ENMC3361

Sensors and Instrumentation

Lecture #17

Project discussion

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Sensors and Instrumentation

Lecture #18

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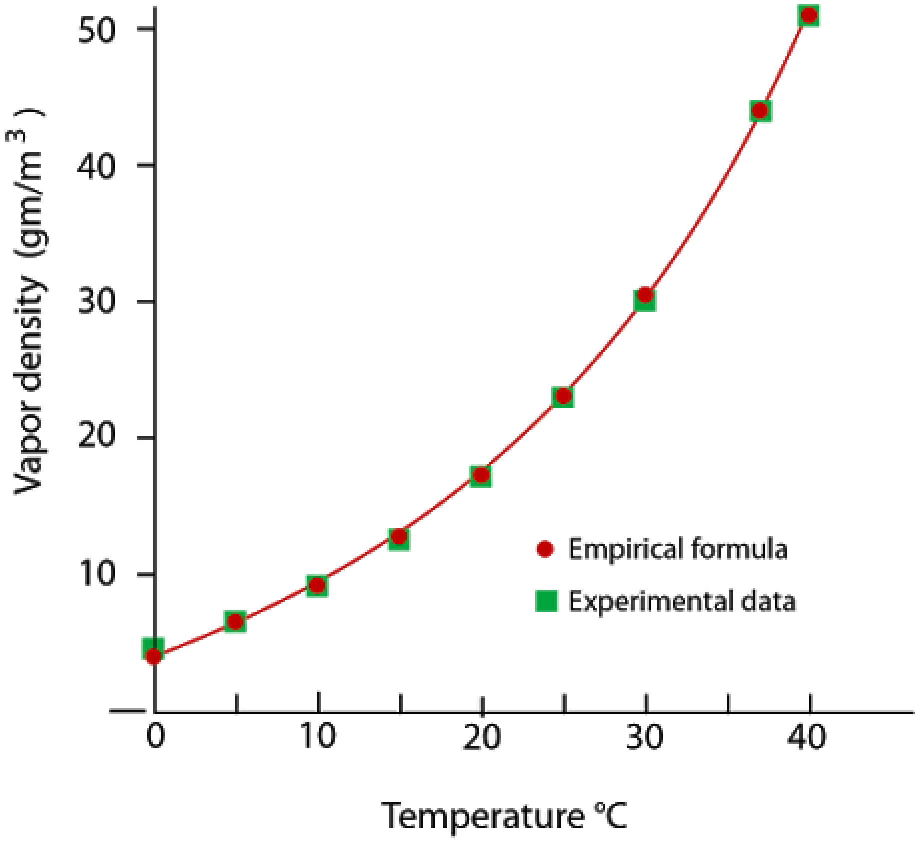
HUMIDITY

HUMIDITY

- Humidity is usually reported as Relative Humidity.

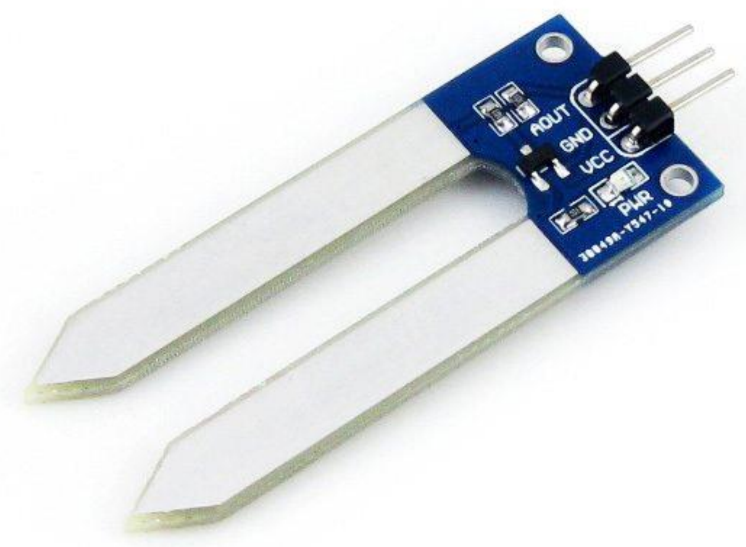
$$H = 100\frac{P_w}{P_s},$$

Where H is RH, P_w is partial pressure of water vapor and P_s is the pressure of saturated water vapor at a given temperature.



HUMIDITY

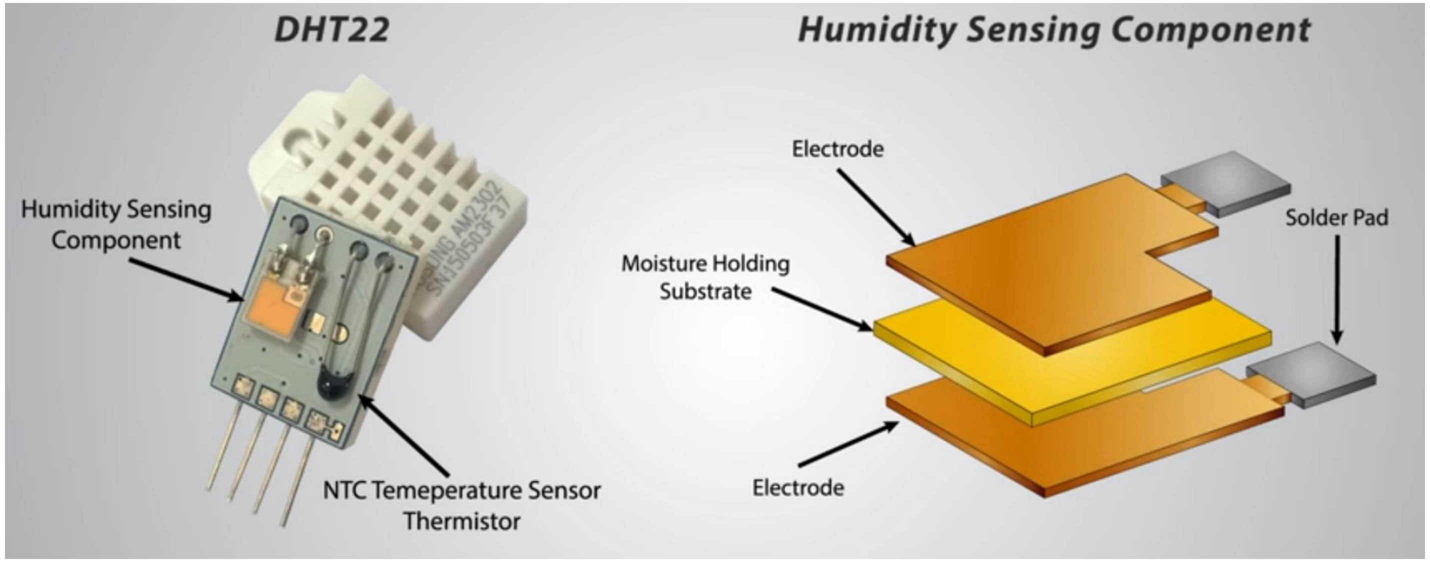
- Humidity sensors work by detecting changes that alter electrical currents or temperature in the air.
- There are three basic types of humidity sensors:
  - Capacitive
  - Resistive
  - Thermal



HUMIDITY

Capacitive

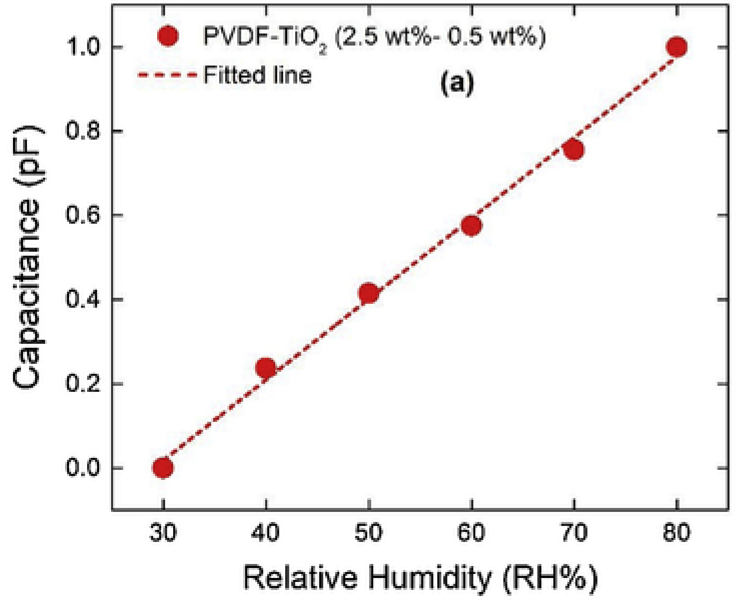
- A capacitive humidity sensor measures relative humidity by placing a thin strip of metal oxide between two electrodes.
- The metal oxide's electrical capacity changes with the atmosphere's relative humidity.
- The capacitive type sensors are the only type to be able to measure relative humidity from 0% to 100%.



