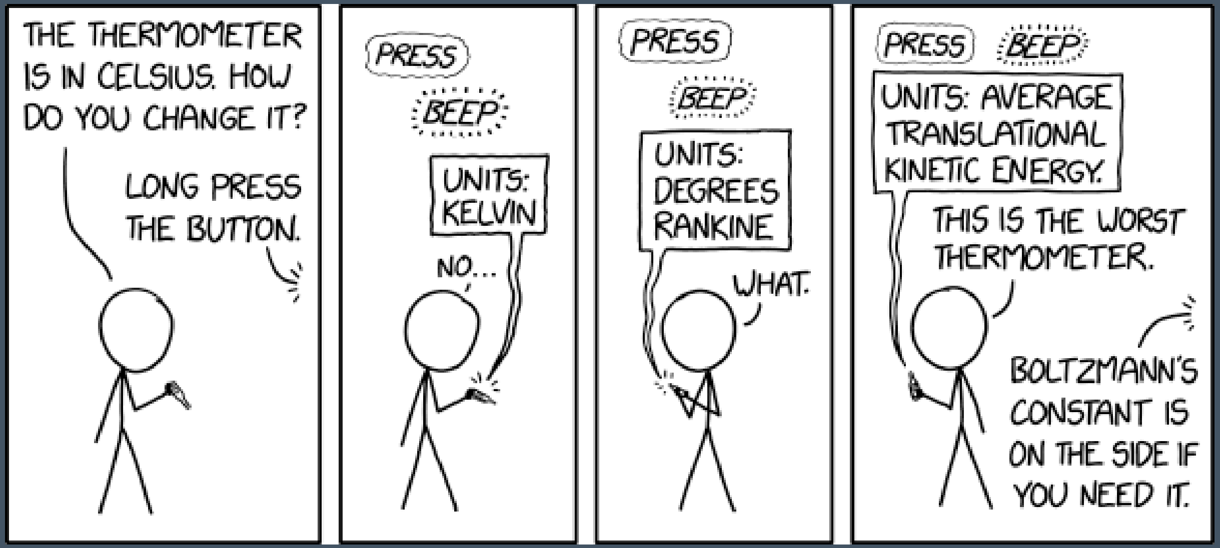
# Measurement Systems

## 1. Introduction to Measurement Systems

Dr. Ronan McCann

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# Course Overview

- Topics:
  - Measurement Systems
  - Sensors
  - Signal Amplification
  - Signal Conditioning
  - Analog-to-Digital Conversion
  - Specialised Sensing Systems
- Design, analysis and implementation of a number of complete measurement systems.
- General principles of measurement systems, including sensors, signal conditioning, signal processing and presentation.
- Lab programme: National Instruments LabVIEW and MultiSim.

# Course Overview

Reading List:

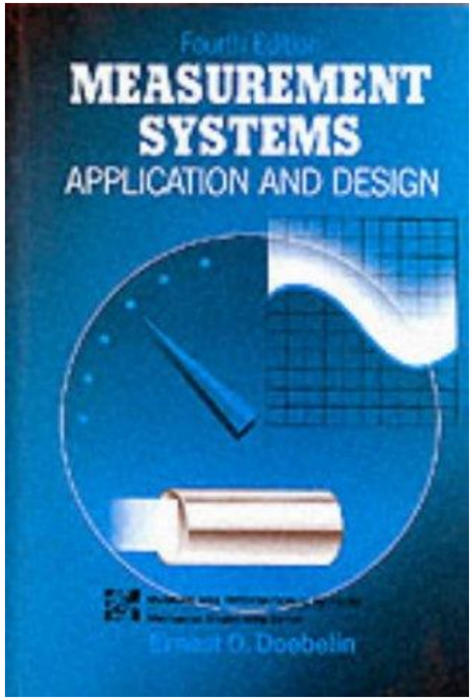
Bentley, J. *Principles of Measurement Systems*.

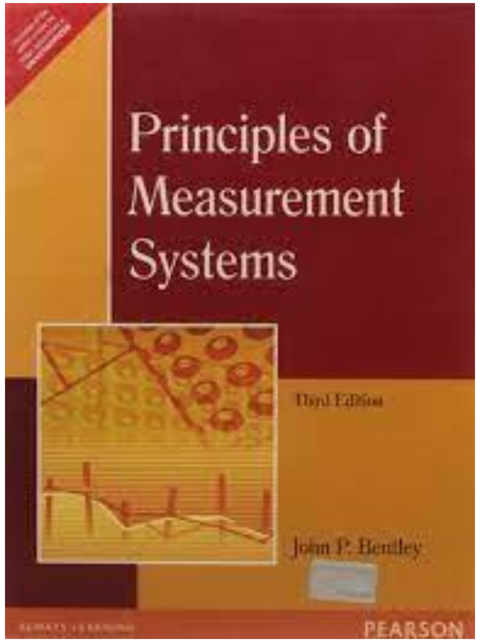
Doebelin, E. *Measurement Systems Applications and Design*. 5th ed.

Horowitz, P. and W. Hill. *The Art of Electronics*..

Lawless, B. *Fundamental Analog Electronics*.

Waldemar, N. *Measurement Systems and Sensors*.



# Course Overview

Structure – must get 40% overall:

- Final Exam: 60% (35% to pass)
- Labs: 30% (3 x 10%) (Week 2-11)<br>(35% to pass, must attend 75%)
- Presentation 10% (Week 12)

Timetable:

- Labs (Computing): Tue 0915-1115hrs W05
- Labs (Physics): Thur 1515-1715hrs W05
- Lectures:

| | | |
|---|---|---|
| Tue | 1615 | FTG12 |
| Wed | 1315 | AT105 |
| Fri | 1215 | F28 |

# Measurement Systems

GPS

Microphone

Accelerometer

Touch

Camera(s)

Orientation

Compass

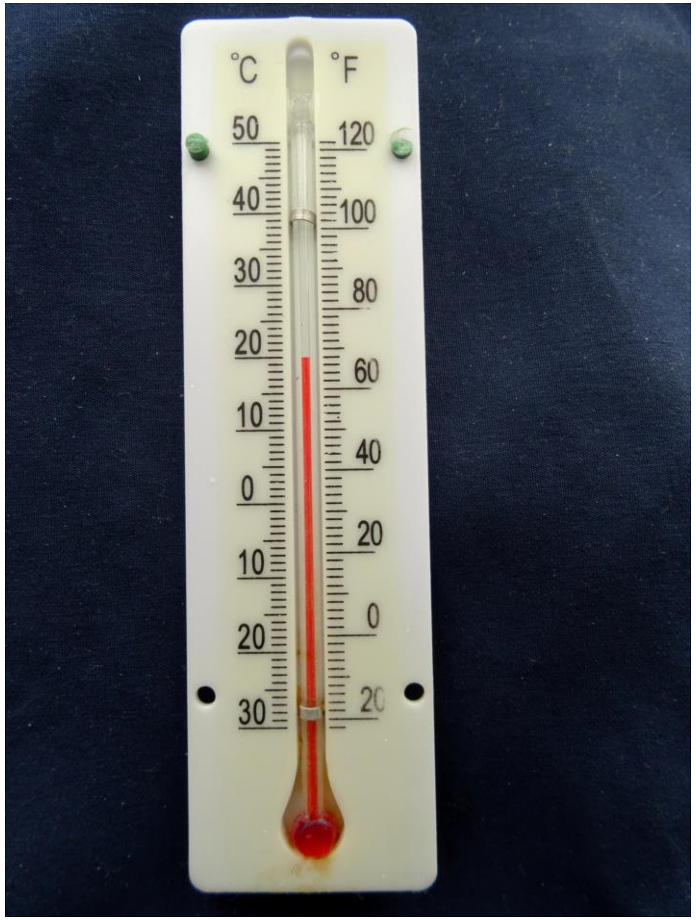
# Measurement Systems

"Dumb"

"Smart"

# Why measure?

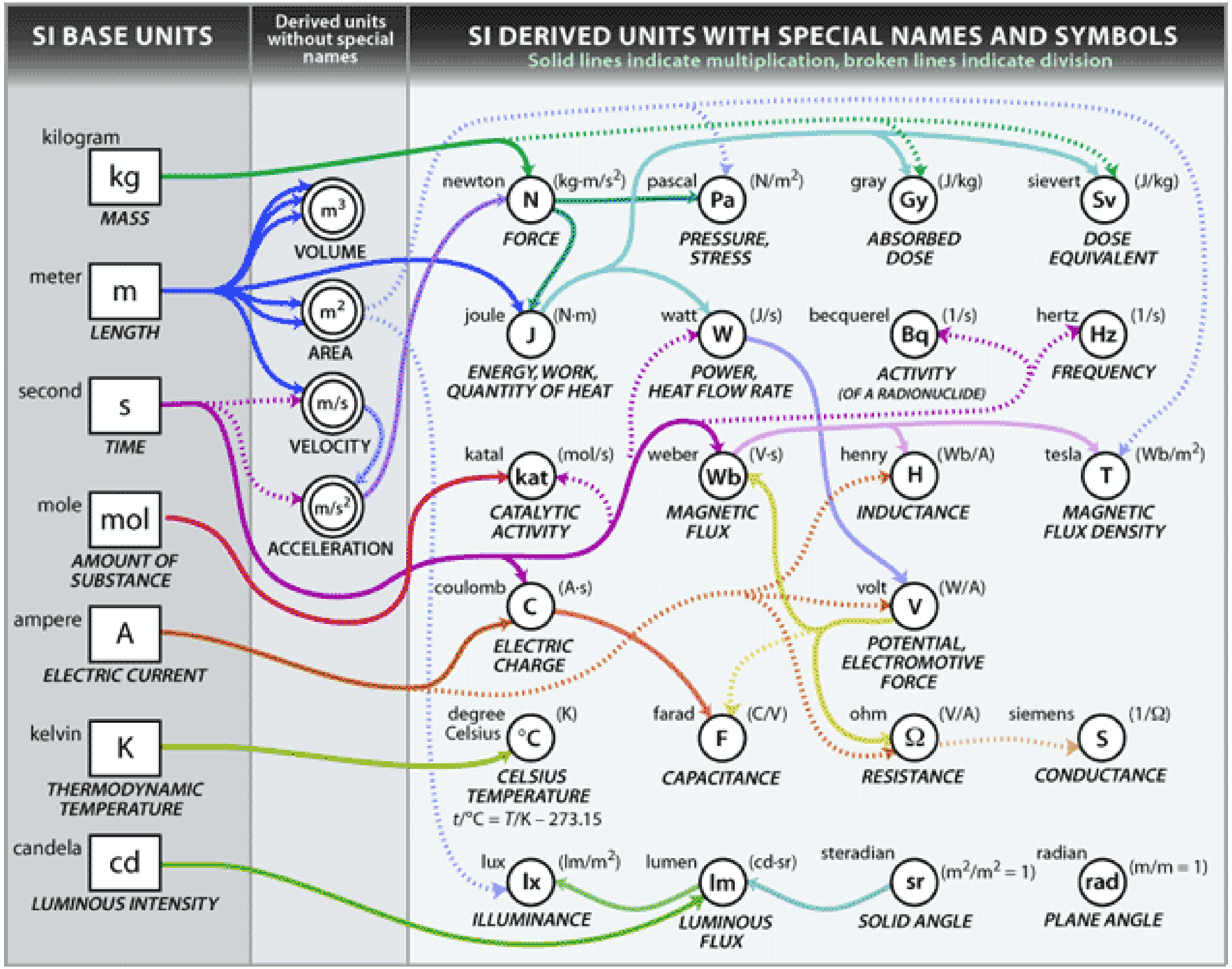
- Numbers allow us compare what we expected to what we saw, and what others saw
- Scientists can test a theory
- Engineers can test a design
- Measurements are how computers sense the world
- Measurements also tell us what you don’t know



# What are measurements?

- Measurements transform the physical world into data
- When we measure an object we determine a "quantity"
- A quantity is:
  - Distinguished (qualitative)
  - Determined (quantitative)
- Examples:
  - distance, time, velocity, acceleration, mass, force
  - What about... Brightness?

