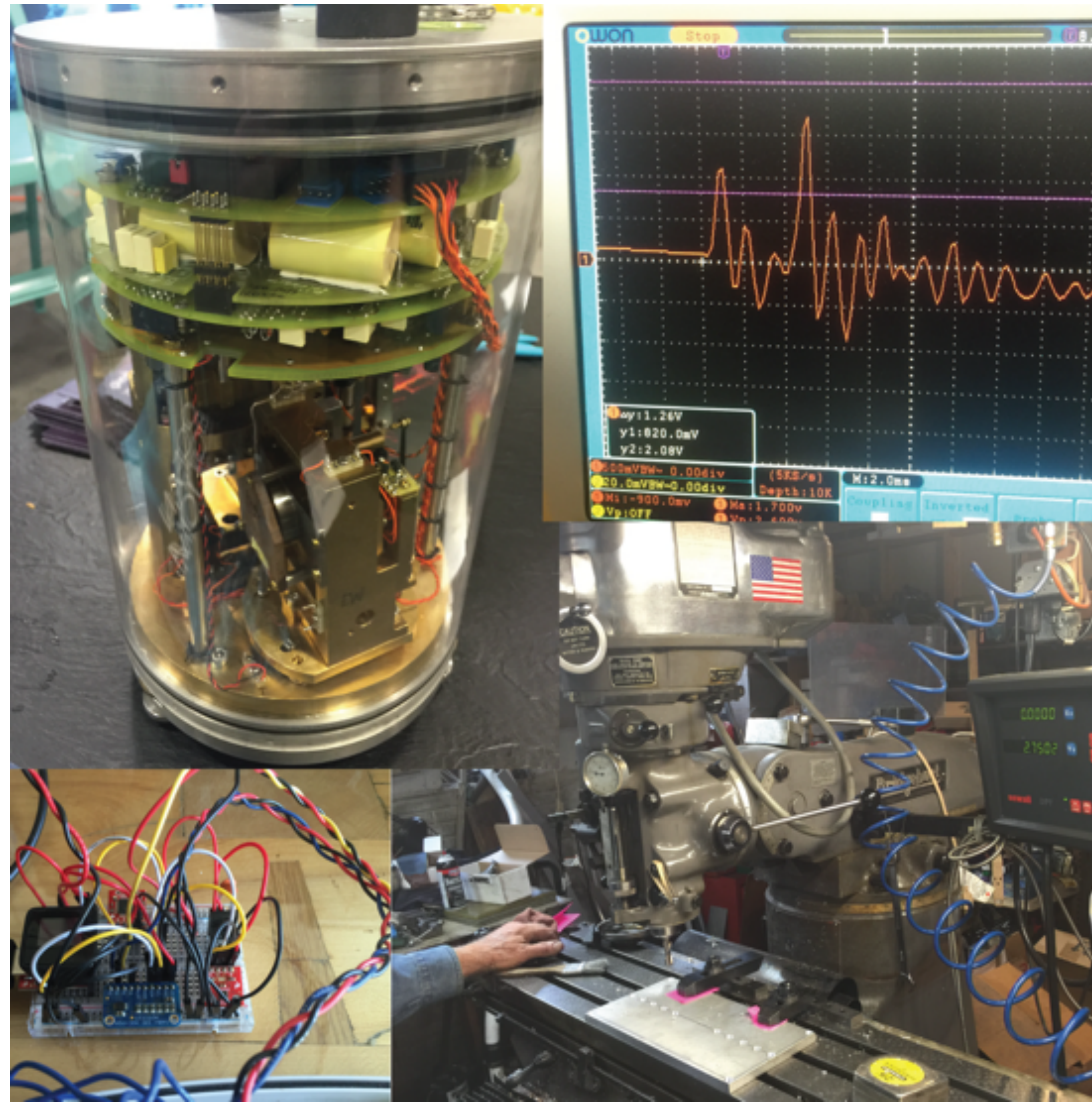
# Transducers

J.R. Leeman and C. Marone

**Techniques of Geoscientific Experimentation**

**October 18, 2016**



**Transducers are devices that convert one form of energy to another - we commonly use them as real-world interfaces**

Active

Passive

Actuator

Bidirectional

# Transducer Selection

**When selecting a transducer, you must have a well defined application and consider a number of variables**

- **Range**
- **Linearity**
- **Sensitivity**
- **Response Time**
- **Stability**
- **Accuracy**
- **Durability**
- **Cost**
- **Signal Conditioning**

**Image: Wikipedia**

# Range is the span of values over which the transducer is rated to perform at

| | Elite Series<br>Best Performance<br>Modular Design<br> | | CPL230<br>Great Performance<br>Compact Multi<br> | CPL350<br>Great Performance<br>Compact Single<br> | CPA100<br>Analog Proximity<br>Lower Cost<br> |
|---|---|---|---|---|---|
| | CPL490 | CPL190/290 | | | |
| **Ranges** | 10-200 µm | 10 µm to 12.5 mm | 10 µm to 12.5 mm | 10 µm to 12.5 mm | 50 µm to 12.5 mm |
| **Typical Resolution* @ 15 kHz** | 0.0007% F.S.* | 0.003% F.S.* | 0.004% F.S.* | 0.004% F.S.* | 0.03% F.S.* |
| **Typical Linearity*** | 0.2% | 0.2% | 0.5% | 0.5% | Nonlinear |
| **Max Bandwidth** | 50 kHz | 15 kHz | 15 kHz | 15 kHz | 15 kHz |
| **Zero/Offset Adjust** | Yes | Yes | No | No | Yes |
| **Gain Adjust** | No | No | No | No | Yes |
| **Setpoint/Switch Output** | No | No | No | No | Yes |
| **Typical Thermal Drift*** | 0.02% F.S./°C | 0.04% F.S./°C | 0.04% F.S./°C | 0.04% F.S./°C | Driver: 0.2% F.S./°C<br>Probe: 0.05% F.S./°C |
| **LED Range Indicator** | Yes | Yes | No | No | Yes |
| **Cost** | $$$$ | $$$ | $$ | $$ | $ |
| **Other Features** | Optional Signal Processing and Meter Module<br><br>Easy DAQ connection | | Embeddable/OEM Design | Embeddable/OEM Design | Remote Zero and Gain<br><br>Setpoint/Switch output |

# Linearity is how much the sensor diverges from an ideal linear sensor output

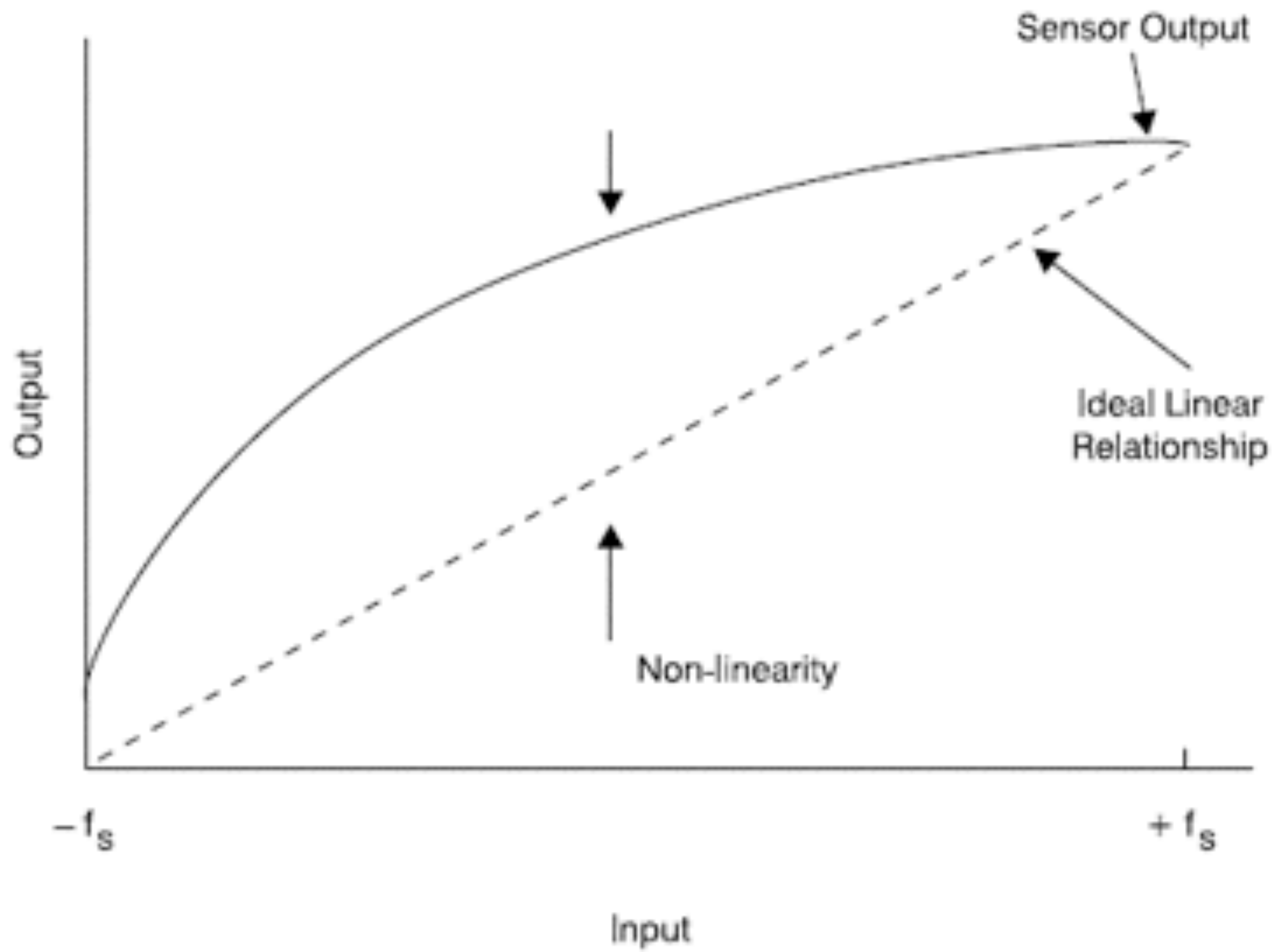



Image: dataforth.com

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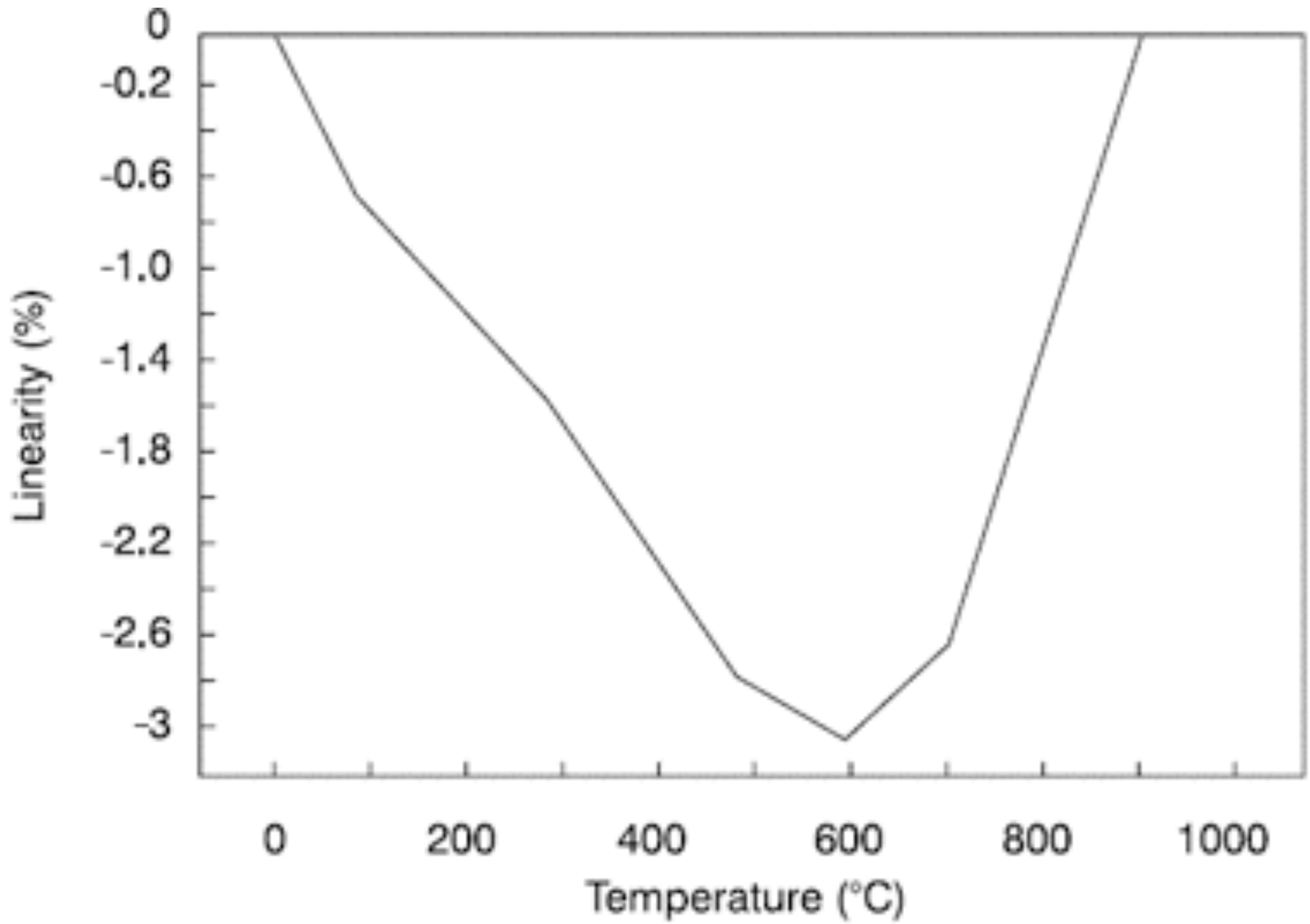