HUMIDITY

Capacitive

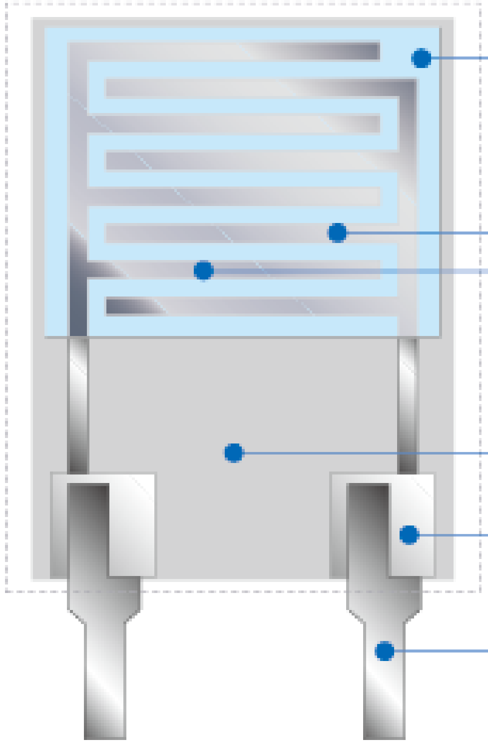
- **Advantage:** the only sensors that can measure to 0% RH.
- **Disadvantage:**
  - The sensor will require a circuit to create the signal at the optimal frequency and measure the capacitance.
  - Regular re-calibration is also required for optimal performance.



HUMIDITY

Resistive

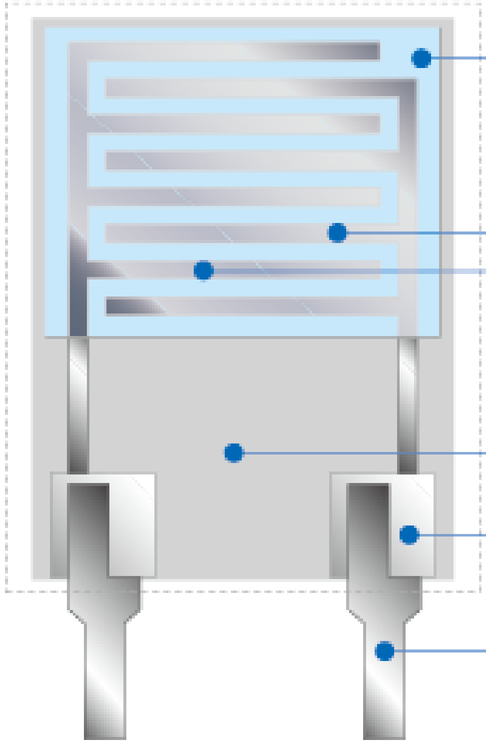
- The principle behind resistive humidity sensors is the fact that the conductivity in non – metallic conductors is dependent on their water content.
- The relationship between resistance and humidity is inverse exponential.
- The low resistivity material is deposited on top of two electrodes.
- The electrodes are placed in comb shaped pattern to increase the contact area.



HUMIDITY

Resistive

- **Advantage:** low cost, small size and minimal requirement for recalibration.
- **Disadvantage:** highly sensitive to chemical vapors and other contaminants.



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Sensors and Instrumentation

Lecture #19

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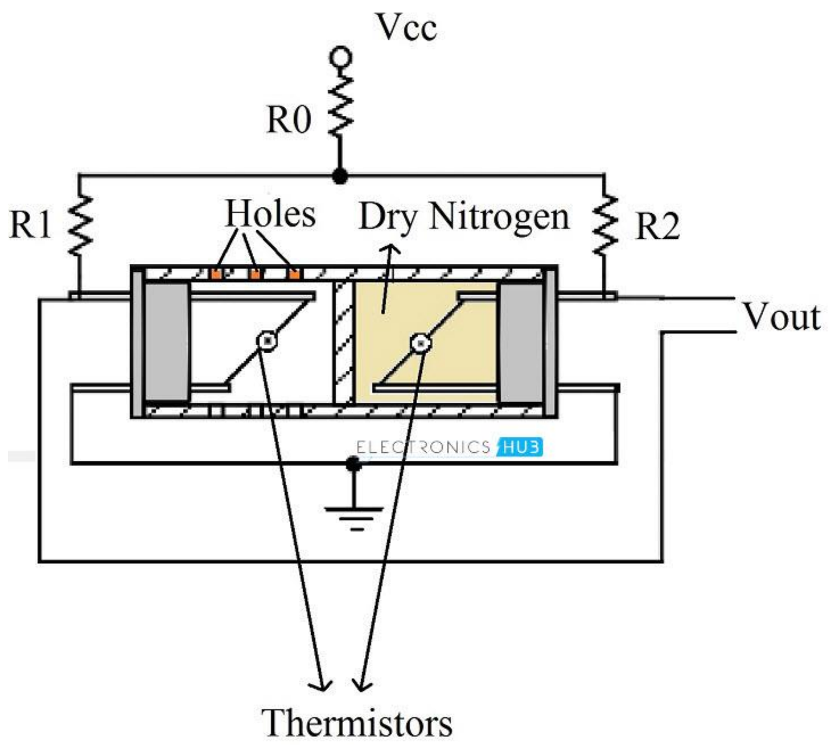
HUMIDITY

Thermal Conductivity

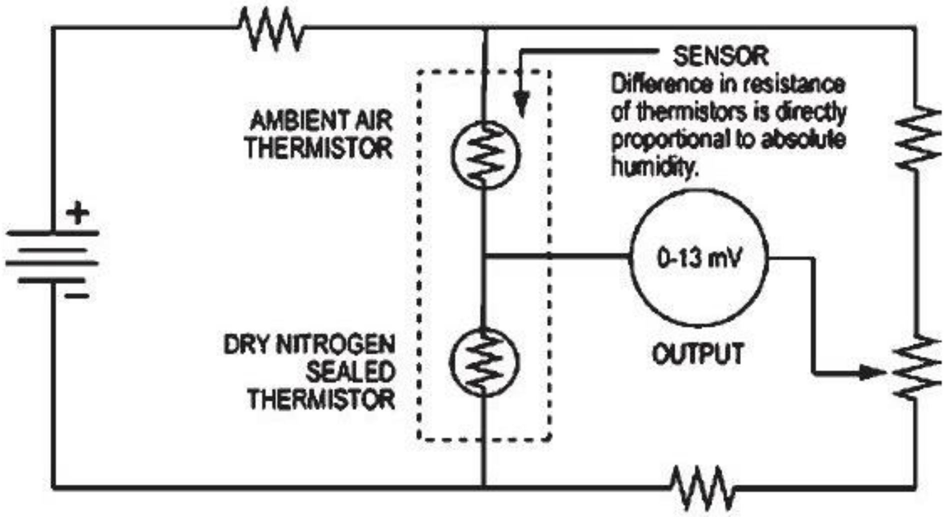
- Measures the thermal conductivity of both dry air as well as air with water vapor.
- Consist of two matched negative temperature coefficient (NTC) thermistor elements in a bridge circuit.
- One is hermetically encapsulated in dry nitrogen and the other is exposed to the environment.



HUMIDITY

Thermal Conductivity

- When current is passed through the thermistors, resistive heating increases their temperature to >200°C.
- Since the heat dissipated yields different operating temperatures, the difference in resistance of the thermistors is proportional to the absolute humidity.



What would be the source of error in this sensor?

CHEMICAL

CHEMICAL

Traditionally, chemical sensing is done in an analytical laboratory with complex benchtop equipment including:

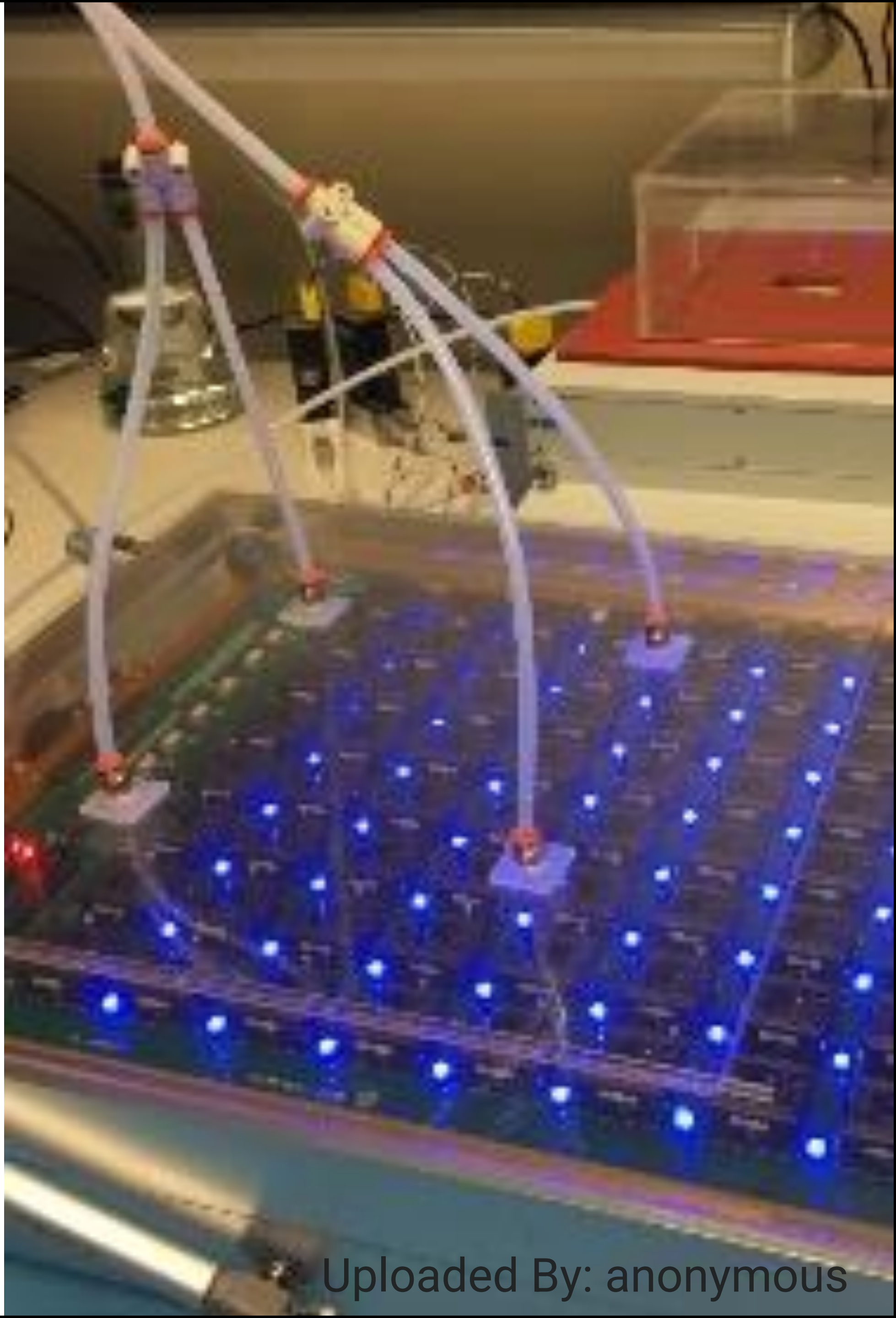
- Mass spectrometry
- Chromatography
- Nuclear magnetic resonance
- X-ray and,
- Infrared technology.

