CONSTRUCTOR UNIVERSITY

Automation

P02 – Sensor Basics & Concepts

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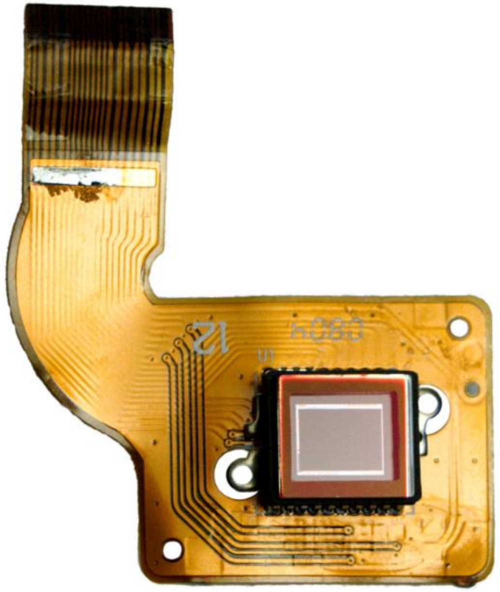
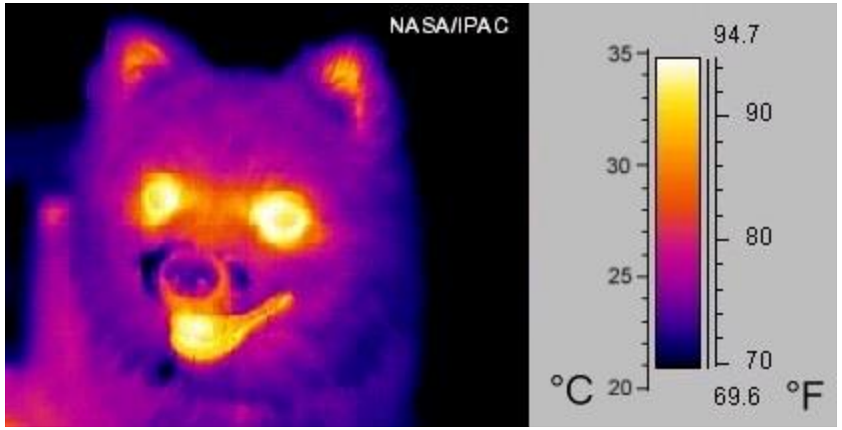
Constructor University

What is a sensor?

Sensor

- measures a physical property
  - single quantity: temperature, light intensity, pressure, single range...
  - more complex: ranges in 2D or 3D, imaging a scene, ...
- and produces an output signal
  - typically an electronic output
  - most often voltage
  - occasionally current or frequency

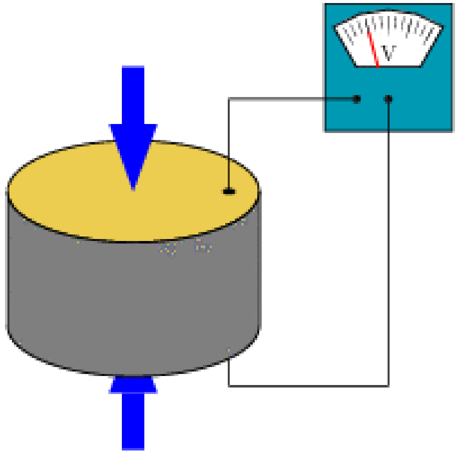


Sensor

transducer
- converts one form of energy into an other
- i.e., to electrical energy in the case of **sensors**
- also generation of mechanical energy is of interest for automation, which is done with **actuators**

example: piezo-electric crystals
- deformation <-> voltage
- used both ways
- i.e., in sensors and in actuators



Sensor

active vs **passive sensor / sensing**

option (1)

- active one needs an external power source aka excitation signal
- e.g., thermistor, i.e., a temperature-dependent resistor

option (2)

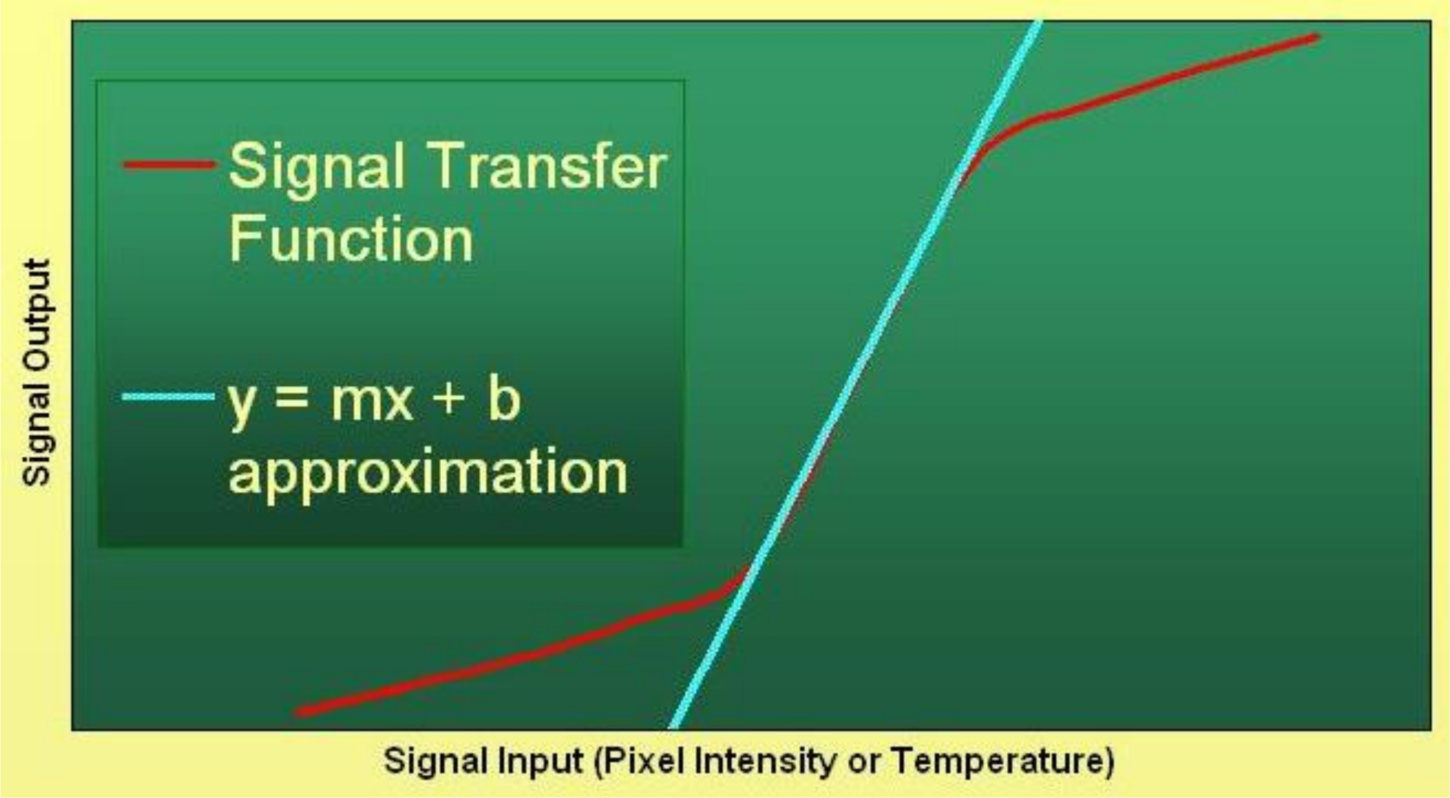
- active one emits a signal into the environment
- e.g., radar sends out RF-waves
- can lead to interferences
  when multiple devices are used in parallel

Transfer Function / Characteristic Curve

Sensor

transfer function aka **characteristic curve (CC)**

- mapping input to output
- often linear, respectively assumed to be linear
- sensor range: maximum & minimum inputs

