SENSORS, INSTRUMENTS AND EXPERIMENTATION

Introduction by Ashok Ranade

Syllabus

Introduction to construction and characteristics of sensors. Experiments involving application of sensors for physical quantities like temperature, pressure, force, torque, strain, velocity, acceleration, linear and angular speed and displacement, volumetric and mass flow rates, illumination, and sound level etc. Introduction to calibration of sensors and data acquisition system

Basic Mechanical measuring instruments: Vernier caliper: Micrometer: Coordinate Measuring Machine: Pressure

Books

- Principles and applications of Electrical Engineering
  Fifth Edition
  By Giorgio Rizzoni
  McGraw-Hill (India)
- References on the net

Examination scheme

- Quiz 1 : 11%
- Mid term test: 22%
- Quiz 2 : 6%
- Assignments : 11%
- Project: 15%
- End term Examination : 35%

All examinations open book and on LMS

Grade Rubric

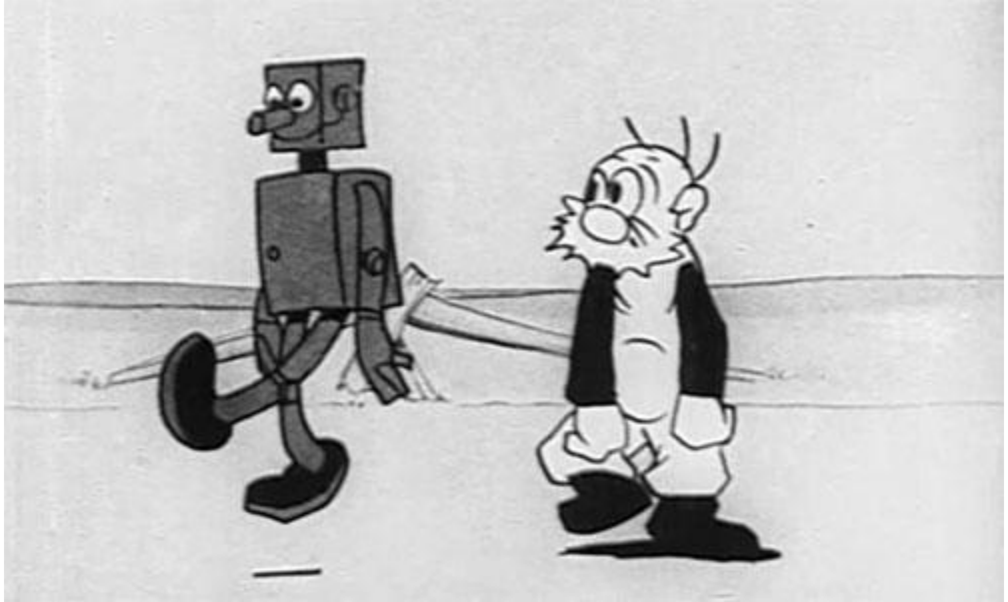
Absolute grading

Grades	A	A-	B+	B	B-	C+	C	D	NP
Marks Range	90-100	80-89	70-79	60-69	50-59	40-49	35-39	30-34	0-29

Measurement and control systems

- Engineering applications require measurement and control of physical quantities
- ❖ Satellite communica
- ❖ Antenna position

Robot position



Other Examples

- Measurement and control of temperature of oven

- M rol of Flow in flood control

Transducers

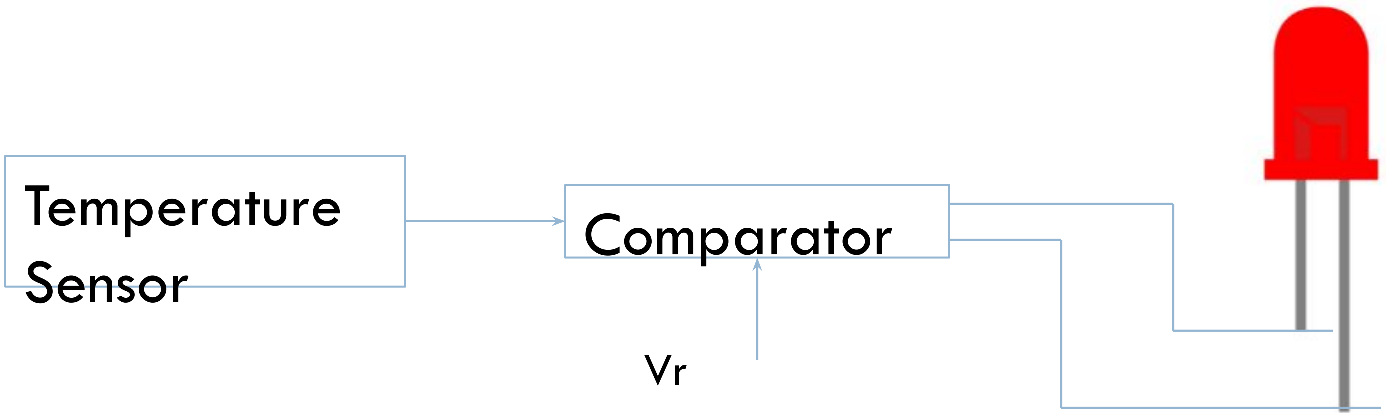
- Capable of converting one physical quantity into another type of physical quantity
- The device which converts a non-electrical quantity into an electric quantity is called a sensor
- Examples

  Thermocouple

  Microphone
- The device which converts an electrical quantity into a non electrical quantity is called actuator
- Heater

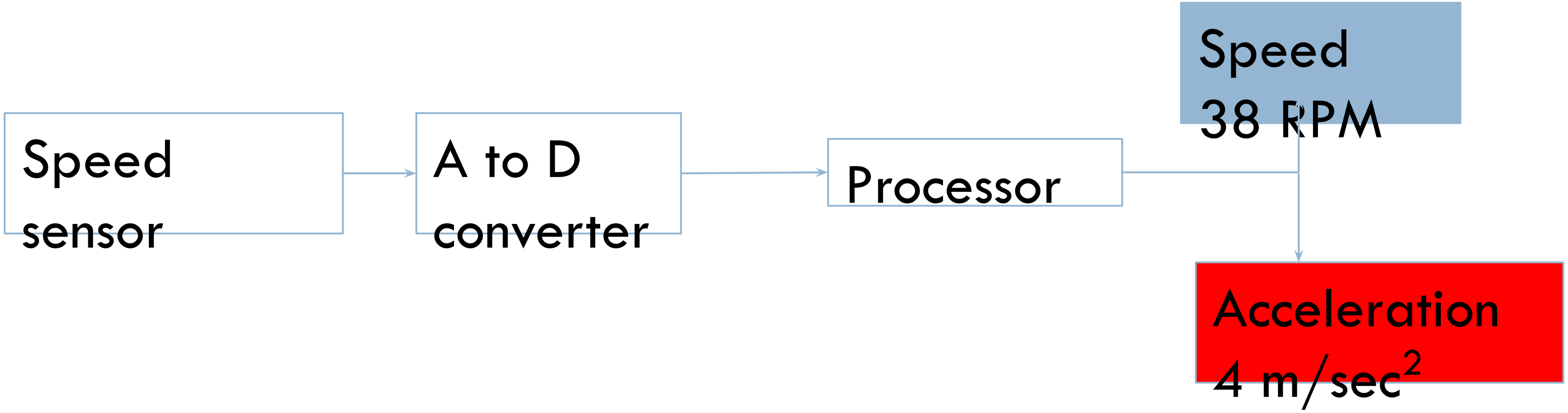
An application

- Temperature alarm



One more application

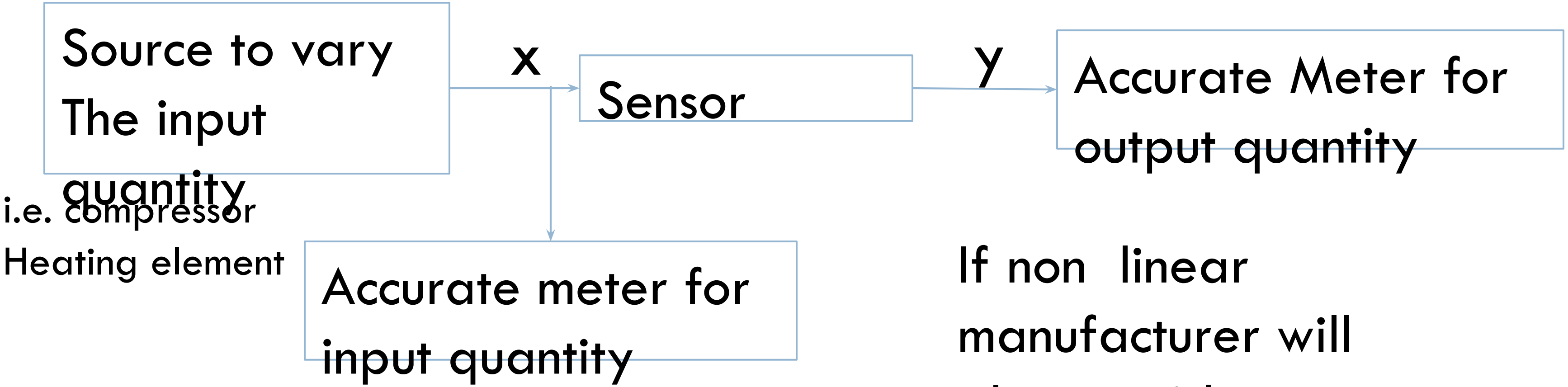
- Speed and acceleration measurement



Input output characteristics of a sensor

- Manufacturers specify the sensor characteristics
- x is the input
- y is the output
- $y = f(x)$

Sensor calibration



$$y = f(x)$$

often a graph is provided by the manufacturer

If non linear manufacturer will also provide polynomial equation

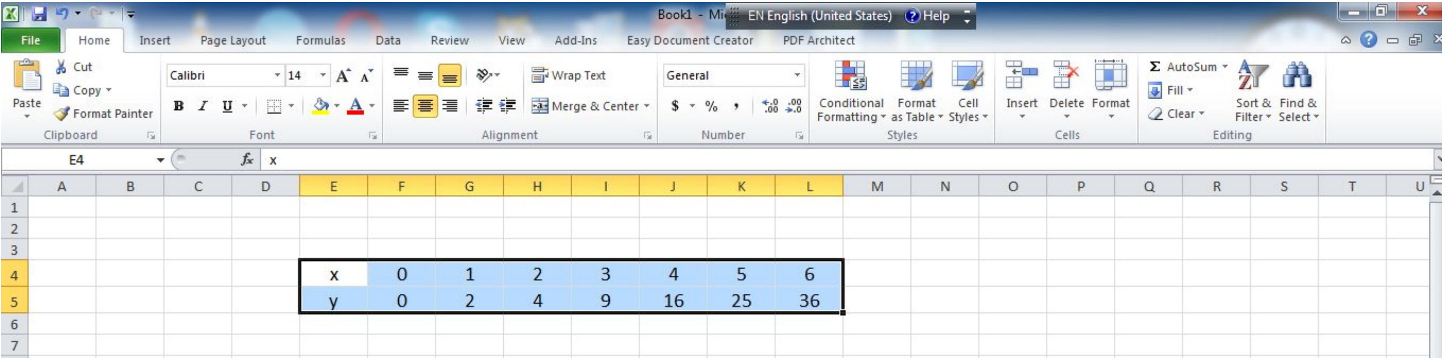
If approximately linear, best fit line is given.

Curve fitting

- This is the process of finding a suitable equation between y and x when table of values of x and y is known.
- Often a polynomial is found

$$y = a_0 + a_1 x + a_2 x^2 + - - a_n x^n$$

- The curve fitting will give the values of constants a_0,a_1 etc
- Other equations are also possible
- Many programming languages have the function for curve fitting
- Excel also has the facility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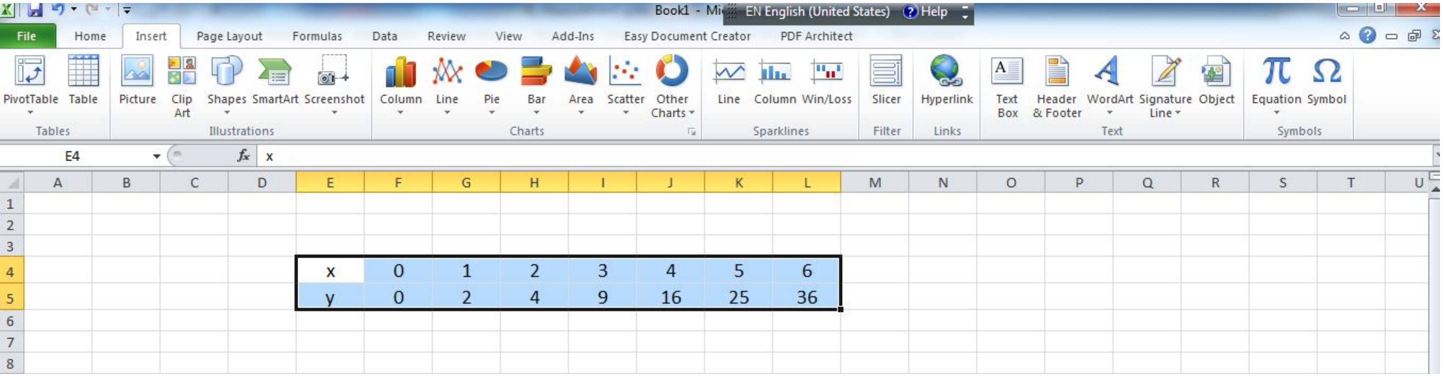
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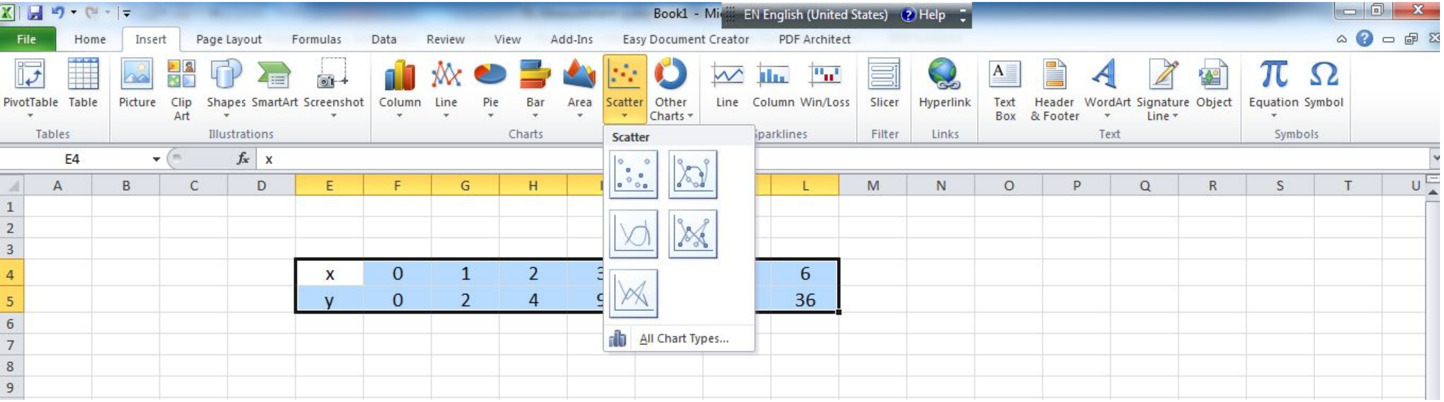
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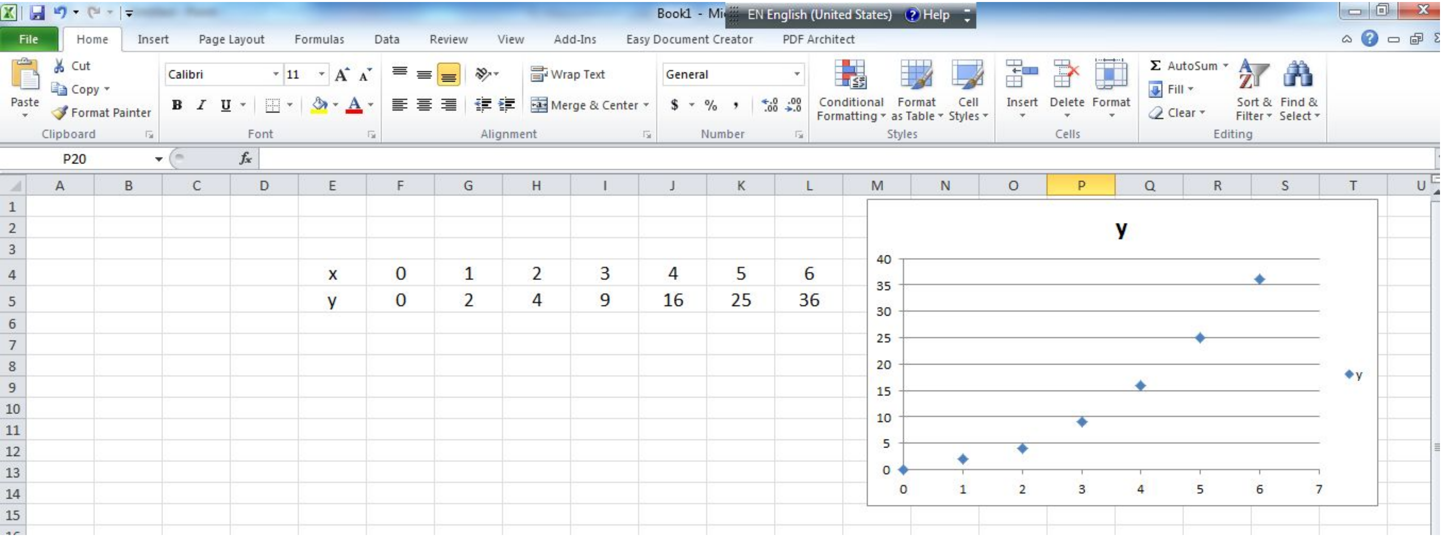
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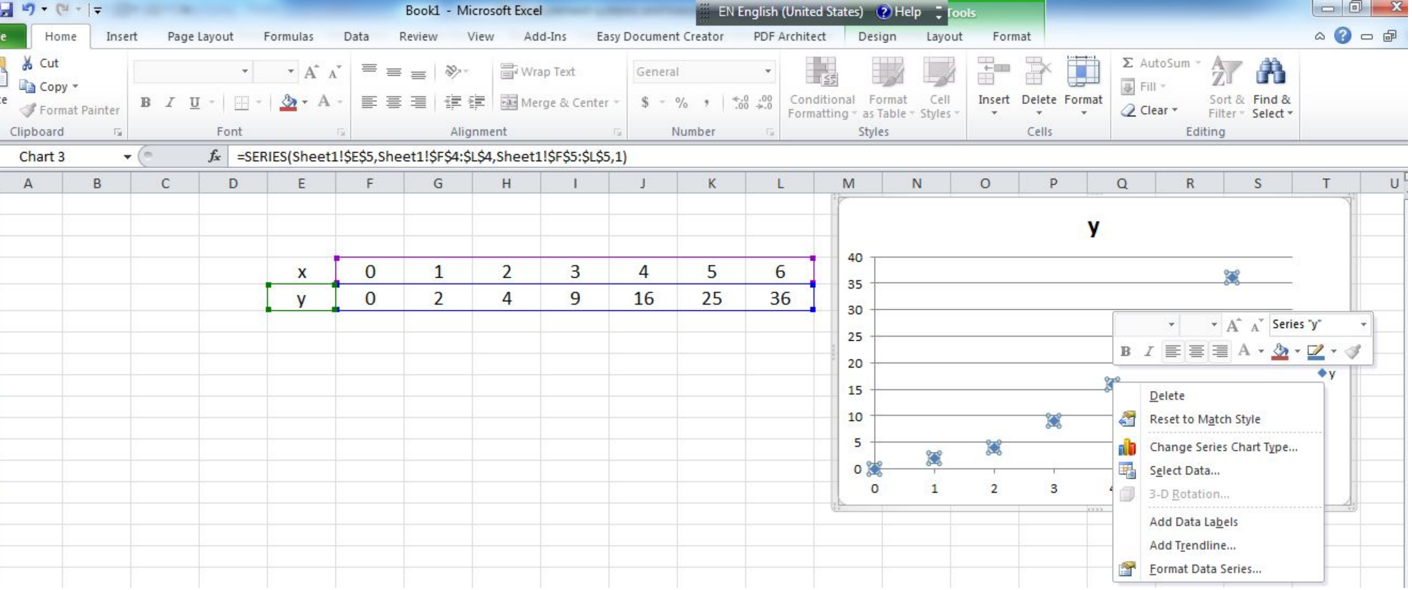

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x 0 1 2 3 4 5 6
y 0 2 4 9 16 25 36
y
Series "y"
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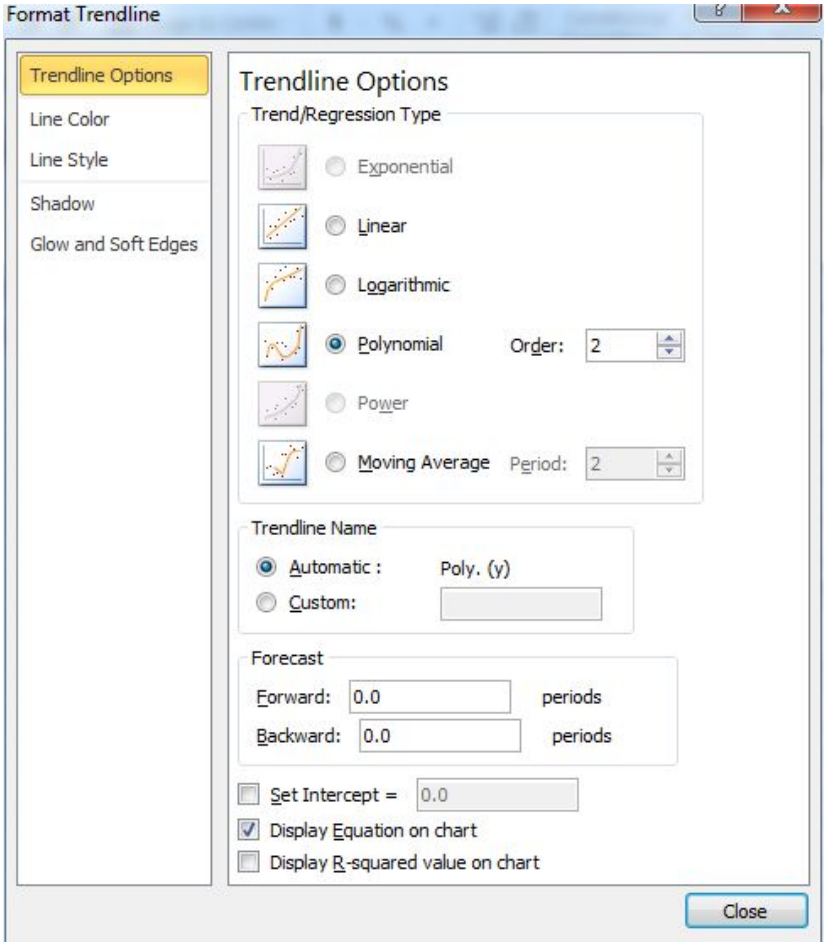
Reset to Match Style
Change Series Chart Type...
Select Data...
3-D Rotation...
Add Data Labels
Add Trendline...
Format Data Series...