- While extremely accurate, the lab is expensive and provides off-line data.

CHEMICAL

Compact/*low-cost* sensors can be classified into 3 categories. Sensors that measure

1. Electrical or electrochemical properties of a median affected by the target chemicals
2. Change in physical property
3. Rate of absorption or release of optical or other wavelengths of electromagnetic radiation



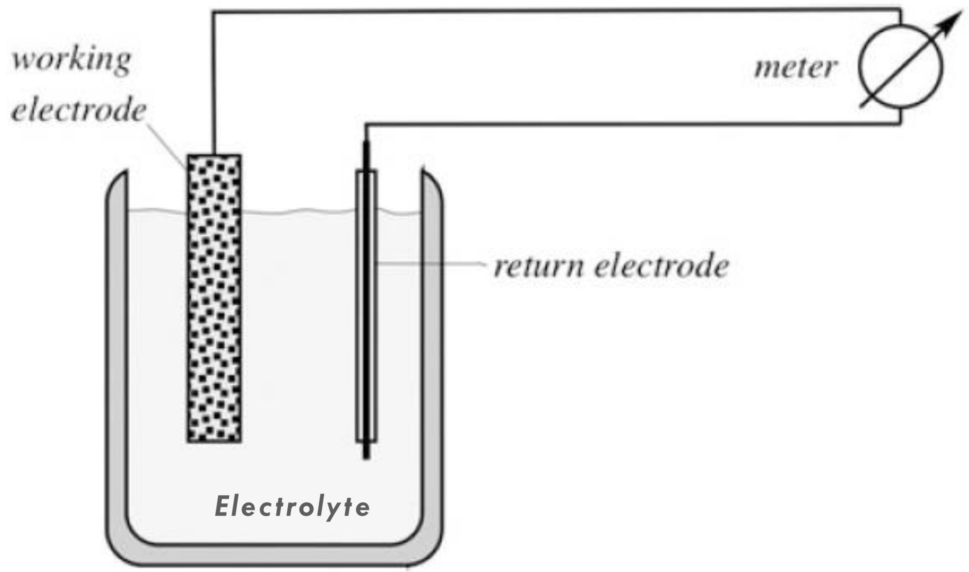
CHEMICAL

Electrochemical

Special electrodes are used, where either

- chemical reaction takes place, or
- the charge transport is affected by the reaction.

- Changes in composition of the electrolyte will result in measurable current change between the working electrode and return electrode.
- Selection of material for electrodes and electrolyte creates sensitivity to the target chemical being measured.

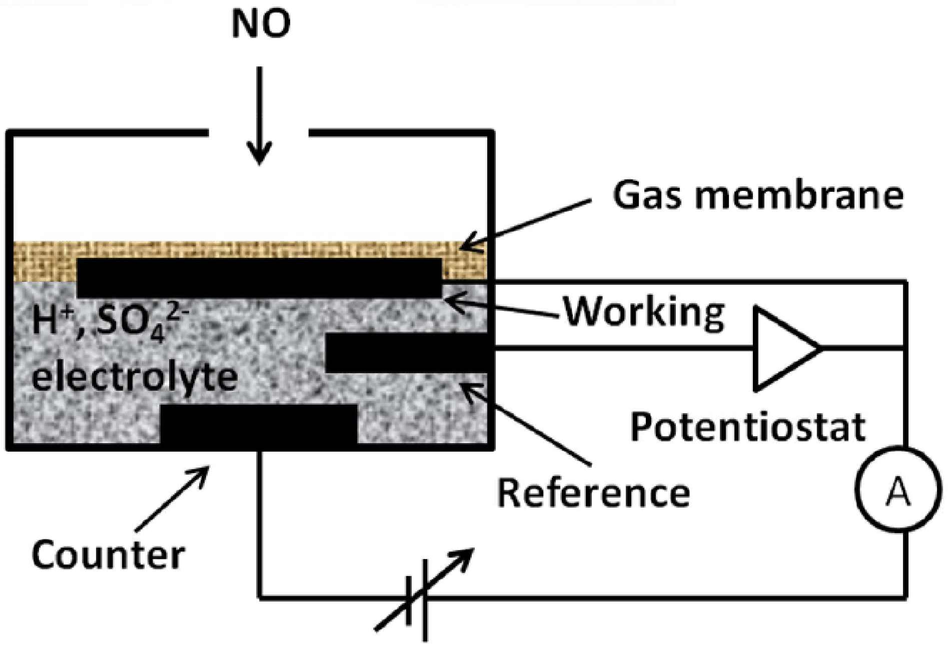


CHEMICAL

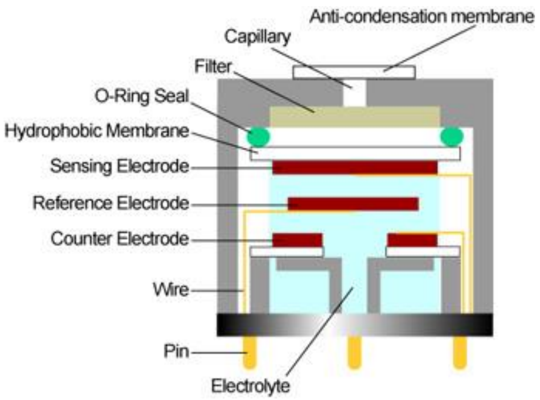
Electrochemical

In a commercial sensor:

- Electrolyte is encapsulated in a casing
- Gas permeates through a hydrophobic membrane
- Voltage is supplied to the working electrodes.
- In the absence of the target gas a negligible current flows through the sensor to provide the baseline zero.
- When target gas is present the oxidization of the gas produces or consumes electrons that facilitate higher charge transport (current).



CHEMICAL



Electrochemical

Selectivity

- Selectivity can be an issue in electrochemical cells.
- There are infinite combination of other chemicals that might interact with the sensors.

- **Solution**
  - Manufacturers aim to minimize cross-sensitivity by selecting optimal cathode and electrolyte solution.
  - Filter placed on the inlet of the sensor
  - Use multiple sensors in a reduction matrix

Low Cross-sensitivity

Interfering Gas	Conc. ppm	O3 Reading ppm
CO	300	0
H_2S	15	< 5
NO_2	20	< 5
H_2	300	0
SO_2	5	0

High Cross-sensitivity

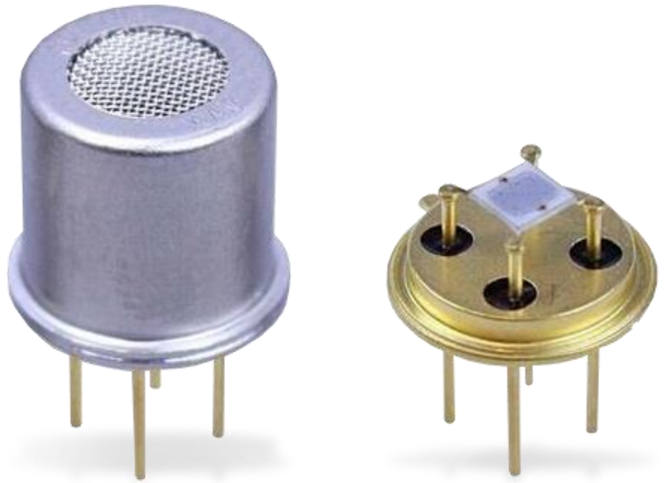
CROSS-SENSITIVITY DATA

Interfering Gas	Concentration	HCL Reading
CO	100 ppm	~ 2 ppm
H_2S	15 ppm	~ 25 ppm
SO2	20 ppm	~38 ppm
NO	35 ppm	0 ppm
NO_2	5 ppm	~ -12 ppm
H_2	100 ppm	~ 2 ppm
Ethylene	100 ppm	0 ppm

CHEMICAL

Metal Oxide Gas Sensors (MOS)