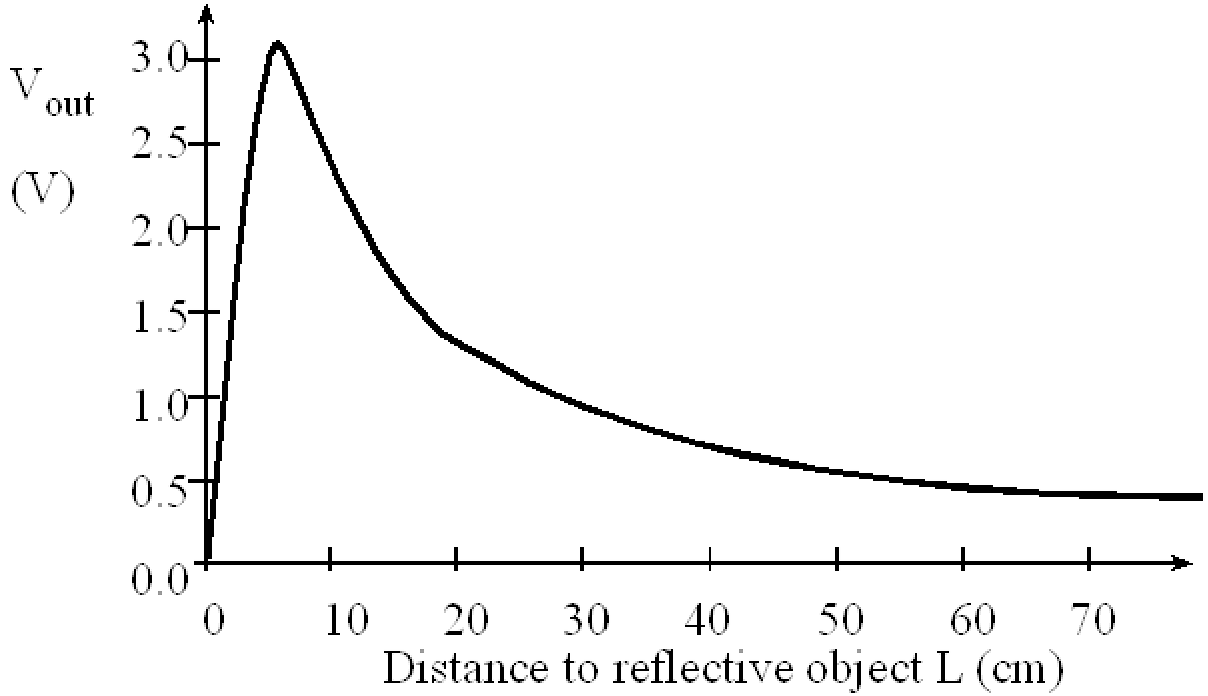


Sensor

transfer function aka **characteristic curve (CC)**

- often linear, respectively assumed to be linear
- but not always...

e.g., Sharp IR distance sensor GP2Y0A41SK0F



Sensor

- cc may also depend on **multiple environment parameters** beyond the physical property of interest
- respectively the property of interest may depend on several physical parameters

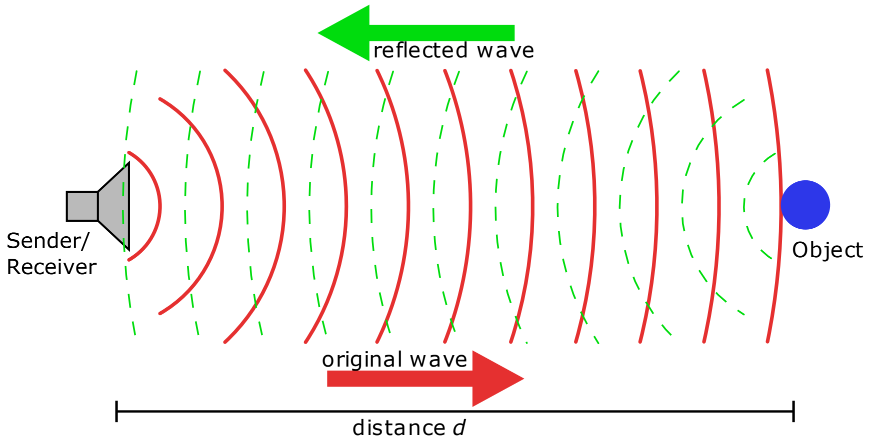
example: **ultrasonic range sensor**

- measures distance *d* to the nearest obstacle
- based on
  - time of flight (ToF) of an ultra-sound signal
  - from the sensor
  - to the nearest obstacle and back

Sensor

ultrasonic range sensor

time of flight to the nearest obstacle and back



$$d = \frac{\Delta t \cdot c_{sound}}{2}$$

speed of sound depends on

- the medium, e.g., air or water (sonar) or steel or...
- the temperature
- partially humidity in air
- ...

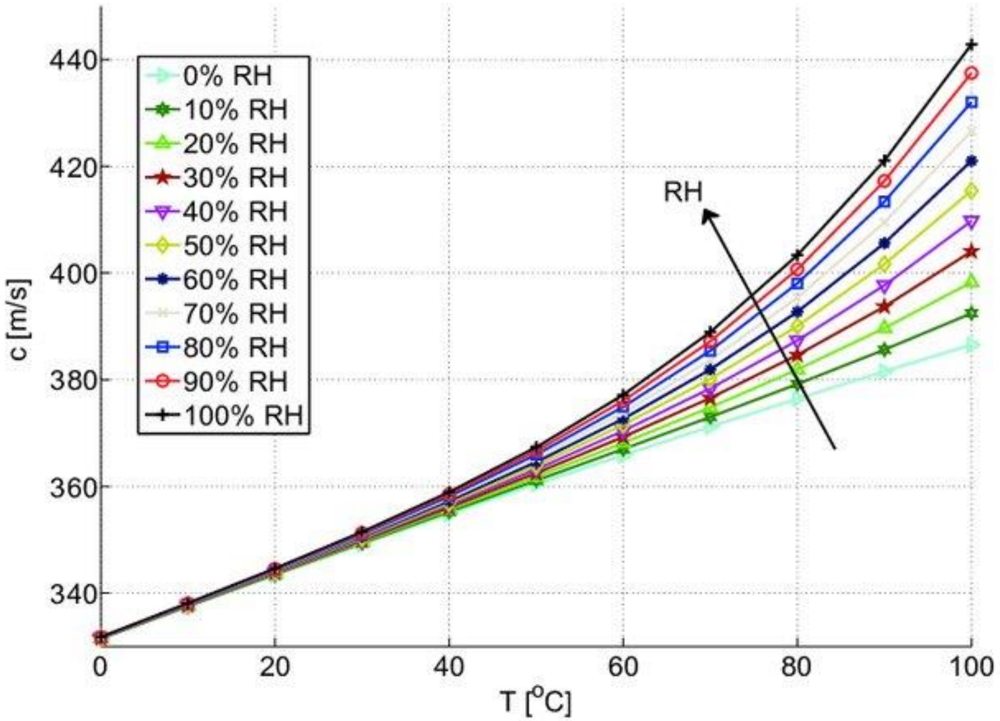
Sensor

ultrasonic range sensor
time of flight to the nearest obstacle and back

$$d = \frac{\Delta t \ \cdot \ c_{sound}}{2}$$

$$c_{sound} = 331.3\,{}^{m}/_{s} \cdot \sqrt{\frac{T}{273.15}}$$

- in air
- 0% humidity



- in air
- with humidity

assuming
constant pressure

Sensor

ultrasonic range sensor: time of flight to the nearest obstacle and back

in case the relevant environment parameters can change or are not known

- we need to measure them, too
- i.e., additional sensors are part of the sensor
- or we will introduce some error(s) that may be avoided

$$\cancel{d = \frac{\Delta t \cdot c_{sound}}{2}}$$

$$d(\Delta t, T, RH, \ldots) = \frac{\Delta t \cdot c_{sound}(T, RH, \ldots)}{2}$$

