INTERNATIONAL INSTITUTE OF INFORMATION TECHNOLOGY
HYDERABAD

Lecture AMH1 - Sensors and Actuators

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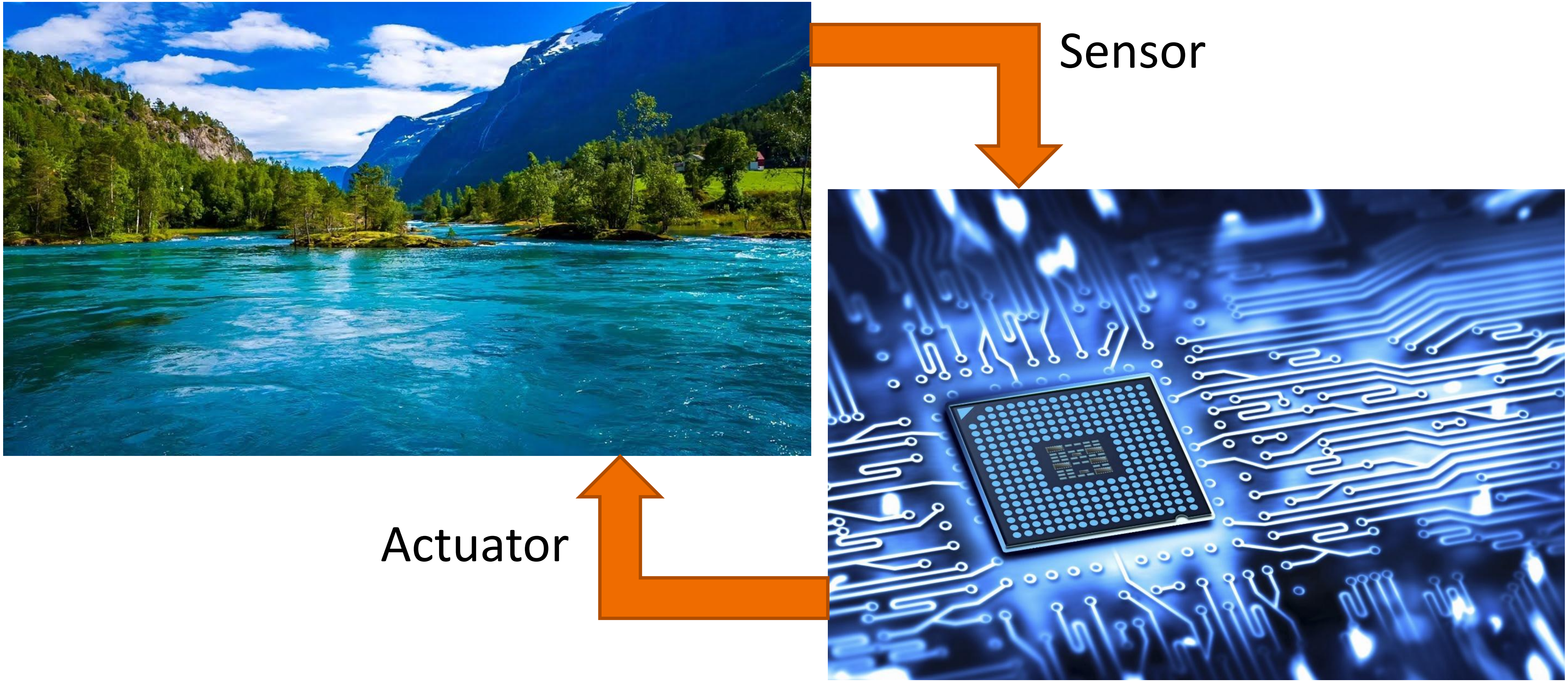
Sensors and actuators



Transducers

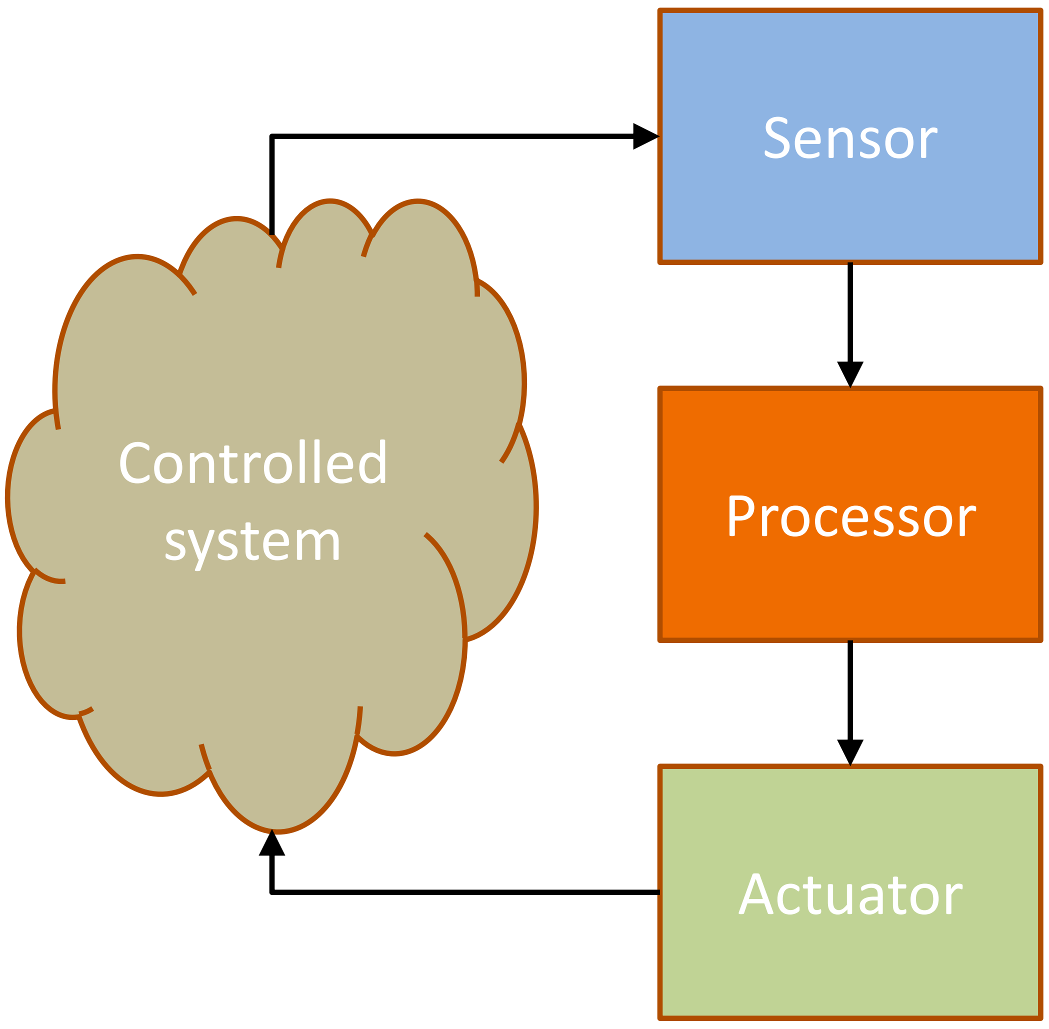
- Transducers convert one form of energy into another

- Sensors and actuators are both transducers
  - Sensors convert a physical phenomenon into electrical signal
  - Actuators convert an electrical signal into a physical phenomenon

- Some things can do both
  - Thermocouple

Transducers

- Physical signals need to be converted into proportional electrical signals (mostly analog voltage)
- Then we digitize the analog voltage using analong to digital converters (ADCs)
- The processor is able to process/store/transmit *only* digital signals (voltages)
- Actuators convert digital signals into physical signals (like light, sound, movement etc.)