Image: dataforth.com

# Sensitivity is the slope of the output - input curve

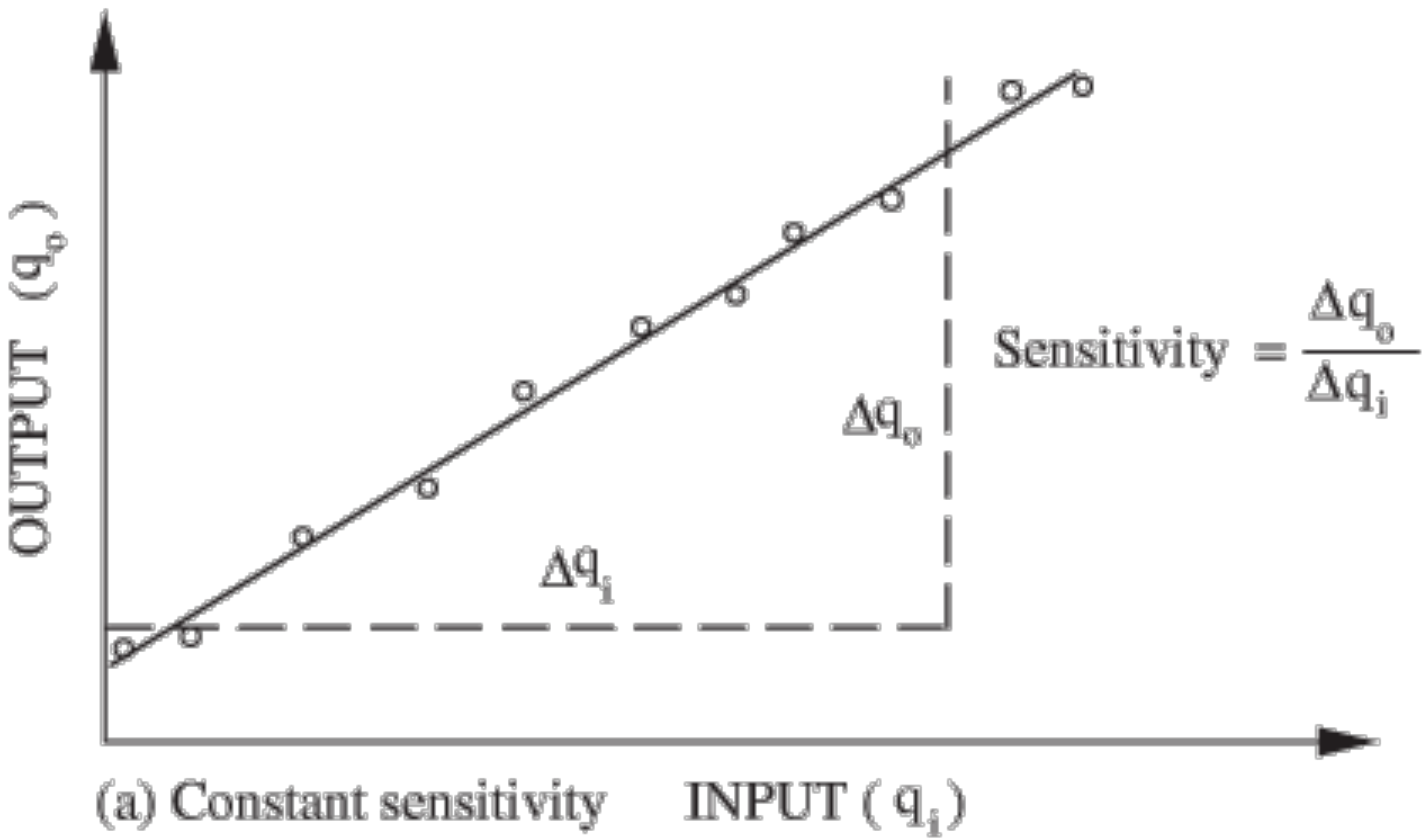



Image: USGS

# Response time is how long the transducer takes to register a change in the physical quantity

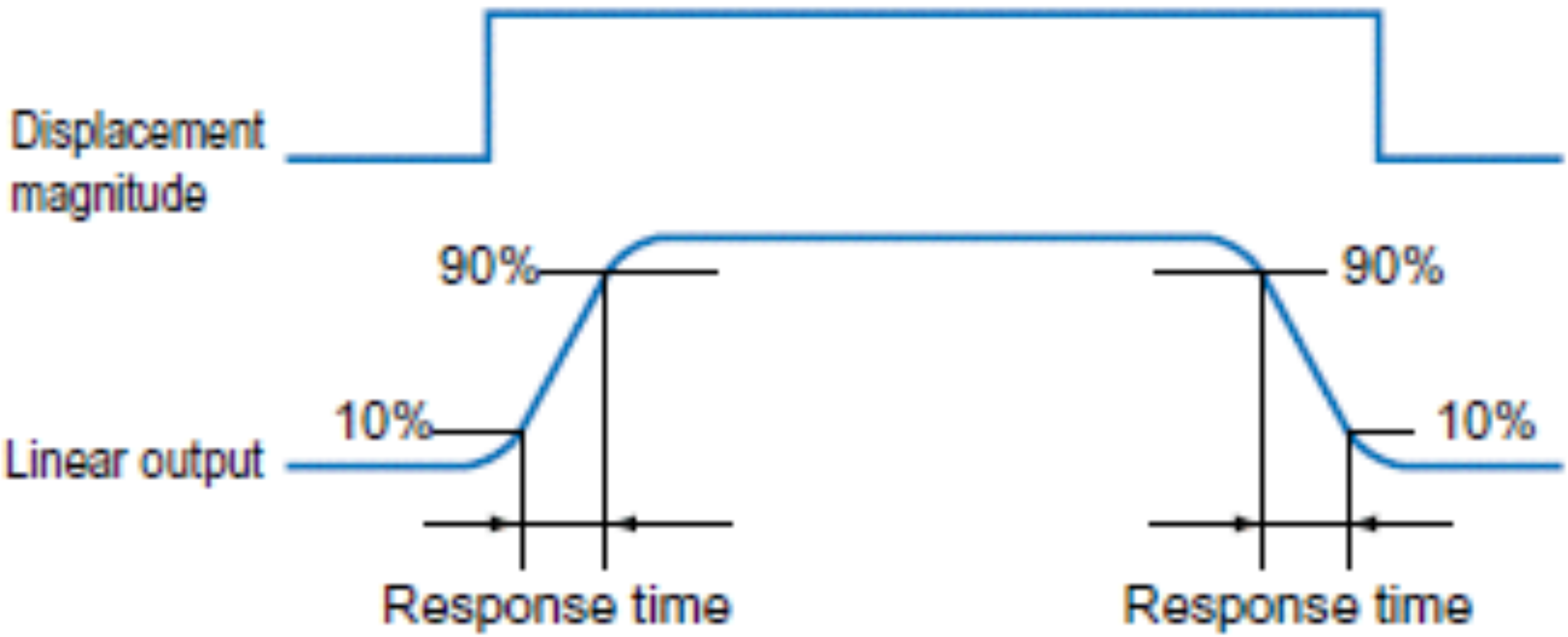



Image: Intech

**Stability is how constant the output of a transducer remains when the physical stimulus is static**

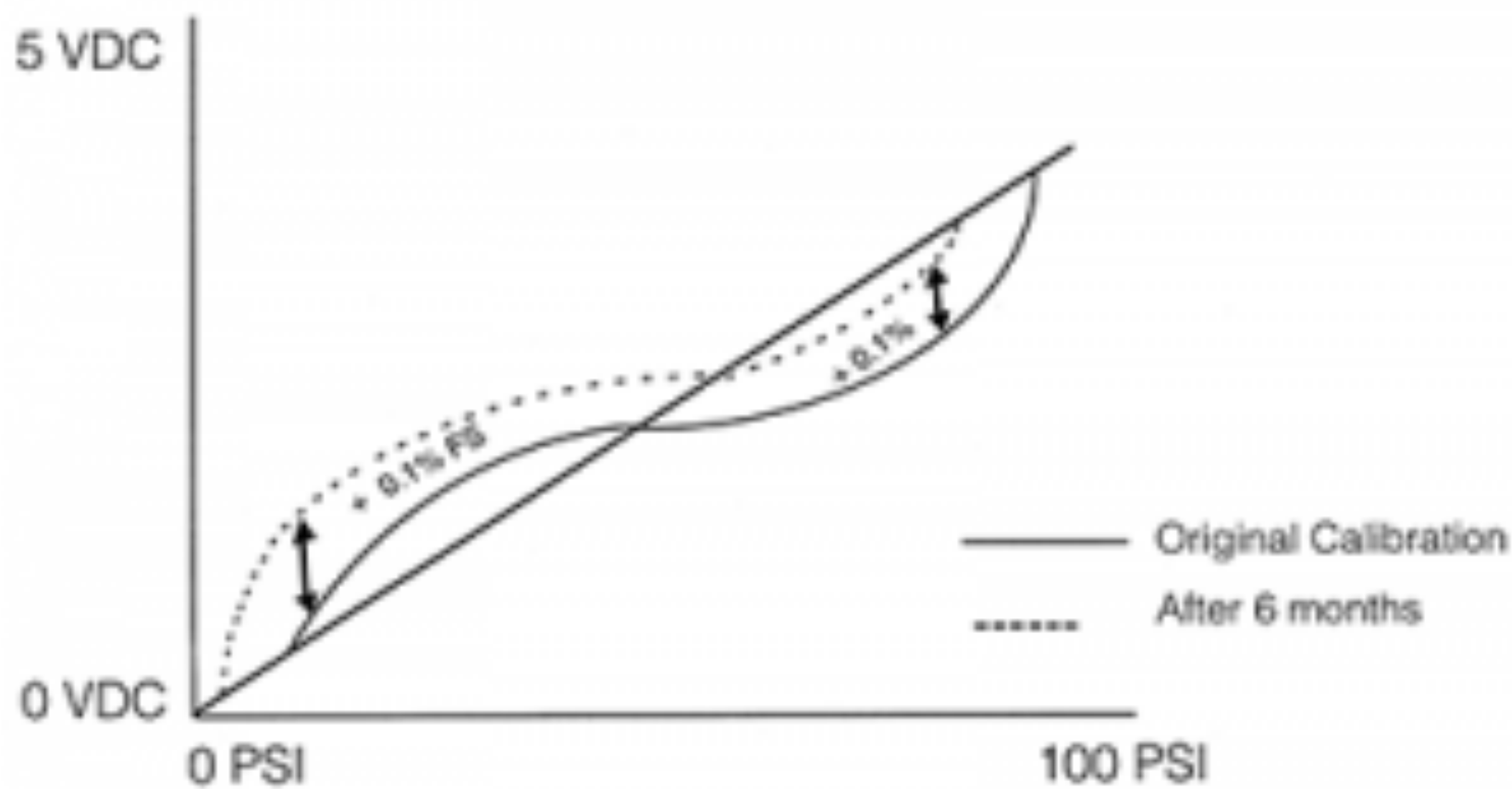
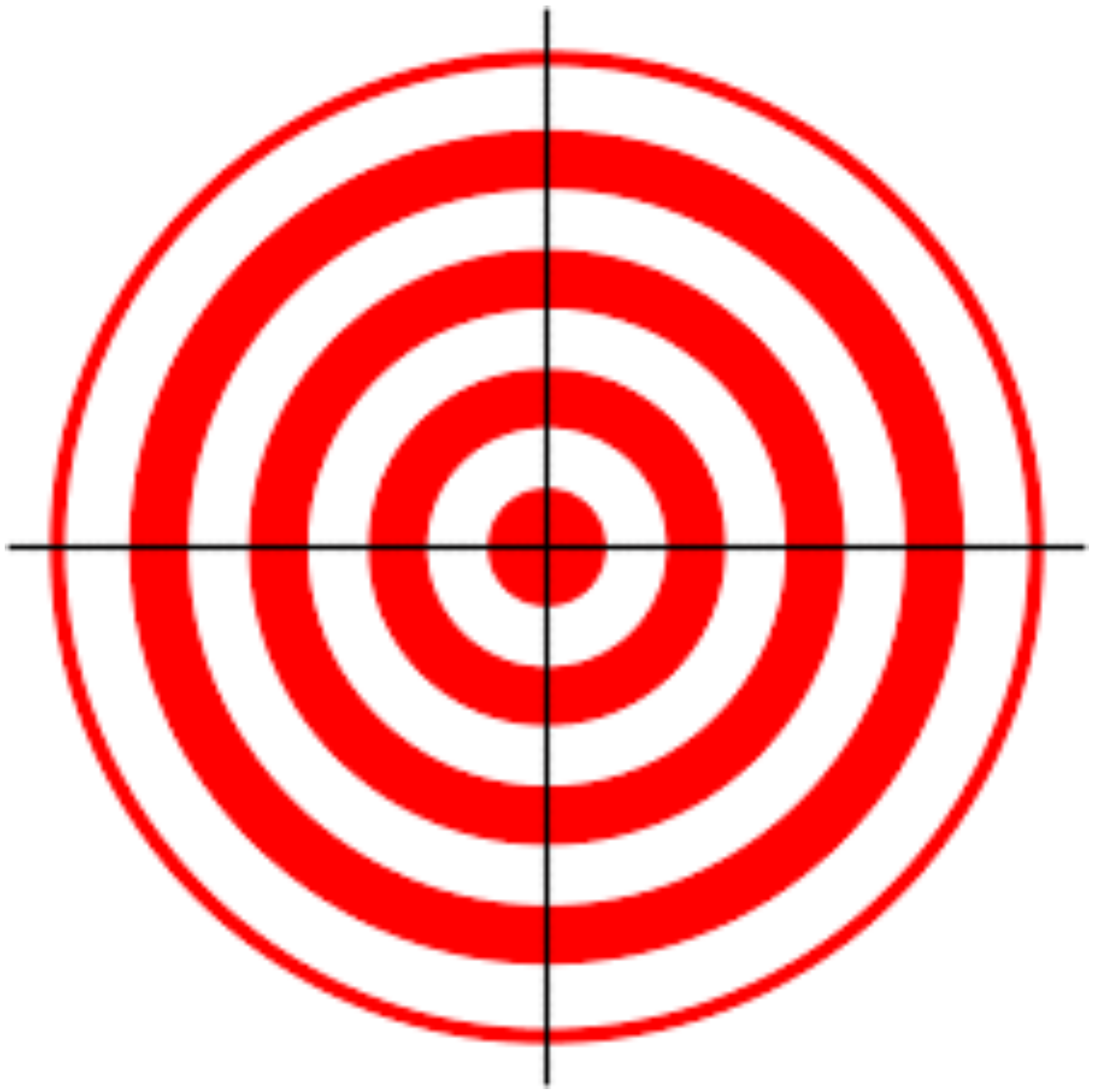