Calibration

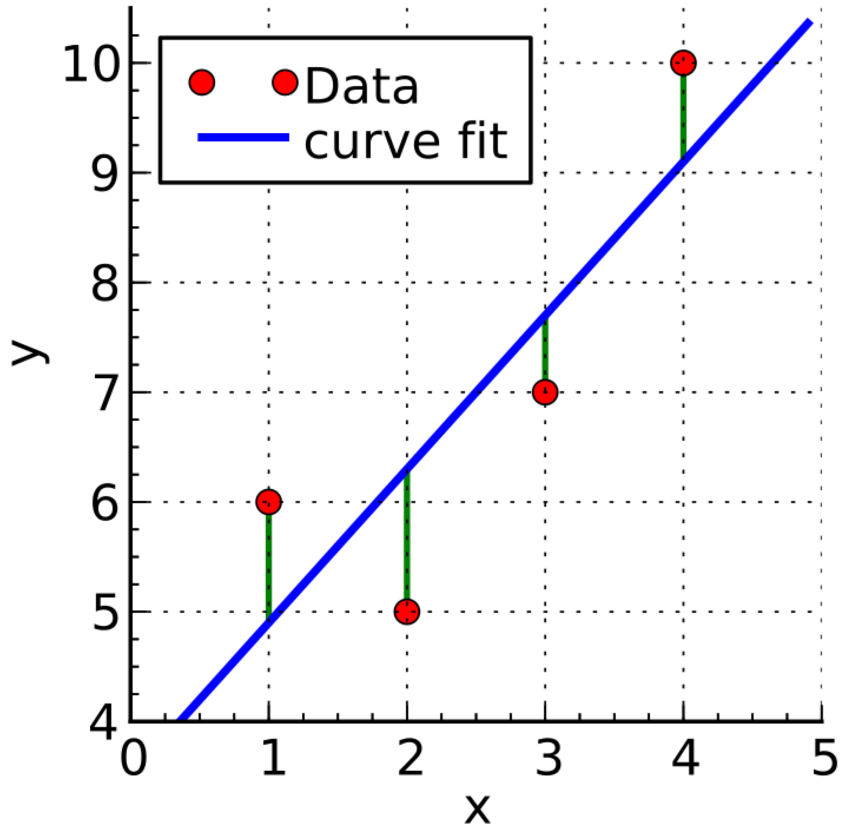
Calibration

fit model parameters to the actual sensor values
e.g., **linear model** $y = ax + b$

Linear Least Squares (LLS)
given n measurements (x_i, y_i)

$$a = \frac{\frac{\sum x_i y_i}{n} - \frac{\sum x_i}{n}\frac{\sum y_i}{n}}{\frac{\sum {x_i}^2}{n} - \left(\frac{\sum x_i}{n}\right)^2}$$

$$b = \frac{\sum y_i}{n} - m\frac{\sum x_i}{n}$$

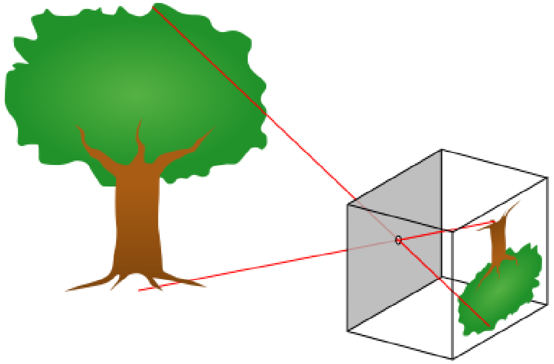


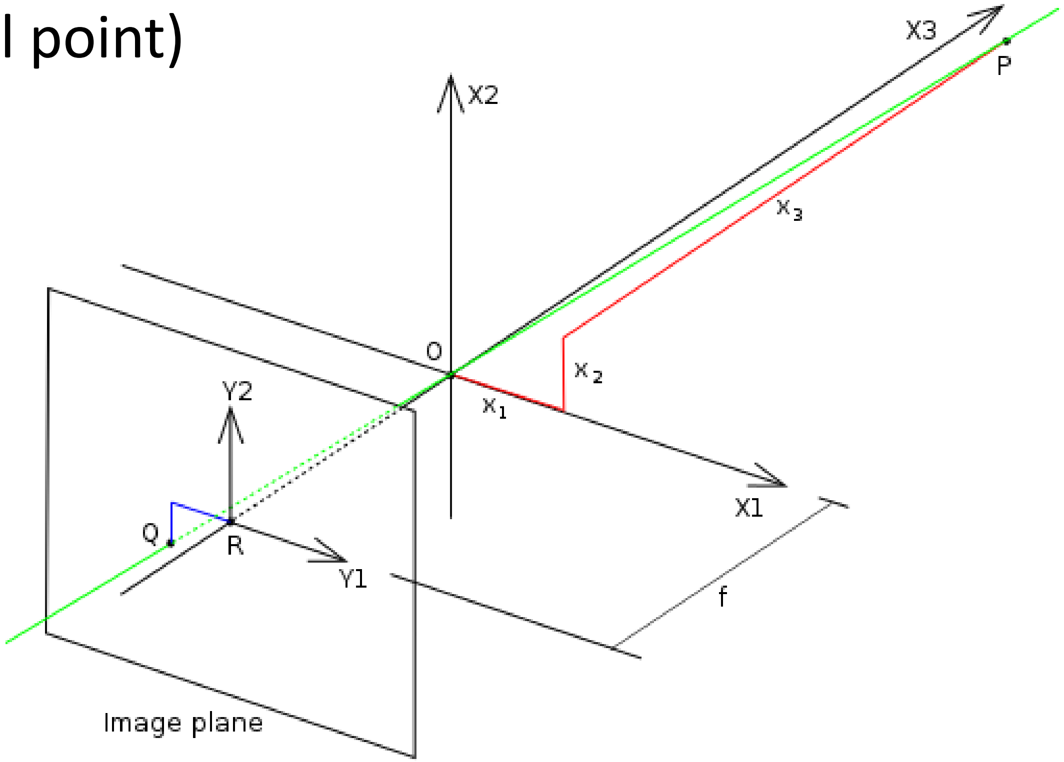
Calibration

sensors and hence also suited models can be quite complex

e.g., **camera calibration**

- pinhole model
  - focal length & image center (aka principal point)
  - imager parameters (#pixels, size)
- or even more advanced
  - including, e.g., distortion coefficients





