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Sensors

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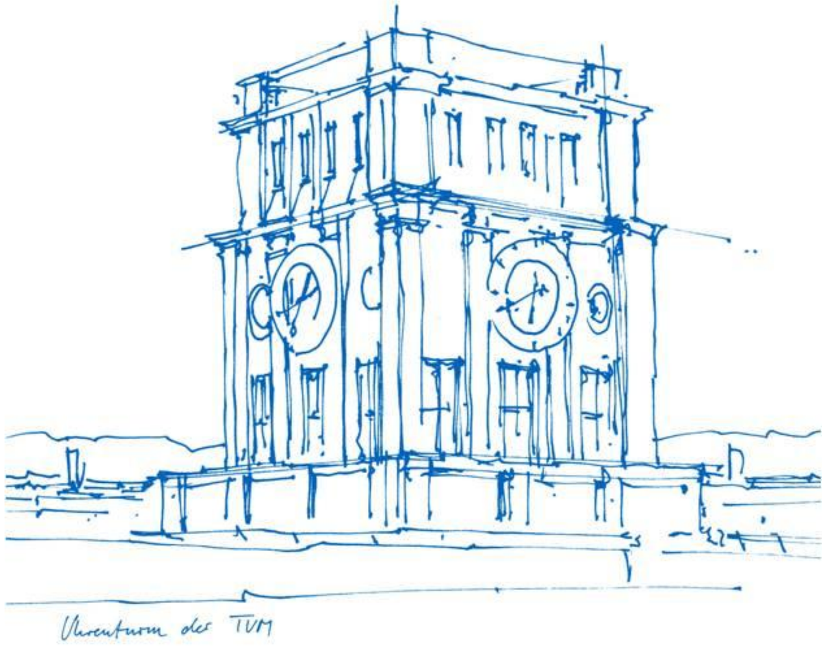

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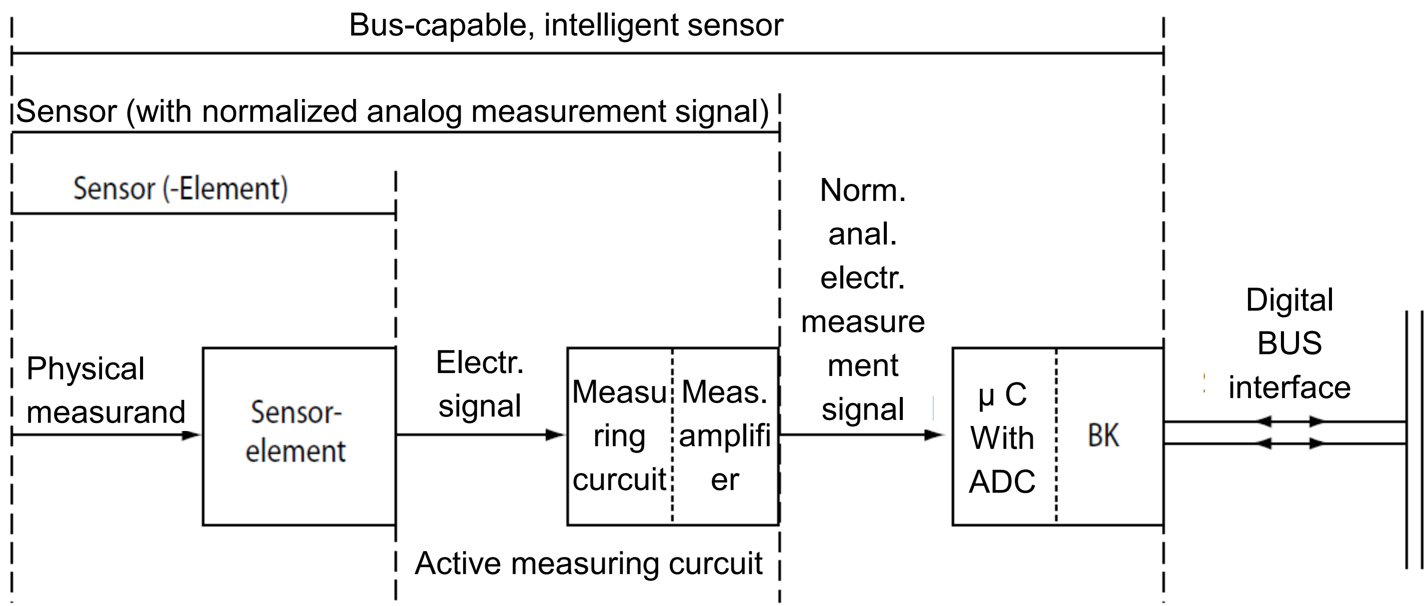
What is a sensor?



"Sensor elements transform physical, chemical or biological measurands into **electrical measurement** signals that have clear, **often linear** correlations with the measured values. The electrical measurement signals obtained are preprocessed with the aid of an active measurement circuit and amplified into a **normalized analog measurement signal**. In a **microcontroller**, the normalized analog signals are converted into **a digital signal format** and processed. A bus coupler is used for adaptation to a **digital bus interface** (bus-capable, intelligent sensor)."

Tränkler & Reindl,Sensortechnik, ISBN 978-3-642-29942-1

What is a sensor?

The first self-contained component that receives a measurand at its input and provides a conditioned measurement signal at its output.