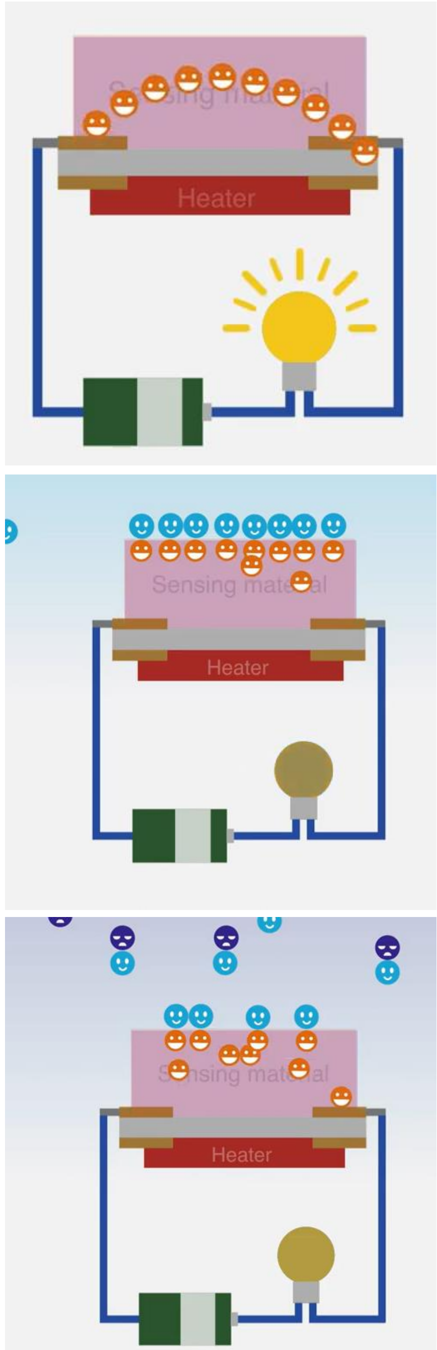
- MOS gas sensors are less expensive to produce and used widely for CO, propane, and other hazardous gas detection.
- Not selective and will react to a wide range of pollutants
- Require more power to operate.



CHEMICAL

Metal Oxide Gas Sensors (MOS)

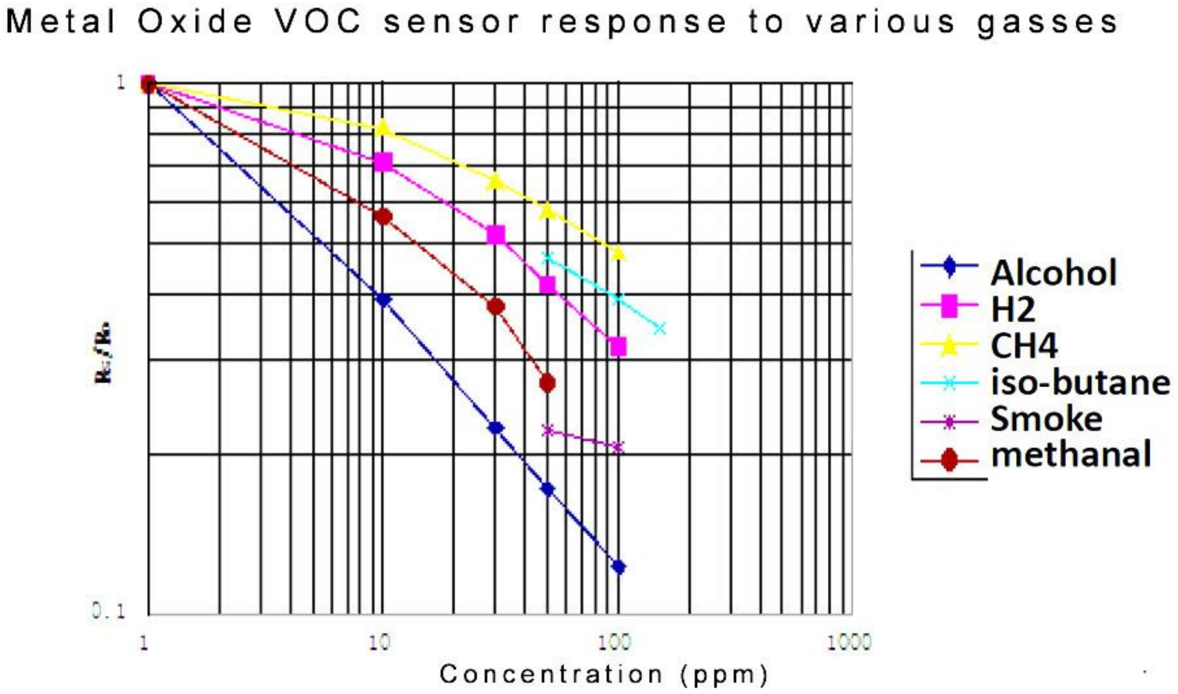
1. When semiconductors (e.g. tin dioxide) are heated in air at high temperature, oxygen is adsorbed on the sensing surface by capturing free electrons.
2. The reduction in free electrons increases the resistance of the sensor.
3. In the presence of reducing gases, the surface density of adsorbed oxygen decreases as it reacts with the reducing gases.
4. Electrons are then released into the tin dioxide, allowing current to flow freely through the sensor.



CHEMICAL

Metal Oxide Gas Sensors (MOS)

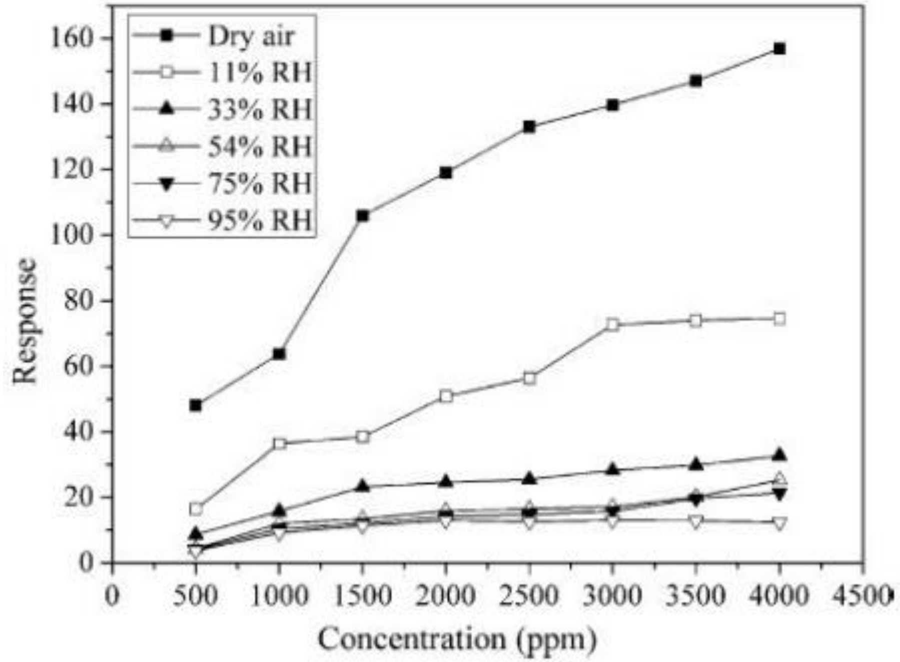
- Selectivity is poor as the sensor is not reacting with any gases but rather the lack of free oxygen.
- The heater is a large source of power which makes MOS sensors unsuitable for wireless applications.



CHEMICAL

Metal Oxide Gas Sensors (MOS)

- Humidity will greatly reduce the sensitivity of a MOS gas sensor.
- Water will react with the free oxygen on the surface to create hydroxyl (OH-).
- Prolong exposure to hydroxyls can also permanently damage the sensor.



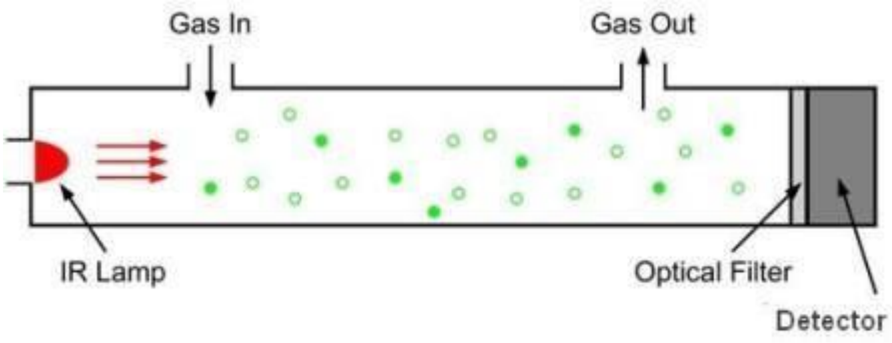
CHEMICAL

Parameter	Metal Oxide Gas Sensor	Electrochemical Gas Sensor
Selectivity	Will react with a wide array of oxygen reducing gases	Can be selective but will still react to oxidizing gases to some extend. Inlet Filters can help
Humidity	The lower the humidity the better. High humidity can permanently damage sensor	Low humidity (<10%) can permanently damage sensor. Change in humidity will affect sensor.
Power	Require about 1W of power	Minimal power 50 mW
Temperature	Zero and sensitivity drift with temperature change. Can operate in lower temperature if heater is appropriately sized.	Below -10C will result in permanent damage of the cell. Zero and sensitivity need to be compensated with temperature change.