# International System (SI) of Units



# International System (SI) of Units

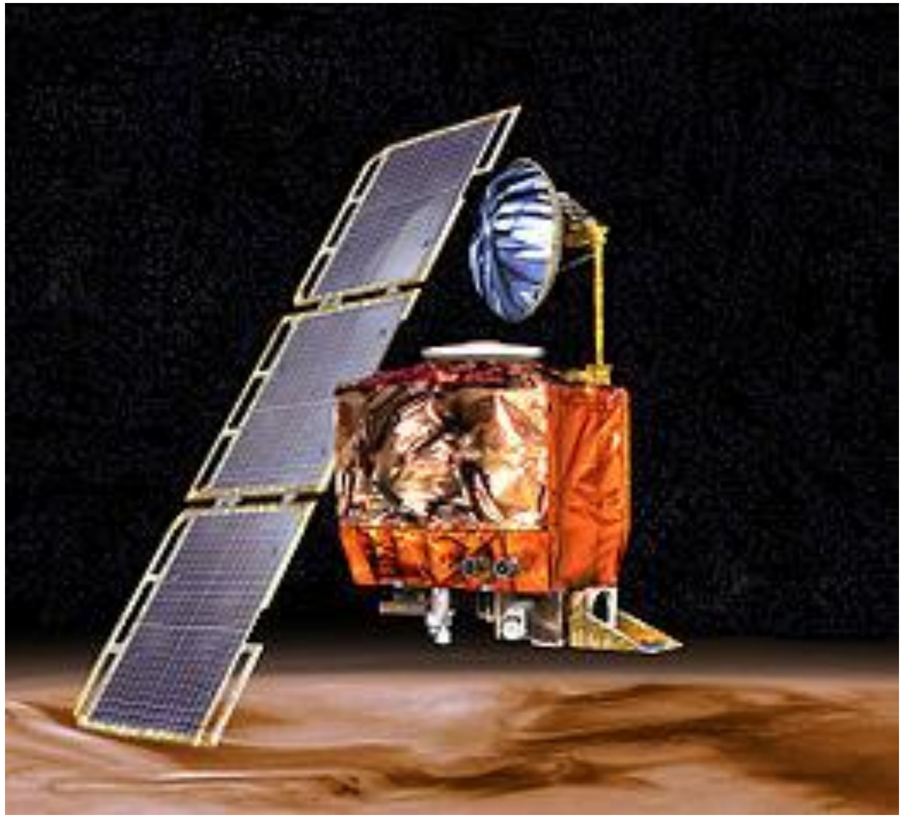
## SI photometry quantities

V·T·E

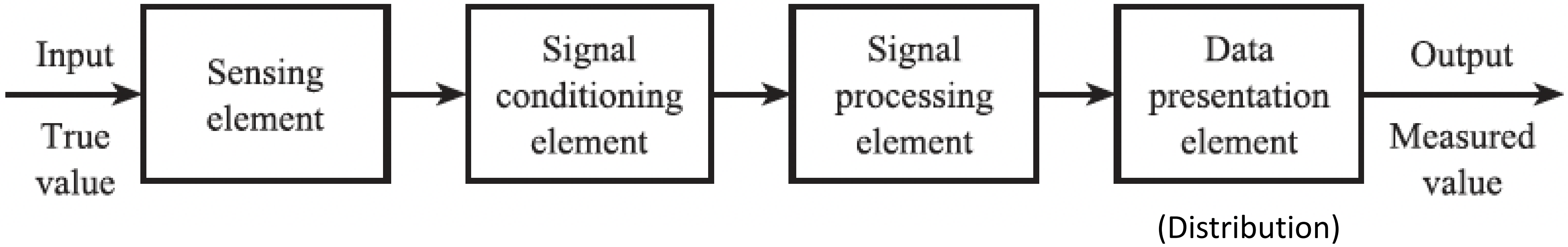
| Quantity | | Unit | | Dimension | Notes |
|---|---|---|---|---|---|
| Name | Symbol[nb 1] | Name | Symbol | Symbol[nb 2] | |
| **Luminous energy** | $Q_v$[nb 3] | lumen second | lm⋅s | **T J** | The lumen second is sometimes called the *talbot*. |
| **Luminous flux, luminous power** | $\Phi_v$[nb 3] | lumen (= candela steradian) | lm (= cd⋅sr) | **J** | Luminous energy per unit time |
| **Luminous intensity** | $I_v$ | **candela** (= lumen per steradian) | **cd** (= lm/sr) | **J** | Luminous flux per unit solid angle |
| **Luminance** | $L_v$ | candela per square metre | cd/m$^2$ (= lm/(sr⋅m$^2$)) | **L$^{-2}$J** | Luminous flux per unit solid angle per unit *projected* source area. The candela per square metre is sometimes called the *nit*. |
| **Illuminance** | $E_v$ | lux (= lumen per square metre) | lx (= lm/m$^2$) | **L$^{-2}$J** | Luminous flux *incident* on a surface |
| **Luminous exitance, luminous emittance** | $M_v$ | lumen per square metre | lm/m$^2$ | **L$^{-2}$J** | Luminous flux *emitted* from a surface |
| **Luminous exposure** | $H_v$ | lux second | lx⋅s | **L$^{-2}$T J** | Time-integrated illuminance |
| **Luminous energy density** | $\omega_v$ | lumen second per cubic metre | lm⋅s/m$^3$ | **L$^{-3}$T J** | |
| **Luminous efficacy (of radiation)** | $K$ | lumen per watt | lm/W | **M$^{-1}$L$^{-2}$T$^3$J** | Ratio of luminous flux to radiant flux |
| **Luminous efficacy (of a source)** | $\eta$[nb 3] | lumen per watt | lm/W | **M$^{-1}$L$^{-2}$T$^3$J** | Ratio of luminous flux to power consumption |
| **Luminous efficiency, luminous coefficient** | $V$ | | | **1** | Luminous efficacy normalized by the maximum possible efficacy |

# Standards are important

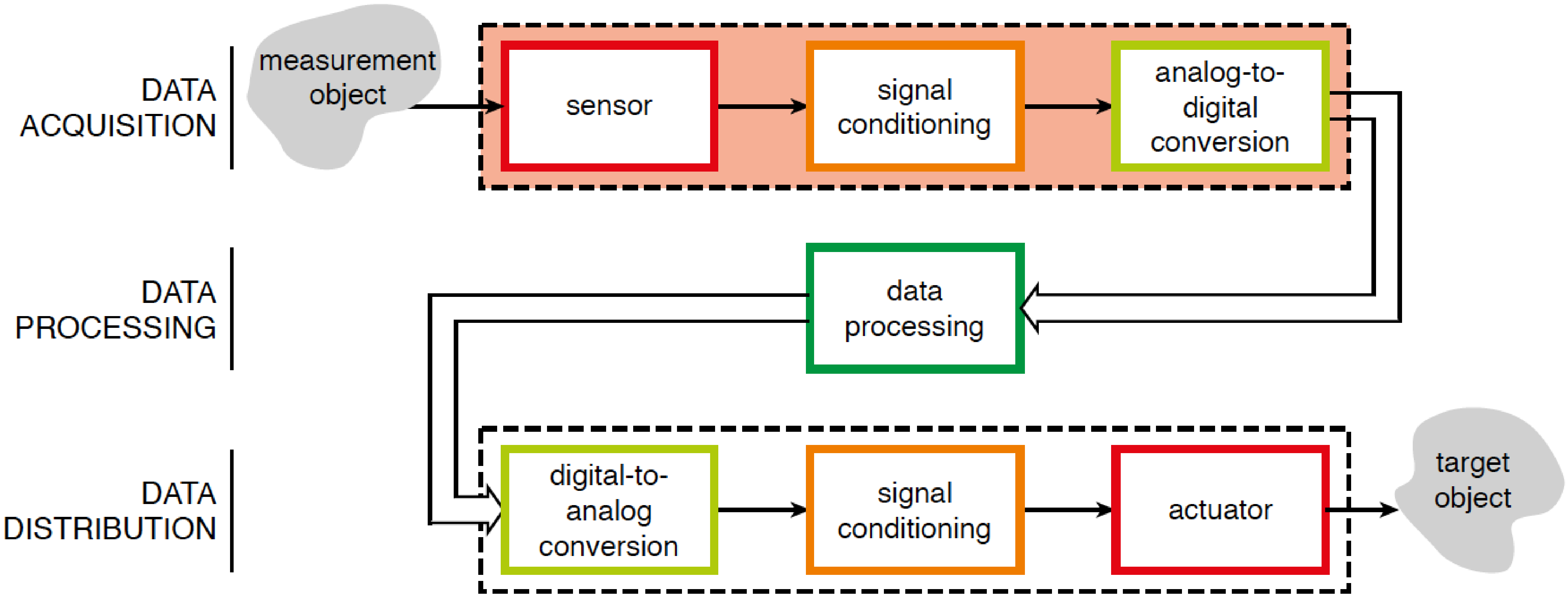
- The Mars Climate Orbiter, launched in 1998 to Mars
- NASA use SI Units
(newton-seconds)
- Lockheed Martin use US customary
units (foot-pounds-second)
- Impulse calculations were off by a factor of 4.5 and
probe went into atmosphere instead of orbit
- How much did this mistake cost?
- Total cost:  $495 million (2022)



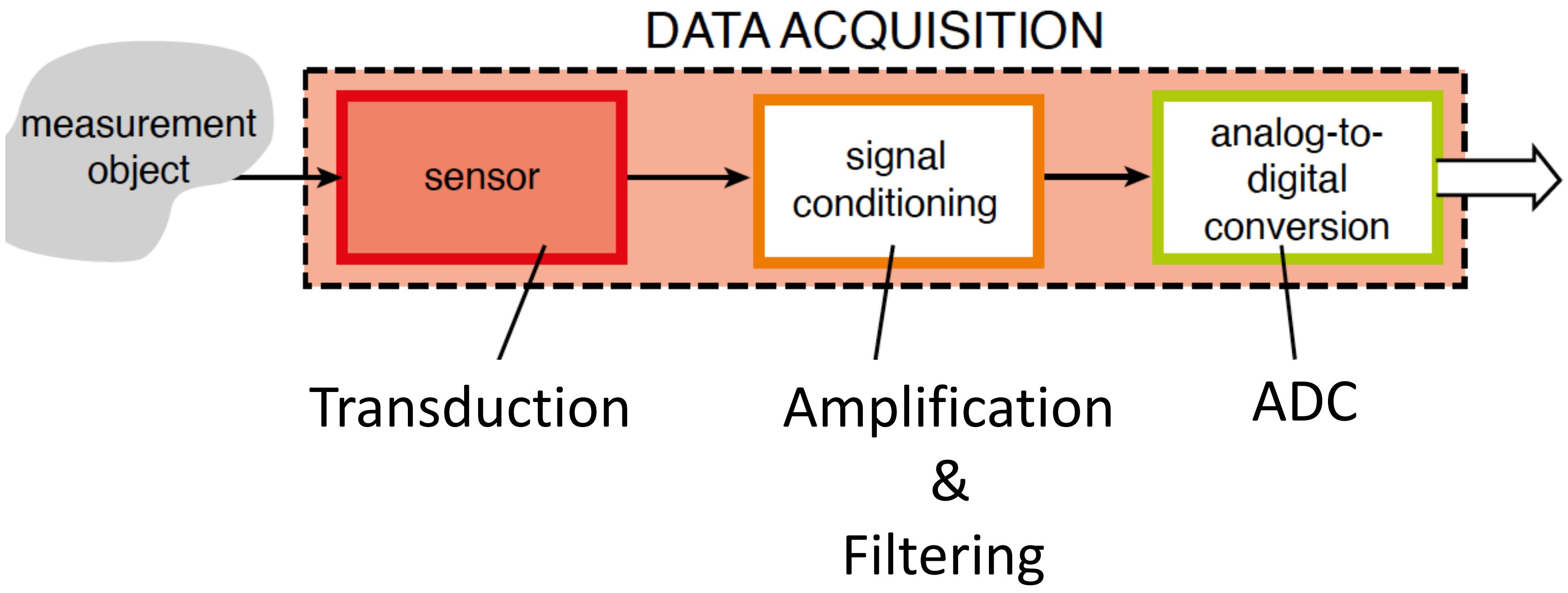
# Overview of measurement systems



# Overview of measurement systems



# Overview of measurement systems

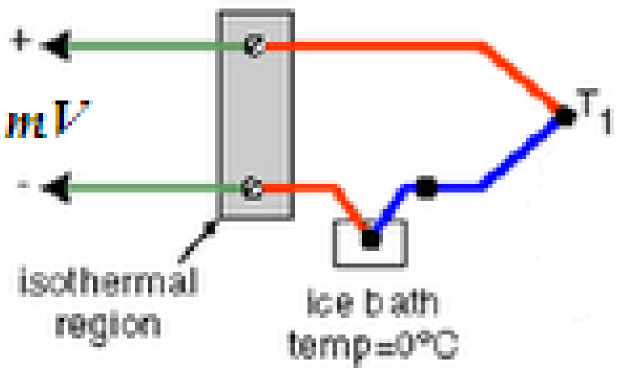


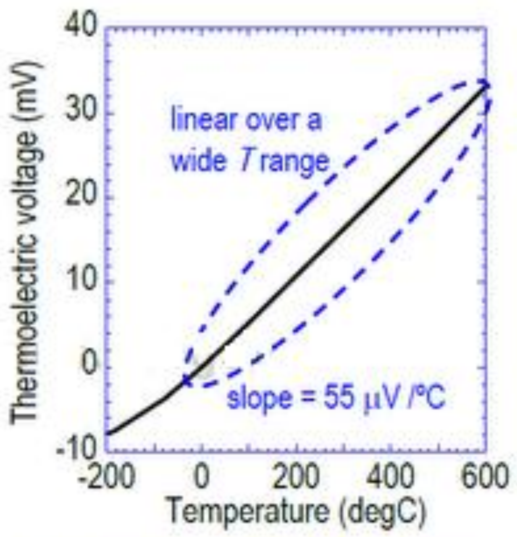
# Sensor

- In direct contact with the process or system being measured and gives an output which depends in some way of the variable to be measured – Process is called Transduction

***Examples***

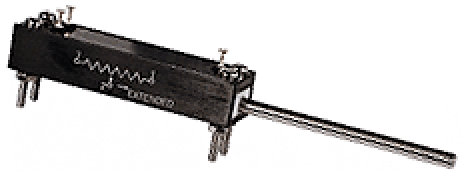
- Thermocouple where mV output depends on the temperature



