-bit R-2R ladder DAC:



[source: electronicsengineering.nbcafe.in]

Resulting voltage:

$$V_0 = V_{ref} * (R_F/R)[b_1/2^1 + b_2/2^2 + b_3/2^3 + b_4/2^4]$$

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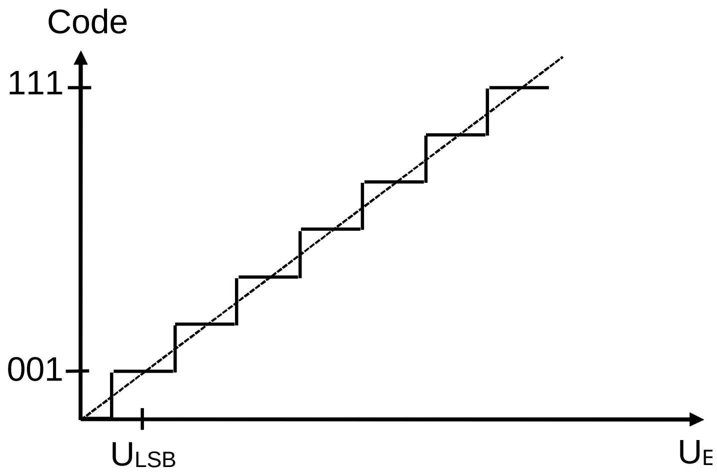
A/D converting errors

Static errors

Characteristic curve of a 3 bit A/D converter:



Problems:

- **Quantisation error**: $\pm 0.5 \times 2^{-n}$; $n =$ number of bits
- Zero-point error (horizontal misalignment) (may be solved with a potentiometer)
- Gain error (wrong gain) (may be solved with a potentiometer)
- Linearity error (may be corrected in software, tricky)

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A/D converting errors

Dynamic errors

Nyquist–Shannon sampling theorem:

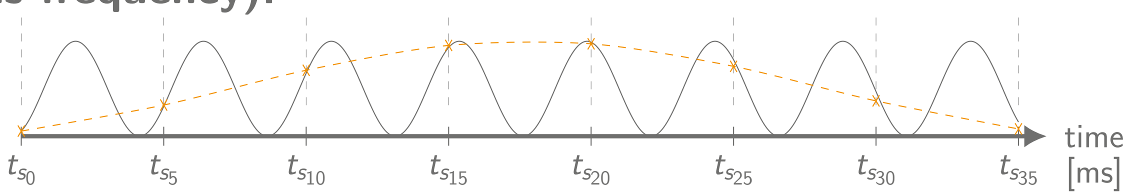
$$f_s > 2 \times f_{max}$$

- $f_s \rightarrow$ Sampling frequency
- $f_{max} \rightarrow$ Maximum frequency of signal

$\Rightarrow$ In practice, $f_s > 10 \times f_{max}$

Possible problems:

- **If f_s is to small ($\Rightarrow$ alias frequency):**
  — Signal with f_{max}
  --- Sampled signal with f_s



- If the **sampling time $\triangle t_s$ has a high jitter**, an additional source of error (unpredictability) is introduced.

$\Longrightarrow$ Mitigation of the problem possible with a sample-and-hold amplifier.

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Real-time clocks: overview

In microcontrollers (and PCs), different real-time clock (RTC) mechanisms exist:

- Clock (absolute time clock)/timer
- Relative clock/relative timer
- Time-out monitoring

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Clock (absolute time clock)/timer

This kind of clocks are often called real-time clocks (RTC).

Clock mode:

- Gives the exact absolute date and time
- Usable for initialising software based time management software

Timer mode:

- Triggers an interrupt at a specified absolute time
- Wake up a device (e.g. from sleep mode)

Variants:

- Battery buffered: Allows working while the device is off
- Radio-controlled: Signal is received from a station (DCF77 or GNSS). Synchronisation can take up to several minutes.

Relative clock/relative timer

Clock mode:

- Allows relative time measurements
- With an appropriate initialisation, an absolute clock can be implemented

Timer mode:

- Triggers an interrupt at a specified relative time
- Wake up a device (e.g. from sleep mode)
- SysTick for the OS

Variants:

- Usually quartz-based with a resolution of $\approx 1\ \mu s$
- Also low-power variants possible: working in sleep mode

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Time-out monitoring

Monitor if an action has been taken place within a defined time period. If not, perform an emergency reaction.