Example Temperature sensor:

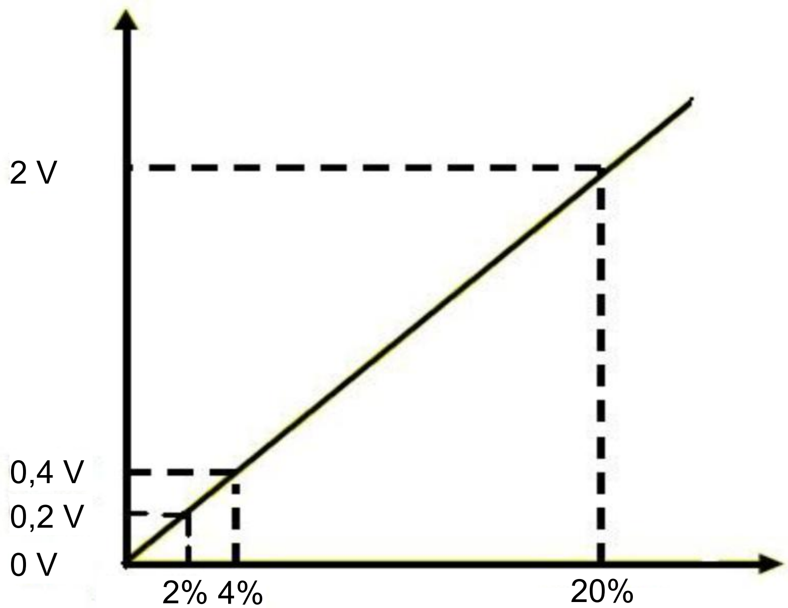
1. Resistance thermometer as sensor element
2. Bridge curcuit transforms change in resistance into change in voltage
3. Amplification of the voltage into „normalized output voltage“
4. Tapping of the normalized output voltage by microcontroller and processing
5. If necessary, transmission via BUS interface

→ Pt 100: 100 Ohm at 0 °C

Tränkler & Reindl,Sensortechnik, ISBN 978-3-642-29942-1

What is a sensor?

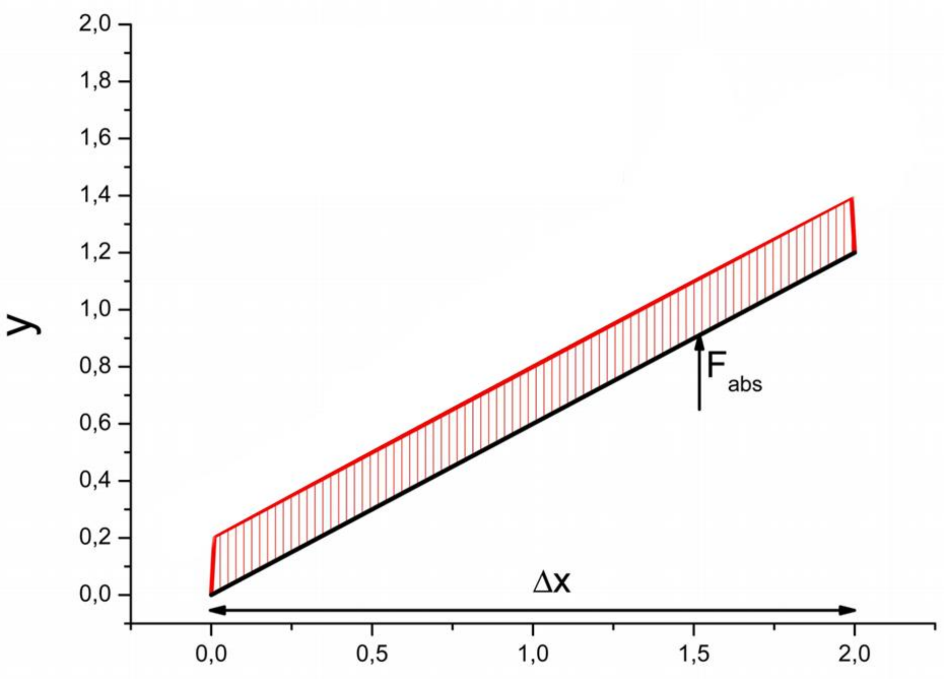
In the optimum case, the quantity to be measured and the voltage are linearly dependent



Measurement errors

Measurement errors

- But: No sensor is actually ideally linear. Every sensor produces errors
- Deviations occur, for example, due to
  - Zero-point error: output value deviates from the actual setpoint when the input value is zero
    - Minimize: Zero-point comparison with other sensors