Image: Setra

Precision refers to the reproducibility of a given measurement



Accuracy is the maximum difference between the real and indicated values

# Durability is how rugged the transducer is to the measurement environment it will be exposed to

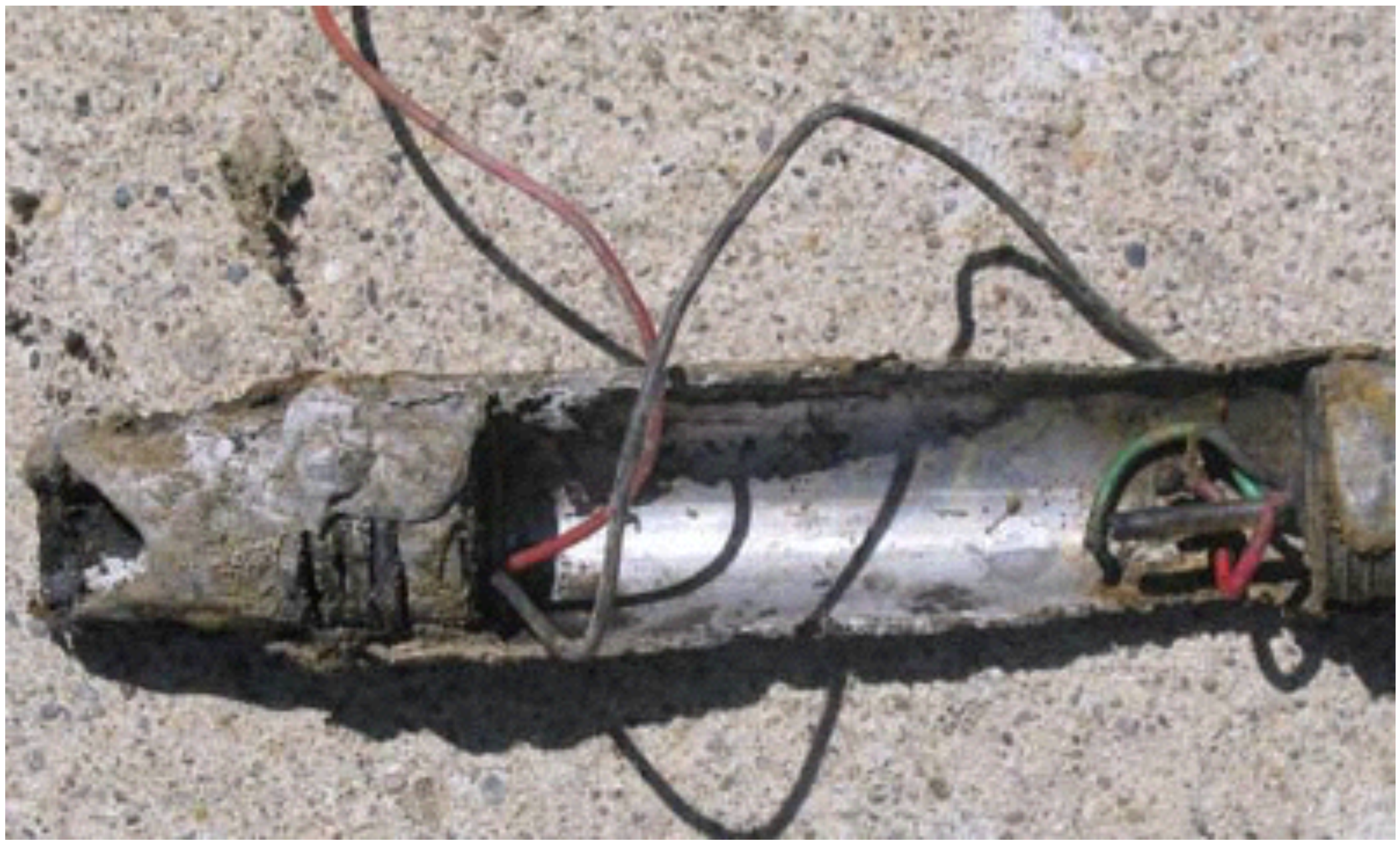


Image: APG Sensors

# Signal conditioning requirements can greatly impact the ease of use and cost of a given transducer


Image: National Instruments

# Offset refers to a DC bias is a given transducer's output

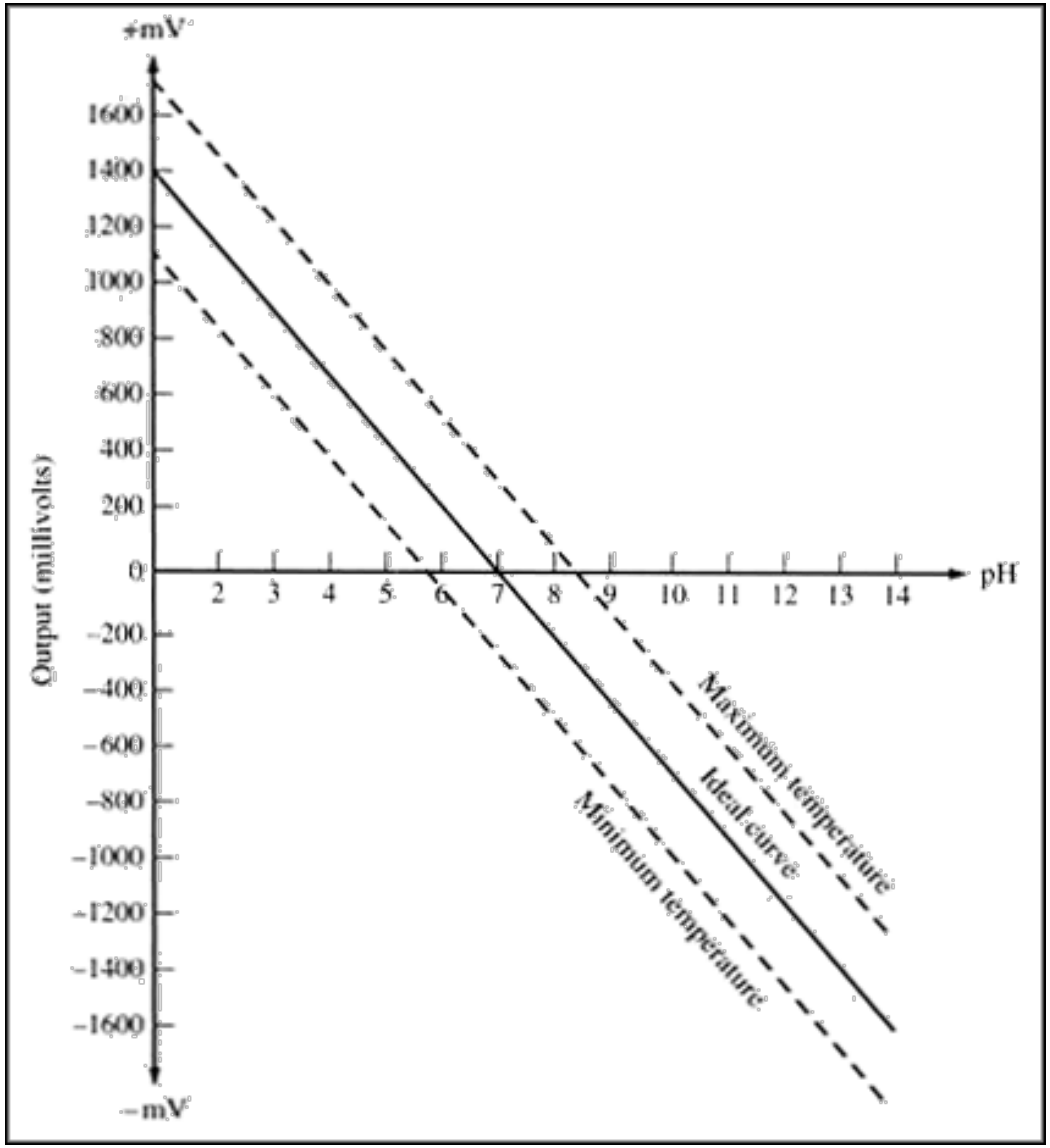



Image: National Instruments

# Hysteresis is the transducer's sensitivity to which direction (up/down) the physical quantity is changing

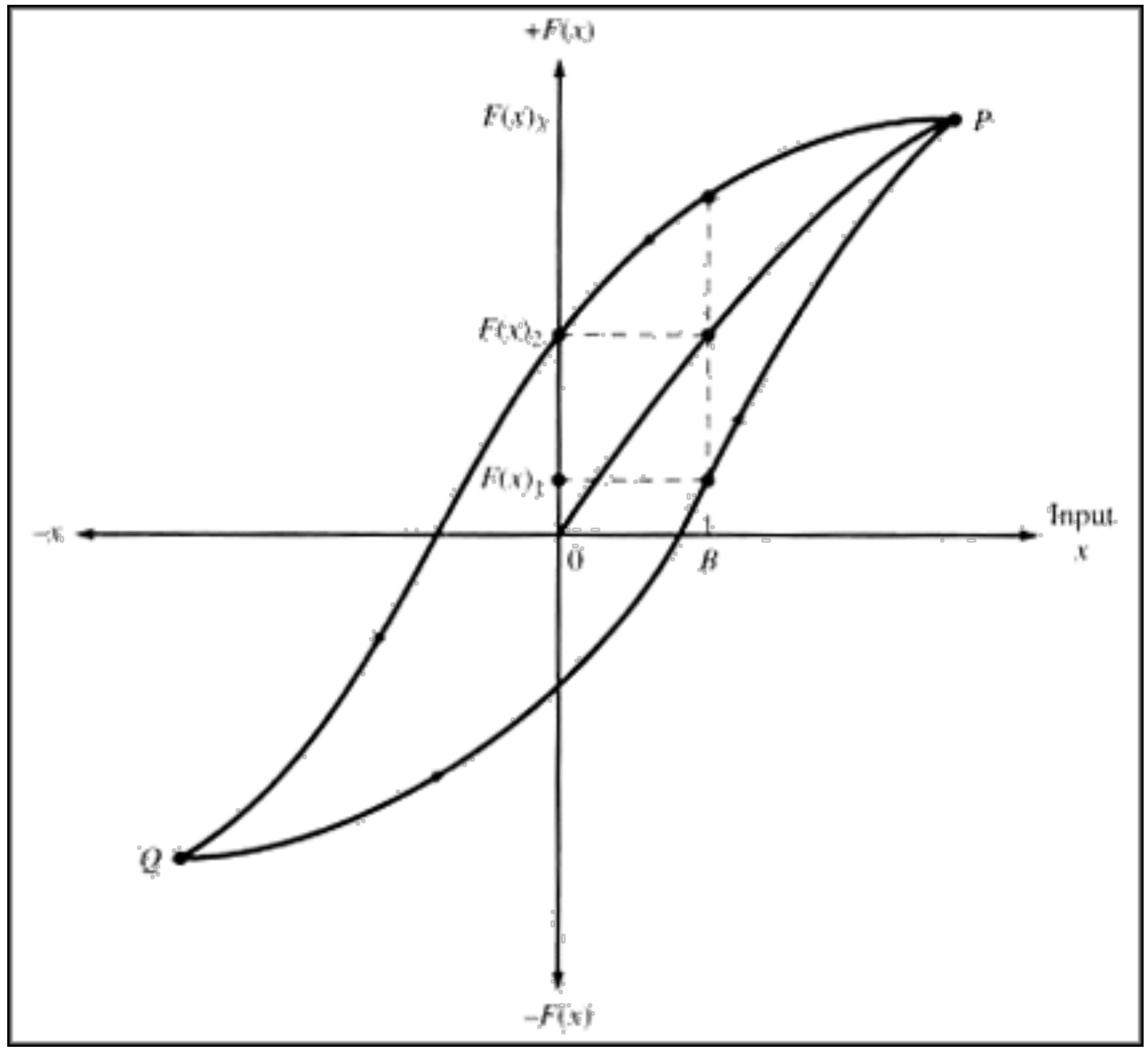



Image: National Instruments

# Dynamic linearity describes how well a transducer's output can follow a rapidly changing quantity

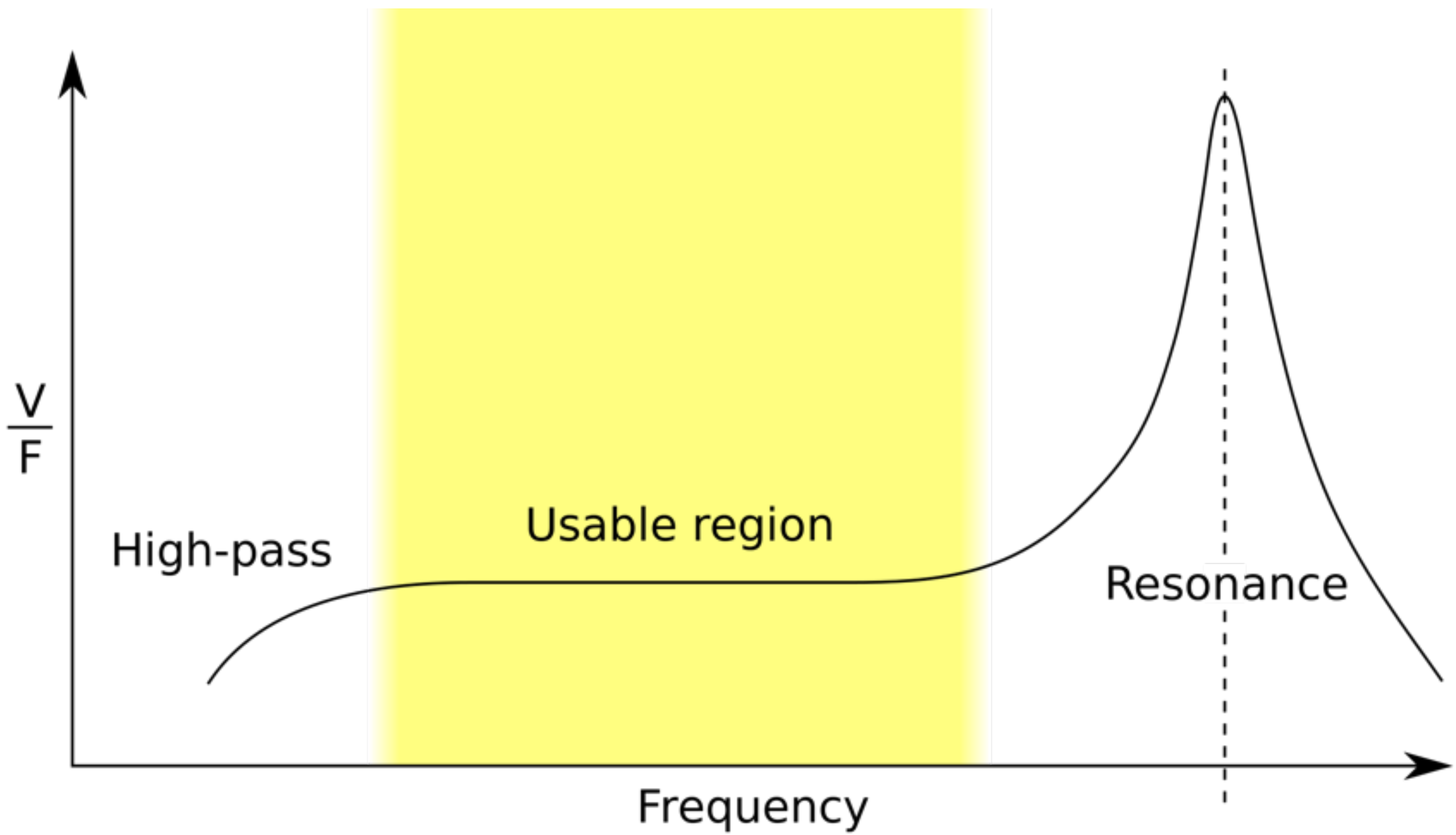
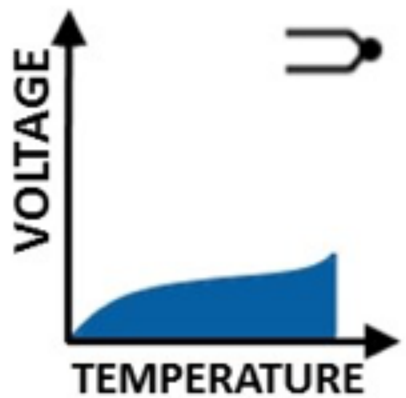
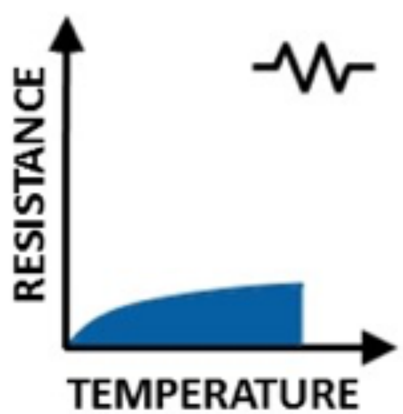
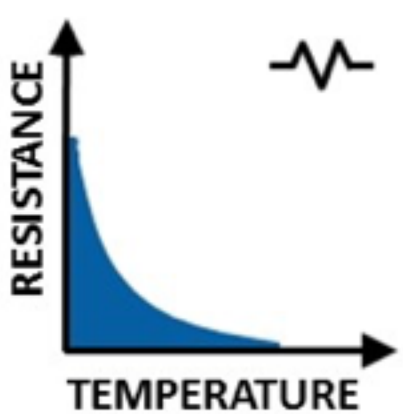



Image: Wikipedia

# Temperature

# Transducers are devices that convert one form of energy to another - we commonly use them as real-world interfaces

| | Advantages | Disadvantages |
|---|---|---|
| THERMOCOUPLES   | ✓ Simple<br>✓ Rugged<br>✓ Inexpensive<br>✓ No external power<br>✓ Wide temperature range<br>✓ Variety of styles | × Nonlinear response<br>× Small sensitivity<br>× Small output voltage<br>× Requires CJC<br>× Least stable |
| RTD   | ✓ Most stable<br>✓ Good Linearity<br>✓ Most accurate | × Low sensitivity<br>× Externally powered<br>× Costly<br>× Small output resistance<br>× Self-heating error |
| THERMISTOR   | ✓ Fast<br>✓ High output<br>✓ Minimal lead resistance error | × Limited temperature range<br>× Externally powered<br>× Nonlinear<br>× More fragile<br>× Self-heating error |

# Each type of temperature sensor has a different output curve

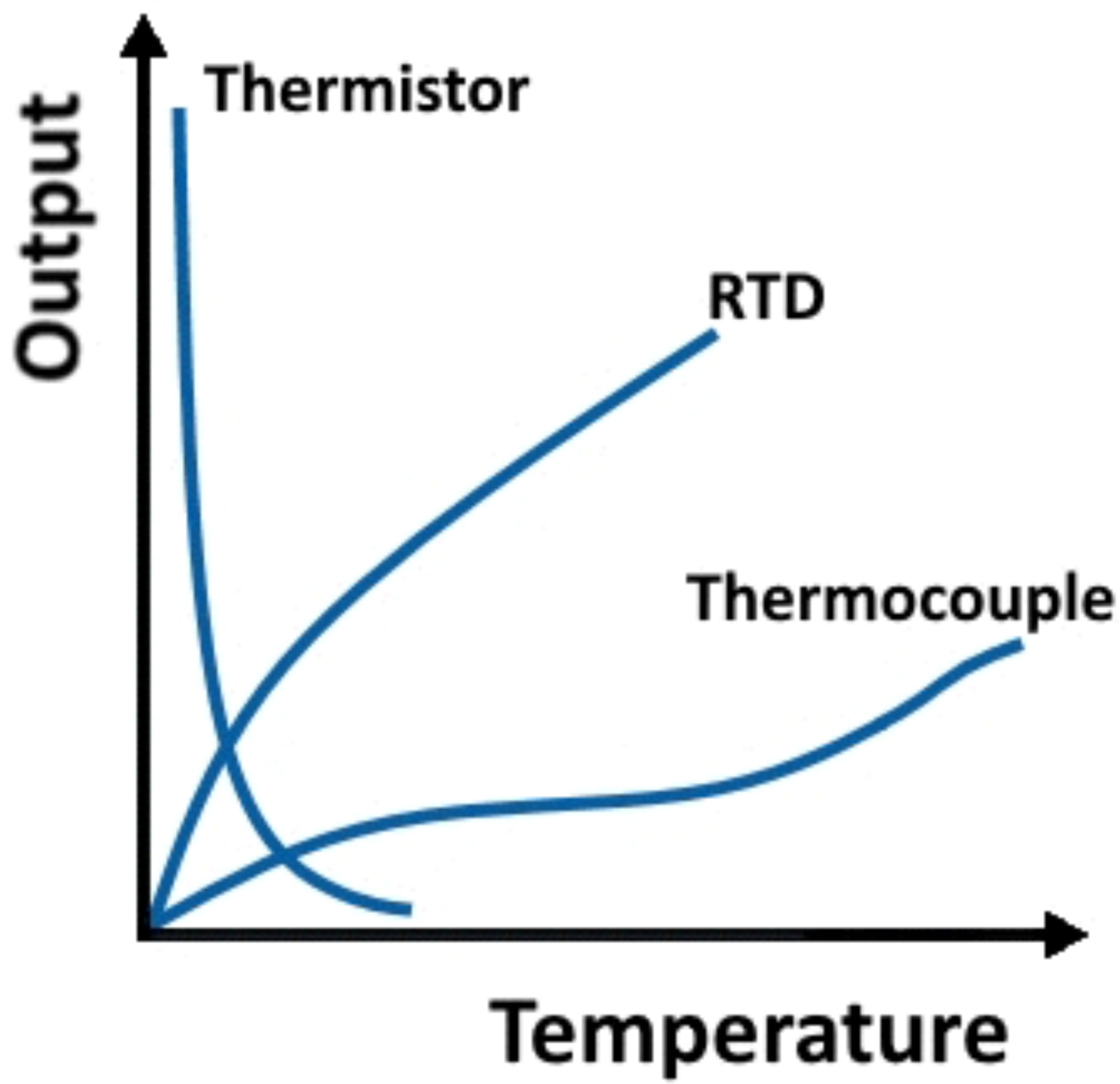



Image: National Instruments

# Thermocouples work on a principle called the Seebeck effect

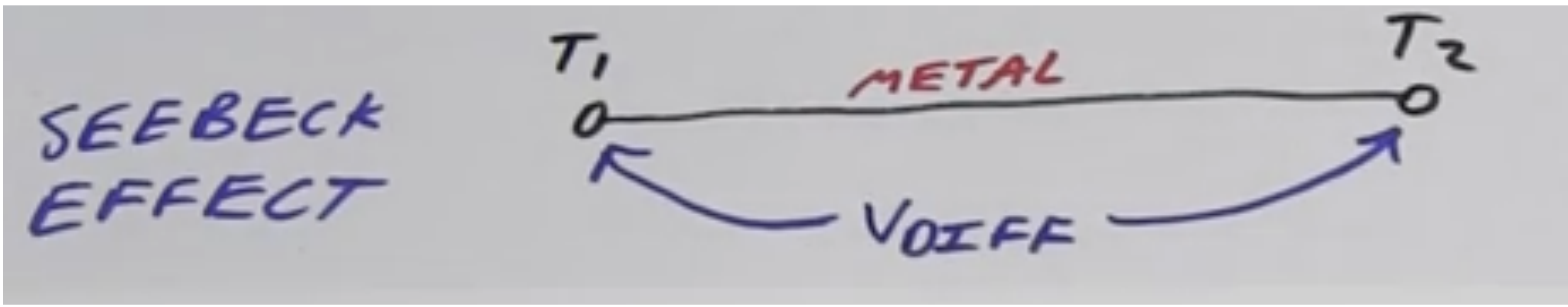



Image: EEVBlog

# Two dissimilar metals are joined to make a transducer

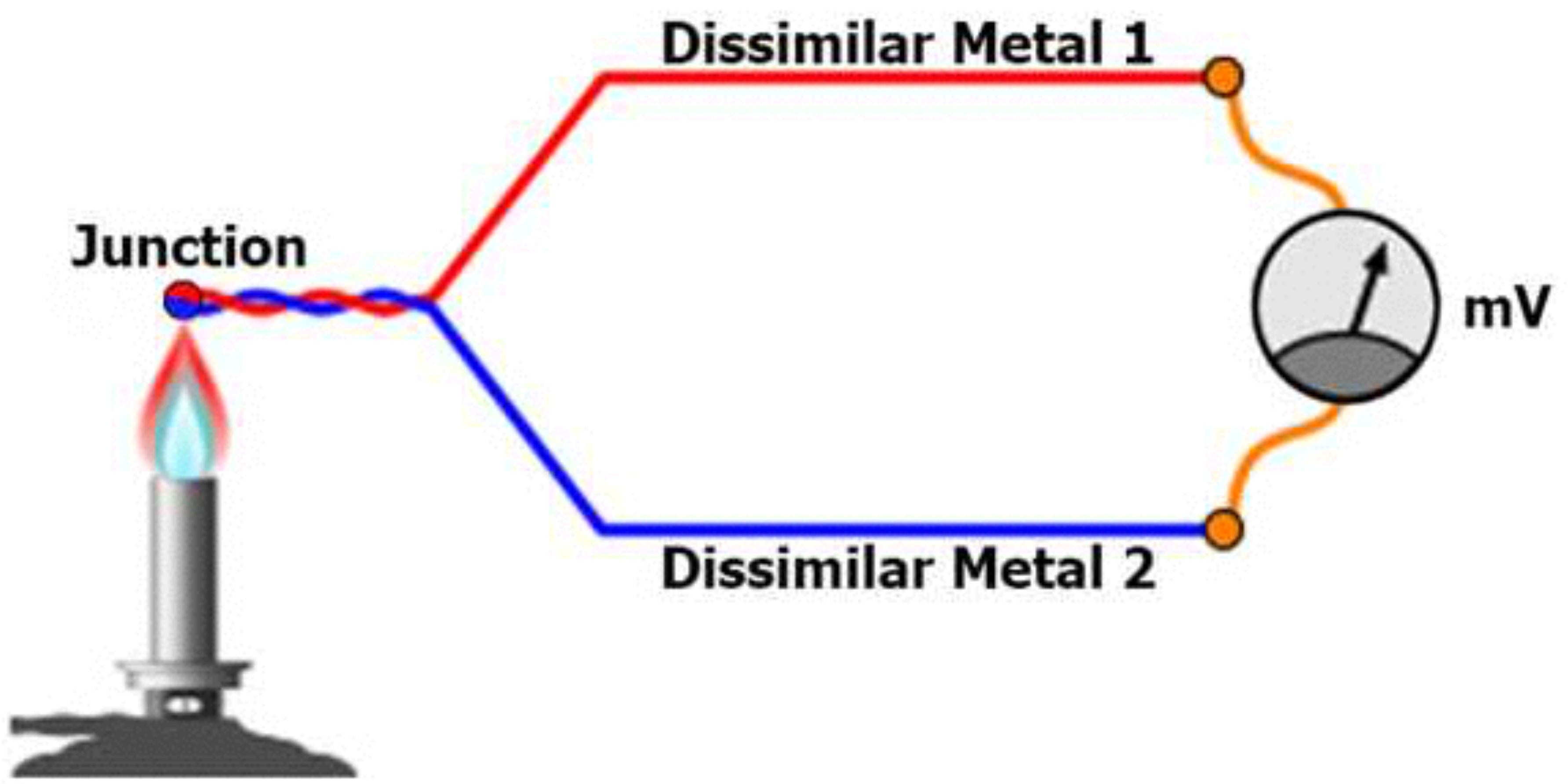



Image: Sterling Sensors

# There are many metal combinations or types of thermocouples

| Common Thermocouple Temperature Ranges | | | |
|---|---|---|---|
| Calibration | Temperature Range | Standard Limits of Error | Special Limits of Error |
| J | 0° to 750°C (32° to 1382°F) | Greater of 2.2°C or 0.75% | Greater of 1.1°C or 0.4% |
| K | -200° to 1250°C (-328° to 2282°F) | Greater of 2.2°C or 0.75% | Greater of 1.1°C or 0.4% |
| E | -200° to 900°C (-328° to 1652°F) | Greater of 1.7°C or 0.5% | Greater of 1.0°C or 0.4% |
| T | -250° to 350°C (-328° to 662°F) | Greater of 1.0°C or 0.75% | Greater of 0.5°C or 0.4% |

