IN 221 (AUG) 3:0
Sensors and Transducers
Lecture 2

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IN 221 Web Page

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Example: Gains of Popular Bridge Amplifiers

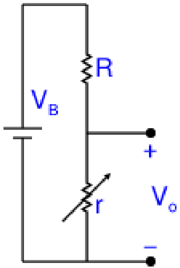
- Proper use of strain gauges requires using them as parts of a *Wheatstone Bridge*.
- The output with strain gauge elements is quite small.
- Usually, it needs to be amplified before any other use.
- HX710 and HX711 are two popular amplifier/digitizer integrated circuits for use with *load cells* having strain gauges.
- HX710: Fixed gain of 128.
- HX711: Selectable gain of 32, 64, or 128.

Gauge Factor

$$\mathrm{GF} = \frac{\Delta R / R_{\mathrm{G}}}{\epsilon} \tag{1}$$

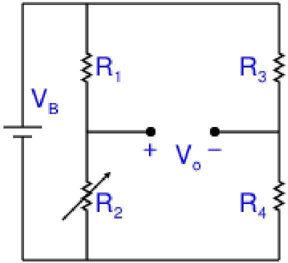
ΔR: Change in resistance caused by strain
R_{G}: Resistance of the strain gauge when there is no deformation
ϵ: Strain = (Change in length) / (Length)
For metallic foil gauges, GF is a little over 2.

Strain Gauge: Voltage Divider Arrangement



Disadvantages: Too much offset!
Let the battery voltage be 5 V, and both *R* and *r* be 100 ohms. The change in *r* may at most be 1 ohm. Then the change in output is 12.44 mV over a base value of 2.5 V. Very hard to use.
Not used.

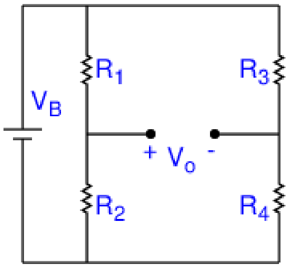
Strain Gauge: Bridge Arrangement



Advantage: No offset output. With minor adjustment, one can make the output nearly proportional to the input.

Much used.

Wheatstone Bridge Arrangement

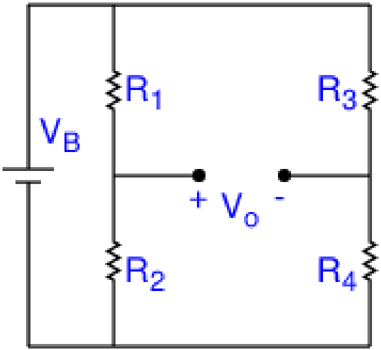


One or more of the bridge arms can be a strain gauge.
Example Usage with a Beam:
R_1, or R_4, or both can be mounted above the beam. R_2, or R_3, or both can be mounted below the beam.
If all resistors in this diagram are strain gauges, then the output will not be affected by a change in the temperature.

Examples where Wheatstone Bridge is used

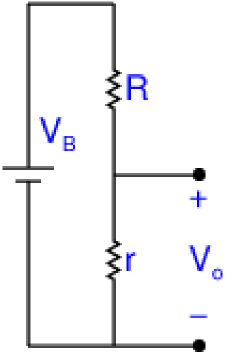
- Strain Gauge
- Many types of Pressure Sensors
- RTD Temperature Sensor
- Some types of Accelerometers

Wheatstone Bridge Output



$$V_o = V_B \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) \qquad (2)$$

Voltage Divider



$$V_o = V_B \frac{r}{R + r}$$

Voltage Divider Analysis

$$V_o = V_B \frac{r}{R + r} \tag{3}$$

- The resistance r is a function of some physical input such as temperature or strain.
- The change in r is small and is usually proportional to the reference value of r.
- So it is the fractional change in r that is determined by the change in the physical quantity that is being sensed.
- Fractional change in common language: Percentage change or per unit change

Question: What value of R maximizes the change in the output for a given fractional change in r?