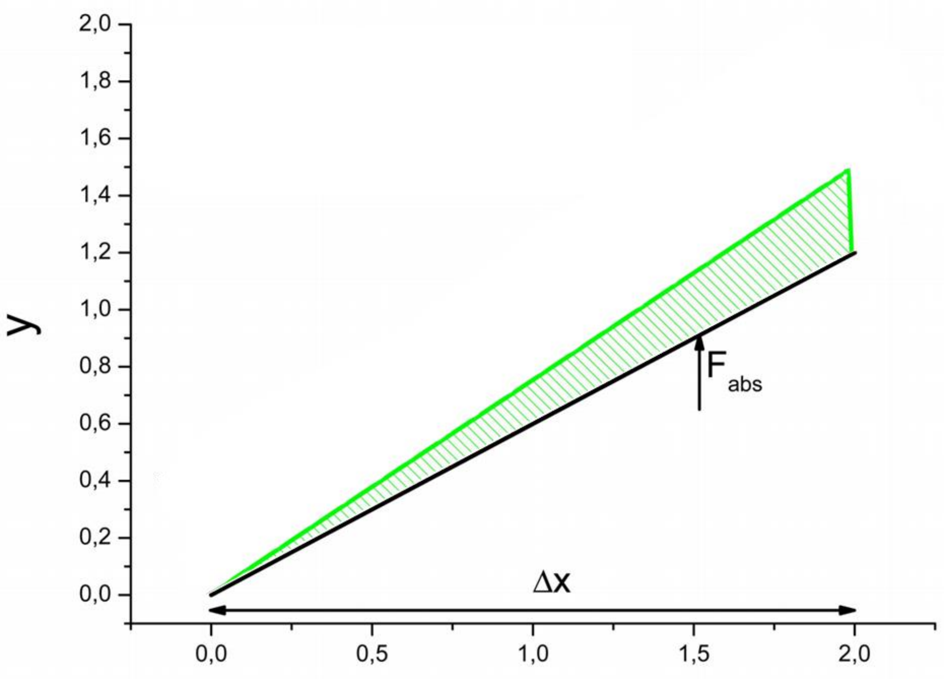


Measurement errors

- But: No sensor is actually ideally linear. Every sensor produces errors

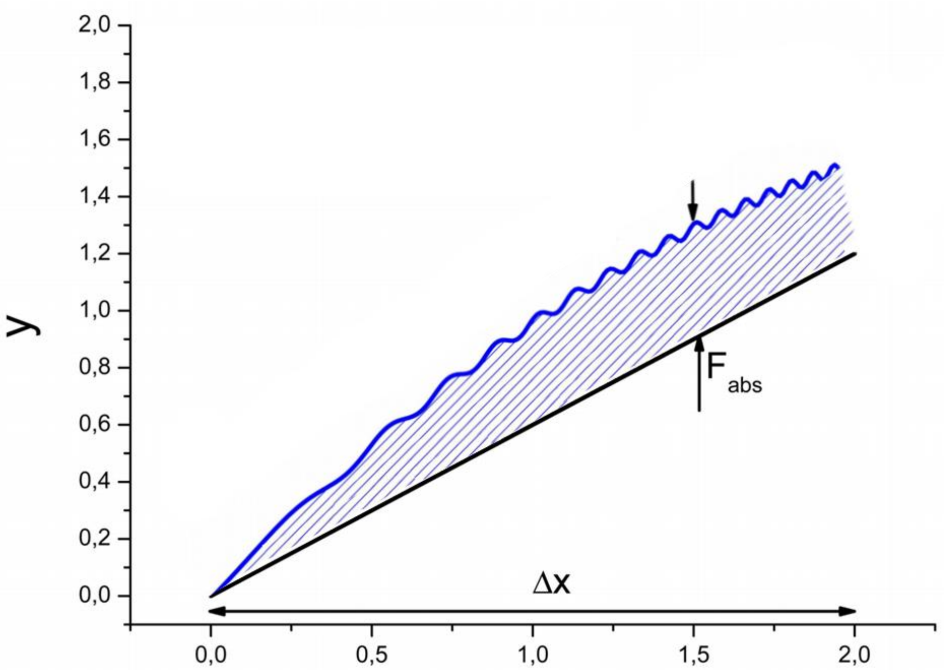
- Deviations occur, for example, due to

  - Slope error: slope from one point to another is not correct
    - Minimize: Measurement of two points as far away as possible