Format Trendline
Trendline Options
Line Color
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Glow and Soft Edges
Trendline Options
Trend/Regression Type
Exponential
Linear
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Order:
2
Power
Moving Average
Period:
2
Trendline Name
Automatic :
Poly. (y)
Custom:
Forecast
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periods
Set Intercept =
0.0
Display Equation on chart
Display R-squared value on chart
Close

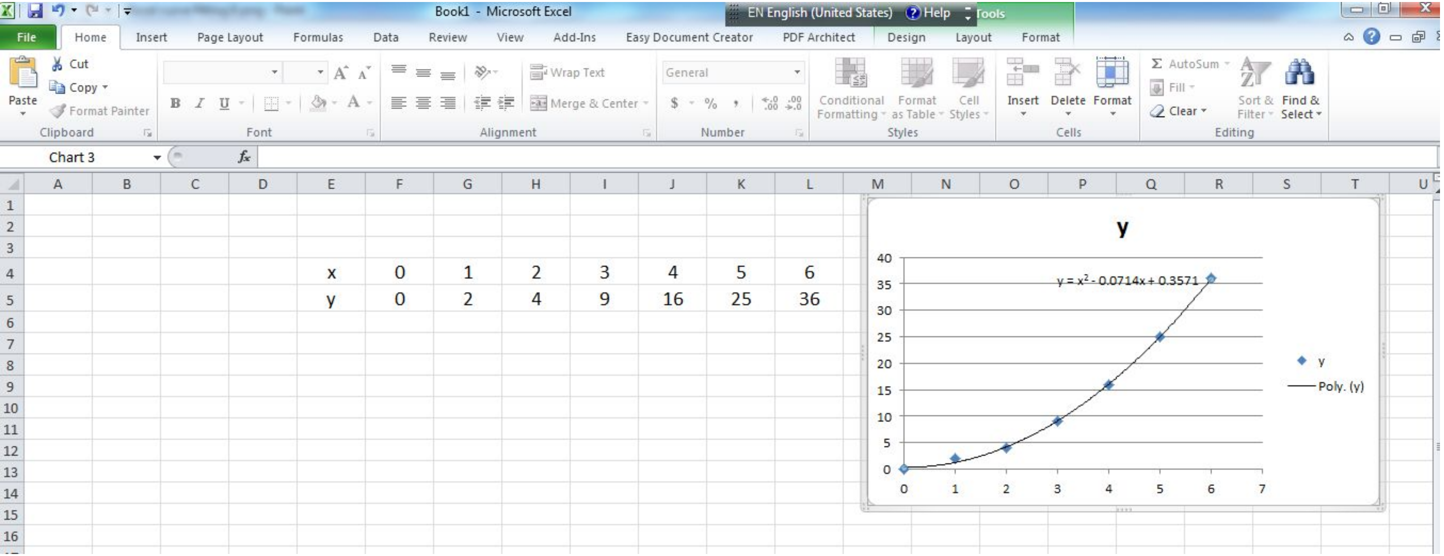
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Chart 3
x 0 1 2 3 4 5 6
y 0 2 4 9 16 25 36
y
y = x² - 0.0714x + 0.3571
y
Poly. (y)
0 5 10 15 20 25 30 35 40
0 1 2 3 4 5 6 7

Class Exercise 1

Let x vary from 0 to 1 with increment of 0.1

Let $y = x^3$

In Excel calculate y for each value of x and find

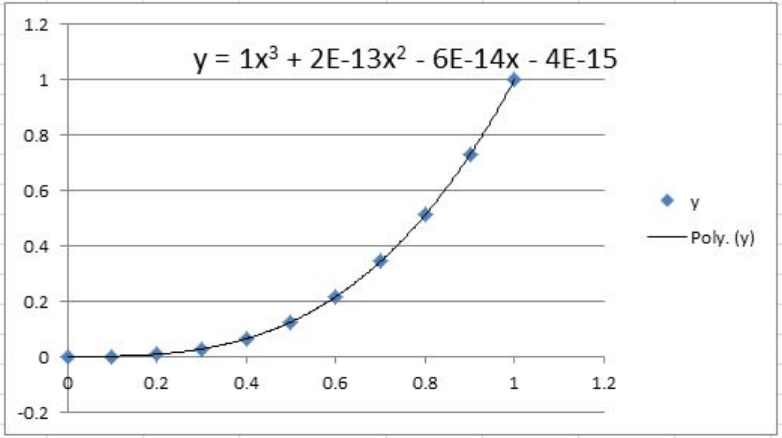
the polynomial for y in terms of x. It will be close to x^3.

Calculate y using the polynomial and compare with original values

Solution to Exercise 1

Class Exercise 1 Lecture 1

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
y	0	0.001	0.008	0.027	0.064	0.125	0.216	0.343	0.512	0.729	1
y calculated	-4E-15	1E-03	0.008	0.027	0.064	0.125	0.216	0.343	0.512	0.729	1



Class Exercise 2

Let x vary from 0 to 1 with increment of 0.1

Let $y = \sqrt{x}$

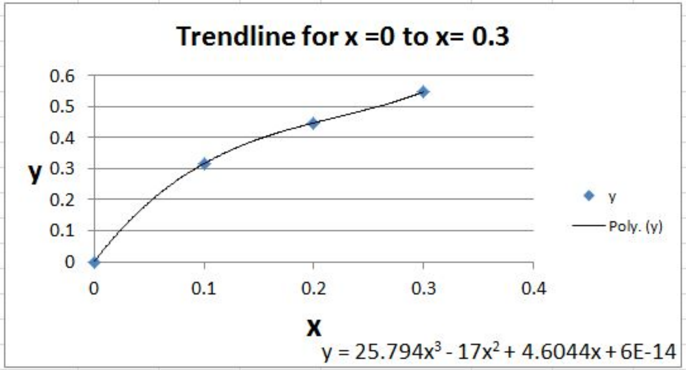
In Excel calculate y for each value of x and find the polynomial for y in terms of x. Calculate y using the polynomial and compare with original values.

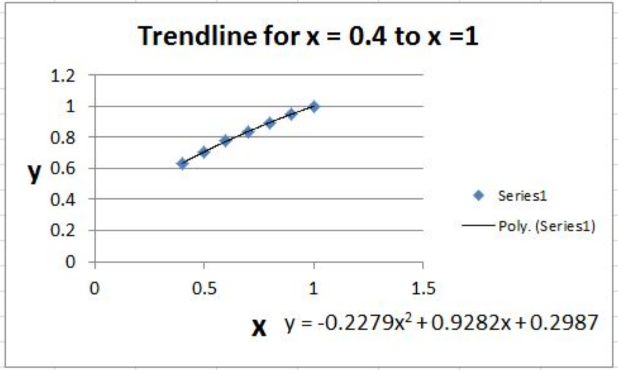
Experiment with two or more trend-lines for more accurate results

Solution to Exercise 2

Solution for Class assignment 2 Lecture 1

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
y	0	0.316	0.447	0.548	0.632	0.707	0.775	0.837	0.894	0.949	1
y calcuated	6E-14	0.316	0.447	0.548	0.634	0.706	0.774	0.837	0.895	0.949	0.999

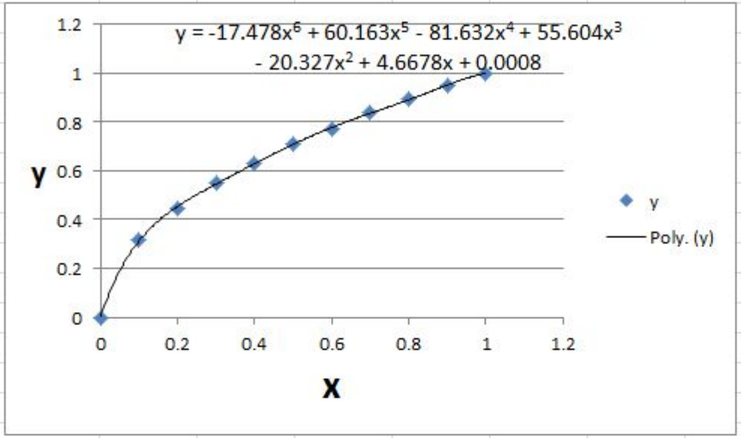




More error with single trendline

A single trend line with 6th order polynomial

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
y	0	0.316	0.447	0.548	0.632	0.707	0.775	0.837	0.894	0.949	1
y calculated	0.0008	0.312	0.454	0.545	0.629	0.708	0.778	0.836	0.891	0.951	0.999



SENSORS INSTRUMENTS AND EXPERIMENTATION

02 Some aspects of instrument design and errors in measurements

By Ashok Ranade

Analog Instrument

- Suppose we want to build an analog temperature measuring instrument with range of 0 to 100 degree C, using a given sensor and a voltmeter
- Sensor characteristics are 10mV/degree centigrade

$V = 0.01T$

- Voltmeter is 0 to 5 volts.

Output of sensor is 1 volt at 100 degrees so for full scale deflection the amplifier with gain 5 is required

$Vo = 0.05T$

Calibrating the meter

$$Vo = 0.05T$$

$$T = Vo/0.05$$

Vo	T
0	0
1	20
2	40
3	60
4	80
5	100

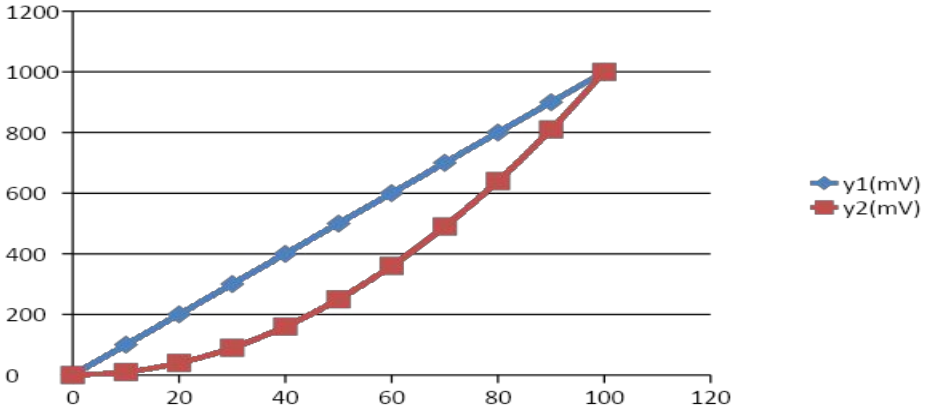
Linear and non linear

x Temp	y_1(mV)	y_2(mV)
0	0	0
10	100	10
20	200	40
30	300	90
40	400	160
50	500	250
60	600	360
70	700	490
80	800	640
90	900	810
100	1000	1000

$$y_1 = 10x$$

$$y_2 = 0.1x^2$$

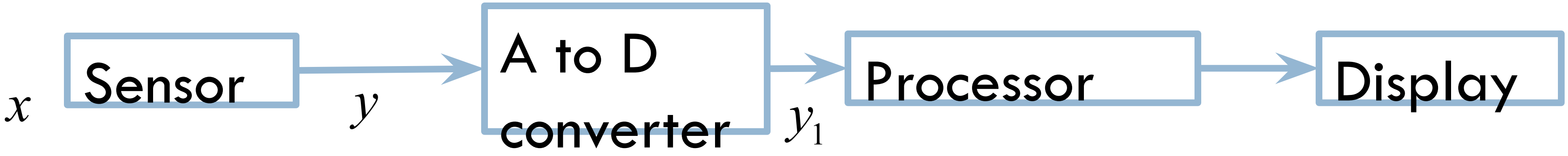
Output in mV



Temperature in degrees Centigrade

Scale is crowded at low temperatures for non linear sensor for analog display

Digital Instrument



$$y_1 = kx$$

$$x = \frac{y_1}{k}$$

$$y_1 = k\,x^2$$

$$x = \sqrt{\frac{y_1}{k}}$$

In general

$$y_1 = f(x)$$

$$x = f^{-1}(y_1)$$

Table look up can be used instead of solving the equation. Will need memory.

Easy calculation for linear sensor

Difficult calculation for non-linear sensor

Algorithm for the Digital instrument

(1) Read y_1

(2) calculate $x = f^{-1}(y_1)$ or get x from look up table

(3) Send to display

(4) Delay

(5) Go to (1)

Class Exercise 2.1

A force sensor has input output characteristics given by $V = 2\sqrt{F}$

Where V is the output voltage and F is the force in Newtons

We wish to build an analog Force meter which uses a voltmeter of the range 0-10 volts. The calibration should be valid for the force range from 0 to 10 Newtons. (Full scale). So in your block diagram you have Force sensor and 0 – 10 dc voltmeter. What else you need? Think and design the complete block diagram for the meter . Show the calibration so that you get one decimal digit accuracy.

Solution to Exercise 2.1

We have $V = 2\sqrt{F}$

So when F = 10 Newtons

V = 6.324555 volts

Clearly we can not get full scale deflection if we connect the output of sensor to the voltmeter. So we need an amplifier with gain = 10/6.324555

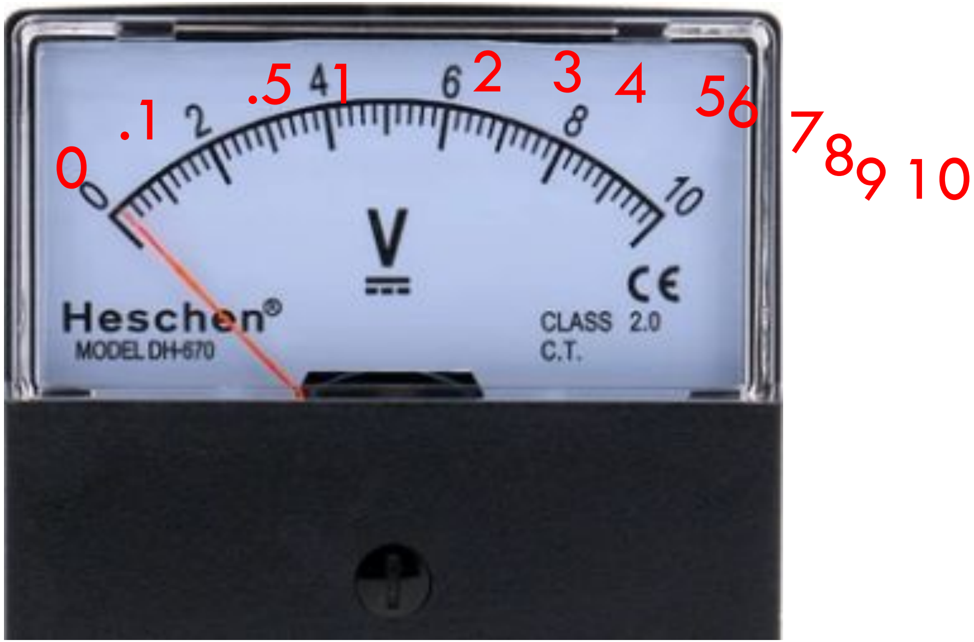
= 1.581139

Block diagram

F → Force sensor → $V = 2\sqrt{F}$ → Amplifier → Vo →

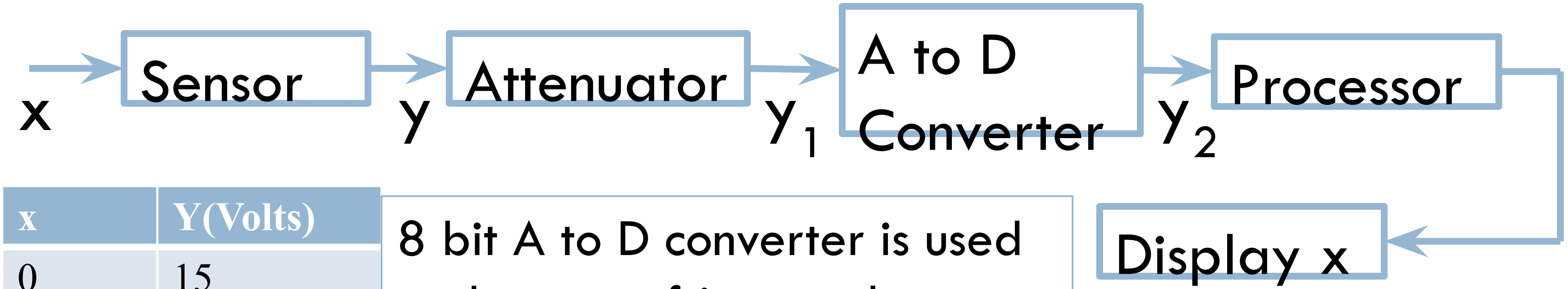
Calibration

F	V	Vo
0	0	0
0.1	0.632	1
0.5	1.414	2.2
1	2	3.2
2	2.828	4.5
3	3.464	5.5
4	4	6.3
5	4.472	7.1
6	4.899	7.7
7	5.292	8.4
8	5.657	8.9
9	6	9.5
10	6.325	10



Exercise 2.2

Consider the block diagram below



x	Y(Volts)
0	15
3	2

8 bit A to D converter is used and range of input voltage to ADC is 0 to 5 volts. Obtain the expression for x in terms of y_2 that processor will use

Solution to Exercise 2.2

$$y = mx + C$$

$$m = \frac{-(15-2)}{3-0} = \frac{-13}{3}$$

$$y = \frac{-13}{3}x + C$$

$$At\ x = 0\ y = 15$$
$$Hence\ C = 15$$

$$y = \frac{-13}{3}x + 15$$

Since ADC accepts the maximum input of 5 volts $y_1 = y/3$

$$y_1 = \frac{-13}{9}x + 5$$

Since ADC is 8 bit its output ranges from 0 to 255. And 255 corresponds to $y_1 = 5$. Also ADC is linear so

$$y_2 = \frac{255}{5}y_1$$

Substituting for y_1 and rearranging we get the final answer

$$x = \frac{(y_2 - 255)\times 45}{-255\times 13}$$

Error in measurements

- What is Error ?

  Difference between measured and true value

  usually in % of full scale reading

$$Error = \frac{Measured\ value - True\ value}{True\ value} \times 100$$

$$Error = \frac{8.2 - 8}{8} \times 100 = 2.5\%$$

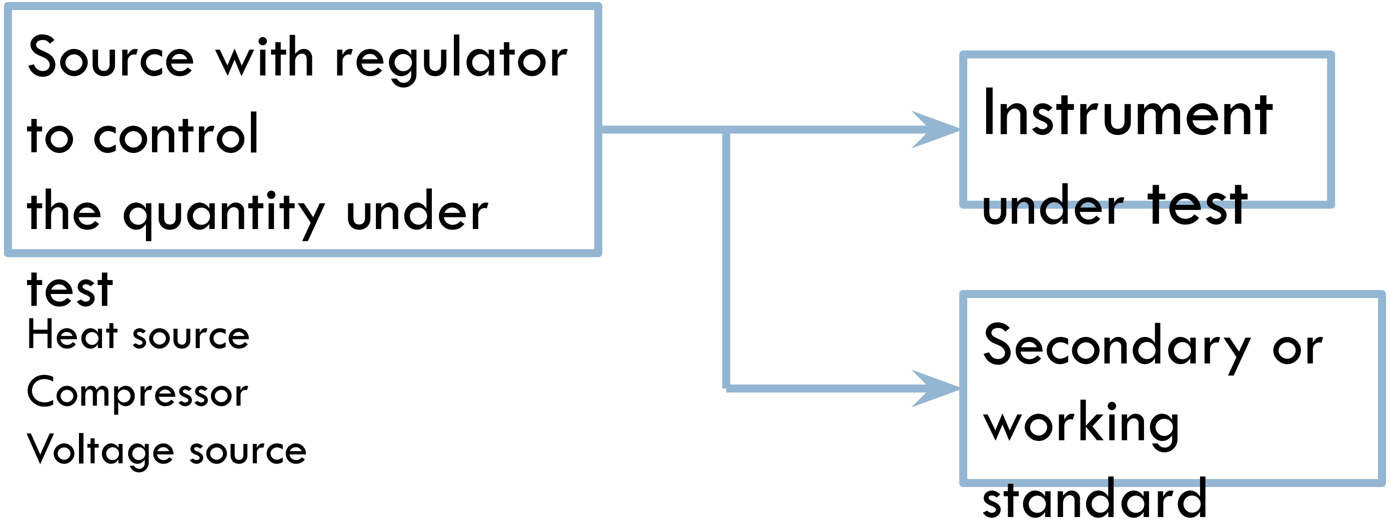
- Accuracy

What is a true value ?

- As measured by an instrument without error

  This does not exist
- However highly accurate instruments called Primary standards are available
- These are available in International and National laboratories
- Less accurate instruments are calibrated using Primary standards
- These are secondary standards more often used
- Working standards

Calibration procedure

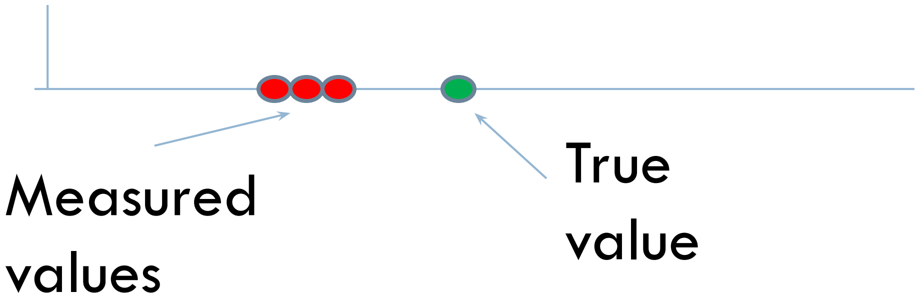


Heat source
Compressor
Voltage source

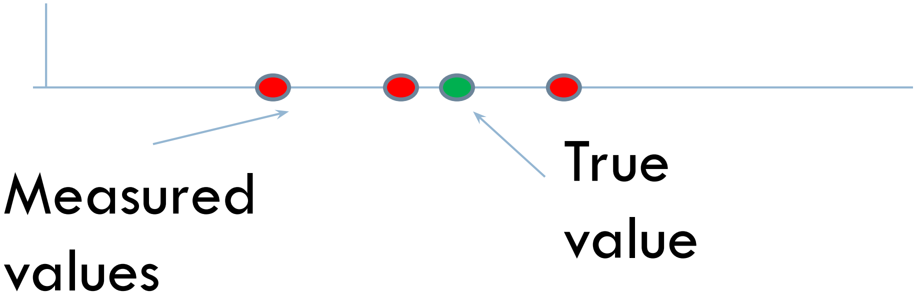
Types of Measurement errors

- Two types of errors
  - Systematic errors
    - Due to instrument inaccuracies
    - Faulty design of an experiment
      - Repeatable
  - Random errors
    - Human errors
    - Noise
      - Not repeatable

Error distributions (Magnitude)

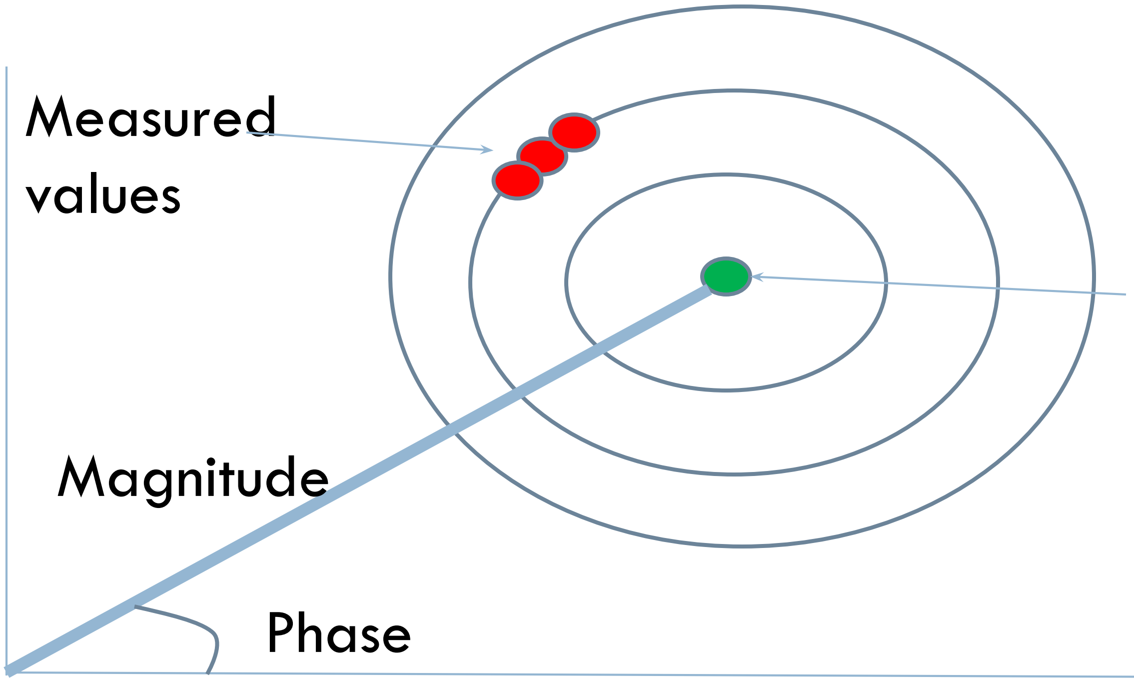


Systematic errors (Magnitude measurement)



Random Errors

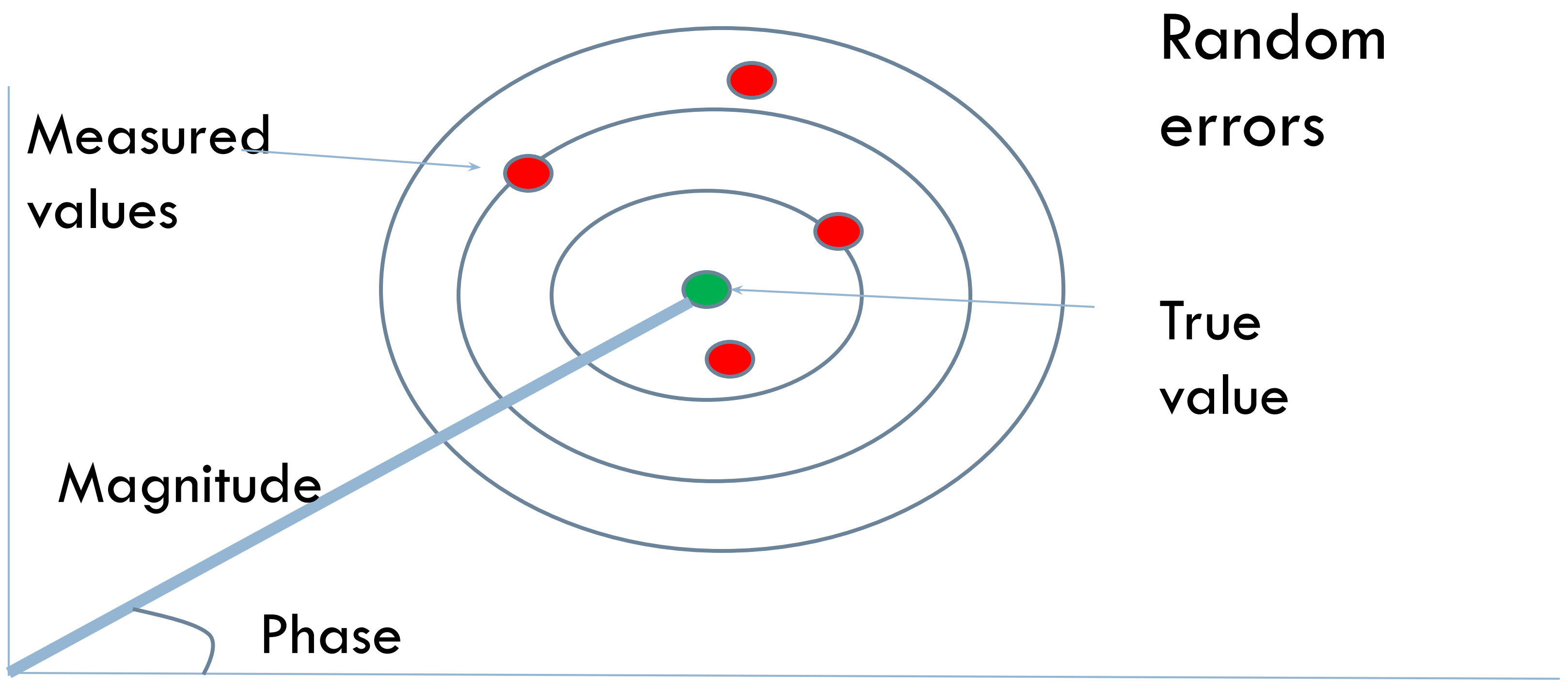
Error distribution (Magnitude and phase)



Systematic errors

True value

Error distribution (Magnitude and phase)



Average of many readings

- We will take two examples

(1) An object is to be weighed. Then to get better accuracy , it will be weighed many times. Let us say the readings are W_1, W_2, --- W_n. And we will take average of these readings

Measuring input-Output Characteristics

(2) We wish to find input – Output characteristics of a device (i.e. Sensor).

