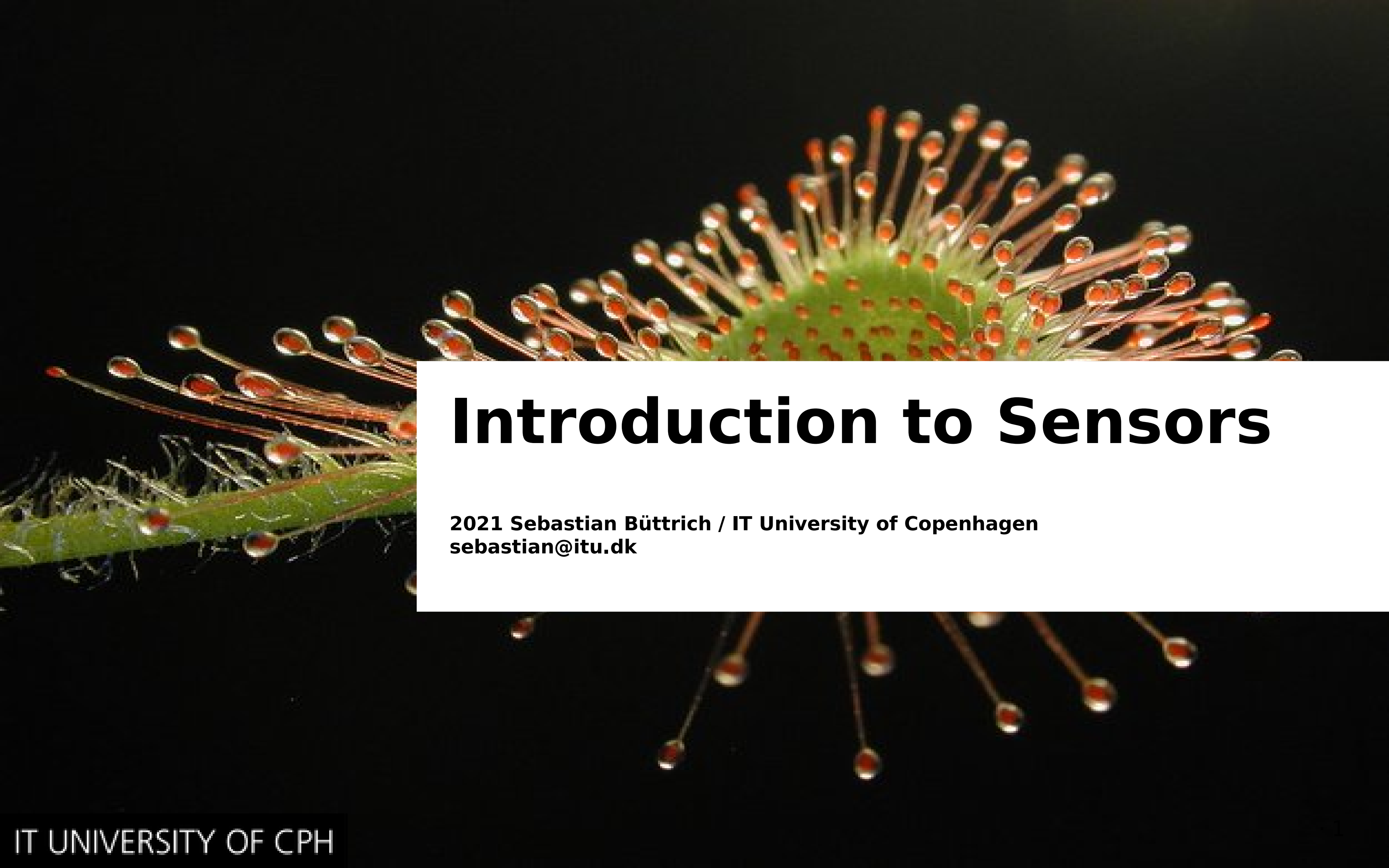


Introduction to Sensors

2021 Sebastian Büttrich / IT University of Copenhagen
sebastian@itu.dk

Motivation – why we talk about sensors

- **Data-centric ML**
  - The **importance of quality** data sets
- So far, we have mainly looked at human-generated data (voice, photography, social media ..)

  but there is a whole other class of data, which is generated through **scientific measurement**.
  - Its importance e.g. in Environmental Science, Earth Observation, Energy transition, Climate Change, Logistics, Buildings, Urban Planning, Agriculture, Aquaculture, ... to name a few.

Sensors / Definition I

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

  Does a plant have sensors? (Shown on title slide: Drosera rotundifolia)

Sensors / Definition II

Note terms that might be problematic:

real world,

physical world

“to translate into data” -

data is not inherently there – it is a human construct,

created under technical, social, cultural conditions

Sensors / Definition IV

Clarification:

we will distinguish between the

the sensor -

and the

full **sensor node**, which includes a **sensor** and an

embedded system, a board, a device

(with processor/MCU, memory, storage, I/O,

on-board communications, networks, etc)

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.*

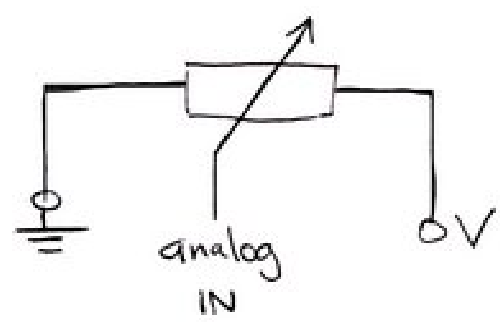
source: purpleair, plantower

Sensors / Principle

- A sensor typically transforms a “real world” property into a

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

  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. light sensors, watermeters
- **Powered / Non-powered**

  – do we need to power the sensor in order for it to work?
- **Physical / Chemical / Biological**
- Field readiness, autonomy
- Cost: low-cost vs. (expensive) lab grade sensors

Sensors / Overview I

Push Button

Displacement

Pressure, weight, bend, vibration

Distance

Proximity

Position

Motion

Acceleration

Orientation (Magnetic, Gyroscope)

Hall/Reed

Voltage / Current

RF Intensity

Light

Sound

Pressure, barometer

Temperature Humidity, soil moisture

Wind (speed, direction)

Radioactivity

Water

- → Level, flow, chemistry

Air

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

Biological / Health

- → heart, pulse, breath, eye, ...

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 Celsius is equal in magnitude to unit kelvin.