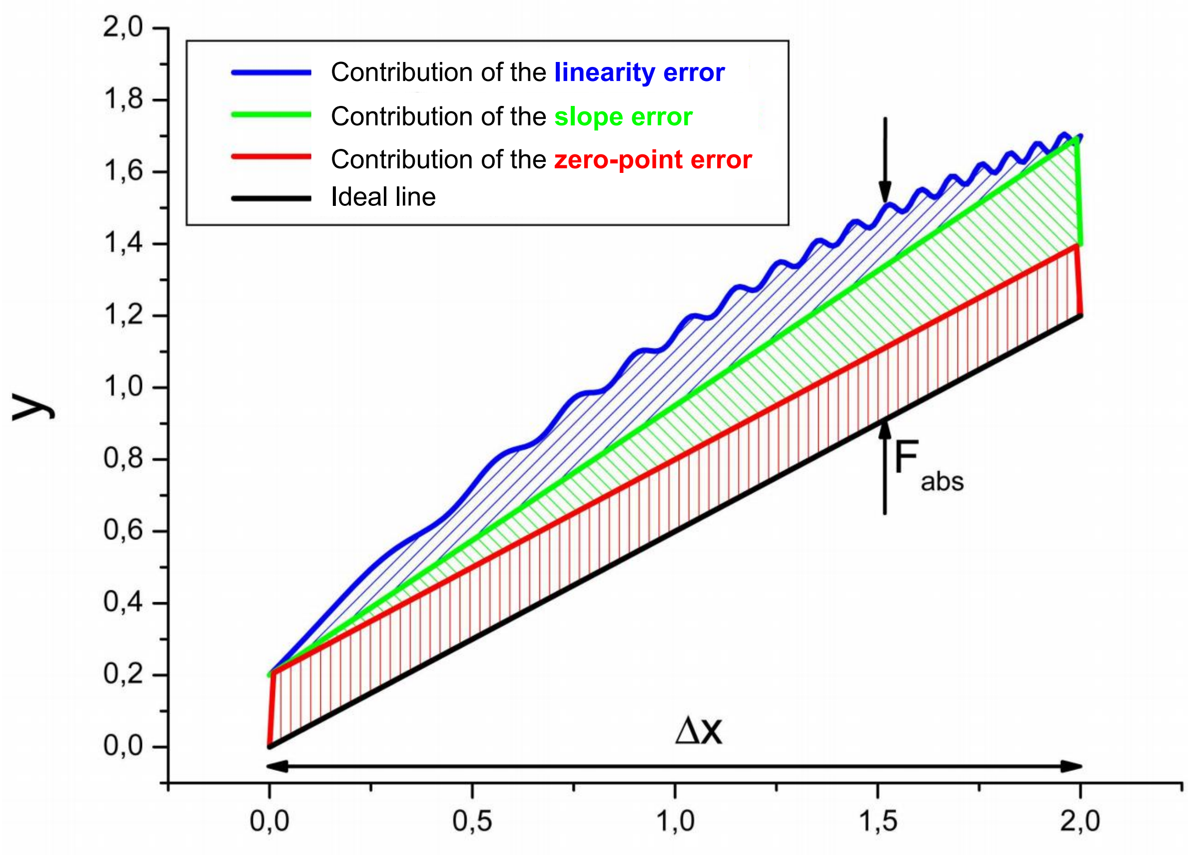
Measurement errors

- But: No sensor is actually ideally linear. Every sensor produces errors
- Deviations occur, for example, due to
  - Linearity error: Deviation of the ACTUAL characteristic curve from the TARGET characteristic curve
    (possibly not linear at all!)
    - Minimize: Compare as many measuring points as possible and describe line by mathematical model



Measurement errors

- If these errors add up, large deviations can occur!



http://www.physik.uni-oldenburg.de/Docs/epkos/Messtechnik.pdf

Measurement errors

- But why do measurement errors occur? Aren‘t the sensors calibrated?
  - Temperature (if temperature is not the measurand)
  - Air pressure
  - Humidity
  - Mechanical vibration
  - Supply voltage of the sensor, an amplifier or a measuring circuit
  - Electric / magnetic fields
  - Input or output side feedback effects (e.g. finite internal resistance or similar)

→ Measurement errors must be minimized or compensated by different methods

http://www.physik.uni-oldenburg.de/Docs/epkos/Messtechnik.pdf

Resolution and Accuracy

Measurands

- Measurand is the factor which shall be measured, e.g. temperature, humidity...
- Many physical, chemical or biological properties can be measured.
  - However, not every property can be measured with a sensor for exactly this property.
  - Sometimes it is necessary to draw conclusions about the actual measurand via another measurand.
    - Example: The concentration of a gas in a boiler is directly dependent on the temperature and pressure in the boiler. A gas sensor would not survive the environment of the boiler. Thus, one could still conclude about the gas based on temperature and pressure sensors.

Resolution

- Principles of resolution discussed in lecture "Binary Systems”
- In addition to the errors which occur anyway due to interference variables, additional errors occur, for example
  - by the resolution of the digital converters

    and the associated
  - rounding of the analog values

"Resolution is the ability of a measuring device to reproducibly detect a difference between two slightly different measured values."

https://www.mikrocontroller.net/articles/Aufl%C3%B6sung_und_Genauigkeit

Example:

→ 8 bit converter with 5 V reference voltage: resolution of about 20 mV.

$(8\ b = 2^8 = 256 \quad ; \quad 5\ V$ / 256 = 0,0195 V)

→ 16 bit converter with 5 V reference voltage: resolution of 76 µV So 256 times better!

Accuracy

„**"Accuracy indicates how far the measurement result deviates from the physically absolute true result (whether digital or analog).** Absolute measured values are considered and compared with a more accurate measuring device.“

https://www.mikrocontroller.net/articles/Aufl%C3%B6sung_und_Genauigkeit

- The value is often given in percent (basic accuracy)
  - Accuracy of ± 2 % means that the measured value differs by + 2 % as well as by - 2 % from the physically correct value.

Resolution and Accuracy – Shown on a clock

- Clocks usually have a **resolution** of one second.
- A radio-controlled watch gets the exact time and therefore works accurately.
- A quartz wristwatch loses 10 seconds over e.g. one month from the physically exact time. This watch is therefore **not accurate** but has a **high resolution over a month** (at least as high as a radio-controlled watch)!

Keep in mind:

If a product advertises high resolution, but is not accurate
(results are not exactly reproducible),
it may not be suitable for the desired application!
So also pay attention to the accuracy and not only to the resolution!

Exercise accuracy and resolution

Task: For an experiment, the temperature in a room must be kept at 20°C. The deviation of the measuring sensor must not exceed ± 0.1°C.

Question:

1. What is the minimum required resolution?
2. How high must the accuracy of the sensor be (in %)?

Exercise accuracy and resolution

Task: For an experiment, the temperature in a room must be kept at 20°C. The deviation of the measuring sensor must not exceed ± 0.1°C.

