IN 221 (AUG) 3:0
Sensors and Transducers
Lecture 1

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Sensors and Transducers: General Discussion and Examples

Sensors and Transducers are used for interfacing the physical world to

1. electronic circuits, and
2. computers.

While our objective is to discuss the *working principles* of a number of sensors and transducers, today we will only see some examples.

What is a sensor?

- Device that can be used to detect or measure a given physical quantity.
- Almost always used with other electronics.

Examples of sensors

- Microphone
- Photodiode, LDR (Light Dependent Resistor)
- CCD array (imaging element in digital camera)
- Thermocouple, thermistor
- Search coil, Hall sensor
- Antenna
- Piezoelectric sensors
- Chemical and gas sensors

What is a transducer?

- Device that converts one form of energy to another.
- Usually the input is an electrical signal and the output is some other physical quantity.
- Actuator: Transducer whose output is mechanical motion.

Examples of transducers

- Loudspeaker
- LED (Light Emitting Diode)
- Heater
- Coil
- Antenna
- Motors of various kinds
- Piezoelectric actuators

Examples

Example 1: Smartphone

- Transducers: Speaker, display, buzzer motor
- Sensors: Microphone, camera, accelerometer

Example 2: Making Plastic Sheets from Molten Plastic

- Transducers: Motor, heater
- Sensors for sensing thickness, temperature, and chemicals

Example 3: Generic Closed Loop Control System

- The *plant* will have *transducers*.
- The *feedback* signals will come from *sensors*.

Functional view

- Sensor
  Physical quantity $\rightarrow$ Electrical signal
- Transducer
  Electrical signal $\rightarrow$ Physical quantity

Points to note

- Many applications: Industry, Household appliances, Agriculture, Traffic management, Security, Weather monitoring, Scientific research
- The same device can be used as a sensor or as a transducer.
  - Piezoelectric device
  - Antenna
  - Loudspeaker
- Response is not always linear, not even continuous.
- There are many different kinds sensors and transducers.
- Based on a very wide range of working principles

Types of Sensors

Packaged vs. Constructed

- Many types of sensors are available in packaged form.
- Still, in industrial work, engineers sometimes make their own sensors.

Types of Output

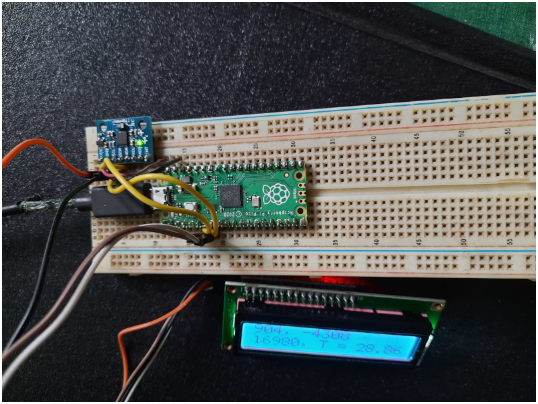
- Analogue output
  - Voltage proportional to the quantity
  - PWM (Pulse Width Modulation): Pulse width proportional to the quantity
  - Note: PWM is still considered analogue and NOT digital.
- Digital output
  - Parallel output
  - Serial output: One of several protocols
    - I^2C
    - SPI
    - ...

Two Examples of Sensor Modules

1. Accelerometer MPU6050
2. Pressure and temperature sensor BMP280

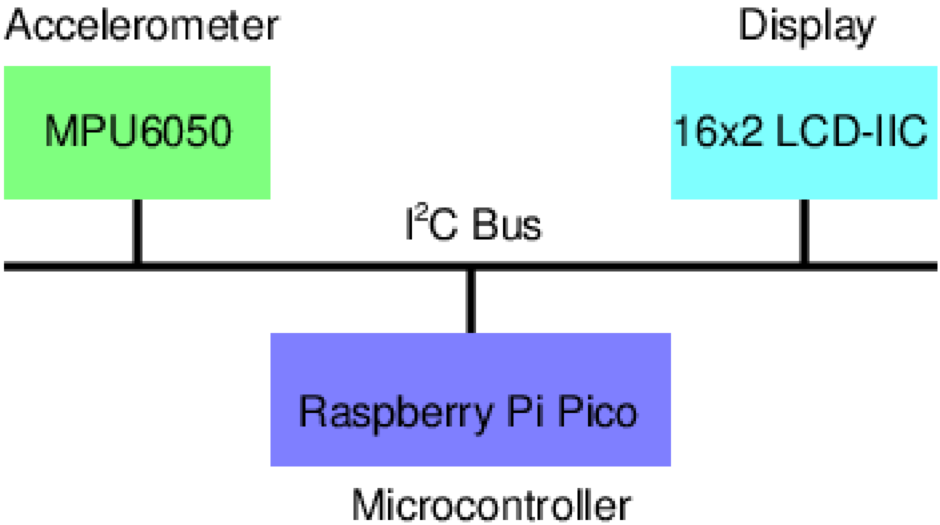
Other examples of readily available sensor and actuator modules will be discussed in the future.