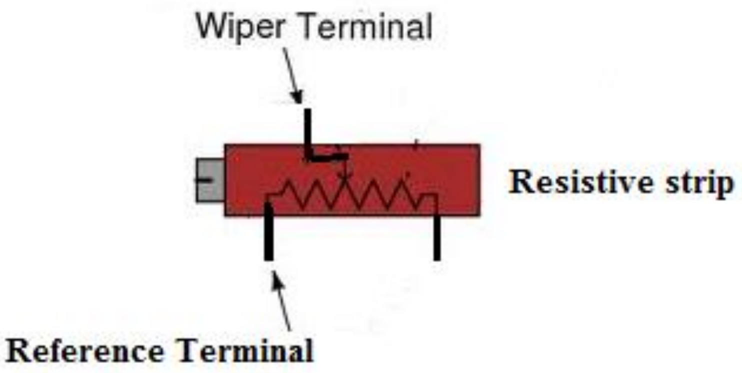




*Thermoelectric voltage of the J-type thermocouple junction*

- A position or linear displacement



*Linear potentiometer construction*

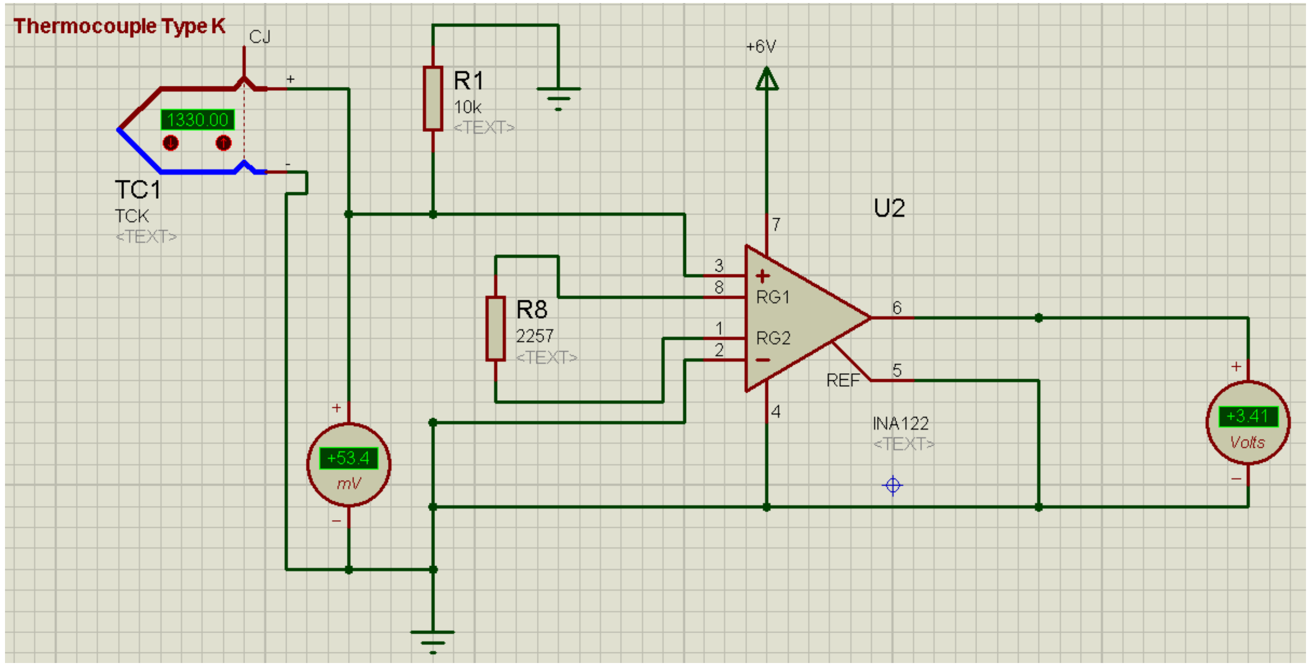


# Conditioning Element

- Takes output from the sensing element and converts it into a form more suitable for further processing (usually into a DC voltage).

***Examples***

• Voltage amplification from mV to V

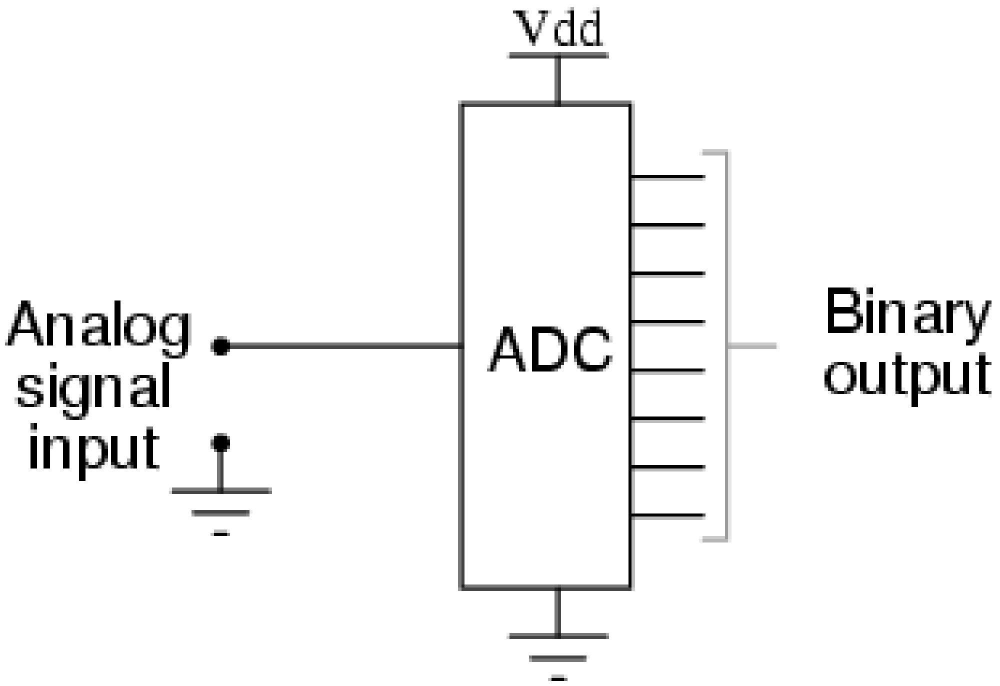


# Analog–to–digital Conversion

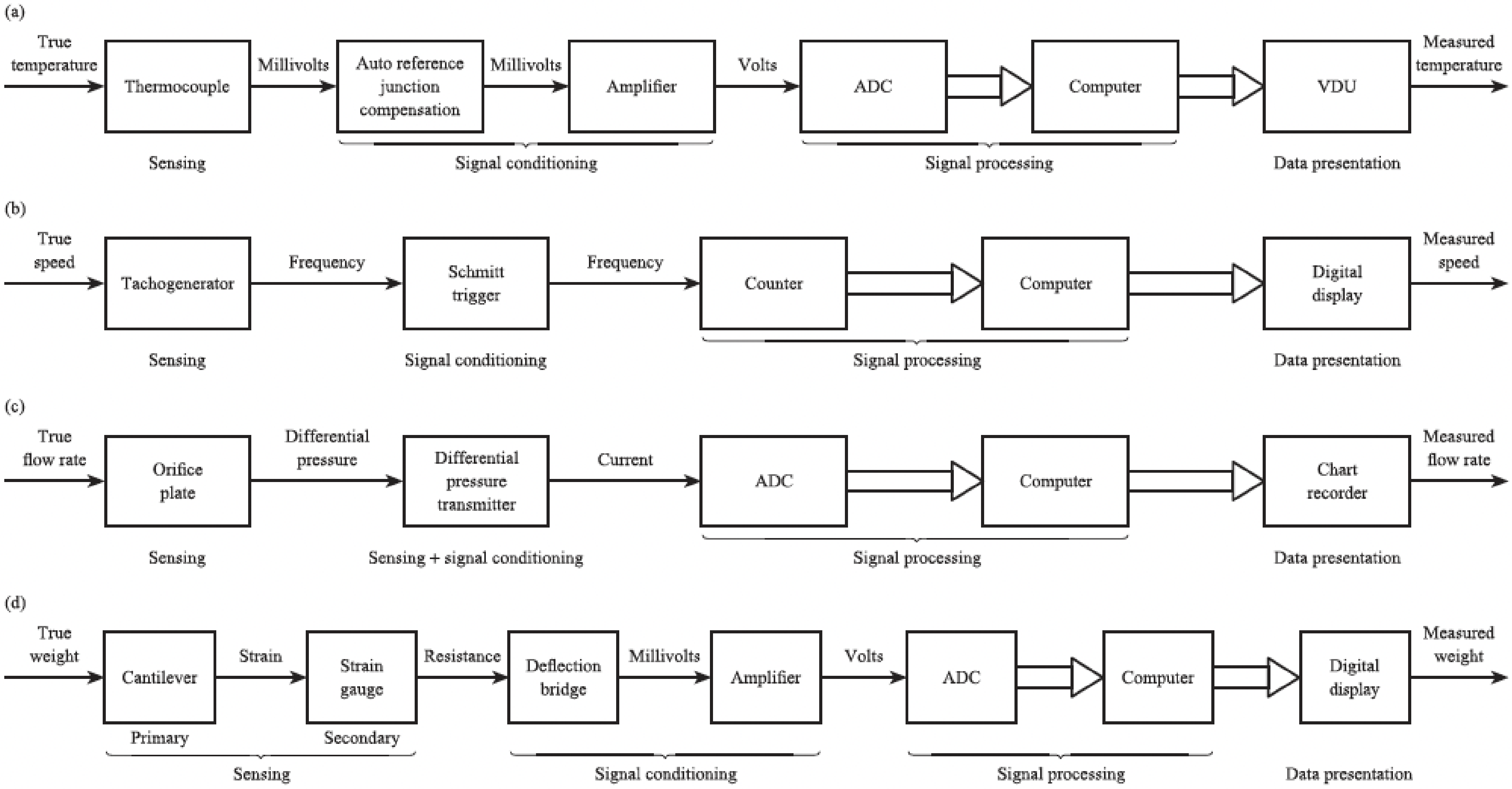
– Takes output of the conditioning element and converts it into a form more suitable for presentation.

***Examples***

• Analog to digital converter, abbreviated ADC

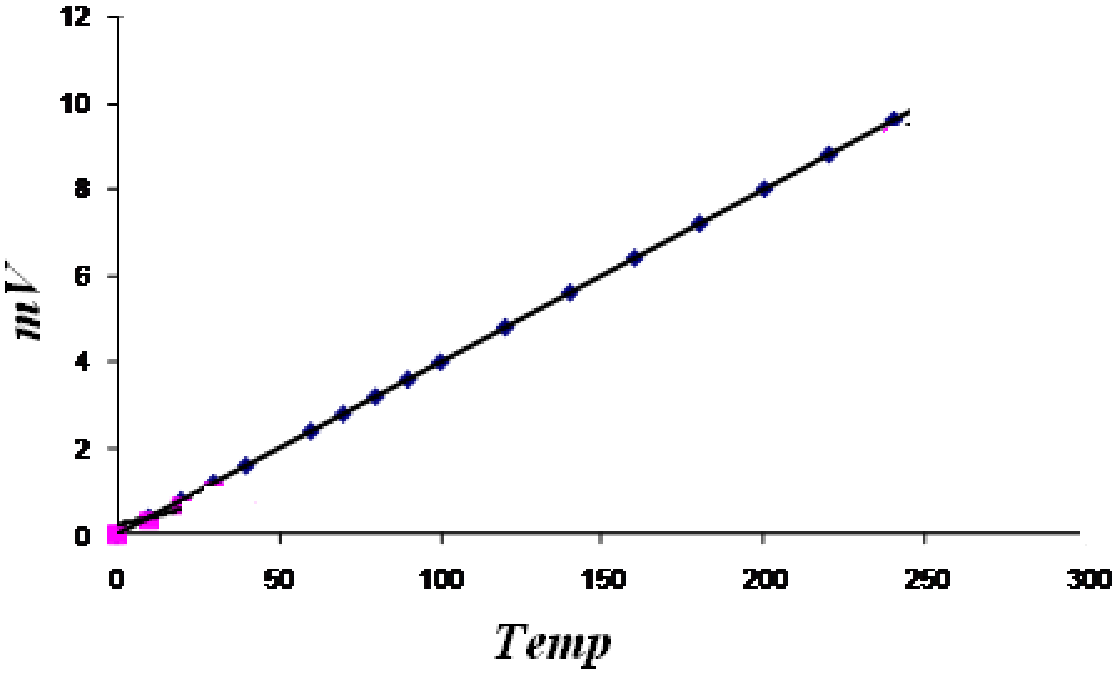



# Types of measurement systems

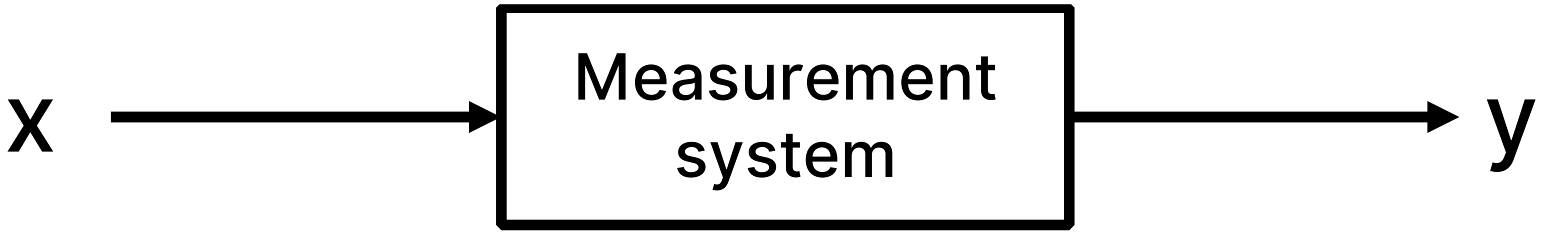


# Range

- All sensors have an operation range
- Input range of $I_{MIN}$ to $I_{MAX}$ and output range of $O_{MIN}$ to $O_{MAX}$
- Example Thermocouple, sensing element that converts temperature to voltage
- Input range 0 oC to 250 oC and output range 0 to 10 mV

