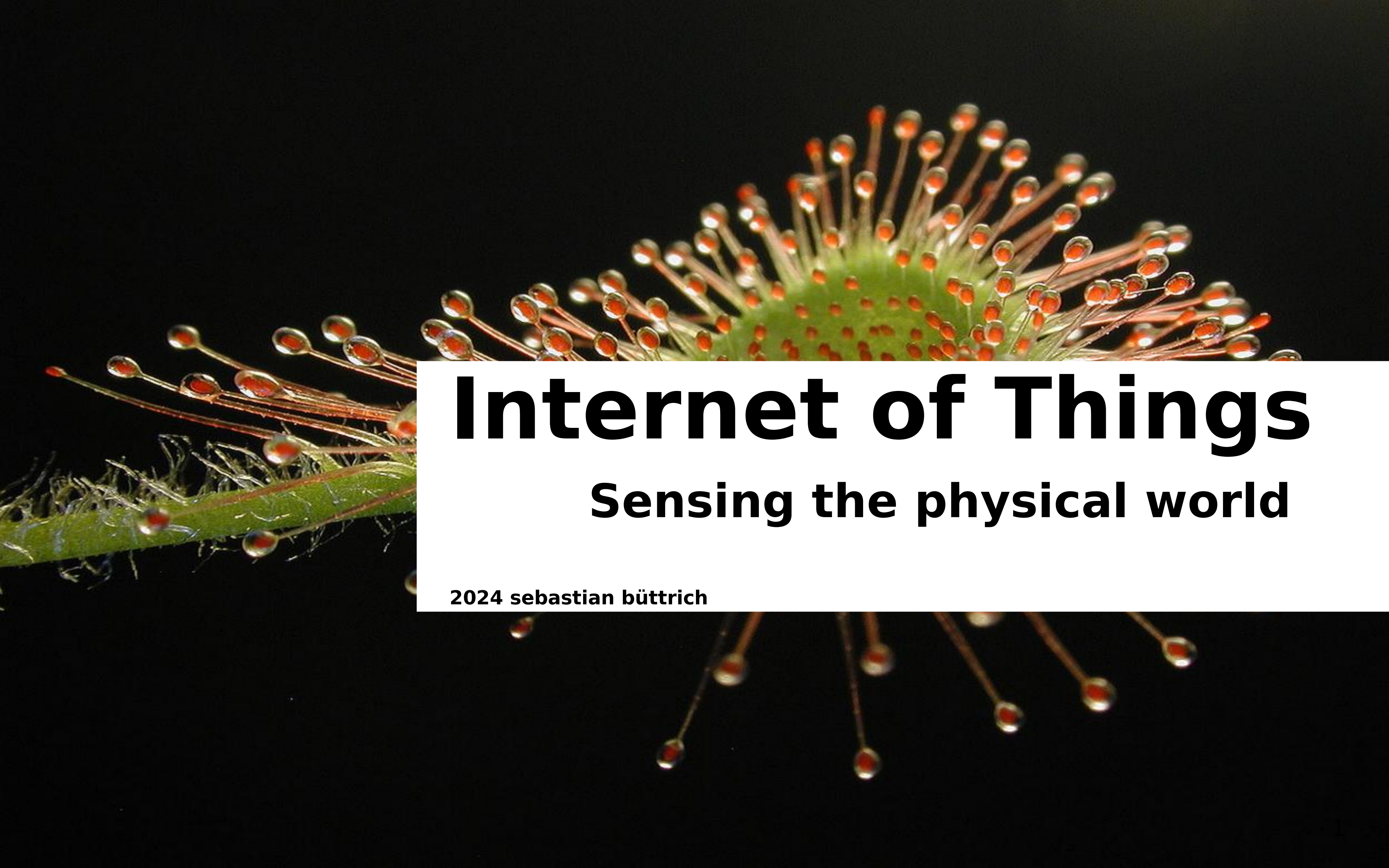


Internet of Things

Sensing the physical world

2024 sebastian büttrich

Agenda: Sensing & Acting

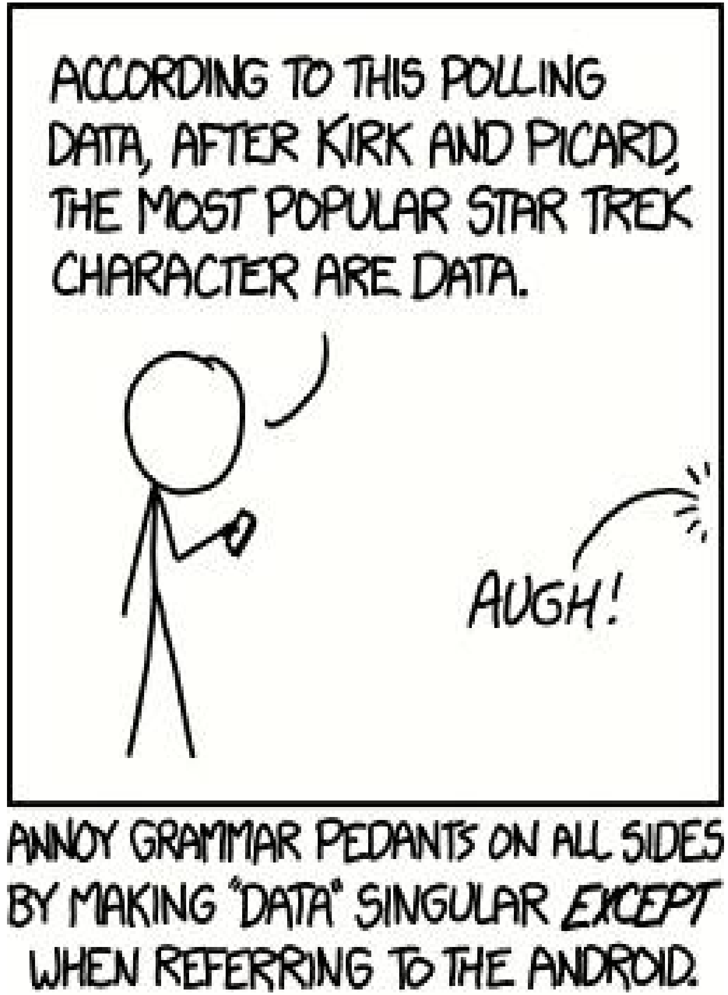
- **What is a sensor?**
- **Types / Classification of sensors**
- **Examples of sensors**
- **Terminology**
- **Calibration, Power, Communications**
- **(A tiny little bit about) Actuators**

Before we start – a side comment

Data is

or

Data are?



Before we start – another side comment

(

Data **– that which is given (from latin: dare, datum).**

But it is neither given nor taken.

It is created.

- **~~Data~~**
- **~~Capta~~**
- **Creata**

Data is never *raw* or *natural*.

)

Thought exercise:

What is temperature?
Definition? Measurement?
What is time?

Sensors / Definition I

- A sensor is a device, module, or subsystem that **transforms a property of the physical world to a signal that can be read by electronic/digital systems.**
- Properties, in the widest sense, can be events, changes, states/static properties.
- As always, there are many possible (and conflicting) definitions.

Sensors / Definition II

- One may prefer a wider definition:

Sensors

Sensors are the bridge between the physical world made of atoms and the abstract world of data.
Humans have sensors that perceive many physical quantities whose output is transmitted by the nervous system and then processed by the brain to transform it in meaningful data.
Man made sensor extend this capability to many other variables.

2

Ermanno Pietrosemoli, ICTP

discuss: .... do plants have sensors?

Sensors / Definition IIb – what about plants?

Do plants have sensors? What are they?

How are they different from our sensors?

e1977530-2 J. WHITE AND F. YAMASHITA

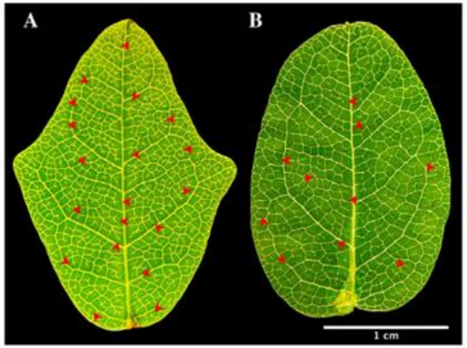


Figure 1. Leaf shapes in Boquila trifoliolata. (a) Non-mimic leaf, with three lobes, dense vascular network. (b) Mimic leaf, with a single lobe in the apex, less dense vascular network. Red asterisks shows examples of free-ending veinlets.

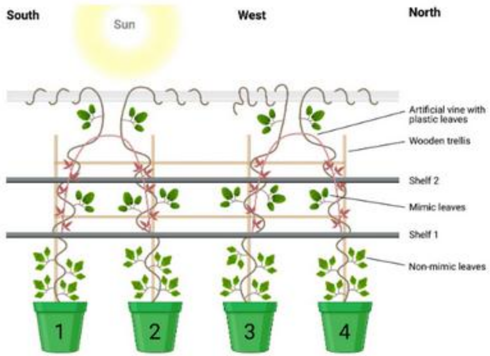


Figure 2. Experimental design. Four *Boquila trifoliolata* plants lined up side-by-side in front of a window and the artificial model vine plant with plastic leaves (red). Leaves below shelf 1 is the non-mimic (control) leaves. Leaves above shelf 1 is the mimick leaves. Created with BioRender.com.

Some are well-known -

but there is a lot we do not understand yet:

White, Jacob, and Felipe Yamashita.

"Boquila trifoliolata mimics leaves of an artificial plastic host plant."

Plant Signaling & Behavior (2021): 1977530. →

Sensors / Definition IIc – what about plants?

Boquila trifoliolata is so weird, it is worth a little detour

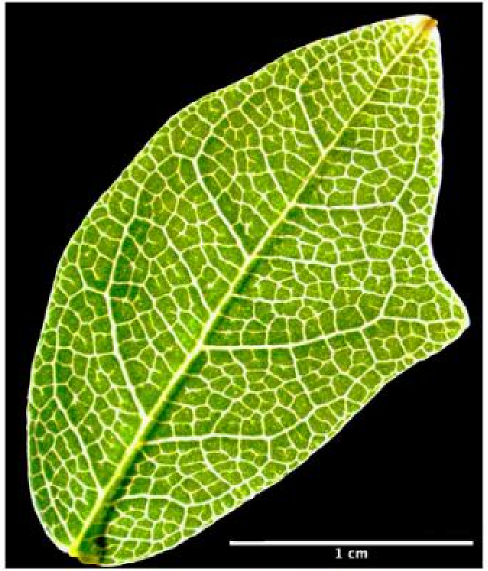


Figure 3. Single lobe mimic leaf. Mimicry attempt to the plastic leaves of artificial host plant.

Figure 4. Plastic leaf of a model artificial plant with longitudinal shape.

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Sensors / Definition IId – what about plants?

Boquila trifoliolata is so weird, it is worth a little detour

"The leaves of Boquila trifoliolata can mimic the leaves of its supporting host, including size, shape, orientation, color, and petiole length, among other features. Moreover, the same individual can mimic two different hosts in a series. … physical contact is not needed for mimicry to take place ...

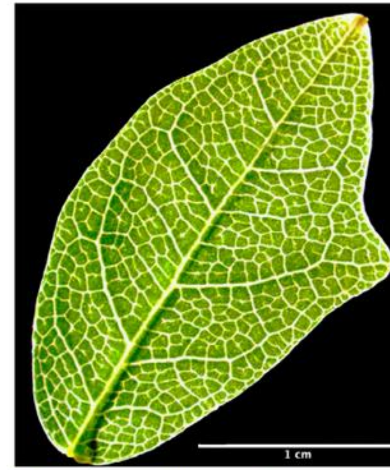
[and it also works with plastic plants!]

... a radical hypothesis has been recently advanced: a plant-specific form of proto-vision akin to the ocelloid-based type of vision found in cyanobacteria and some dinoflagellates (Baluška & Mancuso, 2016, 2017).

According to Baluška and Mancuso, the vine may be able to perceive shapes and colors via somewhat primitive image-forming mechanism (although see Gianoli, 2017)."

White, Jacob, and Felipe Yamashita. "Boquila trifoliolata mimics leaves of an artificial plastic host plant." Plant Signaling & Behavior 17.1 (2022): 1977530.

Segundo-Ortin, Miguel, and Paco Calvo. "Consciousness and cognition in plants." Wiley Interdisciplinary Reviews: Cognitive Science 13.2 (2022): e1578.



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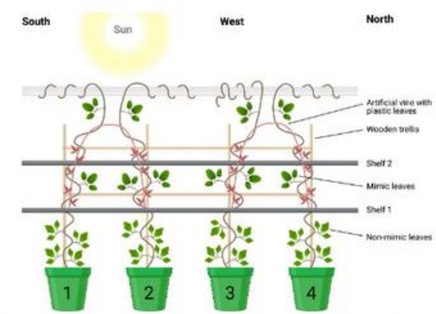

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Sensors / Definition III

- Distinction:

  In our context, we will distinguish between the

  embedded system, a board, or such,

  and **the actual sensor -**

  both of which together make up the sensor node or device.

- In practice, we often find the term **sensor** to denote the whole system, e.g. a *WiFi CO2 sensor, LoRa watermeter.*

Sensors / Principle

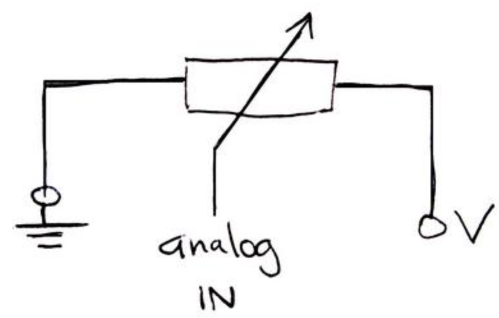
- Typically, the sensor transforms a physical property into a

  voltage (or current, which then gets converted to a voltage)

  which then may be digitized.
- Some **physical effect** is needed to make that transformation.
- To that end, for experiments,

  a voltage source with a potentiometer fully replaces any type of

  (analog) sensor.