CHEMICAL

Nondispersive Infrared (NDIR)

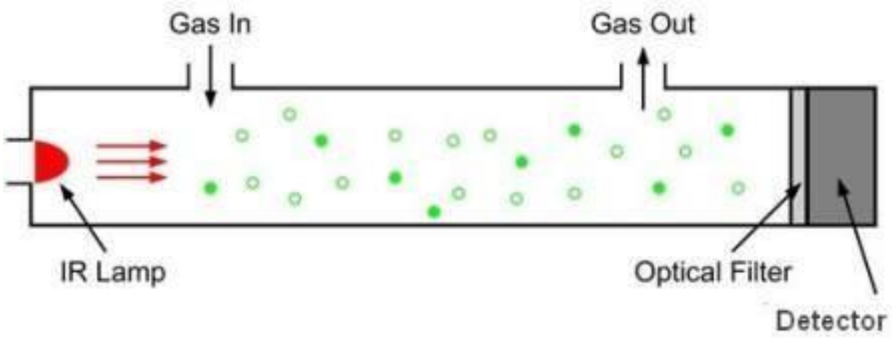
1. An infrared (IR) lamp directs waves of light through a tube filled with a sample of air toward an optical filter in front of an IR light detector.
2. The IR light detector measures the amount of IR light that passes through the optical filter.
3. The IR wavelength must match the absorption band of the target gas. For example 4.2 micron band for CO_2.
4. As the IR light passes through the length of the tube, the target gas molecules absorb the specific band of IR light while letting other wavelengths of light pass through.



CHEMICAL

Nondispersive Infrared (NDIR)

5. At the detector end the remaining light hits an optical filter that absorbs every wavelength of light except the target wavelength (e.g. 4.2 micron for CO_2).
6. Finally, an IR detector reads the remaining amount of light that was not absorbed by the CO_2 molecules or the optical filter.
7. The higher the concentration of absorbing gas the lower the amount of light detected.



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Sensors and Instrumentation

Lecture #20

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Calibration

Calibration Introduction:

What is calibration?

- Calibration is the development of a mathematical model that would describe the behavior of a sensor to the measurand and external environment
- Calibration is the derivation of the static and dynamic characteristics of a sensor.
- Understanding the static and dynamic characteristics of a sensor can be an impossible task.
- Often it is assumed that some characteristics of a sensor are common among all sensors manufactured or at least all sensors in the batch.

Calibration

Calibration Introduction :

The challenge:

To be able to fully characterize all sensor characteristics, the calibration procedure must.

- Provide the exact measurand.
- Hold or change the measurand over time as required by the calibration procedure.
- Control all other factors that may affect sensor response such as external environment and supply voltage.

Calibration

Calibration Introduction :

Measuring Distance:

- A new unit was introduced in 1897 called **Meter** to define distance more accurately and repeatably.
- The challenge was how to calibrate 1 meter?
- The International Bureau of Weights and Measures was created to produce a single prototype meter bar.
- This bar would be the standard of a meter and other meter bars will be produced against it and sent all over the world

Calibration

Calibration Introduction :

Measuring Distance:

- The first issue became temperature variation.
- Thermal expansion forced the Committee to develop a special temperature measuring equipment with a definition of a reproducible temperature scale.
- Not being able to fully control and measure temperature to the required accuracy.
- A new alloy of iron-nickel, which has a coefficient of thermal expansion 20 times less than common steel.
- Which was even not enough, then a new optical method defining 1 meter as:

1650763.73 wavelengths of the orange-red emission line in the electromagnetic spectrum of the krypton-86 atom in a vacuum

Calibration

Calibration Procedure :

Direct Calibration:

- The simplest form of calibration is to generate the measurand and check the sensor response.

- In this method of "Direct calibration" environmental parameters must also be strictly controlled.

- In some cases, it is difficult to produce the measurand with required accuracy.

Calibration

Calibration Procedure :

Co-reference Calibration:

- Another method of calibration is to compare the unit under test with another more accurate and “certified” unit called the standard or reference instrument.
- In this method the measurand does not need to be controlled.
- The first formal procedure for co-reference calibration was developed by USA department of defense in 1950s.
- The procedure called for 10:1 accuracy ration between the reference instrument and the test instrument

Calibration

Calibration Procedure :

Co-reference Calibration:

- 10:1 accuracy ratio was difficult to maintain for electronic sensors, in 1970s the ratio was reduced to 4:1.
- In modern sensors even a 4:1 ratio is difficult to achieve.
- A limited calibration can be performed if a 4:1 ratio is not achievable but required.
- For example:
  - if accuracy of the reference instrument is 1% and the test system has accuracy of 3%.
  - A limited calibration means that the accuracy can be stated only at 4% regardless of the test systems accuracy

Calibration

Sensor VS System:

- When calibrating ideally the entire measurement system should be calibrated rather than just the sensor.

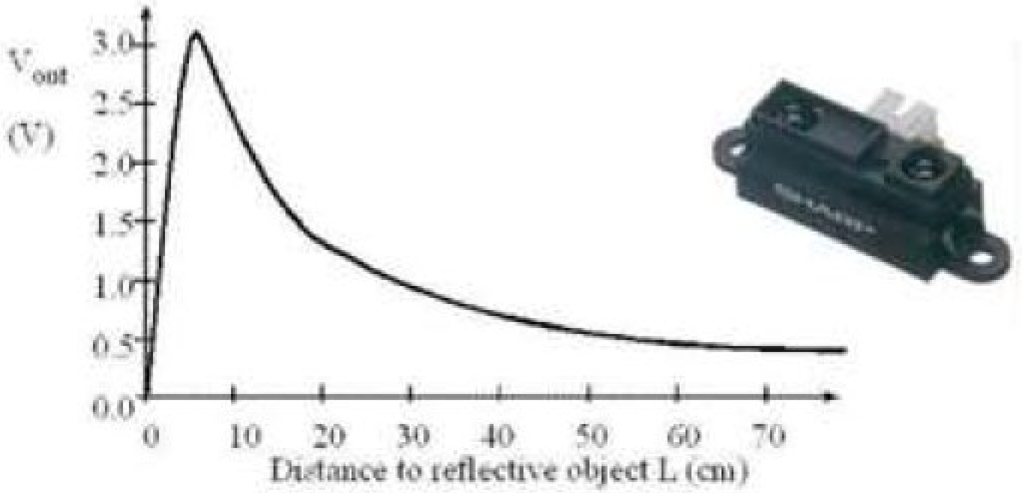
- Signal conditioning circuits, digitization, digital filters, and sampling components can all affect accuracy, rate of response and other sensor parameters

Calibration

Transfer Function:

- In theory, every sensor should have an ideal stimulus-output relationship.
- This mathematical model (transfer Function) would represent the output (E) of the sensor as a function of the stimulus (s).
- The transfer function can be defined as:

$$E = f(s)$$



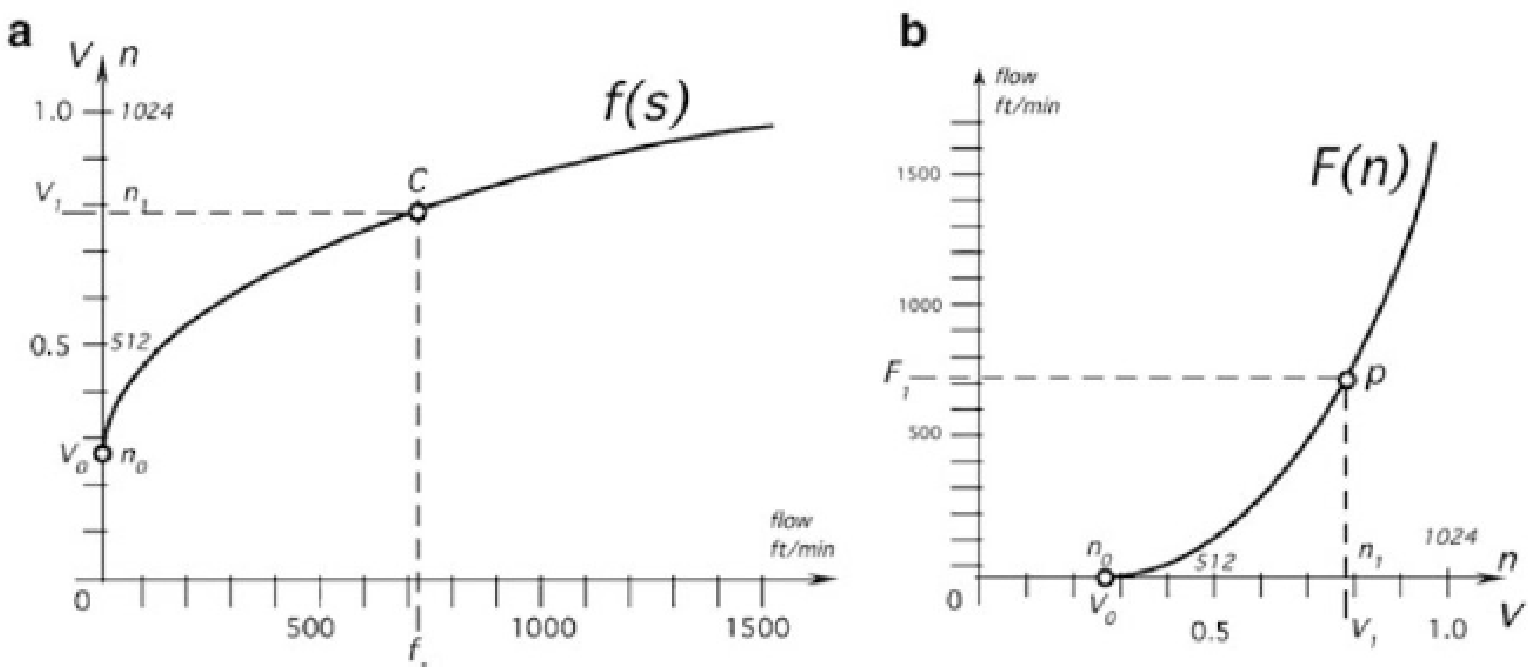
Calibration

Transfer Function:

- The more useful model for sensor design, would be the inverse transfer function that would define the true stimulus given the sensor output:

$$s = f^{-1}(E)$$

$$s = F\ (E)$$



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Transfer Function:

Static VS Dynamic Transfer Function:

- The transfer function $E = f(s)$ is a static transfer function as it is time invariant.
- A dynamic transfer function will have a more complicated time varying parameters.
- For example:

$$E = f(s,\ ds/dt,\ Lt)$$

Where: ds/dt is the time derivative of the stimulus and Lt is the life of the sensor

The End of Lecture #20

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Sensors and Instrumentation

Lecture #21

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Calibration

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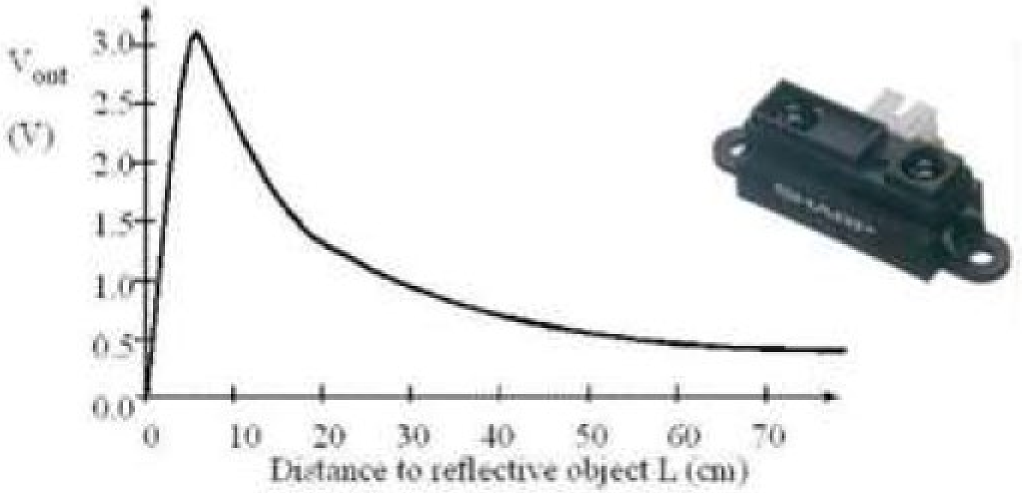

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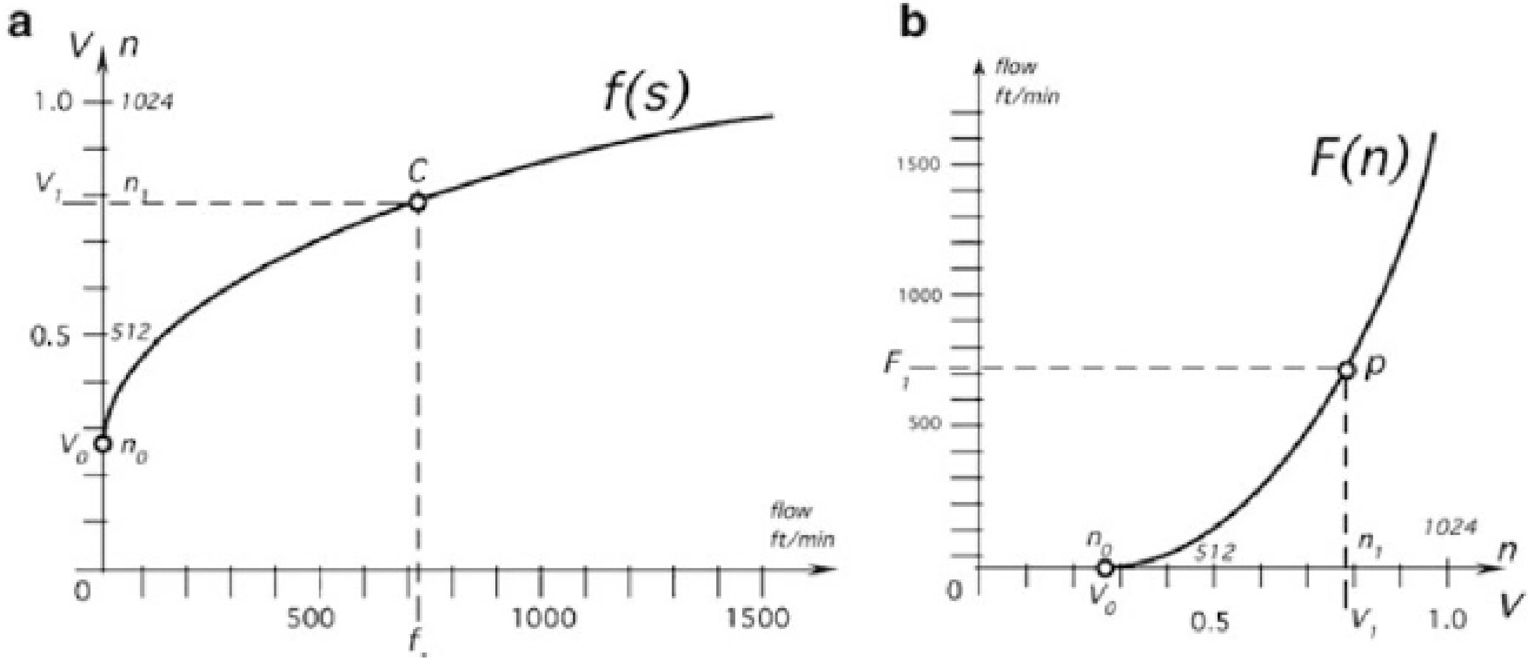

Calibration

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- A dynamic transfer function will have a more complicated time varying parameters.
- For example:

$$E = f(s,\ ds/dt,\ Lt)$$

Where: ***ds/dt*** is the time derivative of the stimulus and ***Lt*** is the life of the sensor

Calibration

Transfer Function:

Ideal VS Actual Transfer Function:

- The transfer function $\boldsymbol{E = f(s)}$ is an ideal transfer function, BUT
- In reality sensors will have drift, random noise, digitization error, etc.

$$E = f(s) + \mu_o + \varepsilon$$

Where: $\boldsymbol{\mu_o}$ is the systematic error and $\boldsymbol{\varepsilon}$ is the random noise

- Systematic error can be minimized through calibration.
- Random noise can be minimized through analog or digital signal processing.

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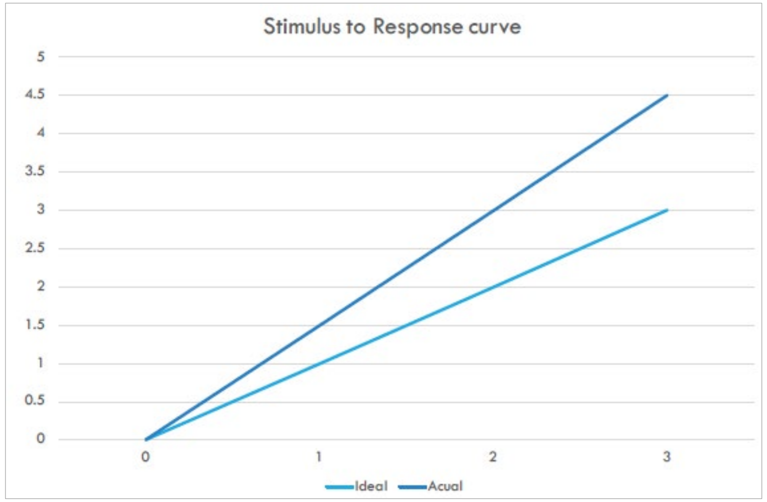
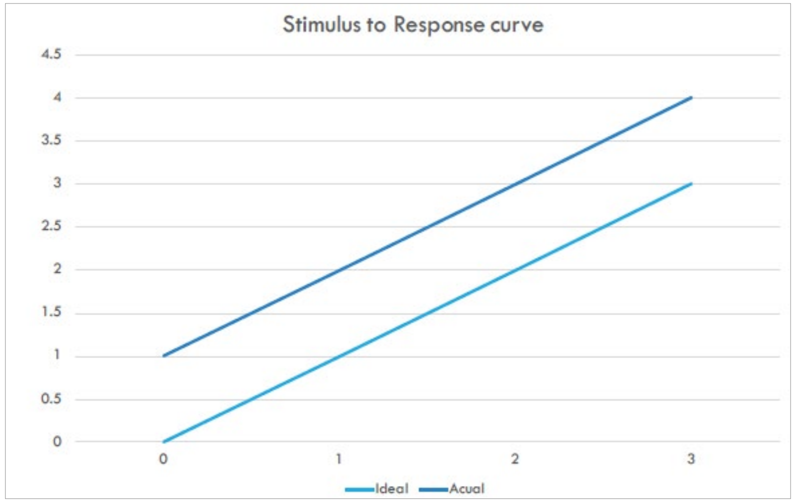
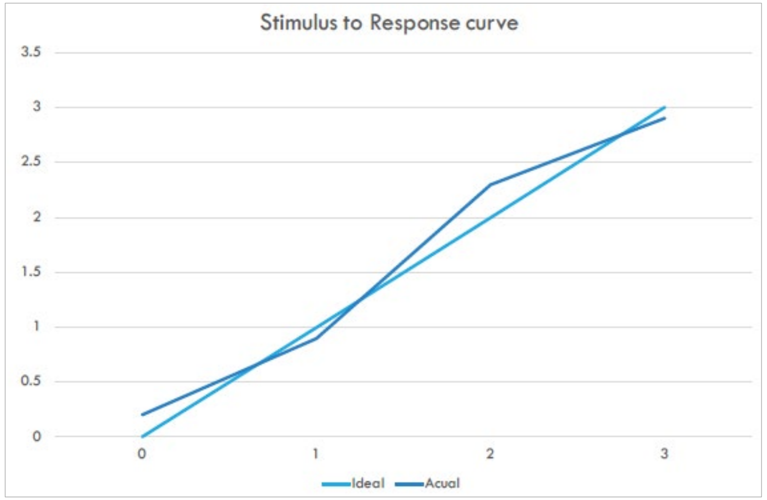
Calibration