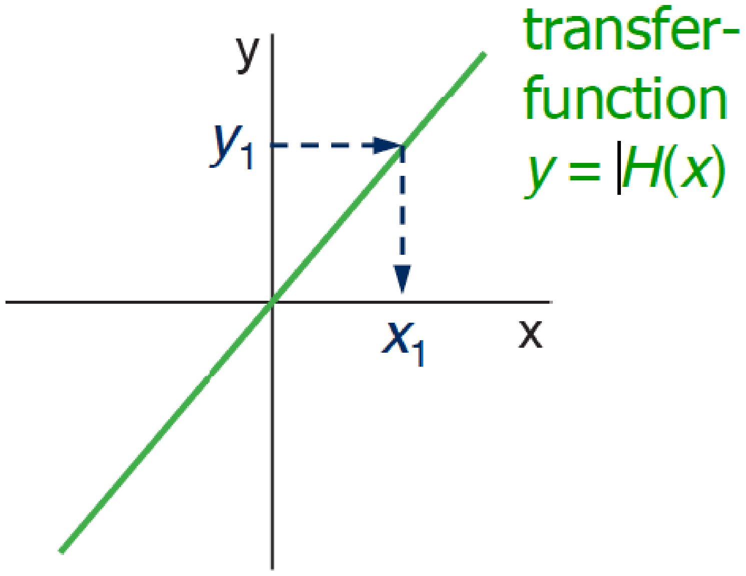


# Transfer Functions



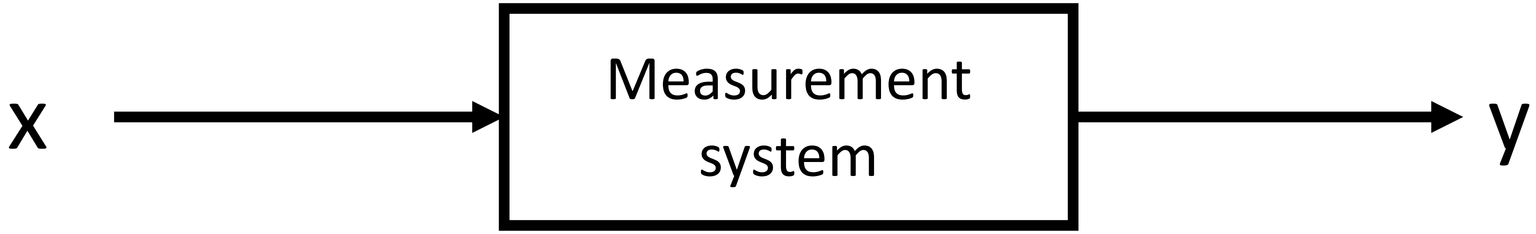

- For each quantity $x_1, x_2, x_3$… we have a corresponding measurement $y_1, y_2, y_3$…

- Or more generally: $y = H(x)$



# Uncertainty

– Every system has some degree of uncertainty




– **Measurement** y of **quantity** x has an **uncertainty** Δy

Randomness
Varying conditions
Resolution
…?

# Uncertainty and error

- Uncertainty is NOT error

- Error: difference between reading and true value
- Uncertainty: doubt in our reading

- How do we quantify uncertainty?

  Standard deviation

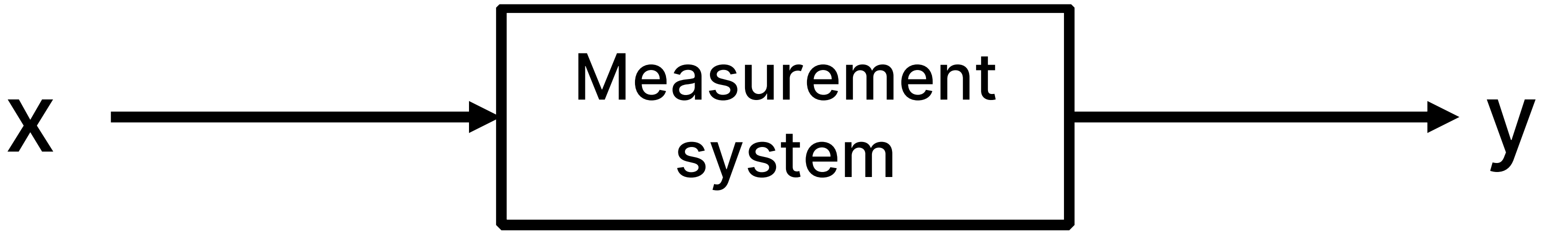
$$s = \frac{\sqrt{\Sigma(x_i - \bar{x})^2}}{n-1}$$

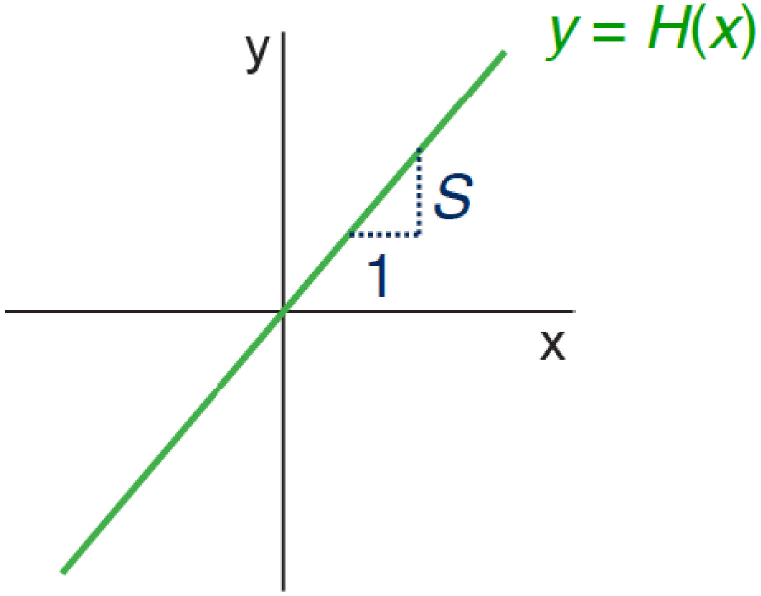
  Confidence Intervals

  z = confidence level

$$CI = \bar{x} \pm z\left(\frac{s}{\sqrt{n}}\right)$$

# Sensitivity



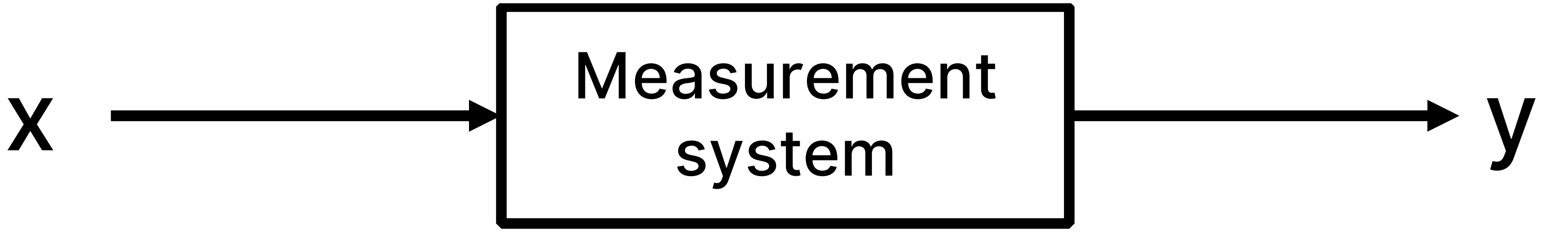




- An ideal sensor would have a linear sensitivity

$$S = \frac{\Delta x}{\Delta y}$$

- A change in x results in a linear response in y

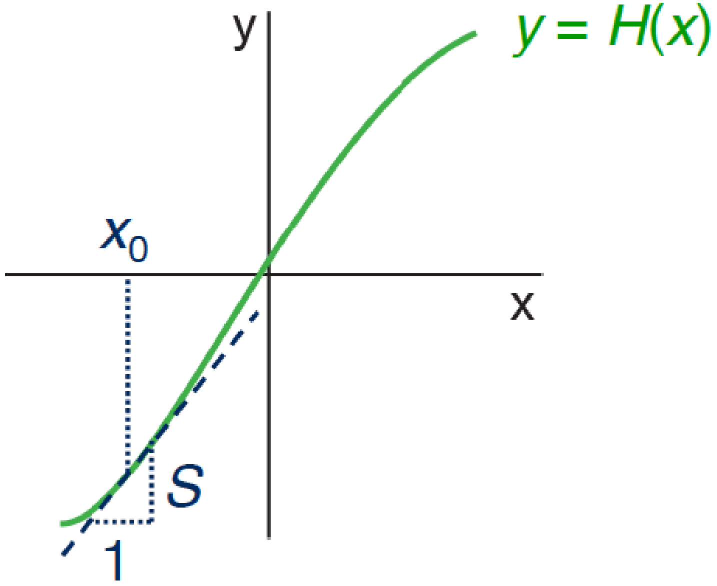
# Linear vs. Differential Sensitivity




- Not all sensors have linear sensitivity responses, some have a differential behavior

$$S = \frac{dx}{dy}$$

- If we understand our transfer function and sensitivity, we can correct for non-linearity



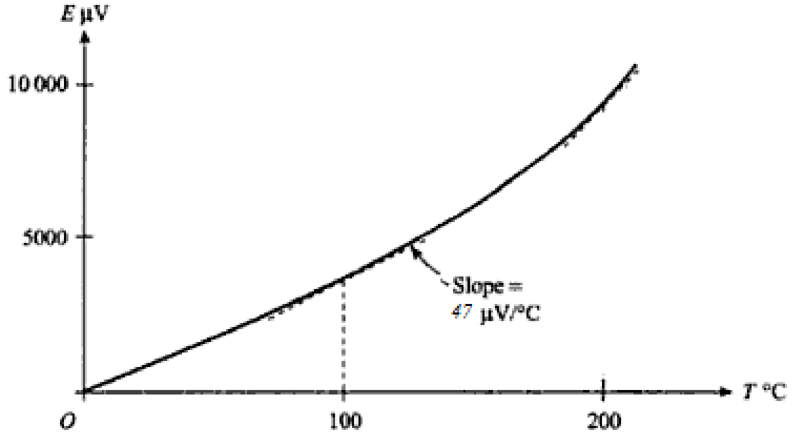
# Example: Sensitivity

$$\frac{dV}{dT} = 38.74 + 6.658\times10^{-2}T + 6.183\times10^{-4}T^2 - 8.472\times10^{-6}T^3$$
$$+ 5.495\times10^{-8}T^4 - 1.8486\times10^{-10}T^5 + 3.1839\times10^{-13}T^6 - 2.2008\times10^{-16}T^7$$

Show that at 100 $^0$C, the sensitivity of the thermocouple above is 47 mV/$^0$C

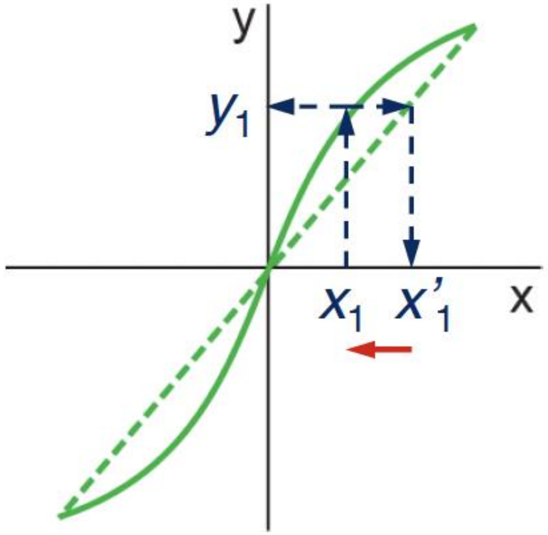
| Temp | Sensitivity |
|---|---|
| 0 | 38.74 |
| 100 | 47 |
| 200 | 55 |
| 300 | 65 |
| 400 | 79 |

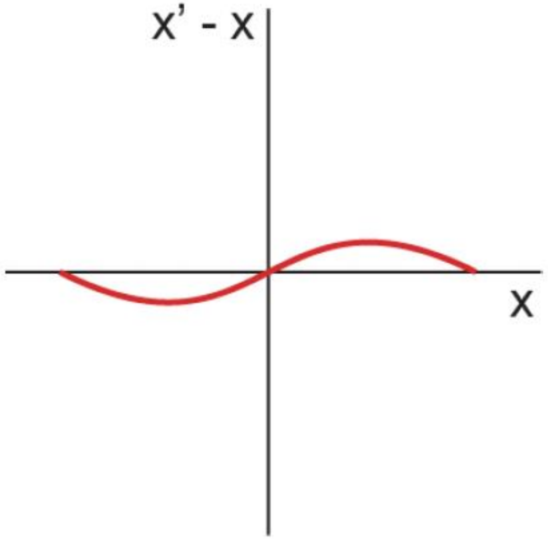
Thermocouple sensitivity.