Example 1: Accelerometer MPU6050

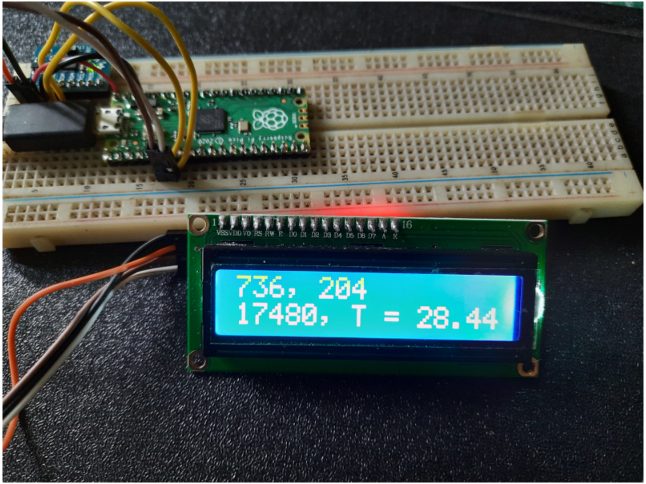


Small board: 16 mm $\times$ 20 mm, MPU6050 Accelerometer module ($\approx$ Rs. 115)
Big board: 22 mm $\times$ 53 mm, Raspberry Pi Pico
Powered from the USB Port

Example 1: Block Diagram

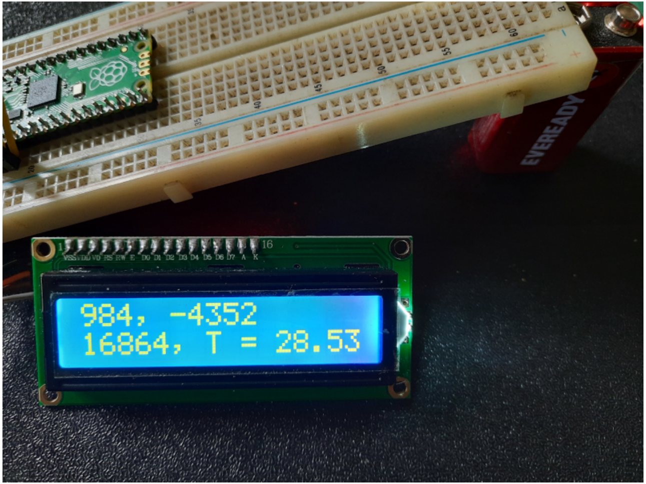


Example 1: Accelerometer MPU6050



First line: x and y components of acceleration in device units
Second line: z component of acceleration in device units, temperature
Horizontal Board: a_z: 17480 device units

Example 1: Accelerometer MPU6050



First line: x and y components of acceleration in device units
Second line: z component of acceleration in device units, temperature
Tilted Board: a_z: 16864 device units

Example 1: Calculations

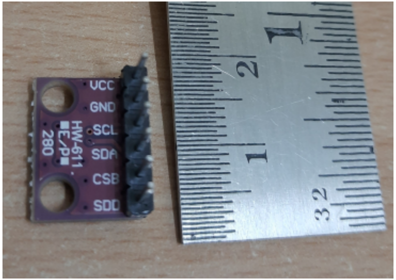
Length of breadboard: 16.5 cm
Height of battery: 4.3 cm

```
akm@akm:~/pico/pico-examples/i2c/lcd_1602_i2c$ lua
Lua 5.3.3  Copyright (C) 1994-2016 Lua.org, PUC-Rio
> math.deg(math.acos(16864/17480))
15.256010576751
> math.deg(math.asin(4.3/16.5))
15.106026666421
>
```