Human sensors

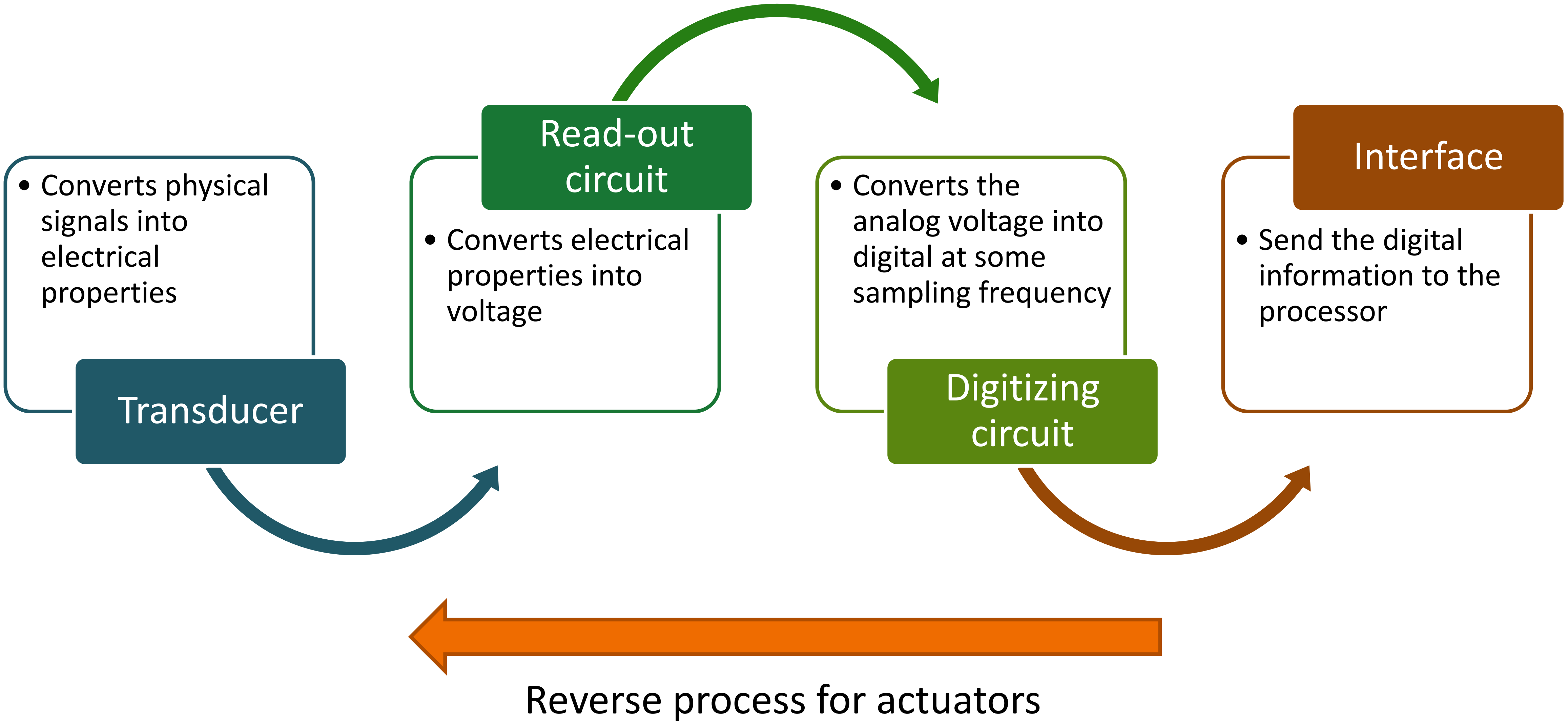
- Human beings are equipped with 5 different types of sensors

American scientists **David Julius and Ardem Patapoutian** have won the 2021 Nobel Prize for Physiology or Medicine for their discoveries of receptors for temperature and touch

So how to transduce to electronics?

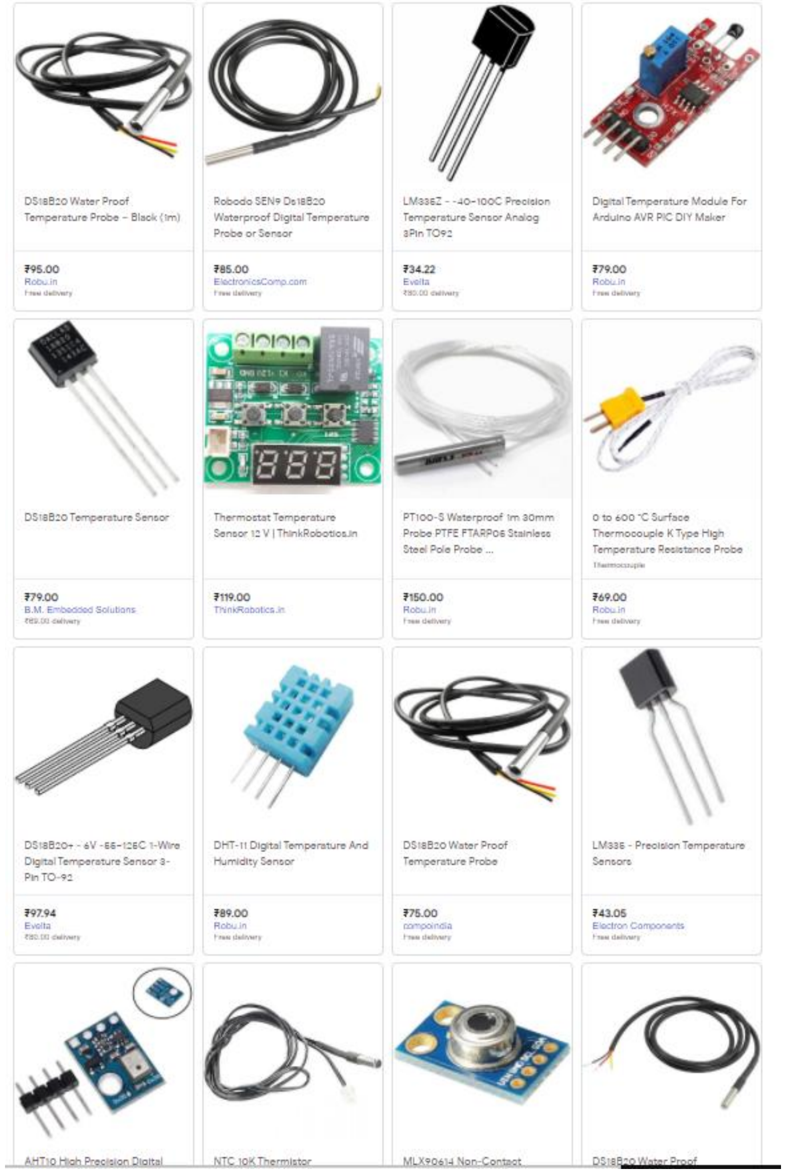
- We need to influence electronic properties using physical entities
- Electronic properties:
  - Resistance
  - Capacitance
  - Frequency
  - Charge density
- Sensors use the change in electronic properties because of physical phenomenon