Watchdog/timeout:

```
action();

//reset counter
feed_the_dog();
```

In the hardware:

```
if(counter > max_counter){
  perform_emergency_reaction();
  //reaction: often restart
}
```

Hartbeat:

```
while(true){
  action();

  //reset counter
  feed_the_dog();
}
```

In the hardware:

```
if(counter > max_counter){
  perform_emergency_reaction();
  //reaction: often restart
}
```

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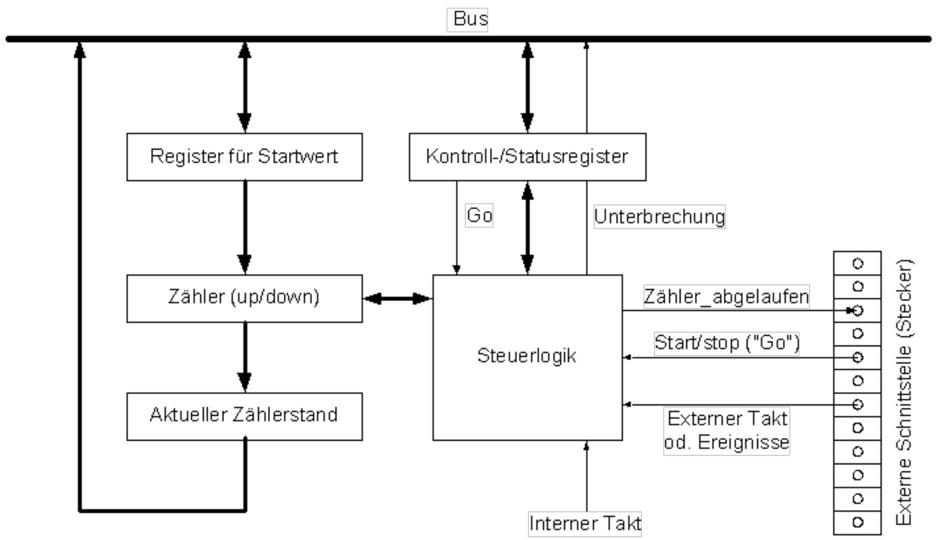
Abstracted real-time clock for lecture



Modes:

- Stop mode*: for time measurements
- Alarm/wake up mode*: generates interrupt after a specified time
- Counting mode: counts events (internal or external), can also generate interrupts
- Repeat mode: for stop, alarm/wake up, or counting mode

Tick:

- Internal clock
- External clock or events

* The stop and alarm/wake up modes are often called capture and compare.

Additionally possible:

- Regular pulses, with an
- Adjustable pulse length (PWM)

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(a) RTC example: stop mode

The time of a program sequence should be measured.

Program:

```
//configure
RTC_COUNTER = 0;
RTC_STATE   = RTC_MICRO_SEC | GO;

//program sequence to measure
do_x();

uint32_t micros = RTC_COUNTER;
RTC_STATE &= ~GO; //stop
```

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(b) RTC example: alarm mode

A task τ should be delayed for x μs.

Task τ:

```
//configure
RTC_IVT     = &rtc_isr;
RTC_COUNTER = x;
RTC_STATE   = RTC_IE_ENABLE | RTC_ALARM_MODE | RTC_MICRO_SEC | GO;

P(semaphore); //wait for x micro seconds
//continue after (x+ >>0) micro seconds
```

RTC ISR:

```
void rtc_isr() {
    V(semaphore);
    IRET; //return from interrupt, depends on HW
}

//This is only a principal view, the ISRs are often encapsulated by
//a HAL (hardware abstraction layer) or an OS
```

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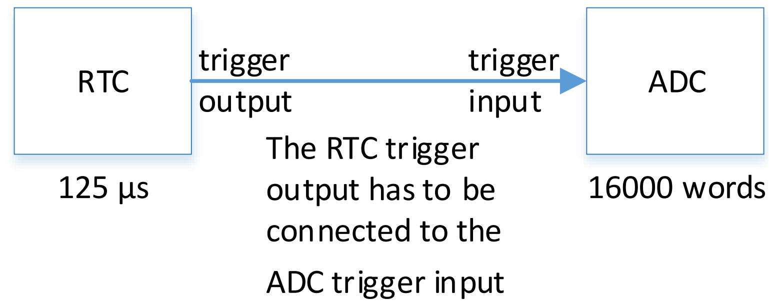
(c) RTC example: analog signal sampling

A signal (± 5 V) should be sampled with a time interval of $125\ \mu$s for a period of 2 s.