Sensors / Classification, types

- **Analog / Digital**

  depending on whether the output is an analog voltage or already digital (→ ADC)
- **Active / Passive**

  with regards to the measurement – does the sensor impact the object of interest? Discuss e.g. watermeters
- **Powered / Non-powered**

  – do we need to power the sensor in order for it to work?

Sensors / Reminder of prerequisites

- SI UNIT system
- Powers of ten

International System of Units (SI)

SI Base Units

Base Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

SI Derived Units

Derived Quantity	Name	Symbol	Equivalent SI units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$m \cdot kg \cdot s^{-2}$
Pressure	pascal	Pa	N/m^2
Energy	joule	J	N·m
Power	watt	W	J/s
Electric charge	coulomb	C	s·A
Electric potential	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Celsius temperature	degree Celsius	°C	K*

*Unit degree Celcius is equal in magnitude to unit kelvin.

SI Prefixes

Factor	Name	Symbol	Numerical Value
10^{12}	tera	T	1 000 000 000 000
10^{9}	giga	G	1 000 000 000
10^{6}	mega	M	1 000 000
10^{3}	kilo	k	1 000
10^{2}	hecto	h	100
10^{1}	deka	da	10
10^{-1}	deci	d	0.1
10^{-2}	centi	c	0.01
10^{-3}	milli	m	0.001
10^{-6}	micro	µ	0.000 001
10^{-9}	nano	n	0.000 000 001
10^{-12}	pico	p	0.000 000 000 001

- Adapted from NIST Special Publication 811
- SI rules and style conventions recommend using spaces rather than commas to separate groups of three digits.

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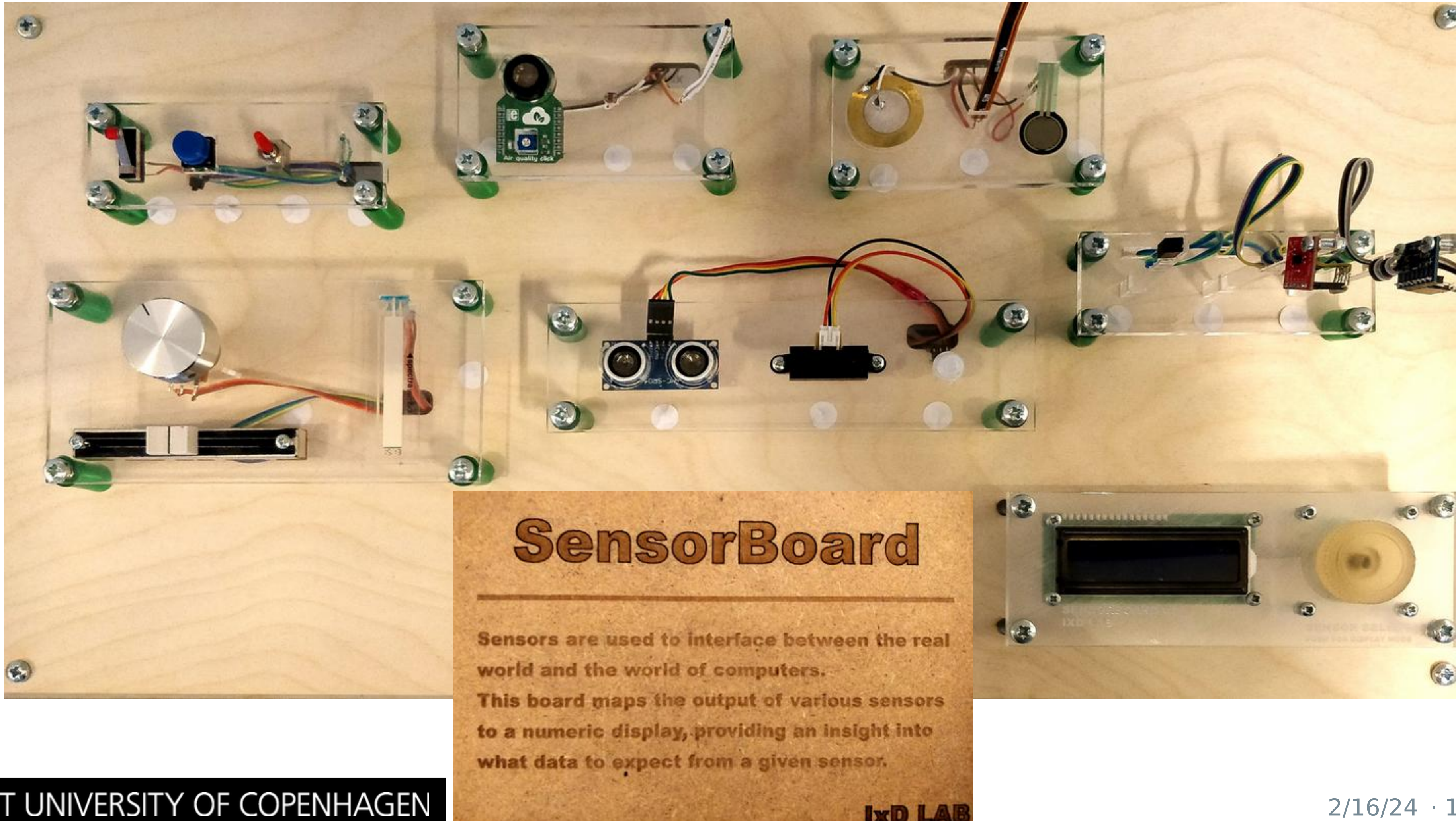
Sensors / Overview I



Sensors / Overview II

Push Button

Displacement

Pressure, weight, bend, vibration

Distance

Proximity

Motion

Acceleration

Orientation (Magnetic, Gyroscope)

GPS

Hall/Reed

Current

RF Intensity

Temperature

Humidity, soil moisture

Light (→ Camera)

Sound

Pressure, barometer

Wind (speed, direction)

Radioactivity

Time (? discuss!)

Water

- → Level, flow, chemistry

Air

- → indoor/outdoor
- → gaseous / particulate
  - → Smoke, Fire

Sensors near you

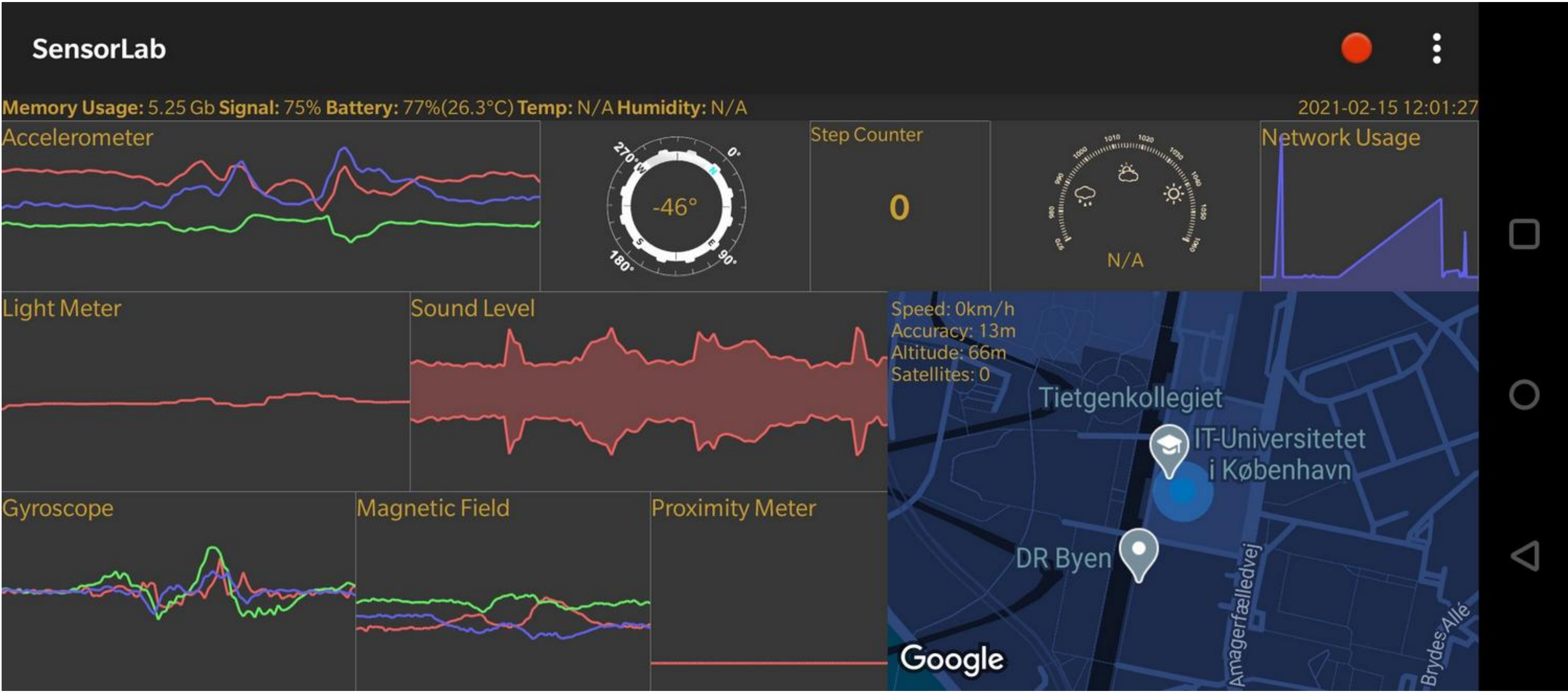
- **The mobile phone**

  is probably the richest collection of sensors you have near you.
- **Your car – if you have one -**

  likely has even more.
- **Your residential smartmeter**

  has dozens of sensors, if it is a modern one.