Sensor systems



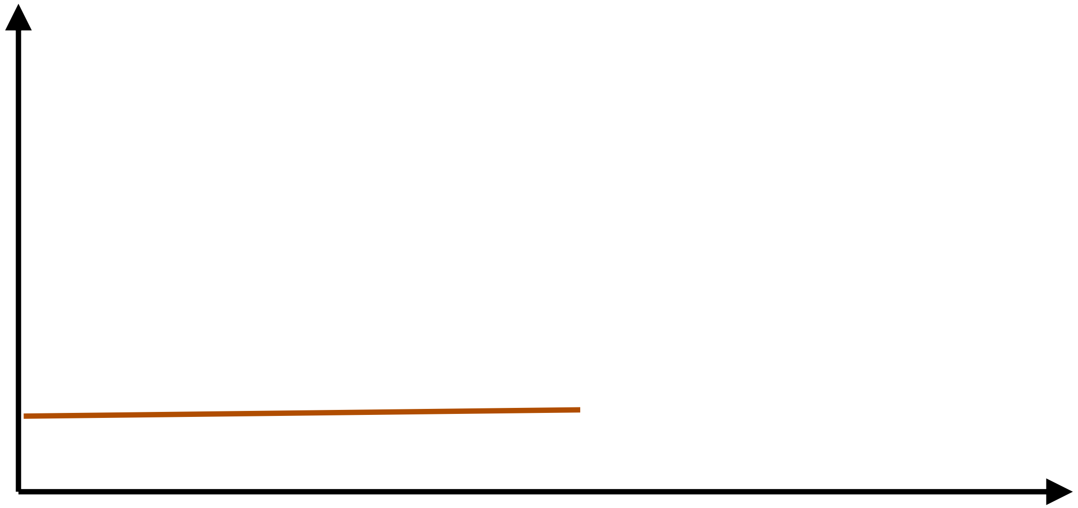
Sensor choice

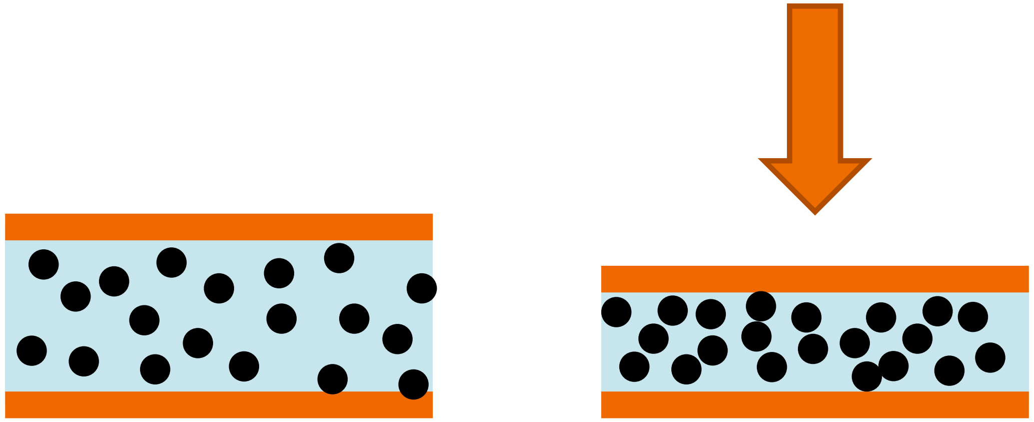
- Lets say we want to measure the temperature of a room…
- We need a temperature sensor… but which one?
- To decide properly, we need to know:
  - Range
  - Sensitivity
  - Cost
  - Availability
  - Ease of installation etc
- Two main factors govern these parameters:
  - The physical principle involved in sensing (transducer)
  - The interface from transducer to processor (read-out circuit)



Flexible pressure sensor

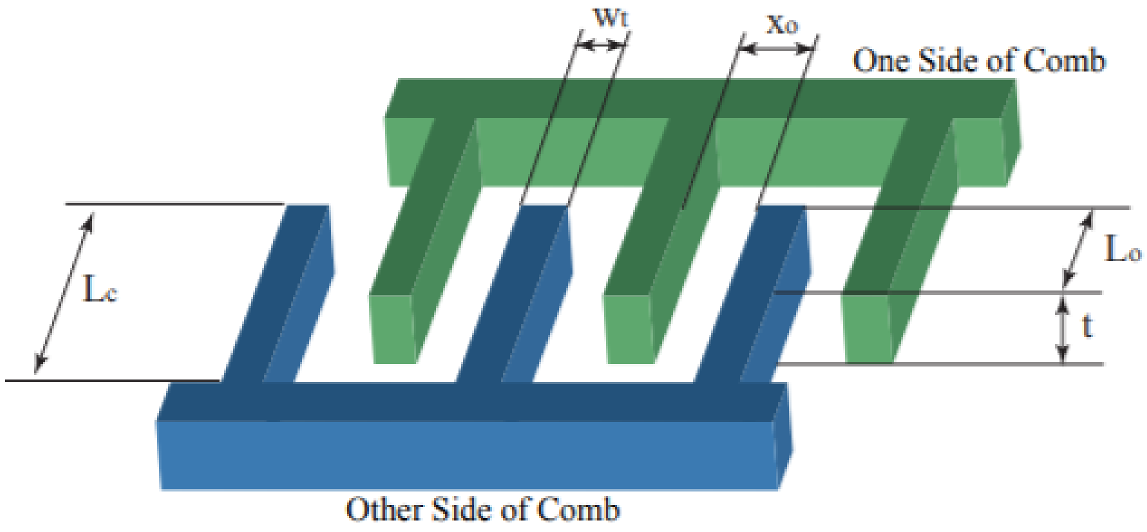
- Force sensitive resistor (FSR) creates change in resistance with change in pressure
- One way of creating these is to produce a conductive polymer composite thin film using conductive particles
- When pressure is applied, the thin film compresses and causes the conductive particles to come together, reducing the resistance between the electrodes
- This can be passed through an RVC to make a force/pressure sensor