- Number of words/s: $\frac{1}{125\ \mu s} = 8000$ words/s
- Within 2 s: $2 \times 8000 = 16000$ word samples



Main program:

```c
volatile uint32_t buffer[16000];

//configure A/D converter
ADC_WORD_COUNT = 16000;
ADC_BUS_ADR    = &buffer;
ADC_STATUS     = ADC_IE_ENABLE | ADC_RTC_TRIGGER_ENABLE
               | ADC_DMA_ENABLE | ADC_CHANNEL0 | GO;
ADC_IVT        = &adc_complete_isr;

//configure RTC
RTC_COUNTER = 125;
RTC_STATE   = RTC_ALARM_MODE | RTC_REPEAT | RTC_MICRO_SEC | GO;
```

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(c) RTC example: analog signal sampling

Alternative solution with alarm mode:

Main program:

```
volatile uint32_t buffer[16000];
volatile uint32_t i = 0;

//configure
RTC_IVT     = &rtc_isr;
RTC_COUNTER = 125;
RTC_STATE   = RTC_IE_ENABLE
            | RTC_ALARM_MODE
            | RTC_REPEAT
            | RTC_MICRO_SEC
            | GO;

P(semaphore); //wait for all samples
```

RTC ISR:

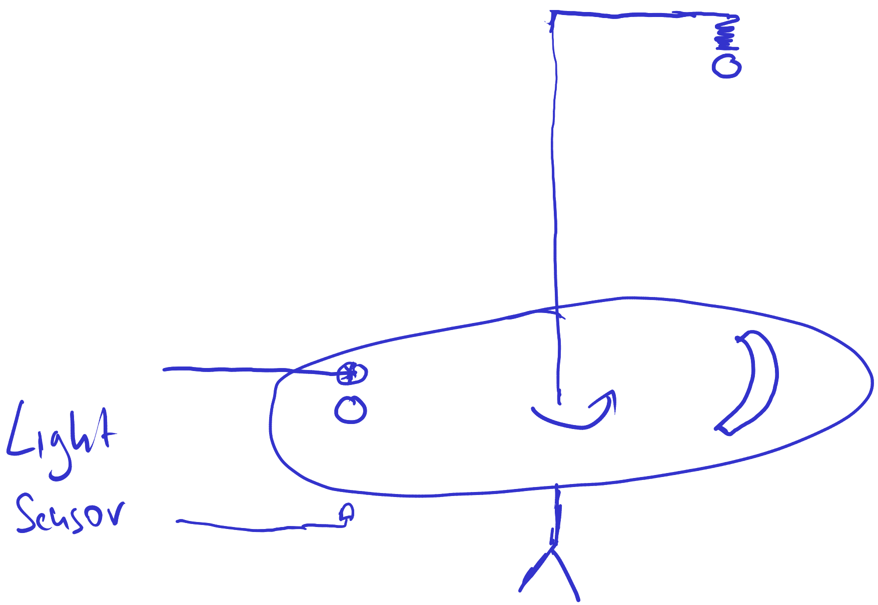
```
void rtc_isr() {
  ADC_soc();       //start of conversion
  ADC_wait_eoc(); //wait for completion
  buffer[i] = ADC_VALUE;

  ++i;
  if(i >= 16000){ //all samples done
    V(semaphore);
  }

  IRET; //return from interrupt,
        //depends on HW
}
```

Problems with this solution:

- There might be an additional timing delay until the ISR is called.
- There is an additional load on the CPU for the data transfer

(d) RTC example: ball drop example

Measure the rotation time of a disc with a light sensor and a hole in the disc.