Image: OMEGA

# The challenge is unintentional junctions in the system

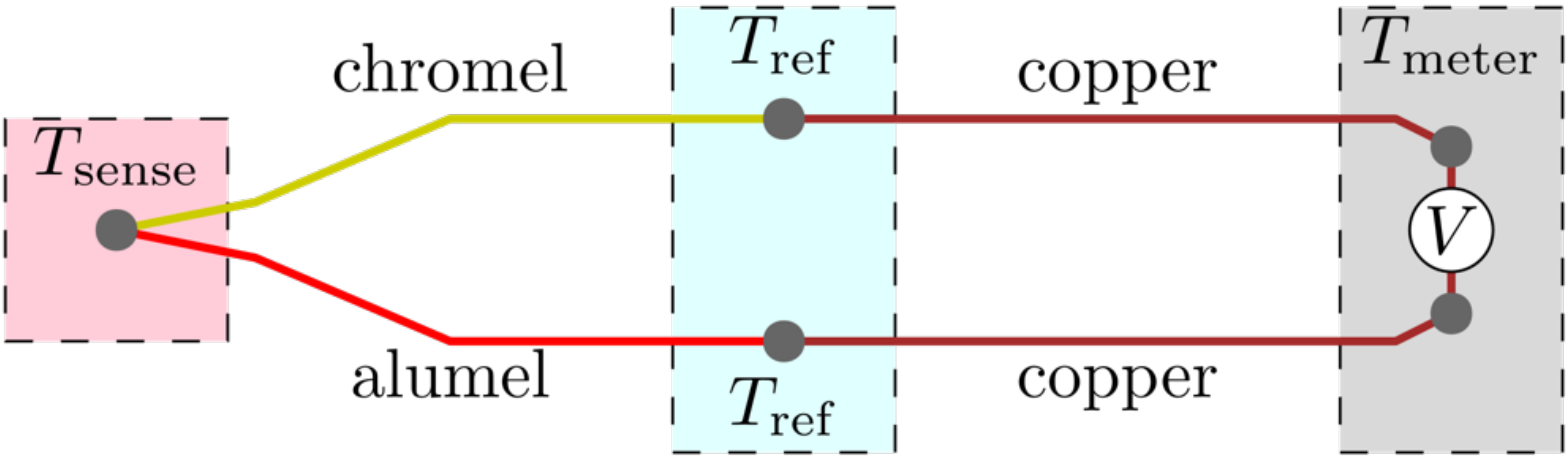



Image: Wikipedia

# The challenge is unintentional junctions in the system

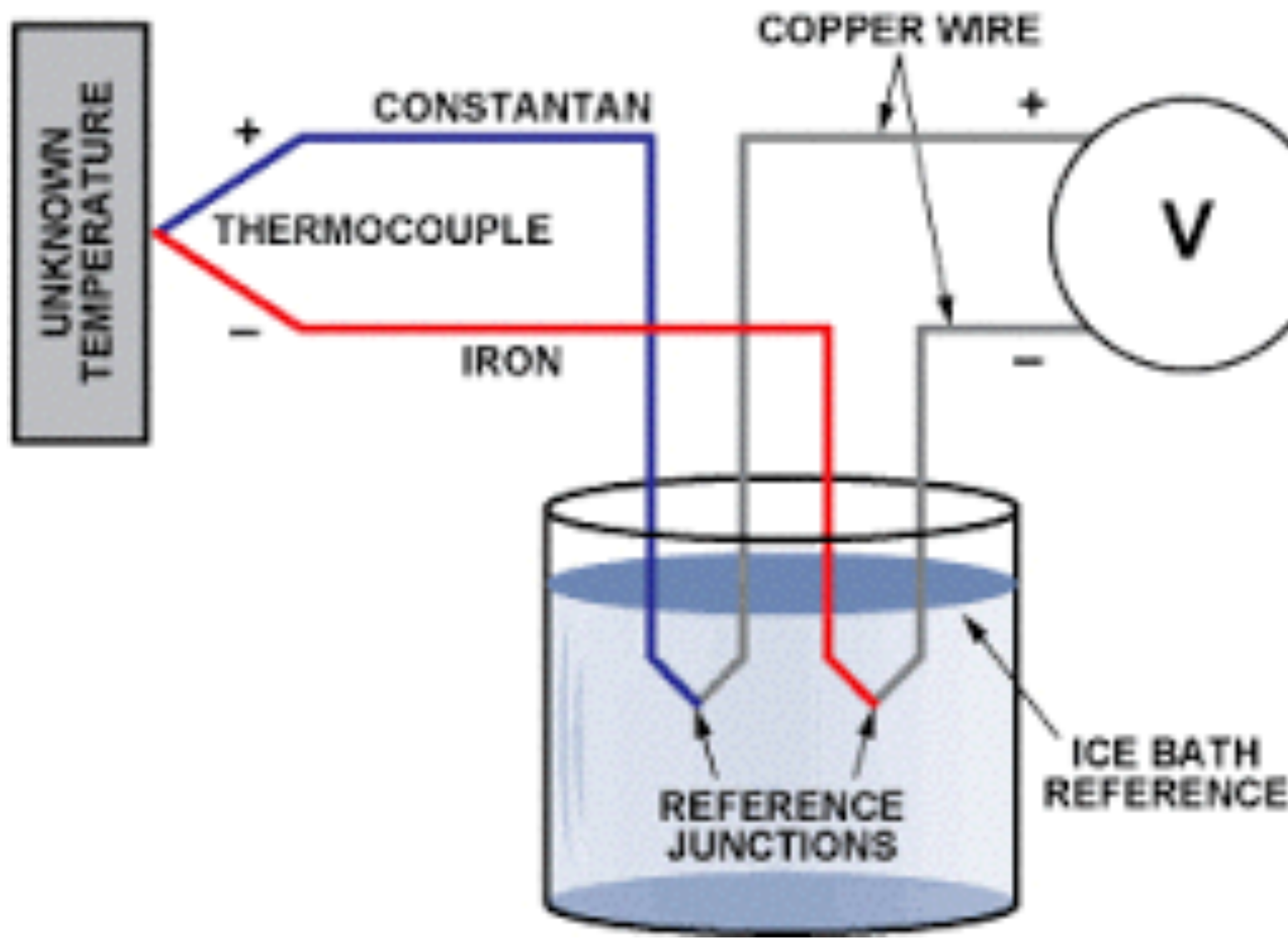



Image: Analog Devices

# We measure the temperature of the “cold junction” and compensate for it with NIST tables

ITS-90 Table for type K thermocouple

Thermoelectric Voltage in mV

| °C | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 | -9 | -10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -270 | -6.458 | | | | | | | | | | |
| -260 | -6.441 | -6.444 | -6.446 | -6.448 | -6.450 | -6.452 | -6.453 | -6.455 | -6.456 | -6.457 | -6.458 |
| -250 | -6.404 | -6.408 | -6.413 | -6.417 | -6.421 | -6.425 | -6.429 | -6.432 | -6.435 | -6.438 | -6.441 |
| -240 | -6.344 | -6.351 | -6.358 | -6.364 | -6.370 | -6.377 | -6.382 | -6.388 | -6.393 | -6.399 | -6.404 |
| -230 | -6.262 | -6.271 | -6.280 | -6.289 | -6.297 | -6.306 | -6.314 | -6.322 | -6.329 | -6.337 | -6.344 |
| -220 | -6.158 | -6.170 | -6.181 | -6.192 | -6.202 | -6.213 | -6.223 | -6.233 | -6.243 | -6.252 | -6.262 |
| -210 | -6.035 | -6.048 | -6.061 | -6.074 | -6.087 | -6.099 | -6.111 | -6.123 | -6.135 | -6.147 | -6.158 |
| -200 | -5.891 | -5.907 | -5.922 | -5.936 | -5.951 | -5.965 | -5.980 | -5.994 | -6.007 | -6.021 | -6.035 |
| -190 | -5.730 | -5.747 | -5.763 | -5.780 | -5.797 | -5.813 | -5.829 | -5.845 | -5.861 | -5.876 | -5.891 |
| -180 | -5.550 | -5.569 | -5.588 | -5.606 | -5.624 | -5.642 | -5.660 | -5.678 | -5.695 | -5.713 | -5.730 |
| -170 | -5.354 | -5.374 | -5.395 | -5.415 | -5.435 | -5.454 | -5.474 | -5.493 | -5.512 | -5.531 | -5.550 |
| -160 | -5.141 | -5.163 | -5.185 | -5.207 | -5.228 | -5.250 | -5.271 | -5.292 | -5.313 | -5.333 | -5.354 |
| -150 | -4.913 | -4.936 | -4.960 | -4.983 | -5.006 | -5.029 | -5.052 | -5.074 | -5.097 | -5.119 | -5.141 |
| -140 | -4.669 | -4.694 | -4.719 | -4.744 | -4.768 | -4.793 | -4.817 | -4.841 | -4.865 | -4.889 | -4.913 |
| -130 | -4.411 | -4.437 | -4.463 | -4.490 | -4.516 | -4.542 | -4.567 | -4.593 | -4.618 | -4.644 | -4.669 |
| -120 | -4.138 | -4.166 | -4.194 | -4.221 | -4.249 | -4.276 | -4.303 | -4.330 | -4.357 | -4.384 | -4.411 |
| -110 | -3.852 | -3.882 | -3.911 | -3.939 | -3.968 | -3.997 | -4.025 | -4.054 | -4.082 | -4.110 | -4.138 |
| -100 | -3.554 | -3.584 | -3.614 | -3.645 | -3.675 | -3.705 | -3.734 | -3.764 | -3.794 | -3.823 | -3.852 |
| -90 | -3.243 | -3.274 | -3.306 | -3.337 | -3.368 | -3.400 | -3.431 | -3.462 | -3.492 | -3.523 | -3.554 |
| -80 | -2.920 | -2.953 | -2.986 | -3.018 | -3.050 | -3.083 | -3.115 | -3.147 | -3.179 | -3.211 | -3.243 |
| -70 | -2.587 | -2.620 | -2.654 | -2.688 | -2.721 | -2.755 | -2.788 | -2.821 | -2.854 | -2.887 | -2.920 |
| -60 | -2.243 | -2.278 | -2.312 | -2.347 | -2.382 | -2.416 | -2.450 | -2.485 | -2.519 | -2.553 | -2.587 |
| -50 | -1.889 | -1.925 | -1.961 | -1.996 | -2.032 | -2.067 | -2.103 | -2.138 | -2.173 | -2.208 | -2.243 |
| -40 | -1.527 | -1.564 | -1.600 | -1.637 | -1.673 | -1.709 | -1.745 | -1.782 | -1.818 | -1.854 | -1.889 |
| -30 | -1.156 | -1.194 | -1.231 | -1.268 | -1.305 | -1.343 | -1.380 | -1.417 | -1.453 | -1.490 | -1.527 |
| -20 | -0.778 | -0.816 | -0.854 | -0.892 | -0.930 | -0.968 | -1.006 | -1.043 | -1.081 | -1.119 | -1.156 |
| -10 | -0.392 | -0.431 | -0.470 | -0.508 | -0.547 | -0.586 | -0.624 | -0.663 | -0.701 | -0.739 | -0.778 |
| 0 | 0.000 | -0.039 | -0.079 | -0.118 | -0.157 | -0.197 | -0.236 | -0.275 | -0.314 | -0.353 | -0.392 |
| °C | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 | -9 | -10 |

**Image: NIST**

# Or use a high order polynomial fit

**Type K Thermocouples** - coefficients of approximate inverse functions giving temperature, $t_{90}$, as a function of the thermoelectric voltage, $E$, in selected temperature and voltage ranges. The functions are of the form:

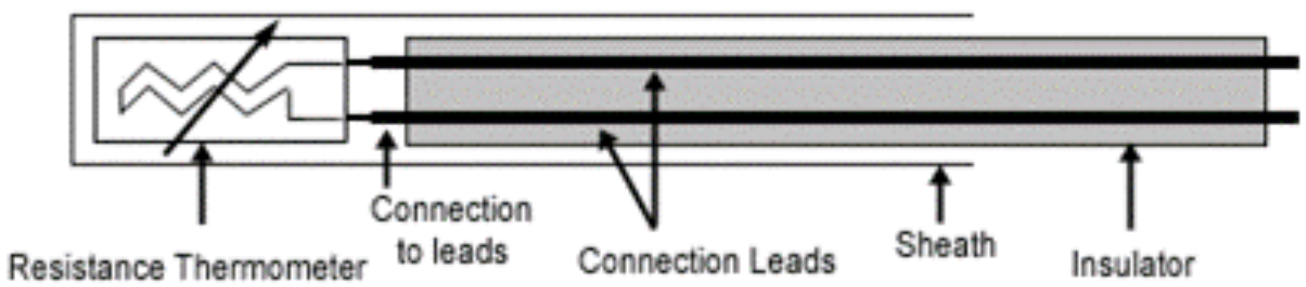
$$t_{90} = c_o + c_1E + c_2E^2 \quad c_iE^i$$

where $E$ is in microvolts and $t_{90}$ is in degrees Celsius.

| **Temperature Range:** | **-200 to 0°C** | **0 to 500°C** | **500 to 1,372°C** |
|---|---|---|---|
| **Voltage Range:** | **-5891 to 0 µV** | **0 to 20,644 µV** | **20,644 to 54,886 µV** |
| $c_0 =$ | 0.000 000 0 .... | 0.000 000 .... | $-1.318\,058 \times 10^{2}$ |
| $c_1 =$ | $2.517\,346\,2 \times 10^{-2}$ | $2.508\,355 \times 10^{-2}$ | $4.830\,222 \times 10^{-2}$ |
| $c_2 =$ | $-1.166\,287\,8 \times 10^{-6}$ | $7.860\,106 \times 10^{-8}$ | $-1.646\,031 \times 10^{-6}$ |
| $c_3 =$ | $-1.083\,363\,8 \times 10^{-9}$ | $-2.503\,131 \times 10^{-10}$ | $5.464\,731 \times 10^{-11}$ |
| $c_4 =$ | $-8.977\,354\,0 \times 10^{-13}$ | $8.315\,270 \times 10^{-14}$ | $-9.650\,715 \times 10^{-16}$ |
| $c_5 =$ | $-3.734\,237\,7 \times 10^{-16}$ | $-1.228\,034 \times 10^{-17}$ | $8.802\,193 \times 10^{-21}$ |
| $c_6 =$ | $-8.663\,264\,3 \times 10^{-20}$ | $9.804\,036 \times 10^{-22}$ | $-3.110\,810 \times 10^{-26}$ |
| $c_7 =$ | $-1.045\,059\,8 \times 10^{-23}$ | $-4.413\,030 \times 10^{-26}$ | |
| $c_8 =$ | $-5.192\,057\,7 \times 10^{-28}$ | $1.057\,734 \times 10^{-30}$ | |
| $c_9 =$ | | $-1.052\,755 \times 10^{-35}$ | |
| **Error Range:** | 0.04°C to -0.02°C | 0.04°C to -0.05°C | 0.06°C to -0.05°C |

**Image: OMEGA**

# RTDs change resistance based on the temperature



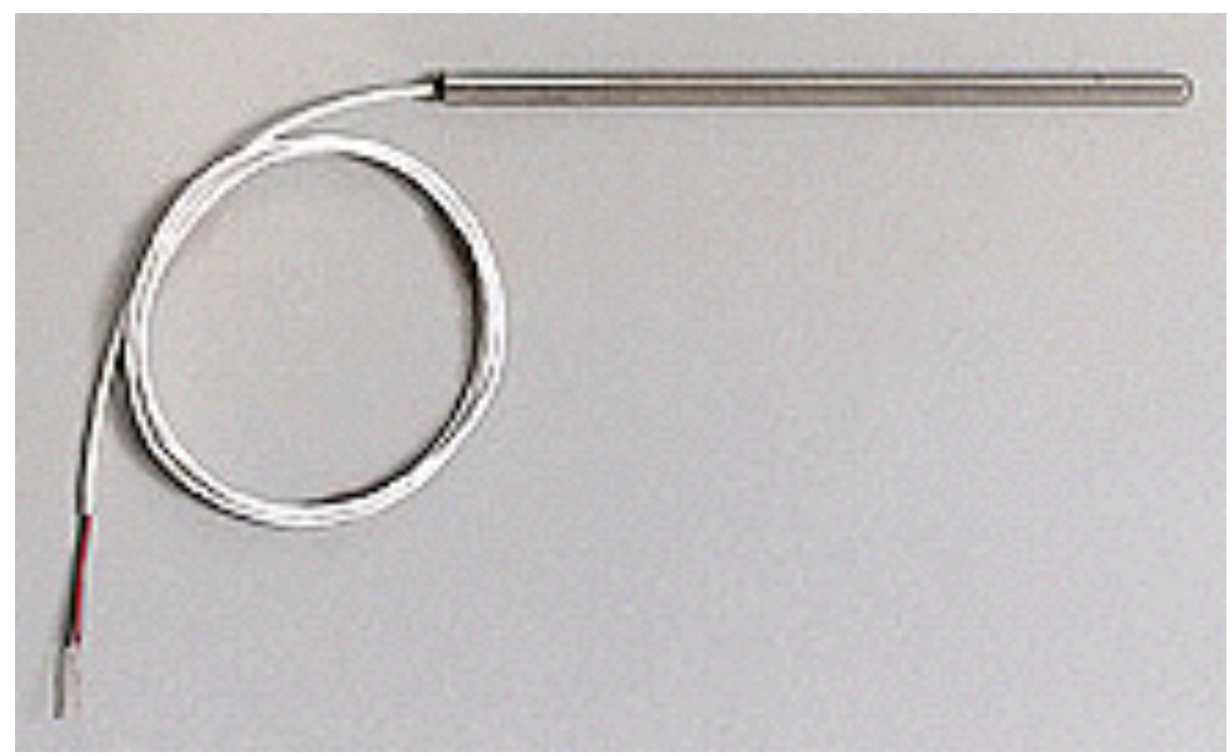
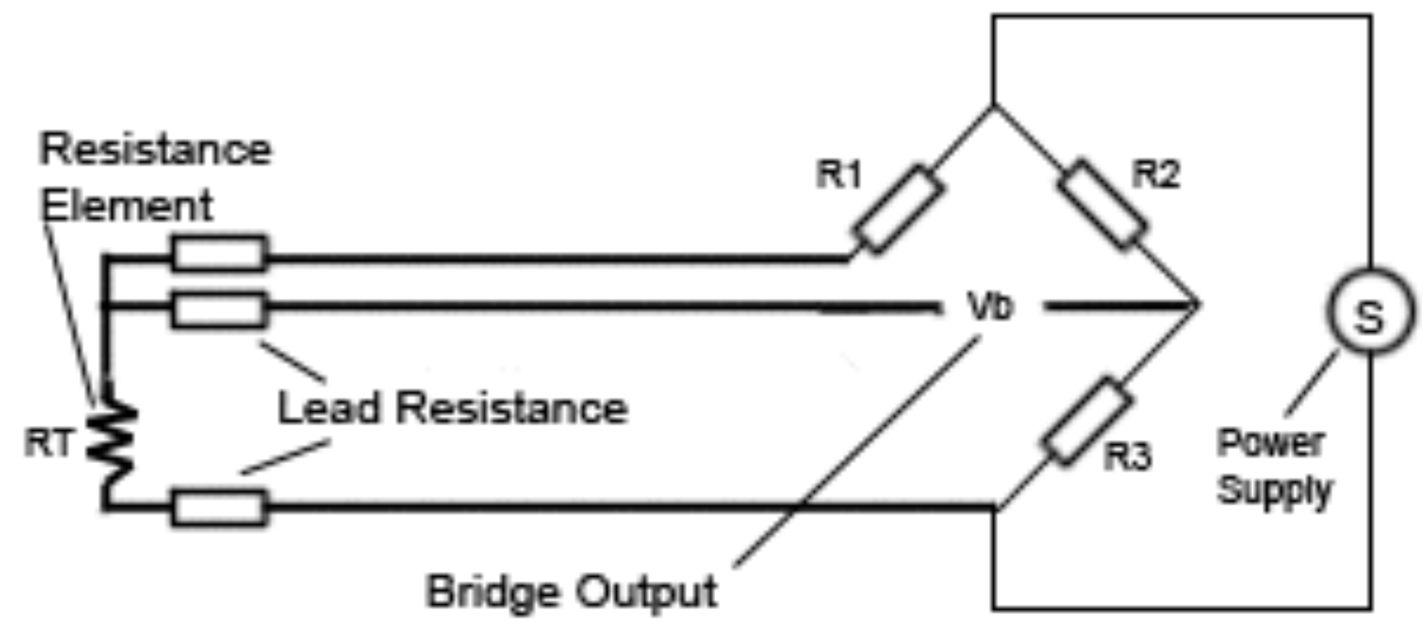
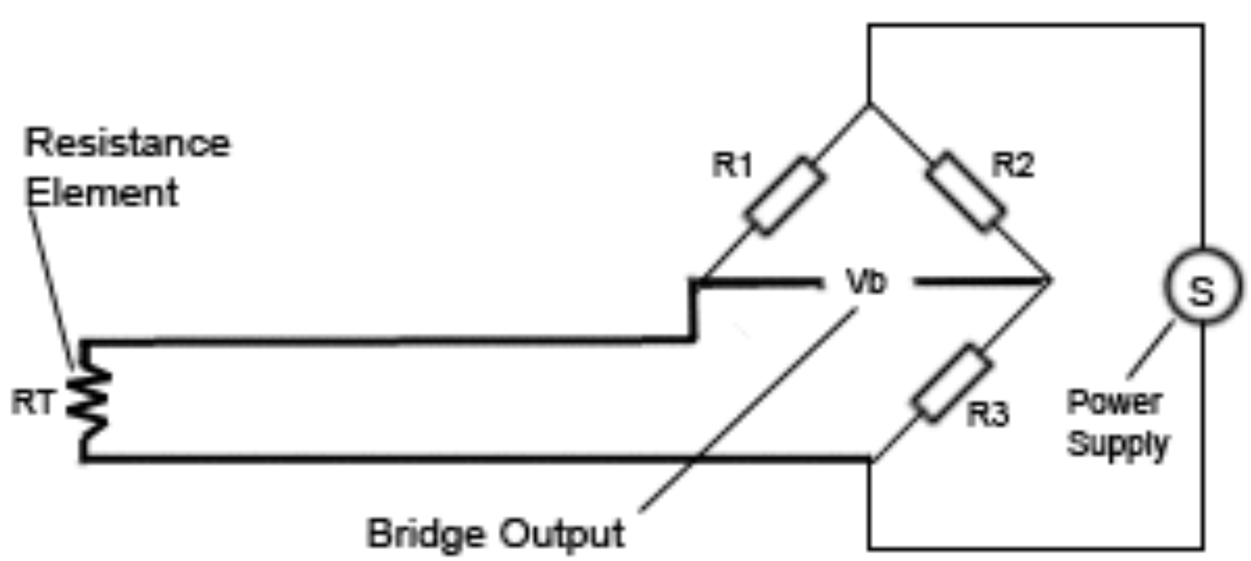