Question:

1. What is the minimum required resolution?
2. How high must the accuracy of the sensor be (in %)?

Solution

1. Minimum required resolution is 0.1°C
2. Calculated: $\frac{0{,}1°C}{20°C} * 100 = 0{,}5\ \%$ → Therfore, accuracy must be at ± 0.5 % at 20°C!

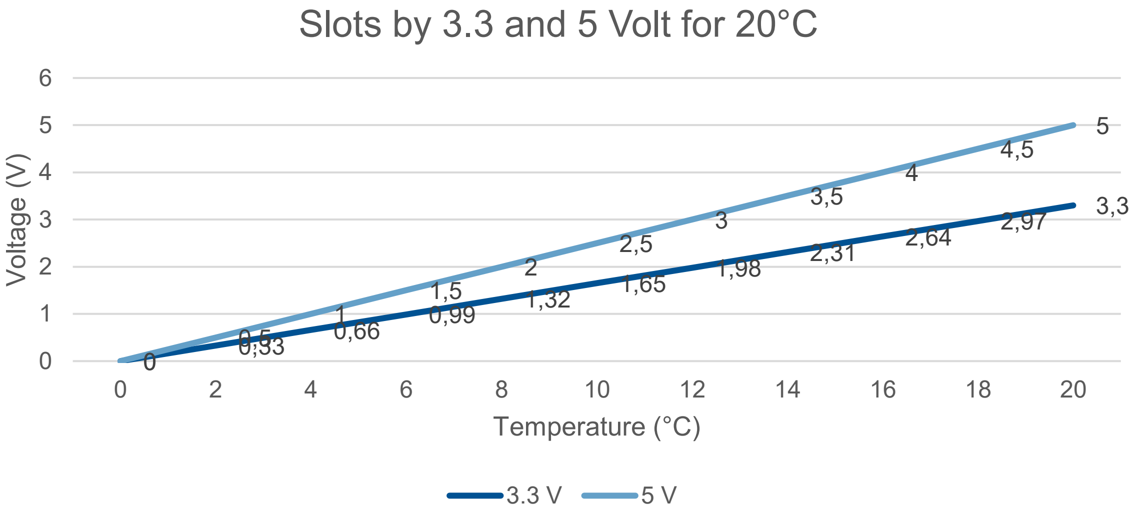
Resolution… a matter of supply voltage?

- Sensors, with which we are working, usually work within a voltage range
  - E.g. 3,3 to 5 Volt
- The sensors sometimes only output a voltage instead of a directly interpreted value (intelligent sensor), which still has to be interpreted by our microcontroller (Arduino/Raspberry).

- Question: With which voltage would you run an analogue sensor with an approved voltage range of 3.3 to 5 volts and why?

Resolution… a matter of supply voltage?

- Question: With which voltage would you run an analogue sensor with an approved voltage range of 3.3 to 5 volts and why?



→ The larger the "gap", the more accurate the microcontroller can work!

→ Some intelligent sensors offer further measuring widths at higher input voltages!

→ Better, with given technology, to work with higher voltage.

Communication

Communication

- Basically, the "simplest" transmission of information is the voltage that the sensor provides as an output signal

- However:
  - It is not possible to communicate with the sensor
    - The sensor "talks" permanently, but cannot accept commands

  - The resolution of the receiver-controller is possibly not sufficient, processing of the signal directly at the sensor would be advantageous.

  - When using many sensors, controller is "flooded" with voltages, possibly not enough ports available

  - No "simple" recalibration can be performed when the sensors age

Communication

- In addition to the analog transmission of signals, the digital transmission of signals is possible.
- These take place e.g. via a BUS system
  - Communication in both directions (sensor ↔ controller) possible
  - Separation of energy and information flow
  - Data transmission of several participants via common transmission path

- Advantage of BUS systems:
  - Flexibility
  - Extension possibilities
  - Use of the data of a sensor at any number of "consumers”
    - Before by cable only in one direction possible, many cables necessary
  - Fewer cables necessary
  - Saving of energy

Communication

Working principle of a BUS System:

The easiest case:

- One master (in our excercises the microcontroller) leads the „talk“, slaves (sensors, actuators) listen (Master-Slave System)

- Transmission by means of two or more lines (depending on the complexity of the system)

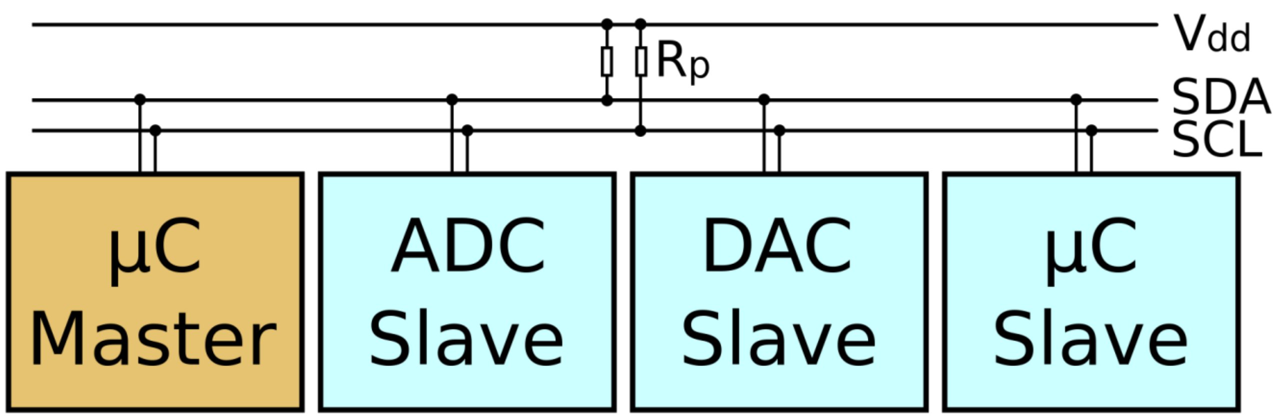
- The following are examples from the world of microcontrollers