Sensor Errors

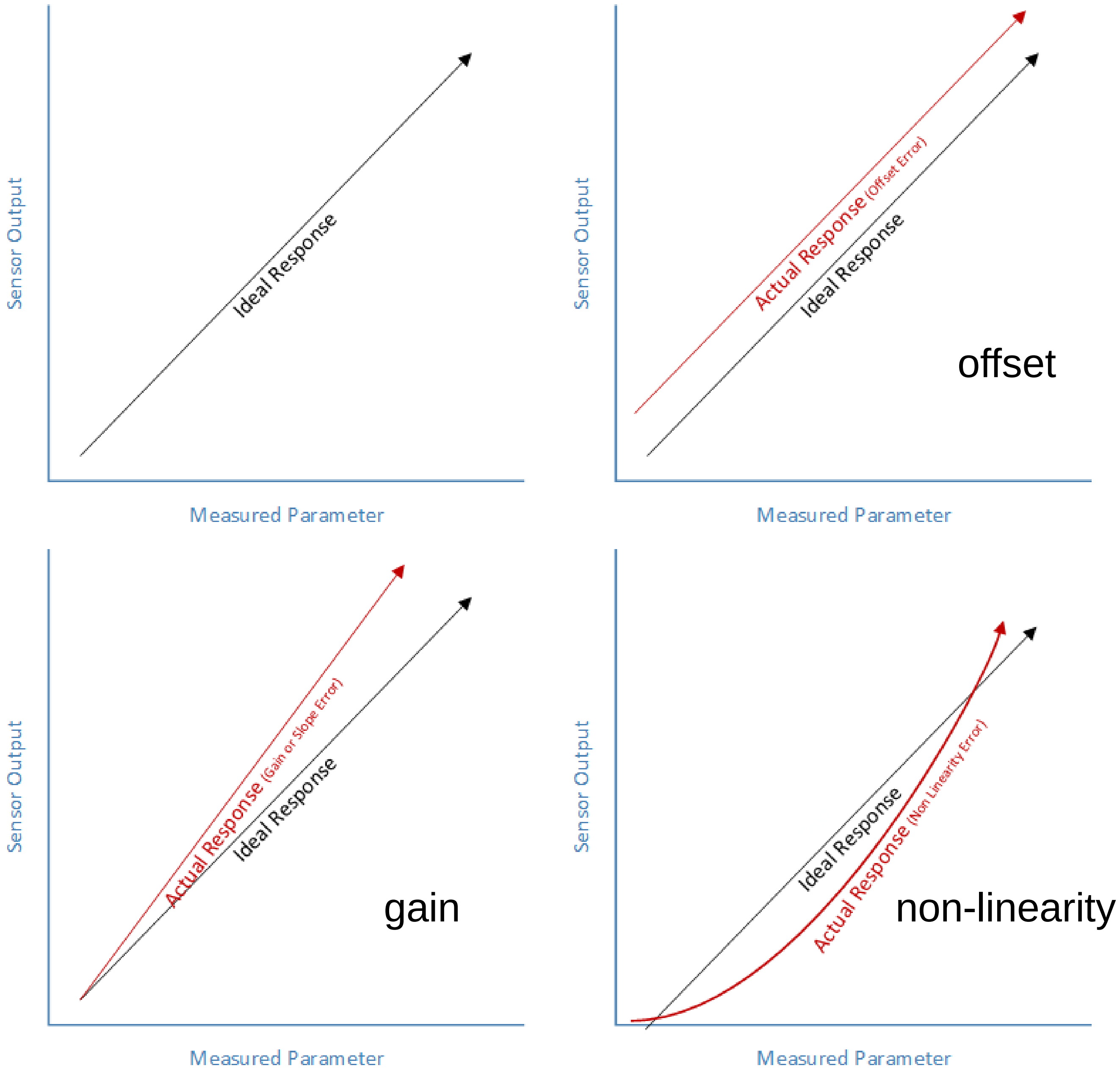
Sensor Errors

given, e.g., a **linear model**

- input x
- output y
- f_{cc}: $y = ax + b$

typical errors

- offset: $b' \neq b$
- gain: $a' \neq a$
- non-linearity: the cc is actually, e.g., quadratic

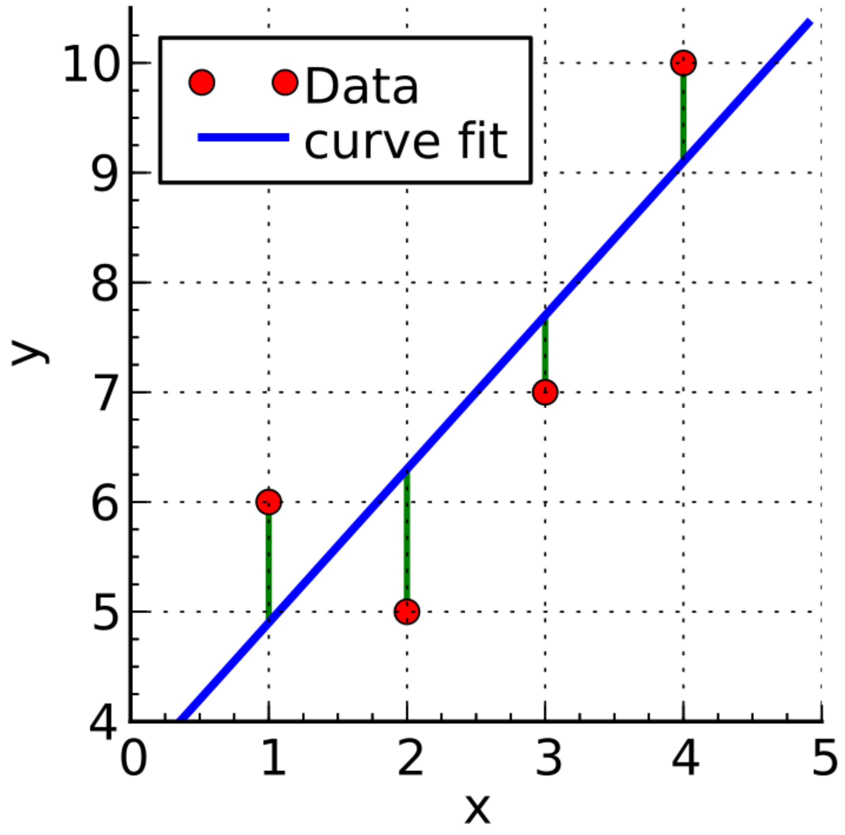


Note on Calibration & Errors

fit model parameters to the actual sensor values
e.g., **linear model** $y = ax + b$

Linear Least Squares (LLS)
- can correct offset and gain (b, a)
- but can only mitigate non-linearity

*if the **cc is non-linear***
then we may need a different model
(and non-linear least squares fitting)

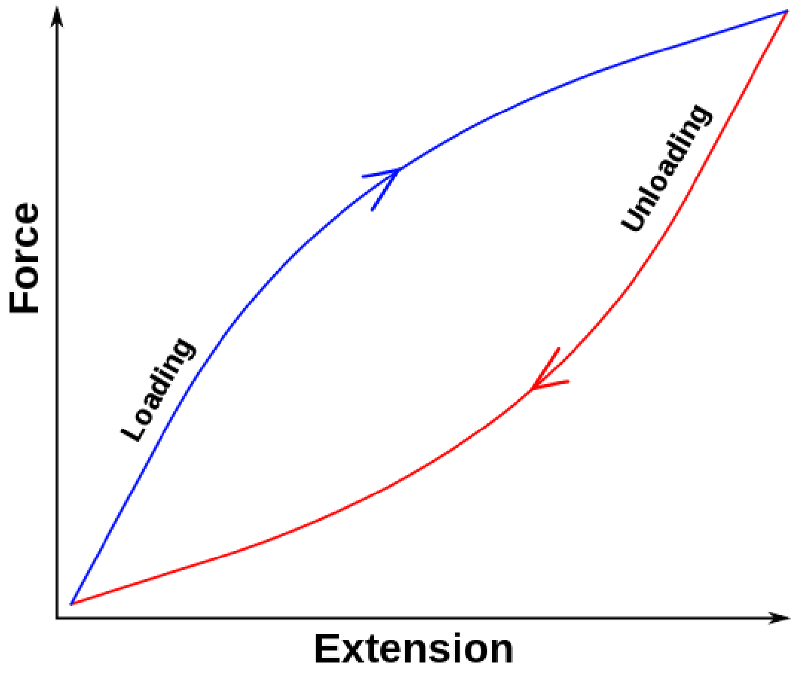


Sensor Errors

cc is a function
- direct, fixed mapping of input to output
- i.e., we assume no “memory” or “state” in a sensor
- almost always, this is correct, respectively a suited model

hysteresis
- output time-depends on the “history”
- e.g., whether the previous value
  was higher or lower than the current output