Let us say input is denoted by x and output is denoted by y. There is a regulator to set x and we adjust the regulator to set x from x_1 to x_n and measure corresponding y_1 to y_n values.

However for better accuracy , each regulator setting is repeated for , say, n_x times and average of each x and y value is taken.

Average of many measurements

- Many values of the variable, say x , are measured

$$x_1, x_2, -- x_n$$

x_1 is the average of n_x number of measurements

x_{11}, x_{12} etc are measured values

$$x_1 = \frac{x_{11} + x_{12} + -- x_{1n_x}}{n_x}$$

$$x_2 = \frac{x_{21} + x_{22} + -- x_{2n_x}}{n_x}$$

$$x_n = \frac{x_{n1} + x_{n2} + -- x_{nn_x}}{n_x}$$

Similar equations apply for y values

Standard Error

- Standard error measures how much discrepancy is likely to be in the sample mean and the population mean.
- Standard deviation measures dispersion of the data set relative to its mean.

$$SD = \sqrt{\frac{\sum_{i=1}^{n_x}(x_{1i} - x_1)^2}{n_x - 1}}$$

$n_x - 1$ is used because x_1 is not a true mean but an estimate. So spread is likely to be more

Standard error formula

- It is expected to depend on SD and n. Larger the n closer will be the mean to the true value.

$$SE = \frac{SD}{\sqrt{n_x}}$$

Drill Exercise 2.2

- An object is weighed 7 times. The measured values are shown below. Clearly there are errors. Find the mean value of the weight and the standard error using Excel

Object weight(in KG)
9.9
10.1
10.4
9.8
9.7
10
9.6

Answers

Object weight(in KG)
9.9
10.1
10.4
9.8
9.7
10
9.6

Mean	9.929
Std Dev	0.269
Std Dev (n-1)	0.291
Std Error	0.11

Accuracy and precision

- Precision

degree of *reproducibility* of a measurement.

More accurate, Less precise

Less accurate, more precise

Resolution

- Smallest measurable increment

A voltmeter capable of measuring minimum value of 1mV has more resolution than the one capable measuring minimum value of 10 mV considering same full scale value for both.

Span and range

- Span : Linear operating range

A temperature transducer may have a linear relation between temperature and output voltage over a temperature range of 0 to 150 degrees centigrade

- Range : The range of measurable values
- Linearity : Conformity to an ideal linear calibration

Non-linearity

- Deviation from the linearity over a specified range

Best fit line

- A practical sensor will have some non-linearity
- Manufacturers specify the best fit line

  Linearization of sensor

  Data pairs (x_1,y_1), (x_2,y_2),(x_3,y_3),---(x_n,y_n)
- Least square method

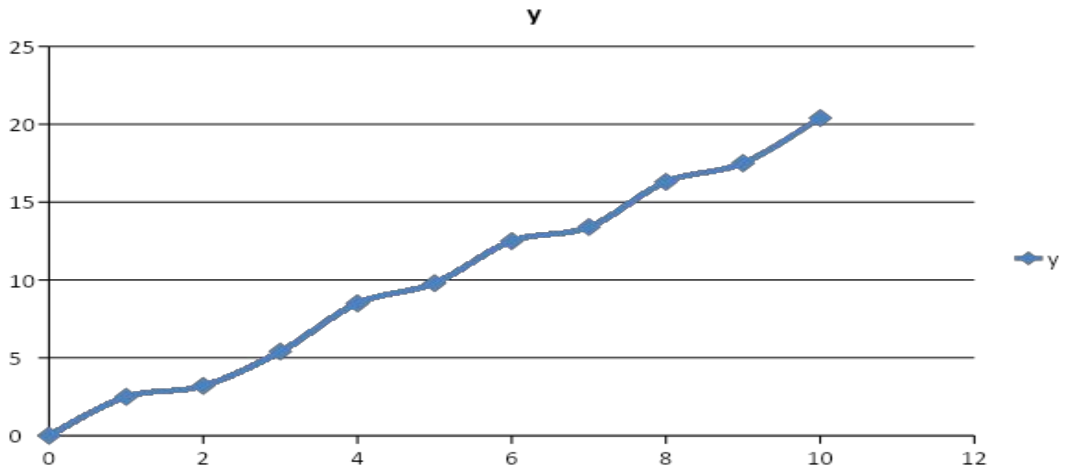
  $y = mx + b$

$$m = \frac{\sum_{i=1}^{n}(x_i - \bar{X})(y_i - \bar{Y})}{\sum_{i=1}^{n}(x_i - \bar{X})^2}$$

$$b = \bar{Y} - m\,\bar{X}$$

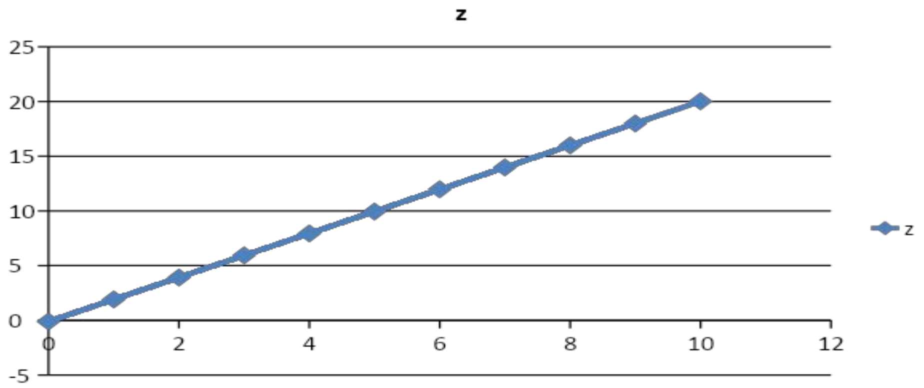
An Example

x	y
0	0
1	2.5
2	3.2
3	5.4
4	8.5
5	9.8
6	12.5
7	13.4
8	16.3
9	17.5
10	20.4

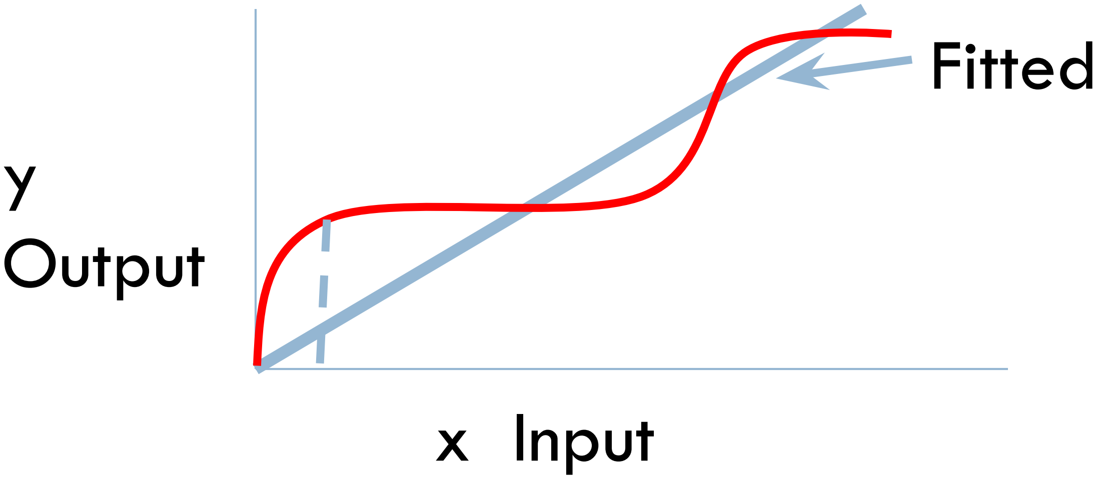


The best fit line

x	y	z
0	0	-0.105
1	2.5	1.907
2	3.2	3.919
3	5.4	5.931
4	8.5	7.943
5	9.8	9.955
6	12.5	11.97
7	13.4	13.98
8	16.3	15.99
9	17.5	18
10	20.4	20.01



Worst case



Max Deviation = Max | $y_{mi} - y_{fi}$ | : i = 1 to n

y_m is y measured and y_f is y fitted

Most likely deviation

$$\sqrt{\frac{\sum_{i=1}^{n} (y_{mi} - y_{fi})^2}{n-2}}$$

n-2 is used due to two reasons

Measured values are mean of samples and not true values

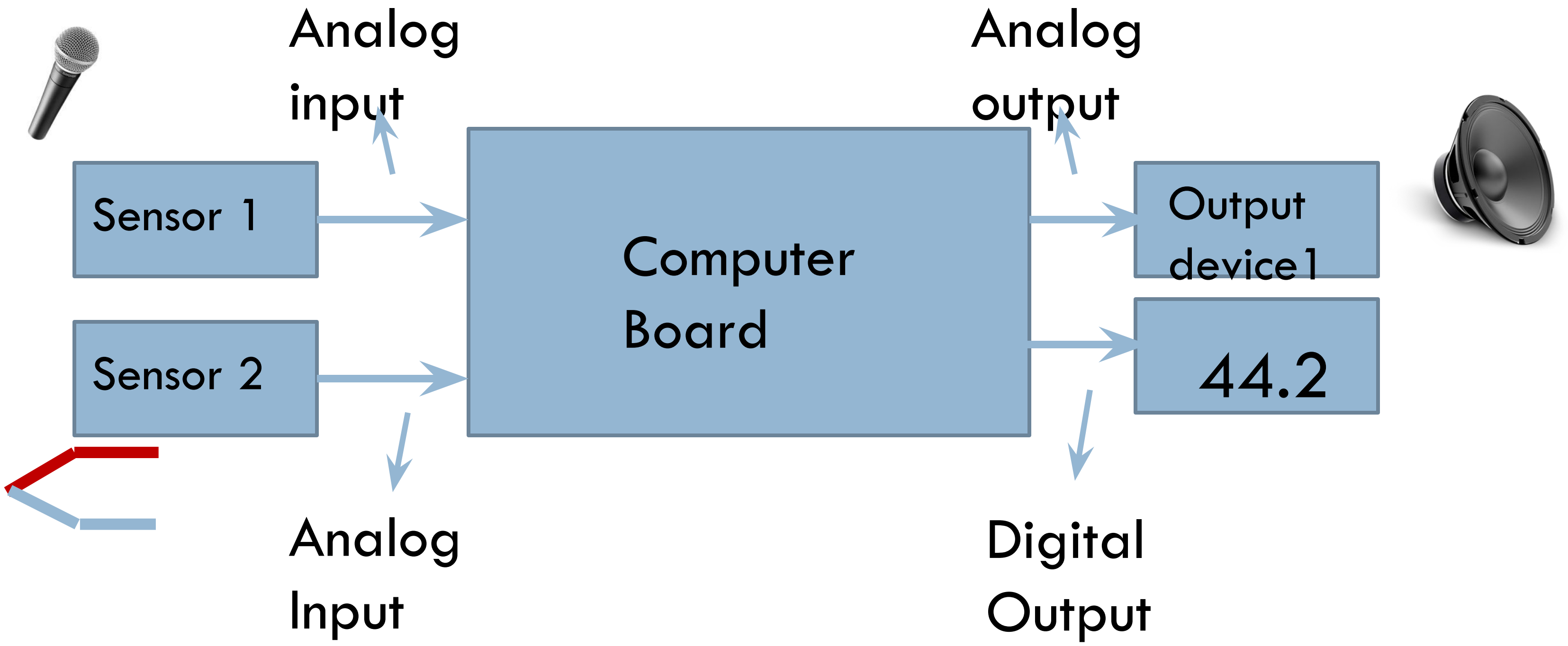
Two variables are involved in measurement , x and y

SENSORS, INSTRUMENTS AND EXPERIMENTATION

03 Computerized measurement and control systems

By Ashok Ranade

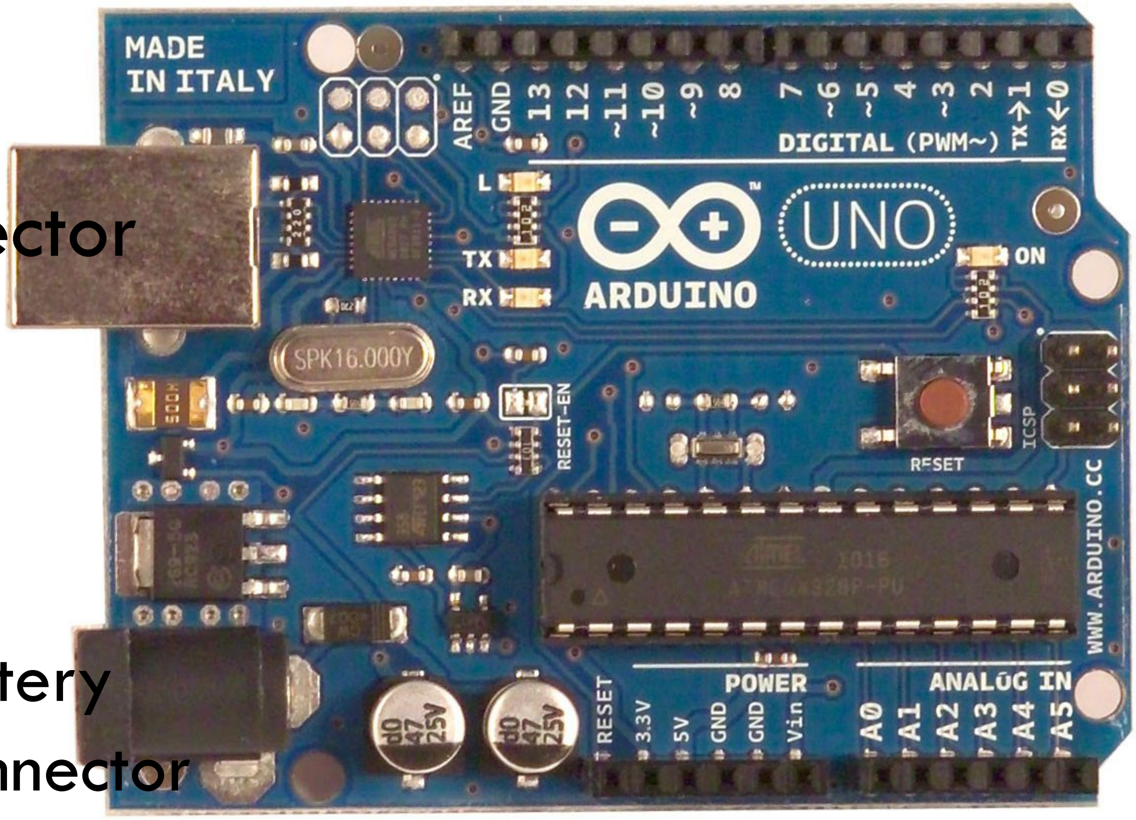
BLOCK DIAGRAM



Development of software

- Software written on a general purpose computer
- Uploaded on the control board
- After this the control board can be used as a stand alone board for some application

USB Connector



Battery Connector

Input/Output Pins

- Analog Input (6 pins)

  Any value between Vmin to Vmax

  For Arduino : 0 to 5 volts
- Digital pins (14)

  Digital Input : 0 or 5 volts

  Digital Output : 0 or 5 volts

  PWM output (6)

  Analog output

Analog to digital converter

- Computer uses numbers in binary form
- A/D converter converts analog input into a multibit binary number
- In Arduino it is 10 bit number
- So 0 volts Corresponds to binary 0000000000

  decimal 0

  5 volts correspond to binary 1111111111

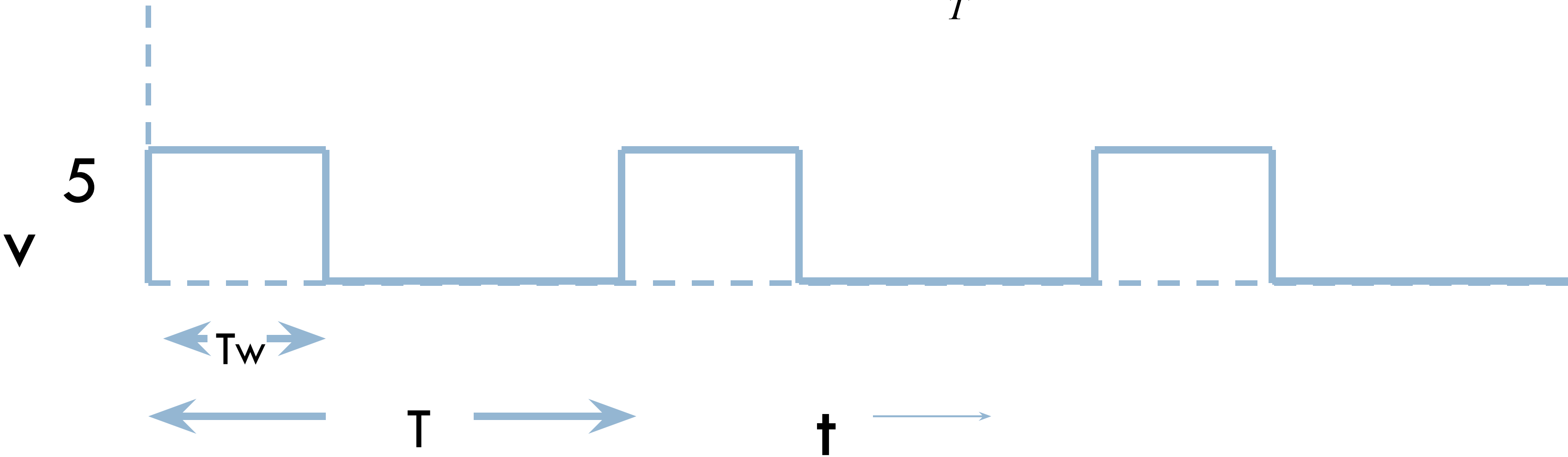
  decimal 1023

Sampling rate of ADC in Arduino

- Sampling rate = 9650 samples/Sec
- Maximum theoretical frequency of the input analog signal is half of this
- Other rates are also possible with advanced programming

PWM waveform

$$Duty\ Cycle = \frac{T_w}{T} \times 100 \quad \%$$



$$Average\ Value = \frac{5 \times T_w}{T}$$

$$Frequency = \frac{1}{T} = 480 \ \ Hz.$$

$$Other\ values\ are\ also\ possible$$

Control of duty cycle

- PWM : Duty cycle

  0% for 00000000 (Decimal 0)

  100 % for 11111111 (Decimal 255)

Program structure

Declarations

```
void setup()
{
  statements;
}

void loop()
{
  statements;
}
```

Program 1(Blinking LED)

Write a program to blink the LED. Turn it on for 1 second and turn it off for 1 second.

Program 1

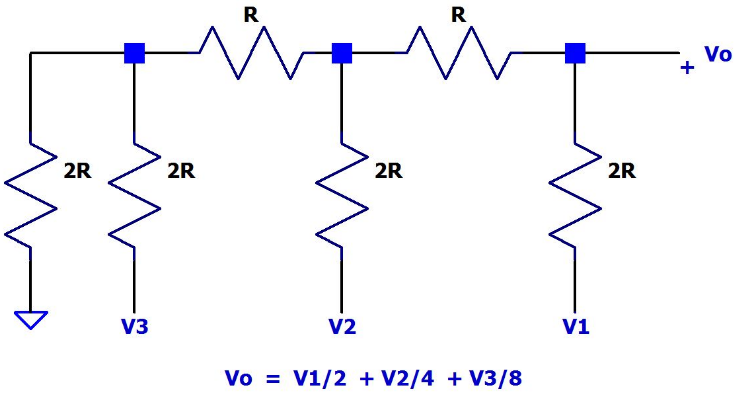
```
int ledPin = 13;                // LED on digital pin 13

void setup()                    // run once
{
  pinMode(ledPin, OUTPUT);      // sets pin 13 as output
}

void loop()                     // run over and over again
{
  digitalWrite(ledPin, HIGH);   // turns the LED on
  delay(1000);                  // pauses for 1 second
  digitalWrite(ledPin, LOW);    // turns the LED off
  delay(1000);                  // pauses for 1 second
}
```

Tinkercad Demo

Class Exercise 3.1
3 Bit D to A converter

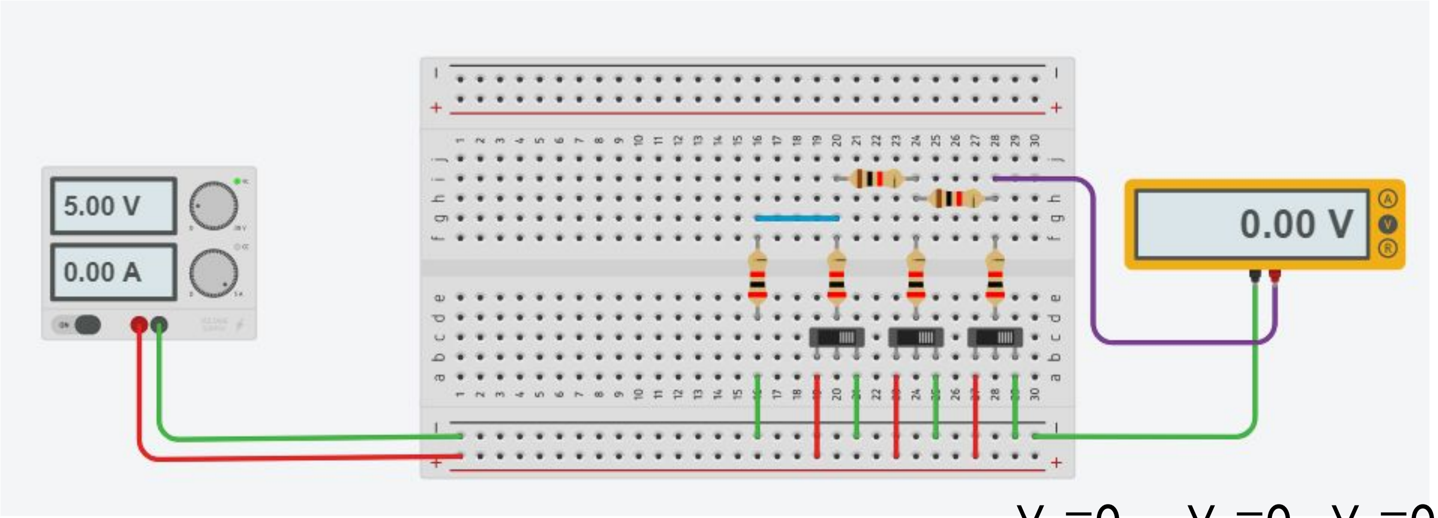


Build in Tinkercad and test. Chose R = 1Kohms (Other values are also possible). Use three slide switches to give digital inputs. Use a multimeter to