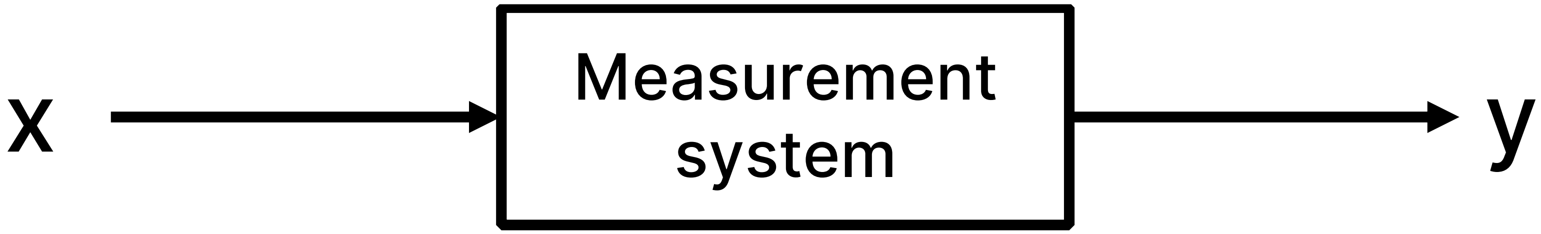
# Non-Linearity

- If we assume the Transfer Function is linear, any deviation will be a problem.
- Not all Transfer Functions are linear, does this result in uncertainty or error?
- Error – a difference between the reading and the true value



# Error and Transfer Functions

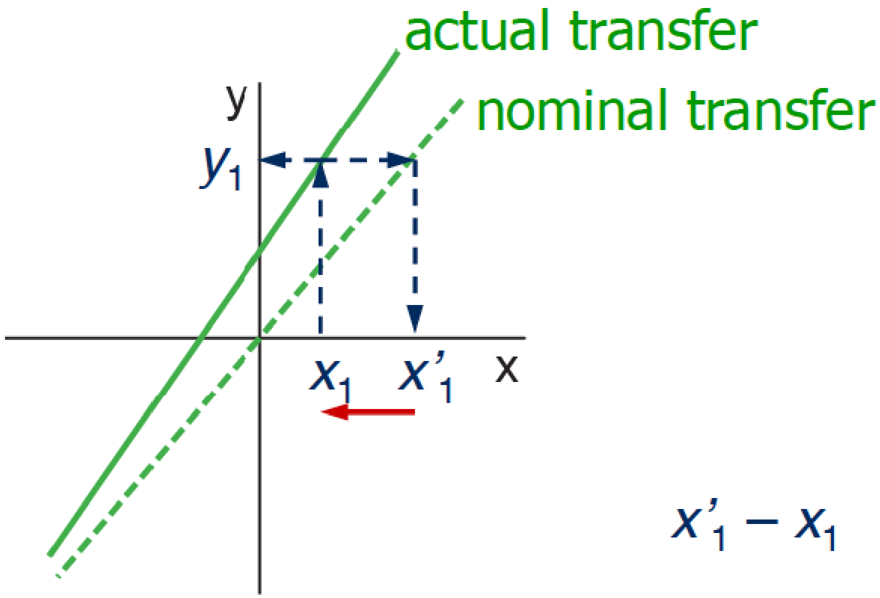



$x_1$ – Actual value of quantity

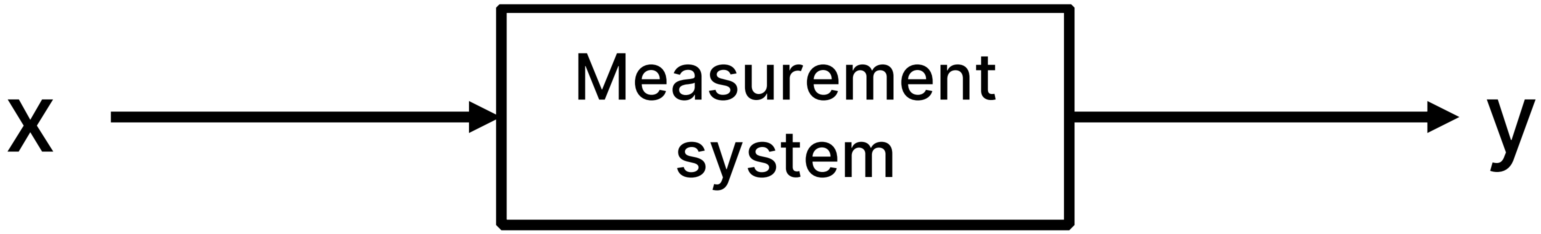
$x'_1$ – Measured value of quantity

$y_1$ – Output signal of measured system

Error = $x'_1 - x_1$



# Error and Transfer Functions



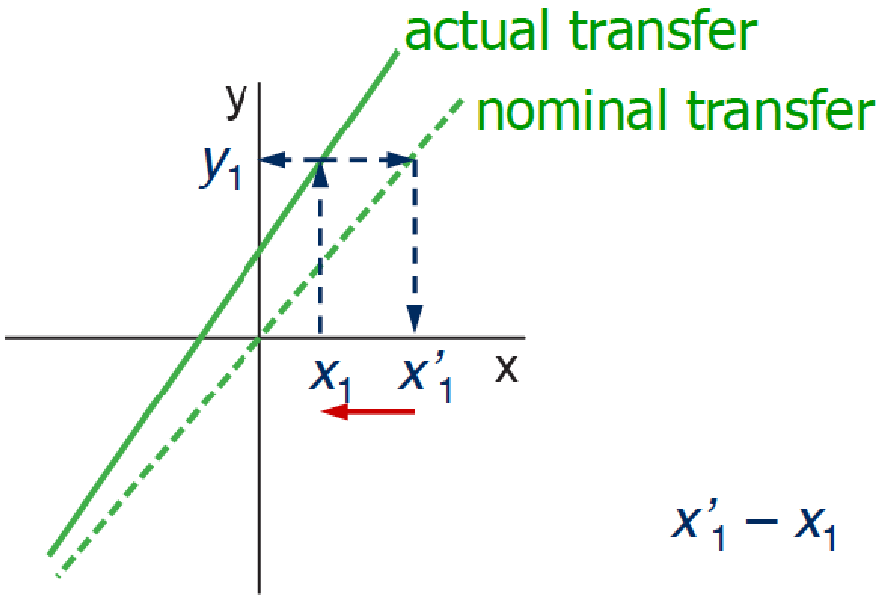

What is the error and the percentage error for the following measurements:

Actual Value = 25 V

Nominal Value = 30 V

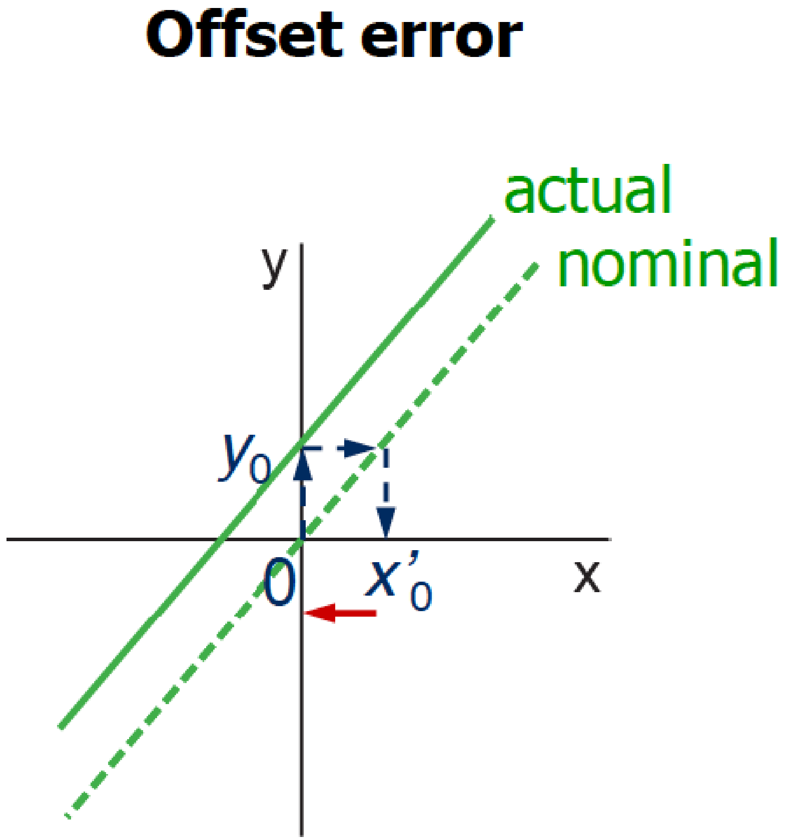
Error = $x'_1 - x_1$ = 30 – 25 = 5V

Percentage Error = (5 / 30) * 100 = +16.7%



# Error and Transfer Functions

- Offset error is a transposition of the reading from actual (real) value to some nominal value
- $y(x) = m * H(x) + c$
- c is the offset value
- Can be linear or non-linear over the sensor's range



# Error and Transfer Functions

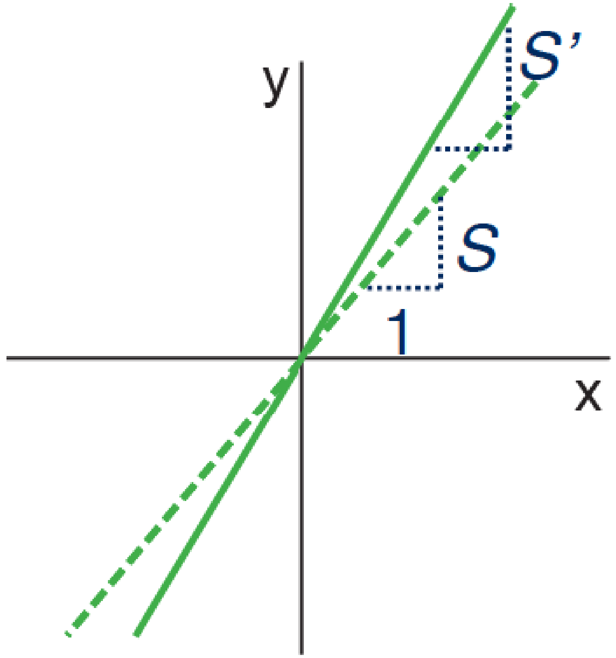
- Gain error is a transposition of the reading from actual (real) value to some nominal value

- $y(x) = m * H(x) + c$

- m is the gain value

- Can be also linear or non-linear over the sensor's range

**Gain error (sensitivity error)**

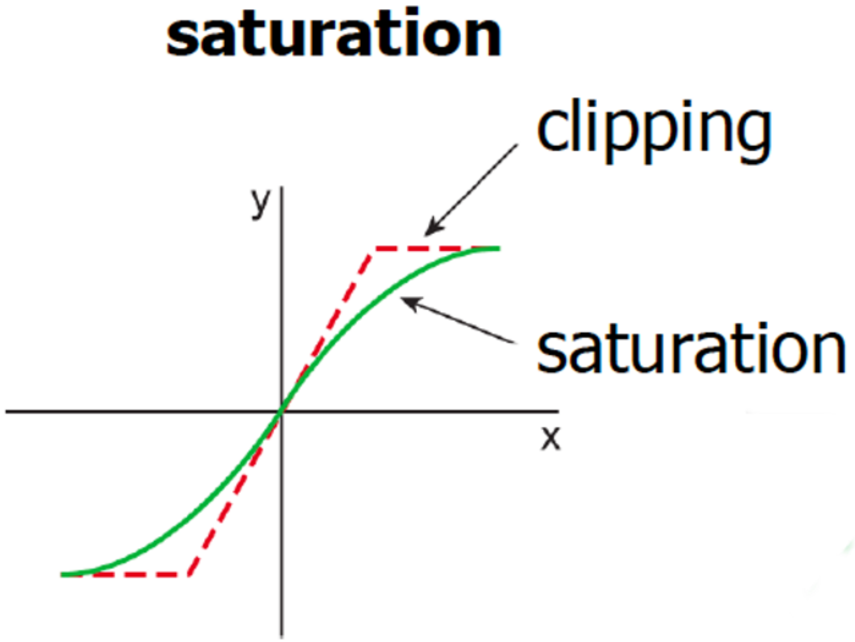


# Non-Linearity – Saturation

- Limitations in the maximum or minimum

- Results in ”clipping” the response

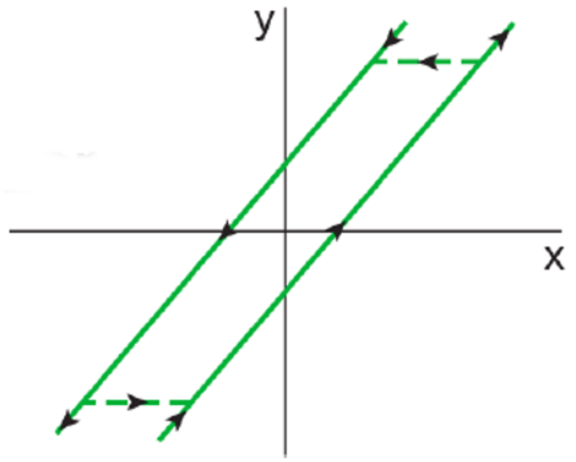
- Loss of information of absolute values