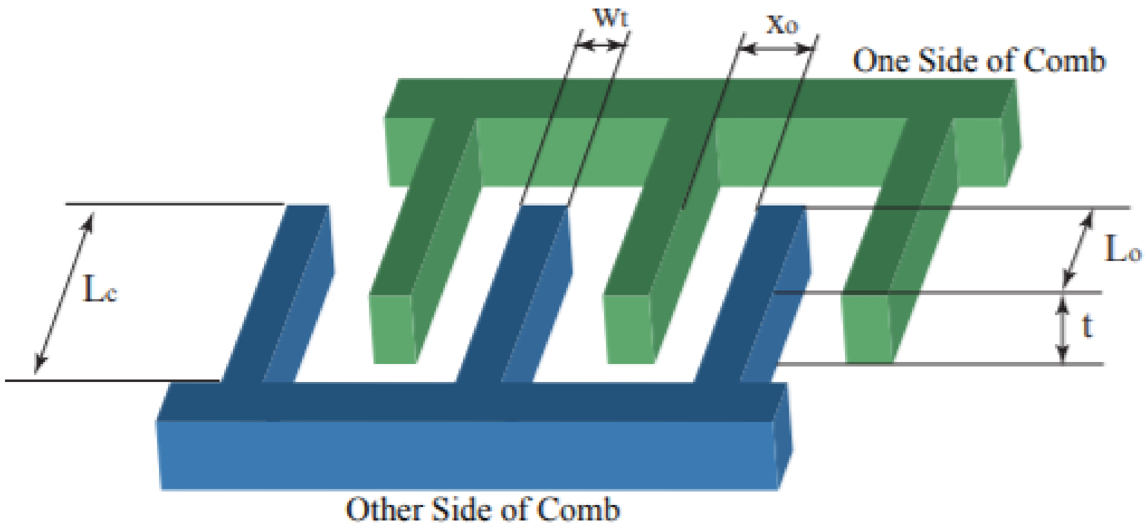
Accelerometers

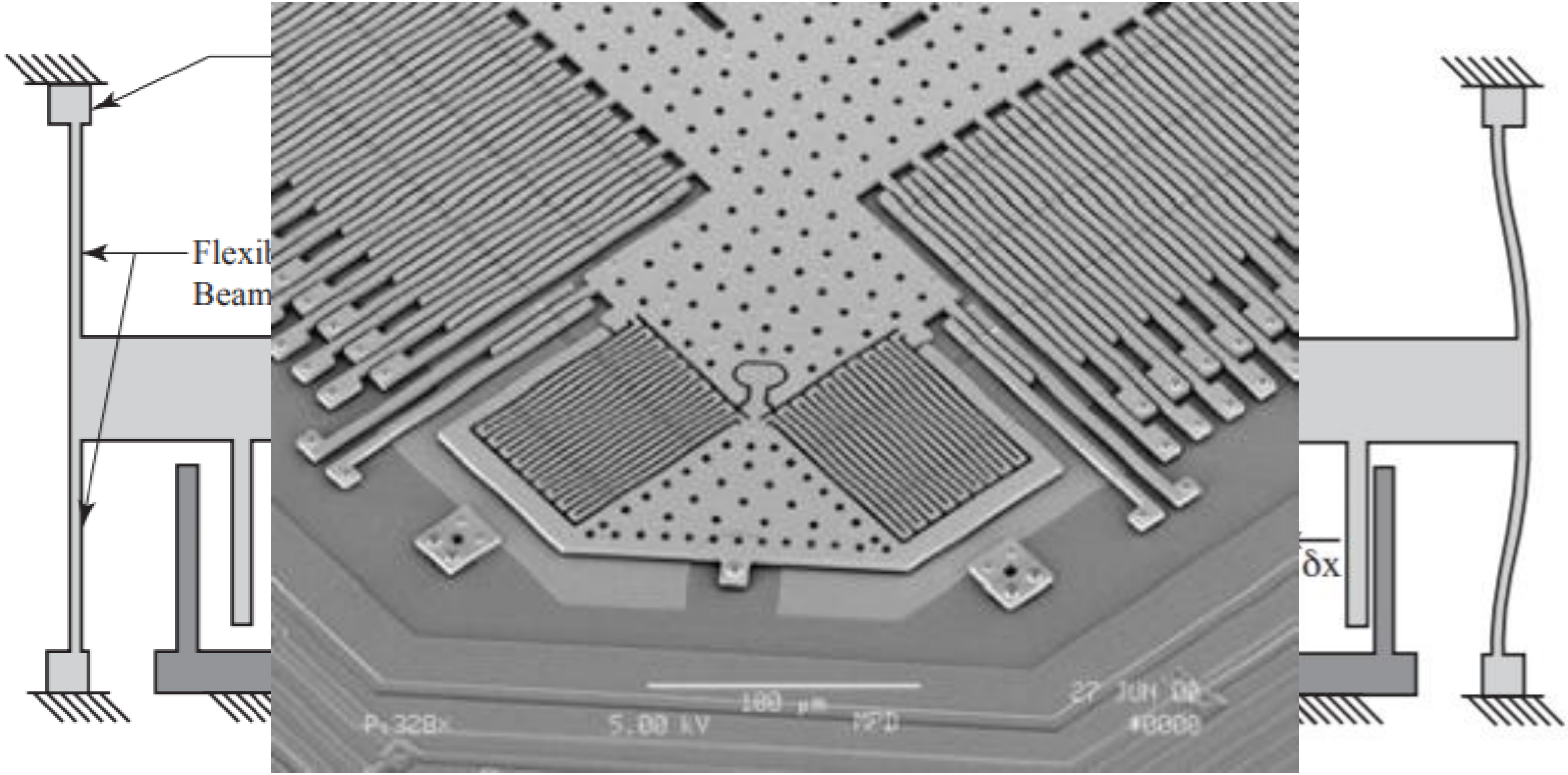
- If you have a linear displacement sensor, you can differentiate the output time series to get acceleration
- But some systems give output only for an accelerating system
- Classic example is the microcomb structure present in all of our smart phones!



Accelerometers

- Most commonly made using interdigitated fingers (or comb drive) with one side free to move and the other side static
- When this structure is accelerated, the free side tilts because of inertia, causing a change in capacitance of the structure
- For a given acceleration, the capacitance difference between the adjacent fingers changes
- With the stiffness of the structure known, the acceleration can be calculated



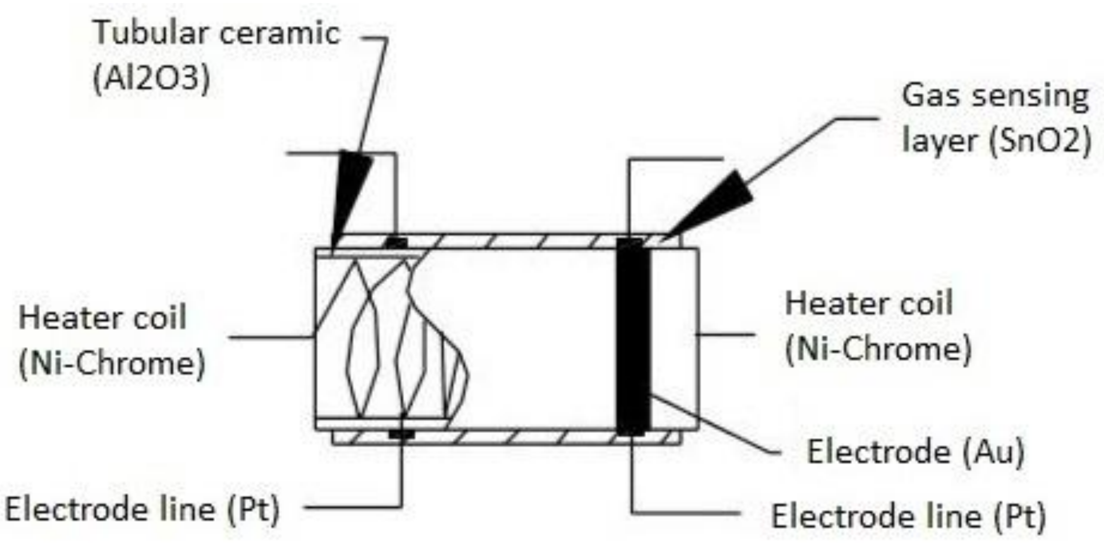

100 µm
5.00 kV

Humidity

- Humidity sensors rely on the fact that electrical properties of thin films changes because of adsorption of moisture on their surface
- This is used in capacitive humidity sensors to create changes in capacitance because of the change in dielectric constant of a metal oxide thin film upon exposure to moisture
- Humidity changes resistivity as well, but that is also very temperature sensitive

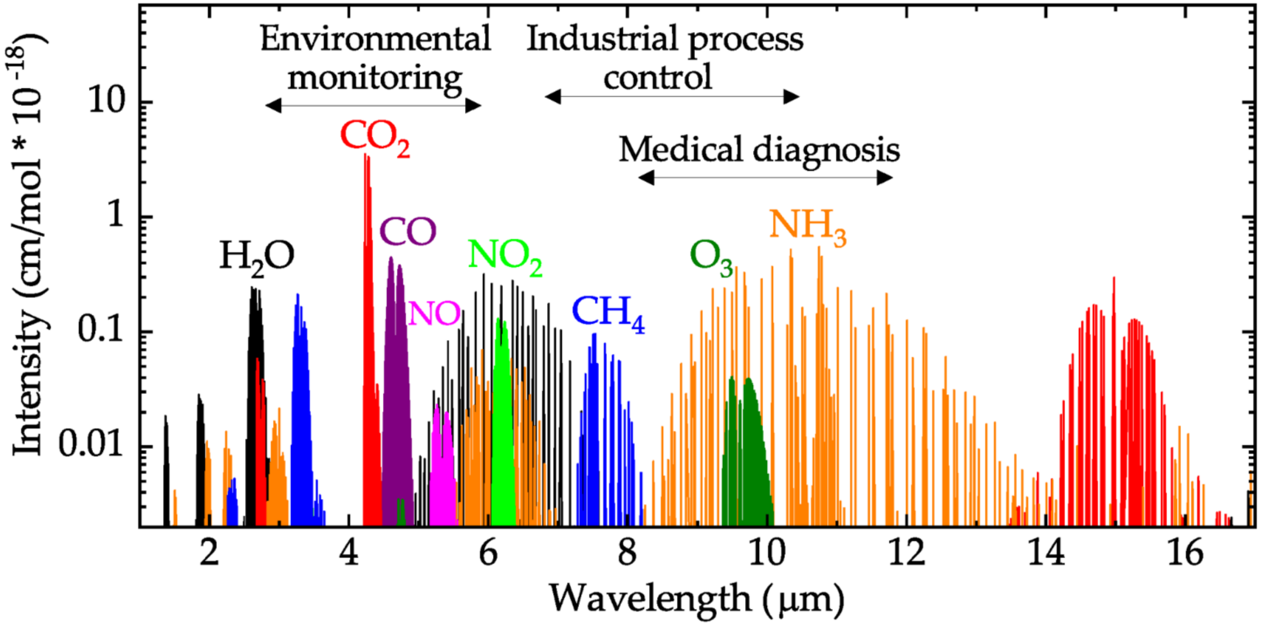
Gas sensors

- Most popular method is the metal oxide gas sensor with SnO_2 as the sensing layer
- Whenever certain gases are present near the thin film, they are adsorbed by it
- The resistance of the thin film changes and the current through it varies which represents the change in concentration of the gases
- The adsorption of different gases is a function of temperature – thus a heater is placed to determine selectivity