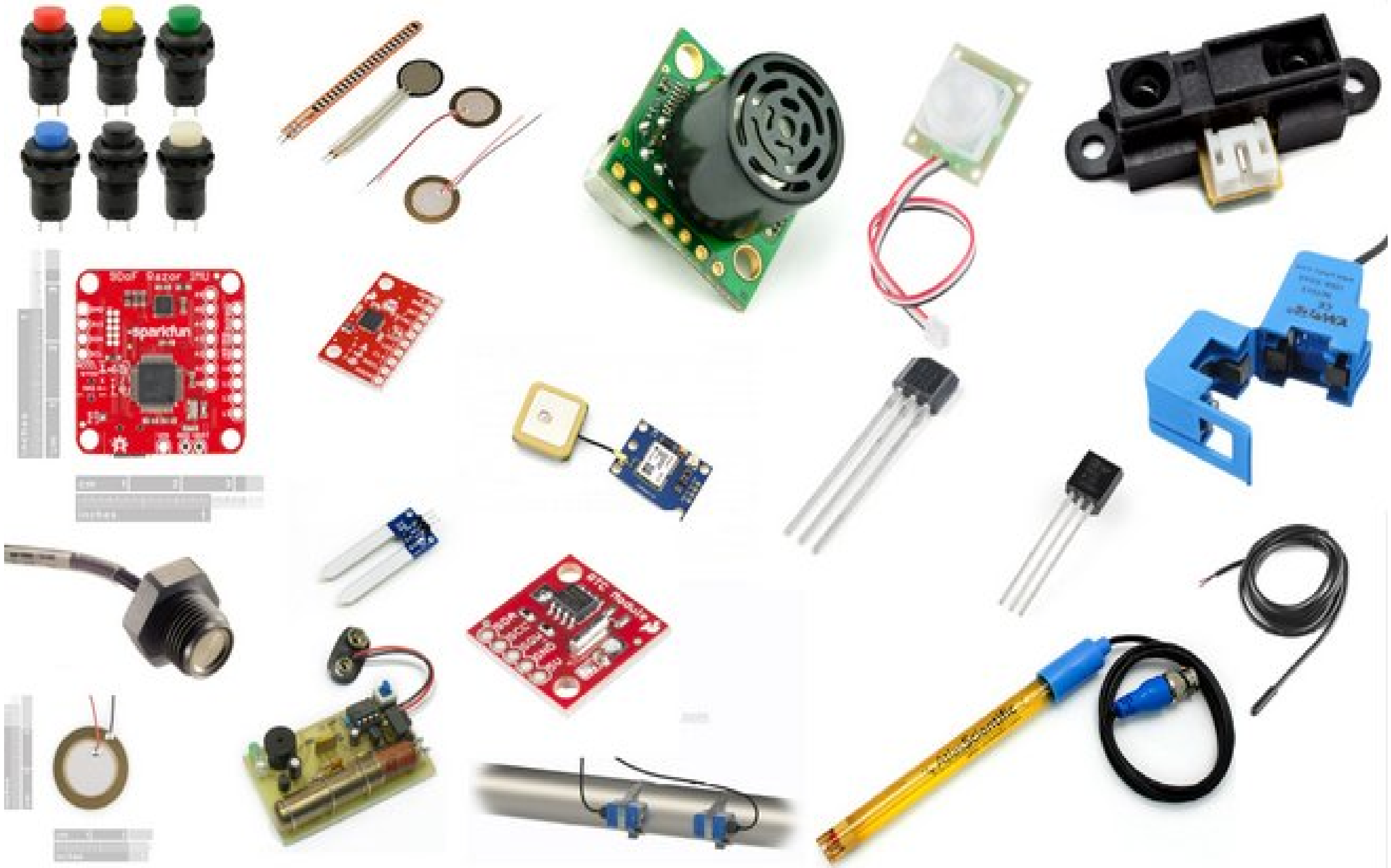
SI Prefixes

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

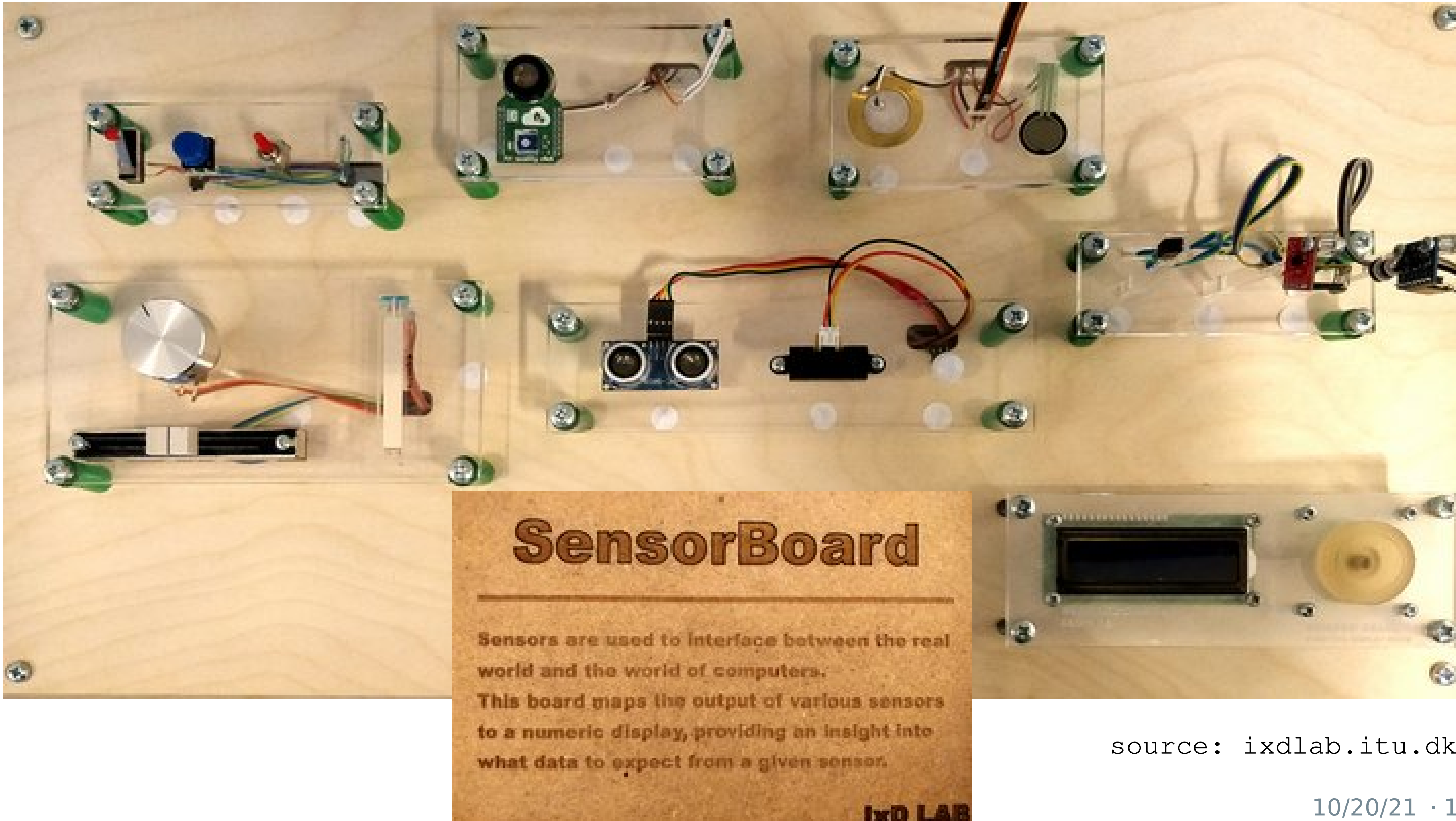
- Adapted from NIST Special Publication 811
- SI rules and style conventions recommend using spaces rather than commas to separate groups of three digits.

FLINN SCIENTIFIC, INC
"Your Safer Source for Science Supplies"