Transfer Function:

Ideal VS Actual Transfer Function:







Calibration

Transfer Function:

Functional Approximation:

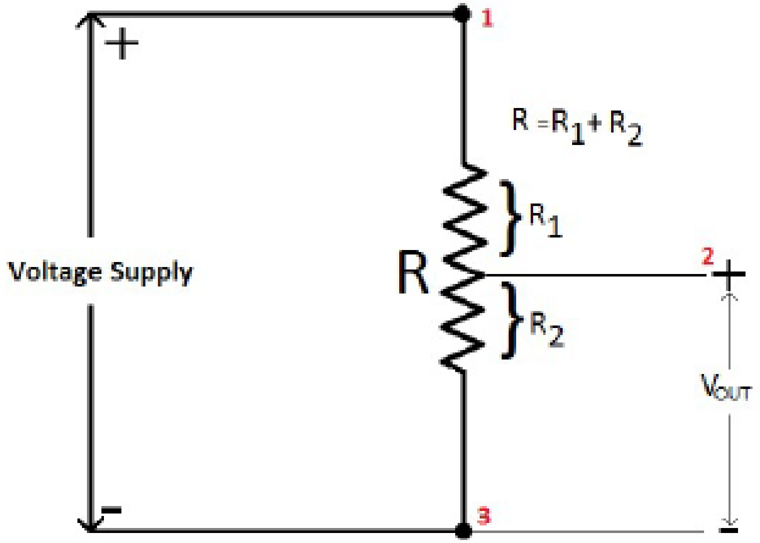
- Ideally the transfer function ***E = f(s)*** or the inverse transfer function of ***s = F(E)*** can be derived from the physical law transduction effect that forms the basis of the sensors.
- For example in a linear potentiometer used to measure distance (***d***), the ohms law can be applied:

$$V_{out} = V_s\, R_2/R$$

Assuming linear change in resistance with distance traveled.

$$V_{out} = V_s d/D$$

$$d = V_{out}\, D/V_s$$

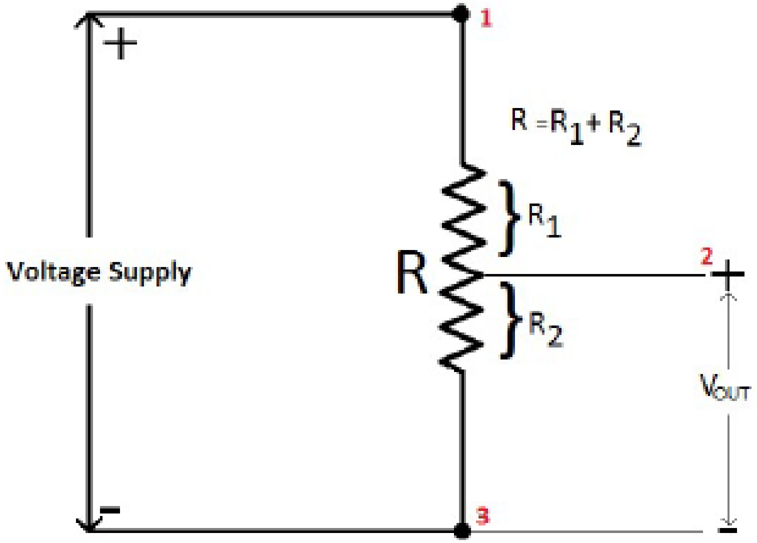


Calibration

Transfer Function:

Functional Approximation:

- The ideal transfer function may differ from the actual transfer function since:
  - The potentiometer will likely have a base resistance and will not go from 0 to R in resistance.
  - The change in resistance will not be exactly linear.
  - Temperature and relative humidity will affect the resistance of the potentiometer.
  - Supply voltage can be different than the ideal assumed voltage



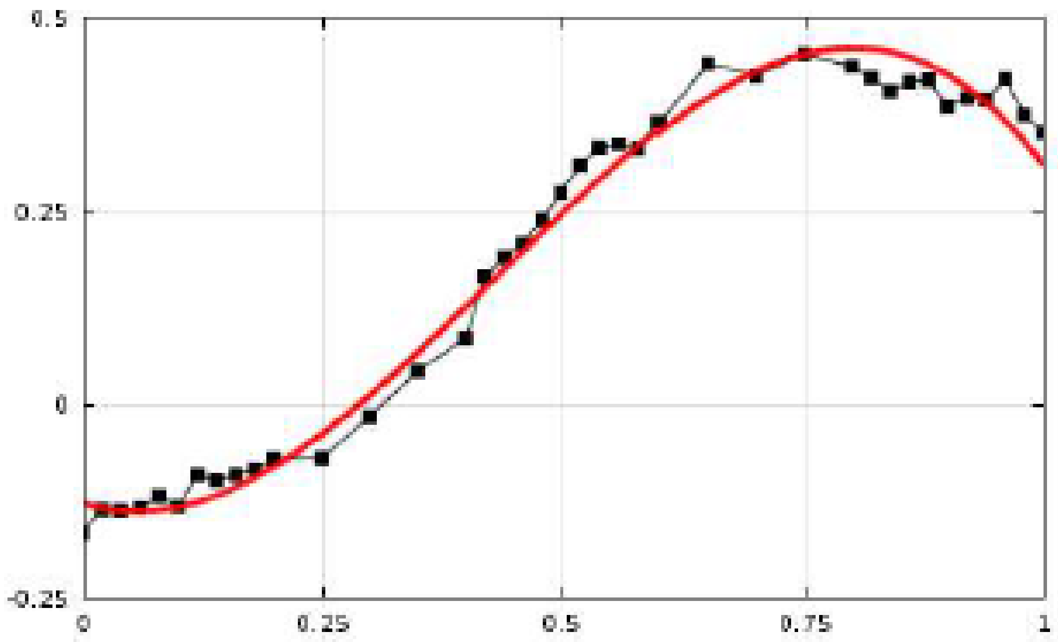
Calibration

Transfer Function:

Functional Approximation:

- Instead of determining the ideal transfer function an approximate transfer function can be obtained.

- Approximation is a selection of a suitable mathematical expression that can fit the calibration data as close as possible.

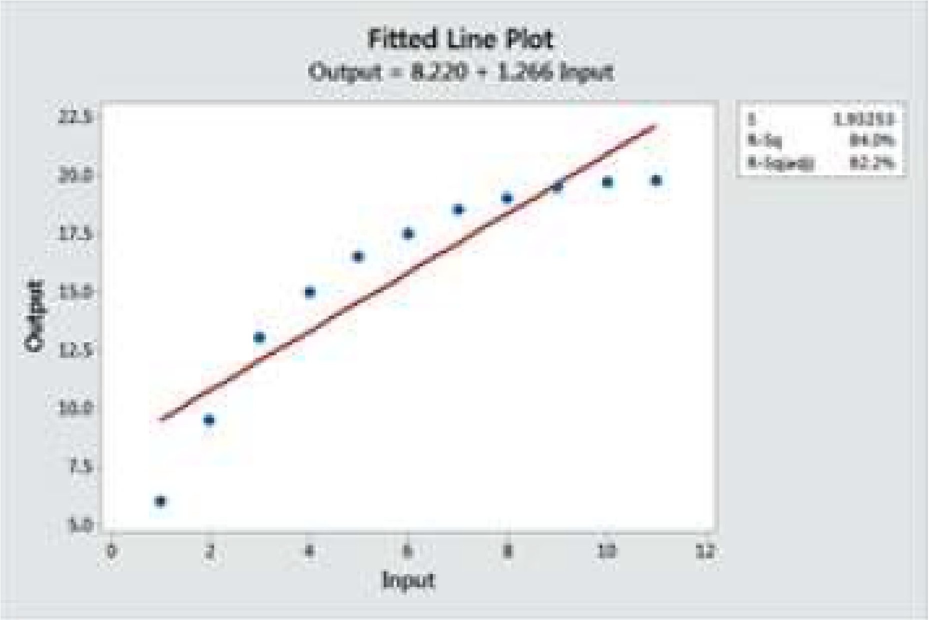


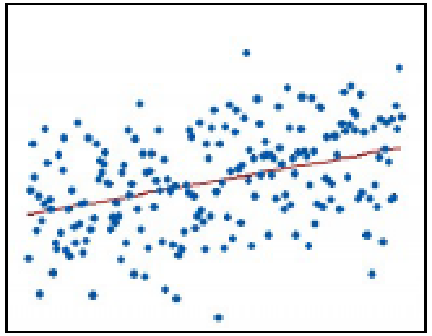
Calibration

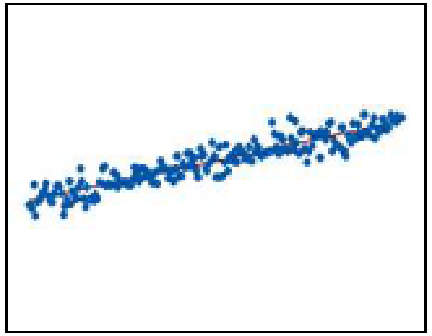
Transfer Function:

Functional Approximation:

- In general, it is better to start with a model and only use more complex ones if required.
- The more complex the model, the larger the data set is required during calibration.
- To test the validity of the model, a number of metrics can be calculated:
  - Standard error of the regression (***S***).
  - ***R***-Squared.
  - Adjusted ***R***-Squared.