Sensors / Mobile Phone



Sensors / Simple examples

Sensors / Buttons

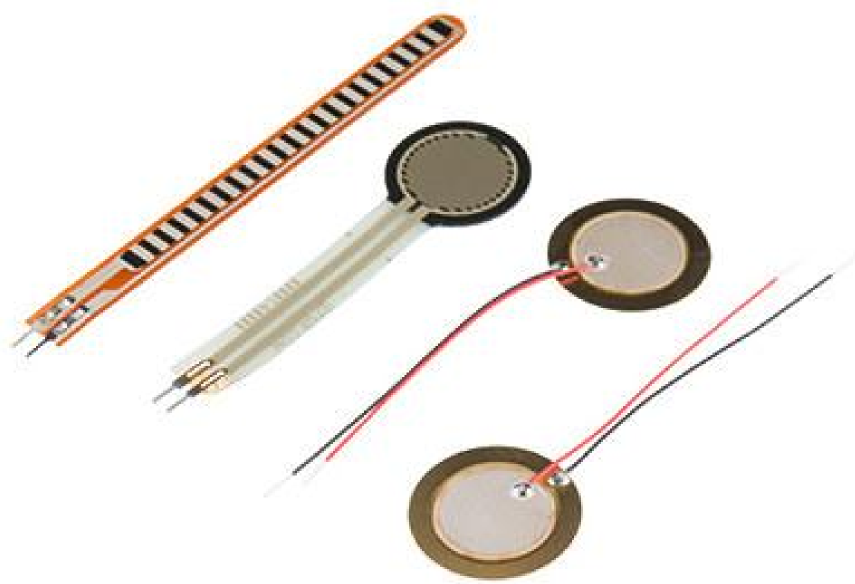
Physical principle

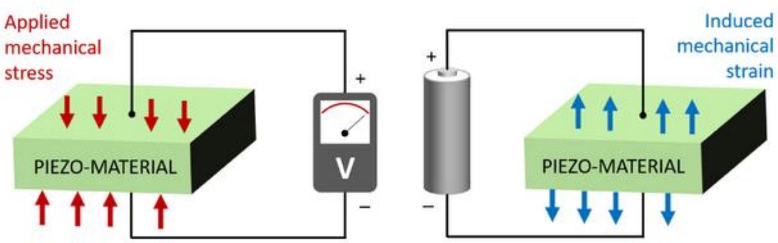
Mechanical, closing circuit

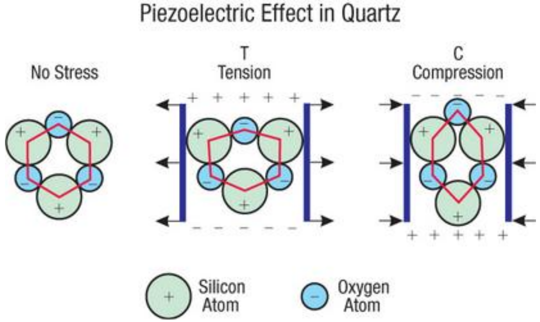
Applications

human interaction

Sensors / Piezo







Physical principle

Piezo effect

Applications

Force

Motion

Bending

Moving

Vibration

Audio

source: sparkfun, sintef.com

Sensors / Distance / Ultrasonic

source: sparkfun

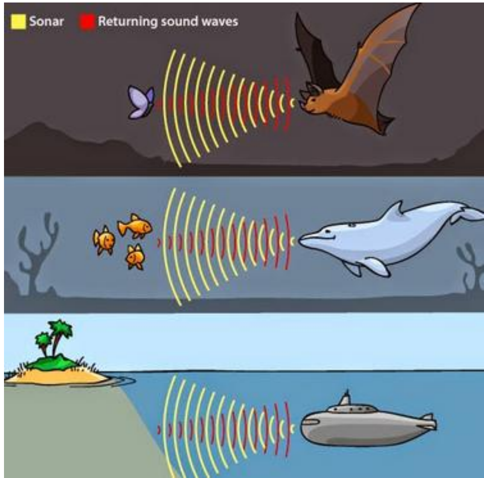
Physical principle

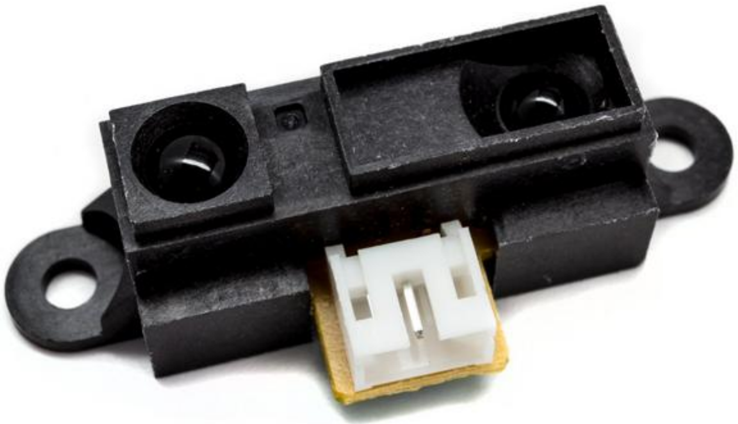
Speed of sound

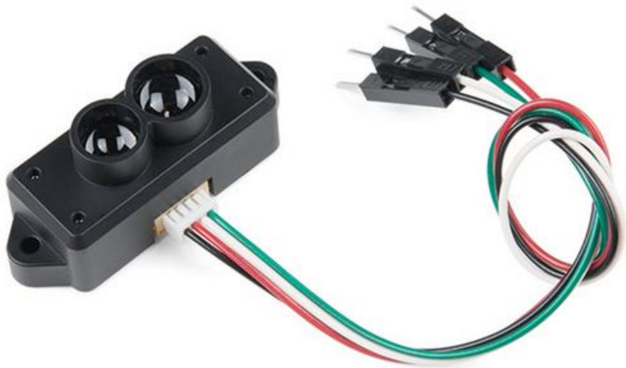
Applications

Distances

e.g. liquid levels







Physical principle

Triangulation

Time of Flight (TOF)

Interferometry

Applications

Distances

source: sparkfun

Physical principle

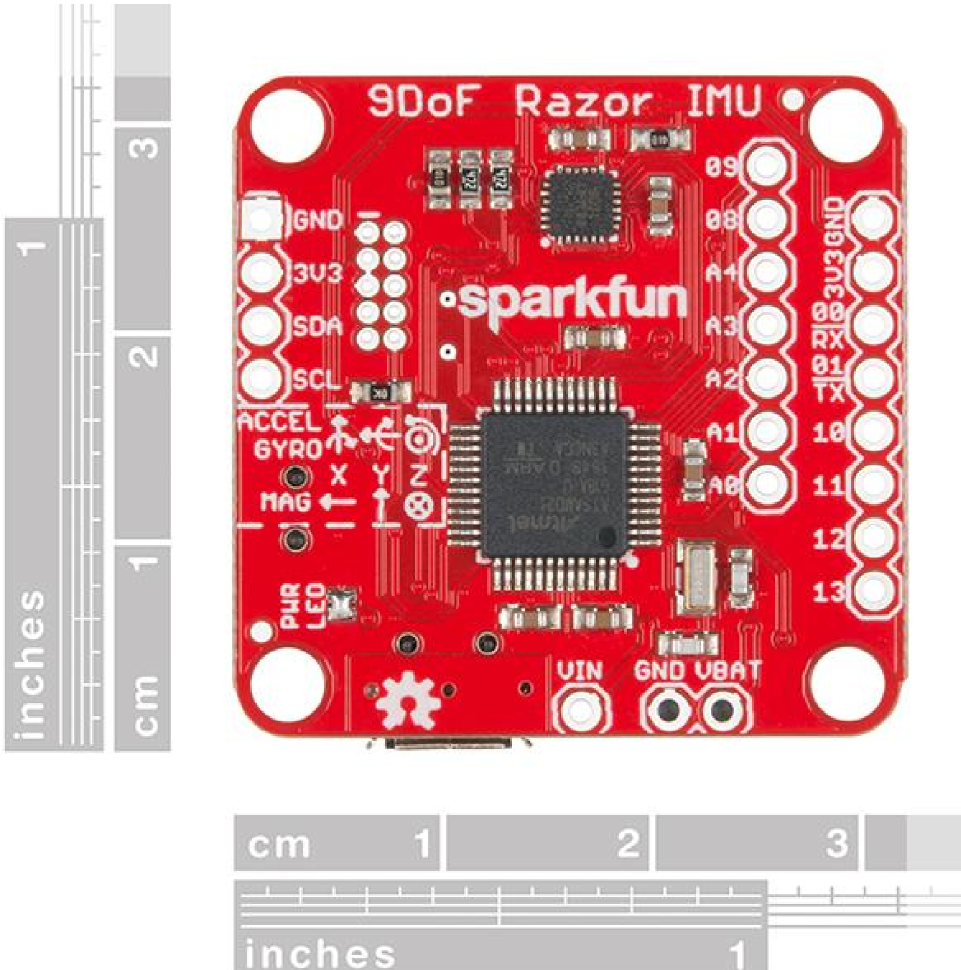
Reflection

Applications

Proximity

source: sparkfun

Sensors / Acceleration, Orientation



Physical principle

MEMS

MicroElectroMechanical

Applications

Acceleration

Motion

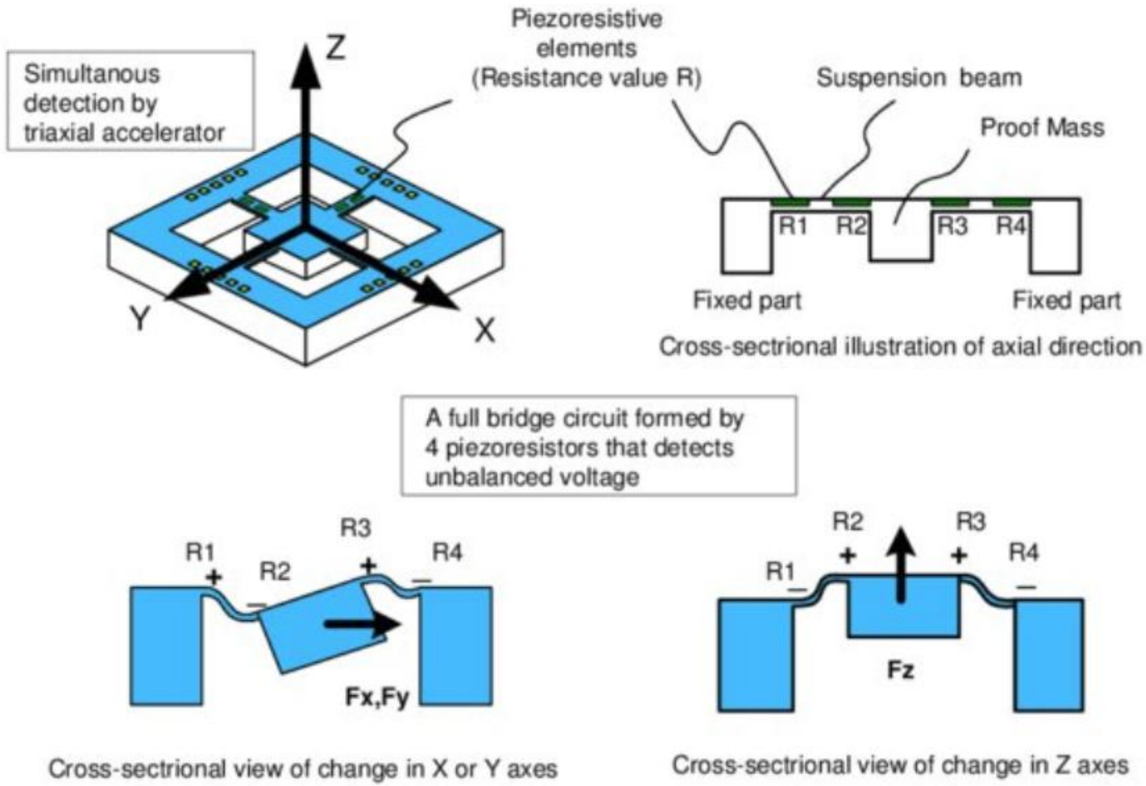
Orientation

Gyroscope

(angular motion)

Compass

Sensors / Acceleration



Physical principle

MEMS

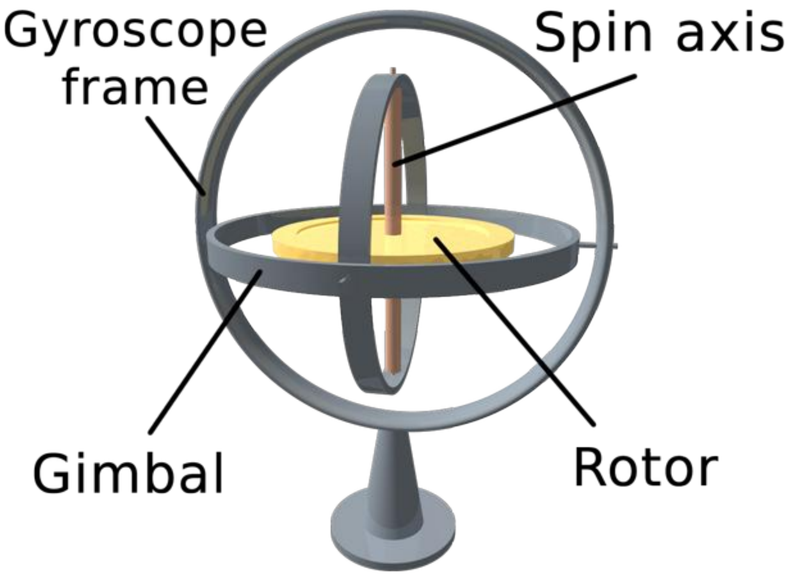
MicroElectroMechanical

Applications

Acceleration

source: Liu, R., Zhang, Z., Zhong, R., Chen, X., & Li, J. (2007). Nanotechnology synthesis study: research report. Texas Department of Transportation.

Sensors / Gyrometer



Physical principle

MEMS

MicroElectroMechanical

Applications

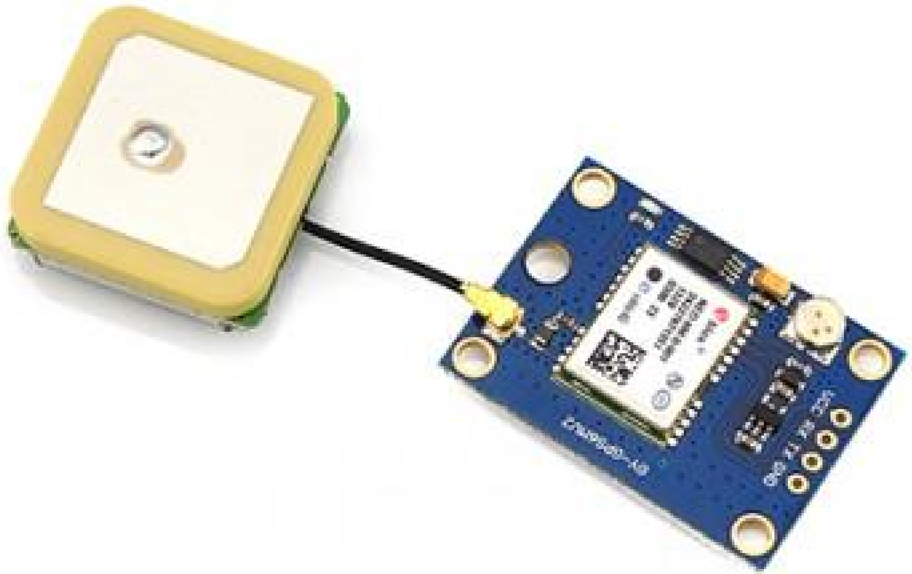
Motion

Orientation

Gyroscope

(angular motion)

Sensors / GPS



Physical principle

Data from GPS Sats

(Is this a sensor?)