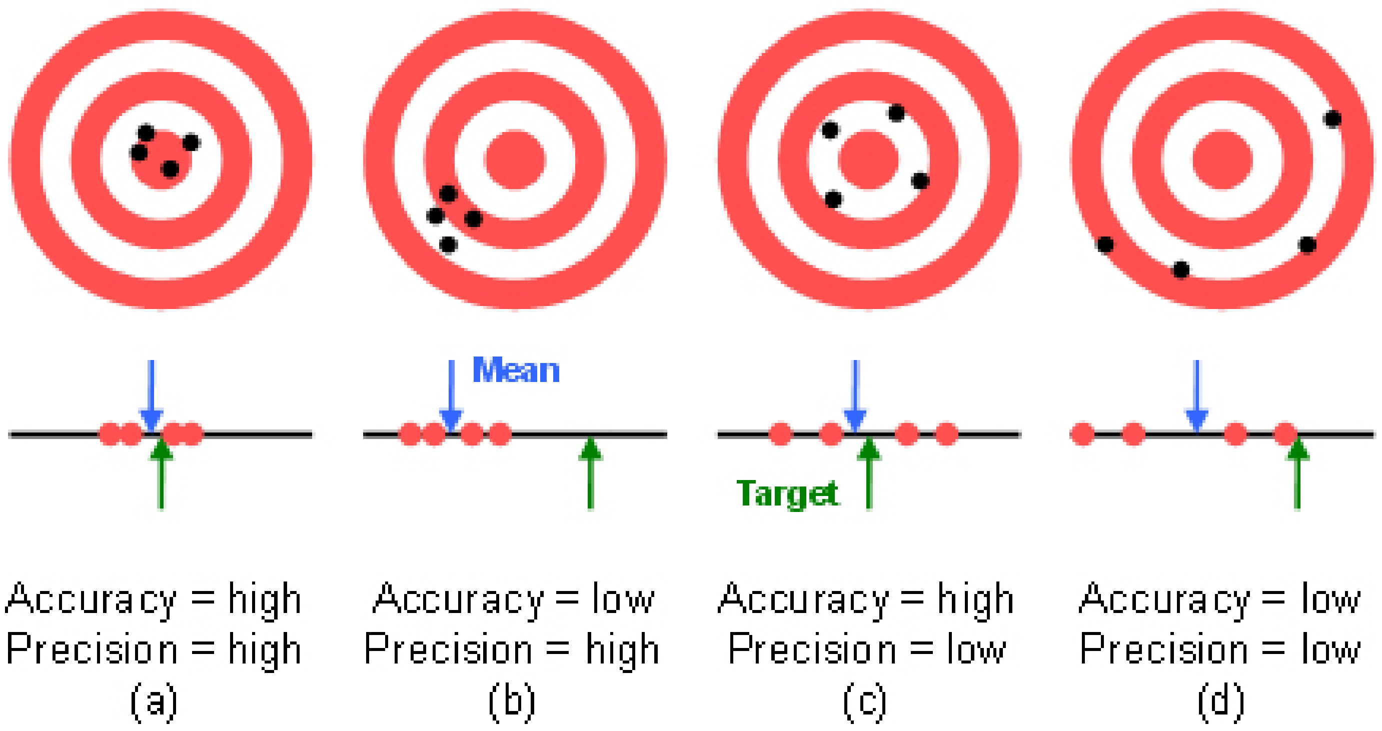
example: rubber band
- some energy is “lost” as heat
- need some “additional” force when pulling
- “loose” some force when the band is released



Quantifying Sensor Errors

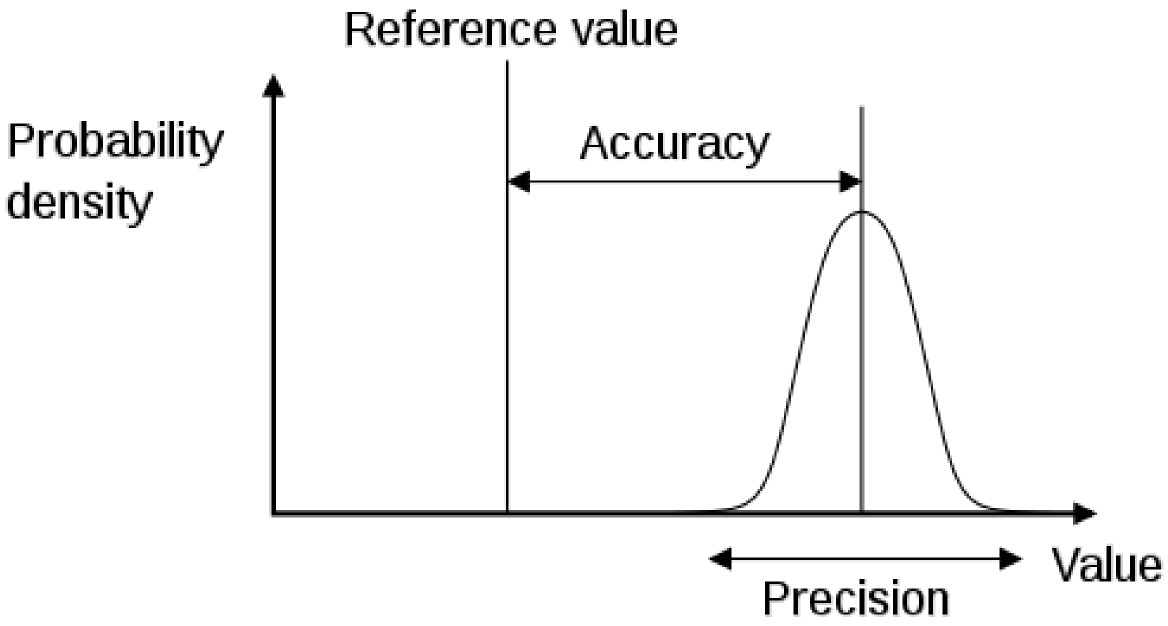
- accuracy: the average amount of uncertainty, respectively error
- precision: reproducibility of the result

example: archer shooting repeatedly at a target



Accuracy & Precision

statistics
- bias = (lack of) accuracy
- variability = (im)precision



note
- no completely fixed terminology
- e.g., International Standards Organization (ISO)
- (lack of) bias known as ***trueness***
- accuracy as combination of trueness and precision

Binary Cases

sometimes we deal with binary cases

- switch is on or off
- object A is part of class X or not
- event E happens or not
- ...

sensor or test output is ***positive (P)*** or ***negative (N)***
which may be correct, i.e., ***true (T)***, or not, ***false (F)***

errors

i.e., 4 cases: TP, FP, TN, FN

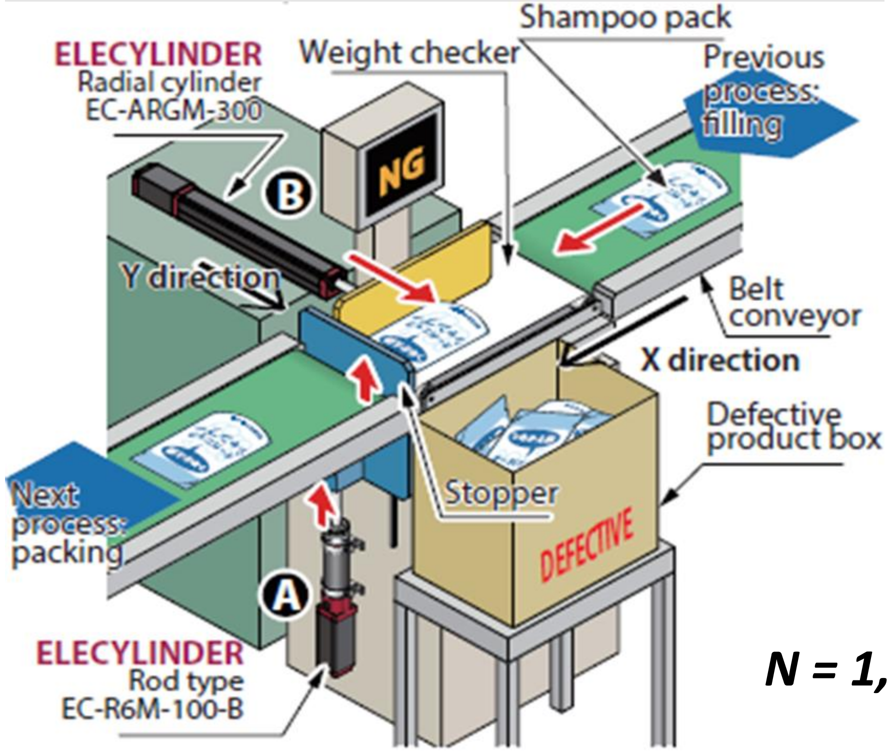
correct assessments

Binary Cases

Confusion Matrix

		test outcome: yes	test outcome: no
ground truth condition	yes	TP	FN
ground truth condition	no	FP	TN

push (separate)



N = 1,000

		weight correct?: yes	weight correct?: no
product not defective?	yes	928	24
product not defective?	no	2	46