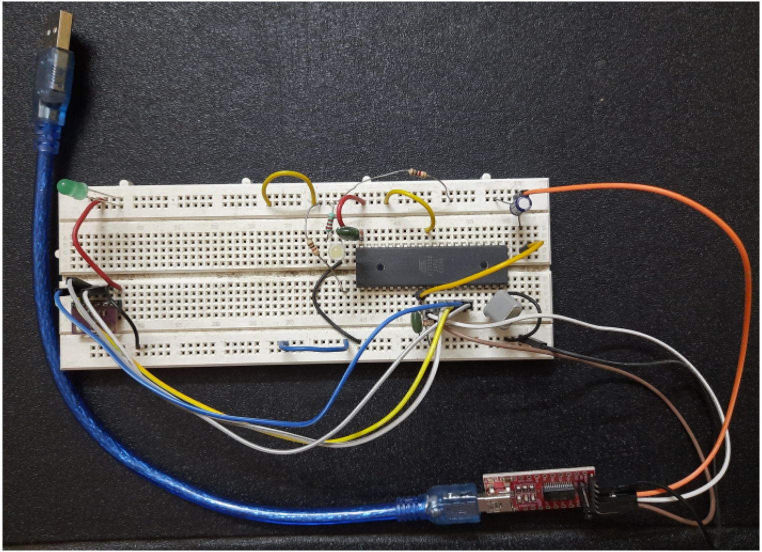
Tilt angle: $\approx$ 15 degrees

Example 2: BMP280

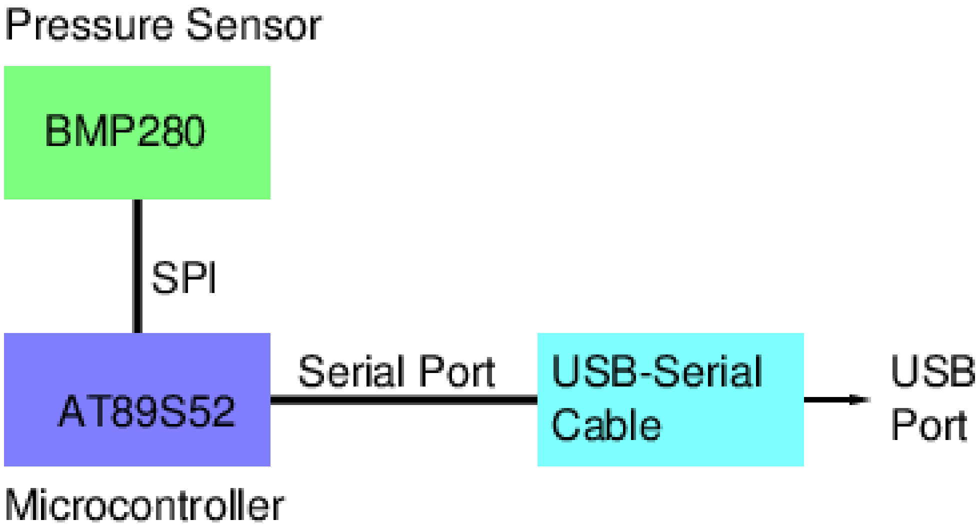
- Pressure and Temperature
- Inexpensive: $\approx$ Rs. 70
- Supports both SPI and $\mathrm{I^2C}$
- Another sensor BME280 can also measure humidity.



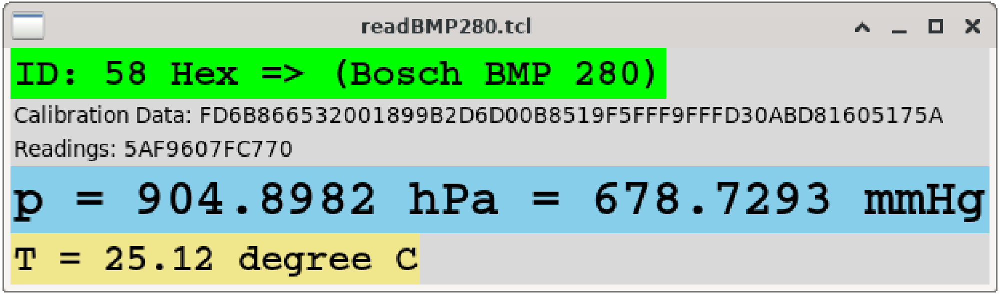
Example 2: System with BMP280



Example 2: Block Diagram



Example 2: BMP280 Output



Questions to ask about any sensor or transducer

- How does this sensor or transducer work?
- How is it fabricated?
- What kind of electronics is used in this sensor or transducer?
- How can we get readings from this sensor?
- How can we drive this transducer?
- What are its applications?
- How much does it cost?