Applications

Position

source: sparkfun

Sensors / Hall

Physical principle

Hall effect

Applications

Magnetic fields

→ Motion

source: sparkfun, xignal

Sensors / Current

source: sparkfun

Physical principle

Induction

Applications

Power

Current

Sensors / Temperature

Physical principle

thermoelectric

Applications

Ambient temperature

source: sparkfun

Sensors / Liquid levels

source: sparkfun

Physical principle

resistive

barometric

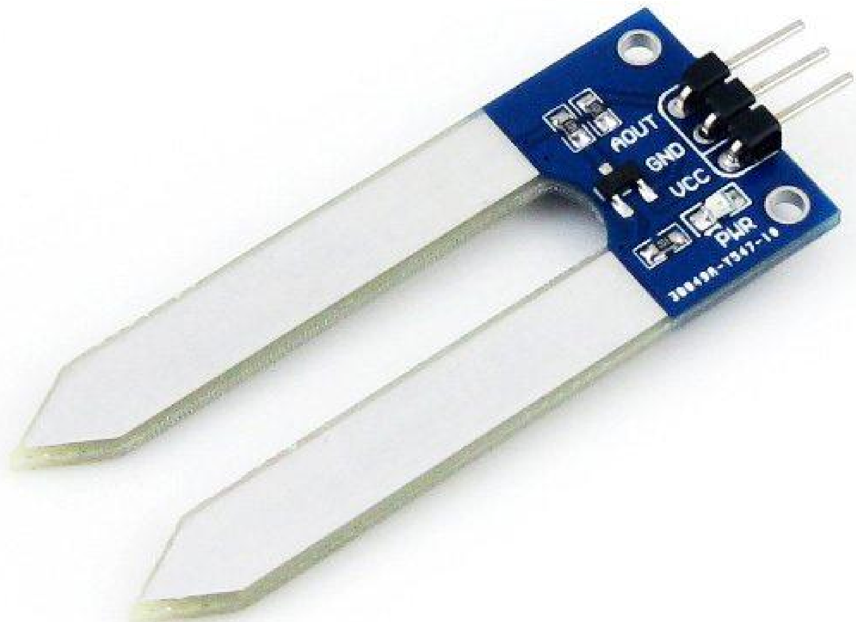
Applications

Liquid levels,

technical,

environmental

Sensors / Soil moisture



Physical principle

Resistance

Capacity

Applications

Agriculture

source: sparkfun

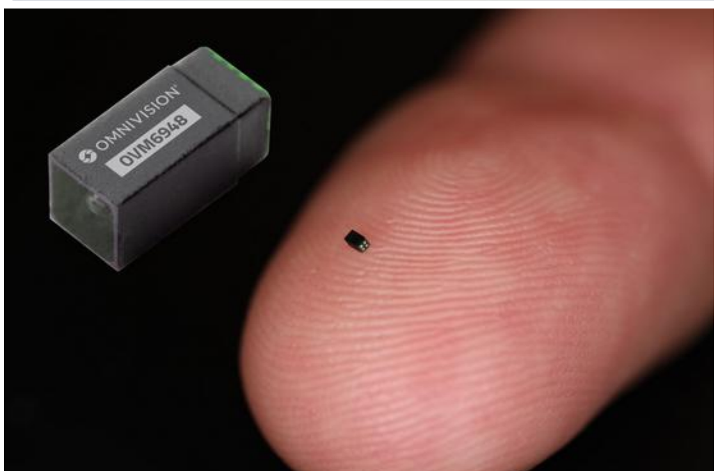
Physical principle

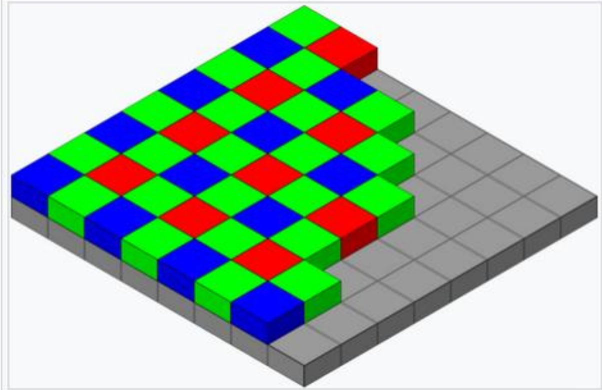
Photoresistance

Applications

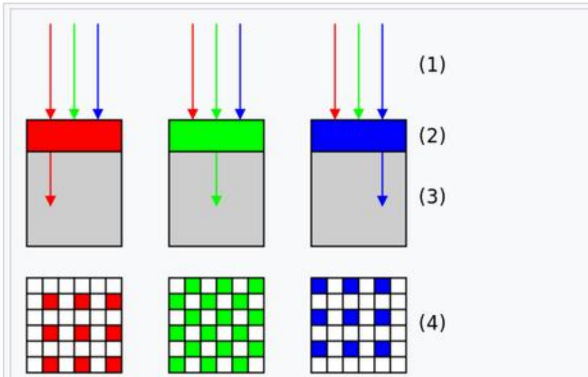
Light :)

Sensors / From light sensor to camera





The Bayer arrangement of color filters on the pixel array of an image sensor



Profile/cross-section of sensor

Many light sensors

... make a camera

(almost)

Other components

Color filters

Optical lenses

Sensors / From light sensor to spectrometer

Principle

Light sensors plus

frequency division

Application

Spectral analysis

Sensors / Sound

Physical principle

Piezo, Mems, other

Applications

Sound :)

source: sparkfun

Sensors / Radioactivity

Physical principle

Ionization

Geiger counter

Applications

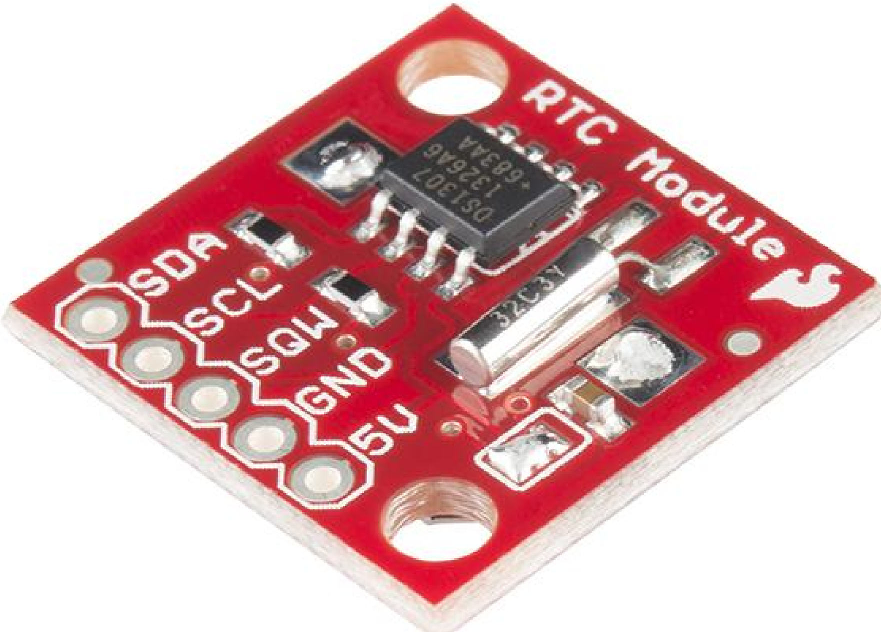
Radioactivity

Gamma rays

→ safecast.net

source: safecast.org

Sensors / Time



Physical principle

?

discuss!

Applications

Real Time Clock

Physical principle

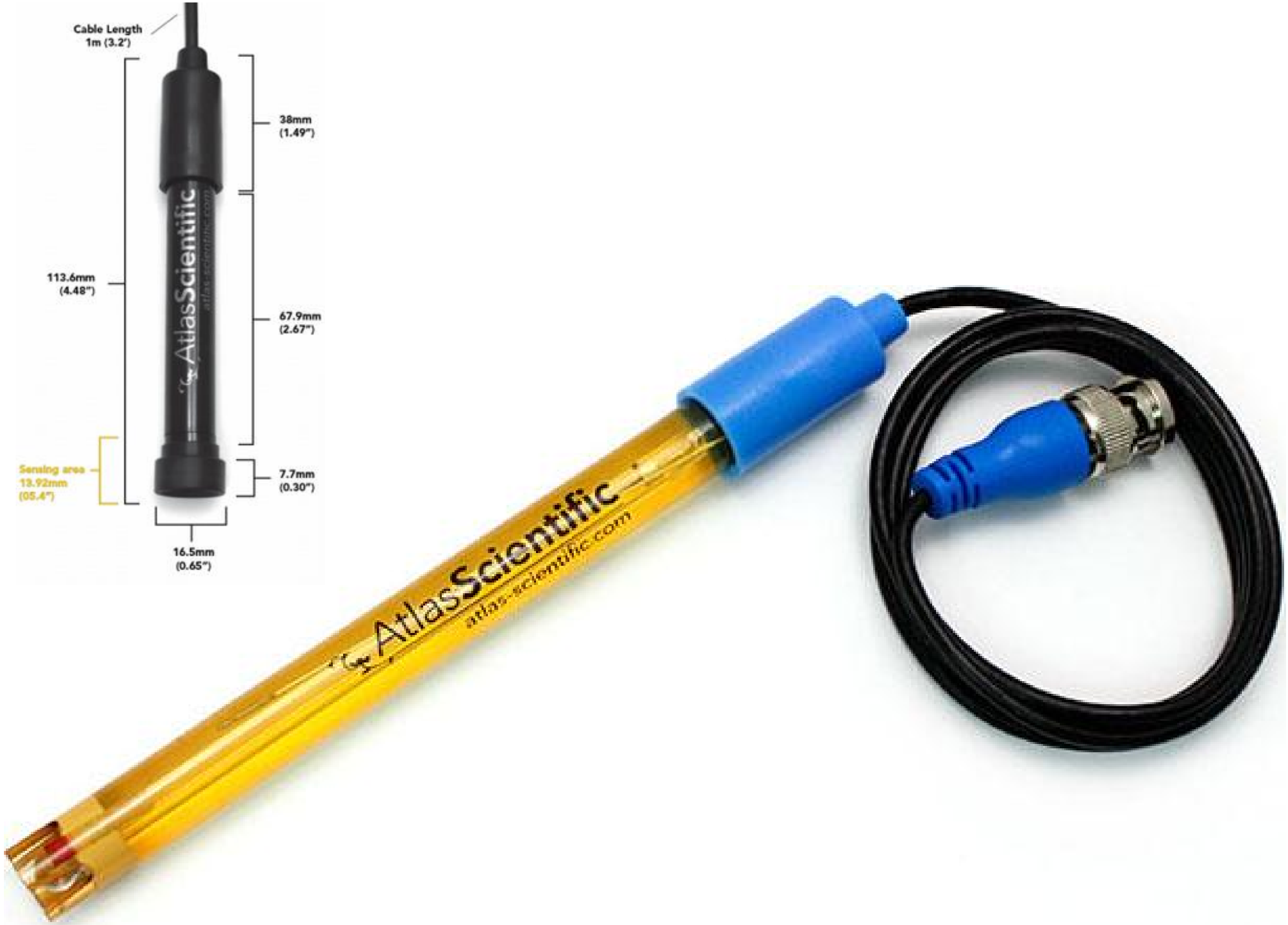
Turbine

Ultrasonic

Applications

Metering

Flows



Physical principle

various

Applications

PH

Dissolved Oxygen

+ a lot more

source: atlas scientific

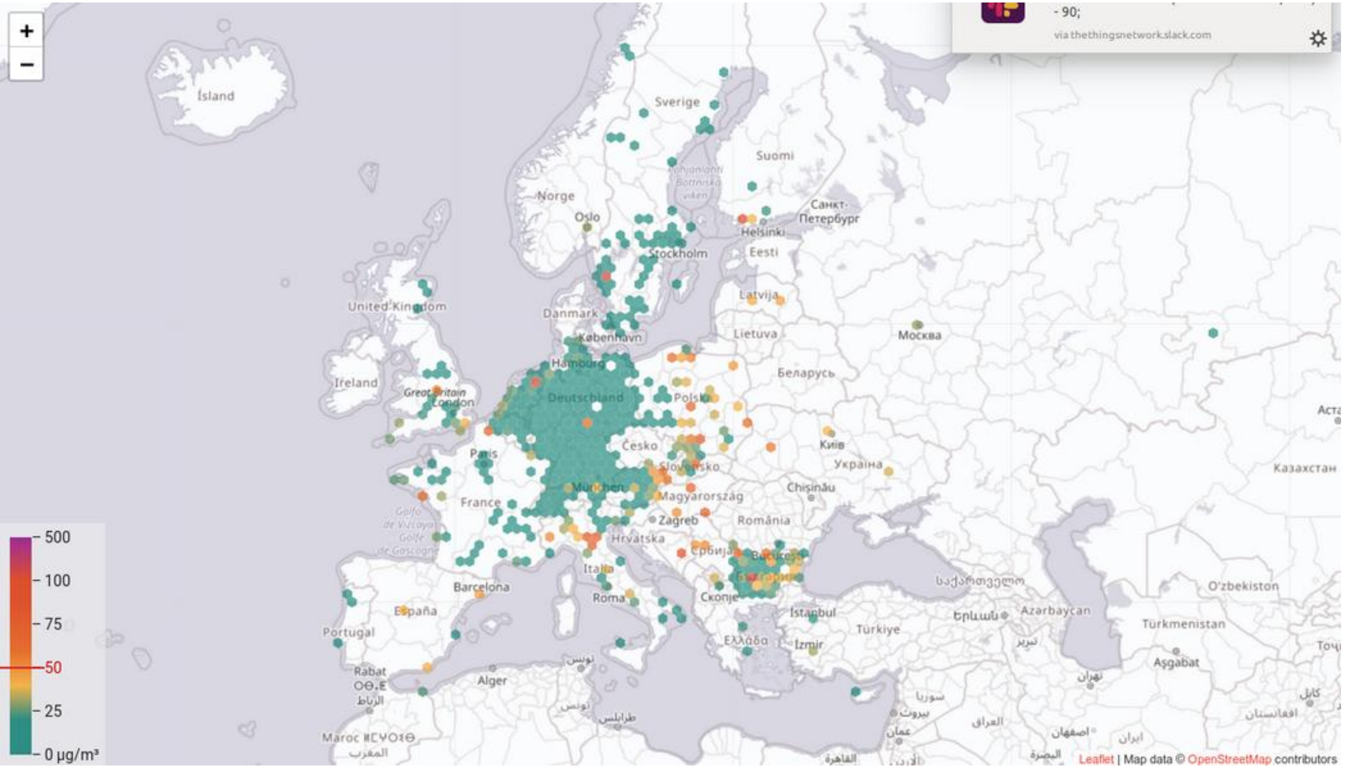
Sensors / Air I

- Air sensors are an especially complex area
- **Indoor / outdoor**

  → different gases/pollution types of interest
- Areas of interest strongly depend on context, location
- Challenge: low-cost sensors vs. “lab grade sensors”
- Citizen science projects, including PITLab’s

  → bAIR.dk → luftdaten.info
- Rapid progress in new sensor types, miniature sensors, MEMS, mobile sensors