Rates of Change

Rate of change of V_o with respect to r:

$$\frac{\partial V_o}{\partial r} = \frac{\partial \left(V_B \frac{r}{R+r} \right)}{\partial r} = V_B \frac{R}{(R+r)^2} \tag{4}$$

Rate of change of V_o with respect to fractional change in r:

$$\frac{\partial V_o}{\frac{1}{r}\partial r} = r\frac{\partial V_o}{\partial r} = V_B \frac{Rr}{(R+r)^2} = \frac{1}{4} V_B \left[1 - \frac{(R-r)^2}{(R+r)^2} \right] \tag{5}$$

This is maximized when $R = r$.

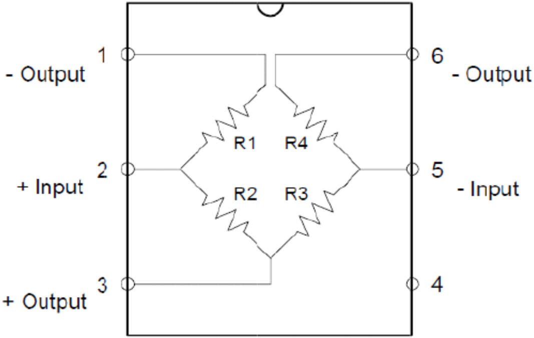
Best Operating Conditions

- So the best value of R is the nominal reference value of r.
- Note that even though the output is proportional to V_B, to keep the components safe, V_B cannot be made too high.
- Using higher V_B values may cause heating of the strain gauge elements.

Example: Pressure Sensor MPS20N0040D

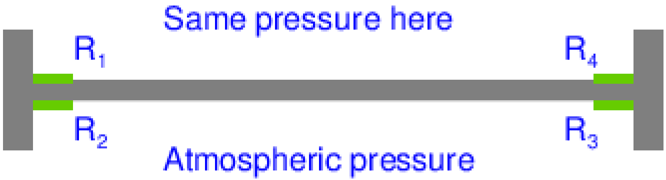
40 kPa differential pressure sensor

Pressure Sensor MPS20N0040D Diagram



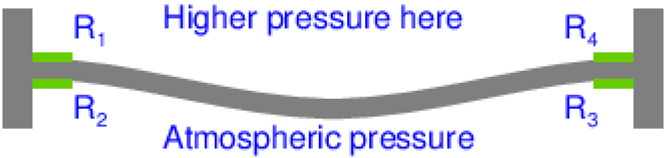
Note: This is the *bottom* view of the sensor. Also, the resistor symbols are different to those of the Wheatstone bridge diagram we have shown earlier.
We do NOT use this convention in our discussion.

Piezo-resistive pressure sensor arrangement



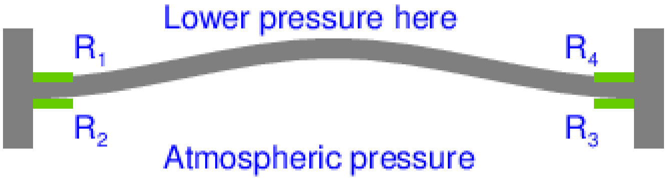
$R_1 = R_2 = R_3 = R_4 = R_0$.
R_0 is approximately $5\,\mathrm{k}\Omega$ in MPS20N0040D.

Piezo-resistive pressure sensor: Higher pressure



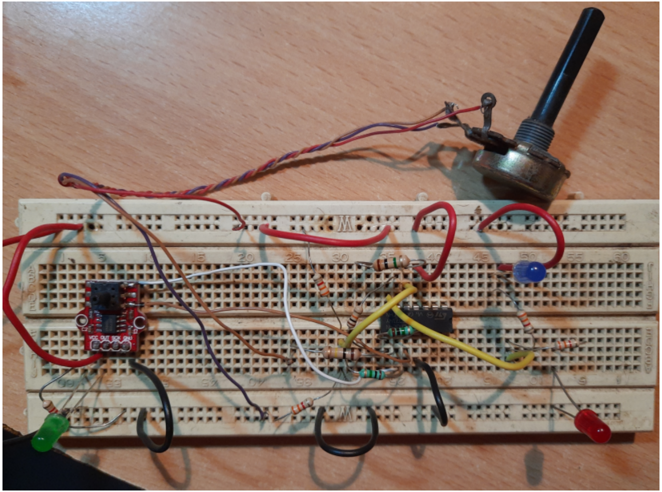
R_1 and R_4 increase due to tension. R_2 and R_3 decrease due to compression.