Reference Books

David Halliday, Robert Resnick, and Jearl Walker

Fundamentals of Physics

Ian Sinclair

Sensors and Transducers

H. K. Tönshoff and I. Inasaki (Editors)

Sensors in Manufacturing

Example Sensors

- Microphone
- Capacitive touch sensor
- LVDT
- Piezoelectric sensors
- Coil
- Resistance thermometer
- Hall sensor
- Strain gauge
- MEMS Sensors

Example Transducers

- Loudspeakers
- Motors
- Solenoids and relays
- Piezoelectric actuators
- MEMS actuators
- Coil for producing magnetic field
- Electric heater

Sensors Based on Change in Resistance

- Strain Gauge
- Load Cell
- Platinum Resistance Thermometer
- Thermistor
- Light Dependent Resistor (LDR)
- Some types of MEMS accelerometers
- Some types of MEMS pressure sensors

Sensors Based on Change in Inductance

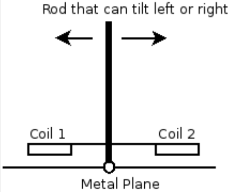
- Proximity sensors using coils
- Some types of pressure sensors
- Linear Variable Differential Transformer (LVDT)

Sensors Based on Change in Capacitance

- MEMS accelerometers
- Pressure sensors
- Angle sensors
- Capacitor microphone

Usually there is no simple formula

Example Sensor: No simple formula

Inductive tilt sensor: 

Example Sensor: Simple formula

Small air-core coil sensing a changing magnetic field.

- Coil area is known.
- Number of turns is known.

Note: Putting an iron core would make the sensor more sensitive, but now the calculations will be harder.

Calibration and Characterization

Whether the sensor or transducer output can be given by a formula or not, we always need to *calibrate* and characterize the device.
Output vs. input measurements for . . .

- . . . a number of different input values,
- . . . a number of different environmental conditions,
- . . . a number of different device samples, . . .

Miniaturization: Advantages and challenges

- Miniaturization: Making sensors smaller in size
- Simplification: Make the construction as simple as possible

Advantages

Miniaturization makes sensors:

- More precise in location
- Faster in response
- Cheaper
- More reliable
- More durable

Challenges

The output signal amplitude usually becomes smaller.

Electronics: Signal conditioning concepts

- Amplification
- Filtering
- Bridge or differential arrangement
- Modulation and synchronous or phase sensitive detection, also known as *lock-in amplifier*

Amplification and Filtering

Amplification

- DC vs. AC: AC amplifier is easier to build.
- Broadband vs. Tuned: Tuned amplifiers are less affected by noise.
- Chopper: Converts DC to AC.
- Single input vs. Differential input
- Can often be integrated with the sensor.

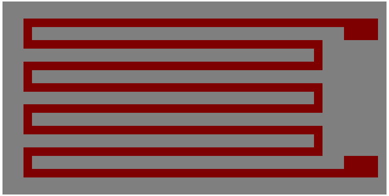
Filtering

- Removes unwanted noise.
- Even simple RC lowpass filter or LC bandpass filter can be quite effective.