Sensors / Air II / Citizen Science

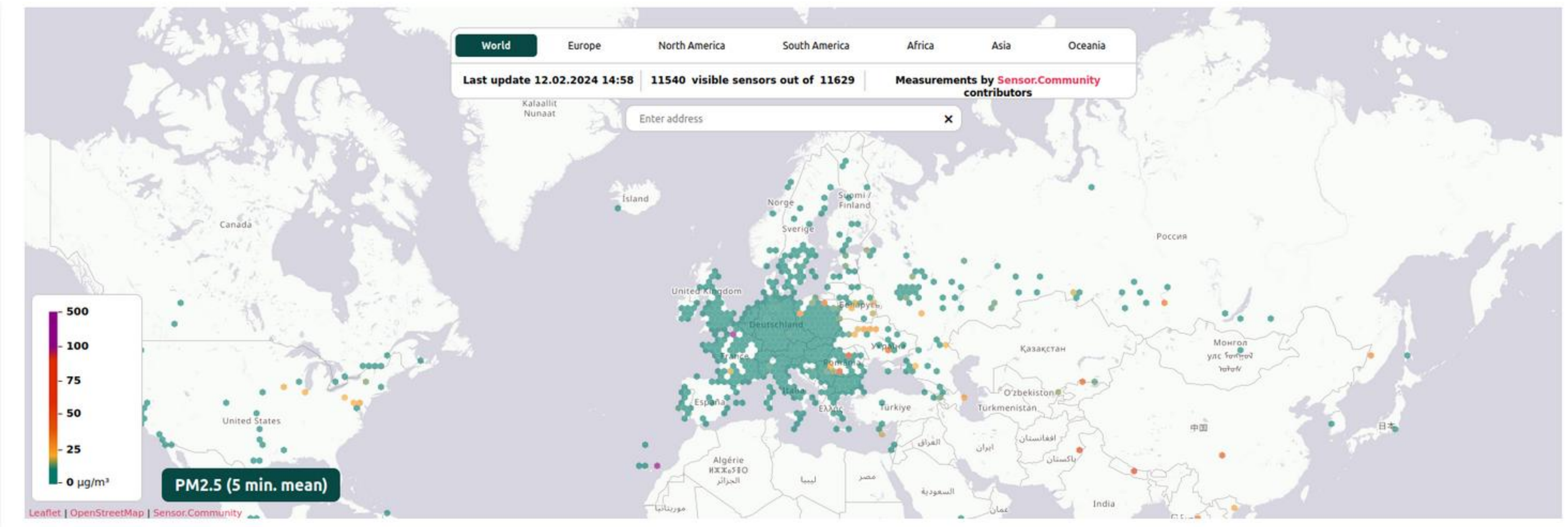


Low-cost sensors are very attractive for monitoring modeling, forecast - however the question of quality is subject of controversial debate

"Wisdom of the Crowd"

source: luftdaten.info

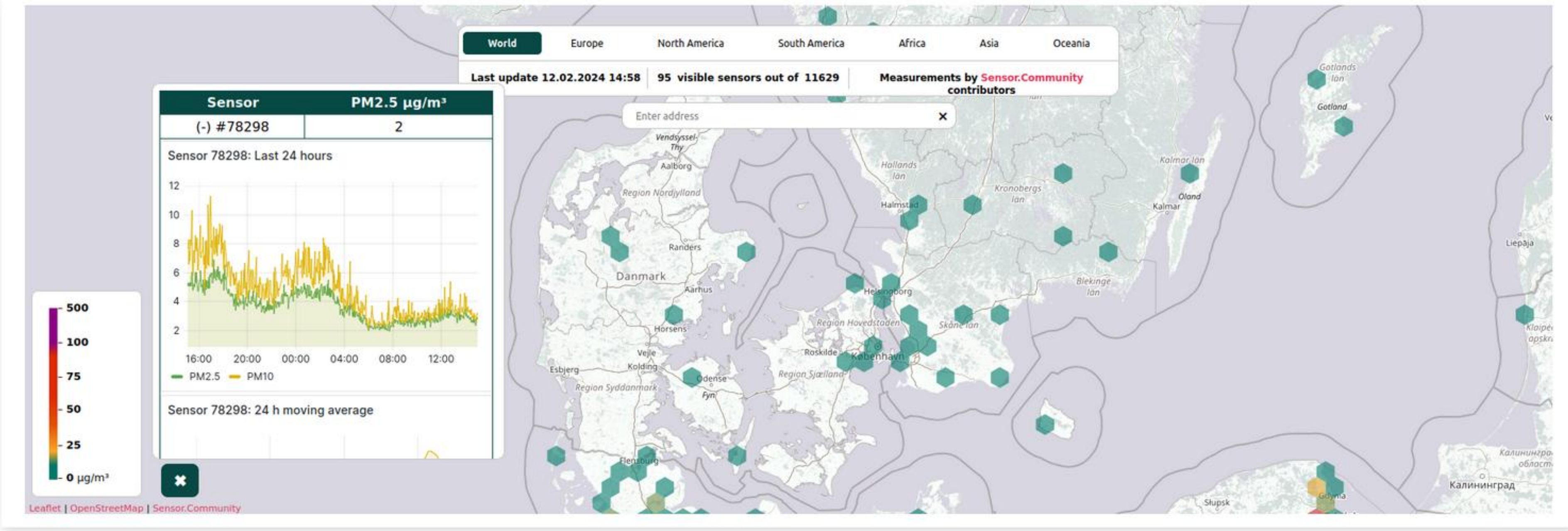
Luftdaten.info becomes sensor.community



source: sensor.community

Sensors / Air IIb / sensor.community denmark

Luftdaten.info becomes sensor.community



source: sensor.community

Sensors / Air III / indoor / CO_2

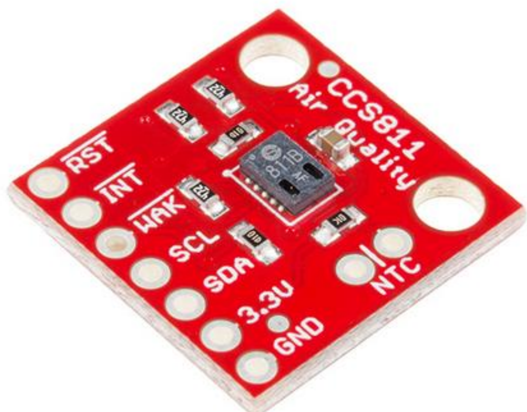
- Focus often on **CO_2 and/or technical gases** (Volatile organic compounds, VOC)
- CO_2 sensors are mainstream
- *CO_2 monitoring is mandatory for public institutions in Denmark such as IT University*
- CO_2 Sensors of types
  Nondispersive Infrared (NDIR), Chemical, MEMS

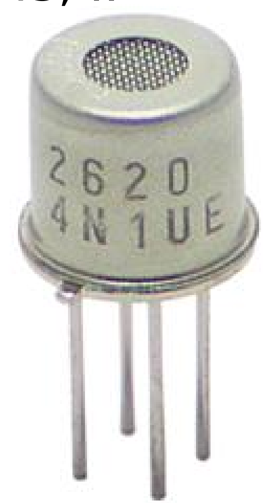
source: figaro, sparkfun, sensirion

Sensors / Air IV / indoor / VOC

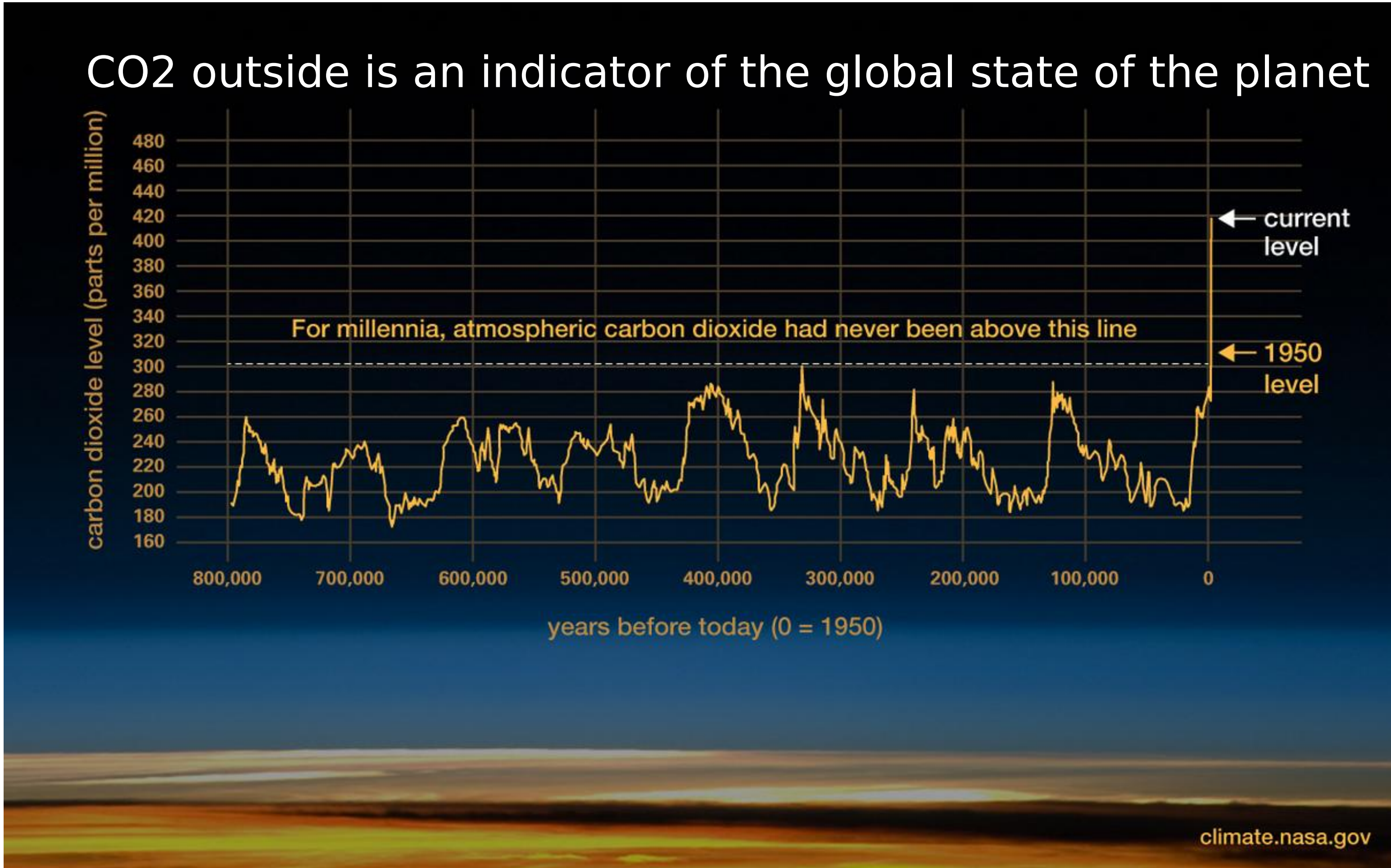
- Volatile organic compounds (VOC)

  come from a variety of sources like construction materials (paint, carpet, etc.), machines (copiers, processors, etc.), food, and even people (breathing, smoking, etc.).
- Various sensor types: gas, electrochemical, MEMS, ..





source: sparkfun, figaro


CO2 outside is an indicator of the global state of the planet
carbon dioxide level (parts per million)
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
For millennia, atmospheric carbon dioxide had never been above this line
current level
1950 level
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
years before today (0 = 1950)
climate.nasa.gov