Binary Cases

4 cases TP, FP, TN, FN
used for a multitude of **metrics**, e.g.,

- **recall** aka sensitivity, hit rate, or true positive rate (**TPR**)
- **selectivity** aka specificity or true negative rate (**TNR**)
- **miss rate** aka false negative rate (**FNR**)
- **fall-out** aka false positive rate (**FPR**)

$$TPR = \frac{TP}{P} = \frac{TP}{TP + FN} = 1 - TNR$$

$$TNR = \frac{TN}{N} = \frac{TN}{TN + FP} = 1 - TPR$$

$$FNR = \frac{FN}{P} = \frac{FN}{TP + FN}$$

$$FPR = \frac{FP}{N} = \frac{FP}{FP + TN}$$

Binary Cases

4 cases TP, FP, TN, FN
used for a multitude of **metrics**, e.g., also

accuracy (**ACC**)

$$ACC = \frac{TP + TN}{P + N} = \frac{TP + TN}{TP + FP + TN + FN}$$

precision
aka positive predictive value (**PPV**)

$$PPV = \frac{TP}{TP + FP}$$

Multiple Classes

Confusion Matrix

		test outcome			
		square	**circle**	**cross**	**dot**
ground truth condition	**square**	94.0%	2.1%	1.3%	2.6%
	circle	3.2%	91.2%	0.2%	5.4%
	cross	0.1%	0.2%	97.3%	2.4%
	dot	2.7%	6.5%	1.2%	89.6%

TP, TN, FP, FN
& metrics

then

- per class
- or in total

Sensors & Digital Systems

Sensors & Digital Systems

Analog (to) Digital Converter (ADC, A/D, A2D)

- converts an analog voltage into a digital value
- typical input ranges: min. 0V - max. 5V / 3.3V / 2.7V
- resolution: #bits, e.g., 8, 10 or 12

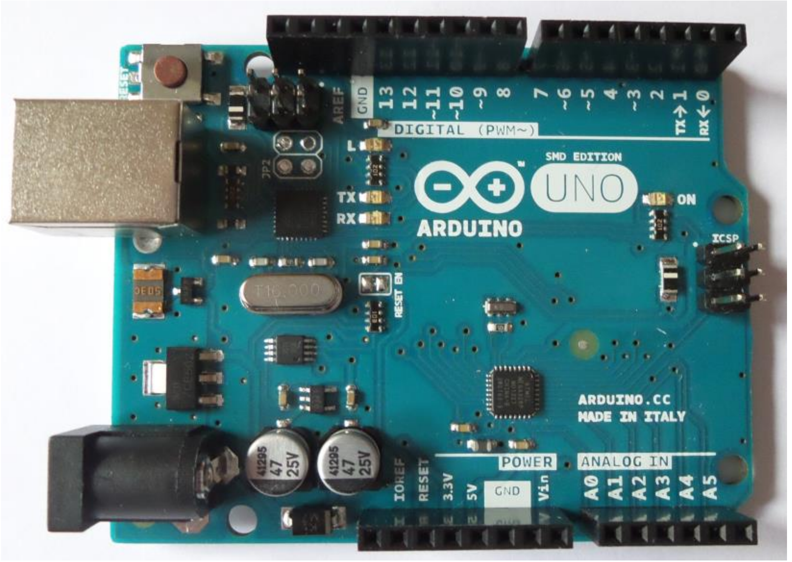
where to find ADCs

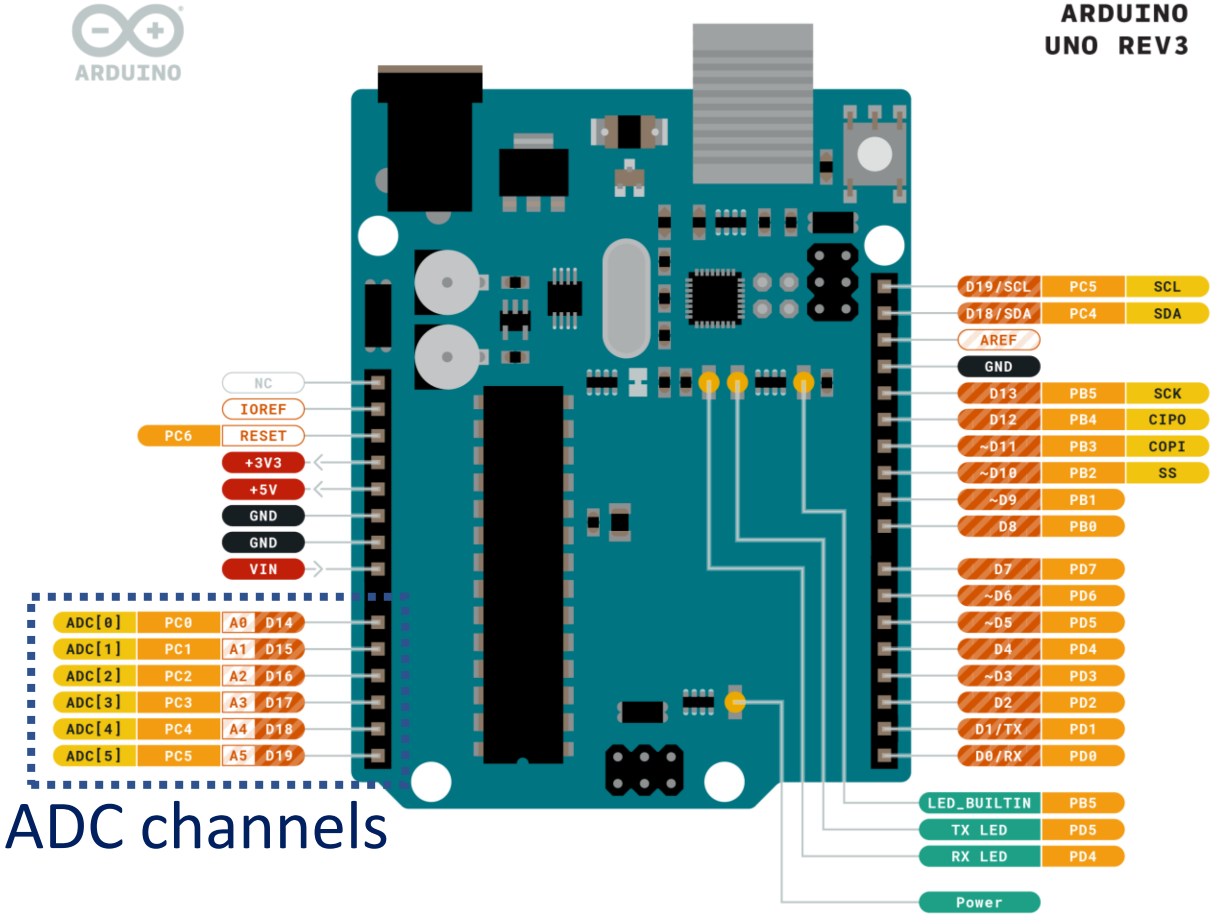
- I/O port of, e.g., a micro-controller
- separate integrated circuit (IC), usually with multiple ADCs