Differential or Bridge Arrangement

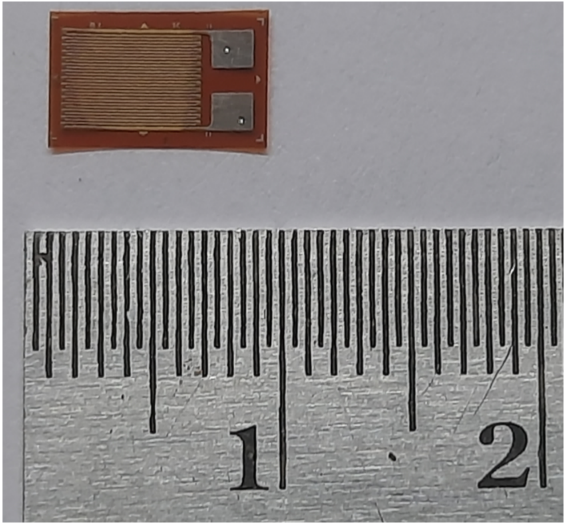
- Two identical sensors as arms of a bridge circuit.
- Of course no two sensors are exactly identical.
- Bridge with nearly identical sensors is better than no bridge.
- Removes common mode signal.
- Examples: Strain gauge, LVDT

Strain Gauge

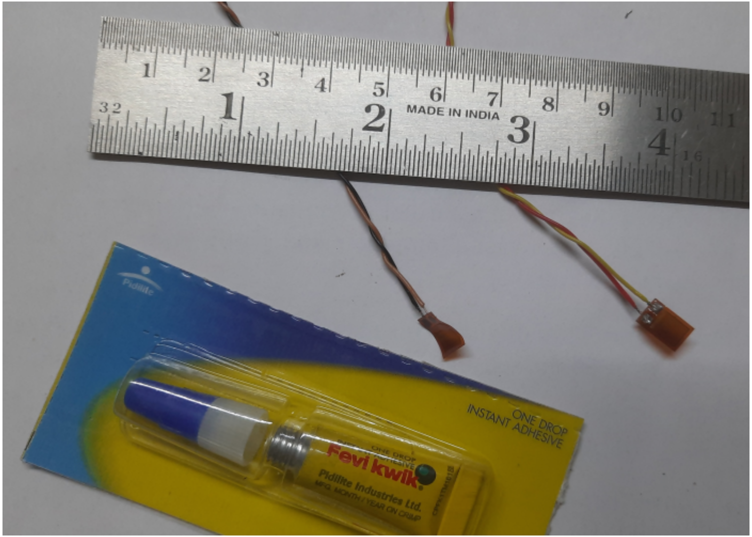


Metal Foil Strain Gauge
Change in resistance is proportional to strain.