What sensors look like



Sensors / Overview II



source: ixdlab.itu.dk

Sensors / Simple examples

Sensors / Buttons

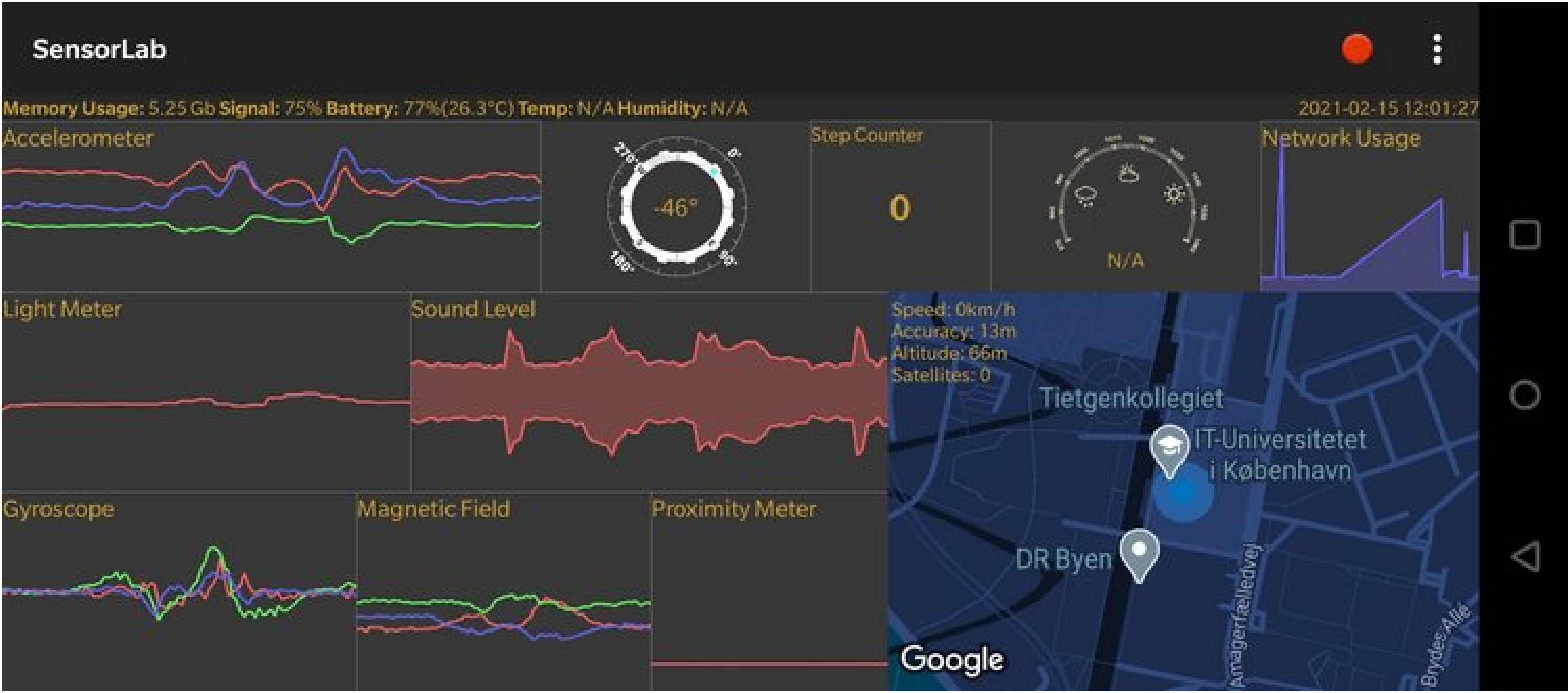
Physical principle

Mechanical, closing circuit

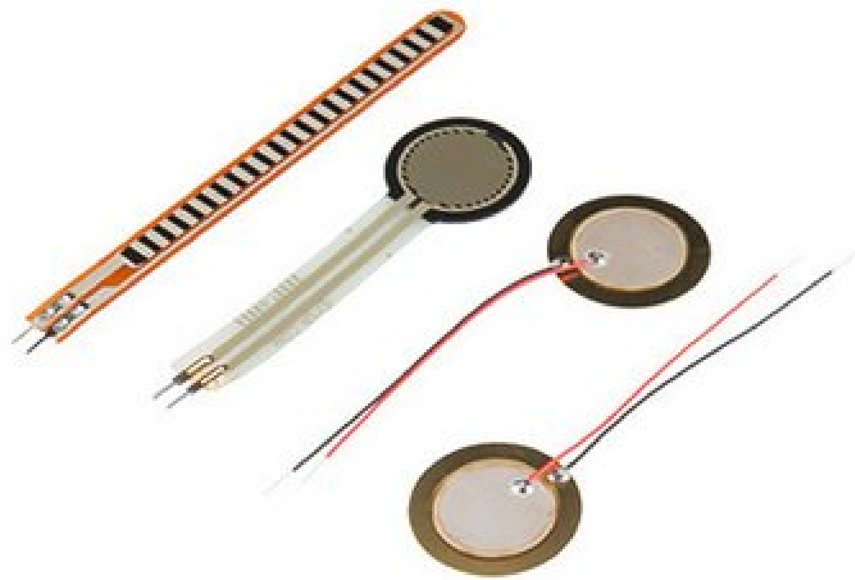
Applications

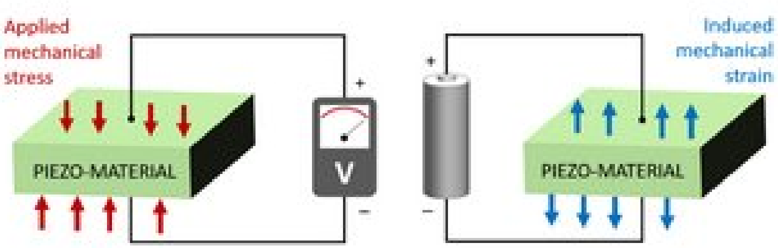
human interaction

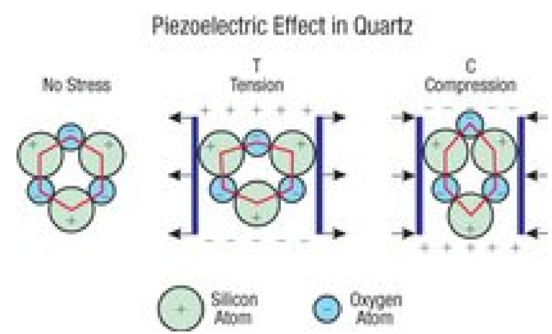
Sensors / Mobile Phone



Sensors / Piezo







Physical principle

Piezo effect

Applications

Force

Motion

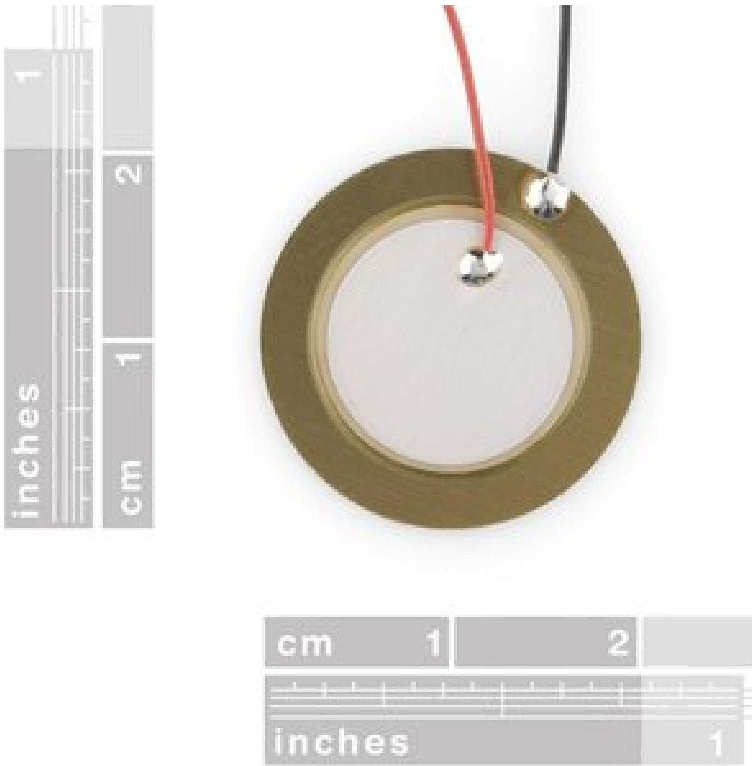
Bending

Moving

Vibration

Audio

source: sparkfun, sintef.com



source: sparkfun

Physical principle

Piezo, Mems, other

Applications

Sound :)

Sensors / Distance / Ultrasonic

source: sparkfun

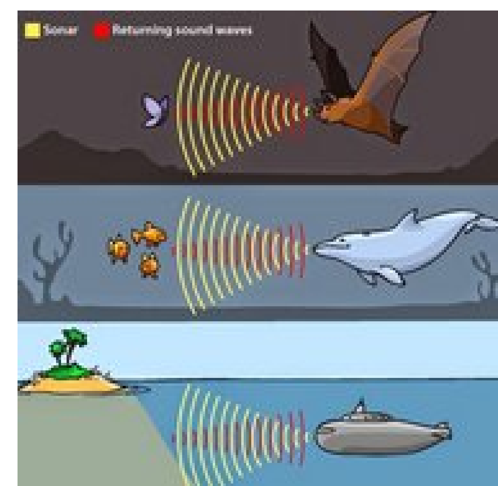
Physical principle

Speed of sound

Applications

Distances

e.g. liquid levels



Sensors / Distance / Infrared

Physical principle

Triangulation

Time of Flight (TOF)

Interferometry

Applications

Distances

source: sparkfun

Sensors / Proximity / Infrared

source: sparkfun

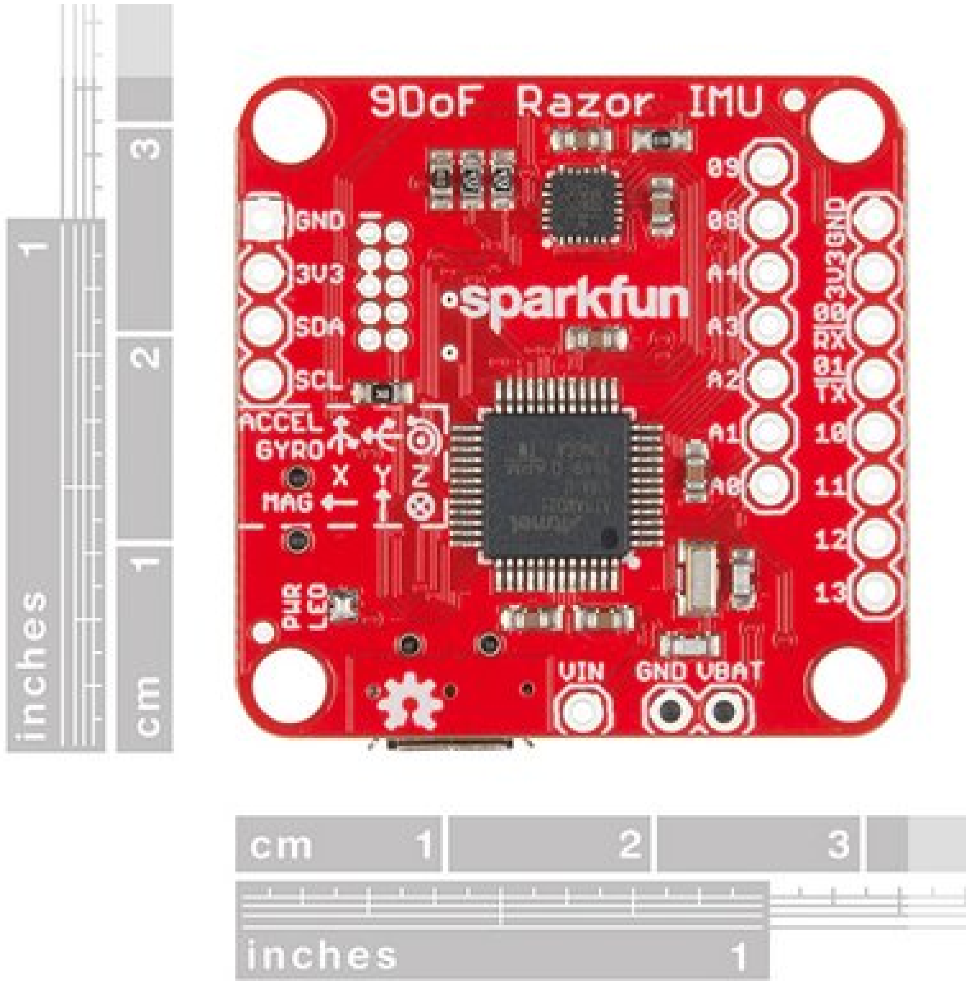
Physical principle

Reflection

Applications

Proximity

Sensors / Acceleration, Orientation



Physical principle

MEMS

MicroElectroMechanical

Applications

Acceleration

Motion

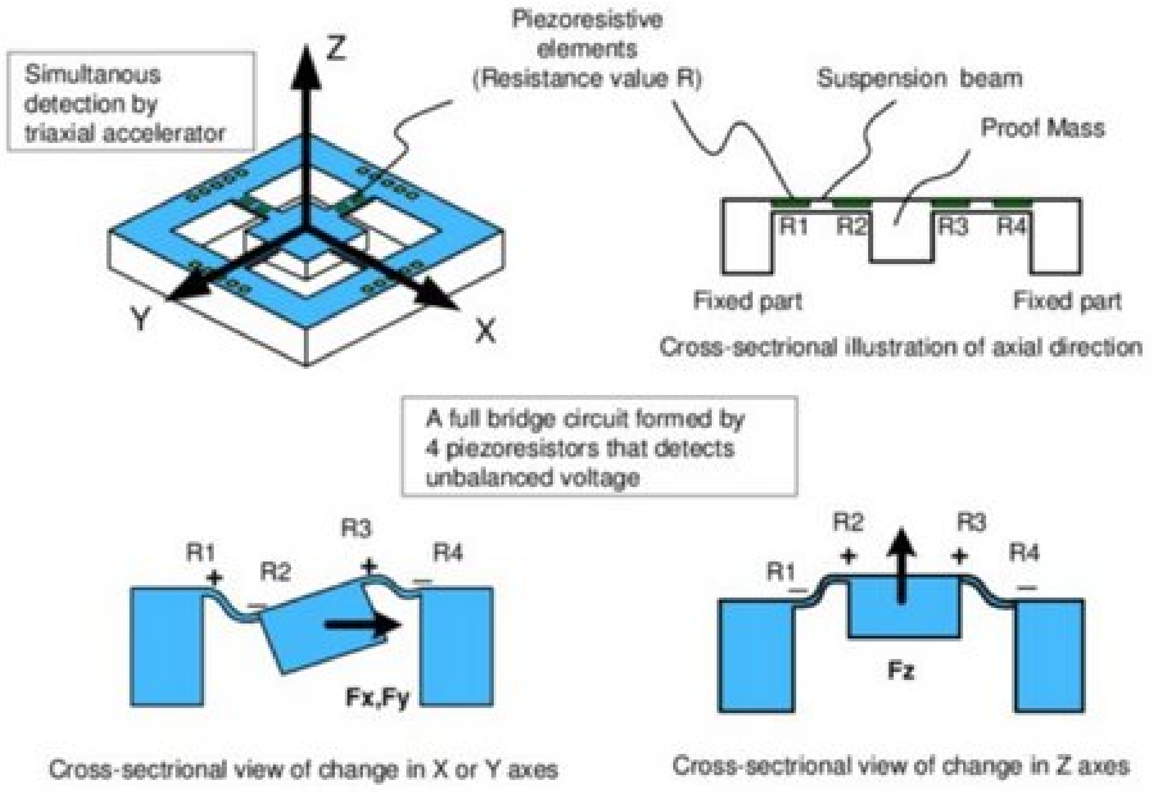
Orientation

Gyroscope

(angular motion)