Calibration

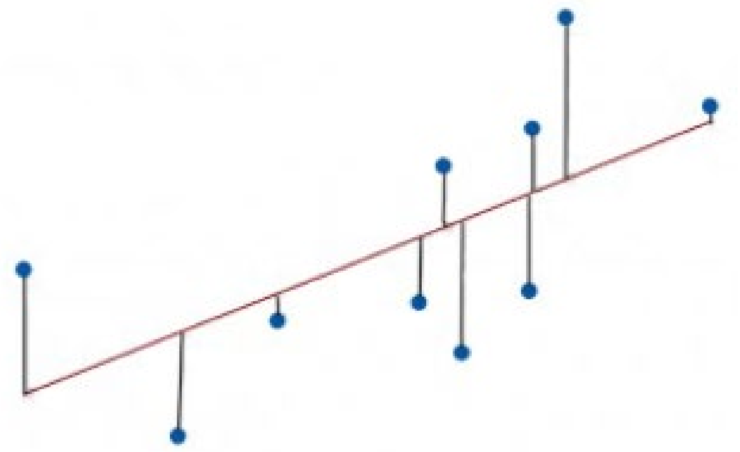
Transfer Function:

Functional Approximation:

- The standard error of the regression (***S***):

  - Represents the average distance that the observed values fall from the transfer function.

  - Values are in the same unit as the measurand.



$$S = \sqrt{\frac{\sum(Y - Y')^2}{N}}$$

Where ***Y*** is the actual value, ***Y'*** is the estimated value and ***N*** is the number of calibration points.

  - Lower ***S*** values mean a better fit of the transfer function.

Calibration

Transfer Function:

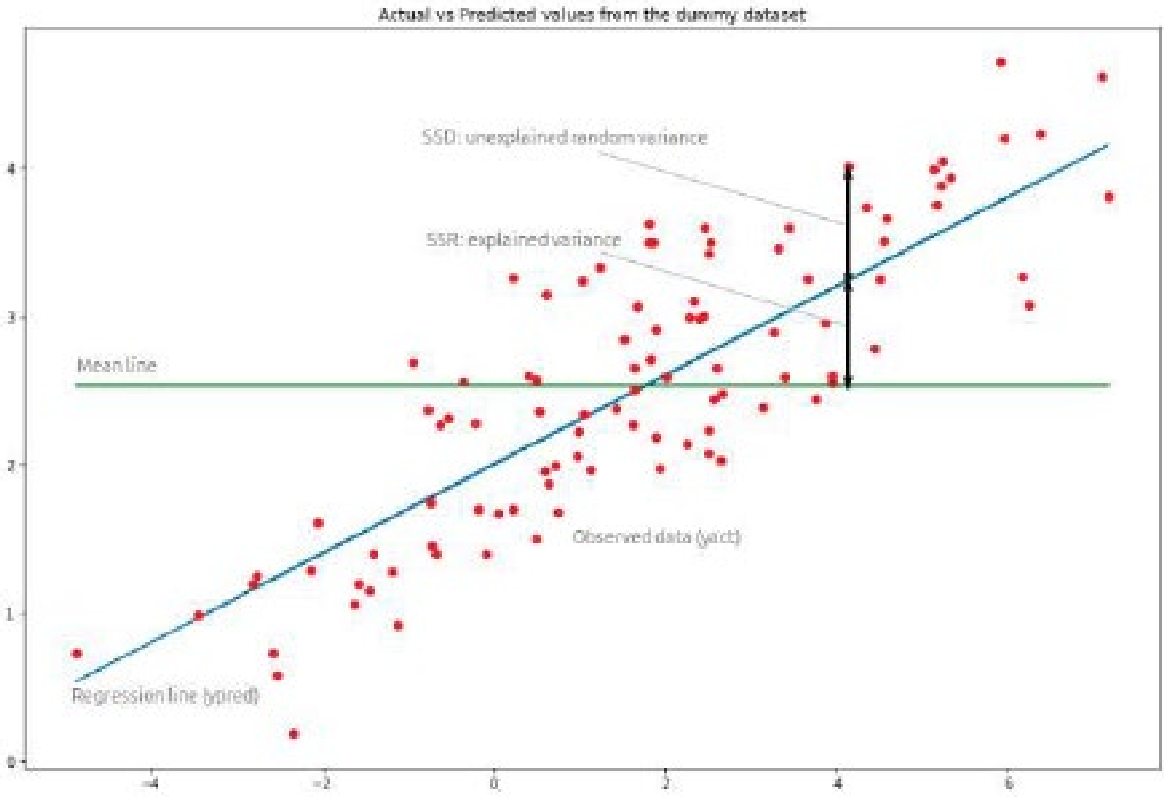
Functional Approximation:

➢ The R-Square Error (coefficient of determination):

- Represents the error between the observed values and the transfer function as a percentage of the total variance of the measurand.

- Values are a percentage of the total.

$$S = 1 - \frac{\sum (Y_n - f_n)^2}{\sum (Y_n - \bar{Y})^2}$$



Where $\boldsymbol{Y_n}$ is the actual value, $\boldsymbol{f_n}$ is the estimated value and $\boldsymbol{\bar{Y}}$ is the average of all $\boldsymbol{Y}$ values..

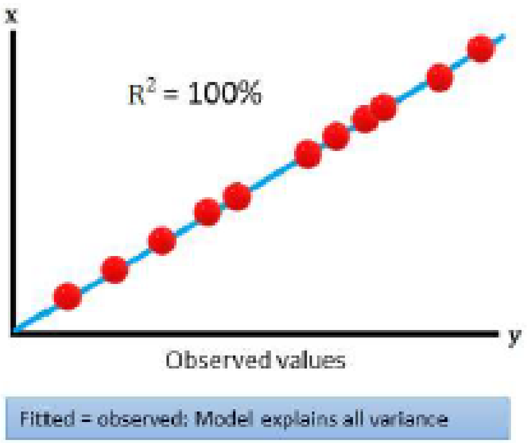
- $R^2 = 1$ is a perfect fit.

Calibration

Transfer Function:

Functional Approximation:

Comparison of R-Squared for different linear models (same data set)



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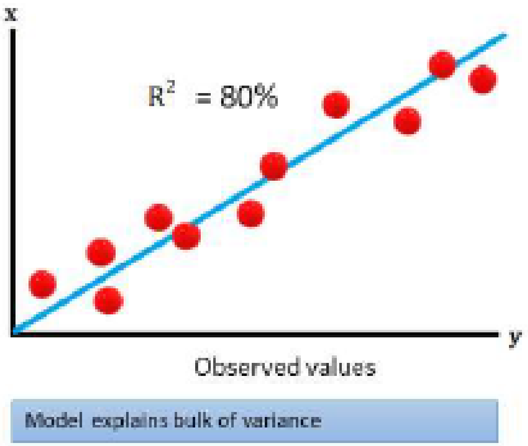
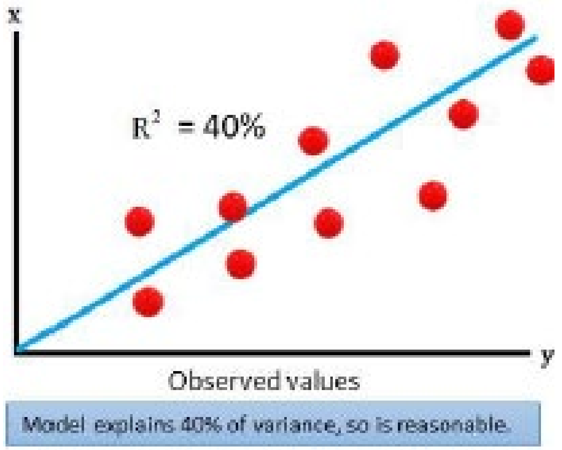
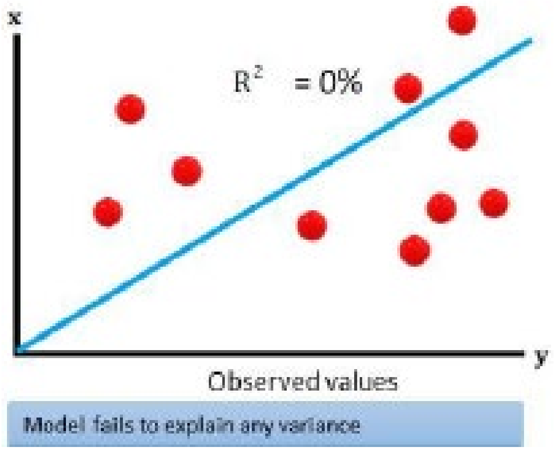


Good



OK



Inconsistent

Calibration

Transfer Function:

R-Square vs Standard error:

- The standard error (***S***) of the regression provides the absolute measure of the typical error between the transfer function and the actual observations:
  - Assuming ***S*** to be close to the population variance it is possible to estimate the precision of the sensor (95% interval) as ±2***S***
- R-squared provides the relative measure of the percentage of the dependent variable variance that the model explains:
  - For example: R2=76% means that the model can only explain 76% of the variance in the data. There is 24% of the variance that is either noise or is not modeled correctly.

The End of Lecture #21