Piezo-resistive pressure sensor: Lower pressure



R_1 and R_4 decrease due to compression. R_2 and R_3 increase due to tension.

Pressure Sensor MPS20N0040D in use

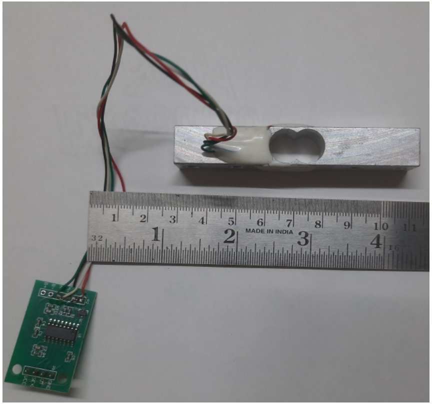


A demonstration will be given later.

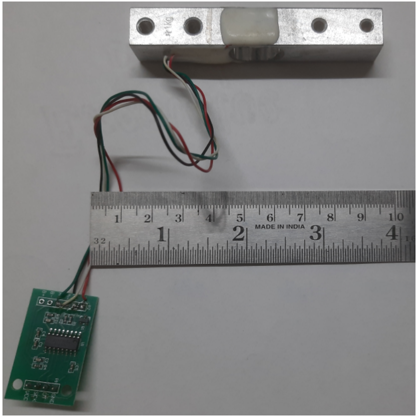
Load Cells

- Converts **force** to **electrical signal**.
- Most load cells use strain gauges attached to metal structures.
- Aluminium and steel are the metals most used.
- Widely used for force and weight measurement.
- Amplification is required for digitization.

Load Cell: Side View

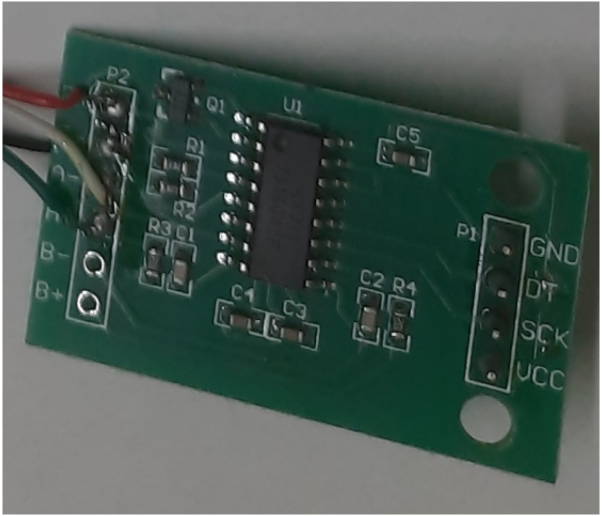


Load Cell: Top View



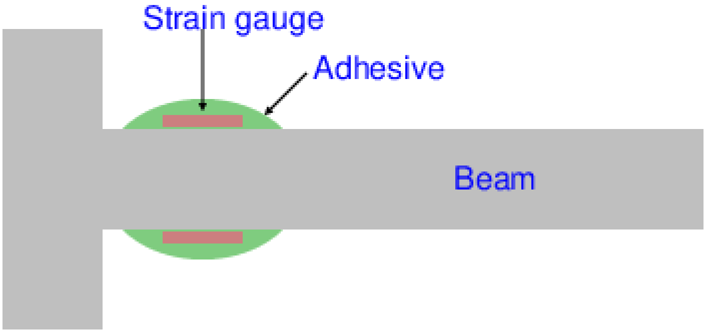
Note the white adhesive used to attach the strain gauge.
The HX711 amplifier/digitizer board is also visible.

Load Cell Amplifier and Digitizer



The HX711 amplifier/digitizer board uses the $\mathrm{I^2C}$ interface.