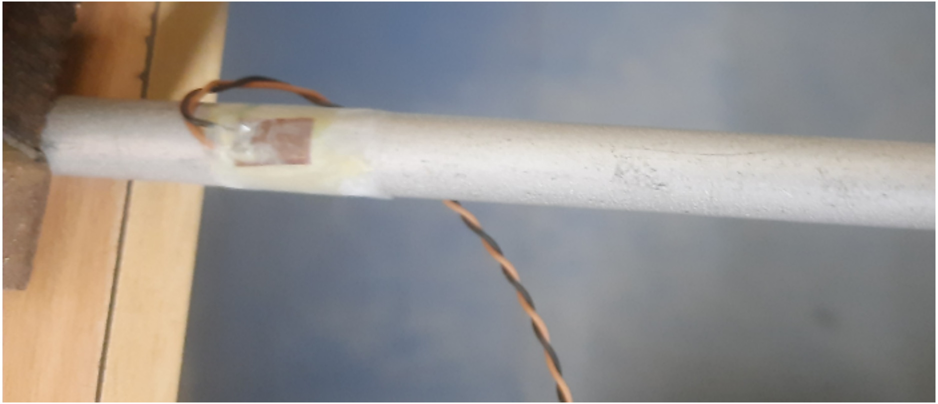
Strain Gauge: Photograph



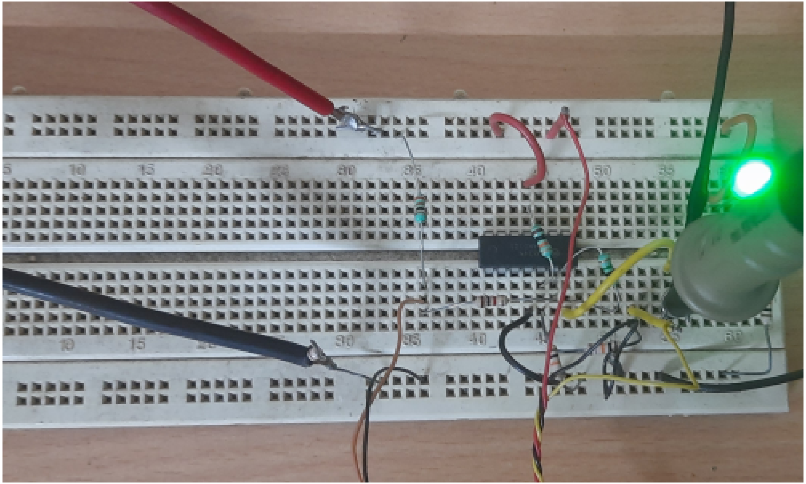
Strain Gauge: Wires Attached



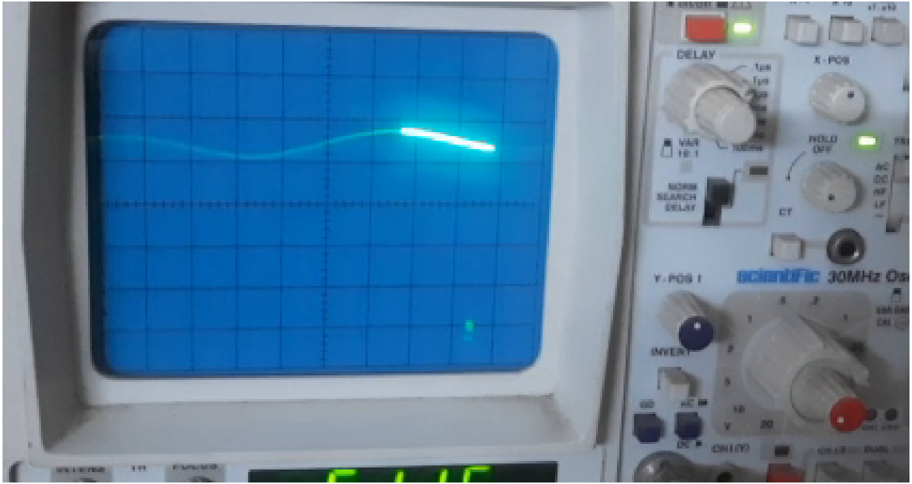
Strain Gauge: Glued to Beam



Strain Gauge: Bridge and Amplifier



Strain Gauge: Output for Vibrating Beam



Strain Gauge: Points to note

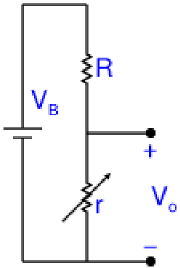
- The output is quite *small*.
- A large amplification close to 1000 was needed.

Gauge Factor

$$\mathrm{GF} = \frac{\Delta R / R_{\mathrm{G}}}{\epsilon} \qquad (1)$$

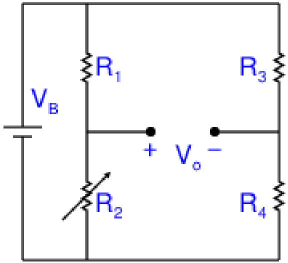
ΔR: Change in resistance caused by strain
R_{G}: Resistance of the strain gauge when there is no deformation
ϵ: Strain = (Change in length) / (Length)
For metallic foil gauges, GF is a little over 2.

Strain Gauge: Voltage Divider Arrangement



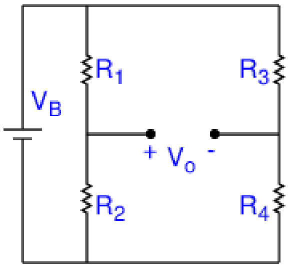
Disadvantages: Too much offset!
Let the battery voltage be 5 V, and both *R* and *r* be 100 ohms. The change in *r* may at most be 1 ohm. Then the change in output is 12.44 mV over a base value of 2.5 V. Very hard to use.
Not used.

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

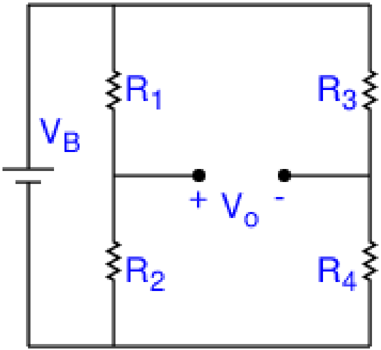


One or more of the bridge arms can be a strain gauge.
Example Usage with a Beam:
R_1, or R_4, or both can be mounted above the beam. R_2, or R_3, or both can be mounted below the beam.
If all resistors in this diagram are strain gauges, then the output will not be affected by a change in the temperature.