V1	V2	V3	Vo
0	0	0	0
0	0	V	V/8
0	V	0	V/4
0	V	V	3V/8
V	0	0	V/2
V	0	V	5V/8
V	V	0	6V/8
V	V	V	7V/8

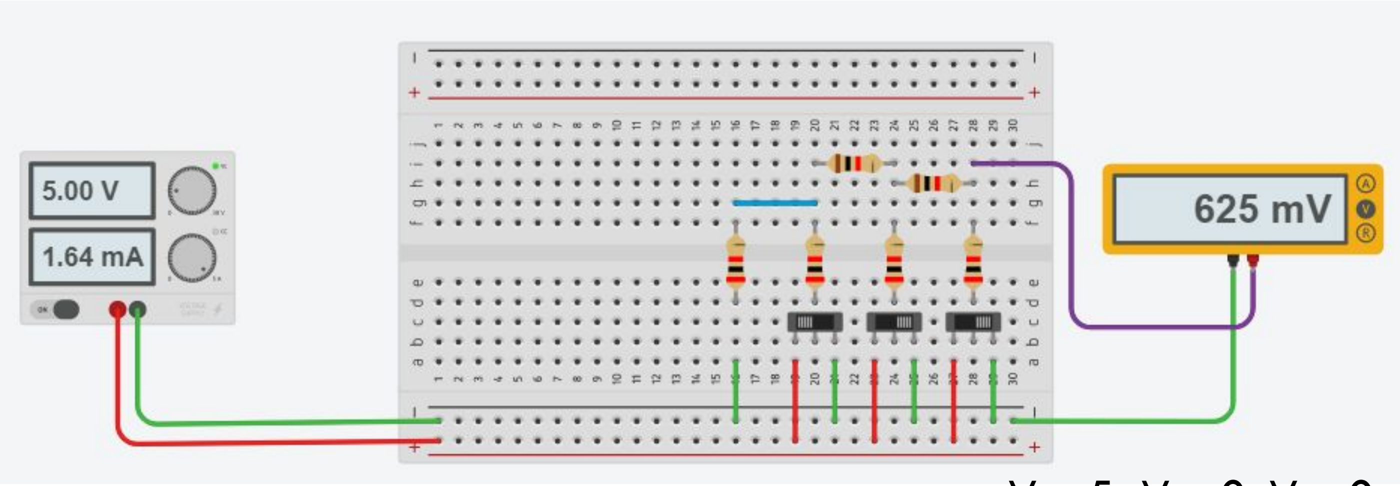
Solution follows

All inputs zero



V_3=0 V_2=0 V_1=0

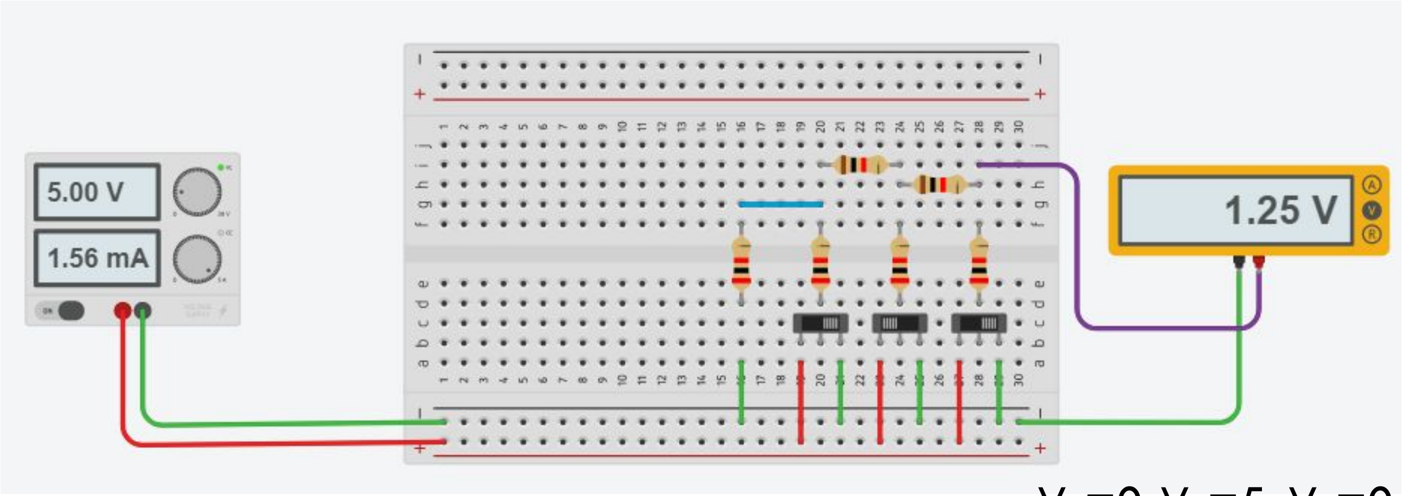
Input 00V



V_3=5 V_2=0 V_1=0

Vo = V/8 = 5/8 = 0.625 volts= 625 mVolts

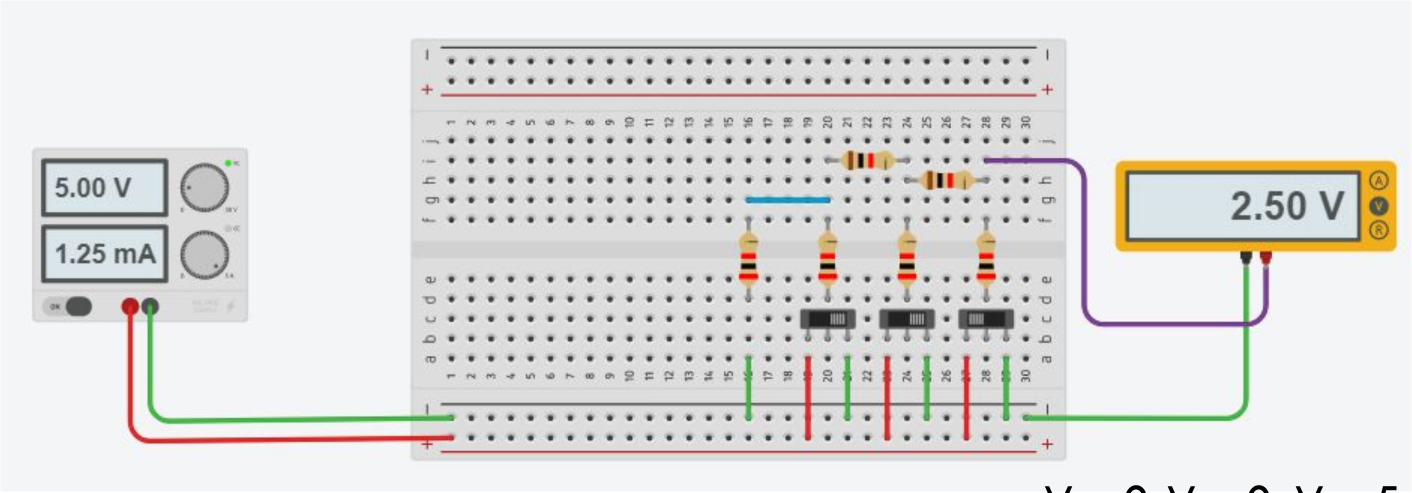
Input 0V0



$V_3=0$ $V_2=5$ $V_1=0$

Vo = V/4 = 5/4 = 1.25 volts

Input V00



$V_3=0$ $V_2=0$ $V_1=5$

Vo = V/2 = 5/2 = 2.5 volts

SENSORS, INSTRUMENTS AND EXPERIMENTATION

04 Arduino exercises

By Ashok Ranade

Digital Read function

- Syntax

  digitalRead(pin)

- Description

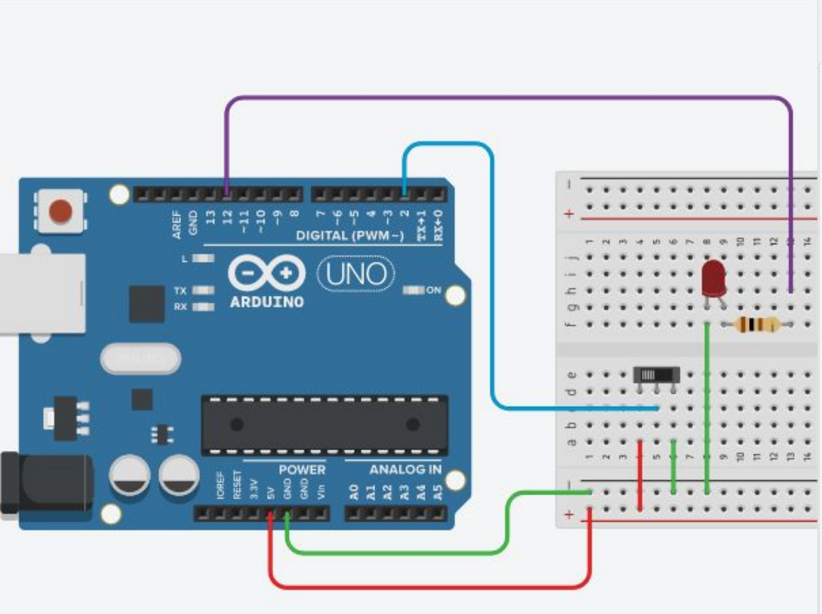
  Reads the value from a specified digital pin, either HIGH or LOW.

- x = digitalRead(Inpin)

Class Exercise 4.1

- Write a program to sense a slide switch. If it is connected to +5 , led connected to pin 12 flashes periodically. Otherwise the led remains off.

Tinkercad simulator



Text

1 (A

```
// C++ code
//
int inPin = 2;
void setup()
{
  pinMode(12, OUTPUT);
  pinMode(inPin, INPUT);
}

void loop()
{
  if (digitalRead(inPin) == HIGH)
  {
  digitalWrite(12, HIGH);
  delay(1000); // Wait for 1000 millisecond(s)
  digitalWrite(12, LOW);
  delay(1000); // Wait for 1000 millisecond(s)
  }
}
```

Analog Read and Serial Communication

- analogRead(potPin)

  x = analogRead(potPin);

  x ranges from 0 to 1023

  This will read the analog voltage from the input pin
- Serial.begin(9600)

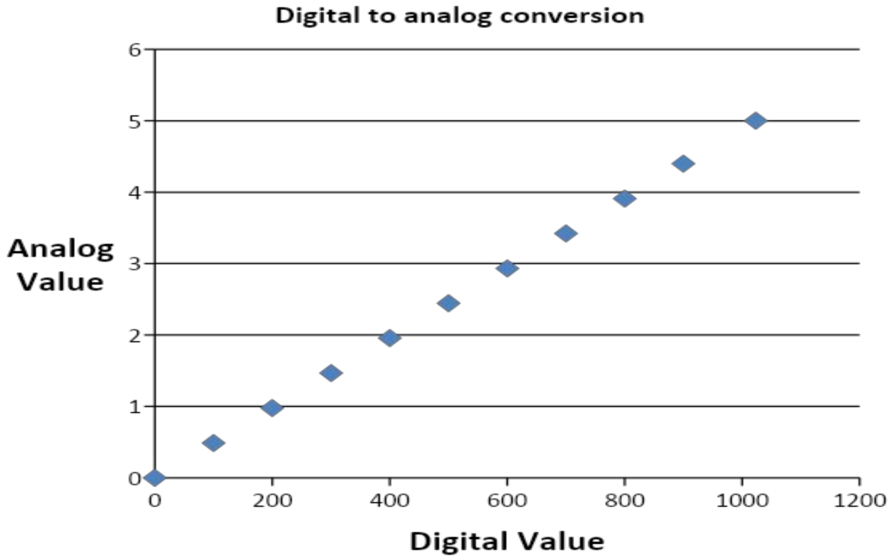
  This will establish serial communication between computer monitor and Arduino. This is in the set up section.
- Serial.println("ADC output");

  Serial.println(x);

Digital to Analog Conversion calculation

$$Analog\ Value = \frac{5}{1023} \times Digital\ value$$

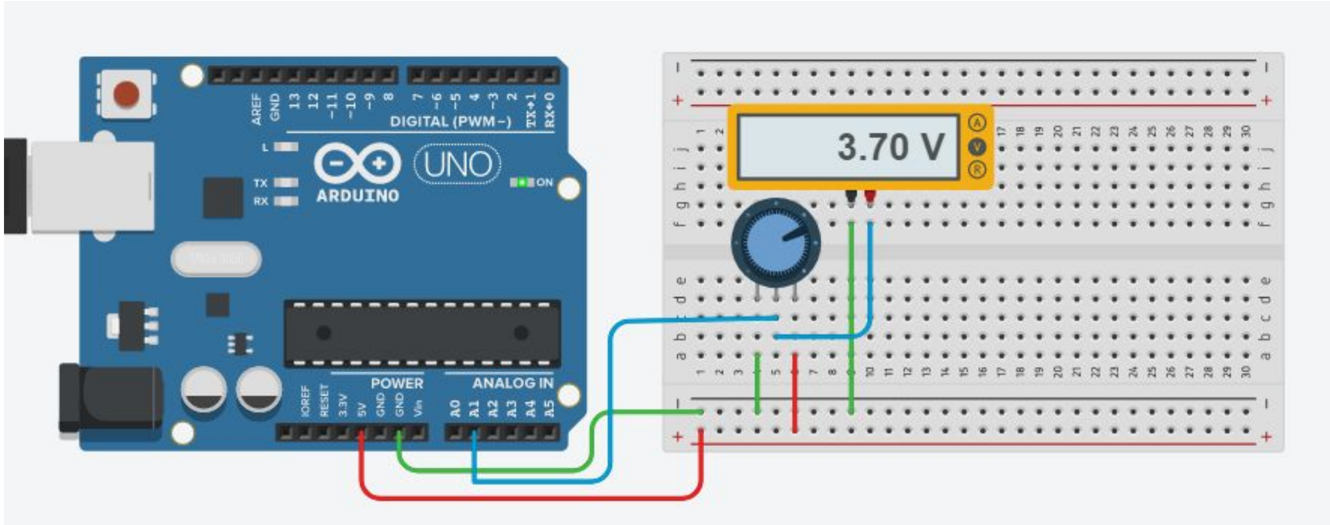
Digital Value	Analog Value
0	0
100	0.488758553
200	0.977517107
300	1.46627566
400	1.955034213
500	2.443792766
600	2.93255132
700	3.421309873
800	3.910068426
900	4.398826979
1023	5



An Exercise 4.2

- A potentiometer is used to generate a voltage varying between 0 and 5 volts.
- The output of the potentiometer is connected to one analog input pin of Arduino. This voltage is measured by a meter.
- Write a program to read the output of the potentiometer. As pot output is varied from 0 to 5 volts, the value read varies from 0 to 1023.
- Next the digital value is converted to analog by using the equation. Both values are displayed on monitor.

Circuit and program



Program

```
int Vi;
float Vo;
void setup()
{
  Serial.begin(9600);
}
```

```
void loop()
{
  Vi =  analogRead(A1);
  Vo = (5.0/1023.0)*Vi;
  Serial.println(“Digital Value");
  Serial.println(Vi);
  Serial.println();
Serial.println(“Analog Value");
    Serial.println(Vo);
  Serial.println();
    delay(2000);
```

analogWrite function

- Certain digital pins can be used as PWM pins
- analogWrite(*pin number*, *value*);

  value is an integer from 0 to 255

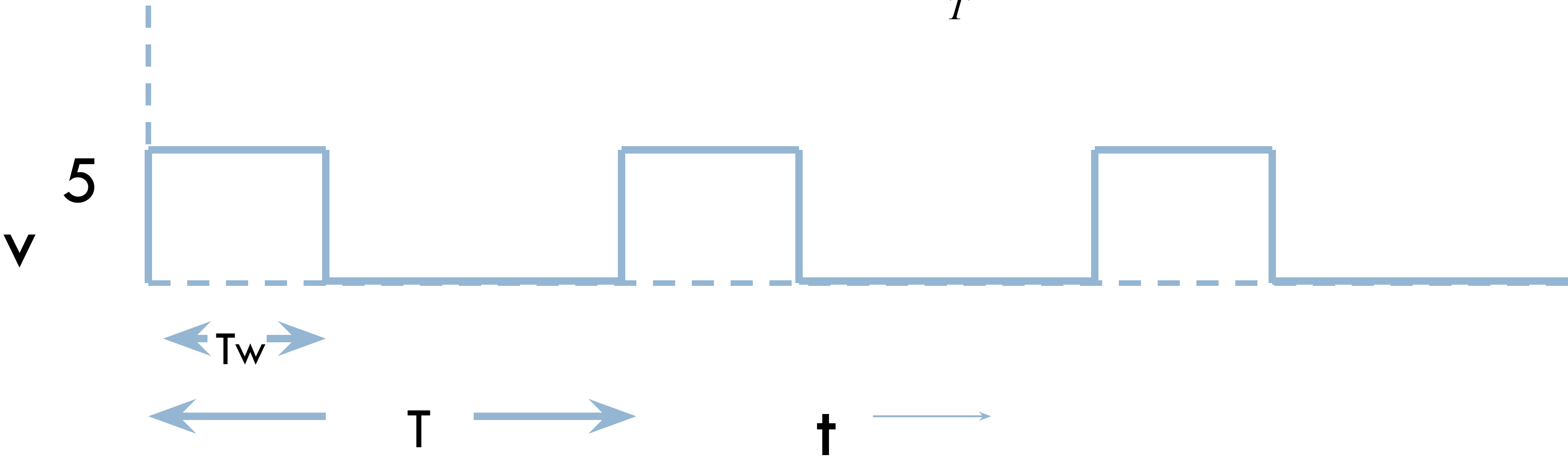
    Decides the duty cycle of the PWM waveform

    value 0 means 0% duty cycle

    255 means 100% duty cycle

PWM waveform

$$Duty\ Cycle = \frac{T_w}{T} \times 100 \quad \%$$



$$Average\ Value = \frac{5 \times T_w}{T}$$

$$Frequency = \frac{1}{T} = 480 \ \ Hz.$$

Other values are also possible

Average value

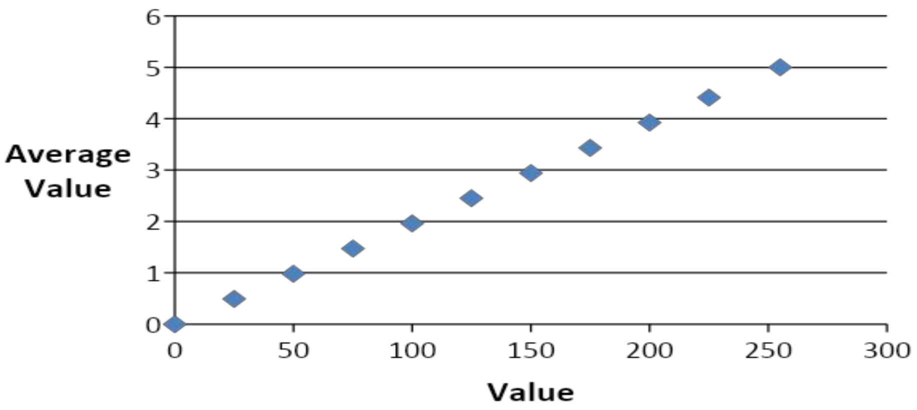
analogWrite(*pin number*, *value*);

$$Average\ value = \frac{5 \times T_w}{T}$$

$$Average\ value = \frac{5 \times value}{255}$$

Value and average value

Value	Average Value
0	0
25	0.490196078
50	0.980392157
75	1.470588235
100	1.960784314
125	2.450980392
150	2.941176471
175	3.431372549
200	3.921568627
225	4.411764706
255	5



Average calculation

analogWrite(*pin number*, *value*);

$$Average\ value = \frac{5}{255} \times value$$

Examples

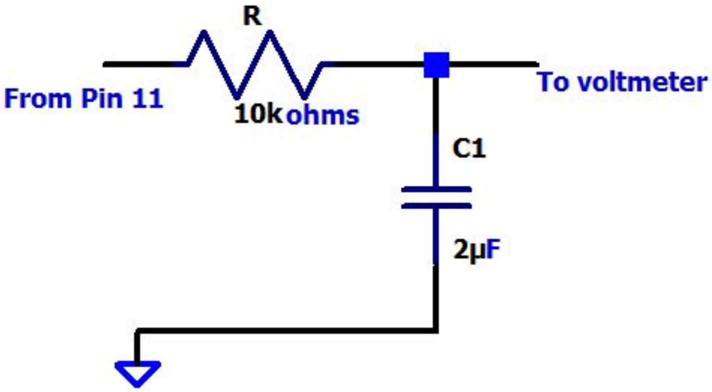
$$Average\ value = \frac{5}{255} \times 31 = 0.6\ volt$$

$$Average\ value = \frac{5}{255} \times 127 = 2.49\ \ volts$$

Class Exercise 4.3

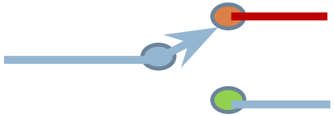
- This exercise will demonstrate how the average value from a PWM output can be extracted by using a low pass first order filter
- Use pin no 11 as output pin. Connect the output of pin no 11 to the R-C low pass filter
- Use pin no 2 as the digital input pin. And use a slide switch which will enable you to connect either +5 or Ground to the input pin no 2.
- Write a program to generate two different average values from pin no 11 for two settings of the slide switch.

Interface circuit



Time constant 20 mS

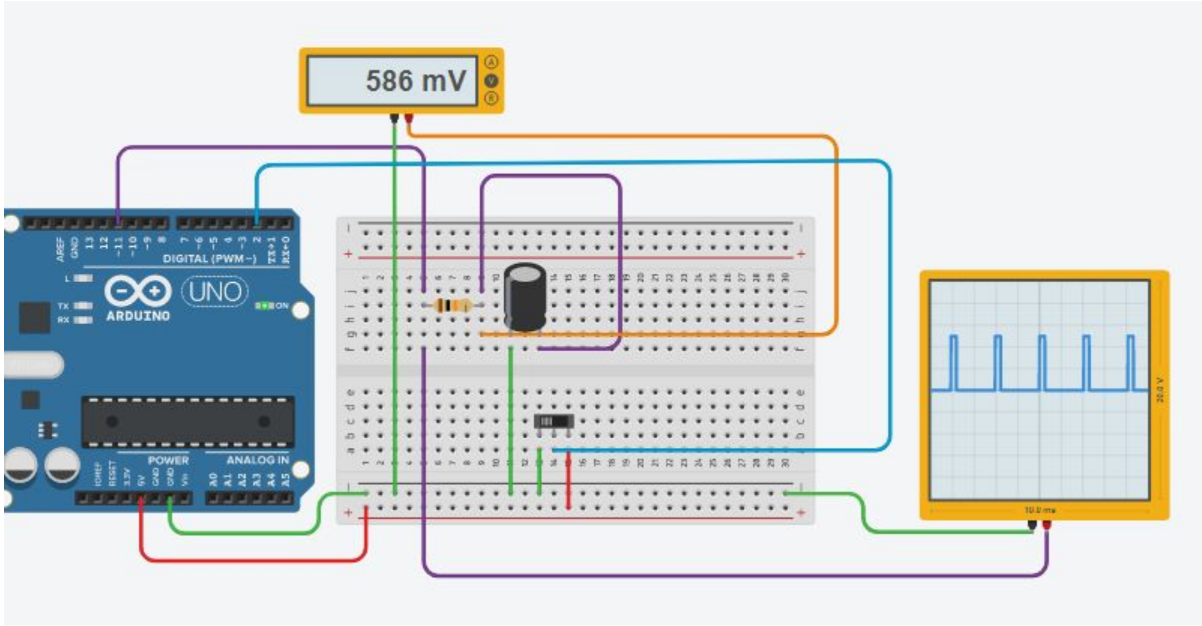
From Digital pin 2



+5 volts

Ground

Connections



Program

```
bool x;
void setup()
{
  pinMode(11, OUTPUT);
}
```

```
void loop()
 {
 x = digitalRead(2);
 if  (x == 1)
 {
   analogWrite(11,127);
 }
 else
 {
   analogWrite(11, 31);
 }
```

CONTROL SYSTEMS

Ashok Ranade

Control system

- What is a control system ?
- It is a system which controls a physical quantity such as temperature or position
- An example

  Toaster

  Function is to bring the bread slices to a desired temperature so that they are nice golden brown.