# Non-Linearity – Hysteresis

- Time or directional change in response
- Can sometimes be eliminated by going slowly ”rate-dependent”
- Can sometimes be the effect of a physical phenomenon e.g. magnetism i.e. “rate-independent”

hysteresis



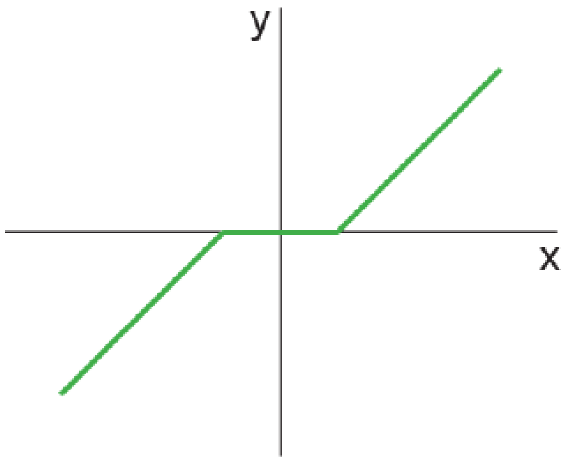



(c)

# Non-Linearity – Dead Zone

- Lack of response over a certain range
- Often occurs near the zero point of a sensor where the initial input is too small to be measured
- Can also occur at non-zero values, or in measurement systems where multiple sensors have been combined and may not overlap

**dead zone**



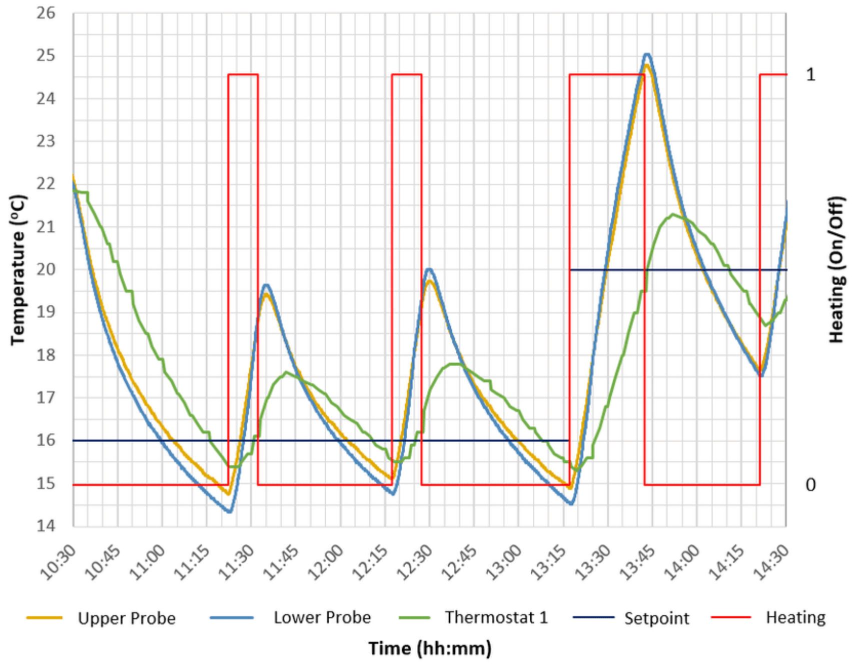



(c)

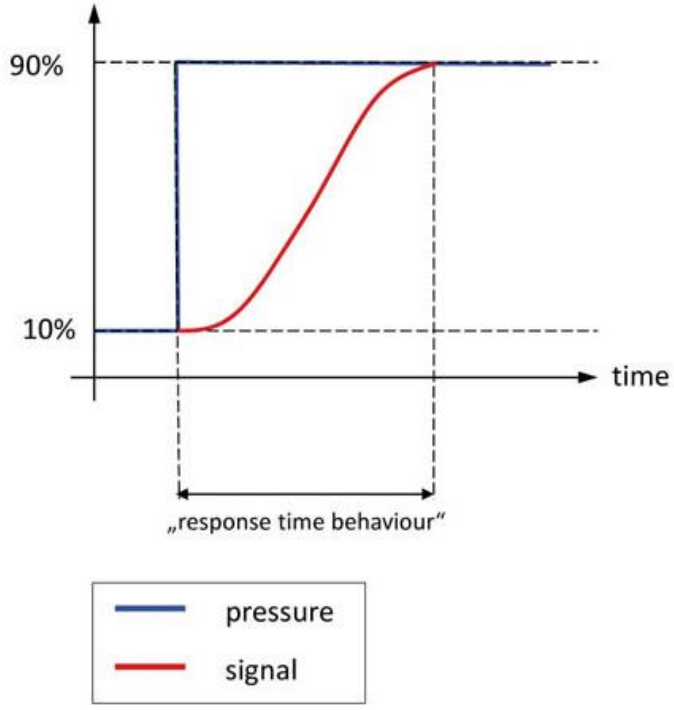
# Ambiguity

— Do we know the type of the error or non-linearity? Think about the sensor!


(a)


(b)

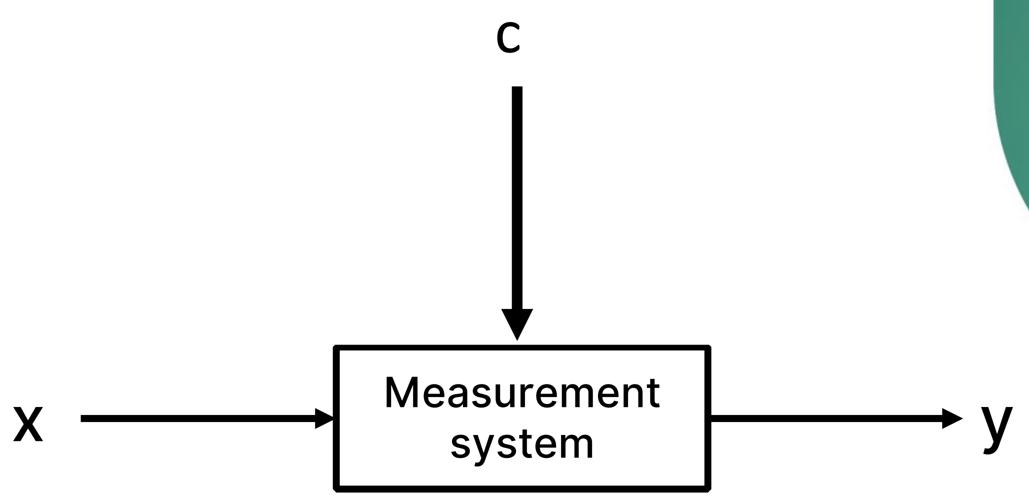


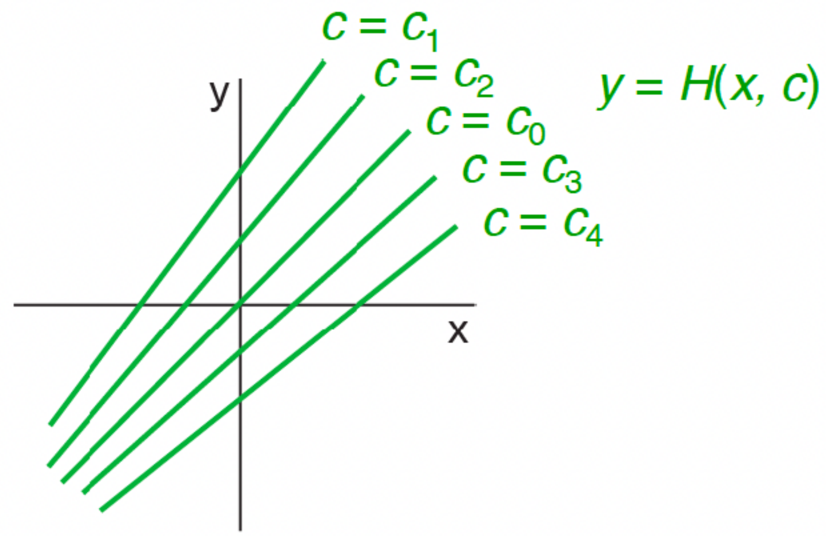

(c)

# Cross Sensitivity

- Certain measurements are influenced simultaneously by multiple physical quantities or phenomena

- This can lead to unwanted deviations in the transfer function



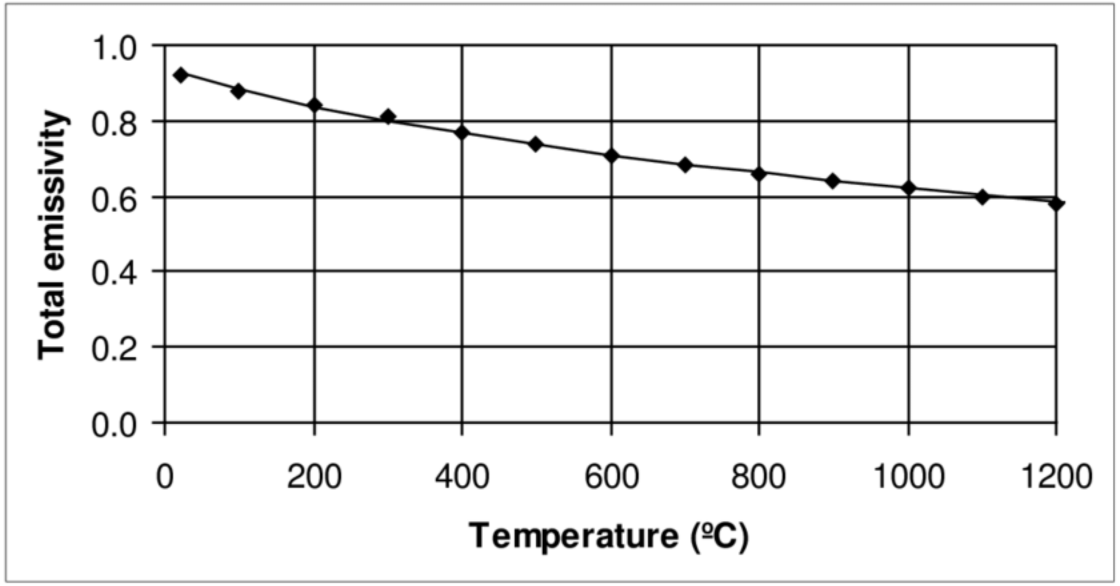
# Cross Sensitivity – Example

- Thermal radiation emission as measured by IR camera imaging

- Stefan-Boltzmann Law:

$$P = \epsilon\sigma T^4$$

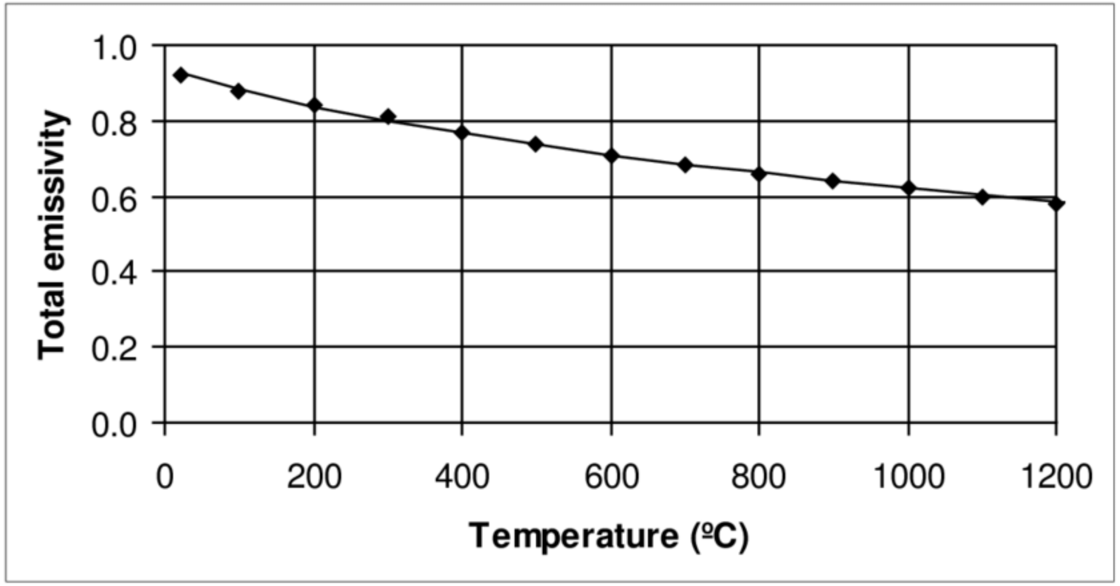
- Emissivity is a function of temperature!




- Absolute vs. Radiant temperature measurement?