Image: Wikipedia/OMEGA

# Multiple signal conditioning strategies can be used depending on the requirements and cost tradeoff



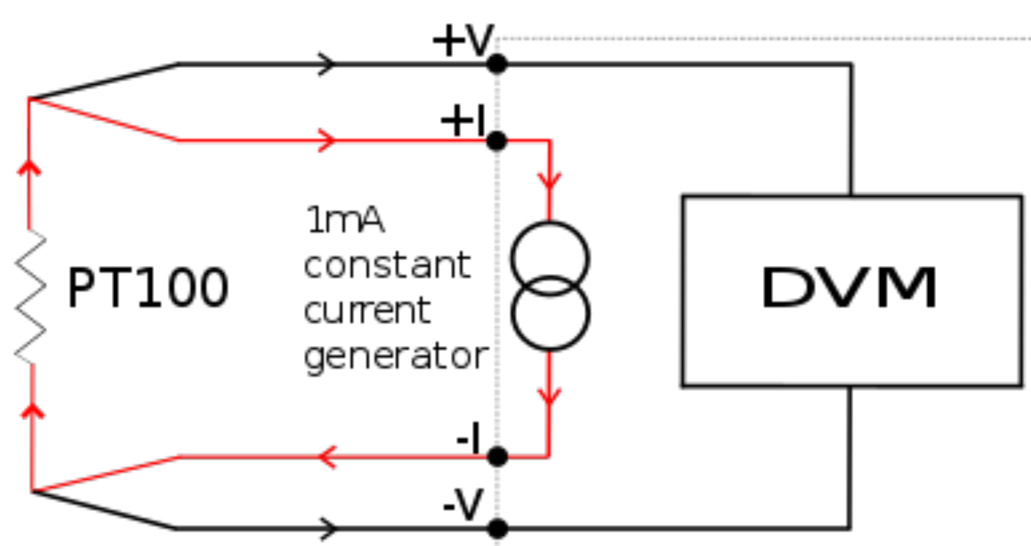




**Image: Wikipedia**

# Thermistors also change their resistance with temperature

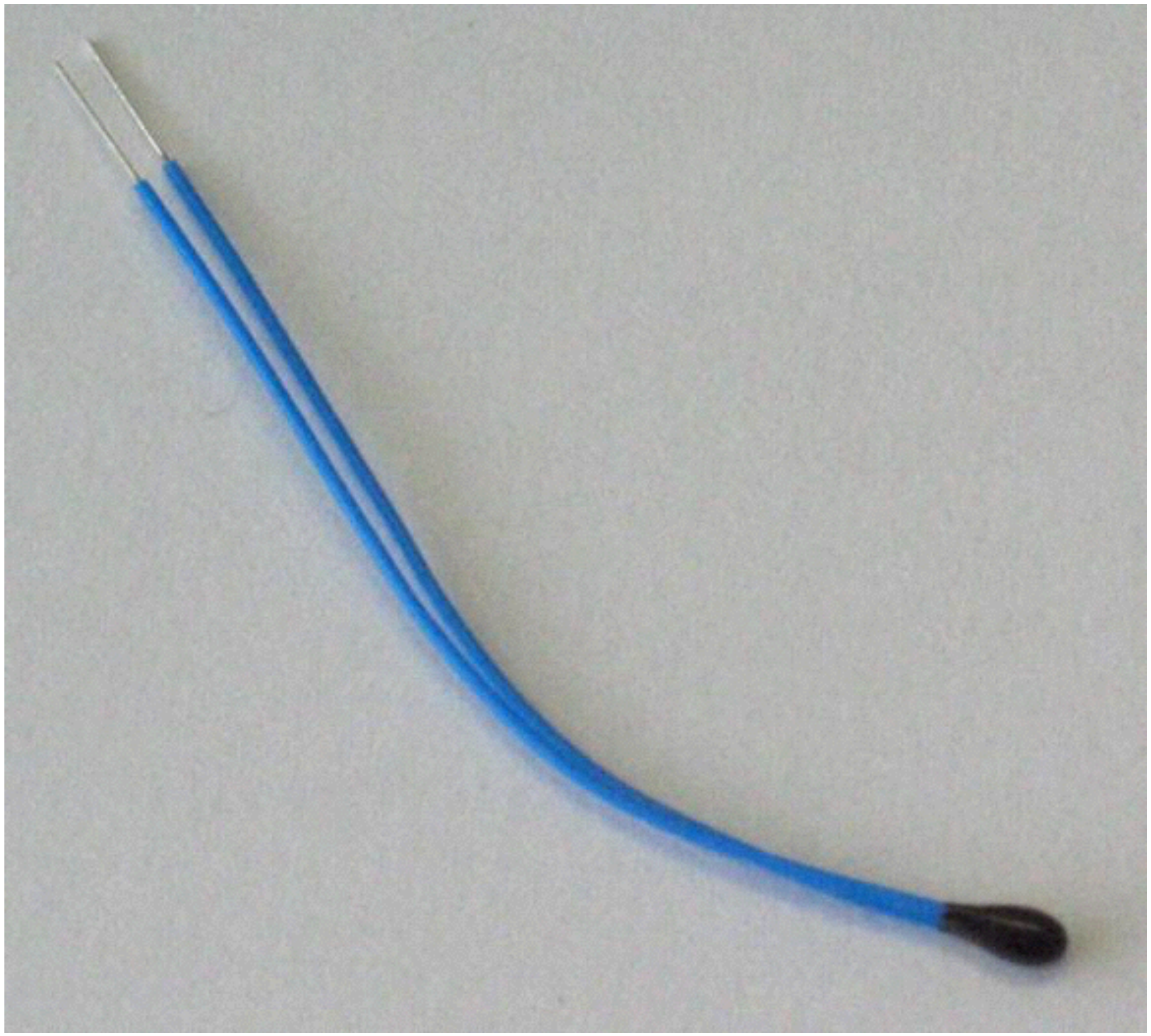
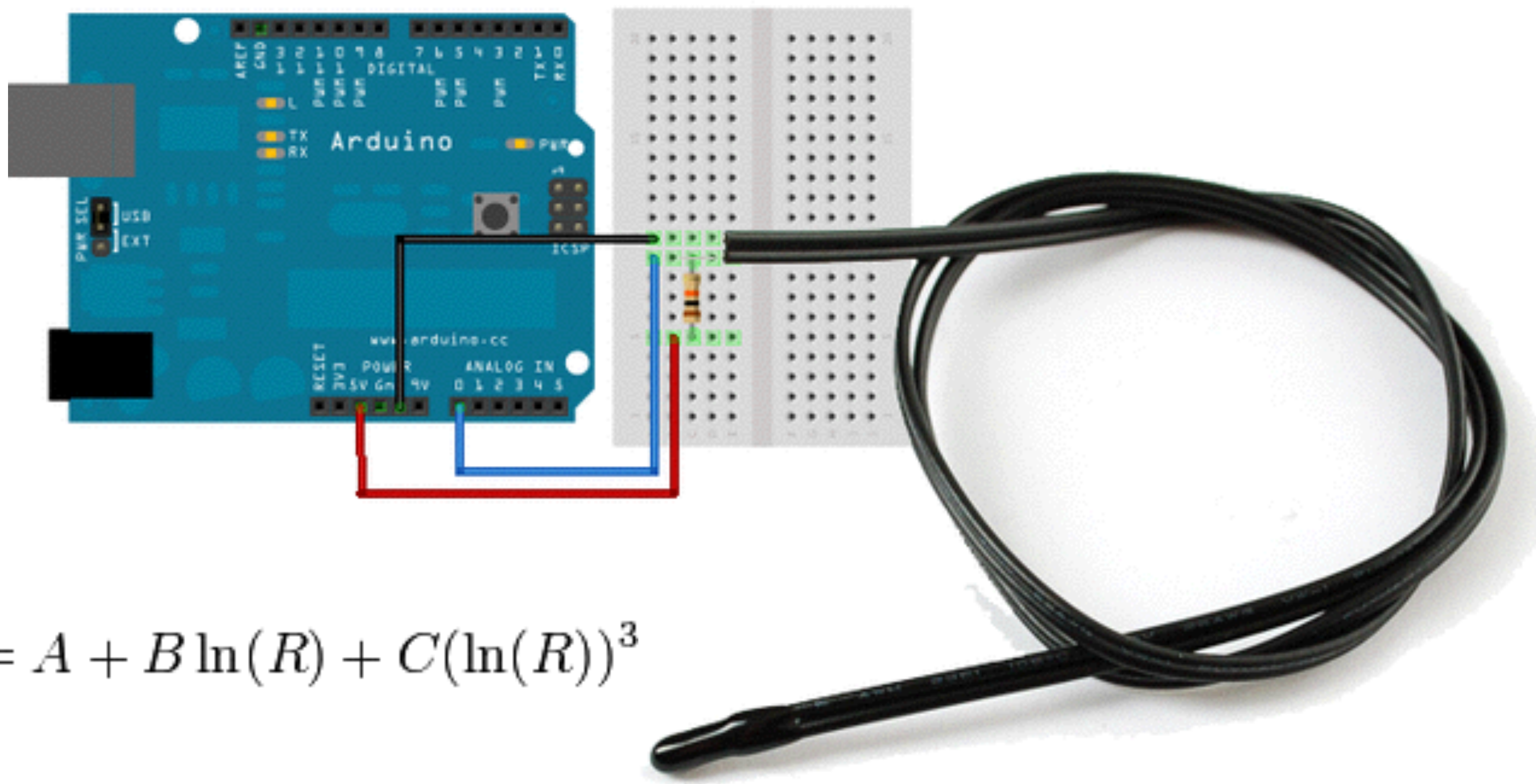


Image: Wikipedia

# Conditioning happens with various resistor bridge/divider circuits



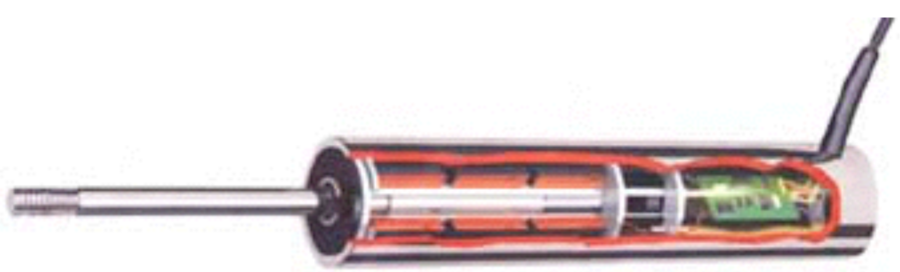

$$\frac{1}{T} = A + B\ln(R) + C(\ln(R))^3$$

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B}\ln\left(\frac{R}{R_0}\right)$$

Image: Adafruit

# Displacement

# Displacement measurements can be performed in absolute or relative ways with a WIDE variety of transducers

# DCDTs/LVDTs are a differential transformer

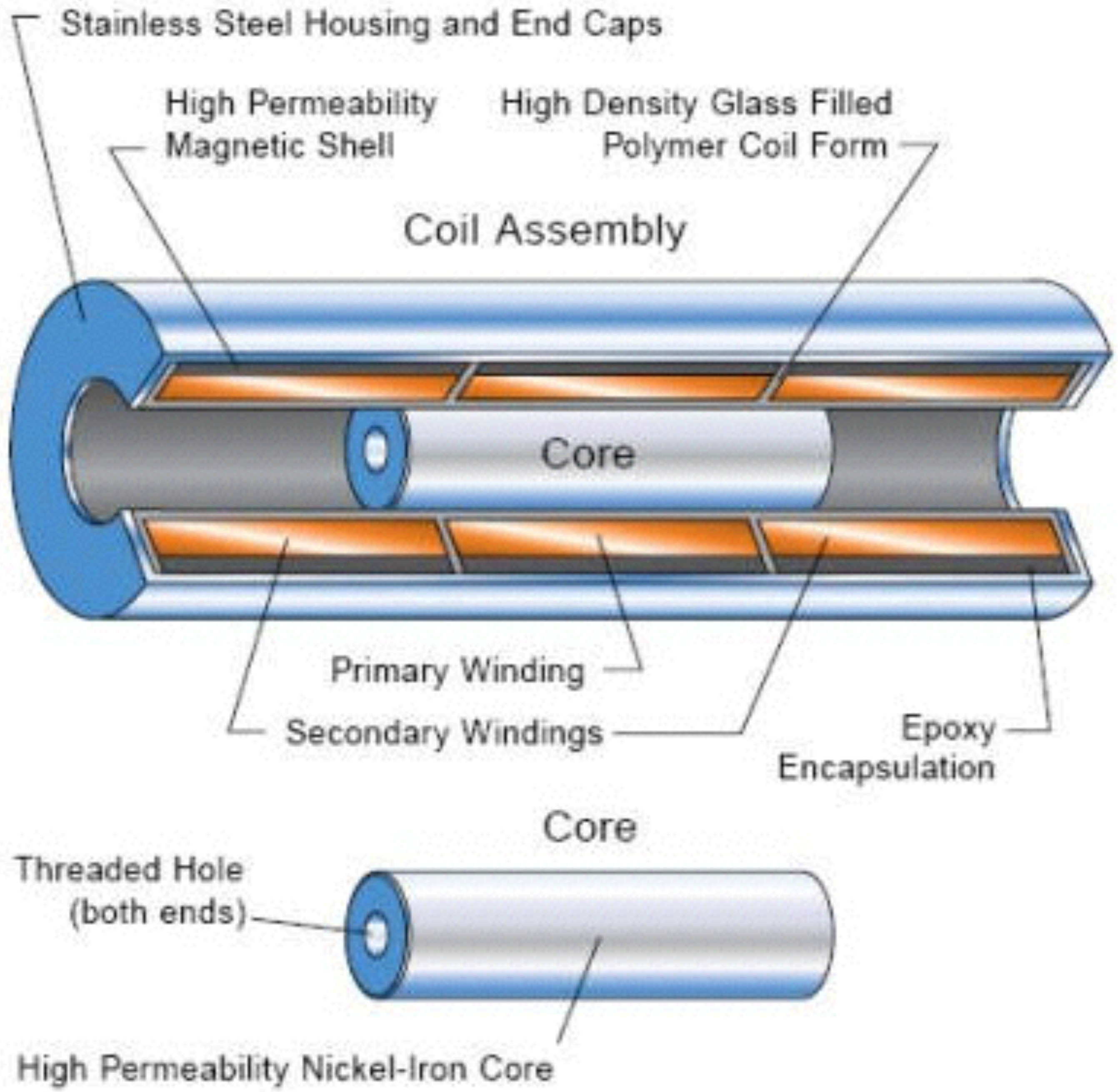



Image: te.com

# DCDTs/LVDTs are a differential transformer

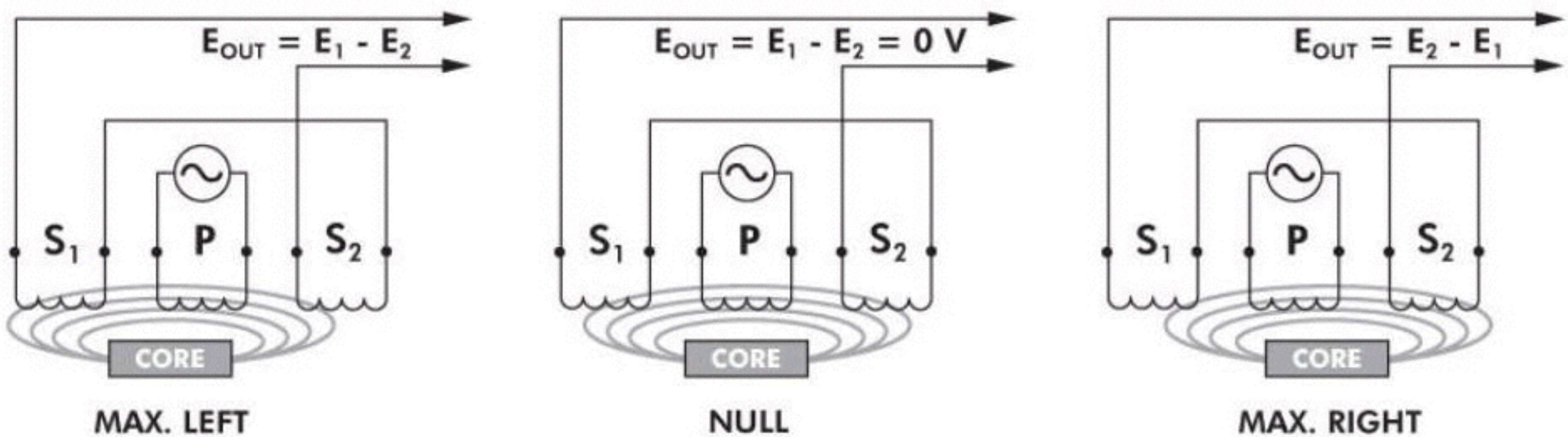



Image: te.com

# DCDTs/LVDTs are a differential transformer

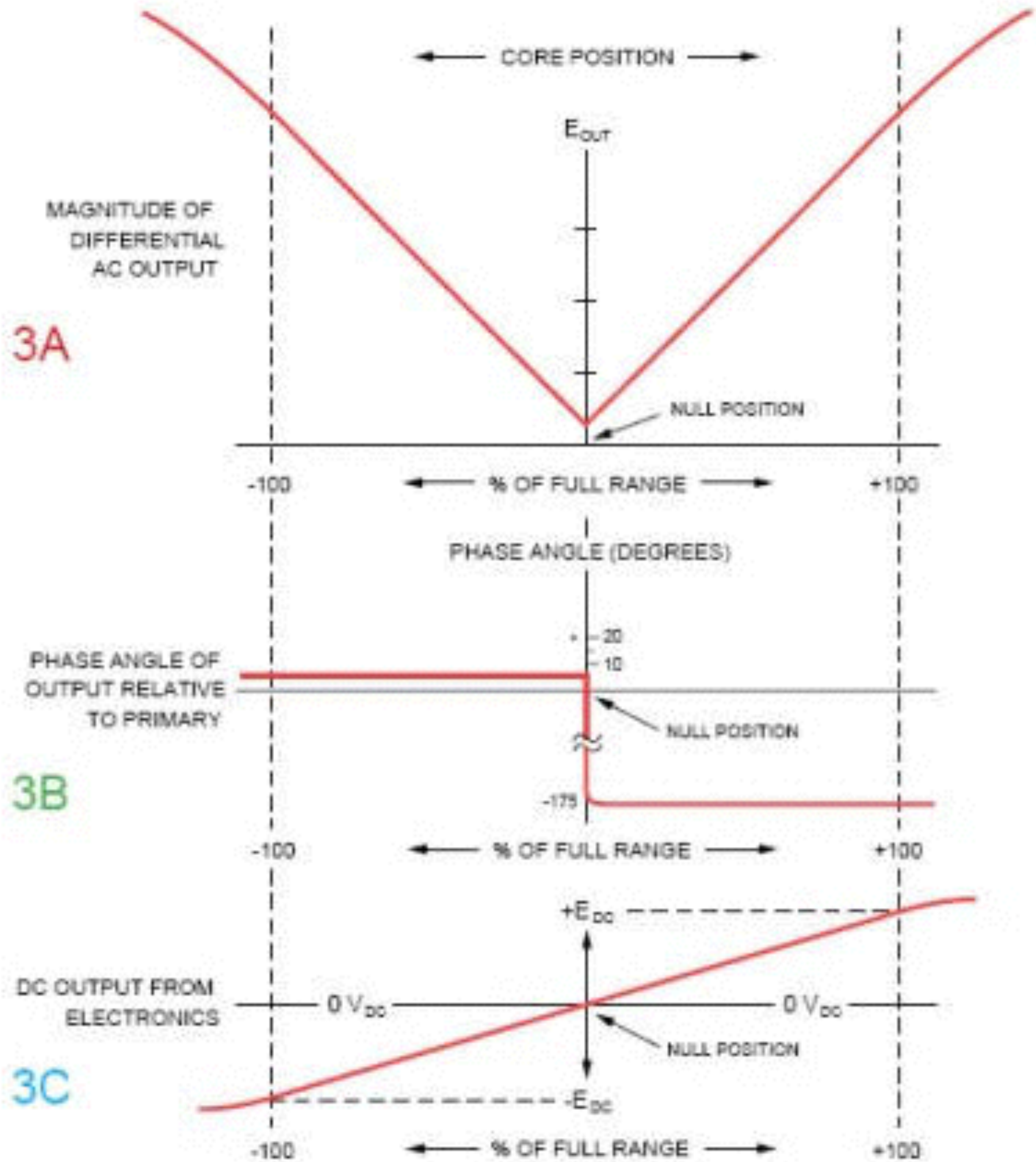



Image: te.com

# DCDTs include all of the necessary driving/conditioning electronics

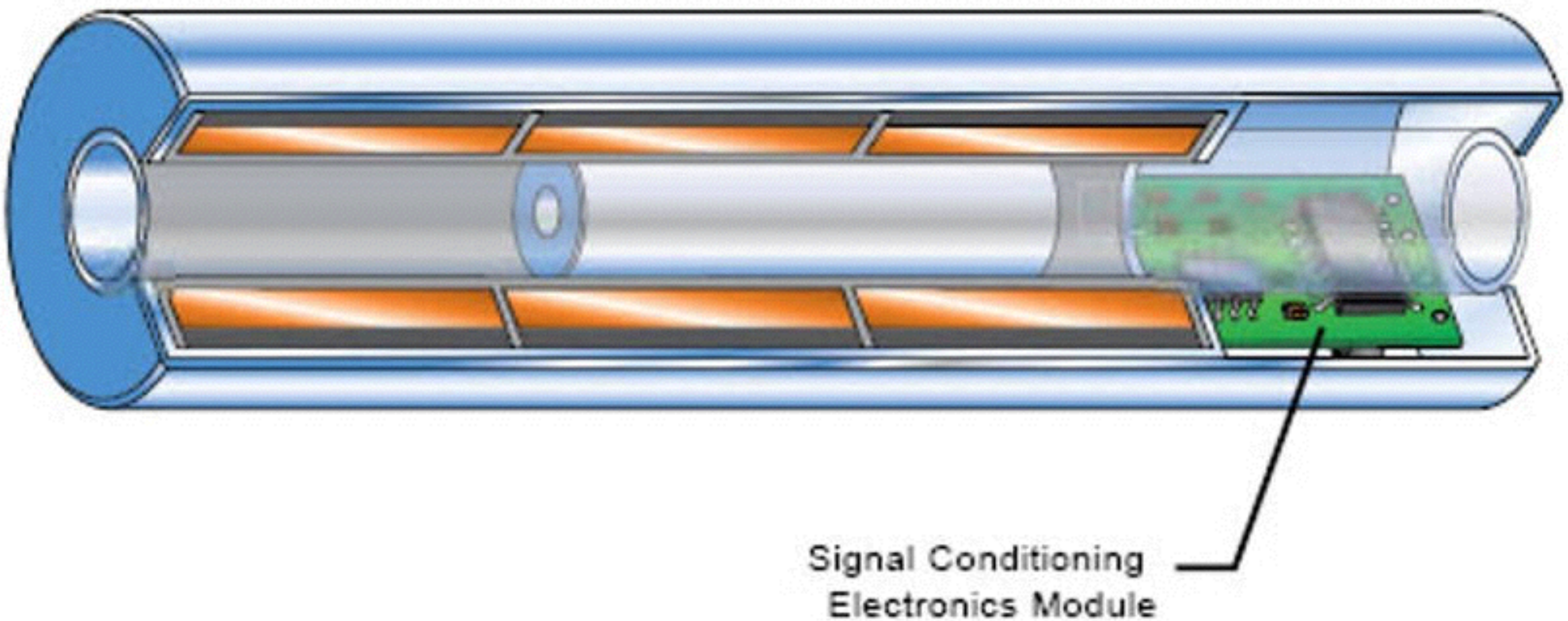
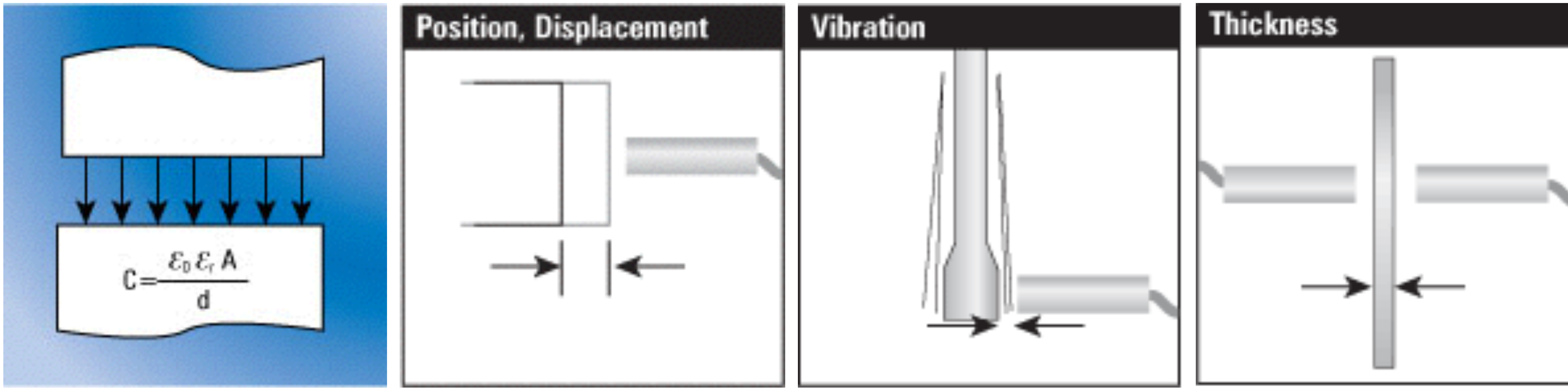