Attaching Strain Gauges to a Beam



If the upper strain gauge is in the tension, the lower one will be in compression and vice versa.

Temperature Sensors

- Thermistor
- Thermocouple
- Resistance Thermometer
- Silicon Diode Sensor
- Silicon Bandgap Temperature Sensor
- Infrared Temperature Sensor

Thermistor

- Resistor whose resistance changes with temperature.
- Usually made of semiconductors.
- Change of resistance is more than that in metal resistors.
- Usually nonlinear.
- Limited range of use: -90 ℃ to 130 ℃
- Two types: NTC and PTC
- NTC: Negative Temperature Coefficient, resistance decreases with increase in temperature
- PTC: Positive Temperature Coefficient, resistance increases with increase in temperature
- NTC type is more commonly used.
- Can be quite sensitive, but not as accurate as other types of temperature sensors.
- Also used to limit starting current.

Thermocouple

- Involves junctions of two different metals.
- Generates a small voltage that is roughly proportional to the temperature difference of the two junctions.
- Based on Seebeck effect
- Many types available: Types K, J, N, R, S, B, T, E, and others.
- Advantage: Wide range (from -270 ℃ to 1700 ℃)
- Advantage: Requires no external power
- Disadvantage: Output is quite small, usually requires amplification
- Disadvantage: Amplification can be challenging

Resistance Thermometer

Resistance Temperature Detector (RTD)

- The resistivity of metals is a linear function of temperature over a wide range of temperatures.
- Usually a very pure form of the metal is used.
- A resistor made of the metal is enclosed in some form of protective housing.
- Commonly used metals: Platinum, Copper, Nickel
- Platinum can work till 600 ℃.

Temperature Coefficient of Resistance (TCR)

Let the resistance of a resistor be R_{ref} at temperature T_{ref} and R at temperature T. Then for metal resistors over a wide range of temperatures,

$$R = R_{\mathrm{ref}}[1 + \alpha(T - T_{\mathrm{ref}})] \tag{6}$$

where α is called the temperature coefficient of resistance (TCR).
T_{ref} is usually 20 ℃.

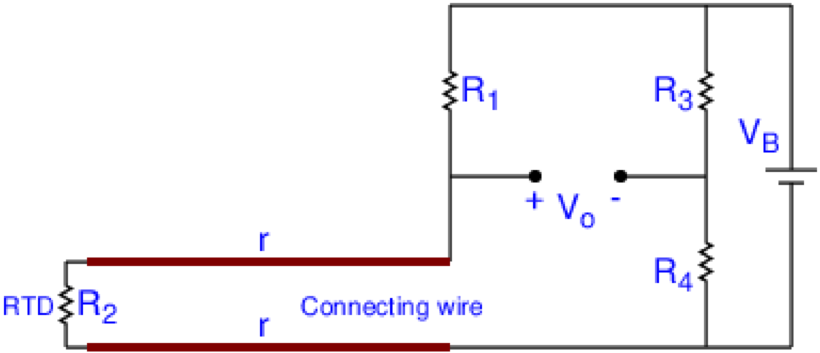
$$\alpha = \frac{R - R_{\mathrm{ref}}}{R_{\mathrm{ref}}(T - T_{\mathrm{ref}})} = \frac{\Delta R}{R_{\mathrm{ref}} \Delta T} \tag{7}$$