  Next : Parts of a control system

  Set the timer and put the supply on

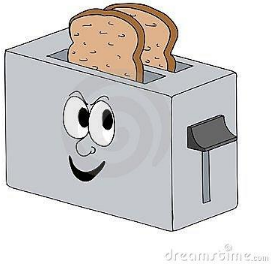
Parts of a control system

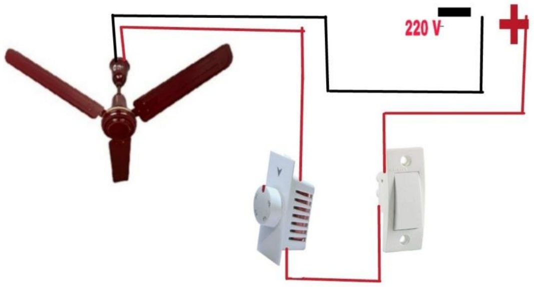
- Control element

  Timer
- Plant

  Heating coil
- Control element

  Regulator
- Plant





Next : Open loop control

Open loop control systems

- The control action is independent of the controlled variable
- Timer setting is assumed to be correct

  But it may have to be different in winter compared to summer
- Also plant … stics mi… e due to ageing

Next : Closed Loop control system

Closed loop control system

- Manual control

  User adjusts a small time on timer

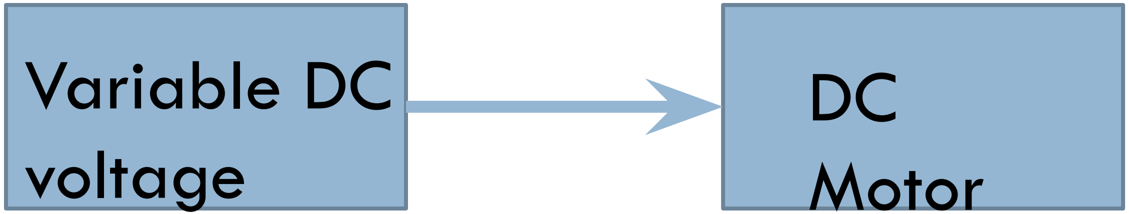
  The user inspects the slices at the end of time

  If not done he/she sets the time again and repeats

  until done
- Control action now depends on the output variable

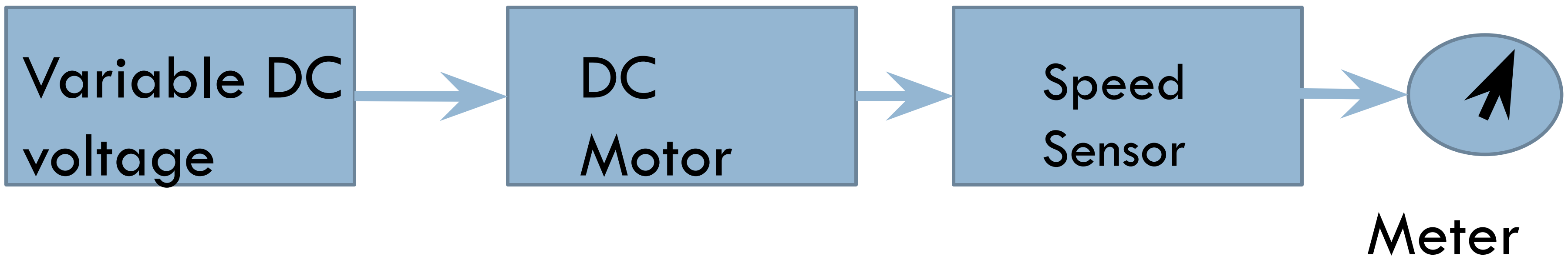
  Next : Speed control of DC motor
- Feedback is used in automatic control systems

Speed control of a DC Motor

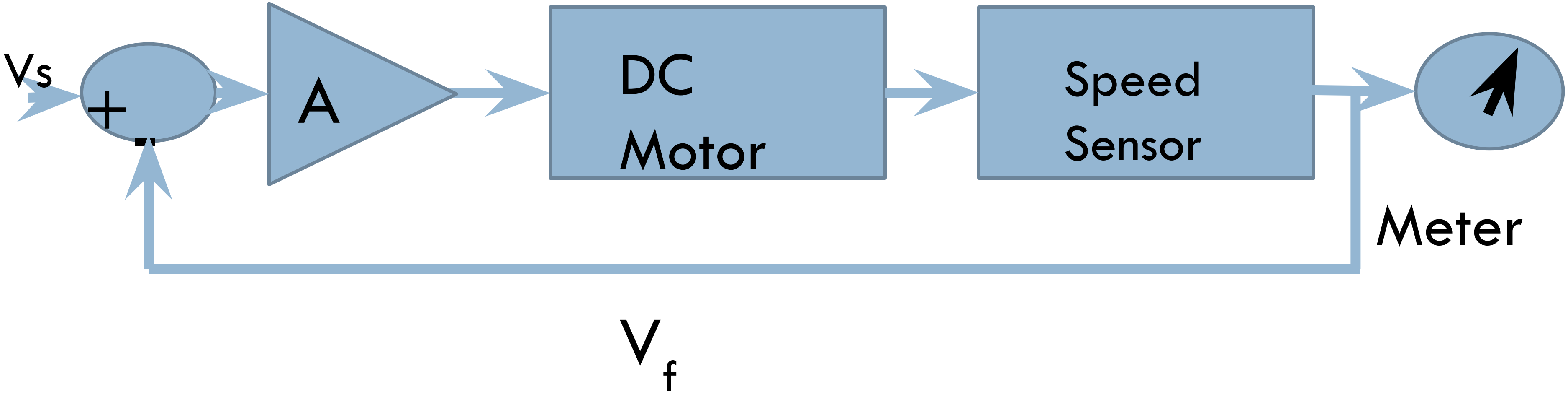


Speed is proportional to DC voltage.
Input DC source can be calibrated in terms of speed.
The knob is set to the desired speed
Speed might change due to change in the load or
ageing

Manual Control

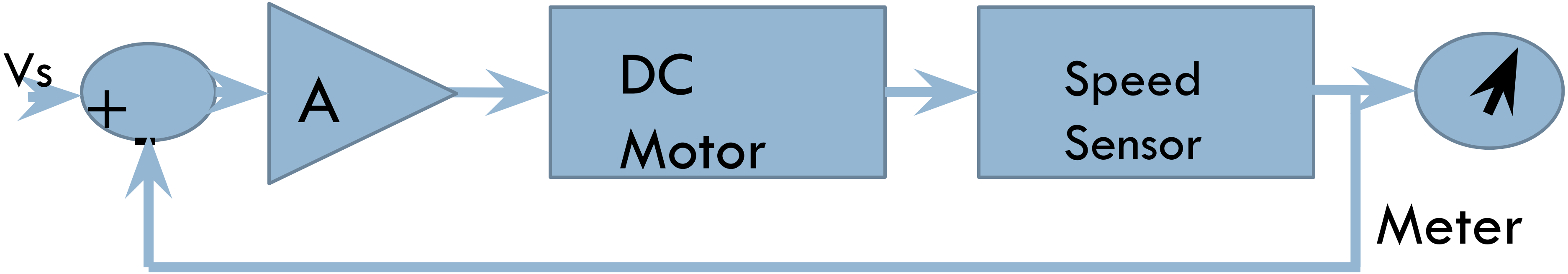


Automatic control



Sensor Characteristics	
Speed	Vf
1000 rpm	1 volt
2000 rpm	2 volt

Steady state calculation



V_f

$$\left(V_s - V_f\right) A K_m K_s = V_f$$

$$V_f = \frac{V_s A K_m K_s}{1 + A K_m K_s}$$

$K_s = V_f / N$

Exercise 5.1

- A dc motor has linear characteristics between input voltage and speed. Two points on this characteristics are

  N = 600 rpm when V = 15 volts

  N = 800 rpm when V = 20 volts

  (1) Find the equation between speed and the voltage.

  (2) when loaded the proportionality constant between speed and voltage becomes 1/3 of the no load value. Find the new speed at V = 15 volts and find the % change in the speed compared to no load

Solution

(1)

$$N = K_m V + C$$

$$600 = K_m \times 15 + C$$

$$800 = K_m \times 20 + C$$

$$800 - 600 = K_m (20 - 15)$$

$$K_m = \frac{200}{5} = 40$$

$$C = 0$$

$$N = 40 \times V$$

(2)

When loaded

$$K_m = \frac{40}{3}$$

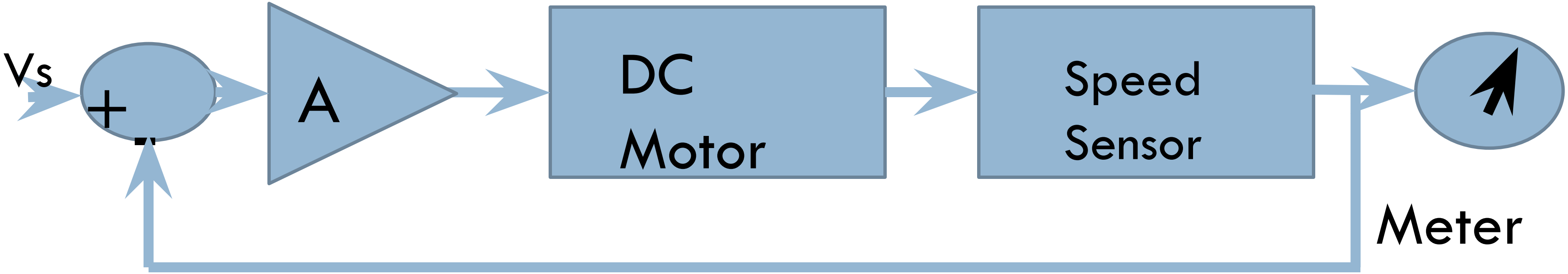
$$N = \frac{40}{3} \times V$$

$$N = \frac{40}{3} \times 15 = 200\ rpm$$

$$\%change\ in\ speed = \frac{200 - 600}{600} \times 100$$

$$= -66.66\%$$

Exercise 5.2



$$V_f = \frac{V_s A K_m K_s}{1 + A K_m K_s}$$

V_f

Consider the above closed loop system. Km = 40 and Ks = 1/160. Find the speed of the motor when

(1) Vs = 5 volts and A = 10

(2) the motor is loaded and Km drops to 40/3

Also find % change in speed

Solution to Exercise 5.2

$$(1)\ V_f = \frac{V_s A K_m K_s}{1 + A K_m K_s} = \frac{5 \times 10 \times 40 \times 1/160}{1 + 10 \times 40 \times 1/160} = 3.571429$$

$$N = \frac{V_f}{K_s} = \frac{3.571429}{1/160} = 571.4286\ rpm$$

$$(2)\ V_f = \frac{V_s A K_m K_s}{1 + A K_m K_s} = \frac{5 \times 10 \times (40/3) \times 1/160}{1 + 10 \times (40/3) \times 1/160} = 2.272727$$

$$N = \frac{V_f}{K_s} = \frac{2.272727}{1/160} = 363.6364\ rpm$$

$\%change\ in\ speed$

$$= \frac{363.6364 - 571.4286}{571.4286} \times 100 = \text{-}36.3636\%$$

Exercise 5.3

- Repeat Exercise 5.2 but with $A = 100$.

Answers

With A =100	
On No load	
Vf	4.807692
N	769.2308
With load	
Vf	4.464286
N	714.2857
% Change	-7.14286

Specification of control systems

- Accuracy of the output in steady state

  Suppose desired temperature is 50 degrees

  In a certain system the output could be within 1 %
- Speed of response
- How fast the desired output is achieved ?

  One system : 5 minutes

  Another system : 10 minutes
- Feedback will help improve both

Next : An example of modelling

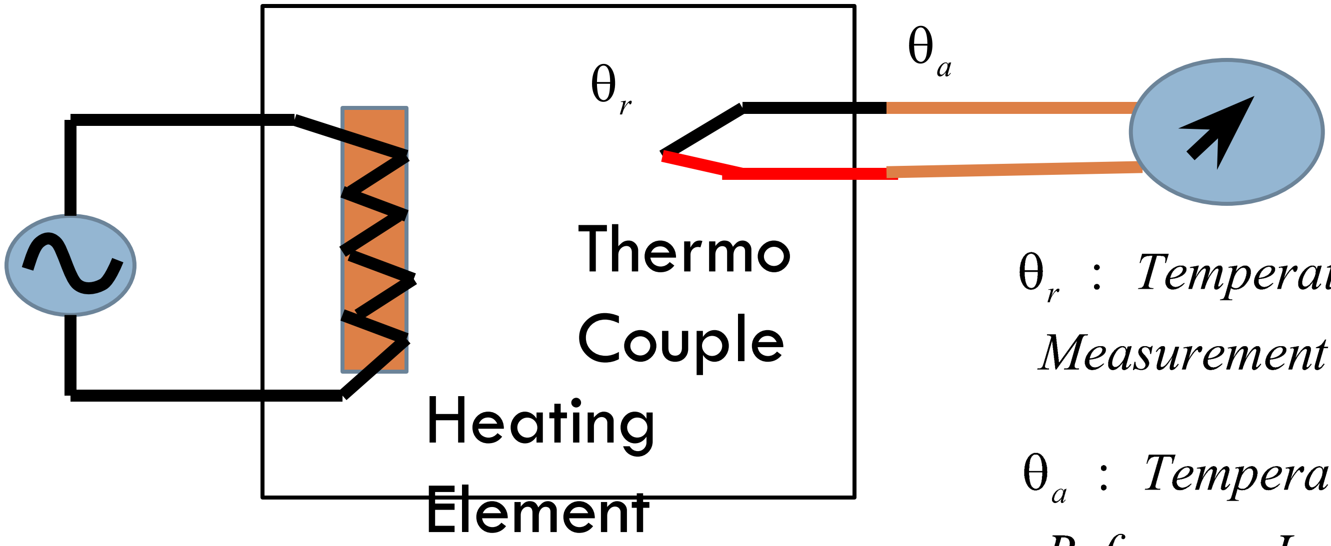
Steps in analysis of control systems

- From the block diagram set up the differential equation for the system
- Solve the differential equation
- Find the steady state error
- Find the speed of response
- The differential equation can be

  First order

  Second order or higher order

Block diagram of an oven



θ_r : *Temperature at Measurement Junction*

θ_a : *Temperature at Reference Junction (Ambient temperature)*

Next : Thermal resistance

Thermal resistance and capacitance

- When the power is supplied the temperature in the oven increases
- The rate of increase depends on thermal resistance and thermal capacitance
- Thermal resistance

This impedes the heat flow(Energy/unit time) from oven to outside

$$H_{out} = \frac{\theta_r - \theta_a}{R}$$

Depends on the materials and geometry

Thermal capacitance

- Consider an oven with no leakage

  The temperature in the oven will start with ambient temperature and increase as the heat energy increases with time. Thus the heat energy is being stored.

- Larger the volume , smaller will be the rate of increase of temperature

$$\theta_r = \frac{1}{C}\int Q\,dt + \theta_a$$

Q is heat flow supplied and stored

C is the thermal capacitance

$$Q = C\frac{d(\theta_r - \theta a)}{dt}$$

C is in watt-sec/degree

Mathematical model of the oven

Heat in = Heat out + Heat Stored

$$q = \frac{\theta_r - \theta_a}{R} + C\frac{d(\theta_r - \theta_a)}{dt}$$

$$q = \frac{\theta}{R} + C\frac{d\theta}{dt}$$

$$qR = \theta + RC\frac{d\theta}{dt}$$

$$\theta = \theta_r - \theta_a$$

$$\theta = qR\left(1 - e^{-\frac{t}{RC}}\right)$$

$$Dimensions\ \ of\ \ R \times C$$

$$\frac{Degrees}{Watt} \times \frac{Watt \times Seconds}{Degrees} = Seconds$$

Next : An example of steady state calculations

Steady state calculations

- In steady state , the temperature in the oven becomes constant and the equation is

$$q = \frac{\theta_r - \theta_a}{R}$$

- A sample calculation

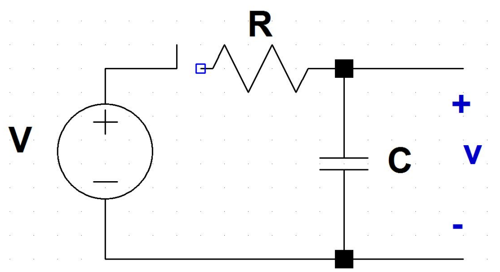
  Suppose we want $\theta_r = 60^0$ and $\theta_a = 20^0$.

  Also R = 0.05 Degrees/ Watt

  Coil wattage q = 40 /0.05 = 800 watts

Electrical Equivalent circuit

- Temperature :   Voltage
- Thermal resistance : Electrical resistance
- Thermal capacitance : Electrical capacitance



Applying Kirchoff's current law

at the output node

$$\frac{V - v}{R} = C\frac{dv}{dt}$$

$$V = v + RC\frac{dv}{dt}$$

$$qR = \theta + RC\frac{d\theta}{dt}$$

$$\theta = qR\left(1 - e^{-\frac{t}{RC}}\right)$$

$$v = V\left(1 - e^{-\frac{t}{RC}}\right)$$

Set point

$$\theta = qR\left(1 - e^{-\frac{t}{RC}}\right)$$

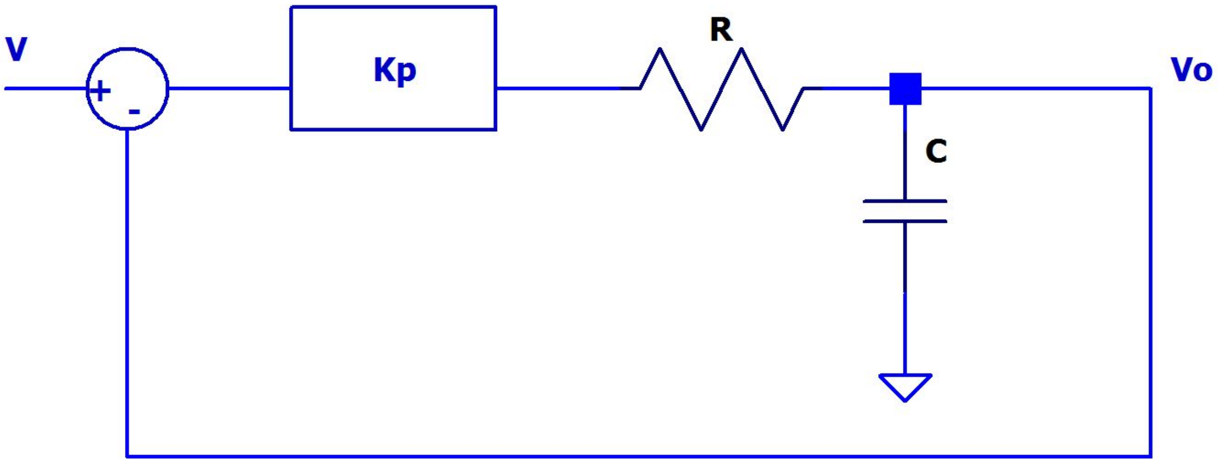
Note that θ reaches qR in steady state. This the desired temperature. Hence qR is called the set point

$$v = V\left(1 - e^{-\frac{t}{RC}}\right)$$

In the electrical Analog V is the set point

Next : Closed loop system

Closed Loop System



$$\frac{(V - V_o)K_p - V_o}{R} = C\frac{dV_o}{dt}$$

Effect of proportional control

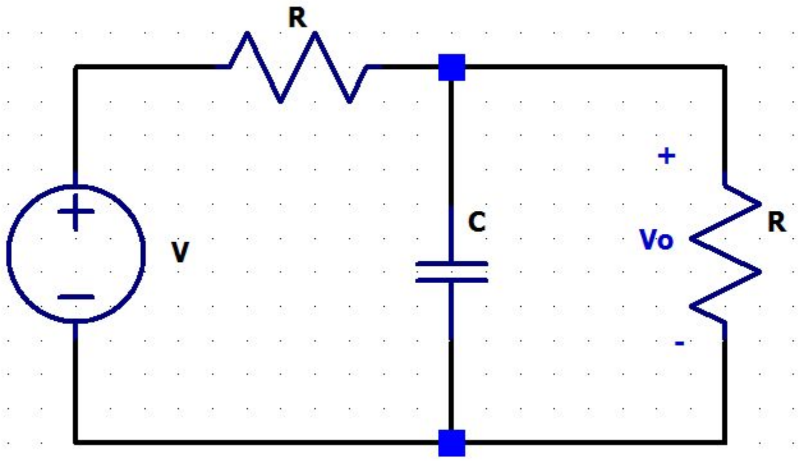
$$\frac{(V - V_o)K_p - V_o}{R} = C\frac{dV_o}{dt}$$

$$\frac{VK_p}{K_p + 1} = V_o + \frac{RC}{K_p + 1}\frac{dV_o}{dt}$$

Time constant is reduced. Faster Response

Steady state error

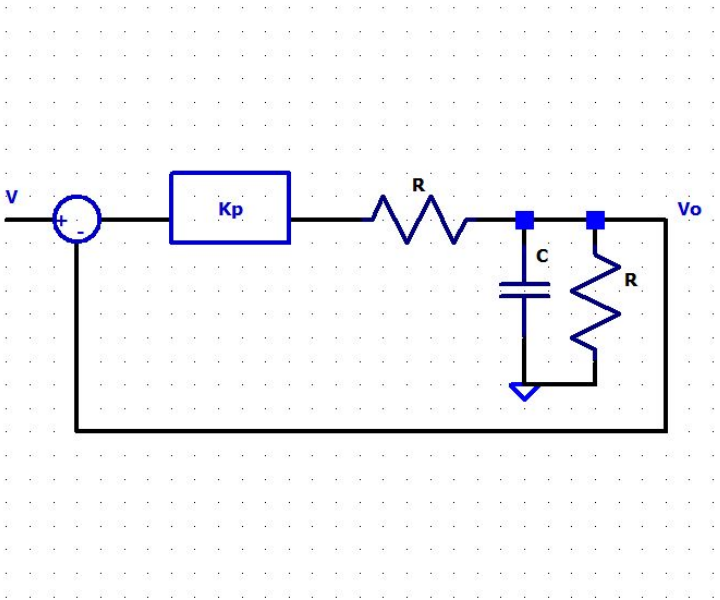
Loading effect in Open loop System



$$V_o = \frac{V}{2}\left(1 - e^{\frac{-t}{RC/2}}\right)$$

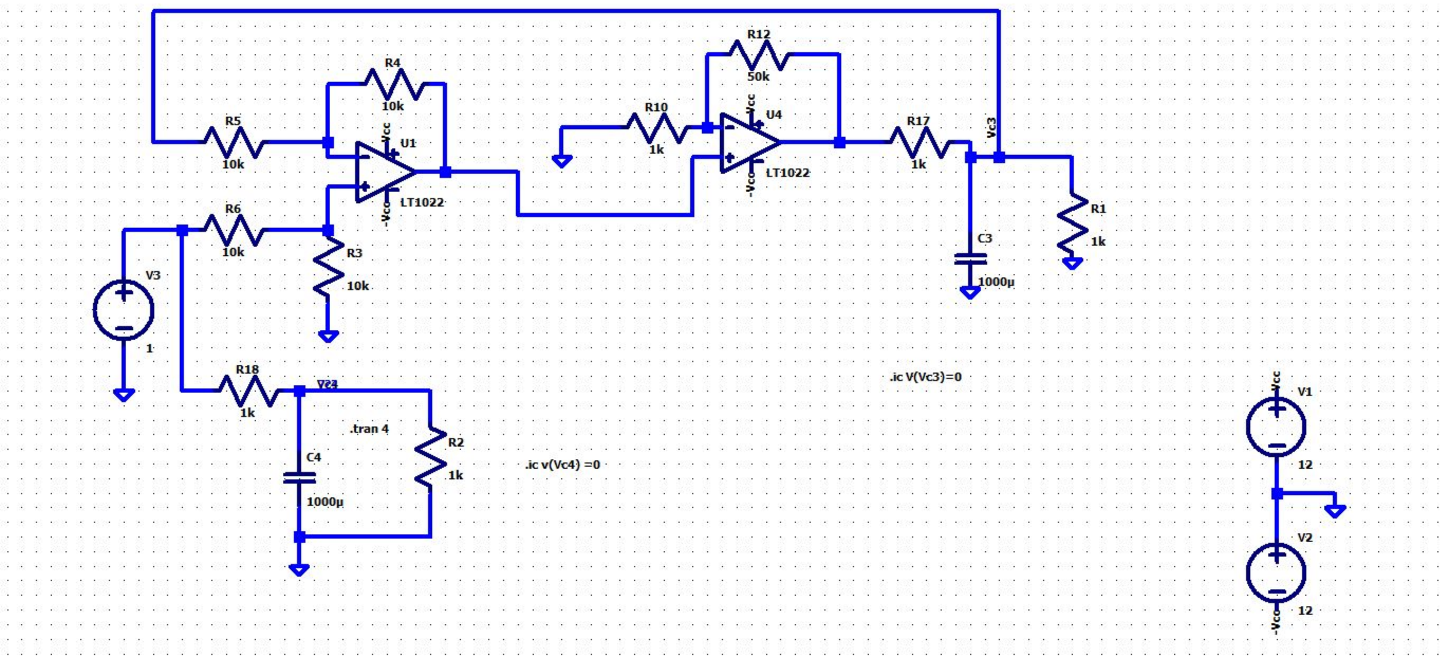
Steady state voltage is reduced to half the value.