Image: te.com

# Capacitive displacement sensors are very low noise and high resolution



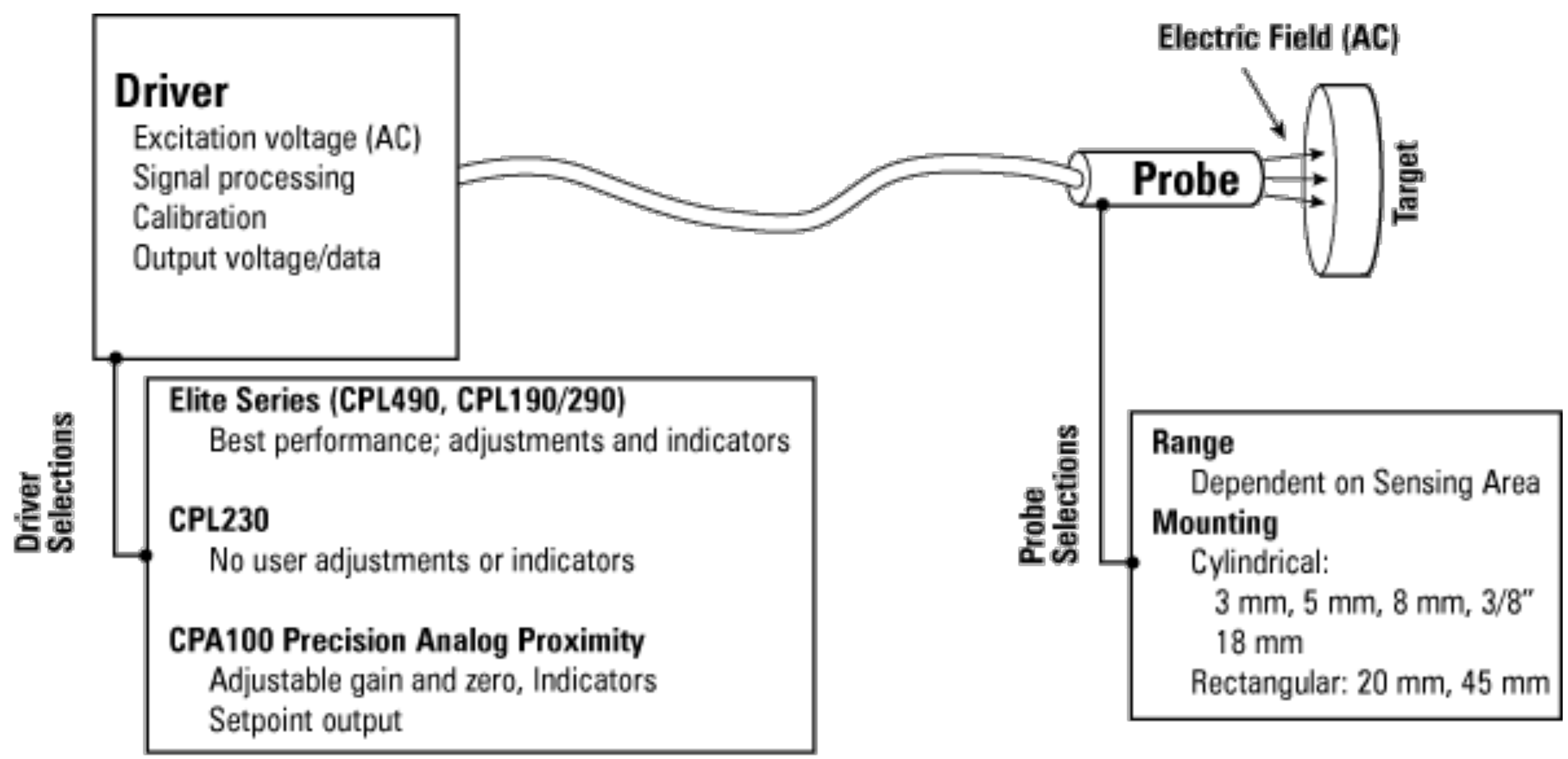




Image: lionprecision.com

# Eddy current sensors are less expensive and still relatively low noise

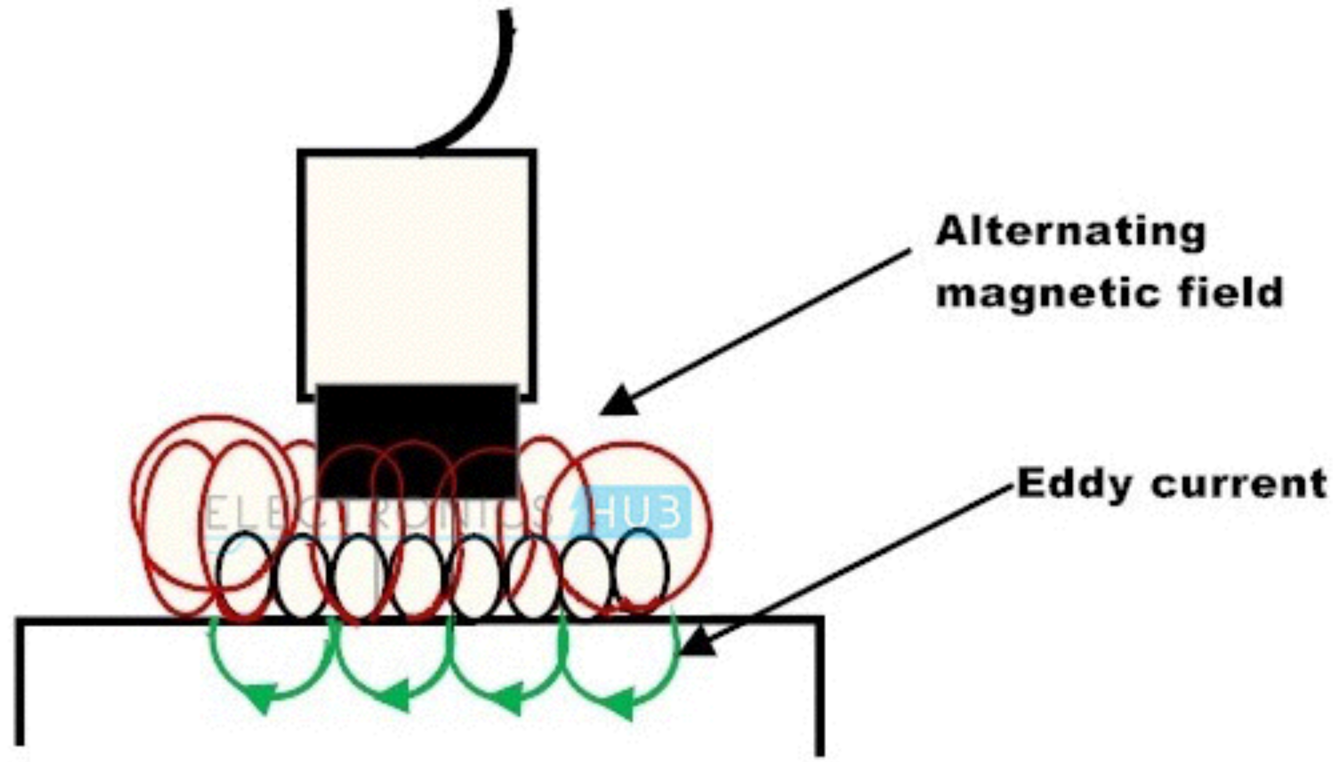


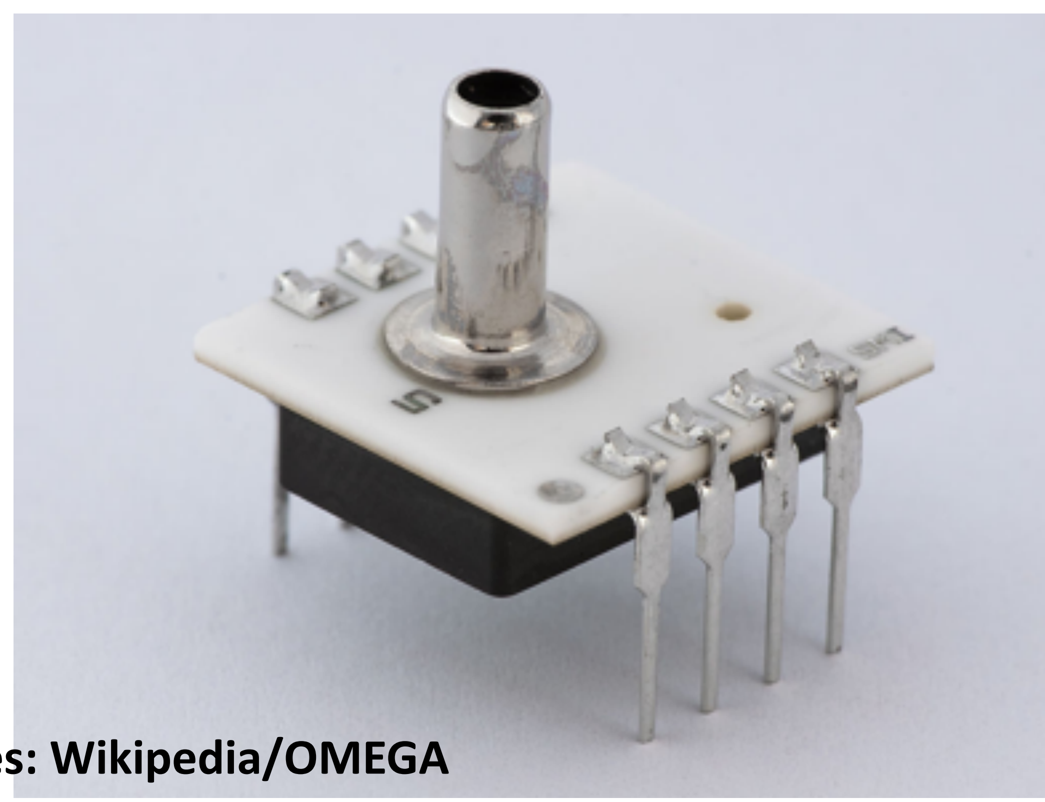

Image: electronics hub/ lionprecision.com

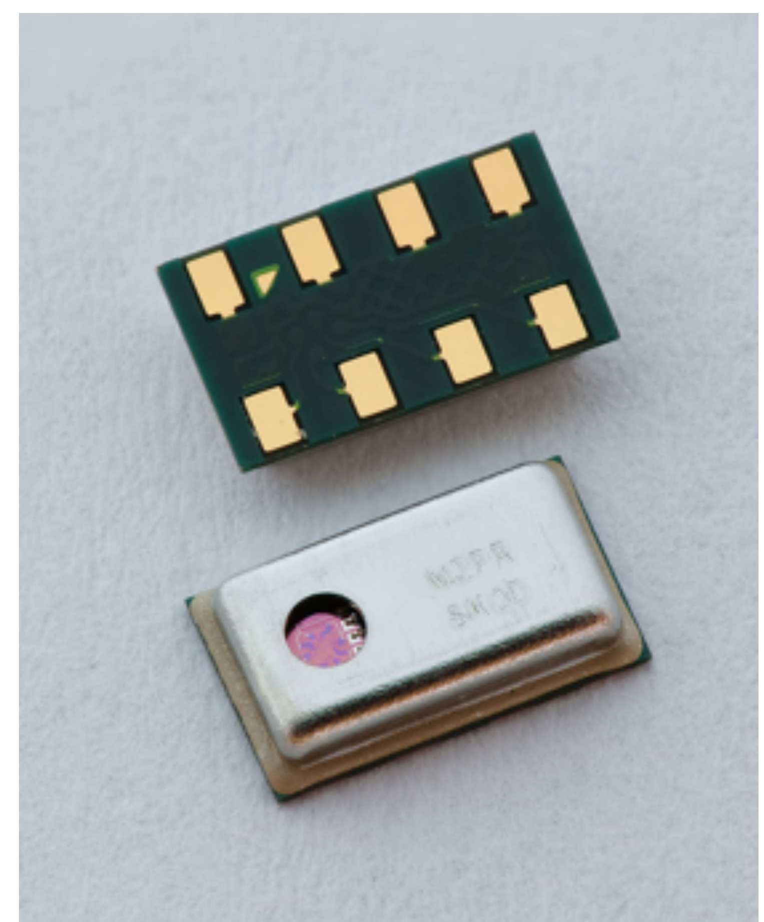
# Pressure

# Pressure transducers come in several types

- **Absolute - measure w.r.t. a perfect vacuum**
- **Gage - measure w.r.t. external (atmospheric) pressure**
- **Vacuum - measure pressures below atmospheric**
- **Differential - measure difference between two points**
- **Sealed - measure w.r.t. a sealed fixed pressure**

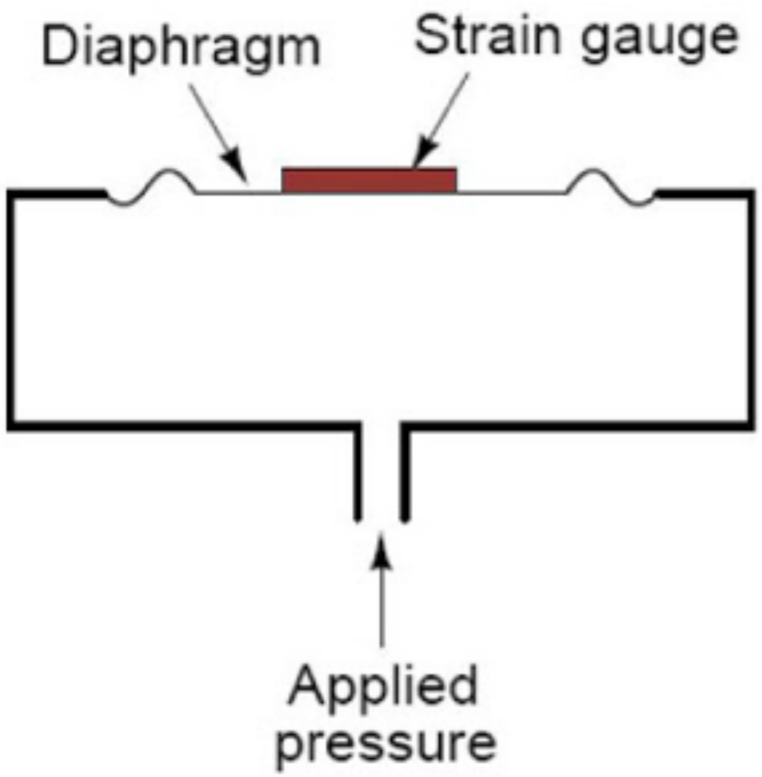
# Housings can vary from PCB mount to industrial