Compass

Sensors / Acceleration



Physical principle

MEMS

MicroElectroMechanical

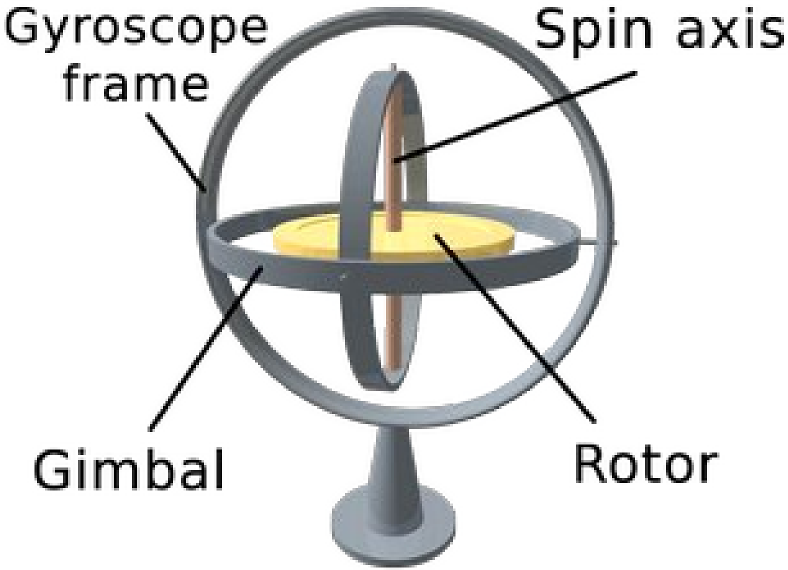
Sensors

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

Sensors

Applications

Motion

Orientation

Gyroscope

(angular motion)

source: sparkfun, wikipedia, MIT Physics

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

source: sparkfun

Physical principle

thermoelectric

Applications

Ambient temperature

Sensors / Liquid levels

source: sparkfun

Physical principle

resistive

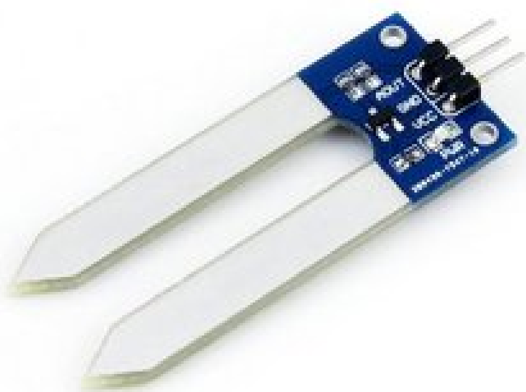
barometric

Applications

Liquid levels,

technical,

environmental



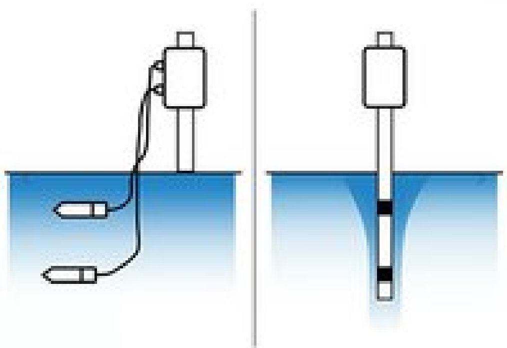
Physical principle

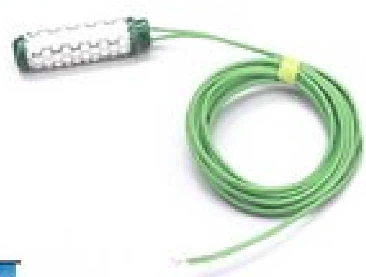
Resistance

Capacity

TDT (time domain transmission)

a.o.





sources: sparkfun, soilsense.io, gropoint.com, davisinstruments, catnip electronics

Physical principle

Photoresistance

Applications

Light :)

Sensors / Radioactivity

source: safecast

Physical principle

Ionization

Geiger counter

Applications

Radioactivity

Gamma rays

→ safecast.net

Physical principle

Turbine

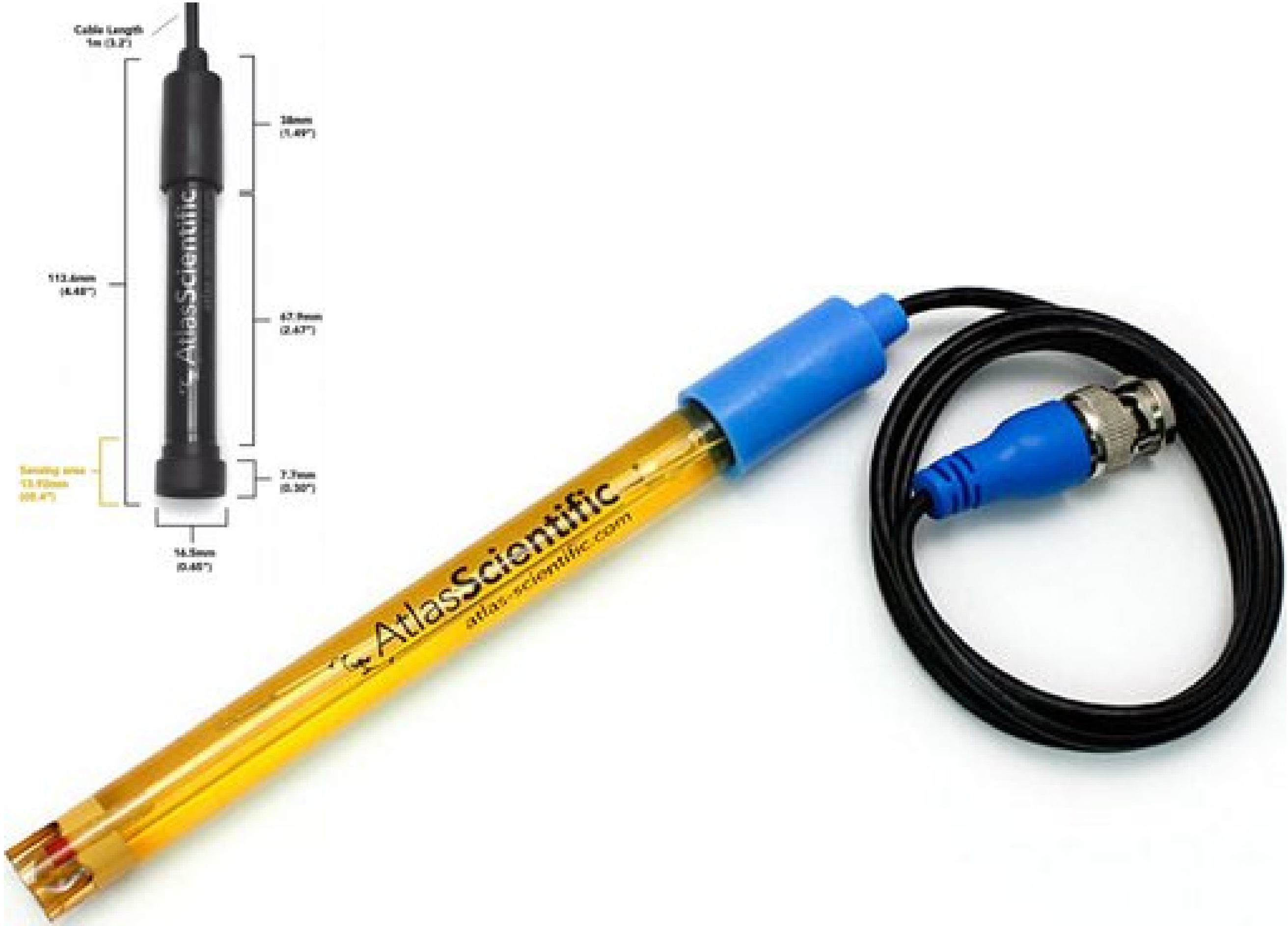
Ultrasonic

Applications

Metering

Flows

Sensors / Water II / Chemistry



Physical principle

various

Applications

PH

Dissolved Oxygen

Chemicals

Nutrients

+ a lot more

source: atlas scientific

Sensors / Water II / Chemistry

Sensors / Air I

Air quality/pollution sensors are an especially complex area

Indoor / outdoor

→ different gases/pollution types of interest

Indoor: CO_2, Volatile Organic Compounds (VOCs), Particulate Matter (PM)

Outdoor: Pollutors widely included in Air Quality Index:

NO_2, SO_2, O_3, PM2.5, PM10

Challenge: low-cost sensors vs. “lab grade sensors”

Citizen science projects: e.g. sensor.community, safecast.org

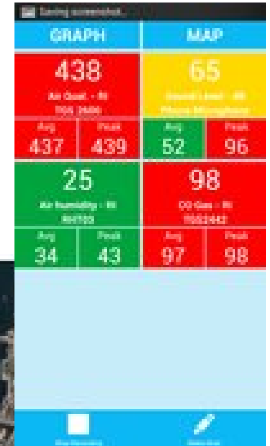
Rapid progress in new sensor types,

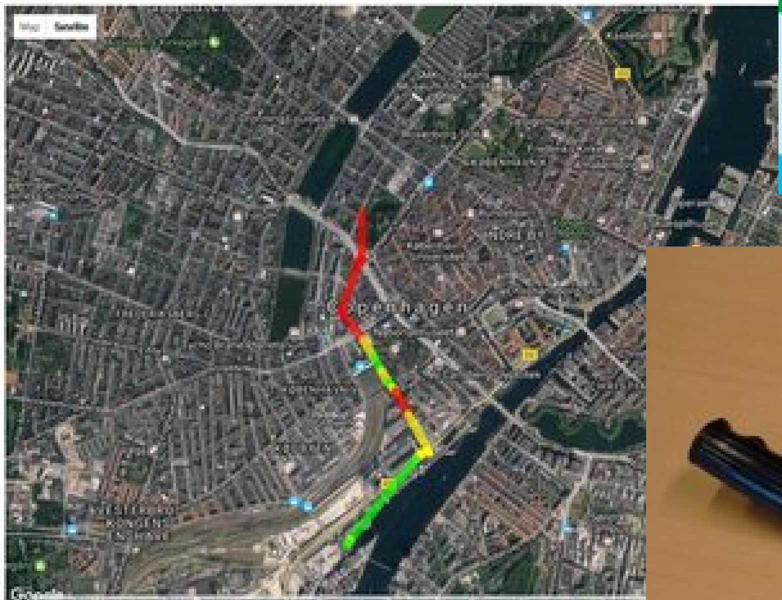
miniature sensors, MEMS, solid state sensors, mobile sensors