Measure rotation time:

```
//configure
RTC_STATE    = RTC_STOP_MODE
             | RTC_MICRO_SEC;
wait_for_hole();
RTC_STATE   |= GO;   //start

wait_for_hole();
RTC_STATE  &= ~GO; //stop
rotation_time = RTC_COUNTER;
```

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(d) RTC example: ball drop example

Discussion on measure rotation time (`wait_for_hole()`):

1. Programmed I/O: busy wait/polling on ⇒ light sensor

⇒ High CPU load, but timely fast with a low uncertainty

⇒ Program design may be hard to write/maintain with other parallel tasks.

2. Light sensor ⇒ digital input $\overset{*}{\Rightarrow}$ ISR (start/stop/get counter RTC)

* Uncertainty in timing of the interrupt reaction time $T_{IRE} = T1 + T2 + T3$

3. Light sensor ⇒ start/stop input on RTC

⇒ Ideal solution in terms of time, but only possible with a suitable RTC

4. Light sensor ⇒ digital input ⇒ ISR ⇒ Task (start/stop/get counter RTC)

⇒ A high degree of uncertainty in terms of time, because additionally multi-tasking (schedling) effects can play a role.

⇒ Program design easier to write/maintain with other parallel tasks.

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(e) RTC example: watchdog

Watchdog functionality:

```
//configure
RTC_COUNTER = x + 2*y; //x = init time
                       //y = cycle time
RTC_STATE   = RTC_ALARM_MODE
            | RTC_RESET_ON_ALARM
            | RTC_MICRO_SEC
            | GO;

//cyclic application
while(true) {
    //here...
    //        ...application code with cycle time y (micro sec.)
    RTC_COUNTER = 2*y; //y = cycle time
}
```

Functionality:

The alarm (watchdog) shouldn't trigger, if the application (cyclic code) is always fast enough.

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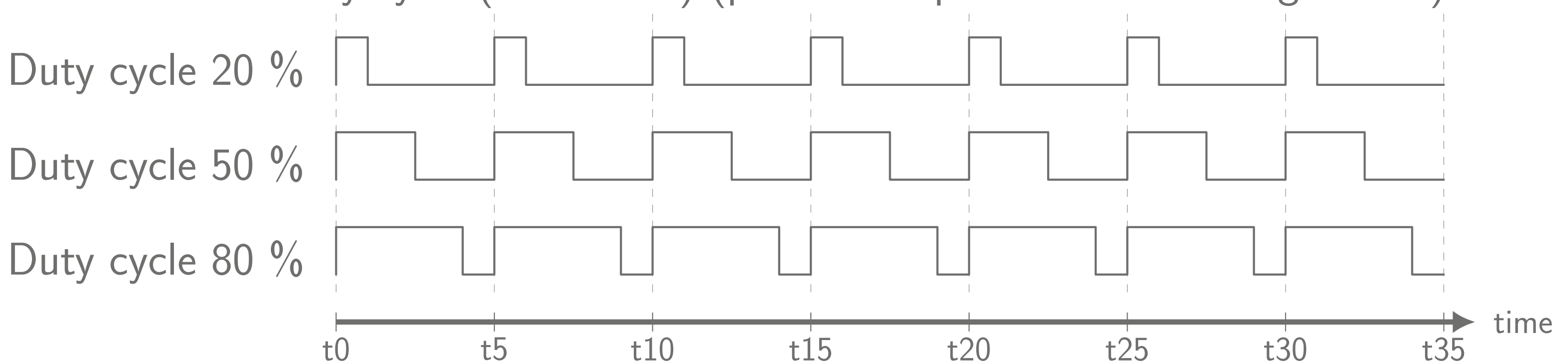
Pulse-width modulation

Pulse-width modulation (PWM) is used to control: engines, LED, ...

- Fixed time period T_P
- Square wave
- Variable duty cycle $(0 - 100\ \%)$ (part of the period where the signal is 1)



Generation possible with software or hardware

Software:

- Pro: May be more flexible than HW based PWM
- Con: CPU intense (I/O controlled by the software) + signal drift!

Hardware:

- Pro: HW based PWM signals can run independently without the CPU
- Pro: May be more accurate (means better predictability) than SW based PWM

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Summary and outlook

Summary

- Digital I/O
- Analog I/O
- Real-time clocks
- RTC examples
- Pulse-width modulation

Outlook

- DMA