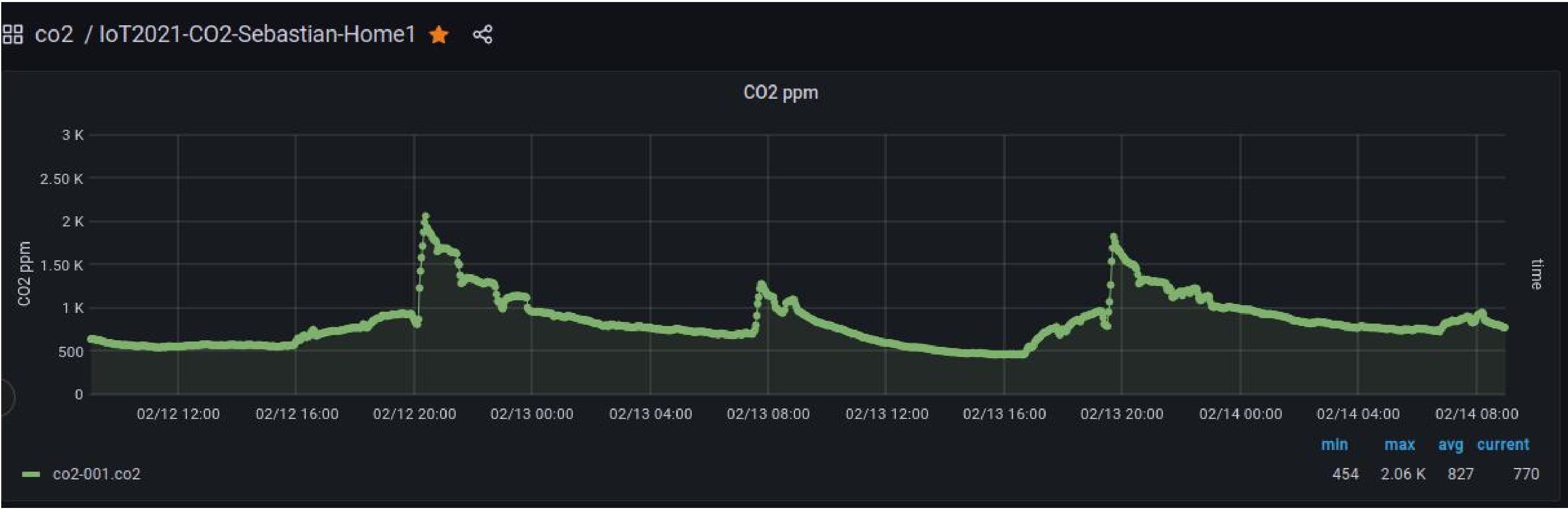
Source: NASA

Sensors / Air IVa / indoor / CO2

CO2 indoors is an indicator of human activity, air circulation, etc

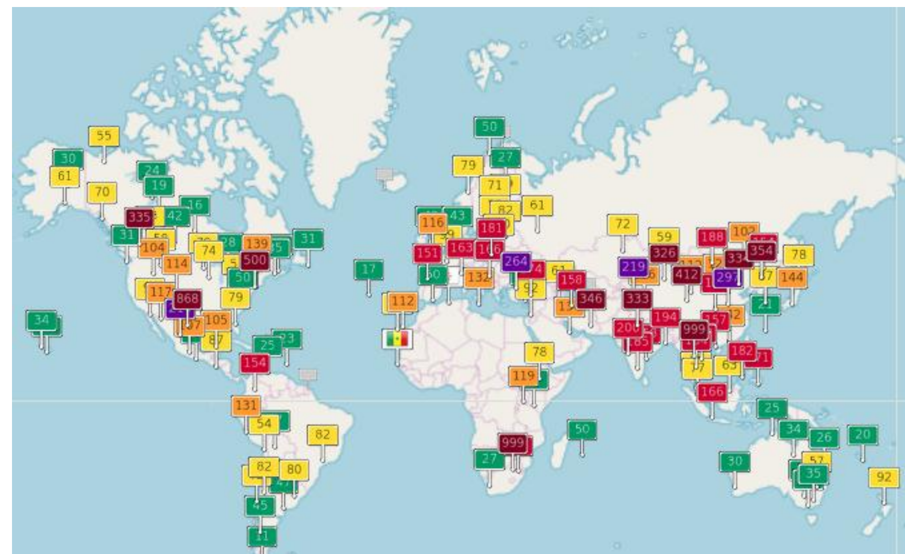
Sensors / Air IVa / indoor / CO2

CO2 indoors is an indicator of human activity, air ciculation, etc



Sensors / Air V / outdoor

- Air quality indices (AQI) are internationally agreed-on standards, and mostly include
  O3 ozone, NO2 nitrogen dioxide, SO2 sulphur dioxide and particulate matter (including PM10 and PM2.5)



source: aqicn.org

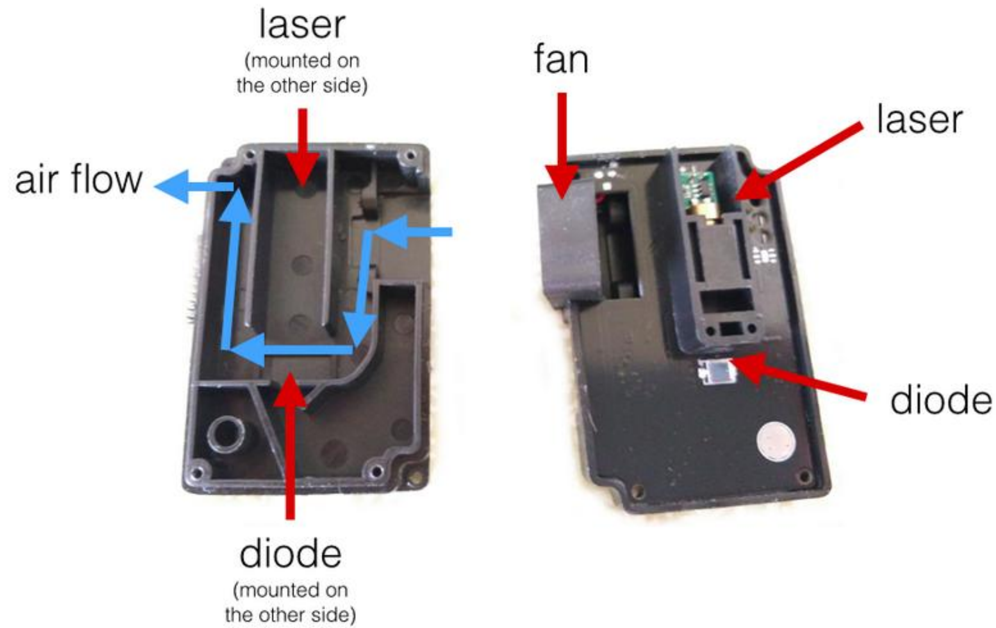
Sensors / Air VI / PM

- Particulate Matter (PM) comes from many sources, and in many places is among the biggest environmental health hazards (car traffic, stoves, fires, road dust, ..)

source: GFDL, https://en.wikipedia.org/w/index.php?curid=48987967

Sensors / Air VII / PM sensors

- Low-cost PM sensors are optical (IR) types, measuring light scattered by particles
- Measurements heavily cross-dependent on humidity, temperature!
- Brands include Nova, Shinyei, Sharp, Plantower, Alphasense and many more



source: Nova, Plantower

Sensors / Air IX / PITLab & AU – NO2, PM

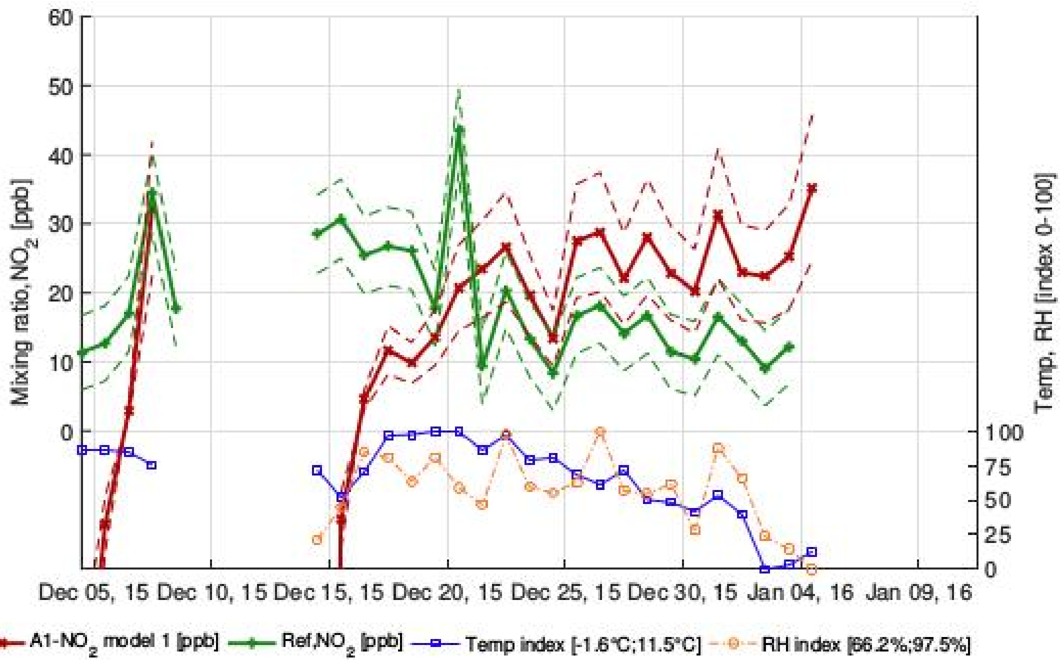
- Collaboration with Department of Environmental Science, AU - NO2 series, calibration, netwoorks, PM sensor collocation at HCAB

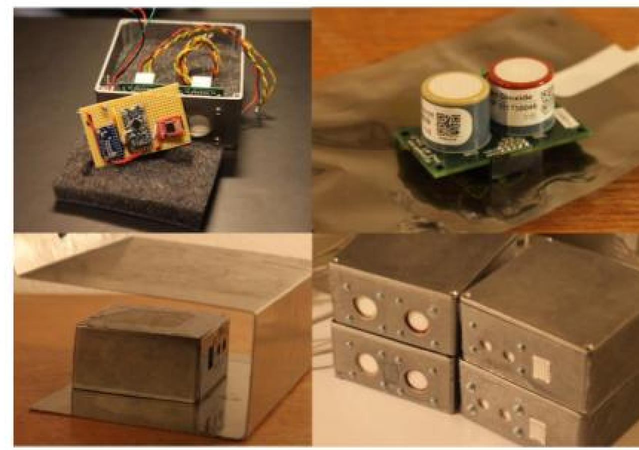
AARHUS UNIVERSITY

DTU Technical University of Denmark

PIT LAB PERVASIVE INTERACTION TECHNOLOGY LABORATORY

IT UNIVERSITY OF COPENHAGEN





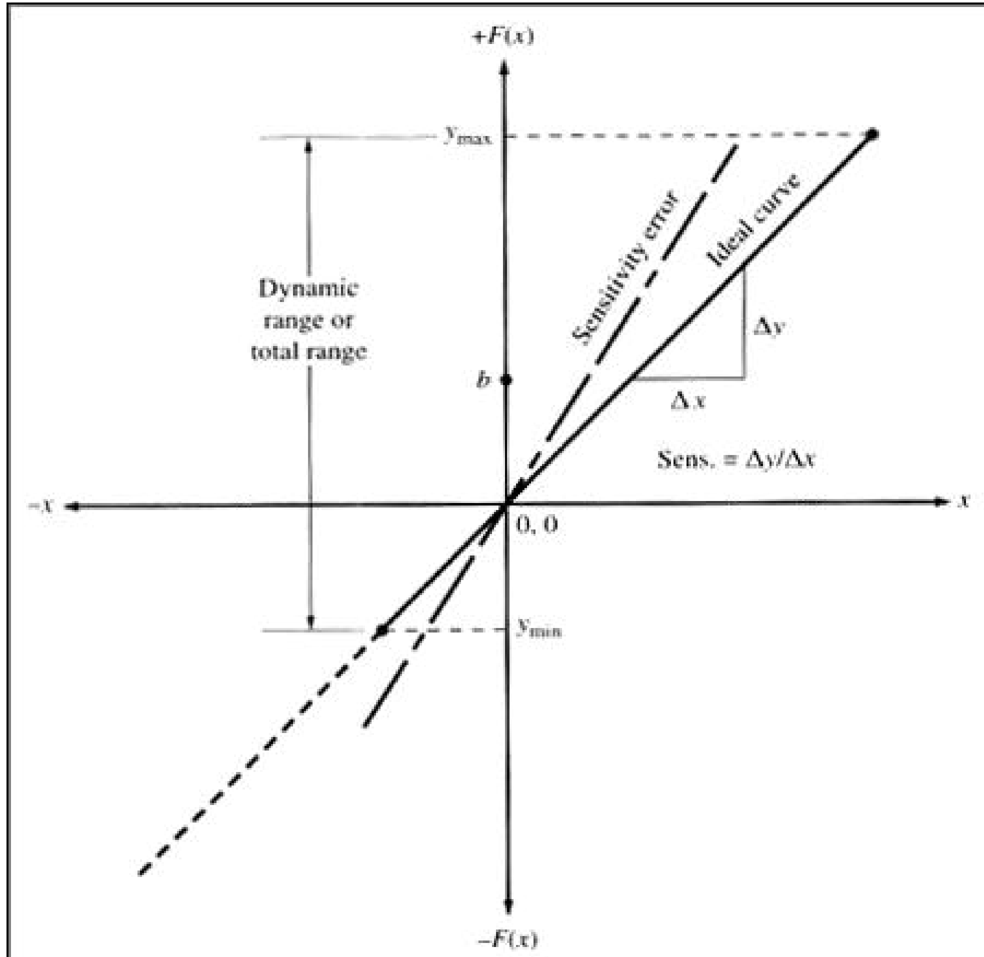
Assessing the applicability of low-cost electrochemical gas sensors for urban air quality monitoring

Sensors / Terminology I

- Sensitivity – minimum change needed to change output
- Range – minimal and maximal values
- Precision – spread/variation
- Resolution – about minimal difference that can be told apart
- Accuracy – bias, closeness to accepted “true” value
- Offset
- Linearity
- Hysteresis
- Drift
- Response Time
- Rate