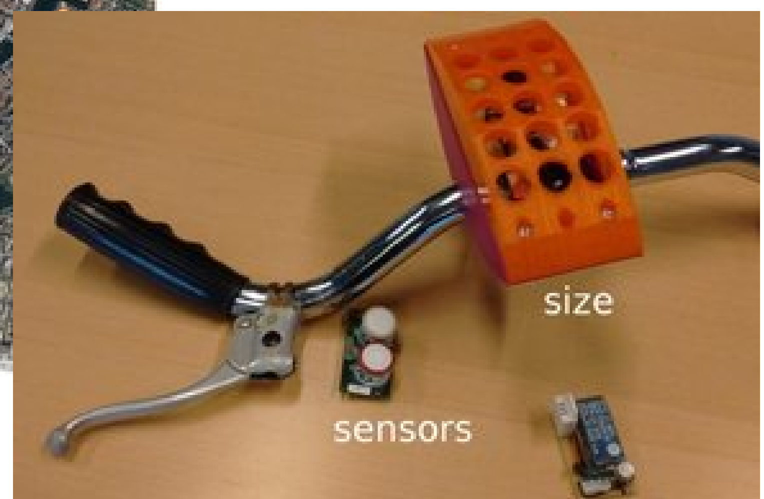
Sensors / Air II

Sensors / “DIY” low cost projects

PIT LAB
bAIR
the air bike







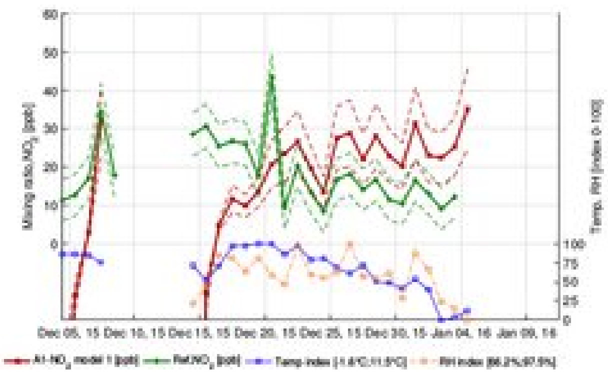
Sensors / low-cost NO_2

AARHUS UNIVERSITY

DTU Technical University of Denmark

PIT LAB PERVASIVE INTERACTION TECHNOLOGY LABORATORY

IT UNIVERSITY OF COPENHAGEN



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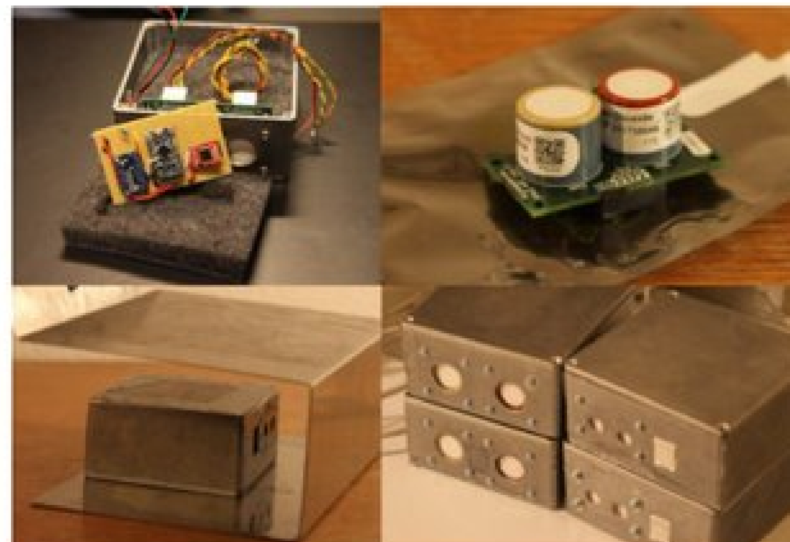
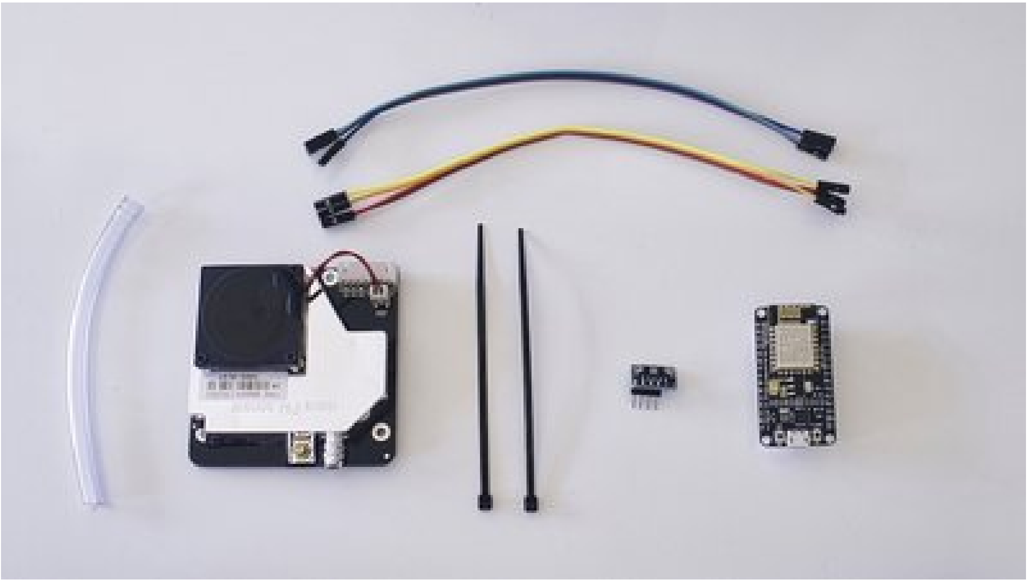
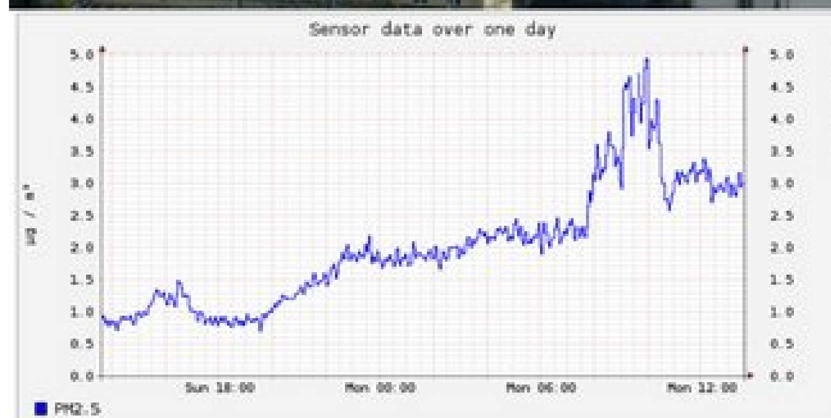


Assessing the applicability of low-cost electrochemical gas sensors for urban air quality monitoring

Sensors / citizen science / sensor.community



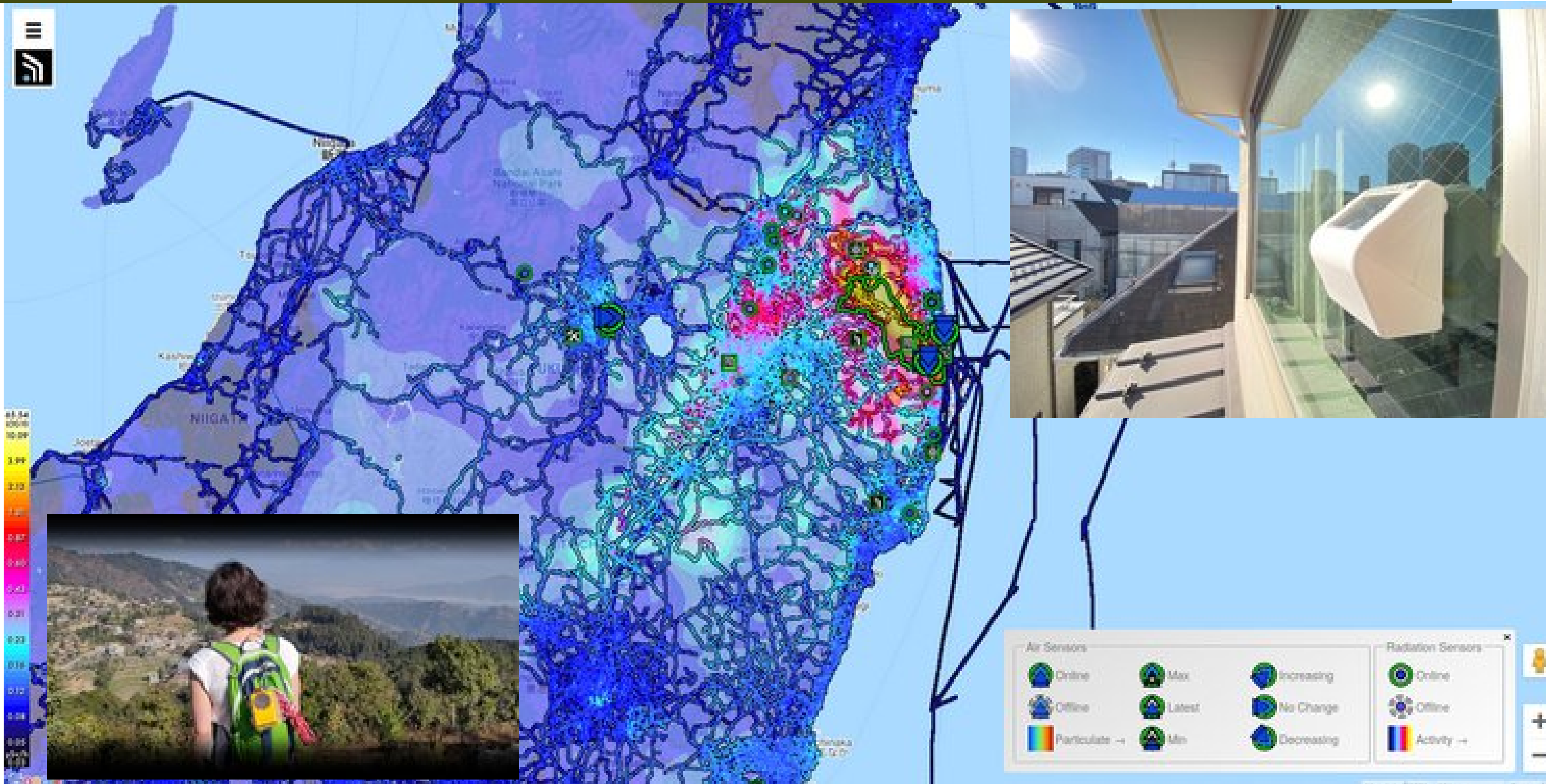


Sensor.Community is a contributors driven global sensor network that creates Open Environmental Data.

"AirRohr" = the Air tube
sensor: SDS011
board: NodeMCU

source: sensor.community

Sensors / citizen science / safecast



source: safecast.org

Sensors / citizen science / #CO2ampel

check on Twitter!