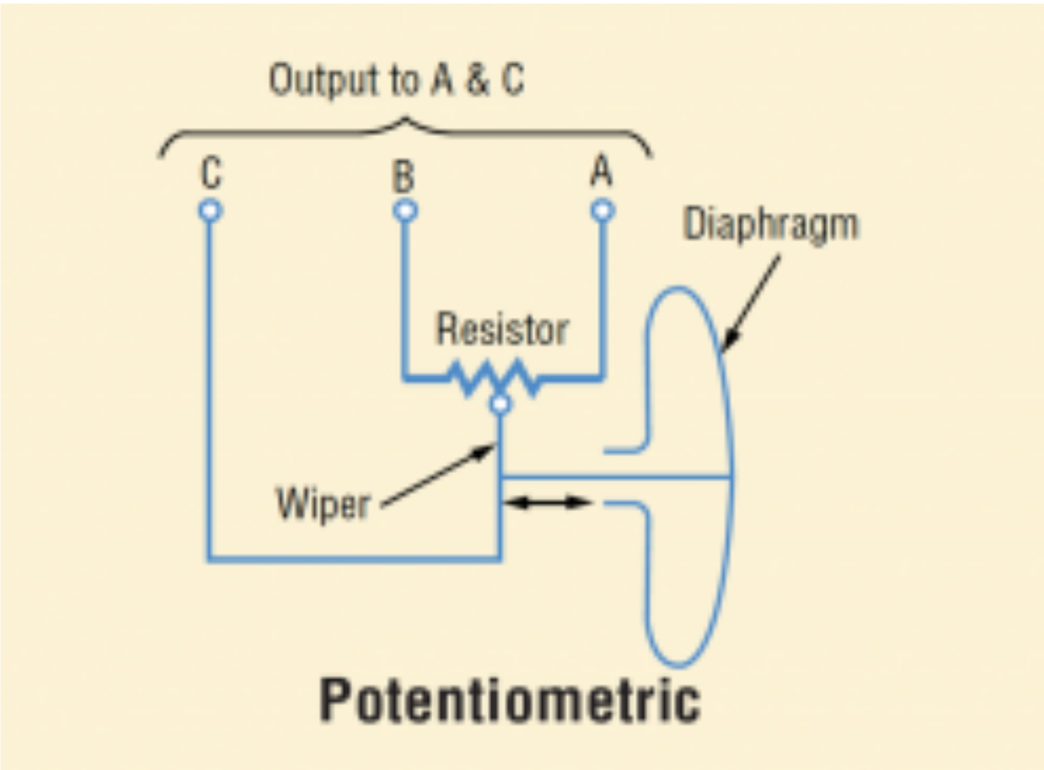



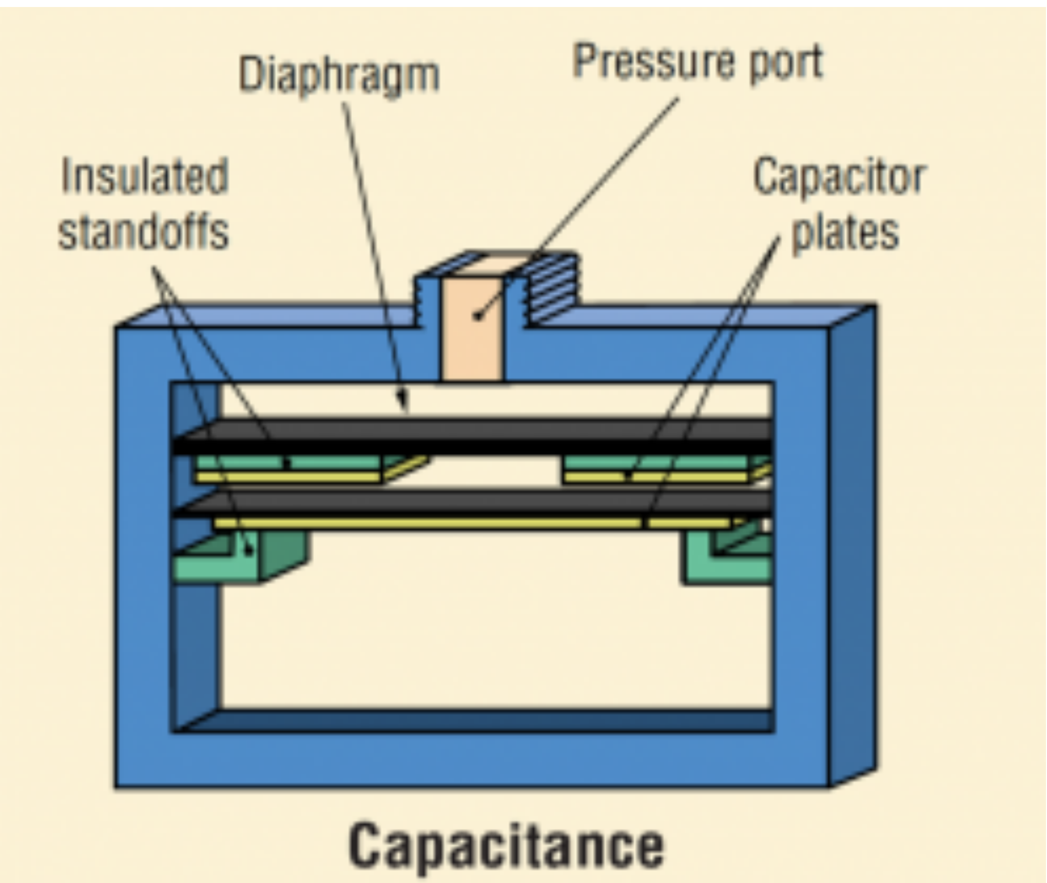


Images: Wikipedia/OMEGA

# Pressure sensors are generally a deflection measurement based technology



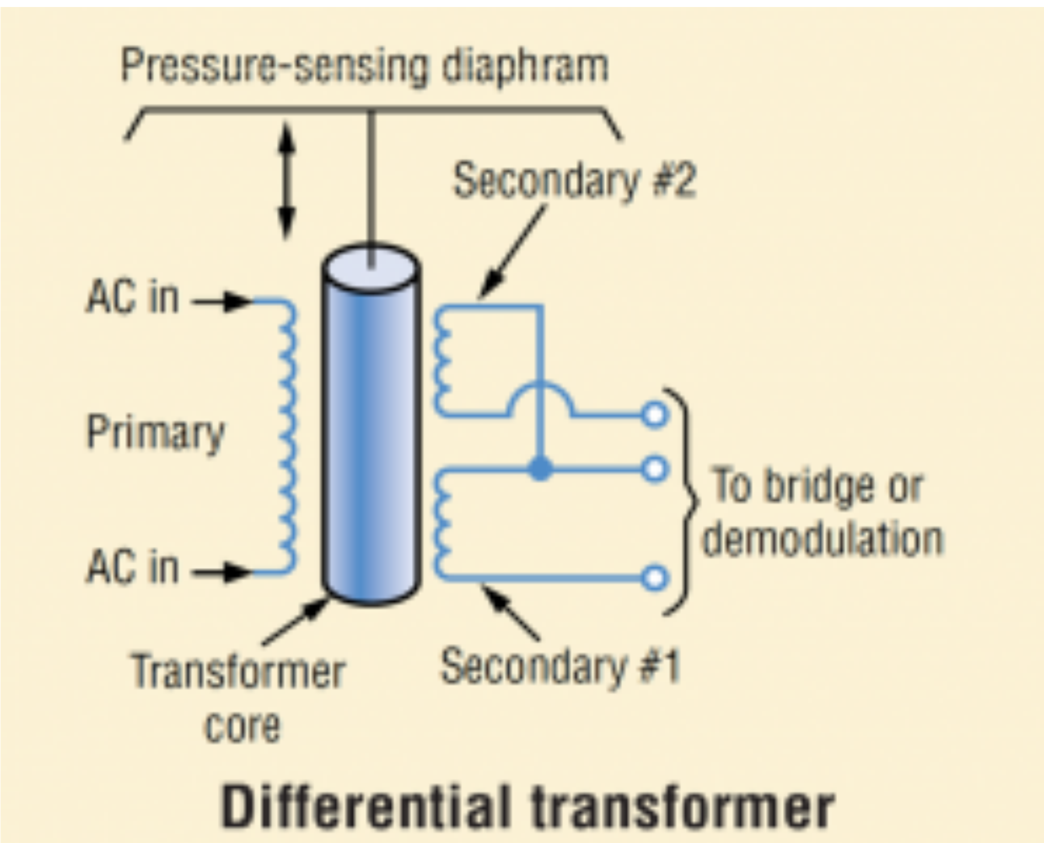
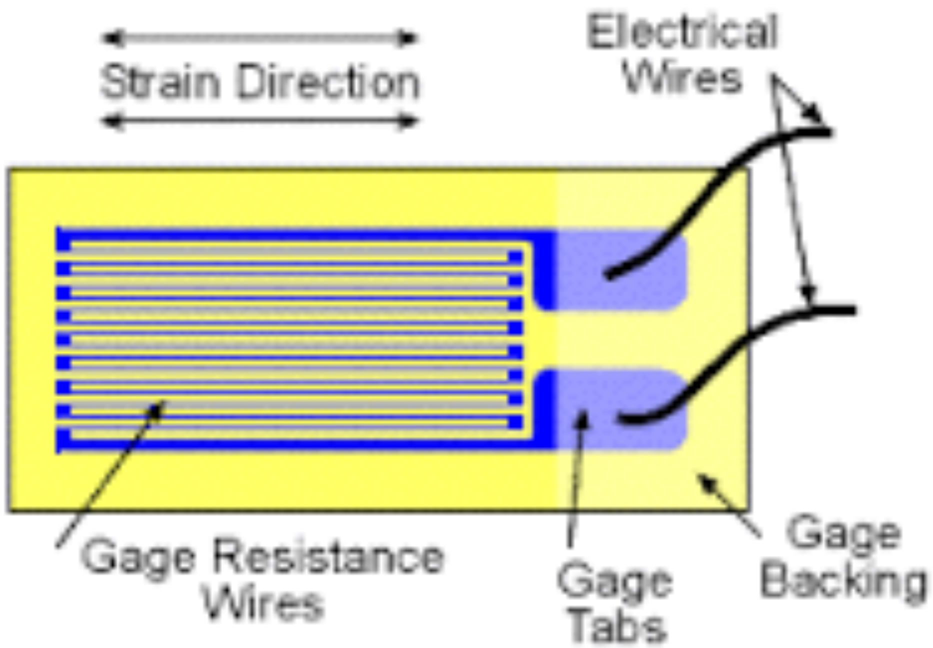




Image: hydraulicspneumatics.com/instrumentationtoolbox.com

# Strain

# Strain gages change resistance based upon their stretching/ compression



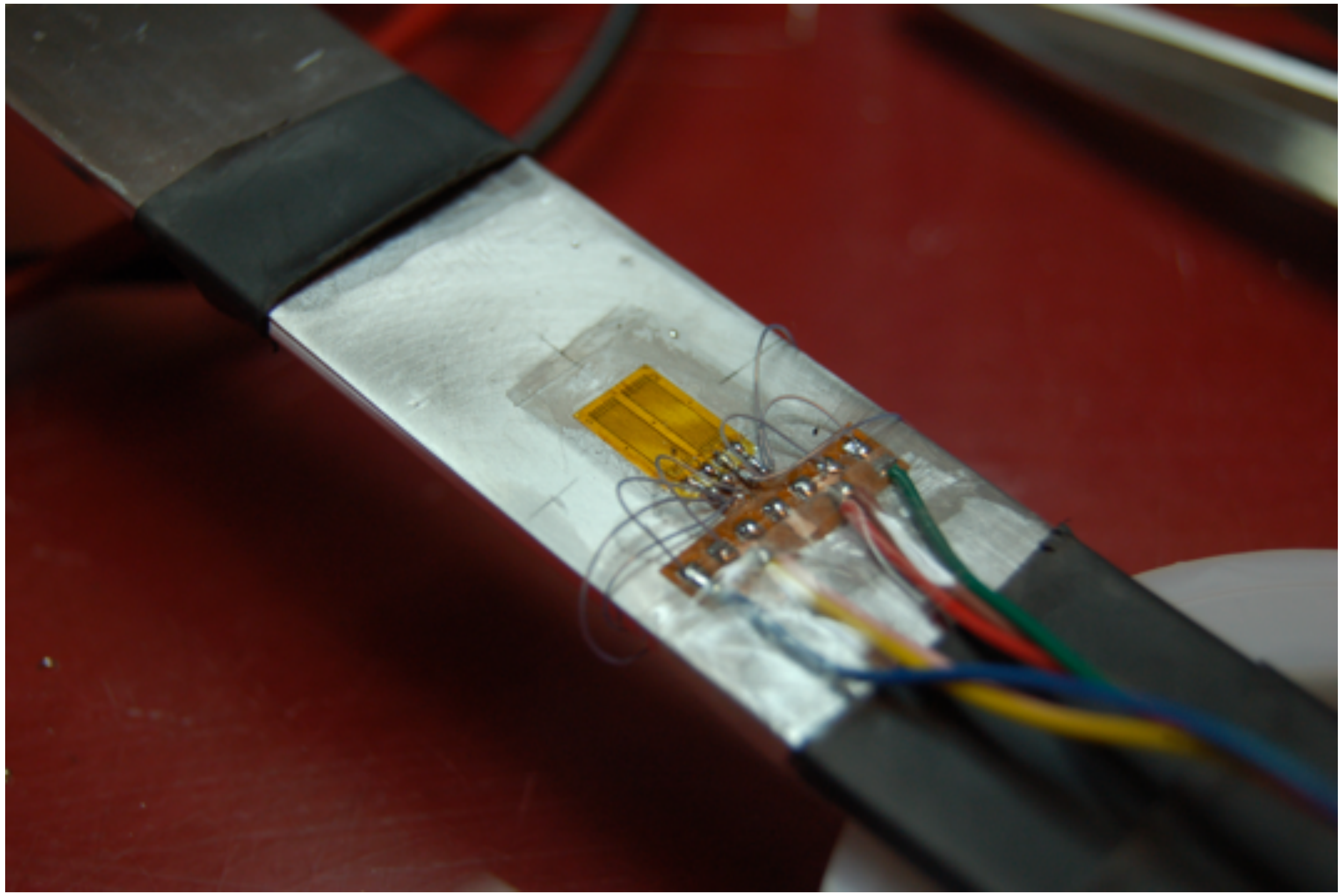
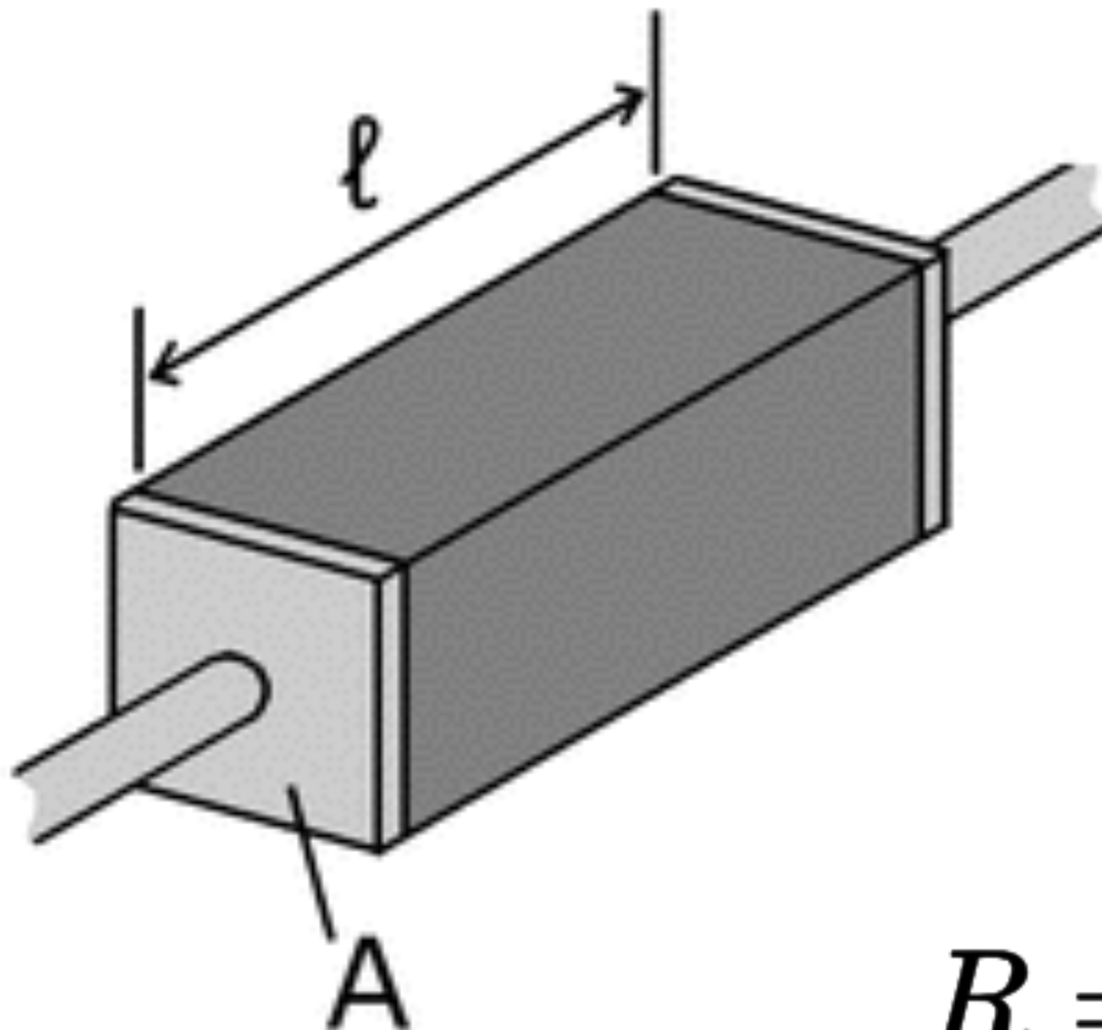



**Image: OU/SensorWiki**

# Resistance of a material depends on the area of contact, resistivity, and length




$$R = \rho \frac{\ell}{A}$$

Image: Wikipedia

# So tension increases resistance, compression decreases resistance

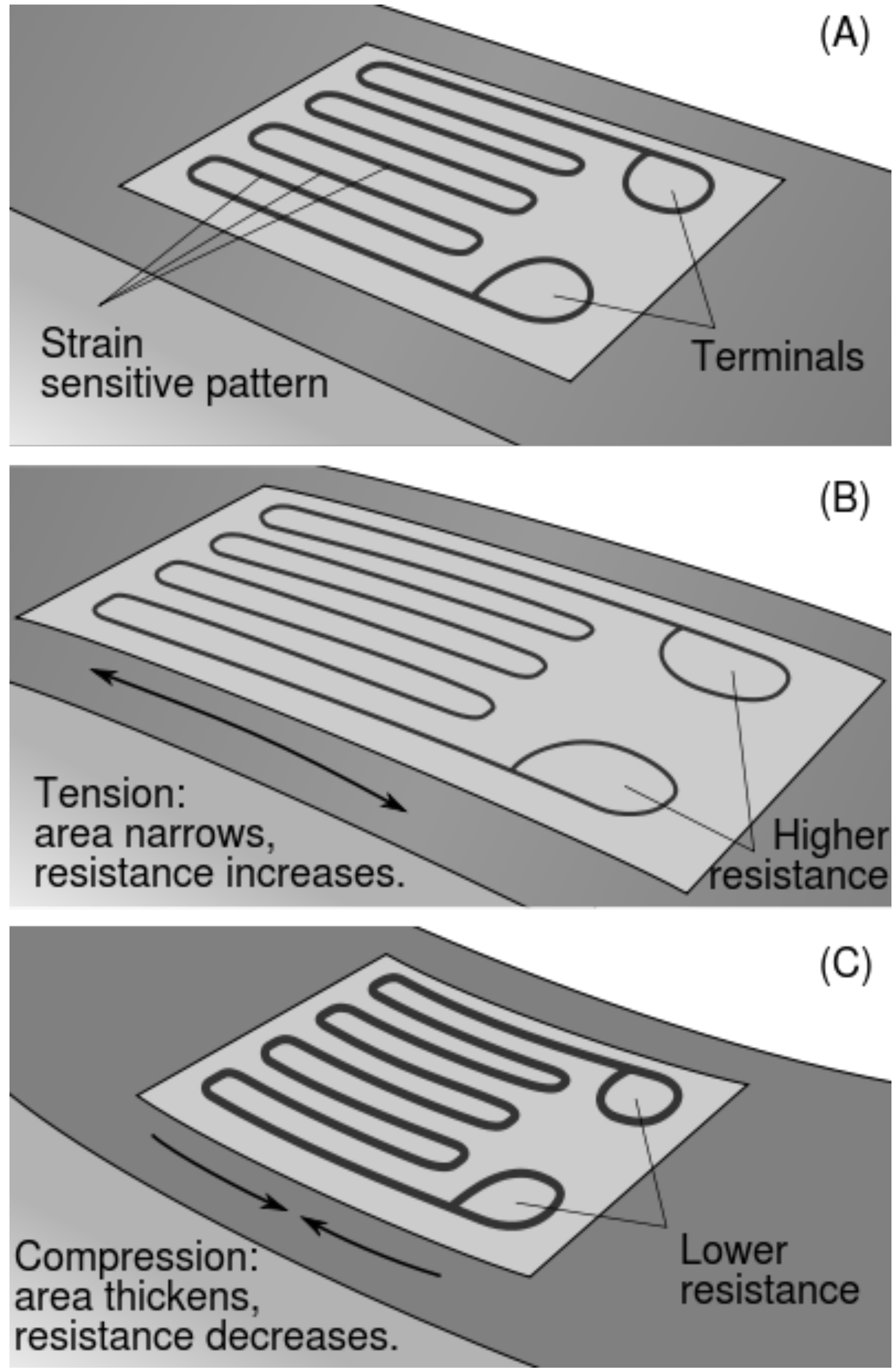
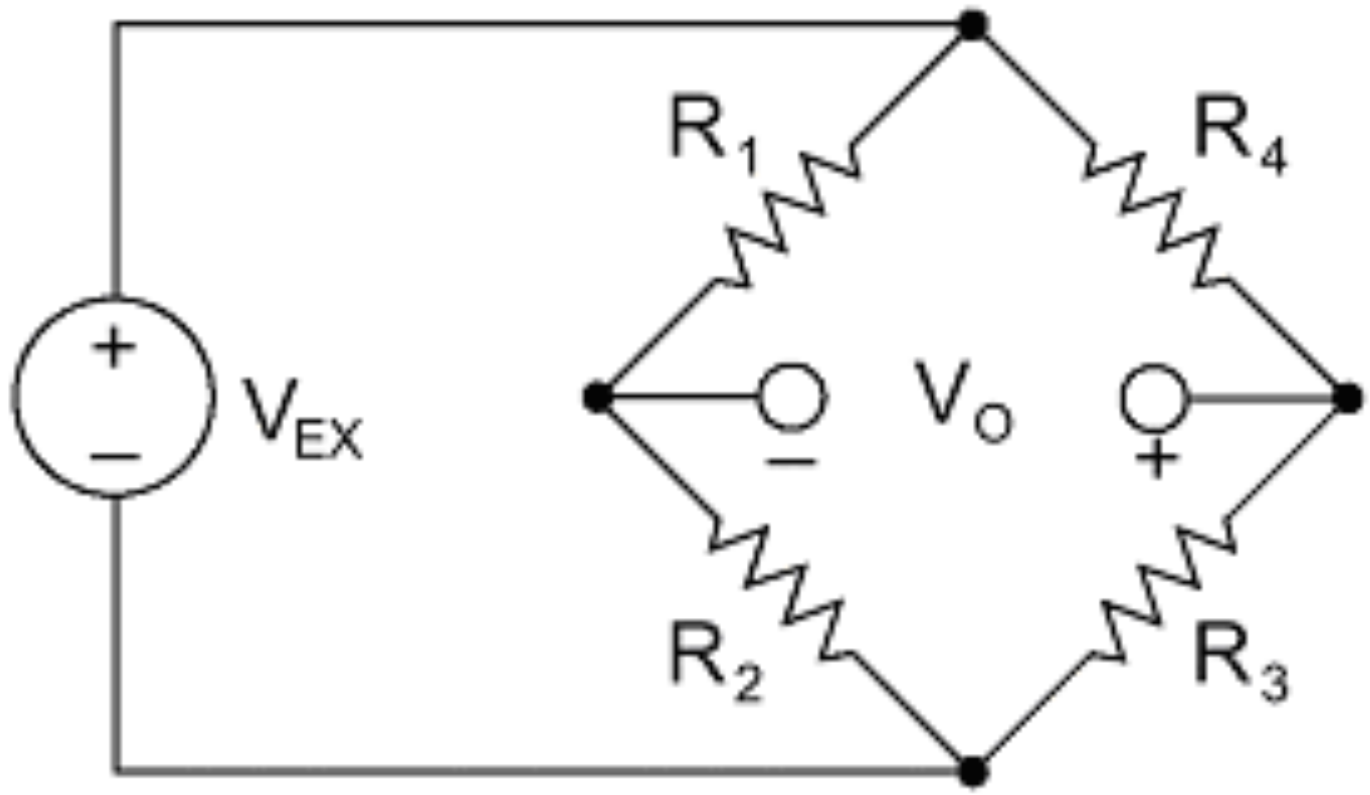