Examples where Wheatstone Bridge is used

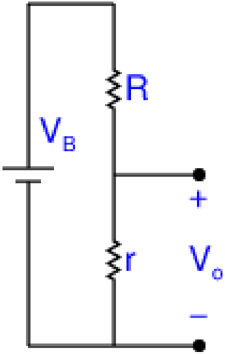
- Strain Gauge
- Many types of Pressure Sensors
- RTD Temperature Sensor
- Some types of Accelerometers

Wheatstone Bridge Output



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

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 $R = r$.

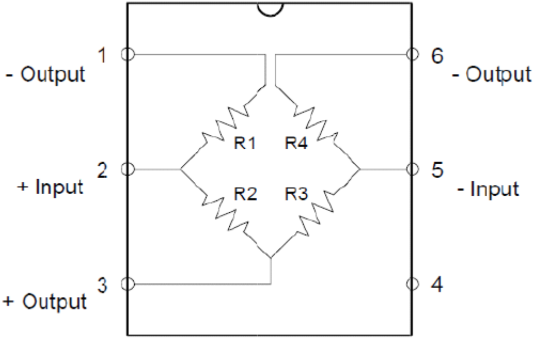
Best Operating Conditions

- 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 values may cause heating of the strain gauge elements.

Example: Pressure Sensor MPS20N0040D

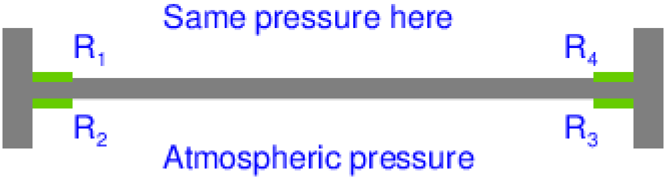
40 kPa differential pressure sensor

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.

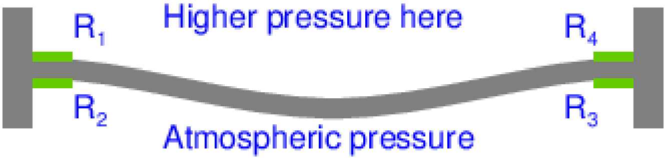
Piezo-resistive pressure sensor arrangement



$R_1 = R_2 = R_3 = R_4 = R_0$.

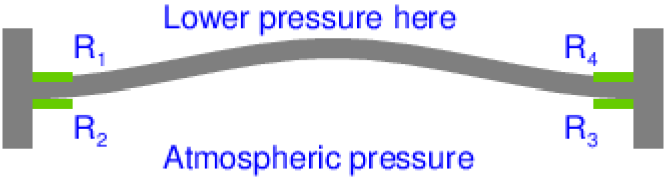
R_0 is approximately $5\,\mathrm{k}\Omega$ in MPS20N0040D.

Piezo-resistive pressure sensor: Higher pressure



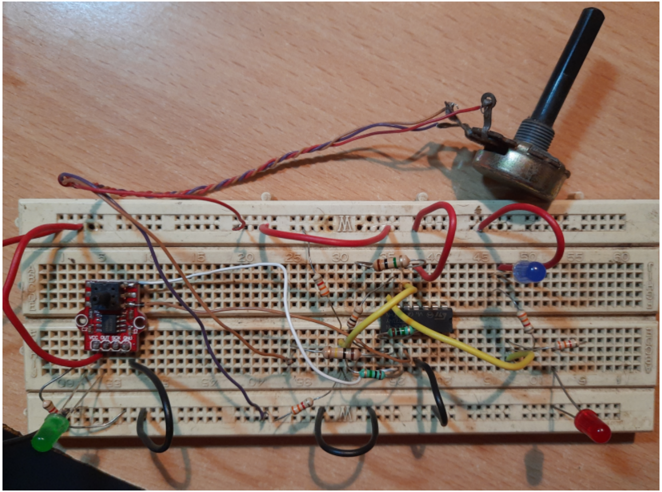
R_1 and R_4 increase due to tension. R_2 and R_3 decrease due to compression.

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.