**15 March, 2021
Re-opening of schools in Germany**

IT UNIVERSITY OF COPENHAGEN

Sensors / Cameras, Images, Video

Among all the sensors we named, some were notably **missing**:

Cameras

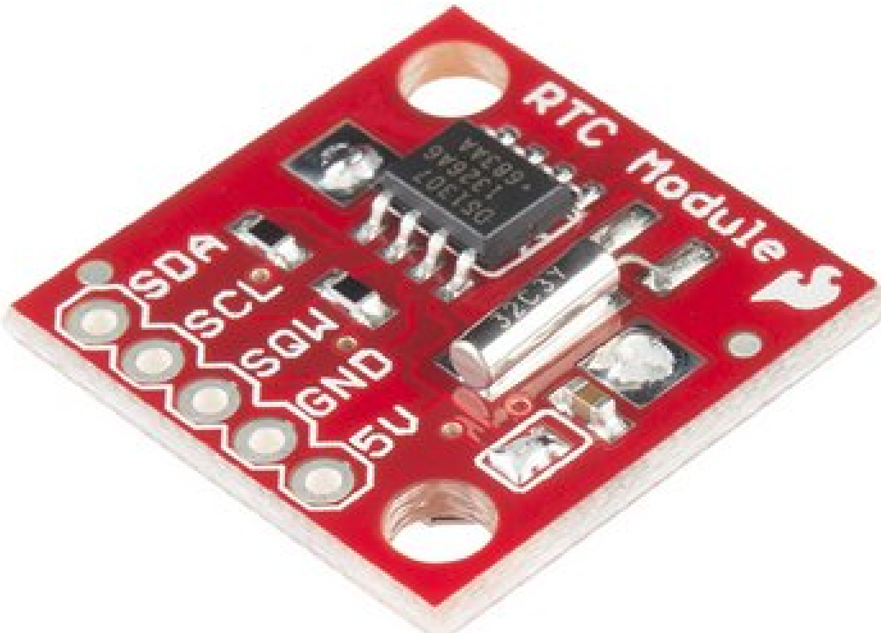
perhaps the richest and most popular source for embedded ML

(but are they sensors?

Camera vs Image Sensor?)

Sensors / Time

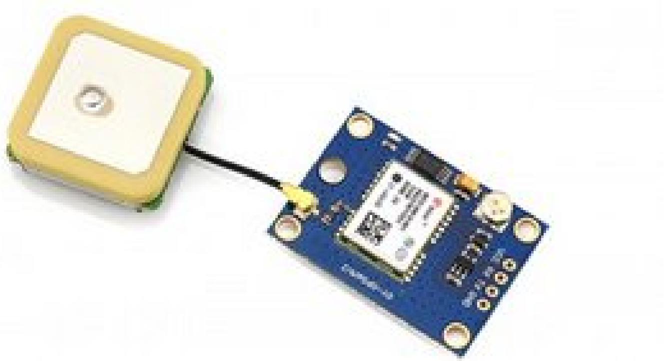
Important in all we do: **Time**

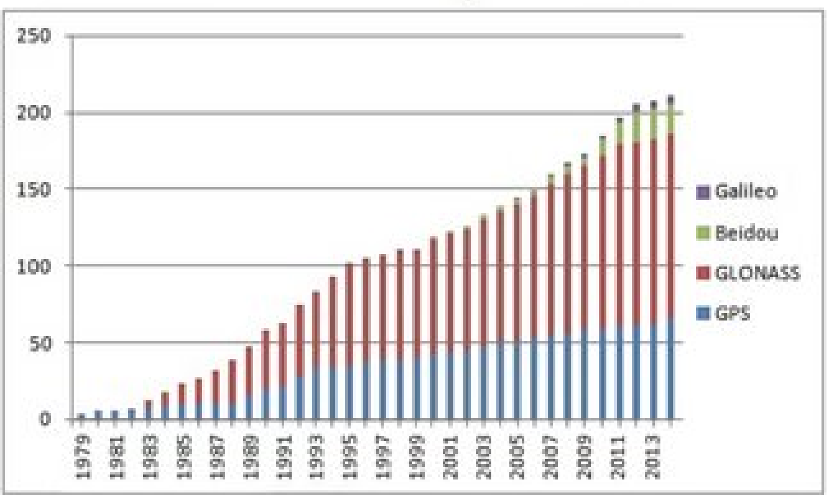


for example a **Real Time Clock (RTC)**

(but are they sensors? for discussion ...)

Equally important: Location





Physical principle

Data from GNSS Sats

GPS

Glonass

BeiDou

(Is this a sensor?)

Applications

Position

(but are they sensors?)

source: sparkfun, taoglas, wikipedia

Sensors / Trends, Future

Driven by - among other trends - ,

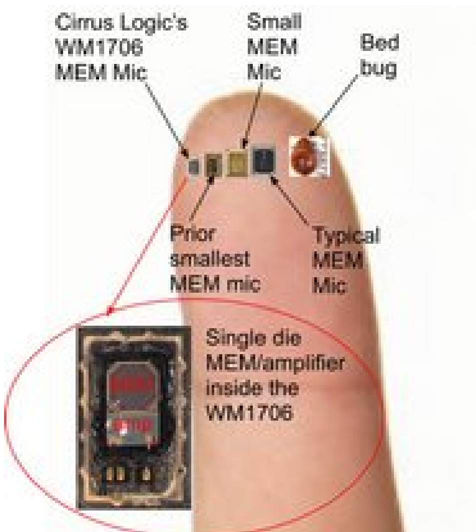
mobile devices, embedded devices,

IoT, data-centric ML:

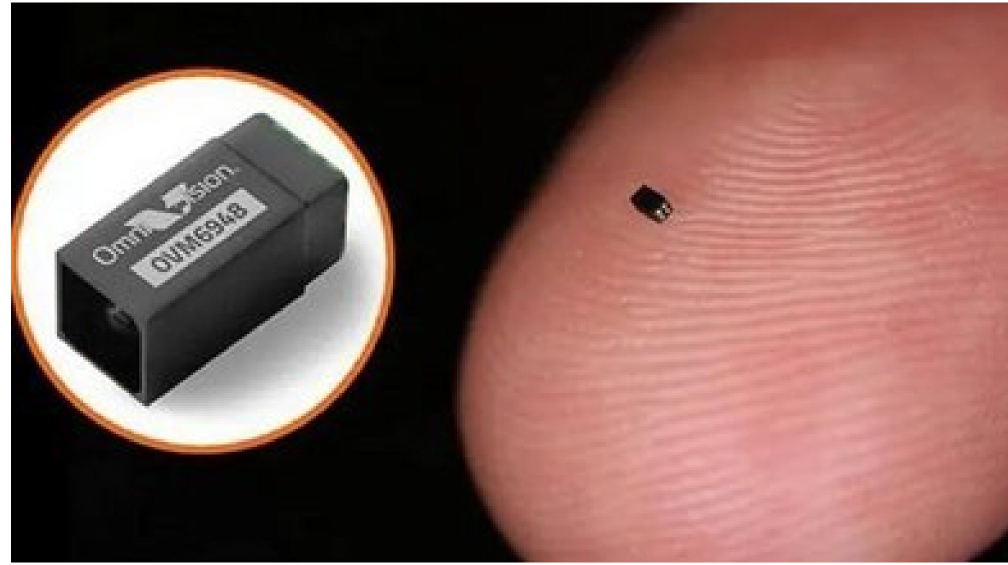
MEMS

(micro electro mechanical systems),

nanosensors



age pixels < 1 µm



OmniVision OV6948 *image sensor*

40k (200x200) pixels

0.575 x 0.575 x 0.232mm

Arduino TinyML kit has OV7675 Camera

CirrusLogic WM1706 microphone

source: abiResearch/cirrusLogic,OmniVision

Sensors / Trends, Future

Remote sensing from satellite:

Optical & whole EM spectrum

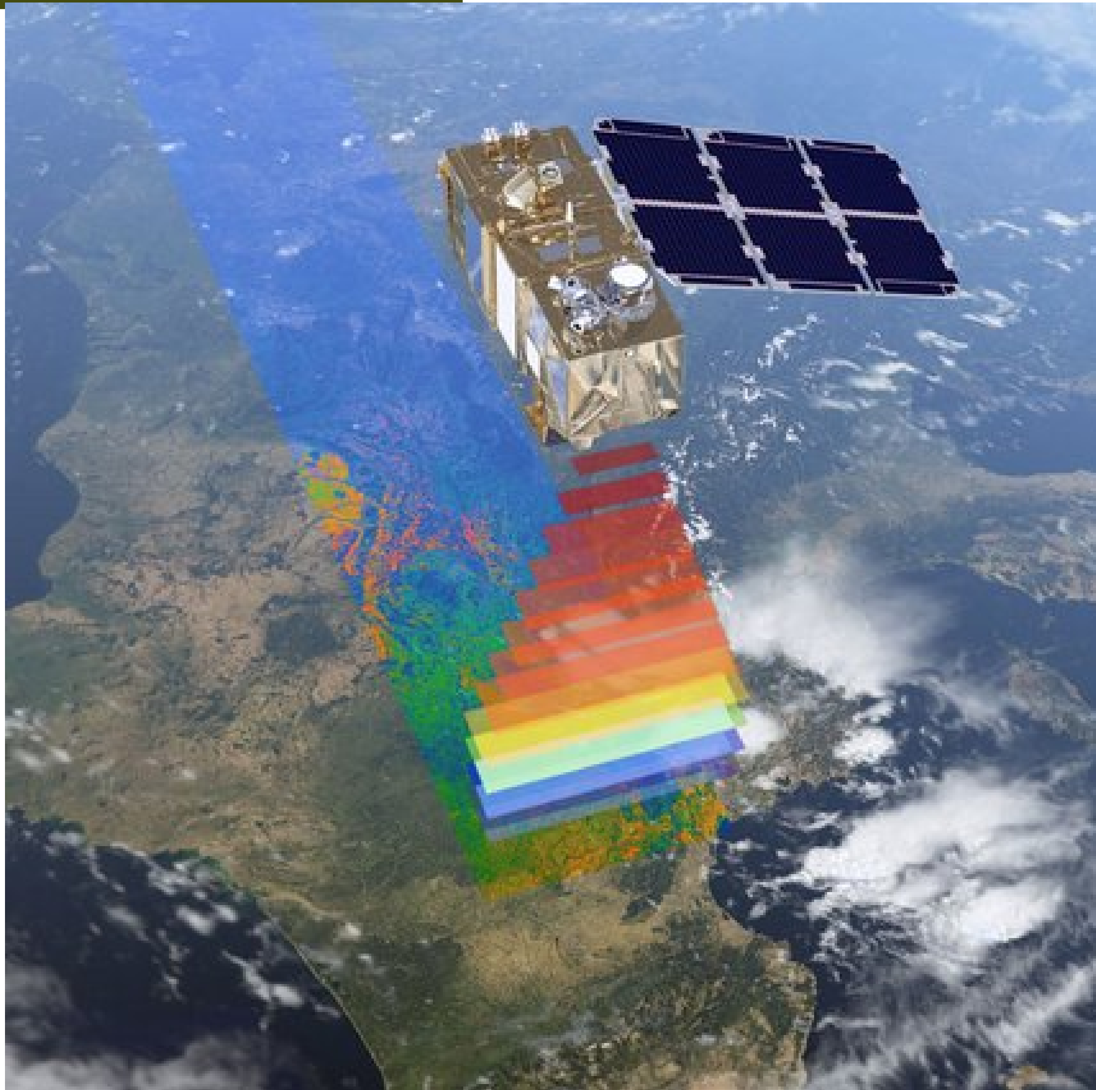
e.g. for

Air quality,

surface,

agriculture,

oceans, ...