Units: per ℃

TCR of Commonly Used Metals

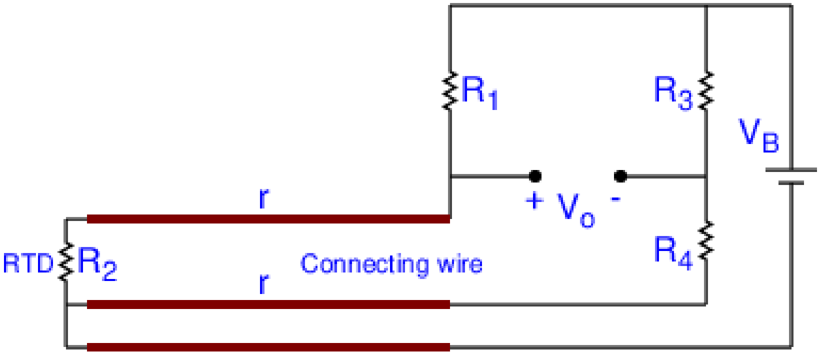
Metal	α
Platinum	3.925×10^{-3} ℃$^{-1}$
Copper	3.9×10^{-3} ℃$^{-1}$
Aluminium	3.9×10^{-3} ℃$^{-1}$
Gold	3.4×10^{-3} ℃$^{-1}$
Silver	3.8×10^{-3} ℃$^{-1}$
Tungsten	4.5×10^{-3} ℃$^{-1}$
Iron	5.0×10^{-3} ℃$^{-1}$
Nickel	6.0×10^{-3} ℃$^{-1}$
Tin	4.5×10^{-3} ℃$^{-1}$
Lead	3.9×10^{-3} ℃$^{-1}$

Two-wire Configuration



Disadvantage: r depends on the length of the connecting wire and only affects R_2.

Three-wire Configuration



Advantage: r affects both R_2 and R_4 equally.

Silicon Bandgap Temperature Sensor

The difference in voltage drop across two identical diodes or base to emitter junctions:

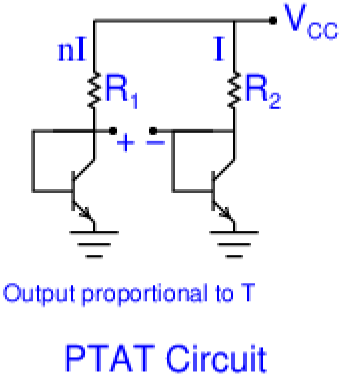
$$\Delta V_{\mathrm{BE}} = \frac{kT}{q} \ln\left(\frac{I_{\mathrm{C1}}}{I_{\mathrm{C2}}}\right) \tag{8}$$

Here I_{C1} and I_{C2} are the diode or the collector currents.

- Can be part of an integrated circuit
- Reasonably accurate
- Inexpensive
- Example: LM35 temperature sensor IC

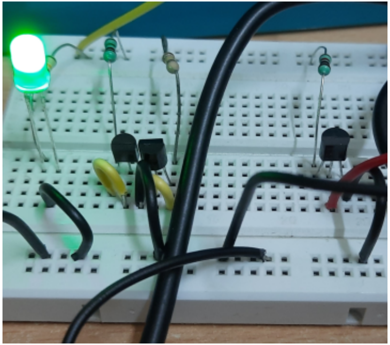
PTAT Temperature Sensor

PTAT: Proportional to Absolute Temperature

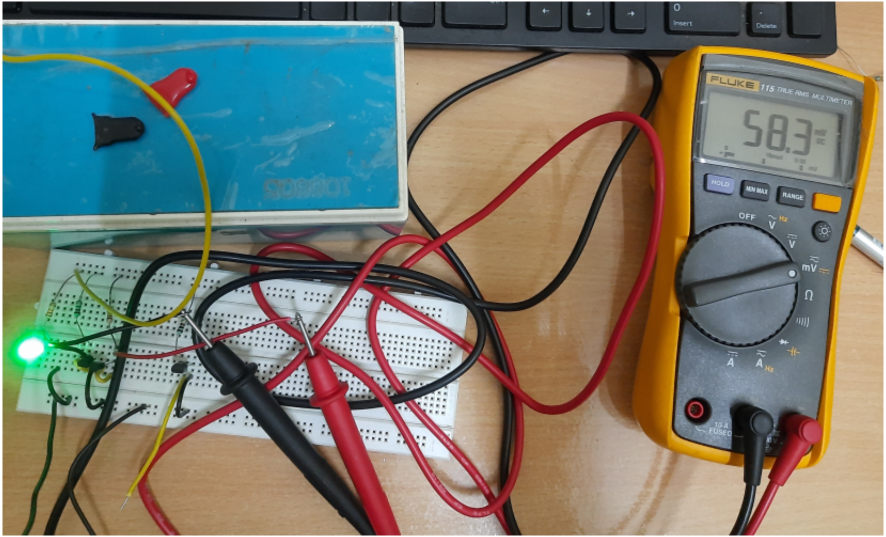


$$\Delta V_{\mathrm{BE}} = \frac{kT}{q} \ln\left(\frac{I_{\mathrm{C1}}}{I_{\mathrm{C2}}}\right) = \frac{kT}{q} \ln n \qquad (9)$$