**Image: Wikipedia**

# Most strain gage circuits are based on the Wheatstone Bridge




$$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + 2}\right] * V_{EX}$$

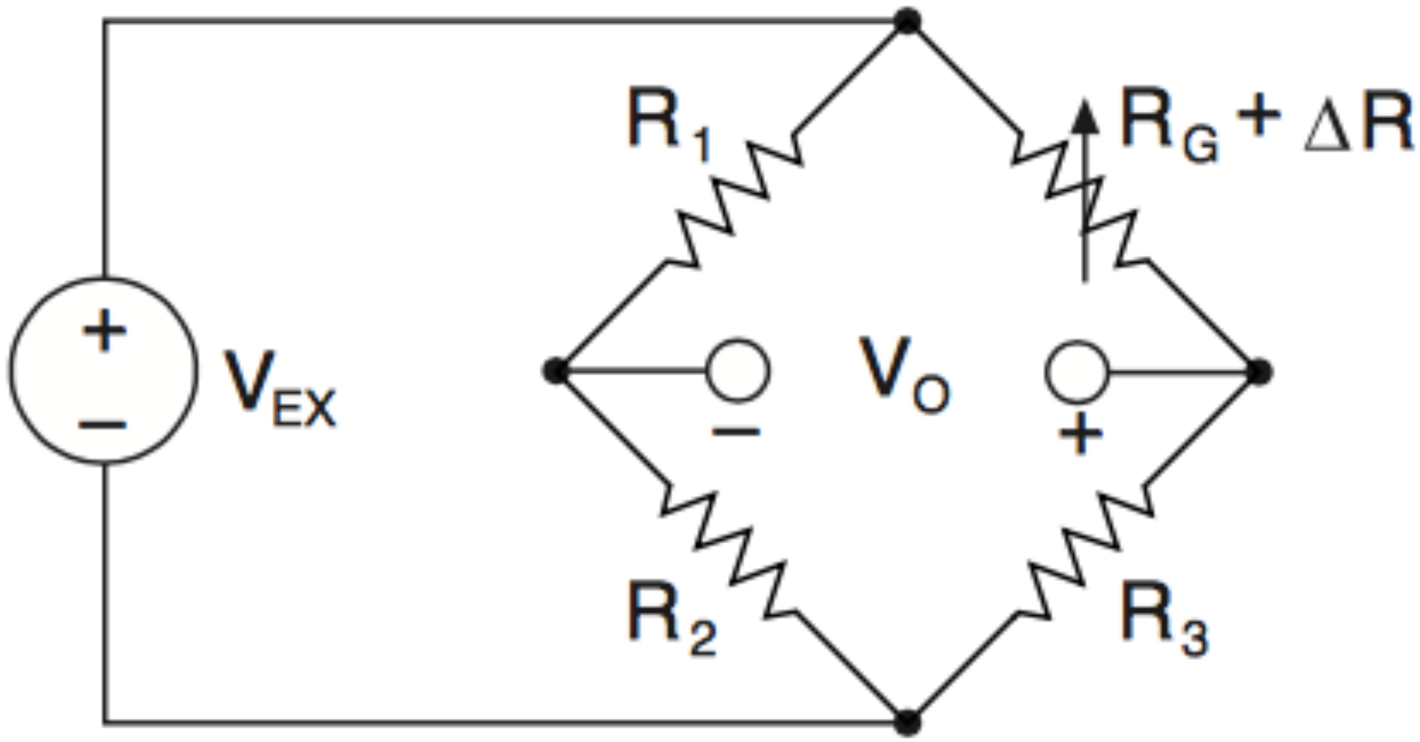
Image: National Instruments

# The gage factor is the relative change is resistance with strain

$$GF = \frac{\frac{\Delta R}{R}}{\varepsilon}$$

Image: National Instruments

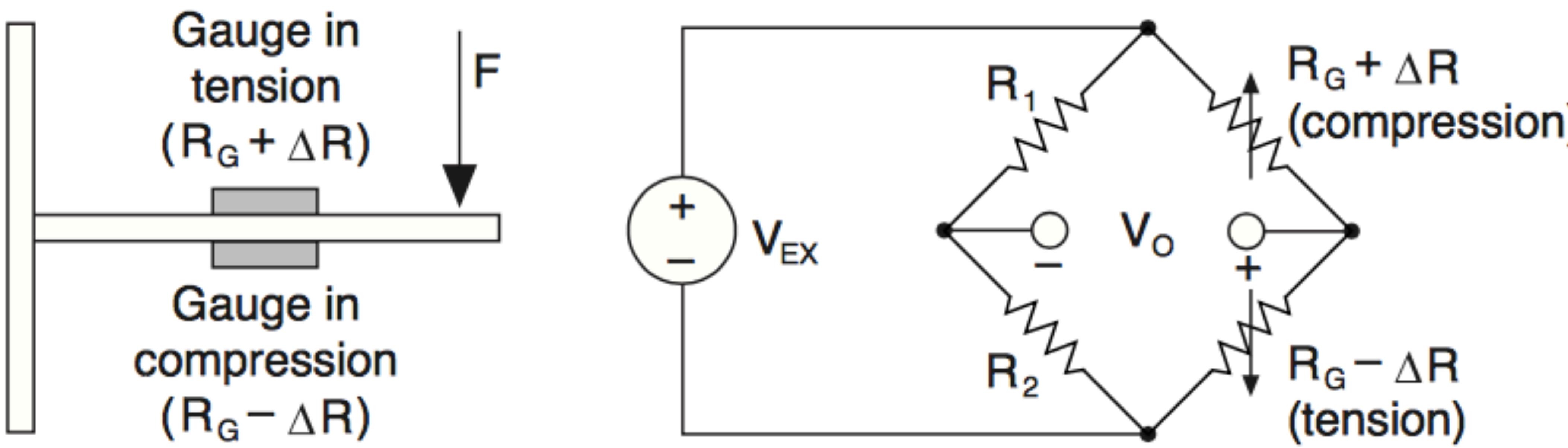
# The quarter bridge is the least sensitive, but only requires one active element




$$\frac{V_O}{V_{EX}} = -\frac{GF \bullet \varepsilon}{4}\left(\frac{1}{1 + GF \bullet \frac{\varepsilon}{2}}\right)$$

Image: National Instruments

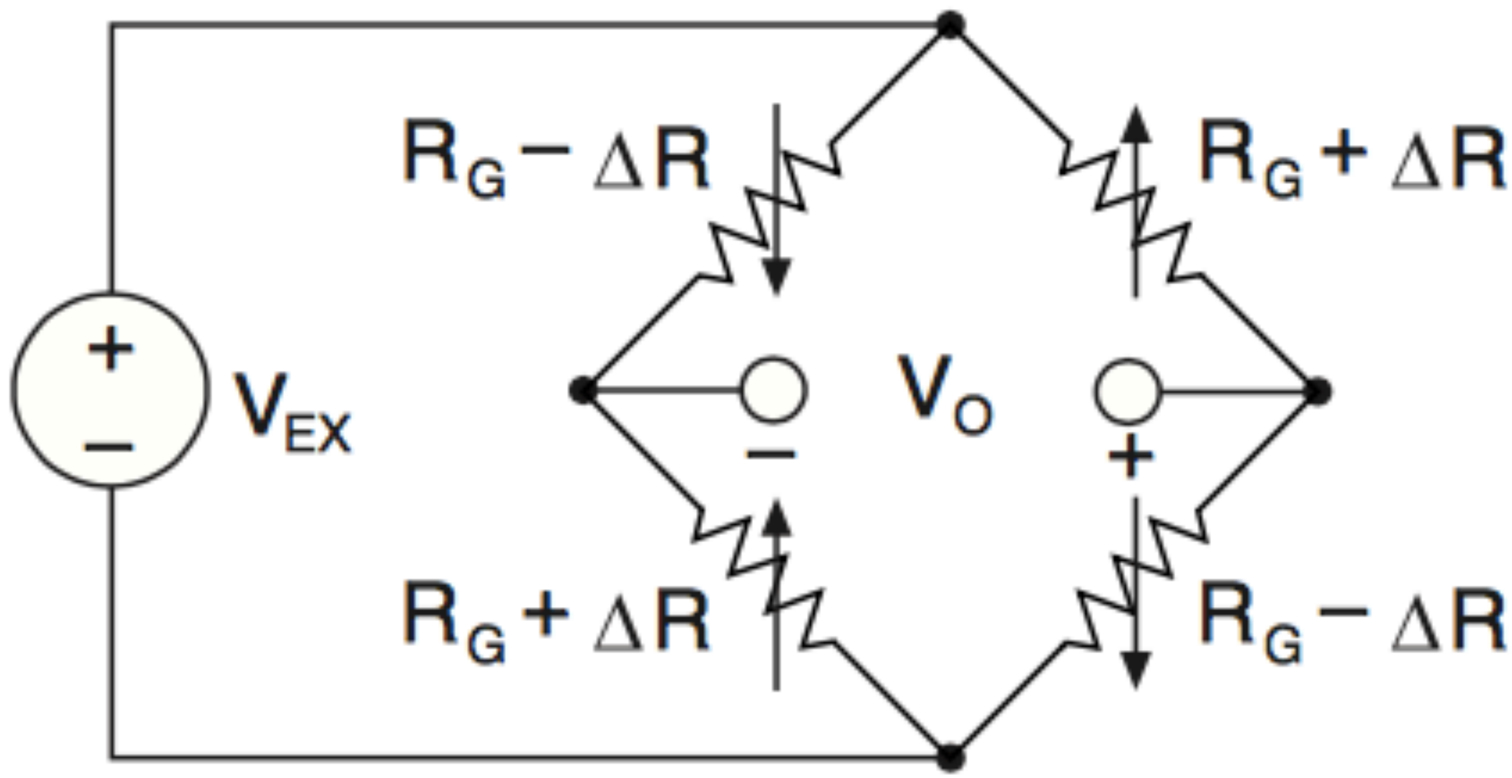
# Half bridges require only two active elements




$$\frac{V_O}{V_{EX}} = -\frac{GF \bullet \varepsilon}{2}$$

Image: National Instruments

# The full bridge is the most sensitive arrangement




$$\frac{V_O}{V_{EX}} = -GF \bullet \varepsilon$$

Image: National Instruments

| Measurement Type | Quarter Bridge | | Half-Bridge | | Full-Bridge | | |
|---|---|---|---|---|---|---|---|
| | Type I | Type II | Type I | Type II | Type I | Type II | Type III |
| Axial Strain | Yes | Yes | Yes | No | No | No | Yes |
| Bending Strain | Yes | Yes | Yes | Yes | Yes | Yes | No |
| **Compensation** | | | | | | | |
| Transverse Sensitivity | No | No | Yes | No | No | Yes | Yes |
| Temperature | No | Yes | Yes | Yes | Yes | Yes | Yes |
| **Sensitivity** | | | | | | | |
| Sensitivity at 1000 με | ~0.5 mV/V | ~0.5 mV/V | ~0.65 mV/V | ~1.0 mV/V | ~2.0 mV/V | ~1.3 mV/V | ~1.3 mV/V |
| **Installation** | | | | | | | |
| Number of Bonded Gages | 1 | 1* | 2 | 2 | 4 | 4 | 4 |
| Mounting Location | Single Side | Single Side | Single Side | Opposite Sides | Opposite Sides | Opposite Sides | Opposite Sides |
| Number of Wires | 2 or 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| Bridge Completion Resistors | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| *A second strain gage is placed in close thermal contact with structure but is not bonded. | | | | | | | |

**Image: National Instruments**

# Temperature plays a role as well though

$$\frac{\Delta R}{R} = GF\varepsilon + \alpha\theta$$

Where

- α = temperature coefficient
- θ = temperature change

Image: National Instruments

# A “dummy gauge” is often used for temperature compensation

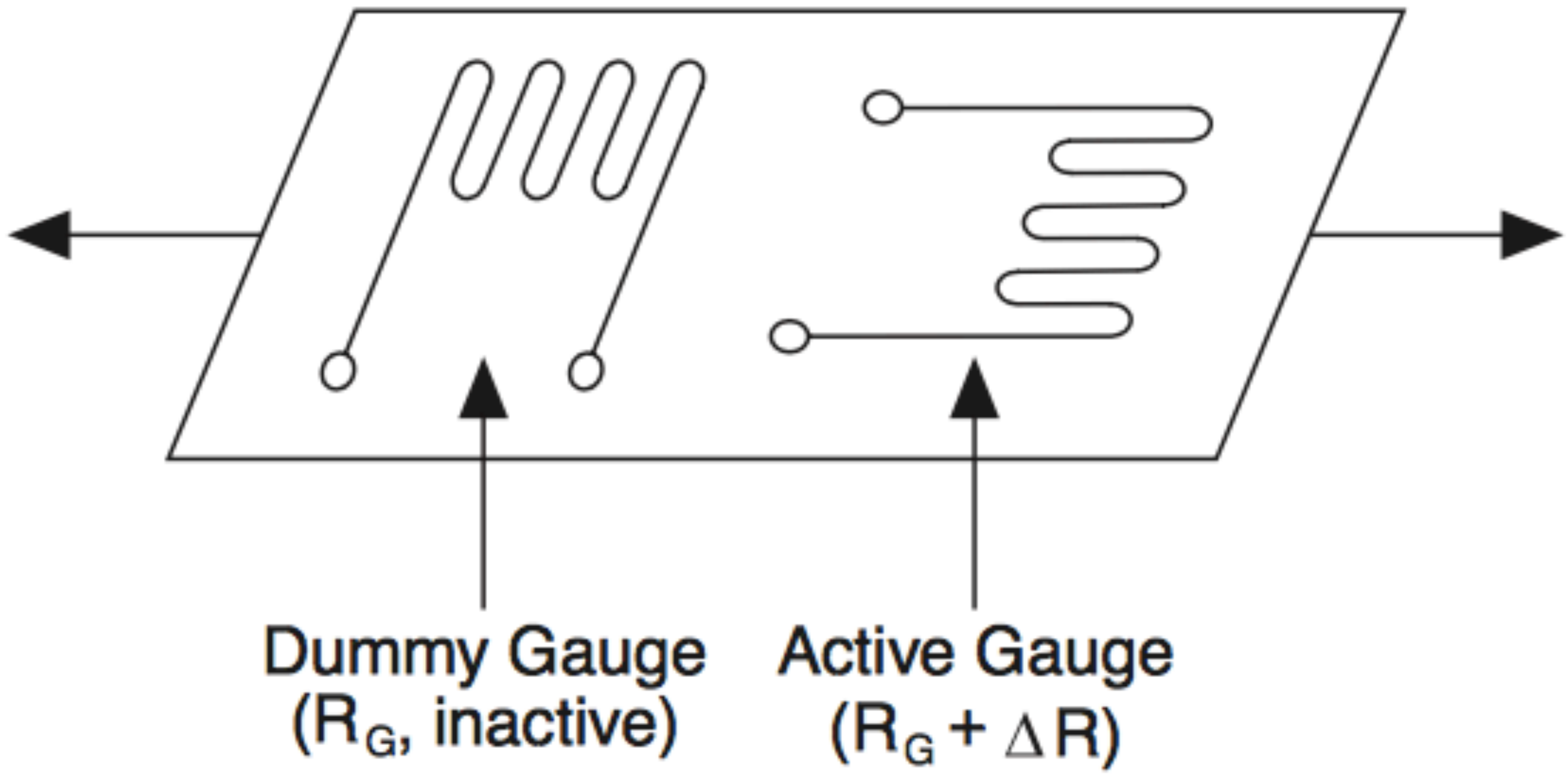



Image: National Instruments

# Careful wiring and creative placement are often necessary

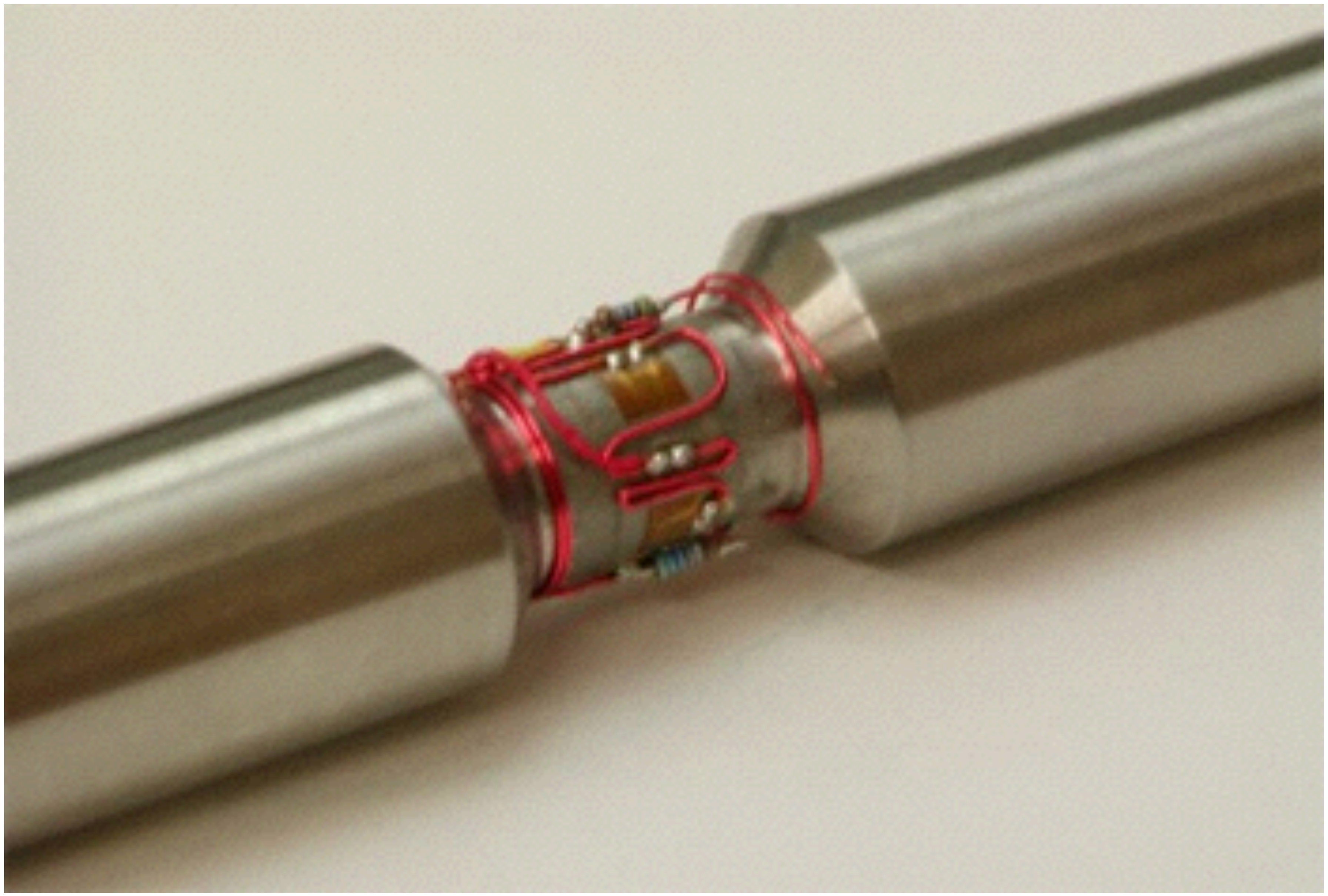
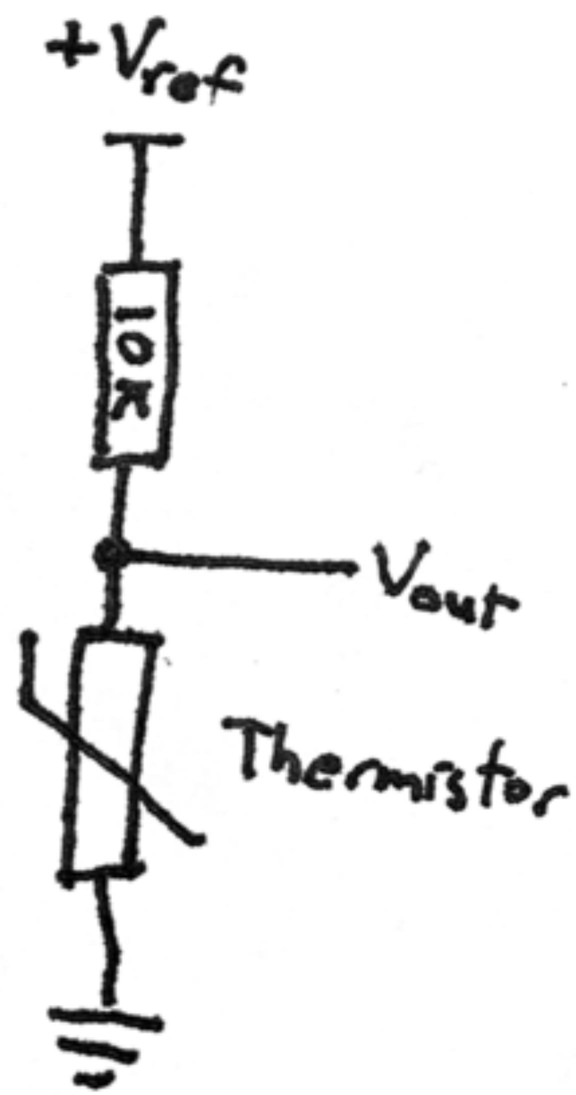


Image: b2bicdesign.com

**Activity: Calculate the temperature measurements from the data included with the "Thermistor Calculation" activity**




# Due : 10/20

**Assignment: Find something to affix strain gauges to for our next lab activity**


# Due : 10/25