Analog Digital Converter (ADC)

e.g., **Arduino Uno R3**
based on Atmel ATmega328

- 6 ADC channels
- 10 bit
- 5V input



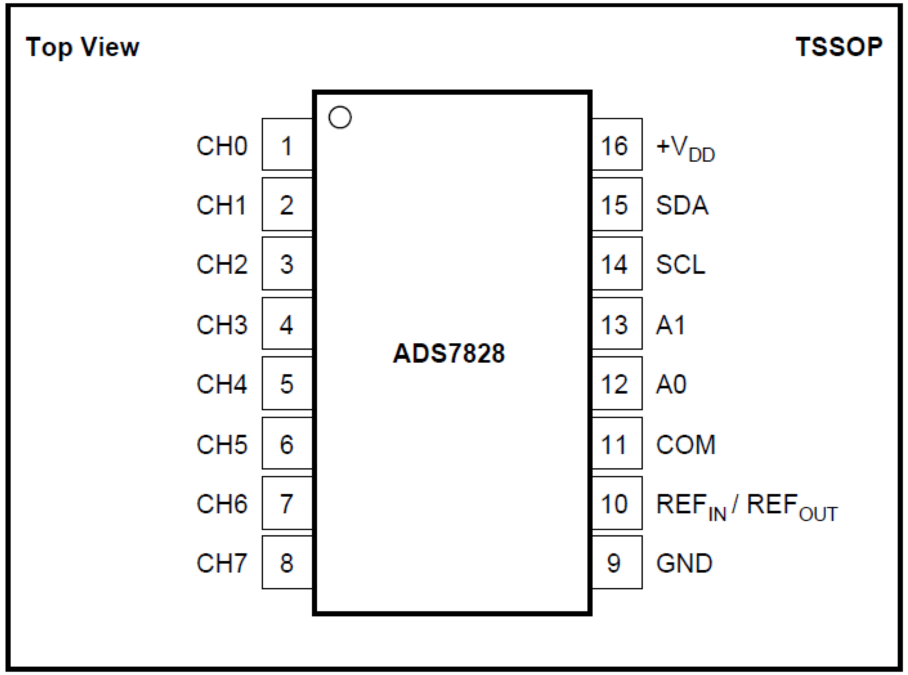


Analog Digital Converter (ADC)

e.g., **Texas Instruments 12-Bit ADC ADS7828E/250**

- 8 channels with 12 bit, 2.7V input
- data bus: I2C (Inter-Integrated Circuit)

PIN CONFIGURATION



PIN DESCRIPTIONS

PIN	NAME	DESCRIPTION
1	CH0	Analog Input Channel 0
2	CH1	Analog Input Channel 1
3	CH2	Analog Input Channel 2
4	CH3	Analog Input Channel 3
5	CH4	Analog Input Channel 4
6	CH5	Analog Input Channel 5
7	CH6	Analog Input Channel 6
8	CH7	Analog Input Channel 7
9	GND	Analog Ground
10	REF_{IN} / REF_{OUT}	Internal +2.5V Reference, External Reference Input
11	COM	Common to Analog Input Channel
12	A0	Slave Address Bit 0
13	A1	Slave Address Bit 1
14	SCL	Serial Clock
15	SDA	Serial Data
16	$+V_{DD}$	Power Supply, 3.3V Nominal

Analog Digital Converter (ADC)

the **resolution** of an ADC, i.e., #bits *N*

- determines the smallest changes in voltage ΔU that can be sensed
- provides an upper bound for the precision

$$\Delta U = \frac{U_{max} - U_{min}}{2^N}$$

example: 12-bit ADC, 0 - 2.7V

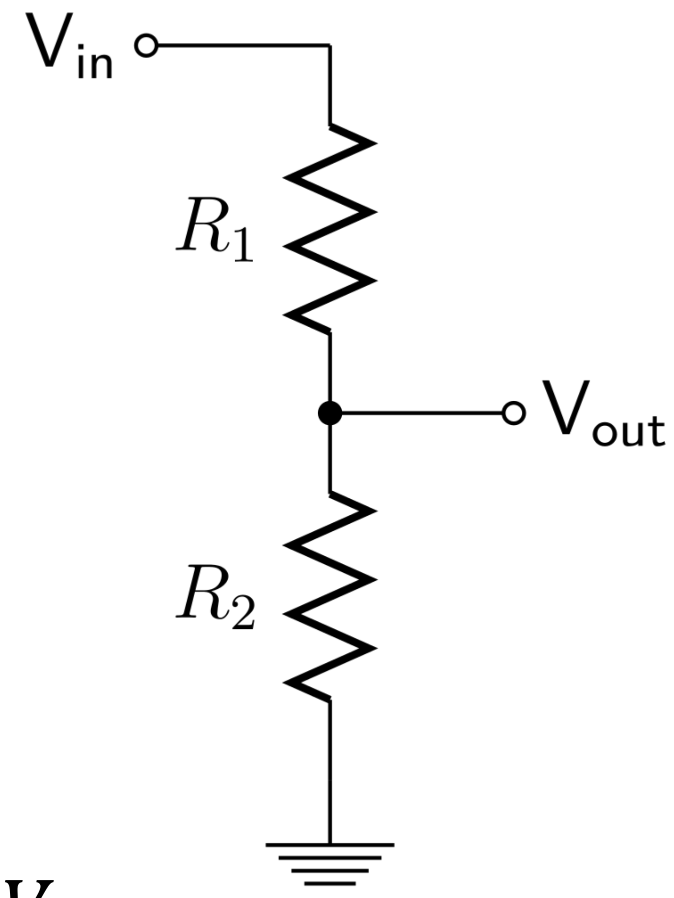
$$\Delta U = \frac{2.7 - 0}{2^{12}} \approx 0.659\ mV$$

Voltage Divider

- passive circuit with two resistors
- to produce an output voltage V_{out}
- that is a fraction of the input voltage V_{in}

e.g., to interface

- a sensor with 0-12V output
- to an ADC with 0-2.7V input



$$V_{out} = \frac{R_2}{R_1 + R_2} \cdot V_{in}$$

Wheatstone Bridge

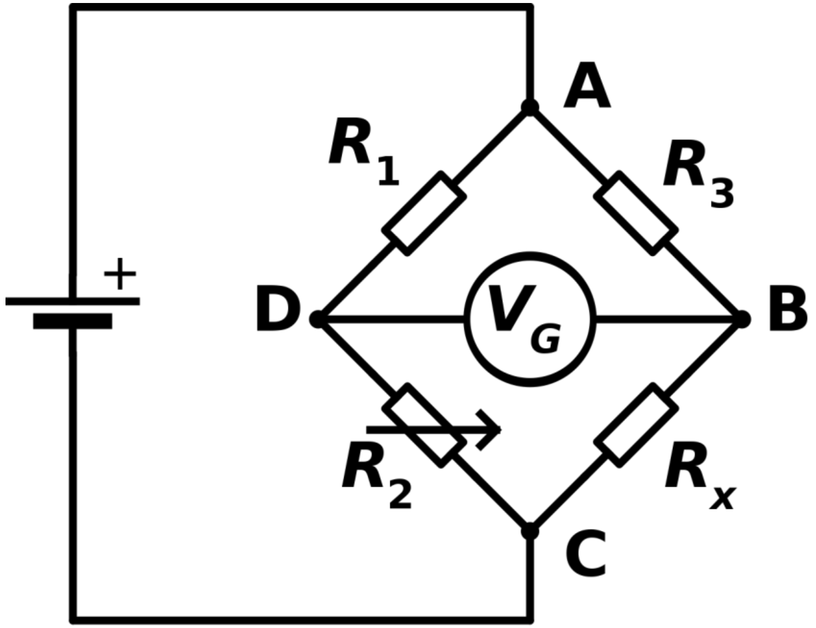
motivation

- some sensors operate by changing their resistance
- e.g., temperature sensors in form of thermistors
- Wheatstone bridge supports precise measurements

(original) operation principle:

- resistors R_1 , R_3 and potentiometer R_2
- fixed but unknown resistor R_x

$\Rightarrow$adjust R_2 until there is
no current flow through V_G



Wheatstone Bridge

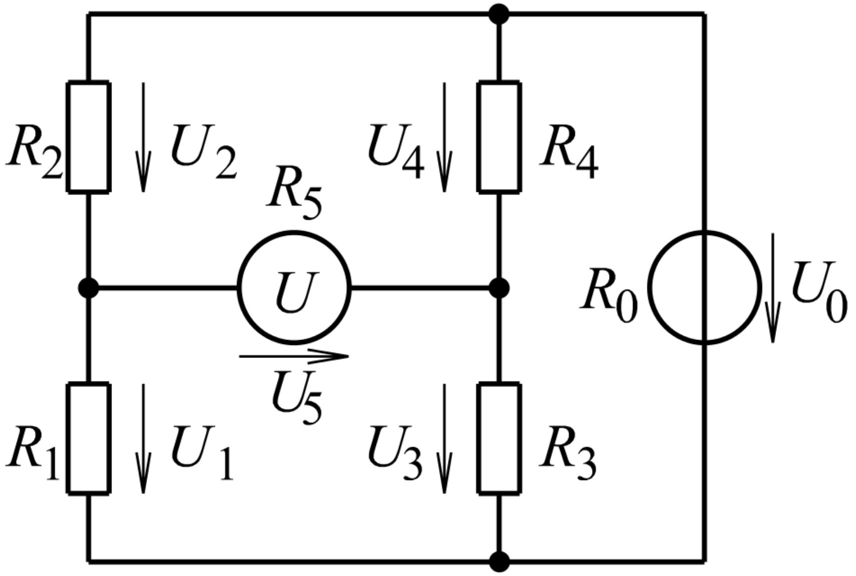
(original) operation principle:

$$U_5 = U_0 \frac{R_1 R_4 - R_3 R_2}{(R_1 + R_2)(R_3 + R_4)}$$

$$U_0 = 0 \Rightarrow R_1 R_4 = R_3 R_2 \Rightarrow \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

three R_i are known,
hence fourth can be computed

re-draw the circuit
(two voltage dividers)



Wheatstone Bridge

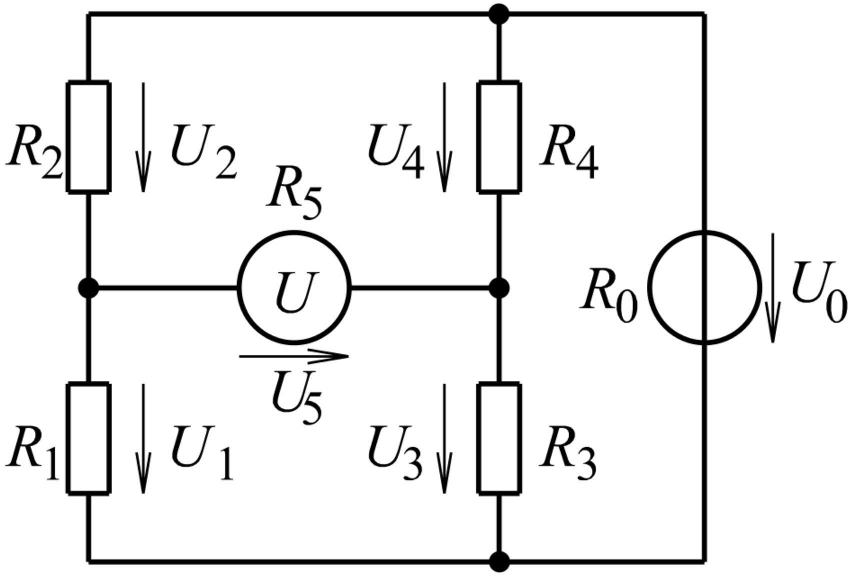
operation principle
for resistance changes $\widetilde{R_1} = R_1 + \Delta R$

re-draw the circuit
(two voltage dividers)

$$U_5 = U_0 \frac{\widetilde{R_1} R_4 - R_3 R_2}{\left(\widetilde{R_1} + R_2\right)(R_3 + R_4)}$$

$$= U_0 \frac{vk}{(1 + v + k)(1 + k)}$$

with $v = \frac{\Delta R}{R_1}$ and $k = \frac{R_2}{R_1} = \frac{R_4}{R_3}$



Wheatstone Bridge

operation principle for $\widetilde{R_1} = R_1 + \Delta R$

$$U_5 = U_0 \frac{vk}{(1+v+k)(1+k)} \text{ with } v = \frac{\Delta R}{R_1} \text{ and } k = \frac{R_2}{R_1} = \frac{R_4}{R_3}$$

- if $v \ll 1 + k$, respectively $\Delta R \ll R_1 + R_2$
- then $U_5 \approx U_0 \frac{vk}{(1+k)^2} = U_0 \frac{\frac{\Delta R}{R_1}k}{(1+k)^2} = \frac{U_0 \cdot k}{R_1 \cdot (1+k)^2} \Delta R = c \cdot \Delta R$
- i.e., U_5 is (approximately) proportional to ΔR

Wheatstone Bridge

operation principle for $\widetilde{R_1} = R_1 + \Delta R$

$U_5 \approx U_0 \frac{vk}{(1+k)^2}$ for $v \ll 1 + k$, resp. $\Delta R \ll R_1 + R_2$

$\max\limits_{k} \frac{k}{(1+k)^2} = \frac{1}{4}$ for $\mathrm{k} = 1$

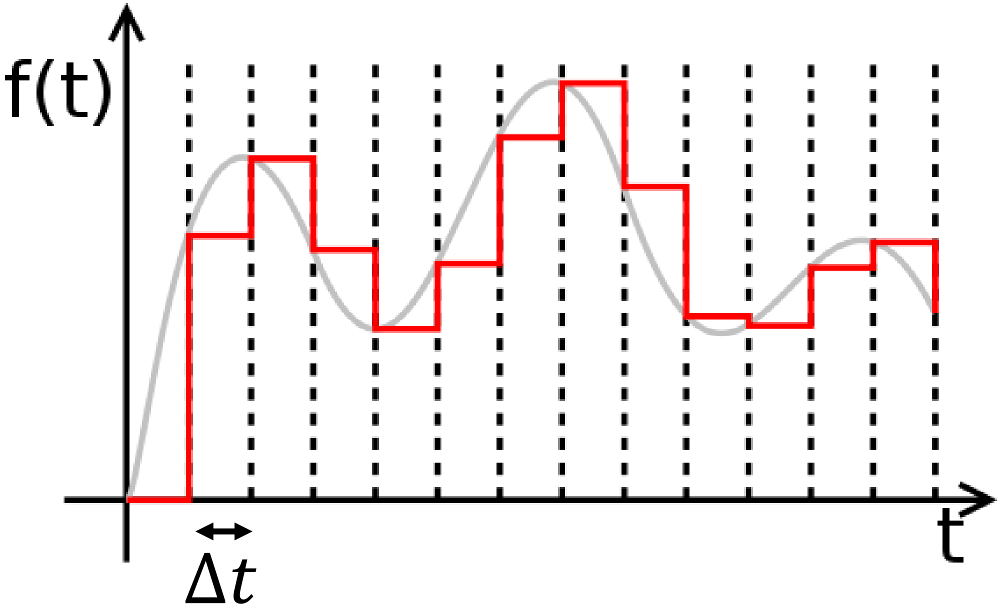
- i.e., for $R_1 = R_2 = R_3 = R_4$
- aka symmetric Wheatstone bridge,
- we get the maximum sensitivity

Time Discretization

analog signal
not only continuous amplitude, but also continuous time

sampling

- measuring an analog signal in discrete time steps
- ideally with a fixed frequency f_s aka ***sampling rate***
- ADCs typically with ***sample and hold***, i.e., take the value at the beginning of the measurement cycle



$$f_s = \frac{1}{\Delta t}$$

Nyquist-Shannon Sampling Theorem

first by Edmund Taylor Whittaker, 1915 (Nyquist, 1928 / Shannon, 1949)
hence aka Whittaker-Shannon or Whittaker-Nyquist-Shannon theorem

- sufficient condition for the **rate of discrete samples** needed to capture a **continuous-time signal** of finite bandwidth
- if a **function *f(t)*** contains **no frequencies higher than B Hertz**, it is completely determined by giving its ordinates at a **series of points spaced *1/(2B)* sec apart**
- i.e., a sampling rate of (at least) ***2B*** aka **Nyquist rate** is sufficient to capture all information from ***f(t)***

Nyquist-Shannon Sampling Theorem

respectively

- given a **sampling rate** of $\boldsymbol{f_s}$ then
  a function ***f(t)*** with a frequency of at most $\boldsymbol{f_s/2}$ aka **Nyquist frequency**
  is guaranteed to be properly represented

what can happen else?

- **aliasing**: two different signals appear to be the same
- **Moire effect**: e.g., "wave-patterns" in 2D images