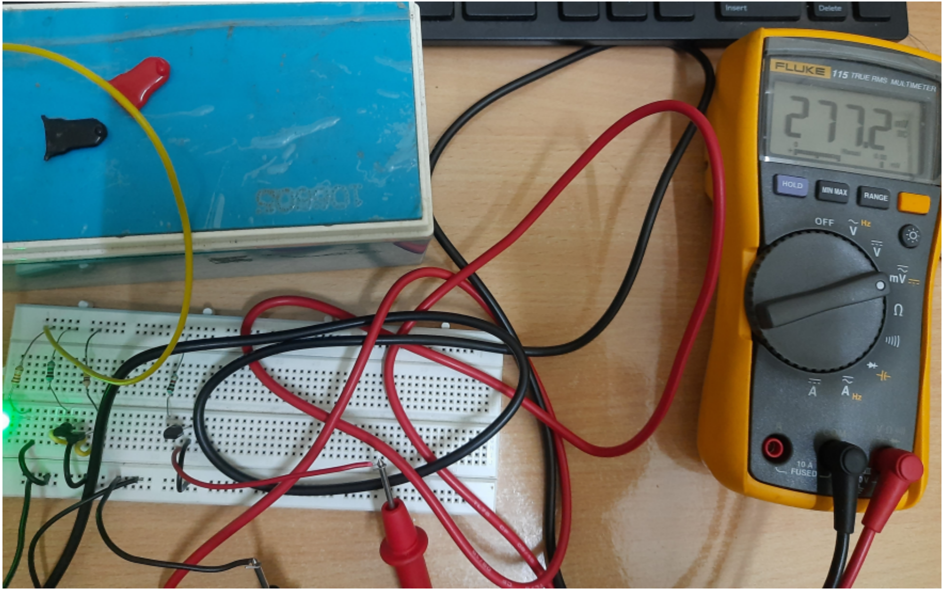
PTAT Circuit



PTAT Output


Insert
Delete
FLUKE
115 TRUE RMS MULTIMETER
58.3
HOLD
MIN MAX
RANGE
OFF
mV

LM35 Output

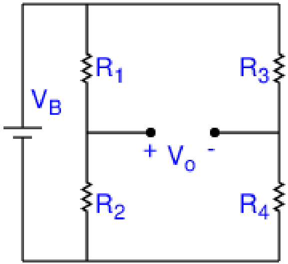


Insert
Delete
FLUKE
115 TRUE RMS MULTIMETER
277.2
HOLD
MIN MAX
RANGE
OFF
Hz
mV
10 A
FUSED

Example PTAT Calculation

In the PTAT constructed, $\frac{I_{C1}}{I_{C2}} = n \approx 10$.
From the LM35 reading, T is 27.72 celsius or $27.72 + 273.15$ kelvin.
Calculation:
$n = 10$.
$T = 300.87\,\mathrm{K}$.
Boltzmann constant: $k = 1.380\,649 \times 10^{-23}\,\mathrm{J\,K^{-1}}$.
Elementary charge: $q = 1.602\,176\,634 \times 10^{-19}\,\mathrm{C}$.
$\frac{kT}{q} \ln n = 59.699\,\mathrm{mV}$ which is close to the $58.3\,\mathrm{mV}$ reading.

Problem: Wheatstone Bridge



$$V_o = V_B \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) \tag{10}$$

Let n be the decimal number formed by the last two digits of your SR number.
Let $R_1 = R_2 = R_3 = 100\,\Omega$, and $R_4 = (100 + n/100)\,\Omega$.
Calculate V_o.