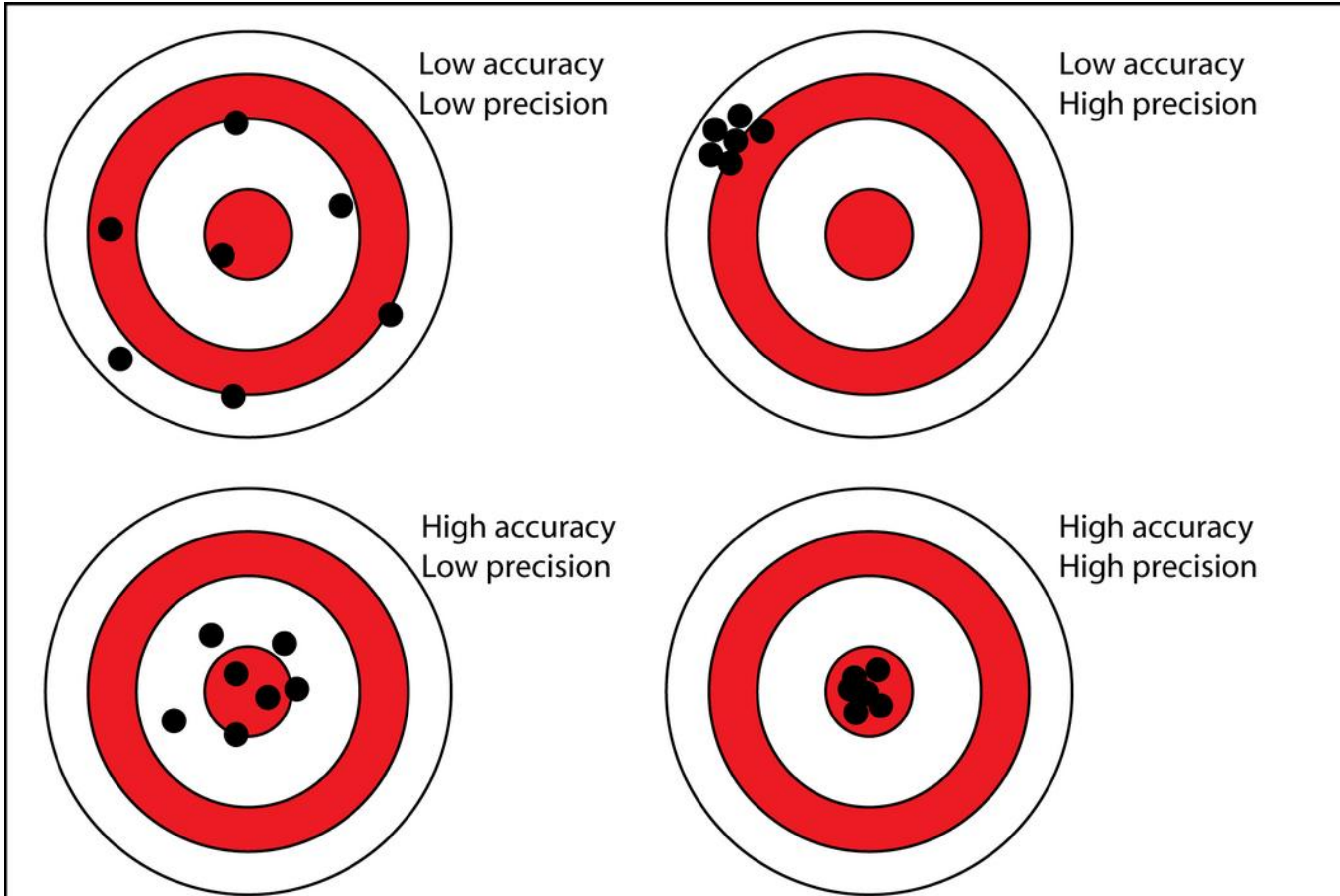
http://www.ni.com/white-paper/14860/en/

Sensors / Terminology II / Sensitivity & Range



source: National Instruments, ni.com

Sensors / Terminology III / Accuracy & Precision



source: http://www.antarcticglaciers.org

Sensors / Terminology IIIa / Accuracy & Precision

source: DASYA

Sensors / A remark on accuracy, precision and bytes

- It makes no sense to send and process more digits than can be trusted
- E.g. when measuring temperature with an accuracy of +- 0.5 C, what is the most economic way of transmitting data? Every byte comes at a cost!
- How relevant is the 10th digit of a GPS reading? (hint: not very!)

  5th digit ~ 1 meter (in central europe) → Haversine formula

.1	10 km
.01	1 km
.001	100 m
.0001	10 m
.00001	1 m

Sensors / A remark on ”Wisdom of the Crowd”

- “Wisdom of the crowd”,

  a term used to describe the impact of deployment in large numbers, can help to achieve

  higher precision and (potentially) accuracy,

  perhaps higher rates,

  however it can *not* correct for insufficient

  range, sensitivity, resolution, response time

  1000 poorly chosen sensors are still a poor choice.

Sensors / Communication in embedded devices I

- **Short distance (intra board)**
- **Moderate data rates (kBps ... Mbps)**
- **Connections for communicating with sensors,actuators**
- **Deep details often not so important to us**
- **Constraints of interest: number of devices, datarates, address spaces, number of wires**
- **For sensors, datarates are rarely an issue**

Sensors / Communication in embedded devices I

Three most popular standards:

- **I²C** (Inter-Integrated Circuit)
- **SPI** (Serial Peripheral Interface)
- **1-Wire**

- **SPI** we often see in controlling radio concentrators in LoRa gateways (higher datarates)
- **I2C** popular for sensors (many! Only 2 wires!)

Sensors / Communication in embedded devices I

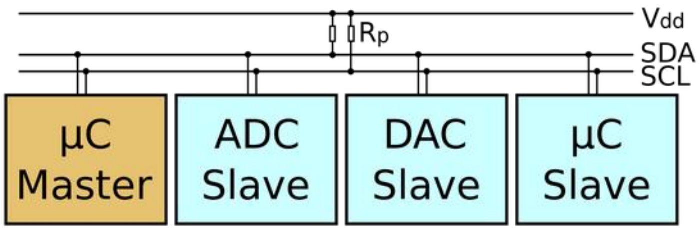
	devices	datarates	wires
async serial	2	230 kbps	2
UART			
SPI	(many)	10 Mbps	4
I2C	1008	100/400 kbps	2

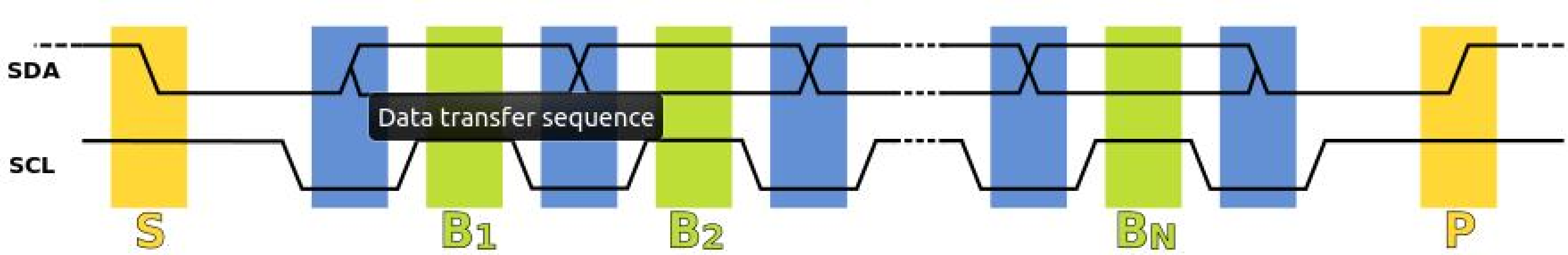
Sensors / Communication in embedded devices II

- **I²C** (Inter-Integrated Circuit), pronounced I-squared-C, is a synchronous, multi-master, multi-slave, packet switched, single-ended, serial computer bus (1982 Philips Semiconductor, now NXP Semiconductors). Two bidirectional wires: Serial Data Line (SDA) and Serial Clock Line (SCL)
- The Serial Peripheral Interface (**SPI**) is a synchronous serial communication interface specification used for short distance communication, primarily in embedded systems (Motorola, 1980s). 4 wires, full duplex.
- **1-Wire** is a device communications bus system designed by Dallas Semiconductor Corp. that provides low-speed (16.3kbps) data, signaling, and power over a single conductor. Similar in concept to I²C, but with lower data rates and longer range.

- **I²C** (Inter-Integrated Circuit), pronounced I-squared-C, is a synchronous, multi-master, multi-slave, packet switched, single-ended, serial computer bus (1982 Philips Semiconductor, now NXP Semiconductors). Two bidirectional wires: Serial Data Line (SDA) and Serial Clock Line (SCL)

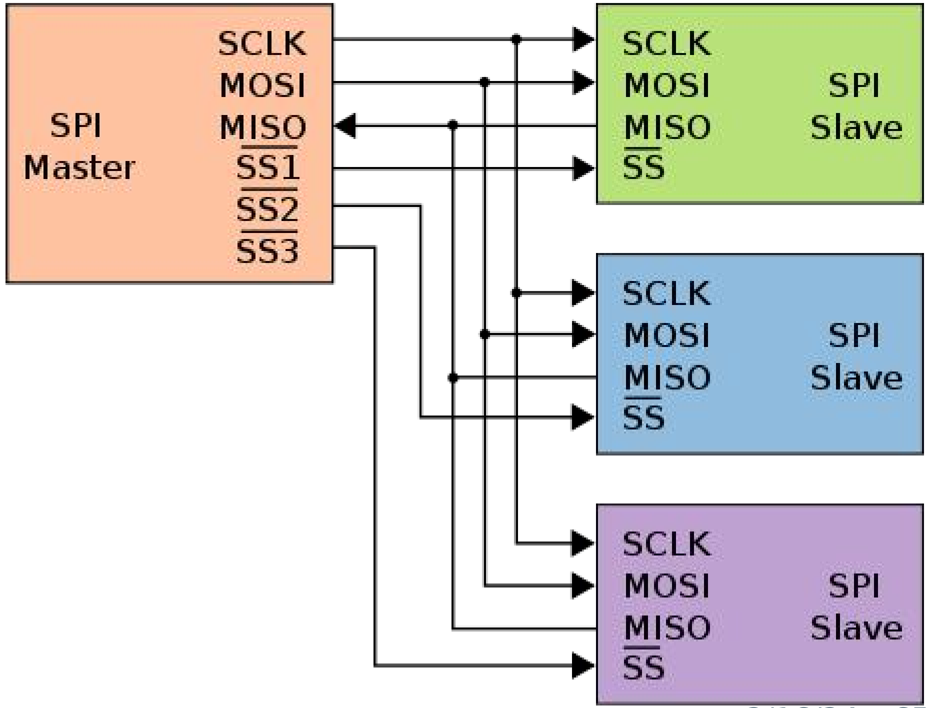
```python
from machine import I2C
# configure the I2C bus
i2c = I2C(0, I2C.MASTER, baudrate=100000)
i2c.scan() # returns list of slave addresses
i2c.writeto(0x42, 'hello') # send 5 bytes to slave with address 0x42
i2c.readfrom(0x42, 5) # receive 5 bytes from slave
i2c.readfrom_mem(0x42, 0x10, 2) # read 2 bytes from slave 0x42, slave memory 0x10
i2c.writeto_mem(0x42, 0x10, 'xy') # write 2 bytes to slave 0x42, slave memory 0x10
```



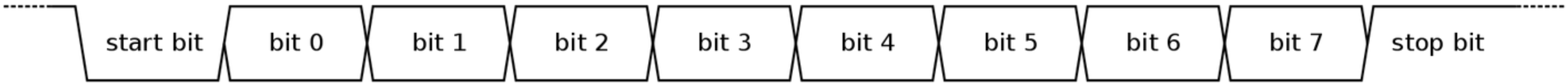


Read more: https://learn.sparkfun.com/tutorials/i2c/all

- The Serial Peripheral Interface (**SPI**) is a synchronous serial communication interface specification used for short distance communication, primarily in embedded systems (Motorola, 1980s). 4 wires, full duplex.



- A **universal asynchronous receiver-transmitter (UART**) is a computer hardware device for asynchronous serial communication in which the data format and transmission speeds are configurable. It sends data bits one by one, from the least significant to the most significant, framed by start and stop bits so that precise timing is handled by the communication channel. It was one of the earliest computer communication devices, used to attach teletypewriters for an operator console. It was also an early hardware system for the Internet. The electric signaling levels are handled by a driver circuit external to the UART. Two common signal levels are RS-232, a 12-volt system, and RS-485, a 5-volt system. .



Sensors / Communication in embedded devices / 1-Wire

- **1-Wire** is a device communications bus system designed by Dallas Semiconductor Corp. that provides low-speed (16.3kbps) data, signaling, and power over a single conductor (+ ground). Similar in concept to I²C, but with lower data rates and longer range.

1 Wire reset, write and read example with DS2432

Sensors / Calibration

- Sensors **always require calibration**, and in many cases frequent re-calibration
- Might be factory-based and/or performed by user
- Calibration needs to be documented
- Might depend on many variables!

3.7.2 Model 2

Model 2 introduces a linear dependency in the zero offsets on temperature and humidity:

$$Y = \frac{WE - WE_0(a_1T + b_1RH) - (AE - AE_0(a_2T + b_2RH))}{S_T} \qquad (3.21)$$

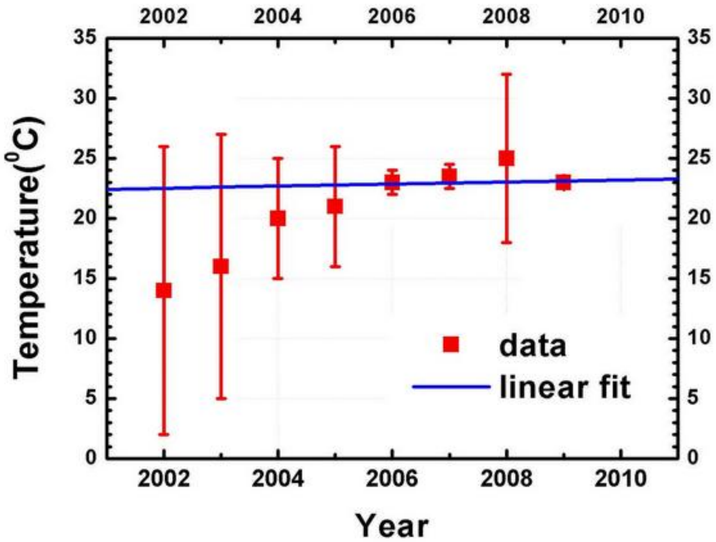
where

a_1, a_2, b_1 and b_2 are four parameters obtained from the calibration

T is temperature [K]

RH is the relative humidity [%]