Loaded system with feedback

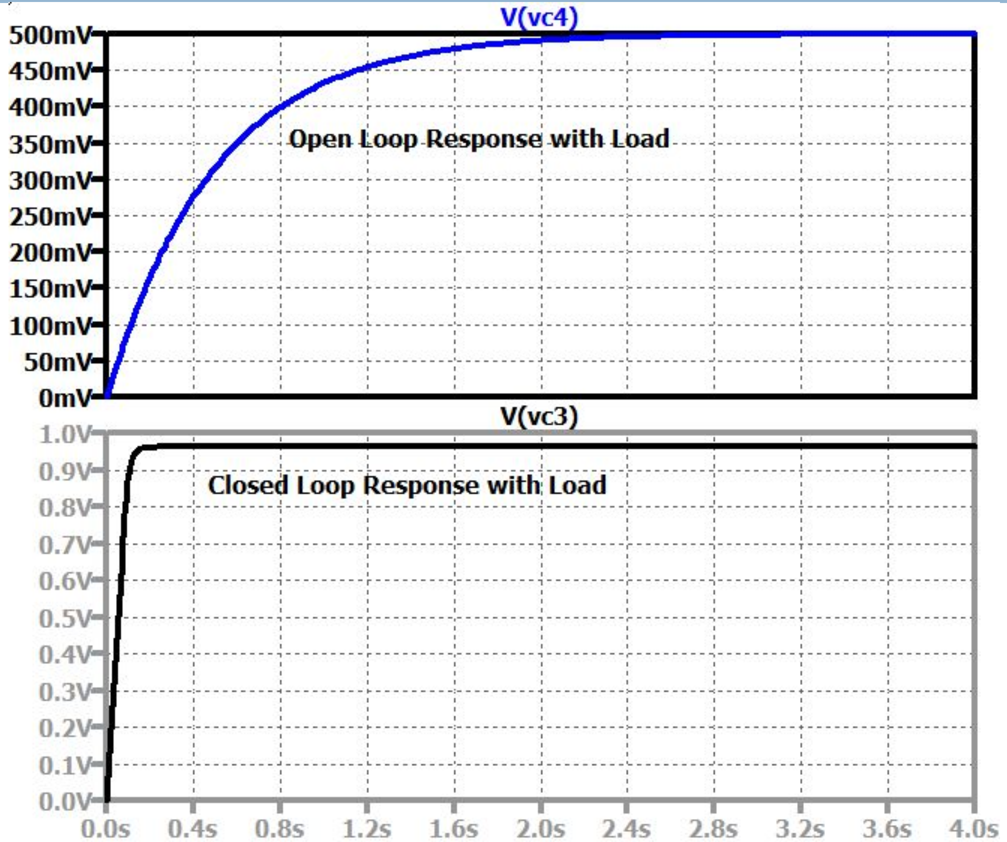


$$\frac{VK_p}{2+K_p} = V_o + \frac{RC}{2+K_p}\frac{dV_o}{dt}$$

LTspice simulation



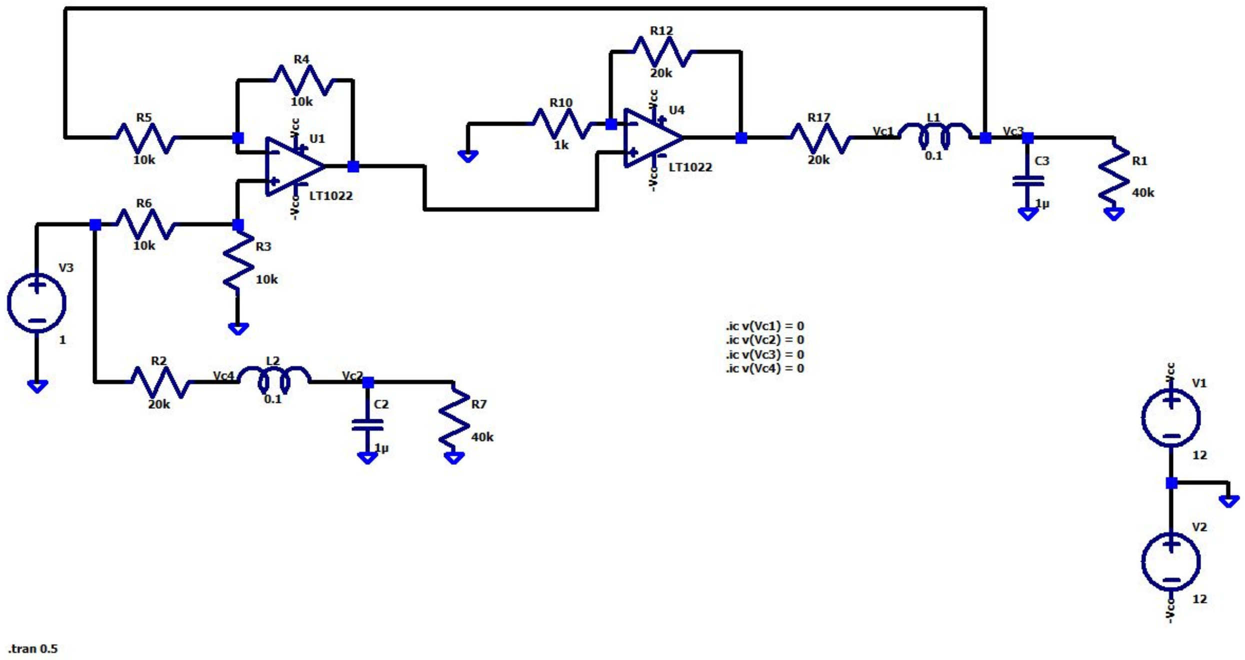
Step response



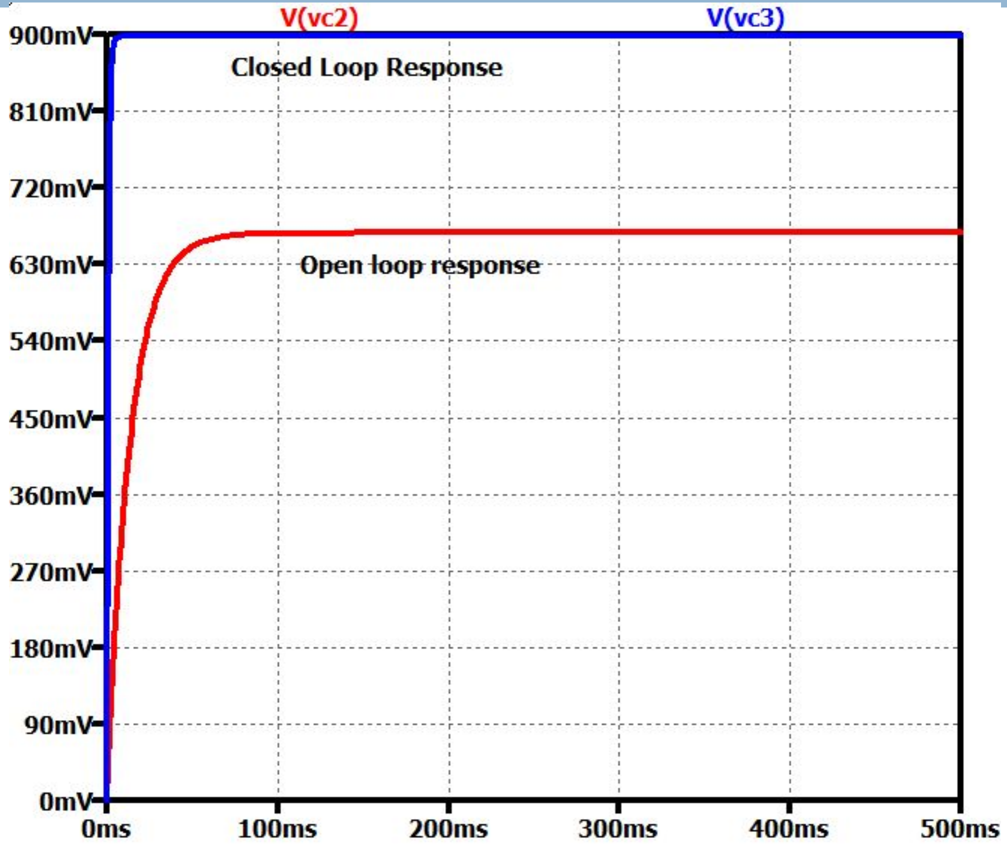
Exercise 5.4

- In the Ltspice simulation shown the load is the first order low pass filter consisting of 1kohms resistor, 1000 μF capacitor and the load of 1 kohms resistor
- Replace this load by a second order low pass filter consisting of 20 kohms resistor, 0.1 H inductor and 1μF capacitor. Use a load of 40 kohms resistor and plot the transient response for open loop and closed loop circuit and compare.

Solution to Exercise 5.4



Open loop and closed loop outputs



SENSORS, INSTRUMENTS AND EXPERIMENTATION

07 Concepts of Stress and Strain

By Ashok Ranade

Hook's Law

- When you apply a Force to an object, it moves if free to move
- If it is not free to move, it gets deformed.
- Hook's law (Applies when deformation is small)

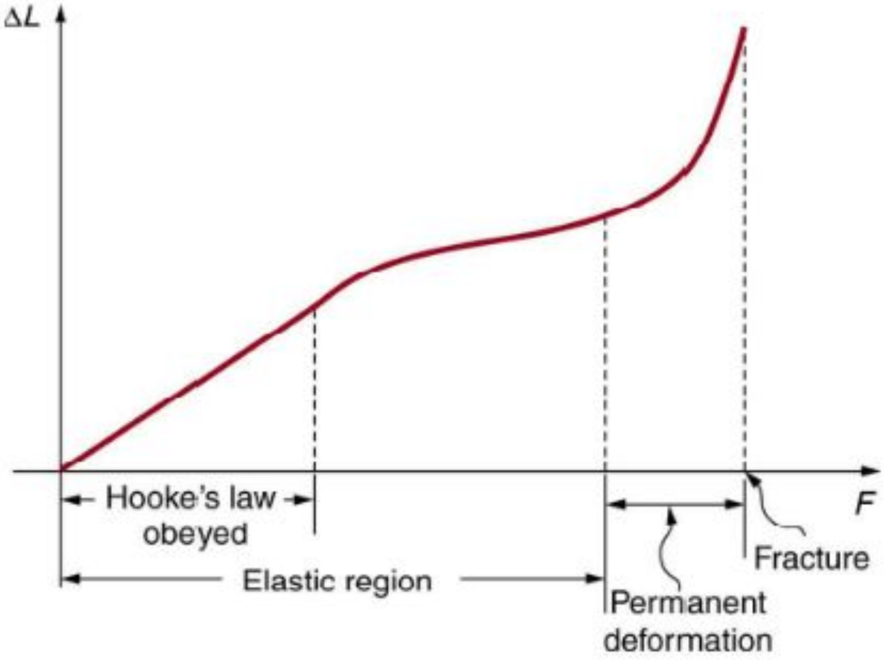
$$F = k\Delta L$$

F is the force applied

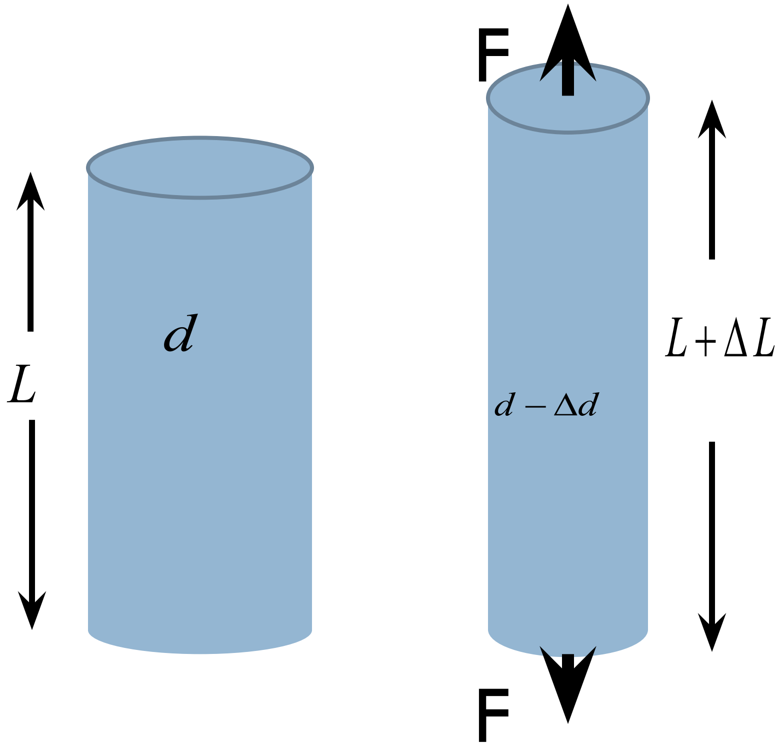
k constant depending on shape and composition of the object and the direction of the force

ΔL The amount of deformation

Deformation vs Force



Axial and transverse strain
Tensile force



Axial strain

$$\varepsilon_l = \frac{\Delta L}{L}$$

Transverse strain

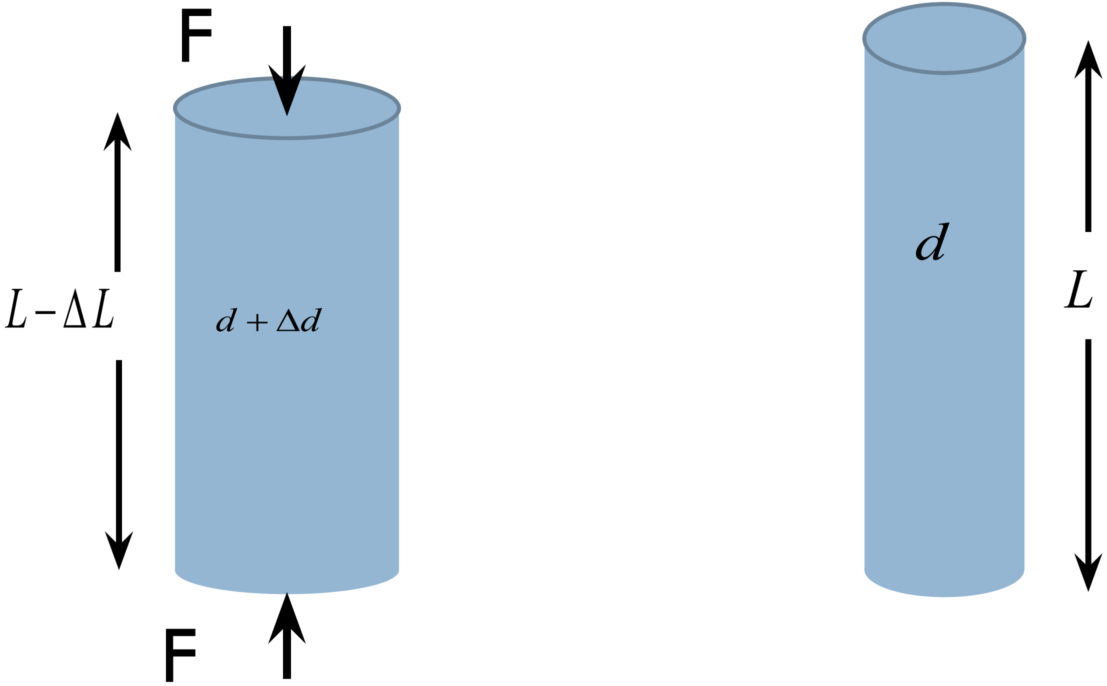
$$\varepsilon_t = \frac{\Delta d}{d}$$

Poisson's Ratio

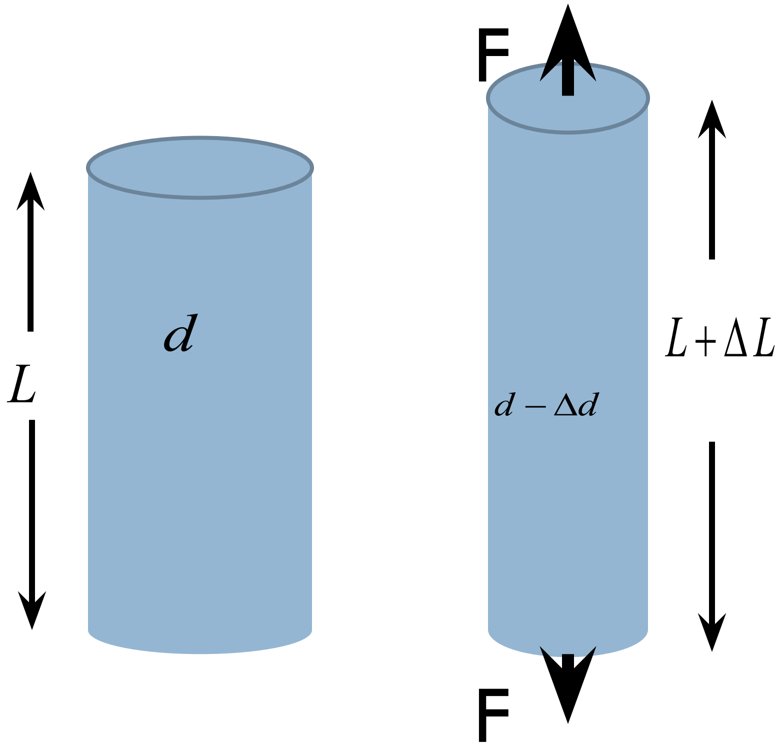
$$\mu = \frac{\varepsilon_t}{\varepsilon_l}$$

Typically Lies between 0 to 0.5

Compressive Force



Young's modulus



$$\Delta L = \frac{1}{Y}\frac{F}{A}L$$

A : Cross sectional area

Y : Young's Modulus

$$\frac{F}{A} = Y\frac{\Delta L}{L}$$

Stress = Y x Strain

$$F = YA\frac{\Delta L}{L} \qquad F = k \times Strain$$

Young's modulus for various materials

Material	Young's modulus (tension–compression) $Y(10^9 N/m^2)$	Shear modulus S $(10^9 N/m^2)$	Bulk modulus B $(10^9 N/m^2)$
Aluminum	70	25	75
Bone – tension	16	80	8
Bone – compression	9		
Brass	90	35	75
Brick	15		
Concrete	20		
Glass	70	20	30
Granite	45	20	45
Hair (human)	10		
Hardwood	15	10	
Iron, cast	100	40	90
Lead	16	5	50

Exercise 7.1

A sculpture weighing 10,000 N rests on a horizontal surface at the top of a 6.0-m-tall vertical pillar. The pillar’s cross-sectional area is 0.20 m^2 and it is made of granite with a mass density of 2700 kg/m^3. Find the compressive stress at the cross-section located 3.0 m below the top of the pillar and the value of the compressive strain of the top

Solution

The volume of the pillar segment with height h = 3.0 m and cross-sectional area A = 0.20 m^2 is

$V = Ah = 0.6\ m^3$

With the density of granite = $2.7 \times 10^3 kg/m^3$, the mass of the pillar segment is

$m = \rho V = 1.6x10^3\ Kg$

The weight of the pillar segment is

$w = mg = 1.568x10^4\ N$

Solution continued

The weight of the sculpture is $w = 1.0 \times 10^4$ N

So the normal force acting

$wp+ws = 2.568 \times 10^4$ N

Stress = F/A = $2.568 \times 10^4/0.2$ = = 128.4 kPa

Y for granite= 4.5×10^7 kPa

Strain = Stress/Y= 2.85×10^{-6}

Note that the stress will be maximum at base

Exercise 7.2

- A 2.0-m-long steel rod has a cross-sectional area of $0.30cm^2$ The rod is a part of a vertical support that holds a heavy 550-kg platform that hangs attached to the rod’s lower end. Ignoring the weight of the rod, what is the tensile stress in the rod and the elongation of the rod under the stress?

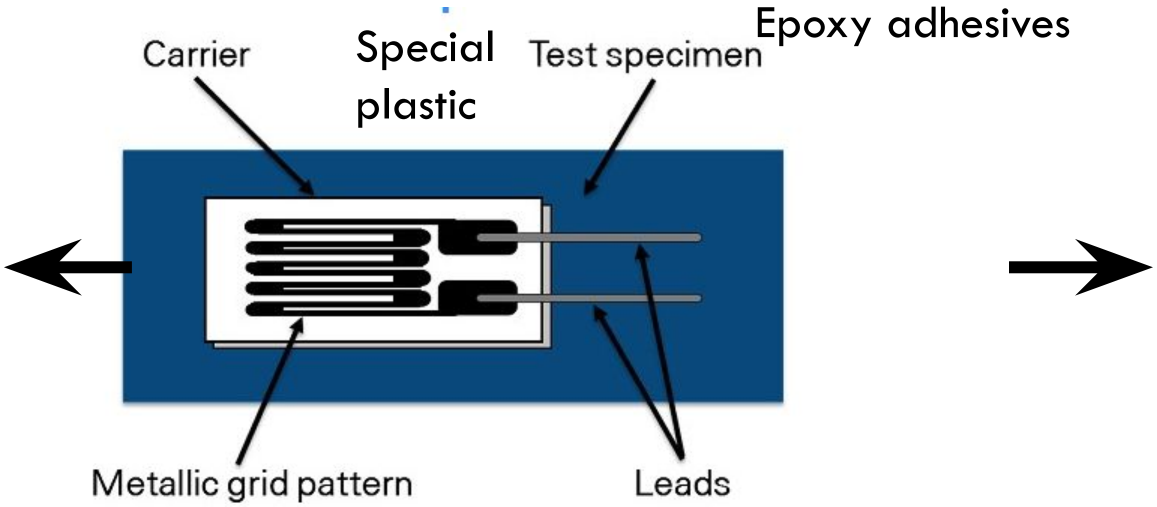
Answers

- Procedure

  Calculate F/A
- Young's modulus for steel is Y $=2.0\times10^{11}$ Pa.
- Calculate ΔL

$$\Delta L = \frac{F}{A}\times\frac{L}{Y} = 1.8mm$$

Strain gauge



Tension will increase the resistance

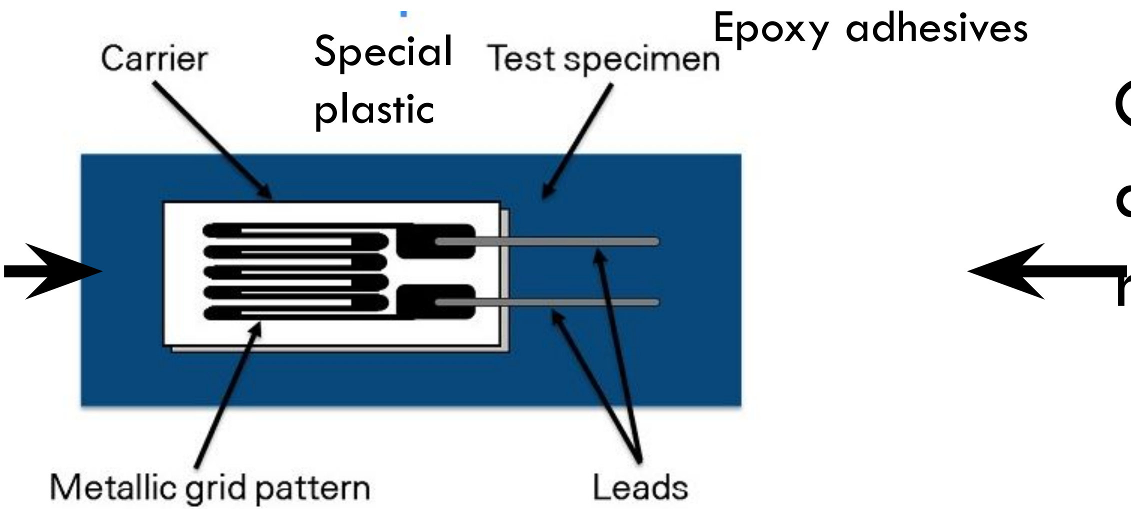
$$R = \frac{\rho l}{A}$$

$$strain : \varepsilon = \frac{\Delta L}{L}$$

$$GF = \frac{\Delta R / R}{\Delta L / L}$$

$$\varepsilon = \frac{\Delta R}{R} \times \frac{1}{GF}$$

Strain gauge



Compression will decrease the resistance

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

$$strain : \varepsilon = \frac{\Delta L}{L}$$

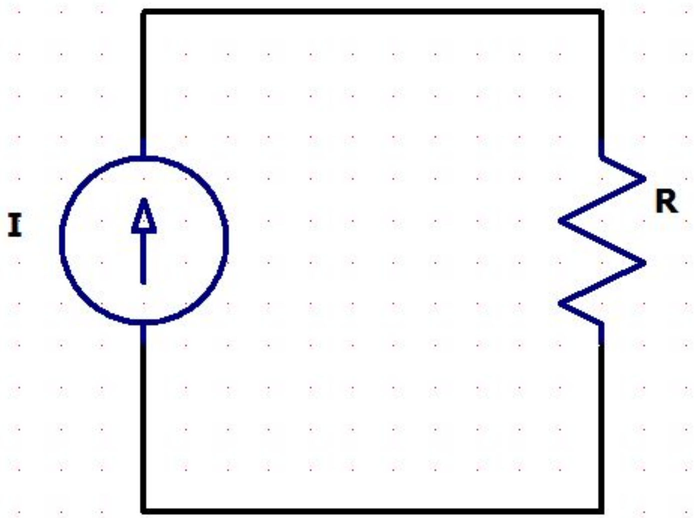
$$GF = \frac{\Delta R / R}{\Delta L / L}$$

$$\varepsilon = \frac{\Delta R}{R} \times \frac{1}{GF}$$

Various gage factors

Material	Gauge Factor
Metal foil strain gauge	2-5
Thin-film metal (e.g. constantan)	2
Single crystal silicon	-125 to + 200
Polysilicon	±30
Thick-film resistors	100
p-type Ge	102