Gas sensors

- Non-disruptive infrared sensor (NDIR) is used for sensing gases based on their spectral response
- An IR LED with a very specific wavelength (depending on the gas to be sensed) is used as the source
- The light passes through the sample gas and a detector detects the incoming intensity
- Very selective to other gases
- Most commonly used for CO_2



Transduction

- Transducing into electrical domain

Sensed quantity	Electrical parameter
Strain, force, pressure	Resistance
Linear acceleration	Capacitance
Angular velocity	Capacitance
Rotation	Frequency
Fluid flow	Frequency (through rotation of turbine)
Temperature	Current, resistance, voltage
Humidity	Capacitance
Light	Current
Sound	Voltage
Magnetic field	Voltage
Gases	Resistance

From electrical parameters to processors

- The electrical parameter needs to be converted to voltage so that it can be read by the processor

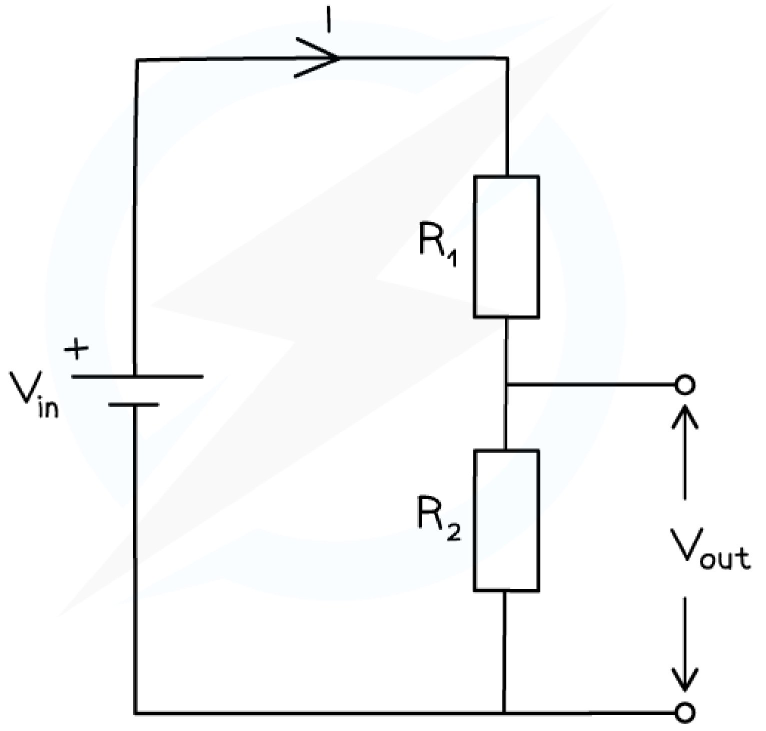
- This requires:
  - Resistance to voltage convertor (RVC)
  - Capacitance to voltage convertor (CVC)
  - Frequency to voltage convertor (FVC)

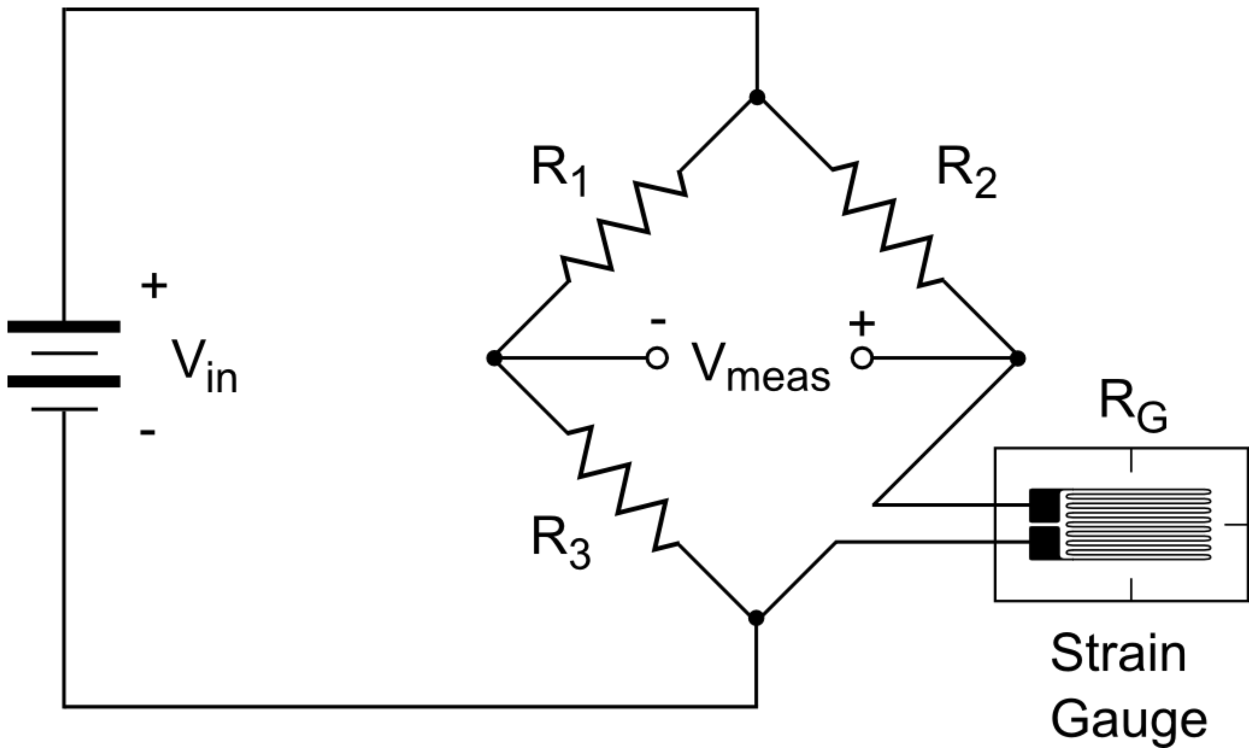
- The voltage produced is then digitized for storage, processing and transmission

RVC example

POTENTIAL DIVIDER EQUATION: $V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$

$$V_{meas} = V_{in} \frac{dR_G}{R}$$





Sensor selection

- Range—Difference between the maximum and minimum value of the sensed parameter
- Resolution—The smallest change the sensor can differentiate
- Accuracy—Difference between the measured value and the true value
- Precision—Ability to reproduce repeatedly with a given accuracy
- Sensitivity—Ratio of change in output to a unit change of the input
- Zero offset—A nonzero value output for no input

Sensor selection

- Non Linearity—Percentage of deviation from the best-fit linear calibration curve
- Zero Drift—The departure of output from zero value over a period of time for no input
- Response time—The time lag between the input and output
- Operating temperature—The range in which the sensor performs as specified
- Deadband—The range of input for which there is no output
- Signal-to-noise ratio—Ratio between the magnitudes of the signal and the noise at the output