Communication

I²C – Serial BUS

- Master - Slave principle
- Two lines, SCL (Serial Clock) and SDA (Serial Data)

- Serial Clock
  - Clock line
  - Either HIGH
  - Or LOW
- Serial Data
  - Data line
  - Either HIGH
  - Or LOW
- Vdd
  - Supply voltage IMPORTANT! All sensors must run with the same voltage, otherwise level shifter necessary!

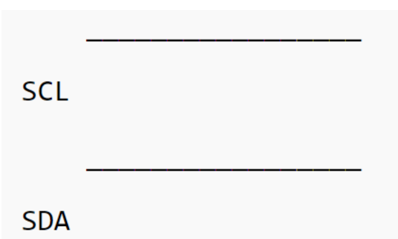


https://de.wikipedia.org/wiki/I%C2%B2C

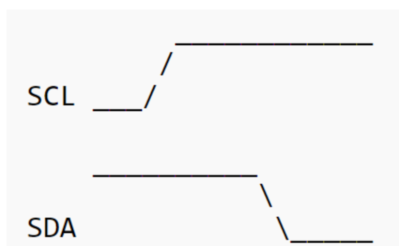
Communication

I²C – Serial Bus

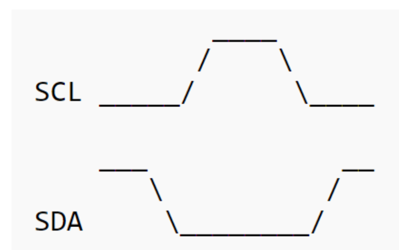
- Basically for understanding: Both lines can take either a high voltage or a low voltage and thus follow the logical 1 / 0 control.
- Examples for commands of the I²C system:



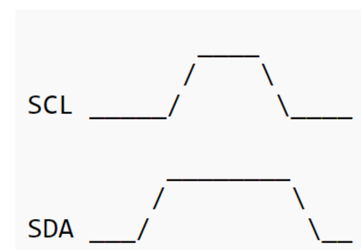
Bus free: both HIGH, Master can access



Start: SDA on LOW, SCL HIGH



logical 0: SCL HIGH, SDA LOW



Logical 1: SCL HIGH, SDA HIGH

http://www.cc-zwei.de/wiki/index.php?title=I2C_Bus_Hintergrundwissen

Communication

I²C – Serial Bus

- Each slave has a specific address and "listens" permanently for signals from the master
  - Addresses are 7-bit = 128 devices possible
- The eighth bit tells the slave whether the master wants to read the slave (0) or write to it (1)
- Structure of the address:

Bit 7	6	5	4	3	2	1	0
I2C - Adress							Read=1 / Write = 0

http://www.cc-zwei.de/wiki/index.php?title=I2C_Bus_Hintergrundwissen

Communication

SPI – Serial Periphal Interface

- Three lines
  - SCLK (SCK) - Serial Clock
    - Clock line
  - MOSI or SIMO - Mater Out, Slave In
  - Miso or SOMI - Master In, Slave Out

  - Important: Naming from the point of view of the BUS participants. So the lines must be connected mostly crosswise!

Decision criteria for sensors

Requirements / decision criteria Sensors

- Static transmission characteristics
  - Measuring range
  - Output span
  - Accuracy
  - Sensitivity
  - Cross sensitivity
  - Influence of disturbance variables

- Dynamic transmission characteristics with the features
  - Measured quantity-independent properties (linear systems)
  - Measured quantity-dependent properties (e.g. creep)
  - Load-dependent properties (e.g. aging)

- Reliability / lifetime
  - Failure rates
  - Failure detection

→ Example initial guess of the Boeing tragedies of 2019!

Tränkler & Reindl,Sensortechnik, ISBN 978-3-642-29942-1

Requirements / decision criteria Sensors

- System capability
  - Standardized output signals
  - Digital bus interface
  - On-site display and control elements
  - Configurability and maintainability

- Costs
  - Unit costs
  - Cost degression at high quantities
  - Maintenance, repair, replacement costs
  - Total system costs for a given lifetime

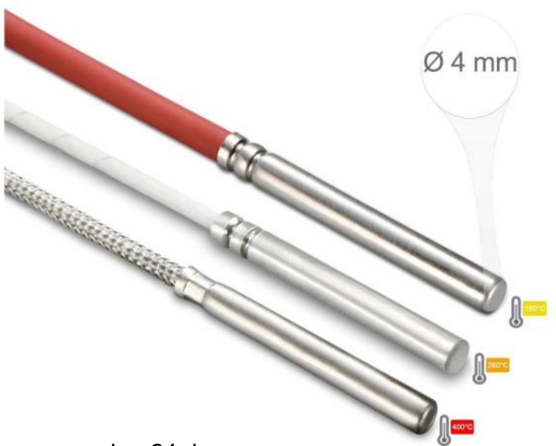
Tränkler & Reindl,Sensortechnik, ISBN 978-3-642-29942-1