Simple method of strain measurement



Voltage across the strain gauge is

$$V = I(R + \Delta R)$$

$$V = IR\left(1 + \frac{\Delta R}{R}\right)$$

$+\Delta R$

Strain gage

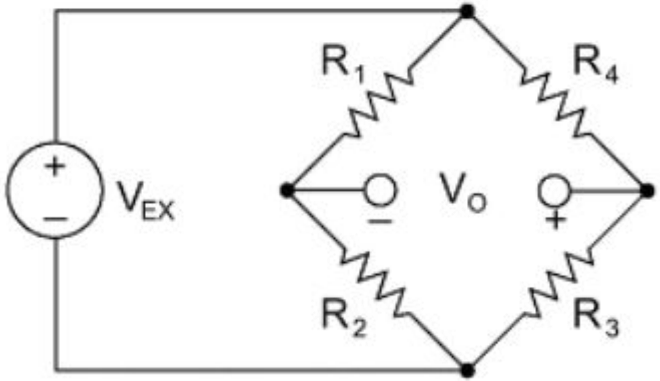
Voltage can be calibrated in terms of strain. But measurement will be very difficult since ΔR/R is very small compared to one.

$$Since\ \frac{\Delta R}{R} << 1$$

We need a circuit where

$$V = k\frac{\Delta R}{R}$$

Bridge circuit

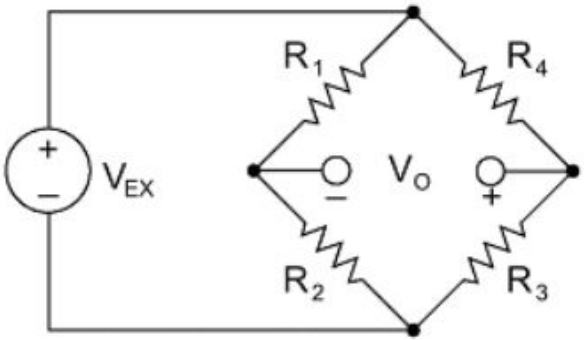


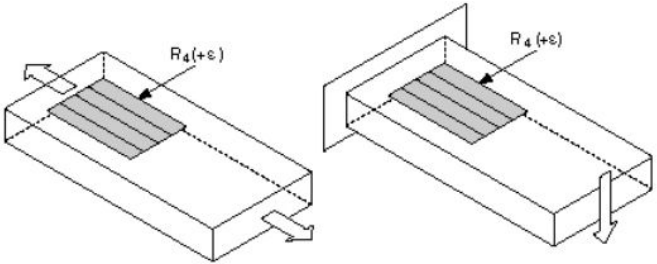
$$V_o = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right) \times V_{EX}$$

Quarter Bridge Configuration 1

Axial or bending strain

R_4 : *Strain gauge*



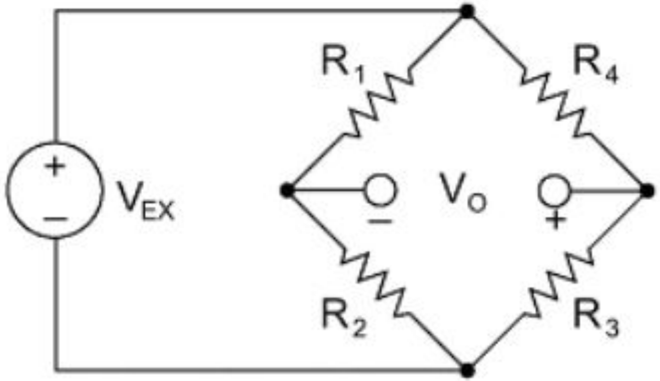


$$R_1 = R_2 = R_3 = R$$

$$R_4 = R + \Delta R$$

$$V_o = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right) \times V_{EX}$$

Quarter bridge Configuration 1



$$R_1 = R_2 = R_3 = R$$

$$R_4 = R + \Delta R$$

$$V_o = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right) \times V_{EX}$$

$$V_o = \left(\frac{R}{R + R + \Delta R} - \frac{R}{R + R} \right) V_{EX}$$

$$V_o = \left(\frac{R}{2R + \Delta R} - \frac{1}{2} \right) V_{EX}$$

$$V_o = \left(\frac{-\Delta R}{4R + 2\Delta R} \right) V_{EX}$$

Calculation for strain

$$V_o = \left(\frac{-\Delta R}{4R + 2\Delta R} \right) V_{EX}$$

$$V_o = \left(\frac{-\Delta R}{R\left(4 + \frac{2\Delta R}{R}\right)} \right) V_{EX}$$

$$V_o = \left(\frac{-\Delta R / R}{\left(4 + \frac{2\Delta R}{R}\right)} \right) V_{EX}$$

$$V_o = \left(\frac{-GF \times \varepsilon}{(4 + 2 \times GF \times \varepsilon)} \right) V_{EX}$$

$$\varepsilon = \frac{-4V_o}{GF(V_{EX} + 2V_o)}$$

Exercise 7.3

- Assume a quarter bridge driven by a 9 volt battery
- Gauge factor has the value of 3
- Next assume that a variable tensile force is applied

This force is adjusted to get the output voltage from 0 to – 130 mvolts in steps of -10 mVolts

- Using a spreadsheet calculate the strain values for each of the output observed

Answers

Vo	Strain(%)
0	0
-10	0.148478099
-20	0.297619048
-30	0.447427293
-40	0.597907324
-50	0.74906367
-60	0.900900901
-70	1.053423627
-80	1.206636501
-90	1.360544218
-100	1.515151515
-110	1.670463174
-120	1.826484018
-130	1.983218917

$$\varepsilon = \frac{-4V_o}{GF(V_{EX} + 2V_o)}$$

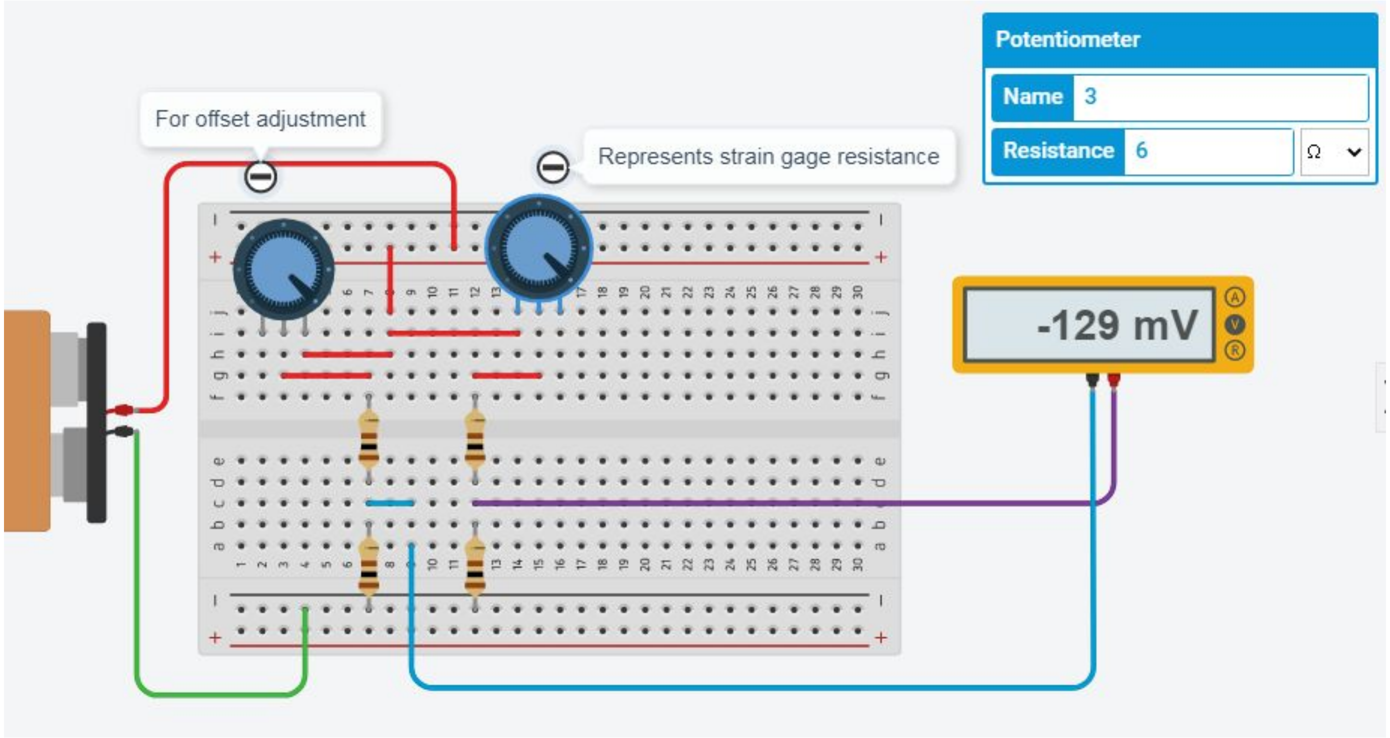
Exercise 7.4

- Next set up a quarter bridge circuit in Tinkercad to measure the output voltage from the bridge. Use 100 ohms bridge resistors and a 9 volt battery.
- Since Tinkercad does not have strain gage use a variable resistance varying from 0 to 6 ohms to represent the strain gauge.
- Use an identical resistance in the other arm to compensate for a possible offset.

Exercise 7.3 continued

- What is the value of output voltage you expect when the resistance is set to 6 ohms? Explain your answer.

Solution



For offset adjustment
Represents strain gage resistance
Potentiometer
Name
3
Resistance
6
Ω
-129 mV

Solution continued

$$\varepsilon(\%) = \frac{\Delta R}{GF \times R} \times 100$$

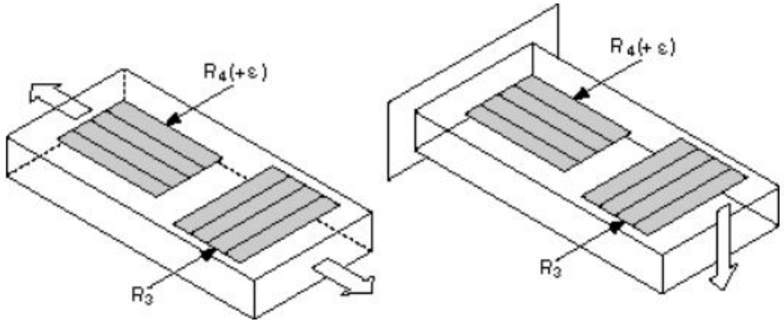
$$\varepsilon(\%) = \frac{6}{3 \times 100} \times 100 = 2$$

From the table in the spreadsheet we expect the output of about -130 mV. We get -129 mV

Quarter Bridge configuration 2

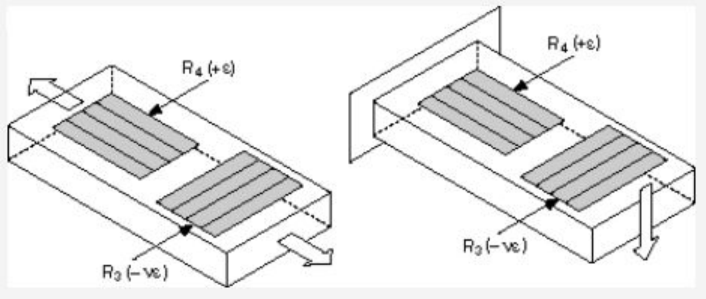
Axial or Bending strain

$$\varepsilon = \frac{-4V_o}{GF(V_{EX} + 2V_o)}$$



R3 is mounted in close thermal contact
but not bonded to the specimen.
So strain does not affect R3 but temperature
Effects are cancelled since ratio of R3 to R4
becomes independent of temperature

Half bridge Strain gage
Axial or bending strain



$$V_o = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right) \times V_{EX}$$

$$R_1 = R_2 = R$$

$$R_4 = R + \Delta R$$

$$R_3 = R - v\Delta R$$

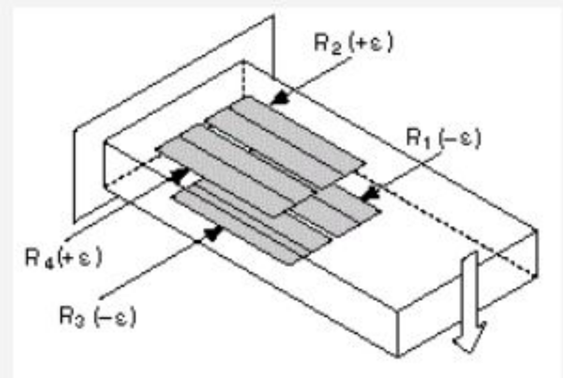
R3 is mounted in close thermal contact and bonded to the specimen.

Temp effects are cancelled since ratio of R3 to R4 becomes independent of temperature

v is the Poisson ratio

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

Full Bridge (Bending strain only)



$$V_o = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right) \times V_{EX}$$

$$R_2 = R_4 = R + \Delta R$$

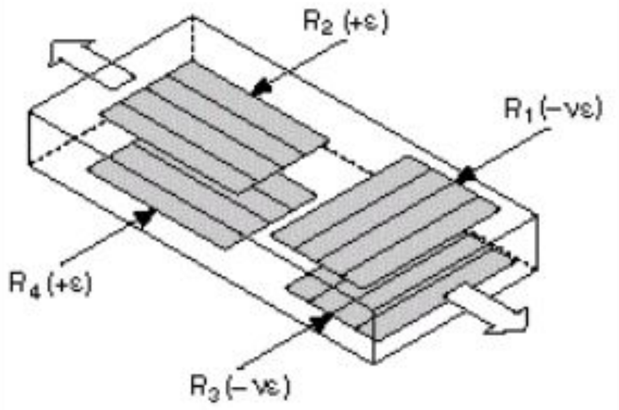
$$R_1 = R_3 = R - \Delta R$$

$$V_o = -\frac{\Delta R}{R} V_{EX}$$

$$V_o = -GF \times \varepsilon \times V_{EX}$$

$$\varepsilon = -\frac{V_o}{GF \times V_{EX}}$$

Full Bridge (Axial strain)



$$\varepsilon = -\frac{2V_o}{GF(\nu+1)V_{EX}}$$

$$V_o = \left(\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}\right)\times V_{EX}$$

SENSORS, INSTRUMENTS AND EXPERIMENTATION

17 Force sensing Resistance

By Ashok Ranade

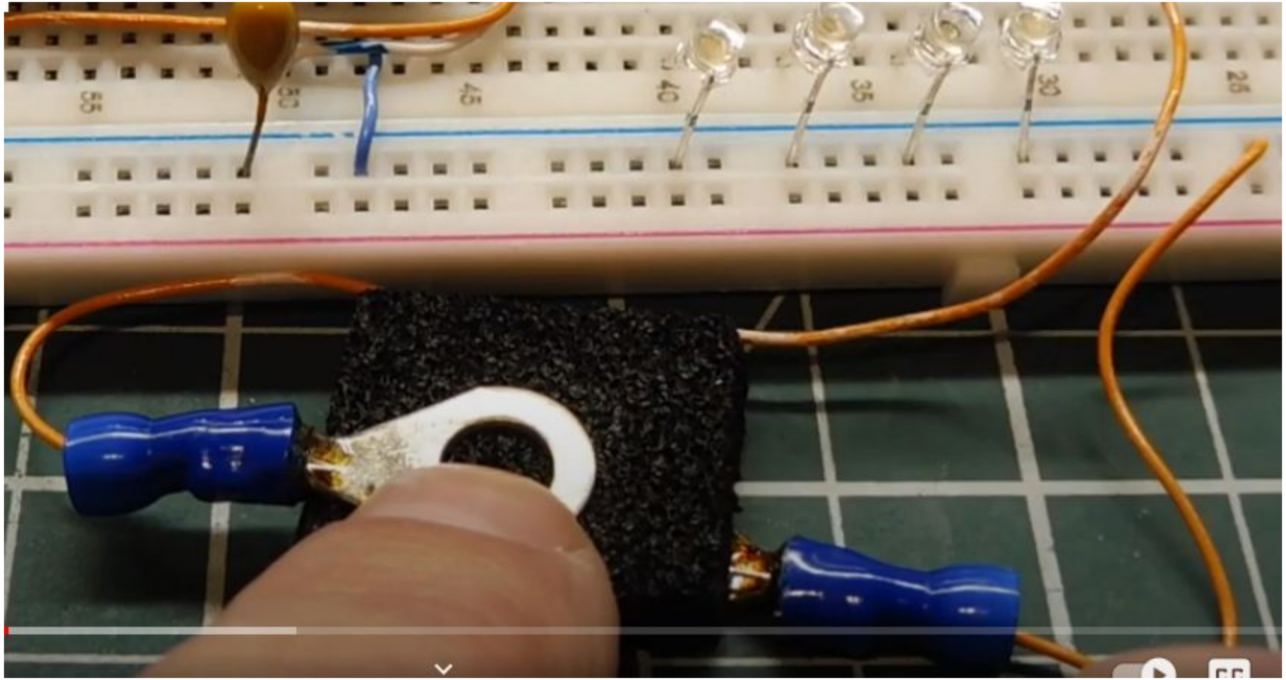
Principles of Force sense resistor

Conducting foam.

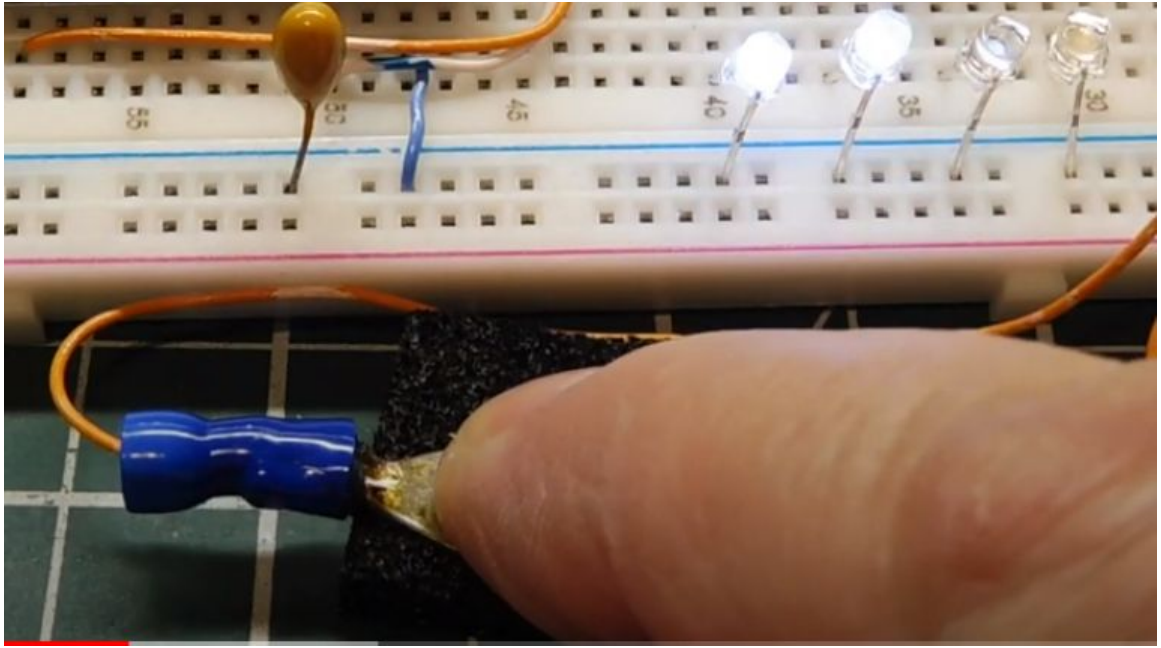
Polyethylene foam filled with carbon.

When pressed the contact resistance will

Foam used as resistor



Resistance change detected



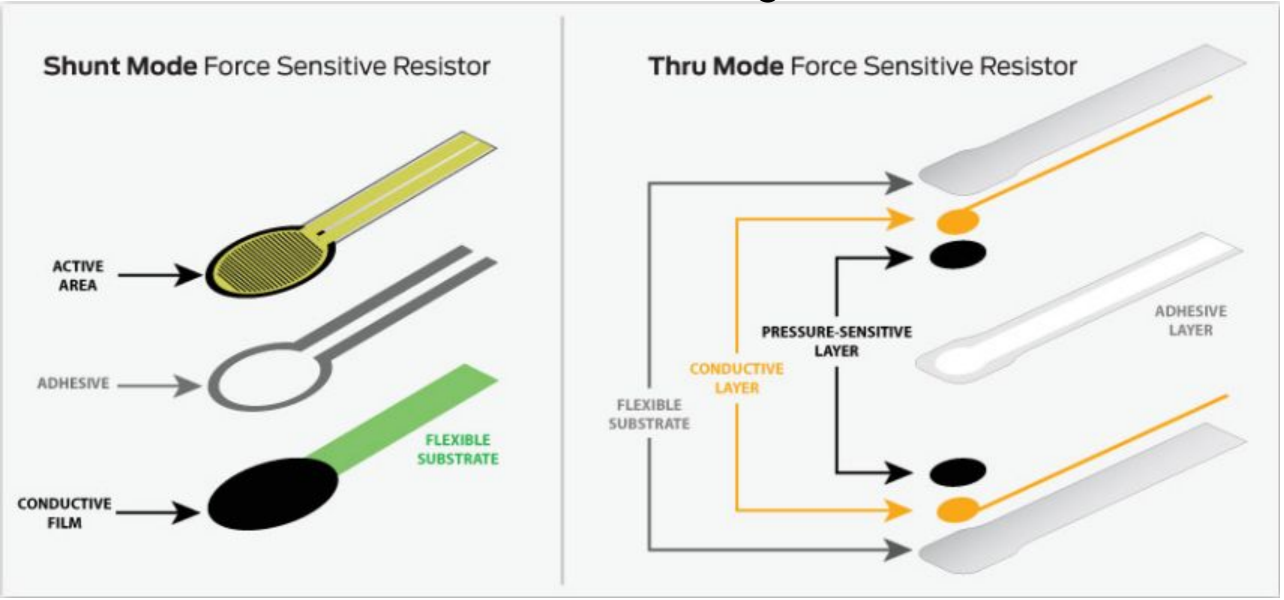
Conducting grid

A polyester film with printed circuit

Conducting fingers

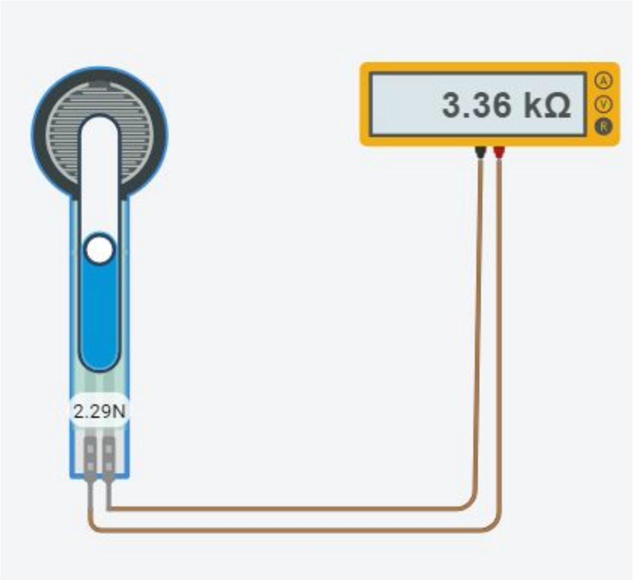
Two types of FSR

Thru mode more sensitive to light forces and more linear. Costlier



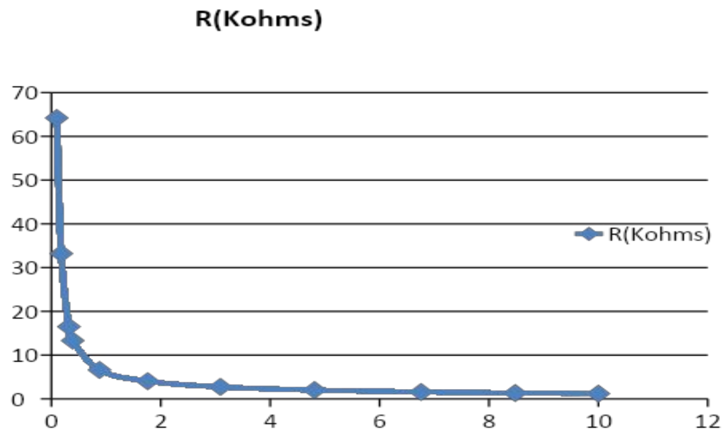
Conducting sheet is polymer sheet with carbon ink