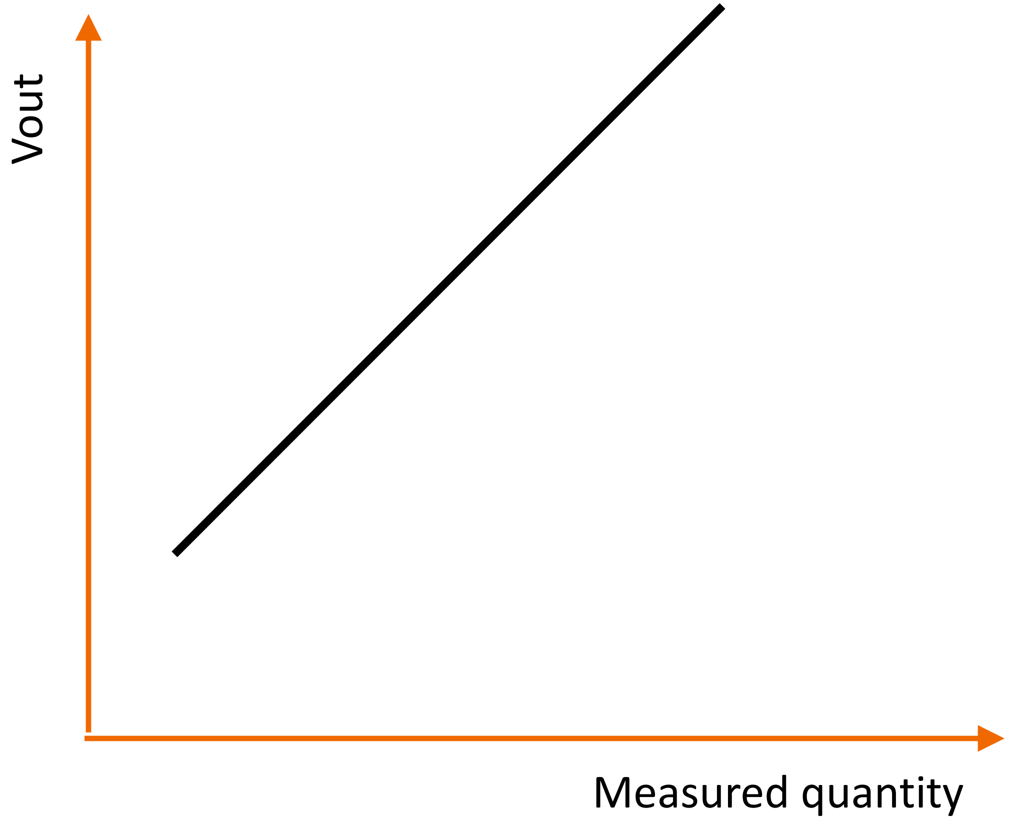
The calibration trap!

- All this is simple enough, however, the biggest hurdle in sensor deployment is calibration
- This ensures that the readings provided by the sensor are accurate and believable
- Particularly vital for medical applications
- Calibration is the comparison of measurement values delivered by a device under test (DUT) with those of a calibration standard

Sensor characteristics

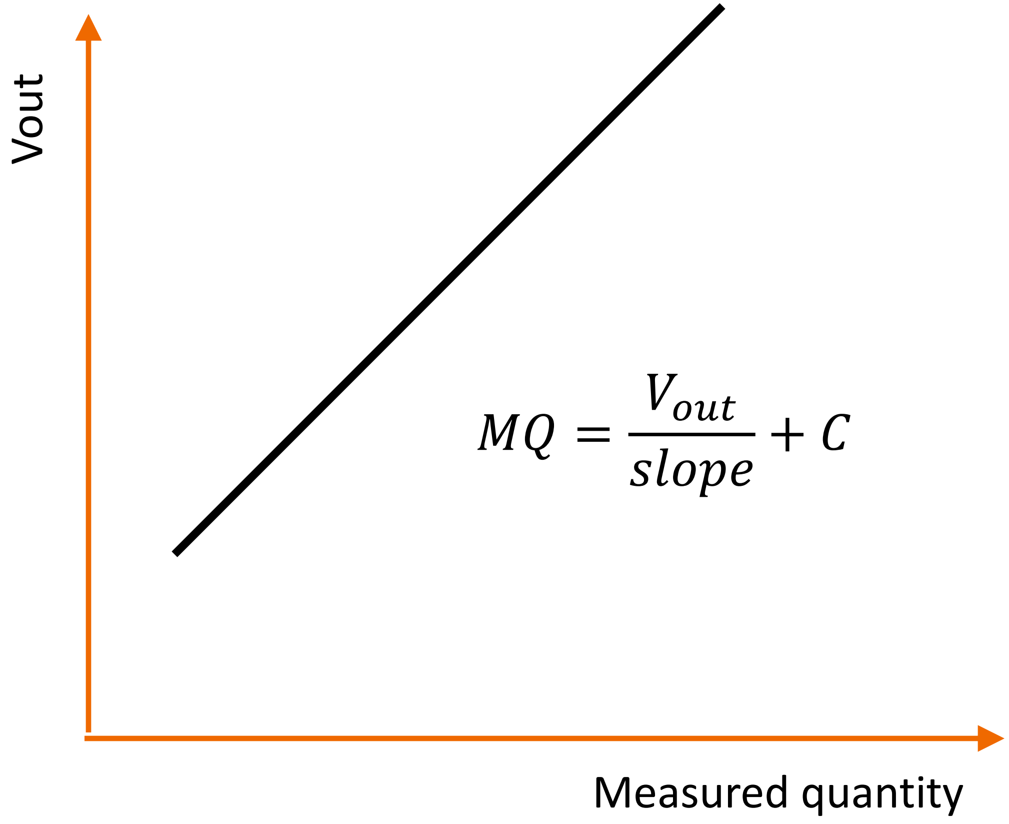
- Our eventual goal is to find out the value of the measured quantity based on the reading of the voltage
- For this, we need a function for MQ in the form of V_{out}
- This is typically the simplest for linear characteristics – that is why they are generally preferred

$$MQ = \frac{V_{out}}{slope} + C$$



Sensor calibration

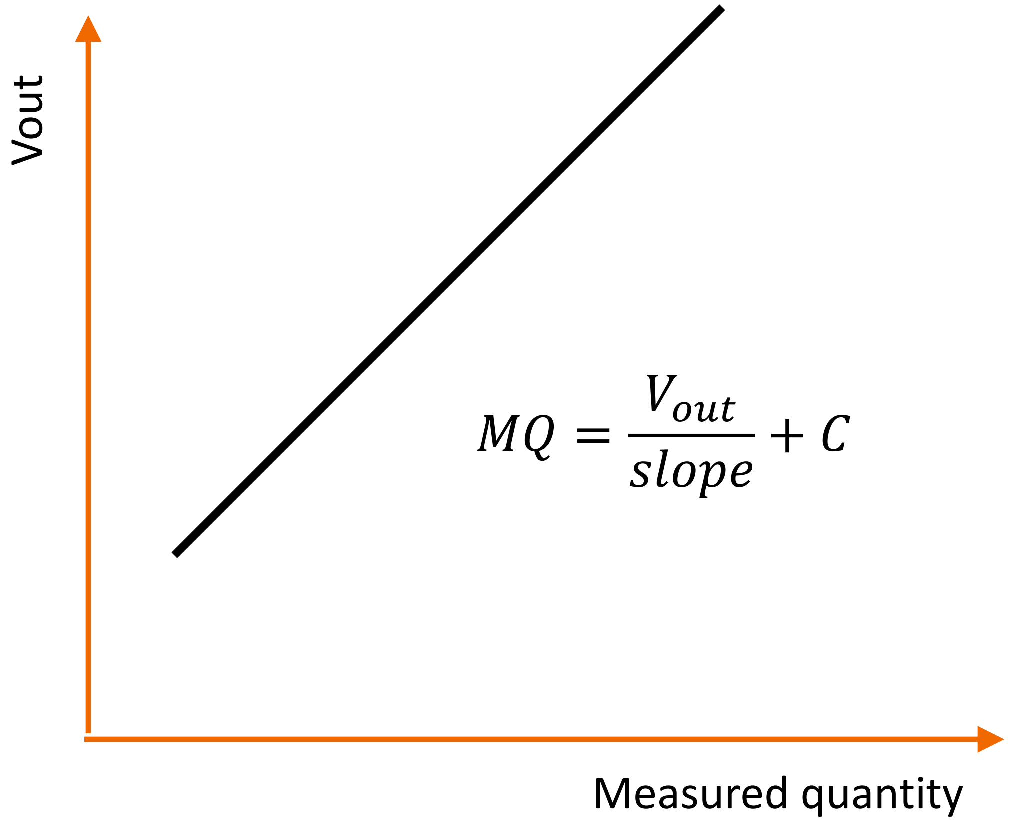
- We have two unknown quantities in the equation, once known, we can calculate the MQ for any V_{out}
- These are typically provided by the sensor manufacturer, however, the biggest problem in IoT design is shift in these values over time