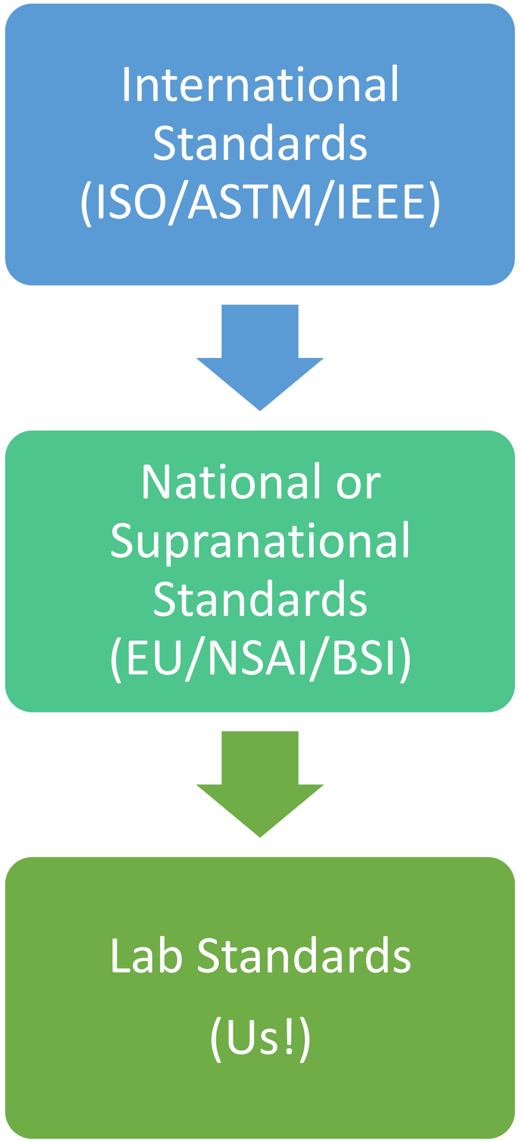
# Cross Sensitivity – Example

- How to solve this problem?
- Ignore it?
  What error do we get?
  Is this acceptable?
- Calibration?
  Measure emissivity first
  Model it
  This is material dependent!
- Do we even need to know?
  Statistical analysis

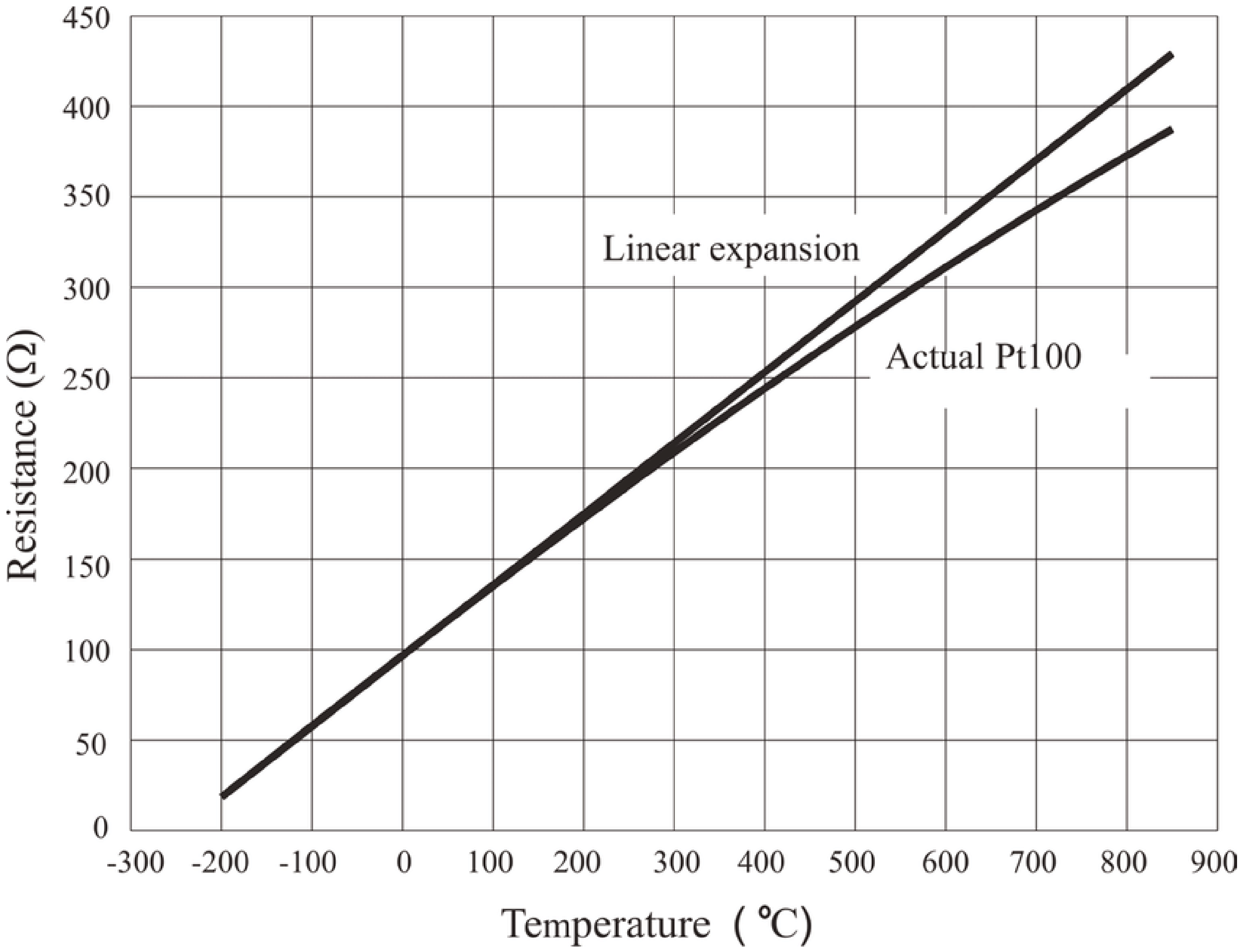


# Calibration

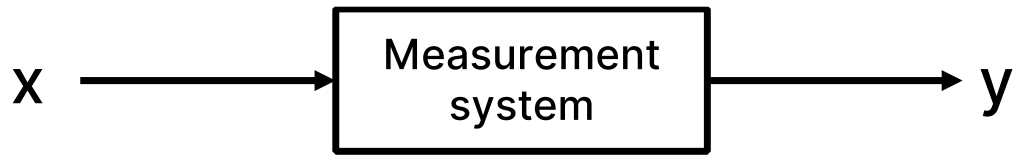
- International standards give us a benchmark to compare two discreet measurements
- Allows us to correct for variation in instrument type, age, etc.
- Generally needs to be done periodically
- International organizations agree and publish standards for calibration and measurements



# Calibration – Example



# Resolution

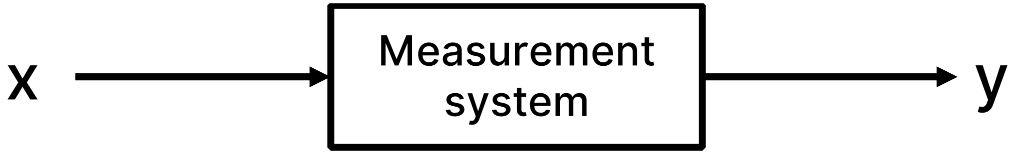




- The resolution is the smallest change in x, that causes a change in y
- Resolution is a cause of uncertainty
- 17.44 V – what is the resolution?
  0.01 V

# Resolution

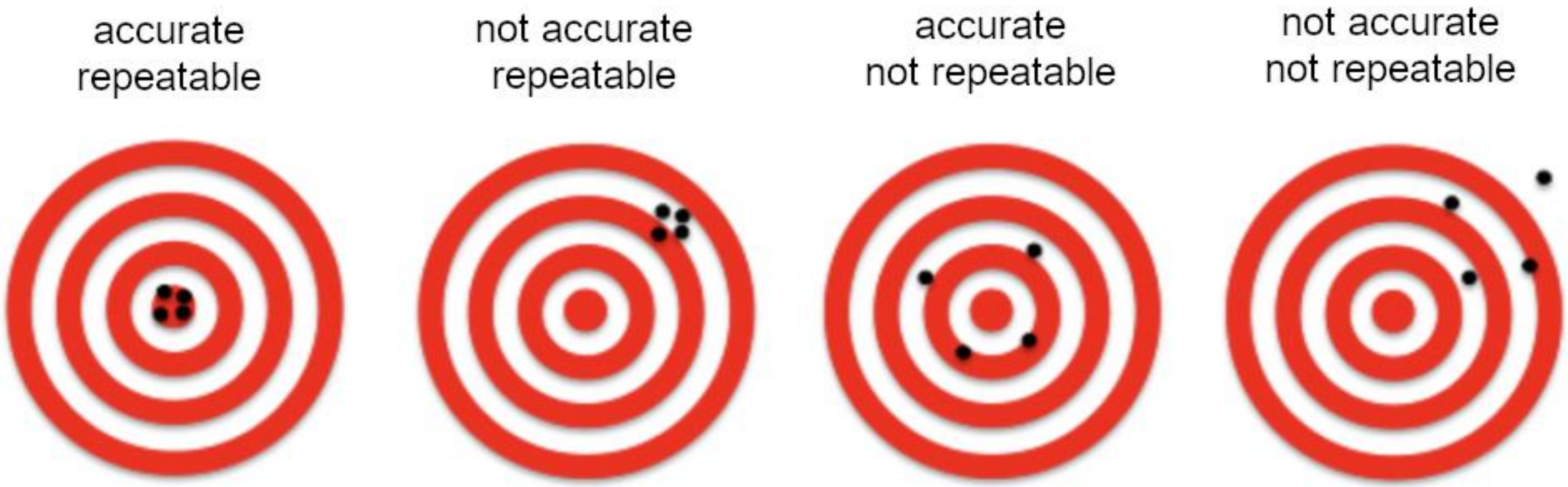
- Two types of resolution:




- Display limitation

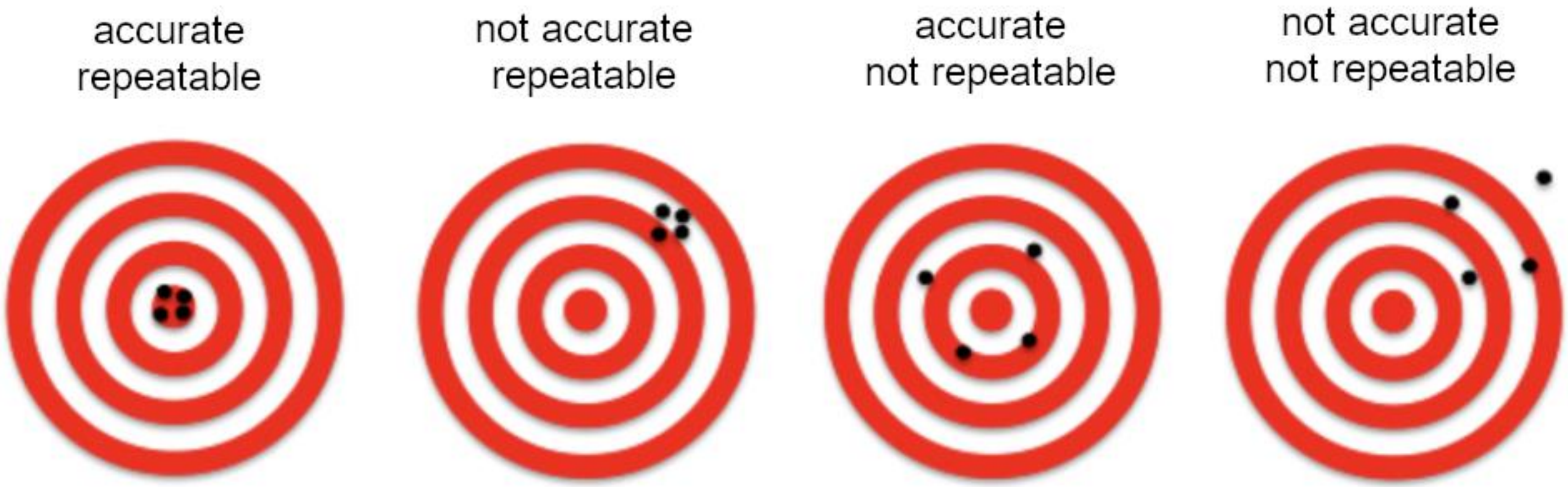

- Sensor limitation

# Accuracy and Reproducibility



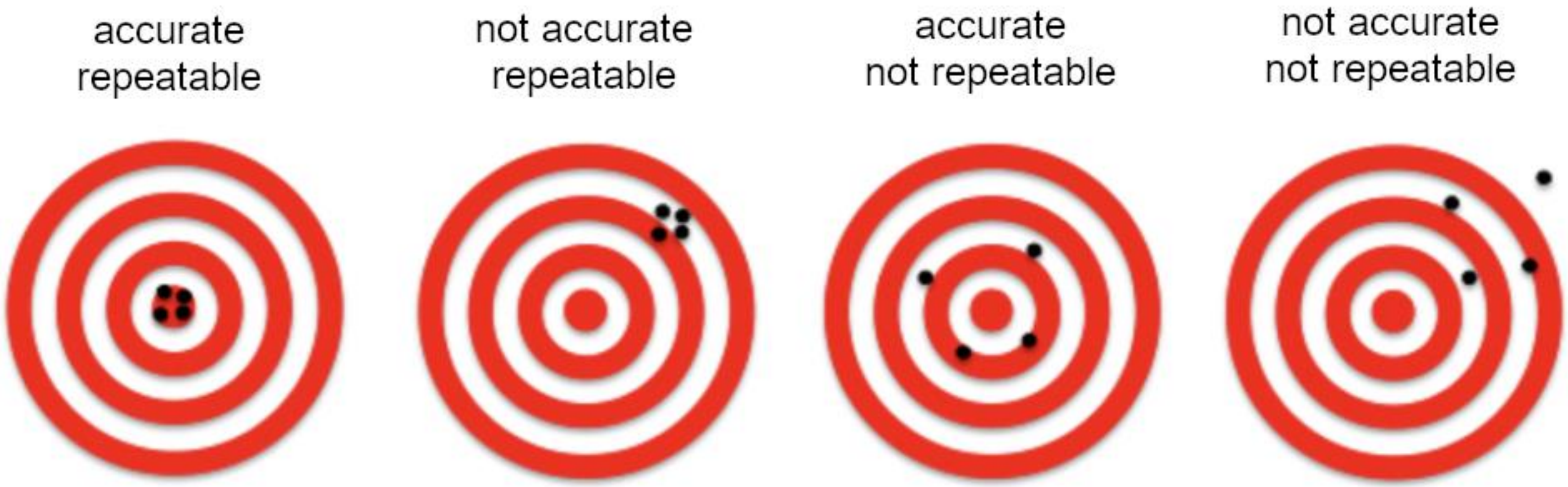

- Accuracy: same as Error. The difference from our reading from the "true" reading
- Reproducibility: the uncertainty in our sensor to find the same measurement each time

# Approximate Error




- Approximate error: error and reproducibility combined
- If error is 5V and the reproducibility is ± 2.5V, what is our approximate error?
- 5V ± 2.5V.
  What is the range of the error?
- 2.5V – 7.5V.
  This is our Tolerance Interval

# Approximate Error




- Tolerance: What we consider acceptable error within our system or sensor

- If we define a maximum tolerance of 0.1V, is a sensor with an approximate error of 15V ± 1% within specification?