Commonly used sensors (cheap & working)

- Today, thousands of different sensors are available
  - Some sensors are commonly used, easy to handle and will be shown in the following slides

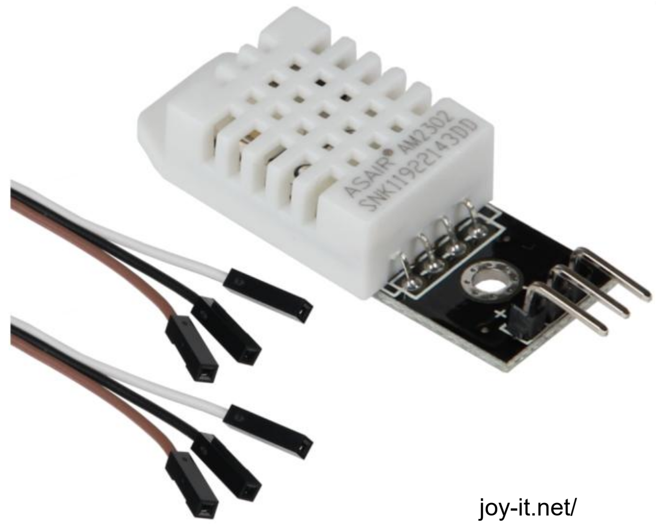
  - Always keep in mind:
    - Does accuracy and resolution fulfill my needs?
    - What about longevity?
    - Any energy supply issues?

Temperature and Humidity



sensorshop24.de


az-delivery.de



joy-it.net/

Pt100 (Analog / Digital)

Voltage	3.3 – 5 VDC
T Range	-200 - 600°C
T Accuracy	Cl A = ±(0.15 + 0.002*t)°C

DS18B20 (Digital)

Voltage	3.3 – 5 VDC
T Range	-55 – 125 °C
T Accuracy	± 0.5 °C (in -10 – 85 °C)
Resolution	12 bit

DHT22 (Digital)

Voltage	3.3 – 5 VDC
T Range	-40 – 80 °C
T Accuracy	± 0.5 °C
H Range	0 – 100%
H Accuracy	± 2% RH

Soil moisture

reichelt.de

www.reichelt.de

Capacitive Soil Moisture (Analog)

Voltage 5 VDC

ARD SEN WET1 (Analog)

Voltage 3.3 – 5 VDC

Gas

neoe.io

seeedstudio.com

Pewatron

MQ135 (Digital)

Voltage	5 VDC
Measurands	CO_2, Alcohols, Benzene, Nox, NH_3

MIX8410 O_2 (Analog)

Voltage	3,3 – 5 VDC
O_2 Range	0 – 25%
Sensitivity	0.1-0.03 mA
Repeatability	± 2%

COZIR CO_2 WR (Digital/Analog)

Voltage	3.3 VDC
CO_2 Range	0 – 100%
CO_2 Accuracy	± 5%

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Microcontroller

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Arduino

Microcontroller Boards – Quick facts

- Very small computer unit
  - CPU
  - RAM
  - ROM
  - Oscillator
  - I/O - connections

- Contains everything which is needed to communicate with the outer world, e.g.
  - CAN / BUS Systems (SPI, I^2C, USB)
  - Pulse Wide Modulation (PWM)
  - A/D converter

- Mostly perform only one program periodically

de.rs-online.com, www.arrow.com

Arduino vs ESP

- Many different fabricants on the market
- Most common known: Arduino and ESP controller
- What‘s the difference?
  - Different hardware achitecture
  - ESP‘s cheaper
  - But: ESP‘s somtimes are harder to program (thats most important within this course!)

Recommendation: Start learning with Arduino and then dive deep with ESP!

Arduino – What the fact?

- Developed in 2005
- „physical Computing“ platform
- Open Source
- consists of Soft- and Hardware
- Hardware = Microcontroller
  - More than 30 different boards available
- Software = Arduino IDE
  - Based on C / C++ (but way more easy)

Arduino MKR 1010

- 8 digital In-/Outputs
- 7 Analogue Inputs (up to 12 bit)
- Operating voltage: 3.3 Volt (!!!!)
- USB port
  - SPI
  - I²C
  - UART

https://store.arduino.cc/arduino-mkr-wifi-1010

Arduino UNO

- 14 digital In-/Outputs
- 6 analogue Inputs
- Operating Voltage: 5 Volt
- USB port
  - SPI
  - ICSP
  - I²C

https://store.arduino.cc/arduino-uno-rev3

Arduino MEGA 2560

- 54 digital In-/Outputs
- 16 Analogue Inputs
- Operating voltage: 5 Volt
- USB port
  - SPI
  - ICSP
  - I²C
  - UART

https://store.arduino.cc/mega-2560-r3

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Arduino MKR 1300

- 8 digital In-/Outputs
- 7 Analogue Inputs (up to 12 bit)
- Operating voltage: 3.3 Volt (!!!!)
- USB port
  - SPI
  - I²C
  - UART

https://store.arduino.cc/mkr-wan-1300

Arduino IDE

- Installation file https://www.arduino.cc/en/Guide/HomePage
- Installation of Arduino MKR Board support
  → Tools → Board → MKR WAN (SAMD Boards)
- Chose board at „tools“ → Board → MKR 1010