$$MQ = \frac{V_{out}}{slope} + C$$

Sensor calibration

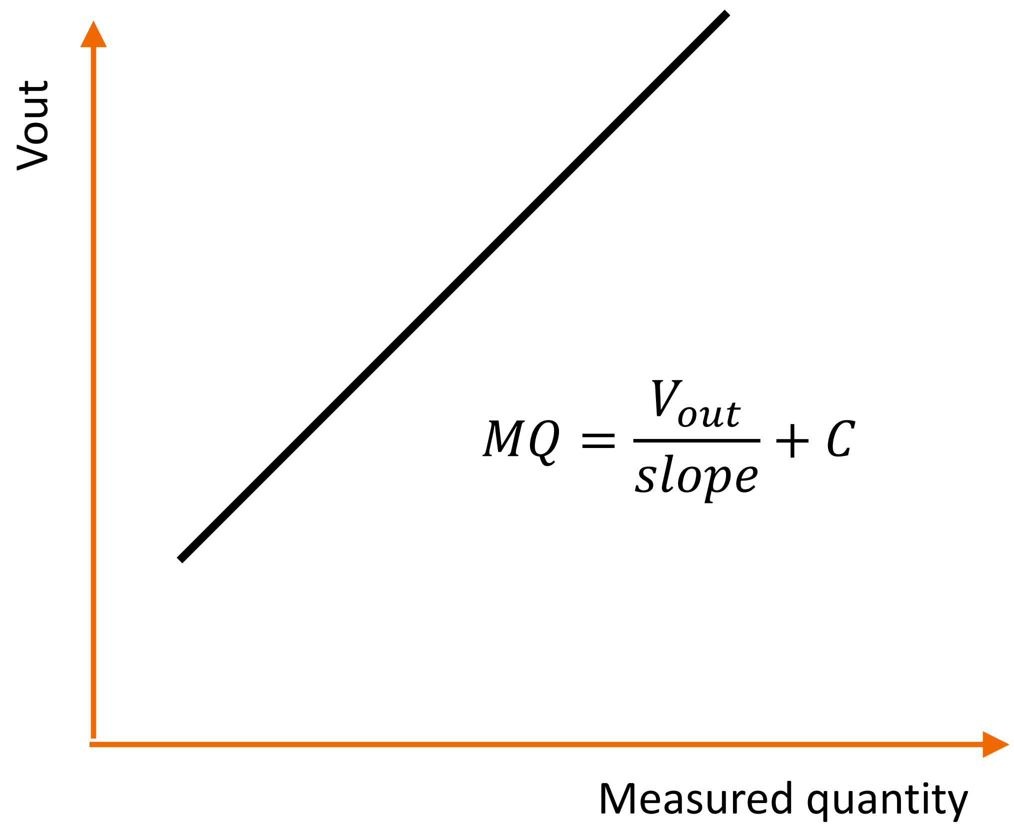
- Calibrating a sensor means determining these values, or if they are known, verifying them
- This can be done by subjecting the sensor to a known stimulant and measuring the readout voltage
- Two points are sufficient to determine the two unknown values
- However, the problem is to provide a *known stimulation* to the sensor



$$MQ = \frac{V_{out}}{slope} + C$$

Sensor calibration

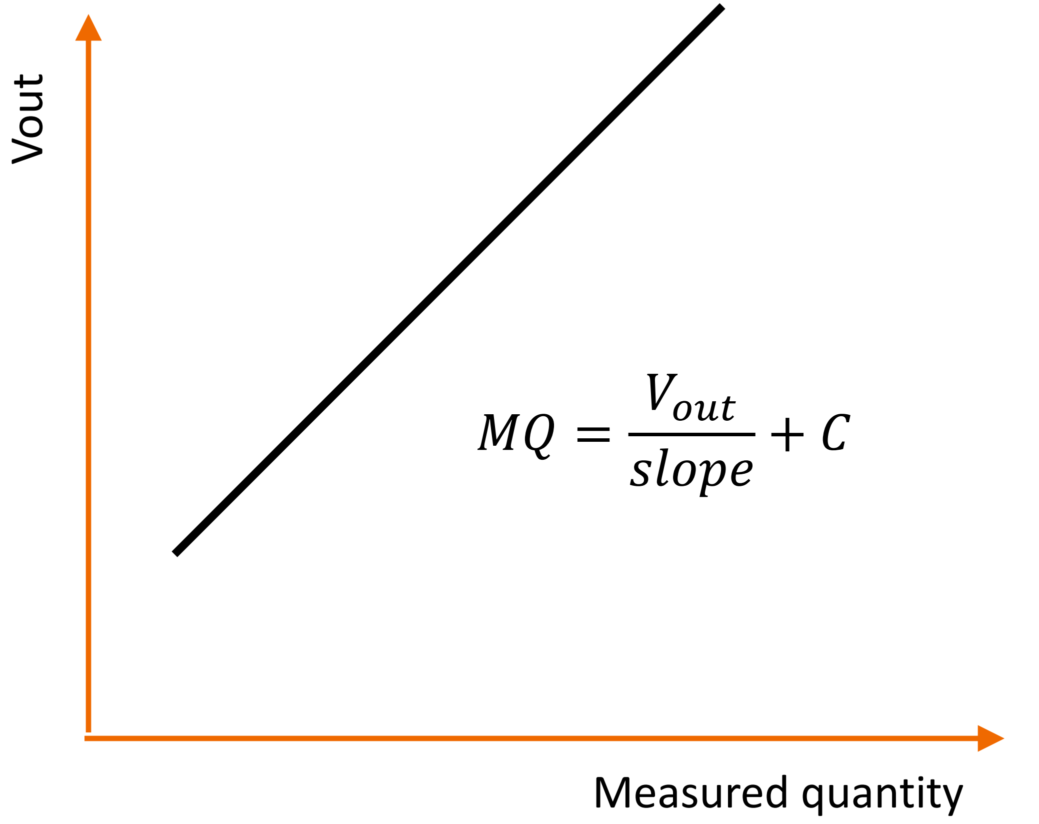
- One easy thing to do is to obtain the sensor output at zero applied input
- This is easily achieved for strain, force, light or acceleration sensors, but now so much for gas, temperature and pressure
- This zero-point provides the value of C, which can be itself be zero for no DC bias situation