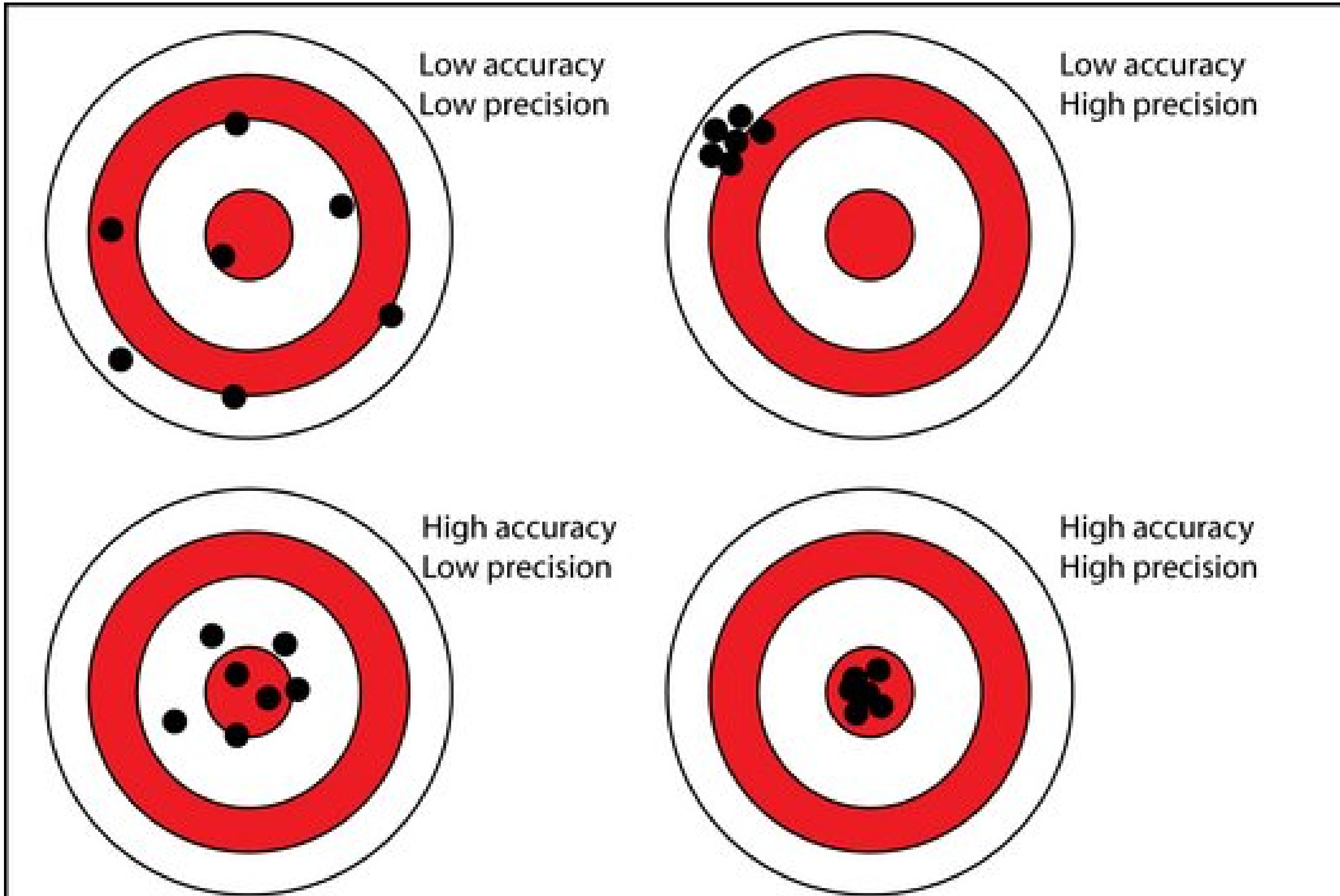
source: ESA / Sentinel

Sensors / Terminology I

- **Sensitivity** – minimum change needed to change output
- **Range** – minimal and maximal values
- **Precision** – spread - ability to give **same** value under same conditions
- **Accuracy** – bias, ability to give **true** value under same conditions
- **Resolution** – minimal difference that can be told apart
- Offset – Bias
- Linearity – over whole range
- Hysteresis – dependence on former history
- Drift – change in offset or behaviour over time
- Response Time – how fast
- Rate – how often

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

Sensors / Terminology III / Accuracy & Precision



source: http://www.antarcticglaciers.org/glacial-geology/dating-glacial-sediments-2/precision-and-accuracy-glacial-geology/

Sensors / Terminology IIIa / Accuracy & Precision

- 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:

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

where

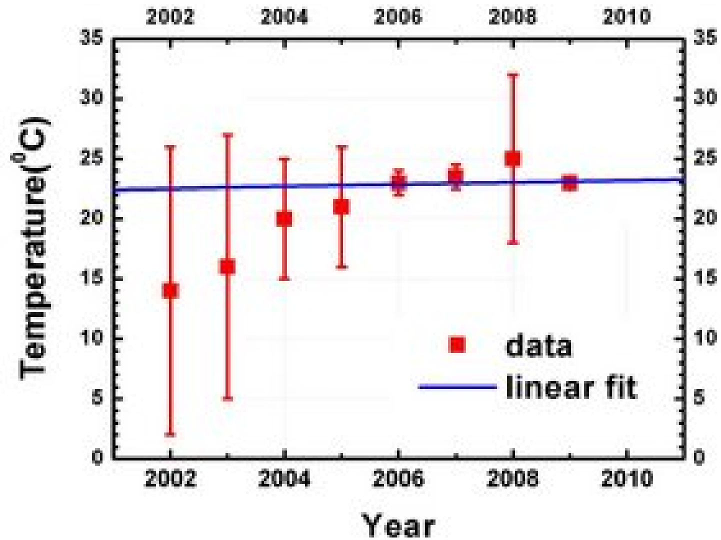
a_1, a_2, b_1 and b_2 are four parameters obtained from the calibration

T is temperature [K]

RH is the relative humidity [%]

Sensors / Errors

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

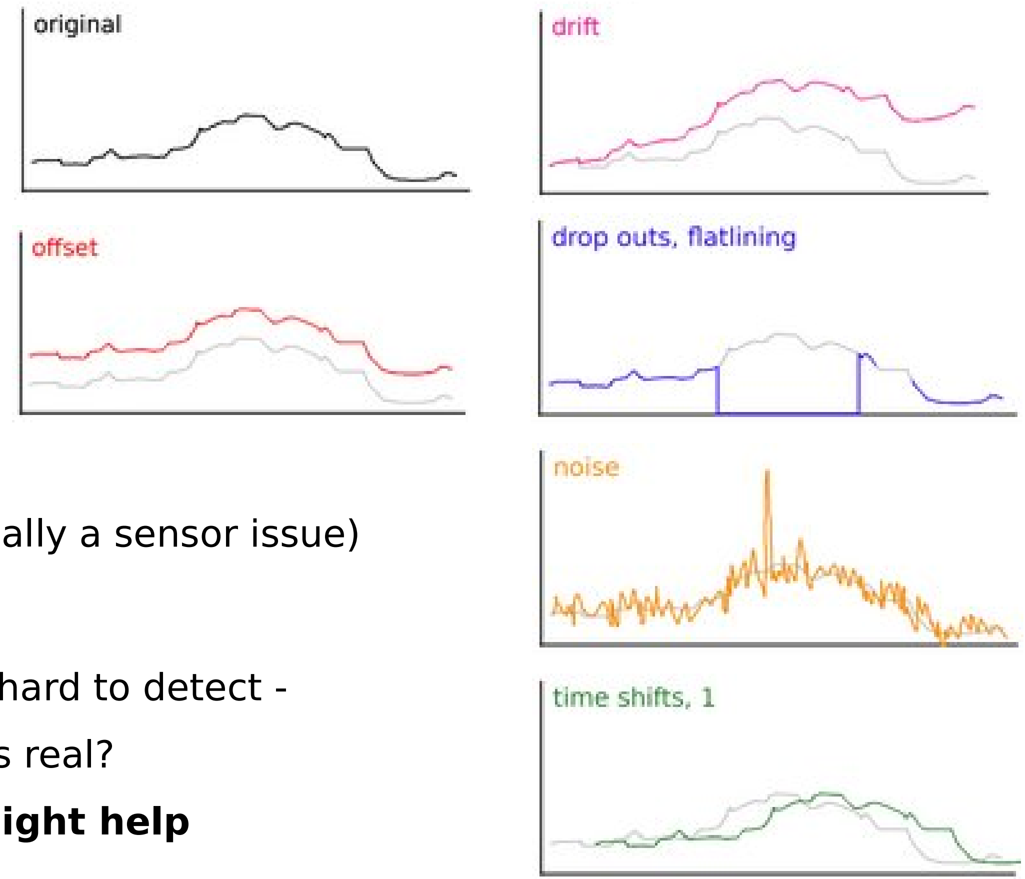


source: http://www.sciencesurvivalblog.com/

Sensors fail in may ways ...

- drop out
- flat-lining
- drift
- offset/bias
- noise
- time shift

(loss of time axis – not really a sensor issue)



sensor failures are often hard to detect -

what is an outlier, what is real?

redundant sensors might help

Sensors / Communication in embedded devices I

- **Short distance (intra board)**
- **Moderate data rates (kBps)**

Three most popular standards:

- **I^2C** (Inter-Integrated Circuit)
- **SPI** (Serial Peripheral Interface)
- **1-Wire**

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.