# Sensor Qualities and Quantities

- Range
- Linearity and non-linearity
- Sensitivity
- Resolution
- Error and Accuracy
- Uncertainty and Reproducibility

# Example – IR Sensor

## Calex PC151MT-0 mA Output Signal Infrared Temperature Sensor, 1m Cable, 0°C to +250°C

RS Stock No.: **553-321** | Mfr. Part No.: **PC151MT-0** | Manufacturer: Calex

**84 In stock for delivery within 2 working days**

– 1 + units

**Add to basket**

Real time stock check

Price Each

**€243.44**
**(exc. VAT)**

**€299.43**
(inc. VAT)

| **units** | **Per unit** |
| --- | --- |
| 1 + | €243.44 |

# Example – IR Sensor

**High Performance PyroCouple Series**

High quality, low cost, non-contact Infra-red temperature sensors suitable for measuring the temperature of inaccessible or moving objects and materials.

Fast response with high stability

Types available with air/water cooled housings

Quick and easy to install

Available as either two-wire or four-wire units

240 ms to 90% response time

Stainless steel housing

M16 x 1 mm mounting thread

Prewired 1 m cable connection

6 V dc minimum sensor voltage

0.95 emissivity

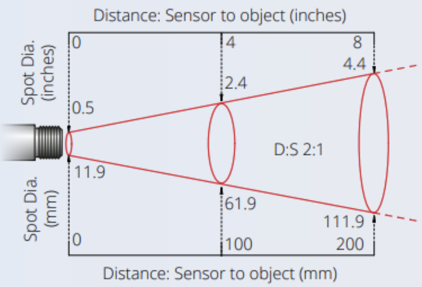
Temperature change varies by model

**Two-wire sensors** transmit the target temperature as a 4-20 mA output and offer a simple solution for most non-contact temperature measurement applications.

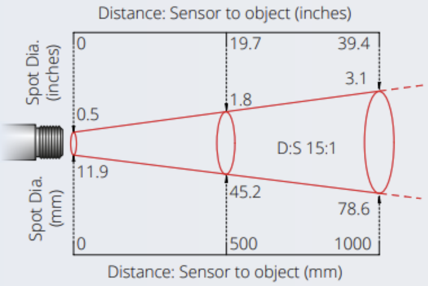
The PyroCouple is a simple infrared temperature sensor with a choice of analogue outputs. No complicated setup is required - just connect a temperature indicator and power supply, and instantly start taking measurements.

It is suitable for non-contact temperature measurement on most non-reflective non-metal surfaces, such as paper, thick plastics, asphalt, painted surfaces, food, rubber and organic materials, among many others.

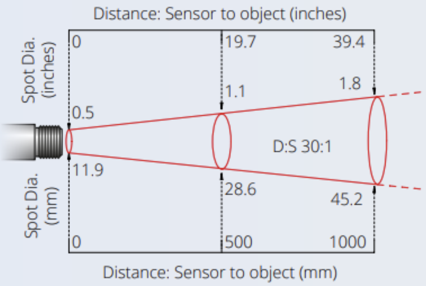
## OPTICS



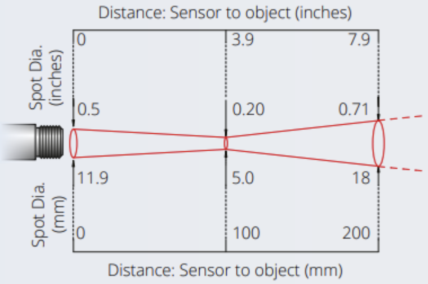

**21** models




**151** models




**301** models




**CF** models

All models can measure at longer distances than shown, with a larger measured spot size.

Diagrams show the diameter of the measured target spot versus the distance from the sensing head (90% energy).

# Example – IR Sensor

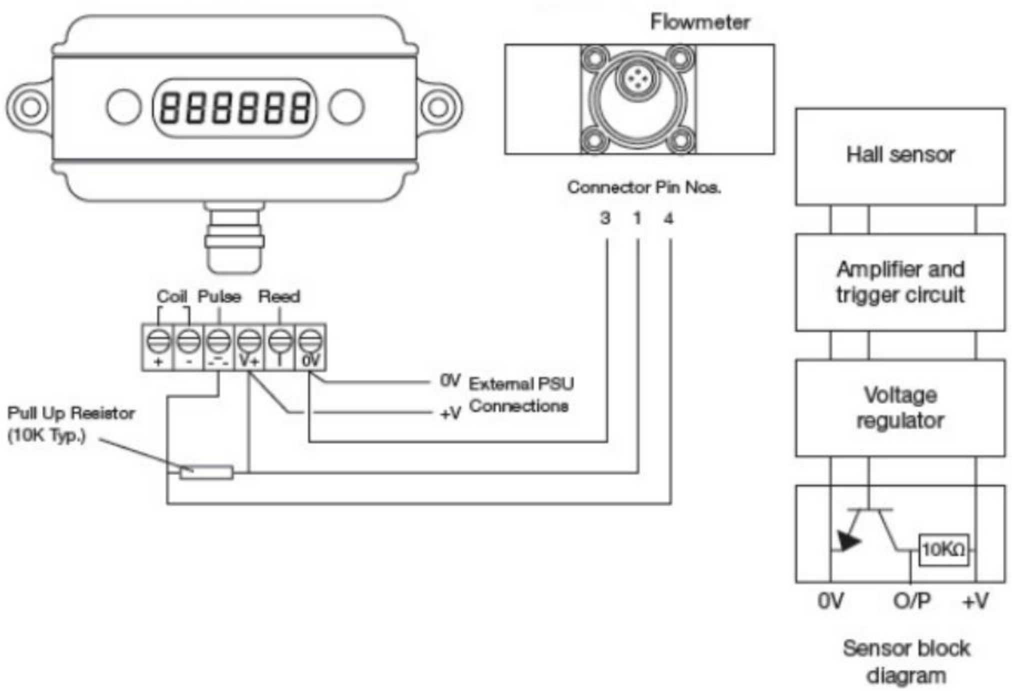
- Temperature ranges from -20°C to 500°C
- Two-wire 4-20 mA output or four-wire voltage/ thermocouple output
- Choice of precision optics for large or small targets
- Fast response with high stability
- Stainless steel housing, sealed to IP65
- Quick and easy installation
- Wide range of accessories
- Fixed emissivity 0.95 for measuring non-reflective non-metals, and painted surfaces (including painted or coated metals)
- Conforms to industrial EMC standards

| General | |
|---|---|
| **Output** | Choice of 4-20 mA, J or K Thermocouple, mV (See "Model Numbers") |
| **Temperature Range** | LT = -20 to +100 °C<br>MT = 0 to 250 °C<br>HT = 0 to 500 °C |
| **Accuracy** | ±1% of reading or ±1°C, whichever is greater |
| **Repeatability** | ± 0.5% of reading or ± 0.5°C, whichever is greater |
| **Emissivity Setting** | Fixed at 0.95 |
| **Response Time** | 240 ms (90% response) |
| **Spectral Range** | 8 to 14 μm |
| **Supply Voltage (at Sensor)** | 6 V DC to 28 V DC |
| **Max. Loop Impedance** | 900 Ω ( 4-20 mA output) |
| **Output Impedance** | 56 Ω (voltage/thermocouple output) |
| **Max. Current Draw** | 20 mA |

| Mechanical | |
|---|---|
| **Construction** | Stainless Steel |
| **Dimensions** | 18 mm diameter x 103 mm long |
| **Thread Mounting** | M16 x 1 mm pitch |
| **Cable Length** | 1m (longer lengths available to order) |
| **Weight with Cable** | 95 g |

| Environmental | |
|---|---|
| **Environmental (IP) Rating** | IP65 |
| **Ambient (Operating) Temperature Range** | 0°C to 70°C |
| **Ambient (Operating) Humidity** | 95% max. non-condensing |

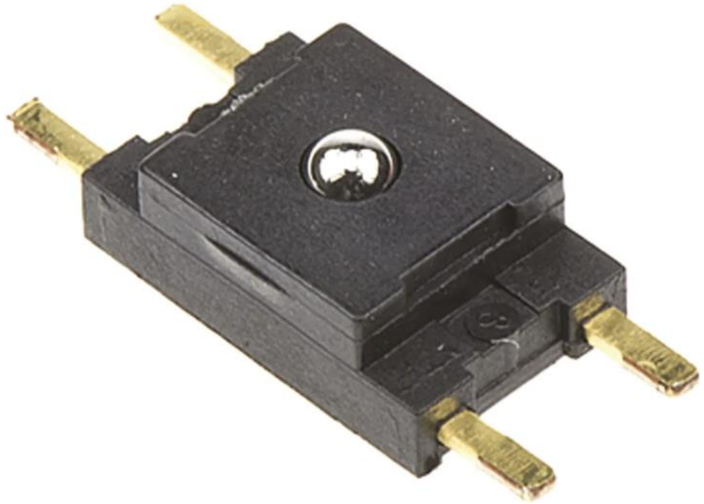
# Flow Sensor


## General Specifications

| | |
|---|---|
| **Device Type** | Turbine |
| **Media Monitored** | Liquid |
| **Minimum Flow Rate** | 0.5L/min |
| **Maximum Flow Rate** | 15L/min |
| **Maximum Pressure** | 10bar |
| **Material** | Stainless Steel |
| **Standard Accuracy** | 1% |
| **Linearity** | 1.0% FSD |
| **Applications** | Active flow alarms, semiconductor plants and drink dispensers |

# Pressure Sensor



## FSS Low Profile Force Sensors

**PERFORMANCE CHARACTERISTICS @ 5.0 ± 0.01 Vdc Excitation*, 25 °C [77 °F]**

| Parameter | Min. | Typical | Max. | Units |
|---|---|---|---|---|
| Null Offset | -15 | 0 | +15 | mV |
| Operating Force | 0 | – | 1500 | grams |
| Sensitivity. | 0.1 | 0.12 | 14 | mV/gram |
| Linearity (B.FS.L.)** | – | ± 1.5 | – | % span |
| Repeatability @ 300 g | – | ± 10 | – | grams |
| Null Shift | | | | |
| 25 °C to 2 °C [77 °F to 35.6 °F] | – | ± 0.5 | – | mV |
| 25 °C to 40 °C [77 °F to 104 °F] | – | ± 0.5 | – | mV |
| Sensitivity Shift | | | | |
| 25 °C to 50 °C [77 °F to 122 °F] | – | 5.5 | – | % span |
| 25 °C to 0 °C [77 °F to 32 °F] | – | 5.5 | – | % span |
| Input Resistance | 4.0 K | 5.0 K | 6.0 K | Ohms |
| Output Resistance | 4.0 K | 5.0 K | 6.0 K | Ohms |
| Overforce | – | – | 4,500 | grams |
| ESD (direct contact, terminals and plunger) | 8 | – | – | kV |

* Non-compensated force sensors, excited by constant current (1.5 mA) instead of voltage, exhibit partial temperature compensation of Span.

** BFSL: Best Fit Straight Line

**ENVIRONMENTAL SPECIFICATIONS**

| | |
|---|---|
| Operating temperature | -40 °C to 85 °C [-40 °F to 185 °F] |
| Storage temperature | -40 °C to 100 °C [-40°F to 212 °F] |
| Shock | Qualification tested to 150 g |
| Vibration | Qualification tested to 0 to 2 kHz, 20 g sine |
| MCTF | 20 million at 25 °C [77 °F] |
| Solderability | 5 sec at 315 °C [599 °F] per lead |
| Output ratiometric | Within supply range |

Note: All force related specifications are established using dead weight or compliant force.

# Summary

- Measurements are quantitative (determinable) and qualitative (distinguishable)

- The transfer function describes the relationship between an quantity x and measurement y

- Error and uncertainty are not the same!
- Accuracy and Repeatability

- Calibration and understanding the sources of error can get us more accurate data