$$MQ = \frac{V_{out}}{slope} + C$$

Sensor calibration

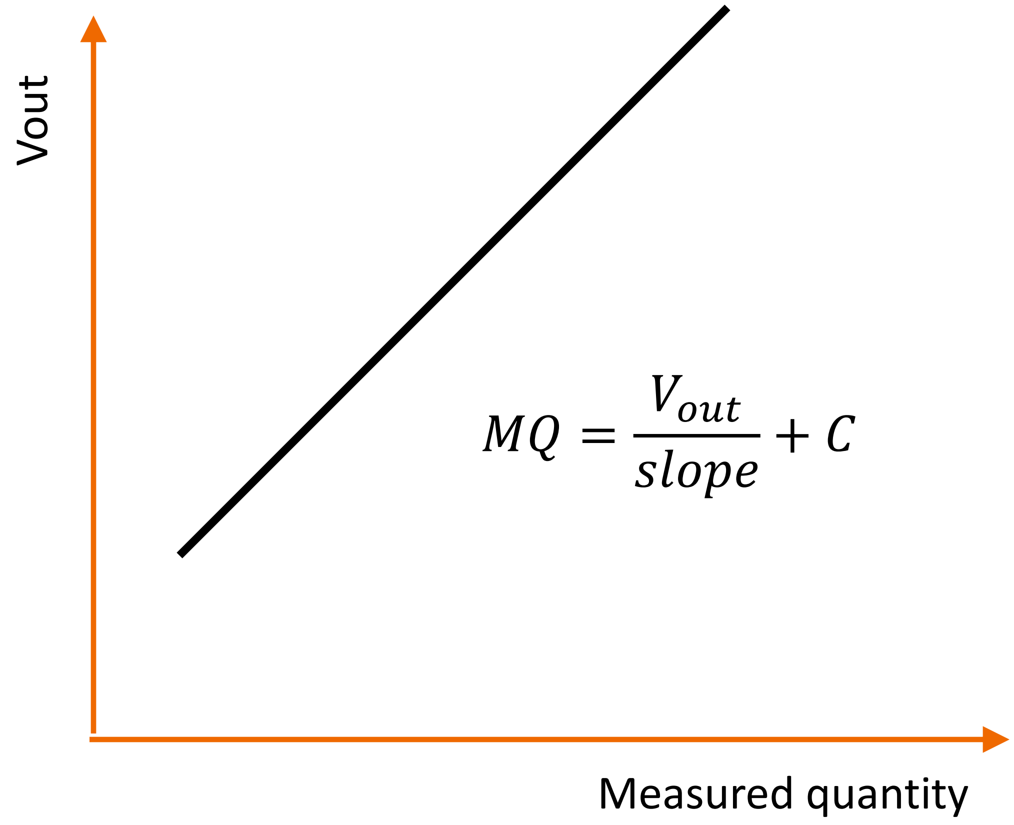
- For non-zero input, we require specific conditions that can be difficult to achieve for some sensors
- Sometimes, physics based calibration can be done – say phase change temperatures for temperature sensor
- In their absence, the best way forward is typically having a gold standard measurement system to determine the value of the quantity in the ambient
- Determining this gold standard is a major challenge



$$MQ = \frac{V_{out}}{slope} + C$$

Sensor calibration

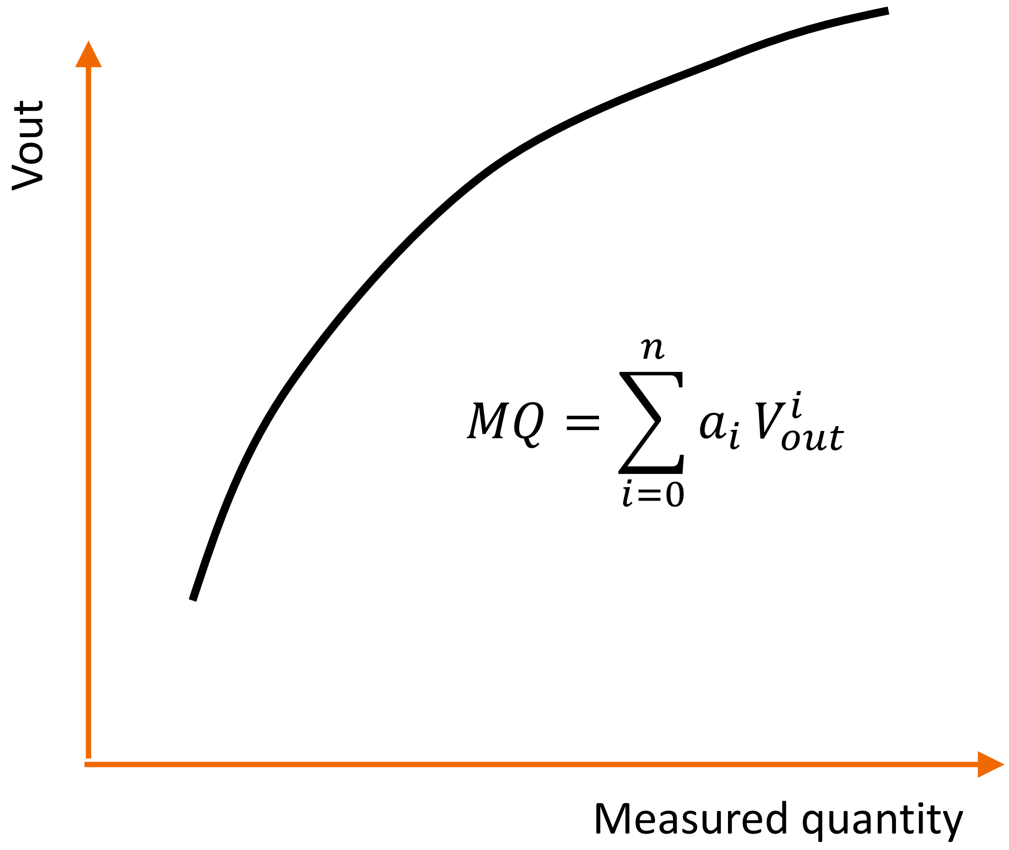
- Another major challenge in IoT deployments is that sensor calibration often drifts with time, i.e., the values of slope and C are functions of time
- There are several strategies:
  - Know the drift in advance and program it into the system logic
  - Recalibrate the sensor over-the-air based on a gold standard
  - Recalibrate by bring the sensor to a conditioned ambient



$$MQ = \frac{V_{out}}{slope} + C$$

Non-linear systems

- No matter how much we try, there are always some systems with non-linear response
- We require multiple parameters to determine the calibration in this case
- New strategies:
  – Use of ML algorithms to determine sensed quantity



$$MQ = \sum_{i=0}^{n} a_i\, V_{out}^{i}$$

https://ieeexplore.ieee.org/abstract/document/9335600

Actuators

- Actuators are devices that take signal in electrical form and transform it into something that can influence the physical world
- We can almost say that this is the end goal of all IoT devices, i.e., influencing or altering the physical world in ways that enhance our safety/ease-of-living
- We can obtain actuation in many forms:
  - Movement
  - Temperature (heating/cooling)
  - Light
  - Sound
- These transducers are typically accompanied with their drive circuits (like RVC, CVC for sensors)

Actuators

Actuator	Physical principal
Motors	Electromagnetism
LED light	Electron-hole pair recombination
Incandescent light	Black body radiation
Electrical heaters	Joule heating
Speakers	Piezoelectricity/electromagnetism
Cooling	Peltier effect, adiabatic expansion

Actuator selection

- Continuous power output—The maximum force/torque attainable continuously
- Range—The range of linear/rotary motion/temperature/light intensity achievable
- Resolution—The minimum increment of output attainable
- Accuracy—Linearity of the relationship between the input and output
- Speed characteristics—output versus speed relationship
- No load operation—Typical operating speed/velocity with no external load
- Power requirement—Type of power (AC or DC), number of phases, voltage level, and current capacity

Actuator calibration

- Similar to sensor calibration

- Given a particular input, what output does the actuator produce?

- Is it on expected lines?

- Can be difficult to measure reliably depending on the type of actuator (**calibration trap!**)

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Thank you

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