- 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

Analog signals require **Analog-to-Digital Conversion**

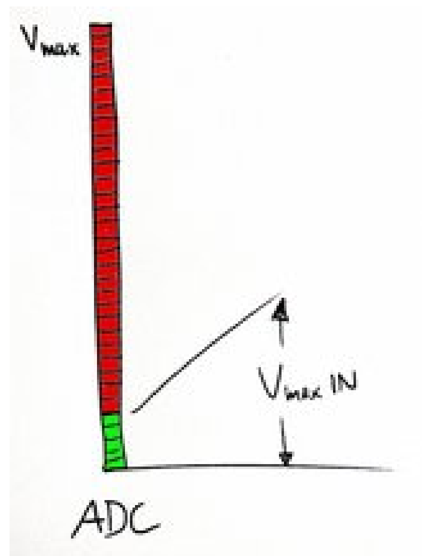
(Rate [kHz], Resolution [bits])

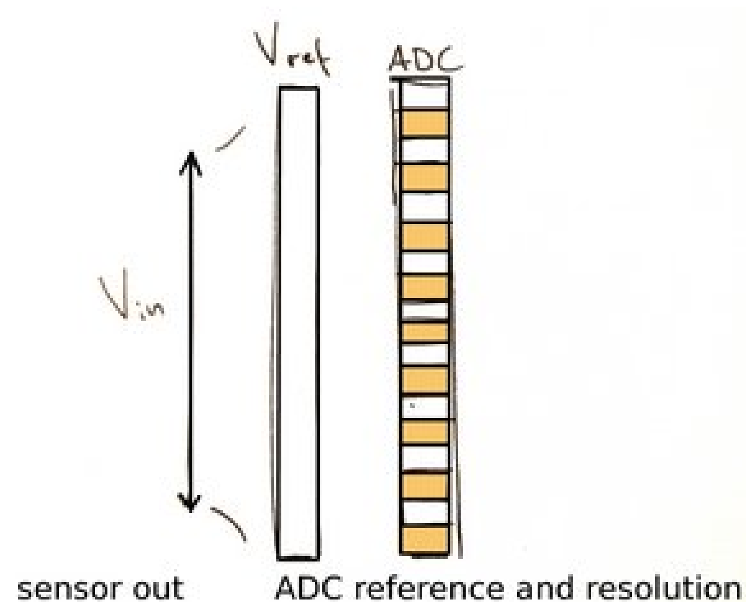
ADC and reference voltage need to match signal range,

else resolution remains unused -

→ Signal conditioning,

Amplification





Sensors / Practical Advice

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

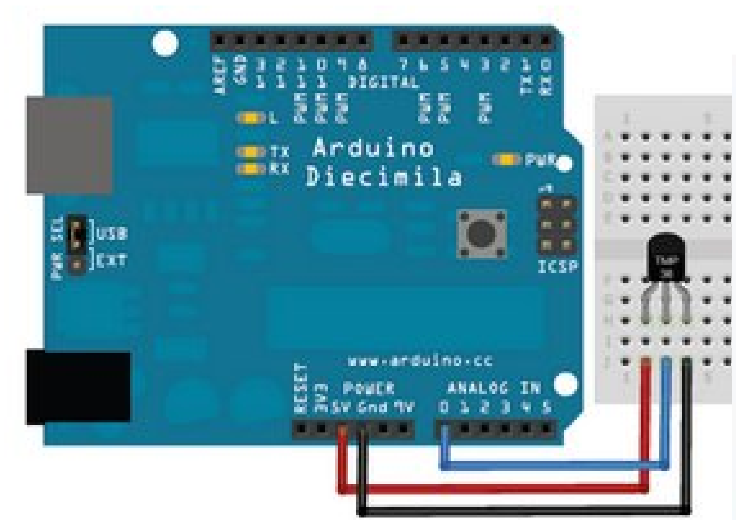
Datasheet Sensirion SCD30 Sensor Module

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




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

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

Sensors / Use Case Water Metering

Sensors / Use Case Utility Meters Retrofiting

technologies:
Wemos/Lolin boards,
LoRa or Wi-Fi

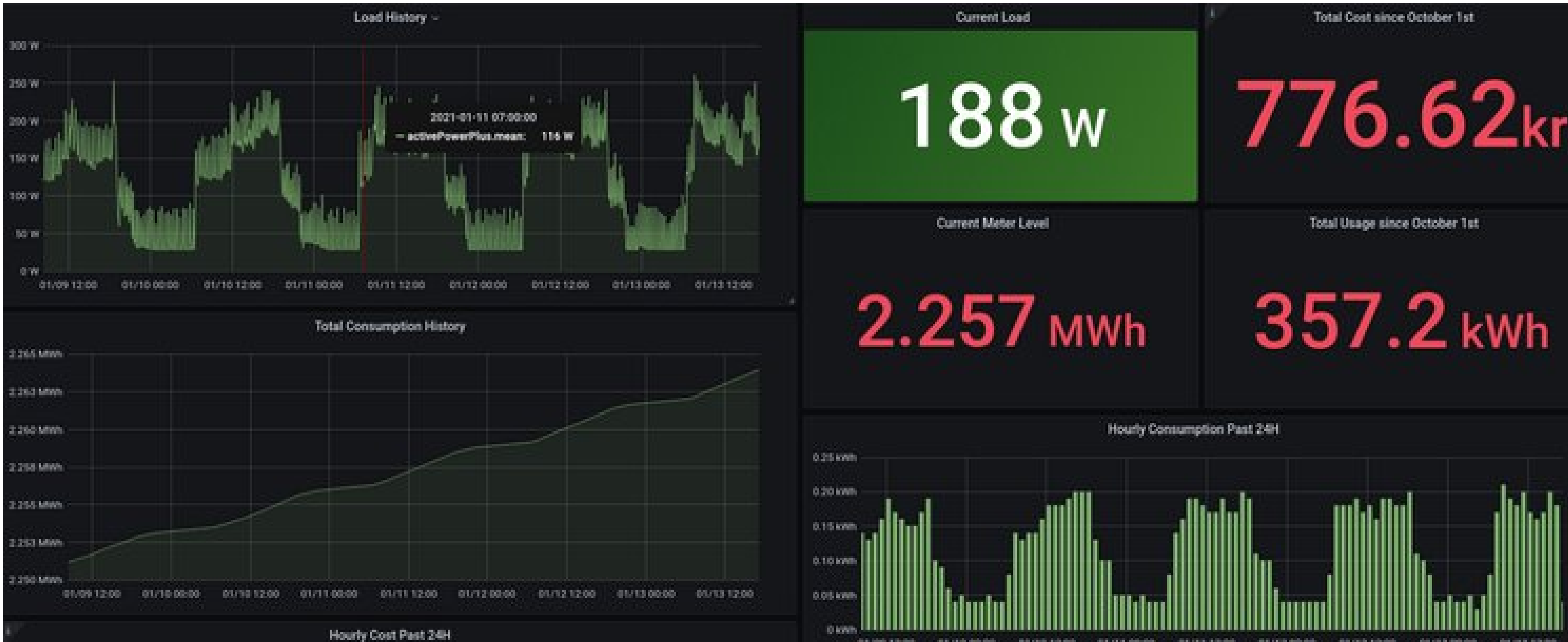
benefit:
fine-grained
consumption data

Note: this is legal (in Denmark),
but **not neccessarily recommended** for copying! :)

Sensors / Use Case Utility Meters Retrofiting

ITU

Residential Electricity



https://www.wemos.cc/en/latest/d1/d1_mini.html

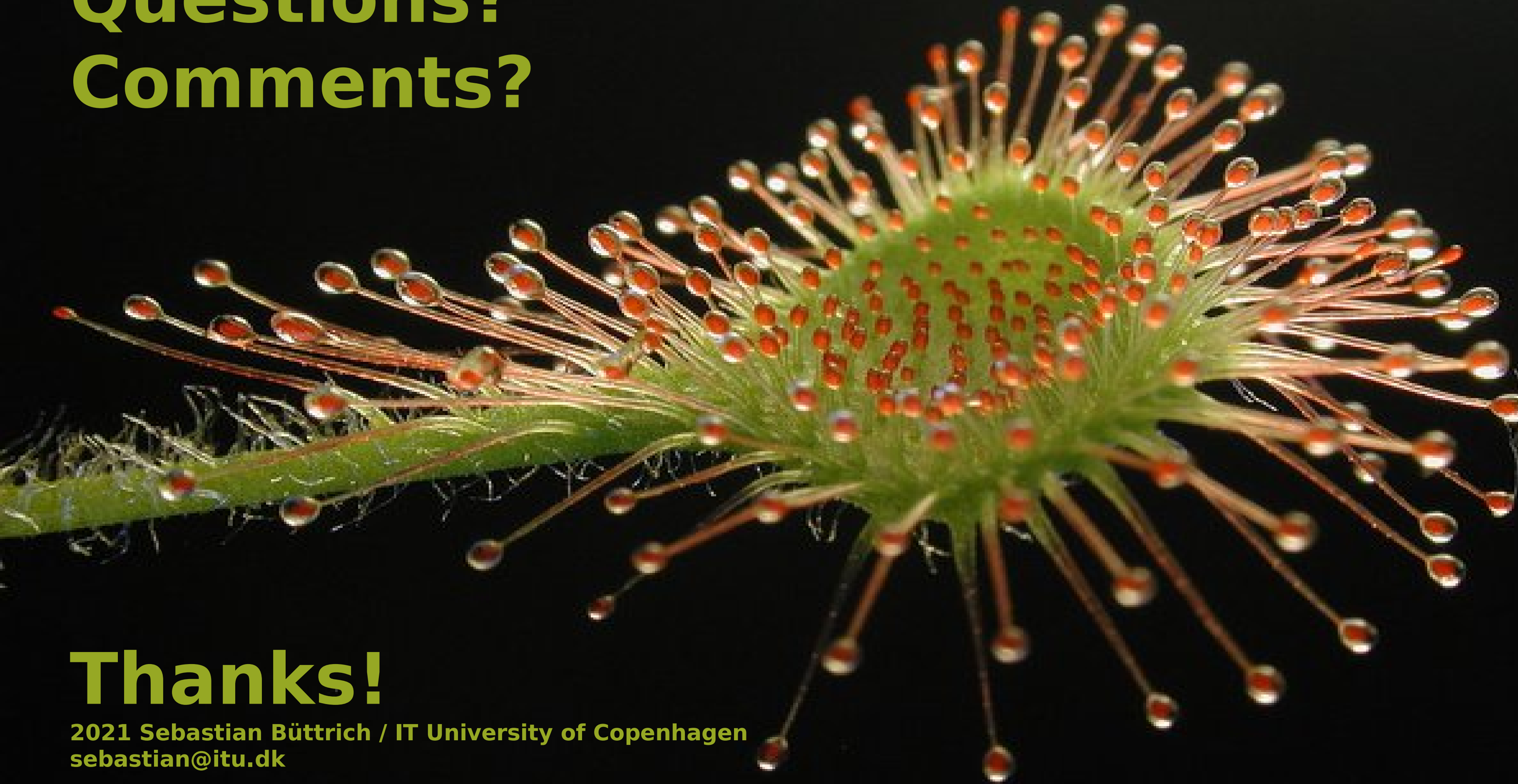
Sensors / Use Case CO_2 at lab

https://www.wemos.cc/en/latest/d1/d1_mini.html

Sensors / Use Case CO_2 at home

https://www.wemos.cc/en/latest/d1/d1_mini.html

Questions?
Comments?



Thanks!

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sebastian@itu.dk