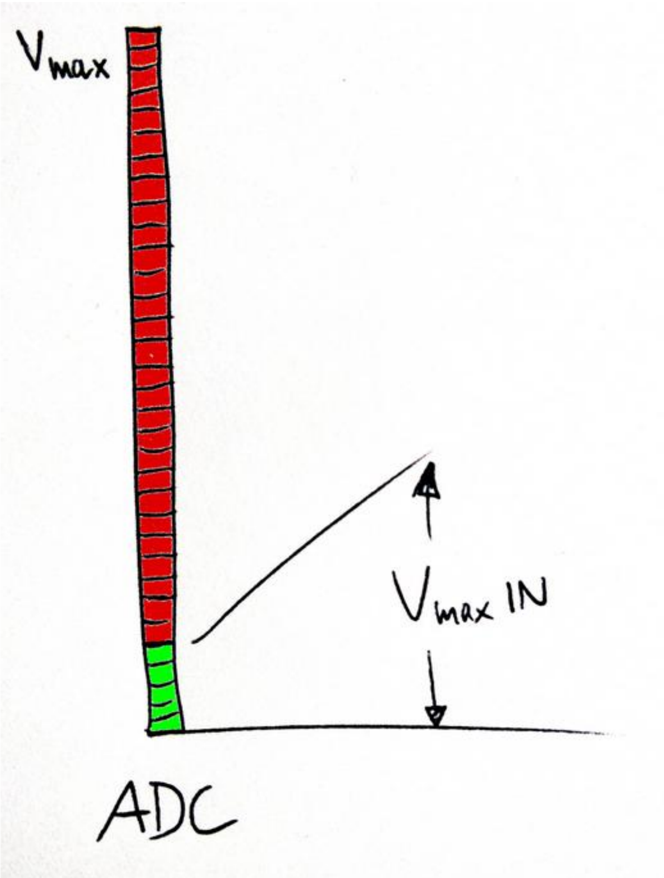
- Sensors **always require discussion of errors**
- In the physical world, **a measurement without discussion of error is useless**

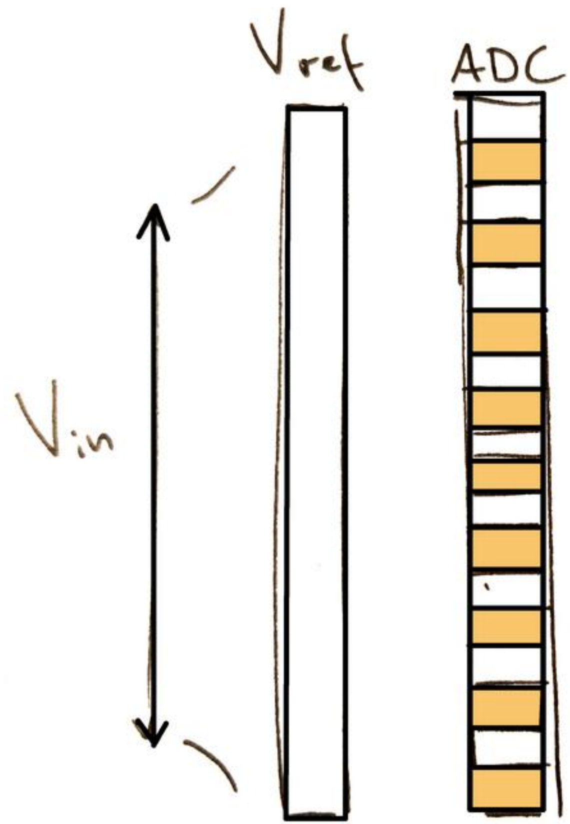


source: http://www.sciencesurvivalblog.com/

- Analog signals require
  Analog-to-Digital Conversion
- Rate, Resolution
- ADC and reference voltage need to match signal range, e.g.
  A 10-bit ADC with U_R=5V converting a 20 mV signal range will give you no more than 5 discrete values
  → Signal conditioning, Amplification

Sensors / ADC





sensor out ADC reference and resolution

Sensors / Power consumption

- Power consumption of sensors is a main concern in autonomous and mobile sensors
- Balance requirements regarding precision vs power
- Careful examination of power budgets, cycles, sleep phases
- Cost of networking – e.g. is it better to get time via network, GPS or via RTC?

- Find the datasheet (and know how to read it!)

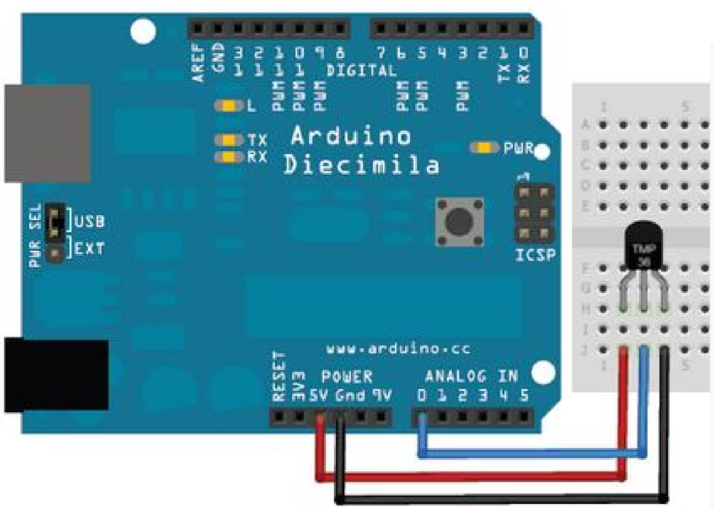
Datasheet Sensirion SCD30 Sensor Module

CO_2, humidity, and temperature sensor

- NDIR CO_2 sensor technology
- Integrated temperature and humidity sensor
- Best performance-to-price ratio
- Dual-channel detection for superior stability
- Small form factor: 35 mm x 23 mm x 7 mm
- Measurement range: 400 ppm – 10.000 ppm
- Accuracy: ±(30 ppm + 3%)
- Current consumption: 19 mA @ 1 meas. per 2 s.
- Fully calibrated and linearized
- Digital interface UART or I^2C

Sensors / Practical Advice

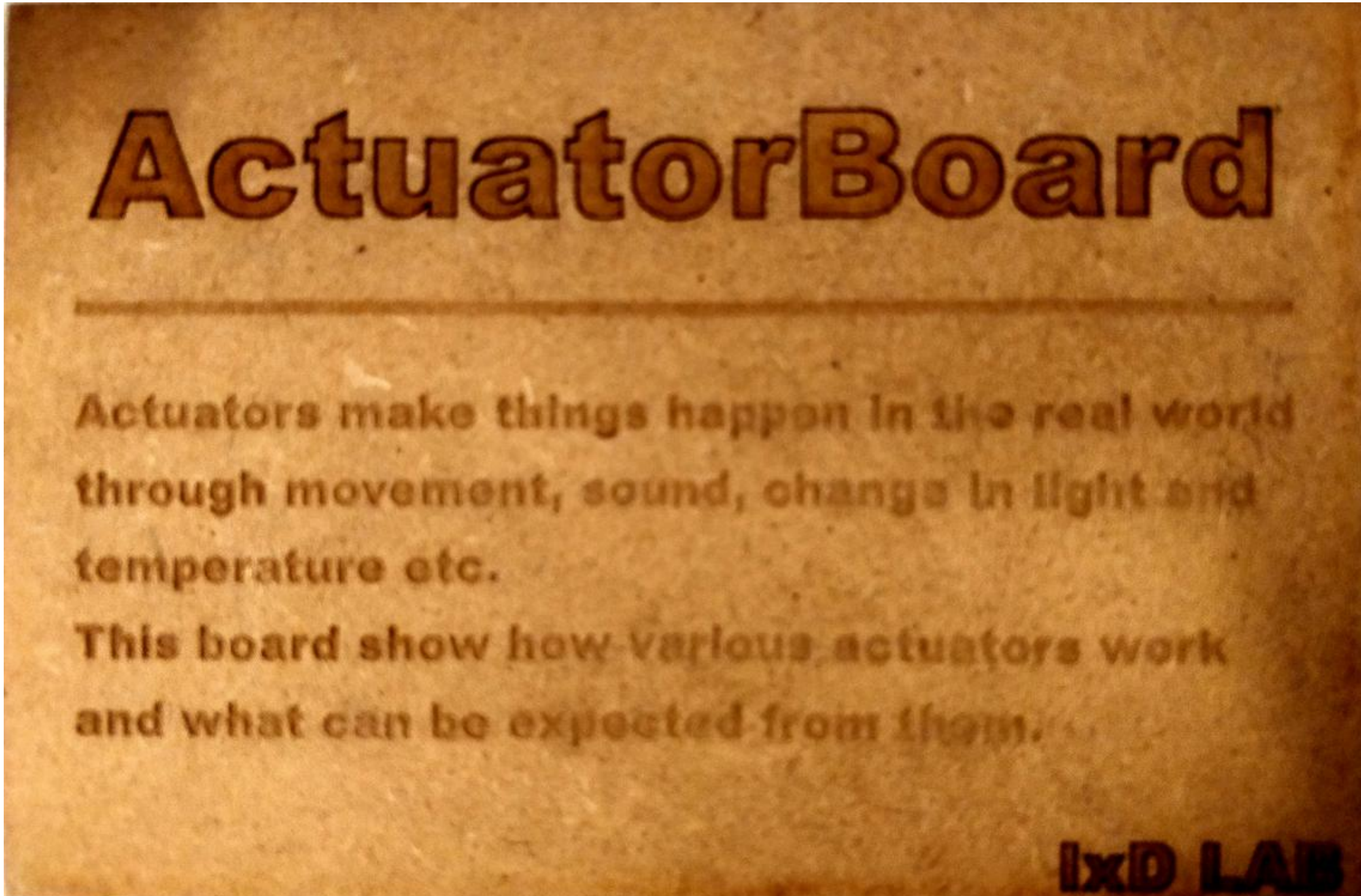
- Find “hookup” guides, applications notes
- Find existing libraries for your platform
  - decoders, calibration routines, etc




```python
import time
from machine import I2C, Pin
from scd30 import SCD30

i2cbus = I2C(1)
scd30 = SCD30(i2c, 0x61)
```

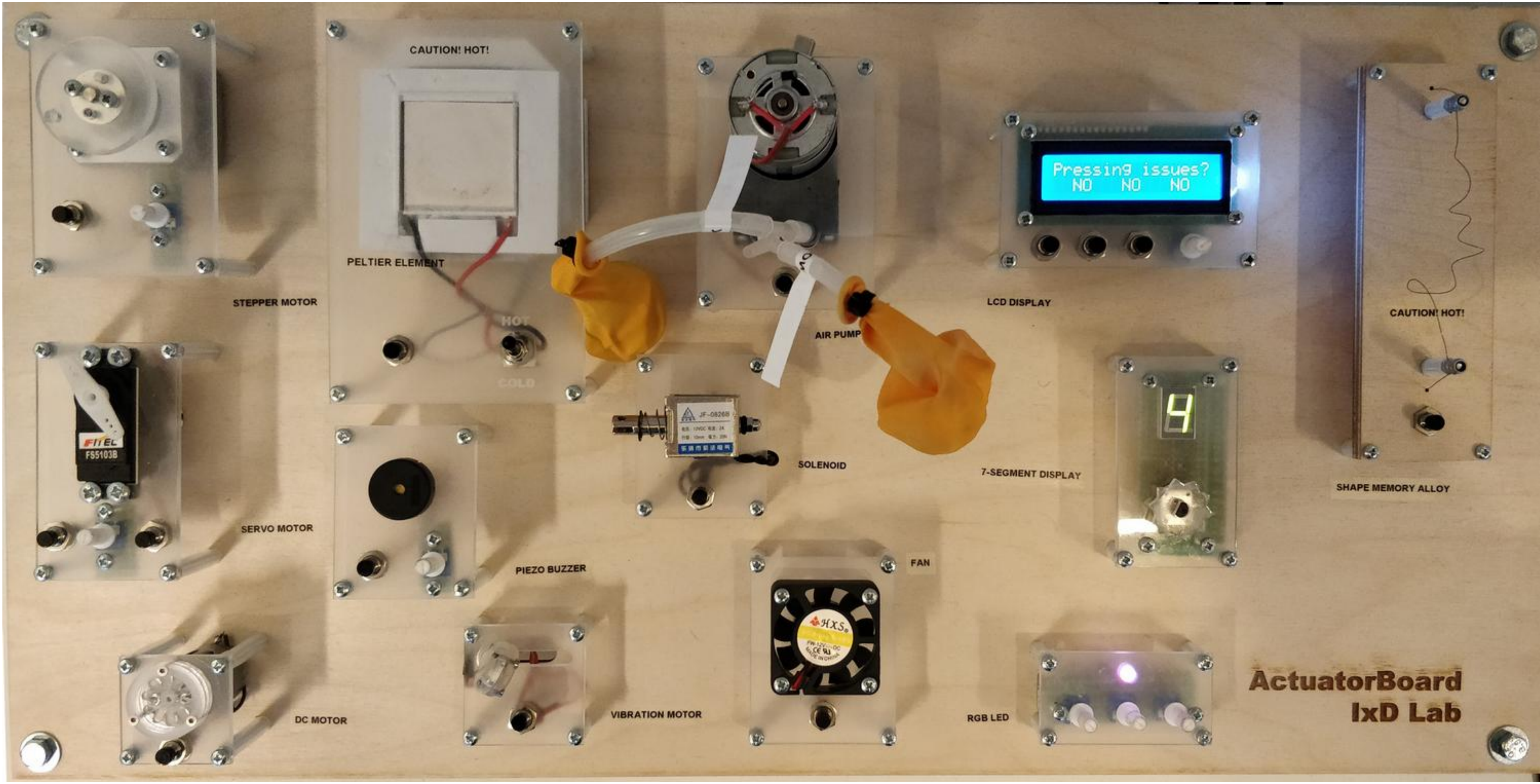
Actuators / Overview I



Actuators / Definition

- Simply speaking, anything that can “move” or change things in the physical world
- Relays, controllers, digital signals,..
- Often a “reverse” sensor
- Motors, solenoids, springs, piezos, valves, pumps, thermal devices, lights, displays (...), ..
- Anything that can be controlled by means of digital switches etc may be actuated

Actuators / Overview II



Take-Aways

- Types / classification of sensors
- Knowledge of examples, standard sensors
- Terminology
- ADC, intra-board communications
- Calibration, errors