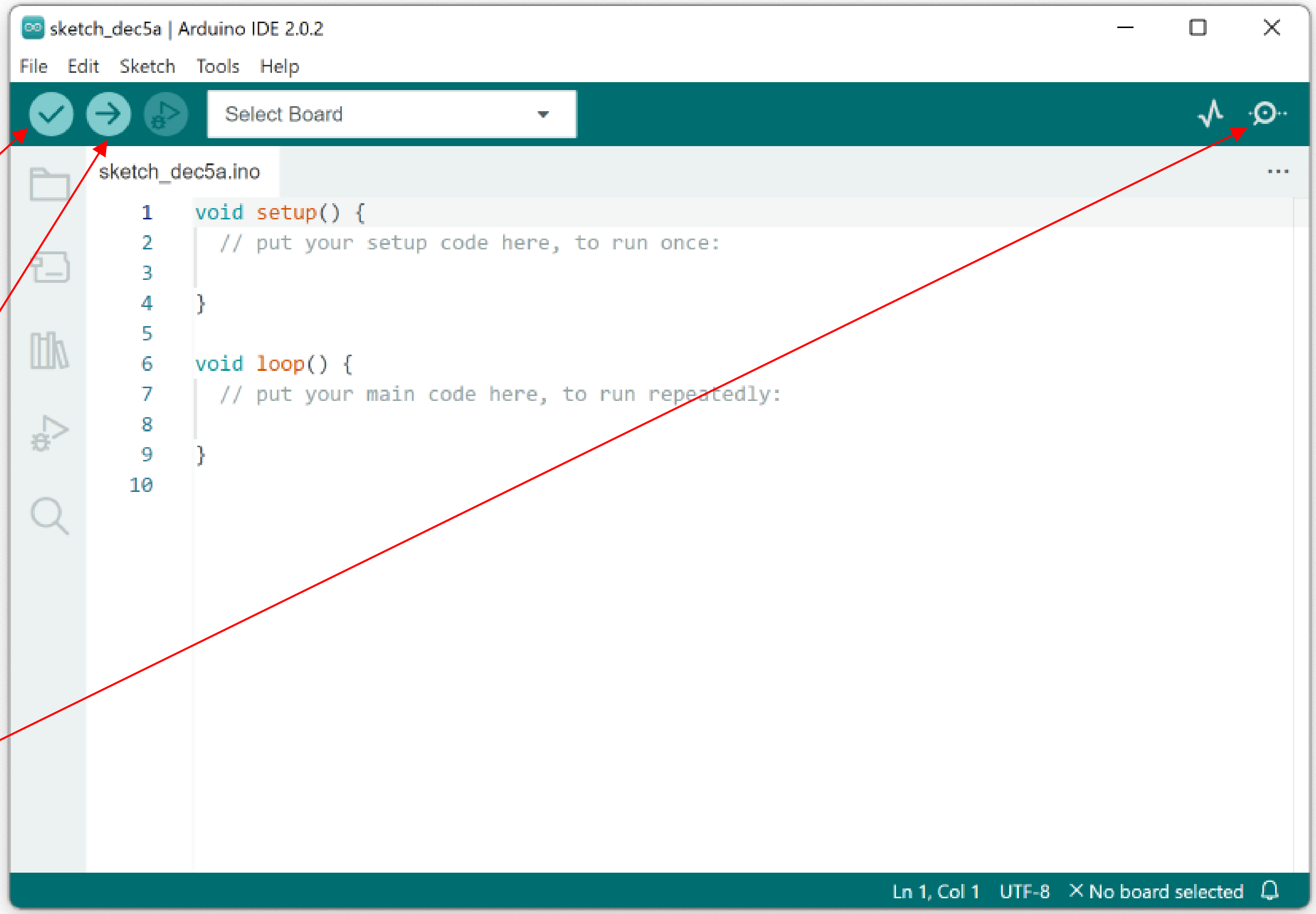
Arduino IDE basics

Sketch = Program

Verify: Test if Sketch is working

Upload: to Arduino

Serial Monitor



Arduino IDE basics

- Libraries
  - Libraries are the core for our programming
  - For nearly every "intelligent" sensor or actuator, which is arduino compatible, a library exists.
  - These libraries already contain basic components for programming
  - They provide certain commands to control the connected sensor / actuator.
  - Installing libraries:
    - Sketch → Include library → Manage libraries →

  - **Important**: Libraries need memory space!

Arduino IDE basics

Coding

- For now, we divide the code area into three basic areas:

1. Definition area:
   1. At the beginning of the code
   2. Setting variables, including libraries etc.
   3. Are available to the entire code

2. Setup area (void setup ())
   1. Contains info for the Arduino
   2. Here is defined, which pins of the Arduino are needed and which function (INPUT or OUTPUT) the should take over

3. Loop
   1. Actual program area. The program is executed line by line
   2. When finished, loop is repeated

Arduino IDE basics

Programming:

- Each line is ended with a semicolon (;) → Main error at the beginning!
- Curly brackets ({}) → At the beginning of related „command groups“ and at the end