Tinkercad simulation

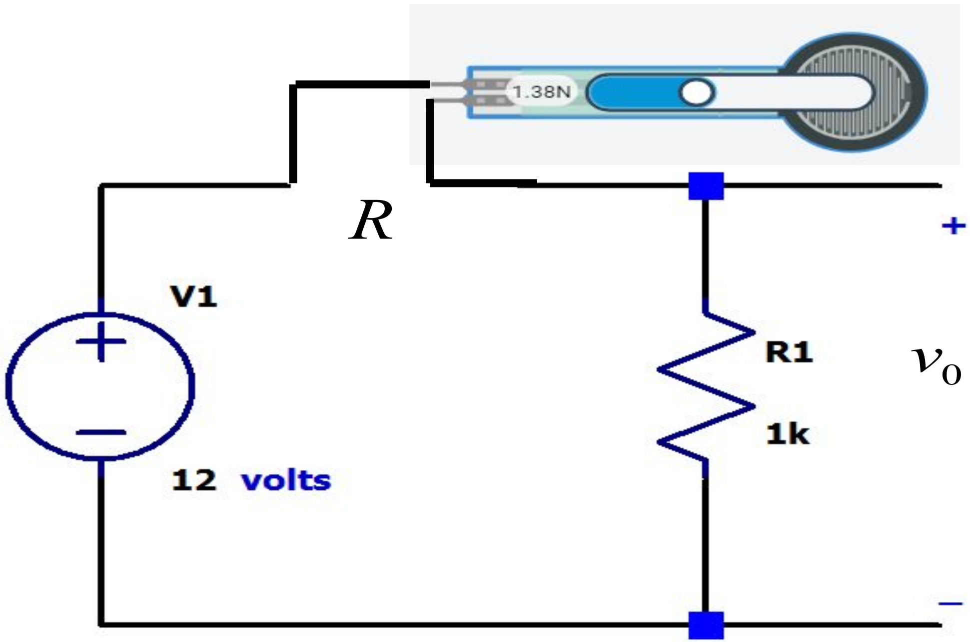


Force vs Resistance characteristics

F(Newtons)	R(Kohms)
0.1	64.2
0.18	33.2
0.32	16.5
0.39	13.3
0.88	6.58
1.76	4.03
3.09	2.72
4.81	2
6.76	1.58
8.48	1.34
10	1.2



Force vs voltage

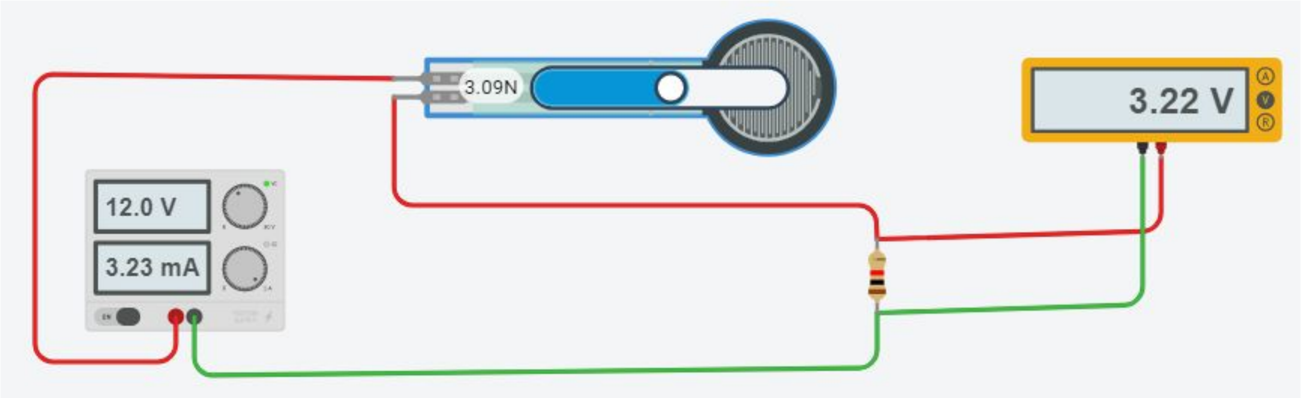


$$v_0 = \frac{V_1 R_1}{R + R_1}$$

If $R_1 >> R$ *the output is almost independent of the sensor*

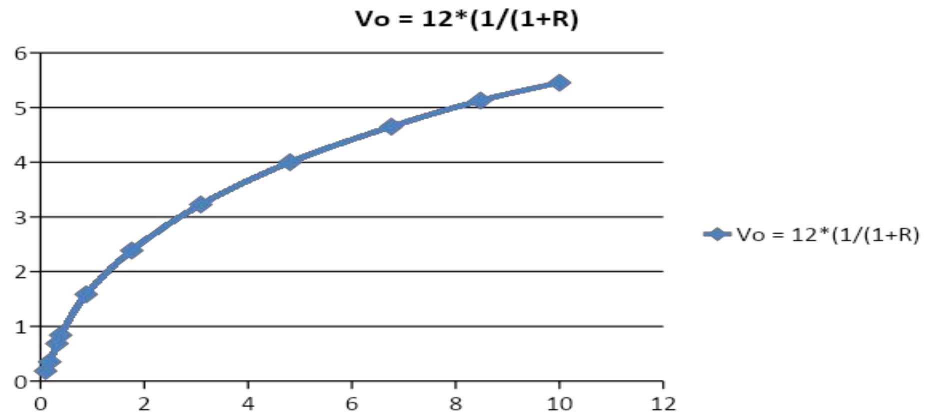
Not a good choice

Tinkercad simulation



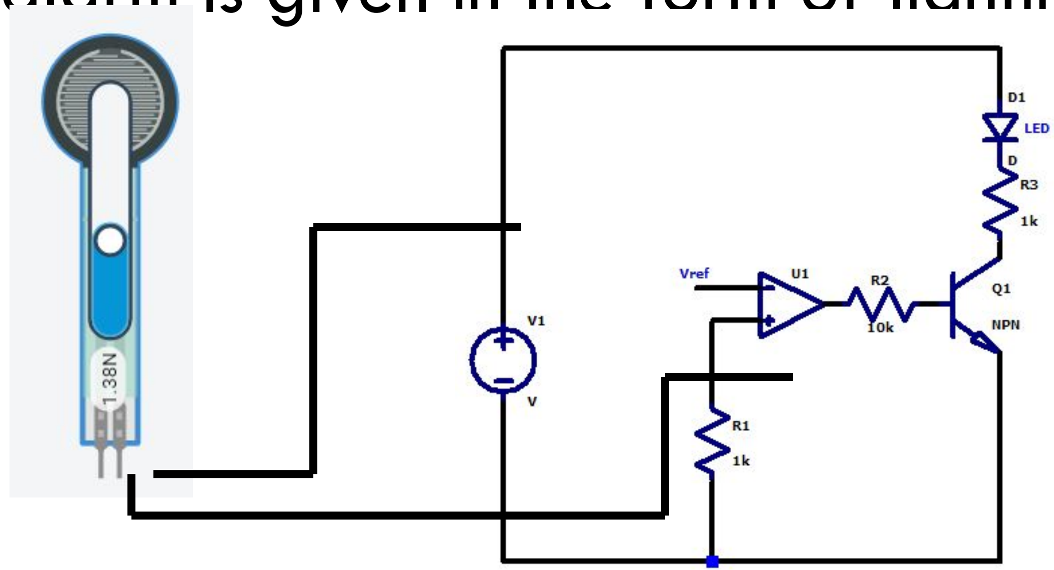
Force vs output voltage

F(Newtons)	R(Kohms)	Vo = 12*(1/(1+R)
0.1	64.2	0.18404908
0.18	33.2	0.350877193
0.32	16.5	0.685714286
0.39	13.3	0.839160839
0.88	6.58	1.583113456
1.76	4.03	2.385685885
3.09	2.72	3.225806452
4.81	2	4
6.76	1.58	4.651162791
8.48	1.34	5.128205128
10	1.2	5.454545455



Force alarm

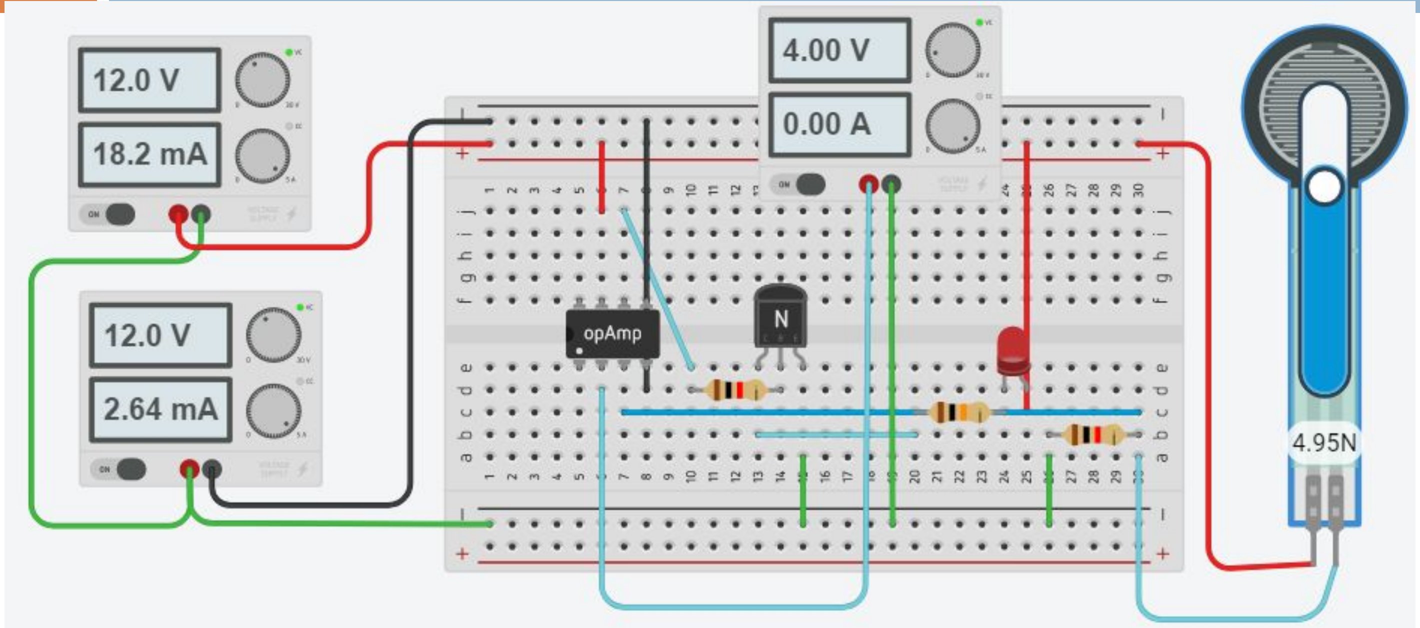
- In this circuit if Force exceeds a certain value an alarm is given in the form of lighting the LED



$V_{ref} = 4$ volts

4.81 Newtons

Tinkercad Simulation



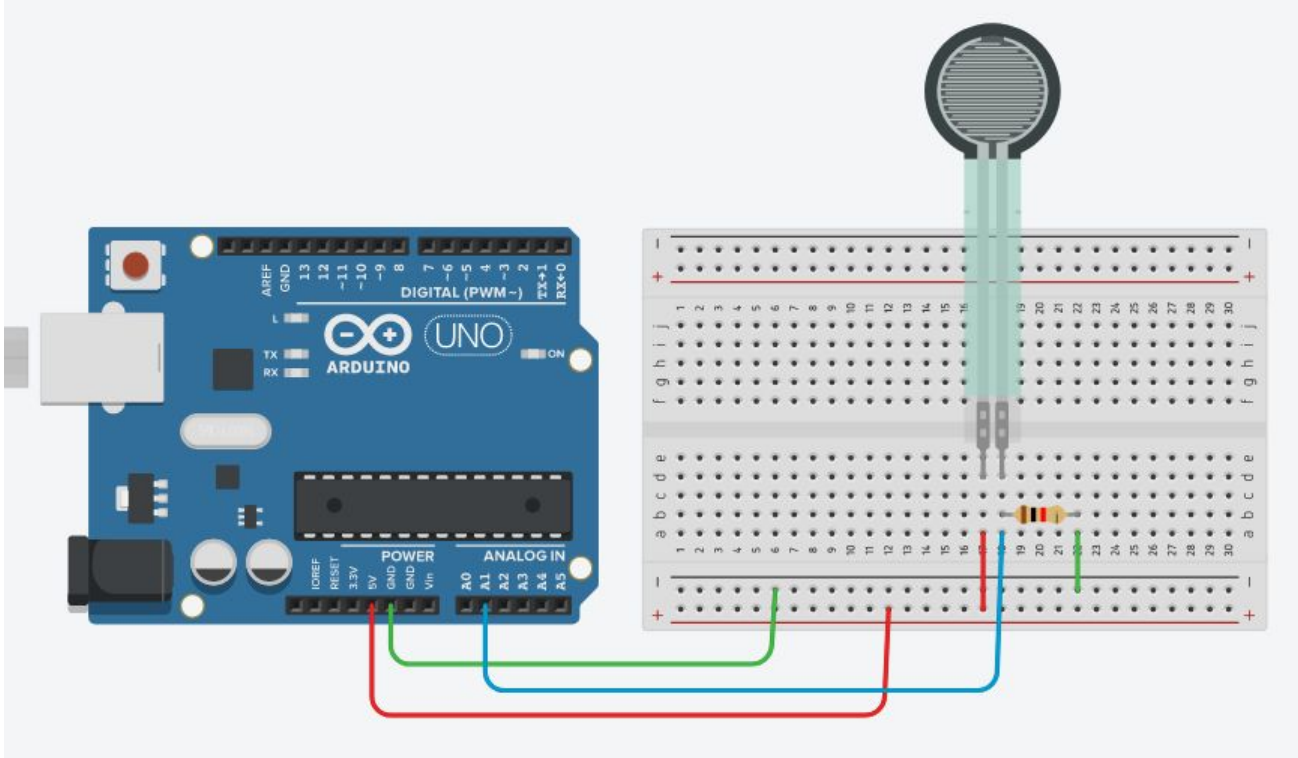
Exercise

- Design and build a force-meter
- Use the suggested circuit for sensing the force
- Use an analog pin to read the input
- Use curve-fitting to convert the input into force in Newtons.

Solution

- A crude solution is given in the next few slides.
- The calibration is good only for larger values of Force
- Students are expected to do better curve fitting

Force-meter circuit

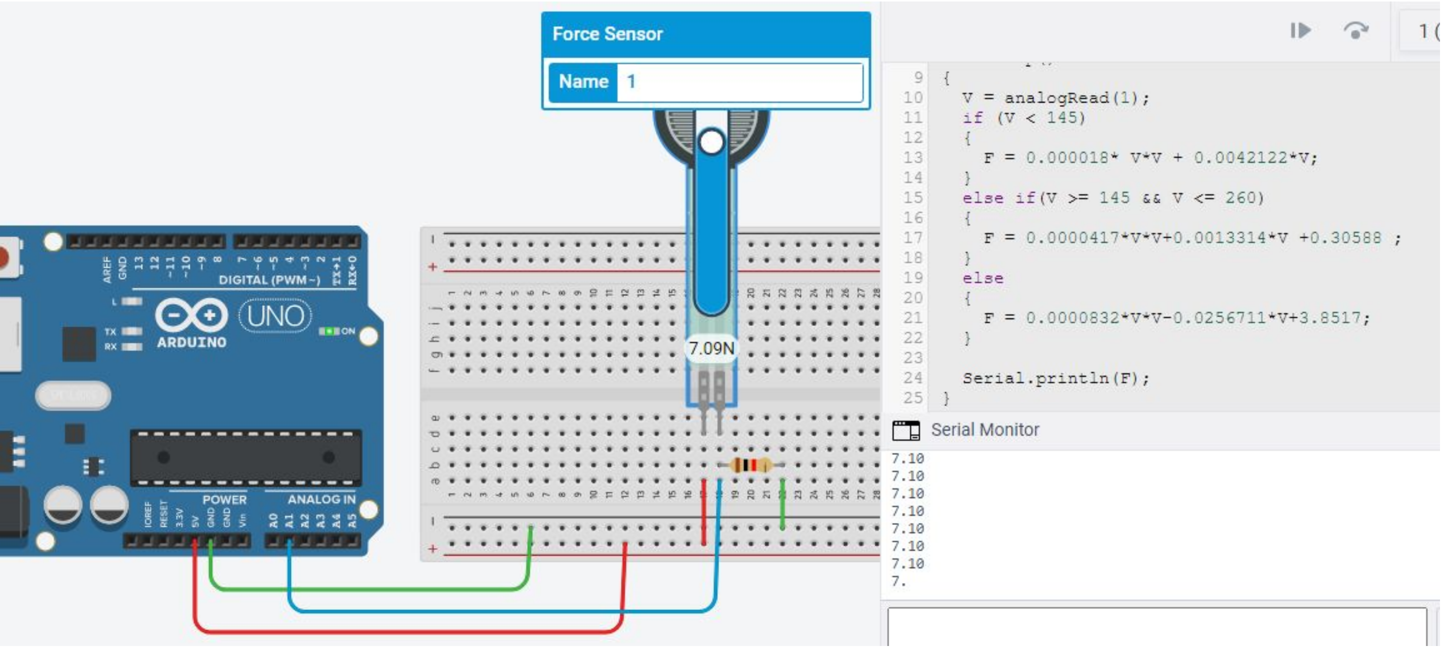


Program

```
float(F);
float(V);
void setup()
{
  Serial.begin(9600);
}
```

```
void loop()
{
  V = analogRead(1);
  if (V < 145)
  {
    F = 0.000018* V*V + 0.0042122*V;
  }
  else if(V >= 145 && V <= 260)
  {
    F = 0.0000417*V*V+0.0013314*V +0.30588 ;
  }
  else
  {
    F = 0.0000832*V*V-0.0256711*V+3.8517;
```

Output



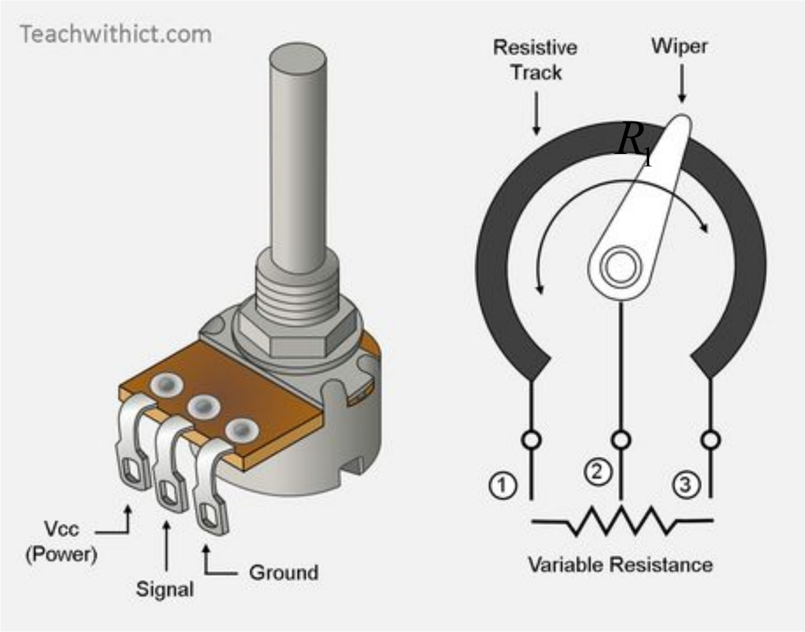
Force Sensor
Name
1
7.09N
DIGITAL (PWM ~)
ARDUINO
UNO
POWER
ANALOG IN
9 {
10 V = analogRead(1);
11 if (V < 145)
12 {
13 F = 0.000018* V*V + 0.0042122*V;
14 }
15 else if(V >= 145 && V <= 260)
16 {
17 F = 0.0000417*V*V+0.0013314*V +0.30588 ;
18 }
19 else
20 {
21 F = 0.0000832*V*V-0.0256711*V+3.8517;
22 }
23
24 Serial.println(F);
25 }
Serial Monitor
7.10
7.10
7.10
7.10
7.10
7.10
7.10
7.

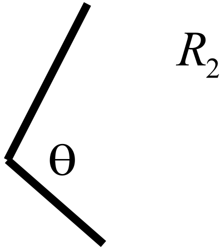
SENSORS, INSTRUMENTS AND EXPERIMENTATION

14 Potentiometer as position transducer

By Ashok Ranade

Potentiometer





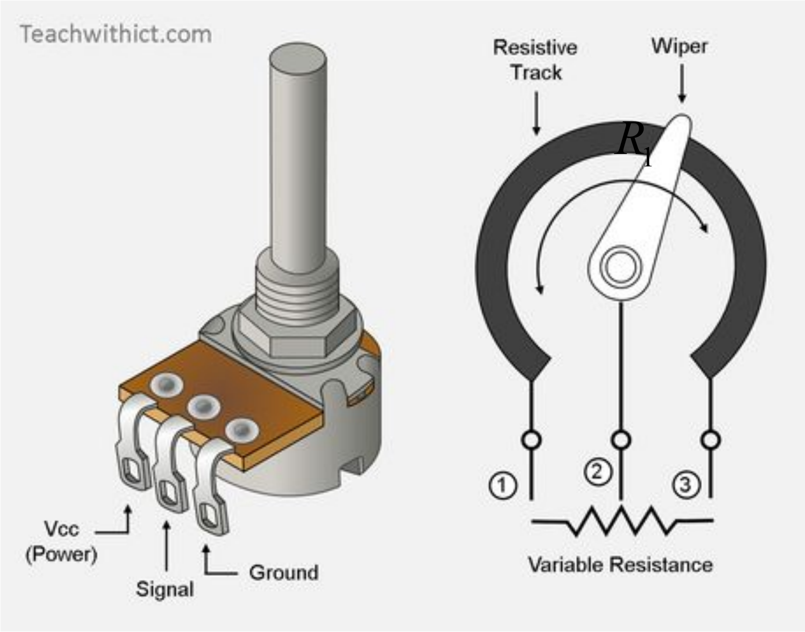
The resistance between 1 and 2 is R_1 *and that between 2 and 3 is* R_2.

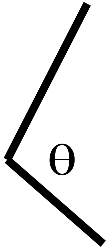
The resistance between 1 and 3 is constant and is given by $R = R_1 + R_2$.

As the wiper is rotated from extreme right(Angle zero) to extreme left (Angle θ_{max}*)*

R_2 *changes from 0 to R and* R_1 *changes from R to 0.*

Potentiometer constant





k depends on the radius and resistive track properties

If θ_{max} *is specified and R is known k can be calculated*

$$R_2 = R \text{ when } \theta = \theta_{max}$$

$$k = \frac{R}{\theta_{max}}$$

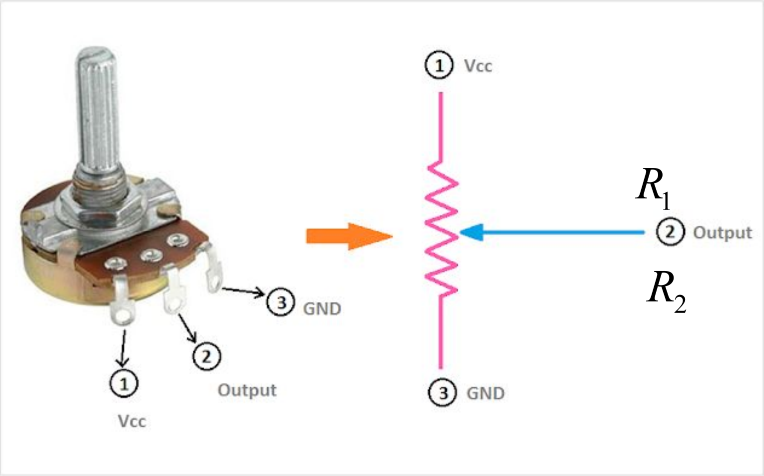
$$if\ \theta_{max} = 300^0$$

$$for\ a\ 10\,k\Omega\ pot$$

$$k = \frac{1}{30}\ k\Omega/degree$$

$$R_2 = k\theta$$

Converting change of resistance into a change of voltage



$$V_{out} = \frac{V_{cc} R_2}{R}$$

$$R = R_1 + R_2$$

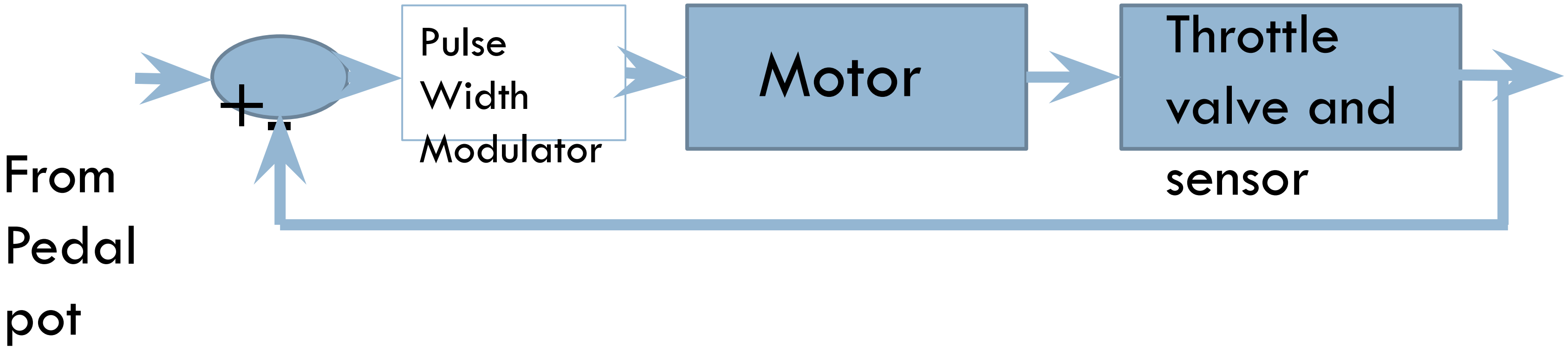
$$V_{out} = \frac{V_{cc} k\theta}{R}$$

$$V_{out} = \frac{V_{cc}\theta}{\theta_{max}}$$

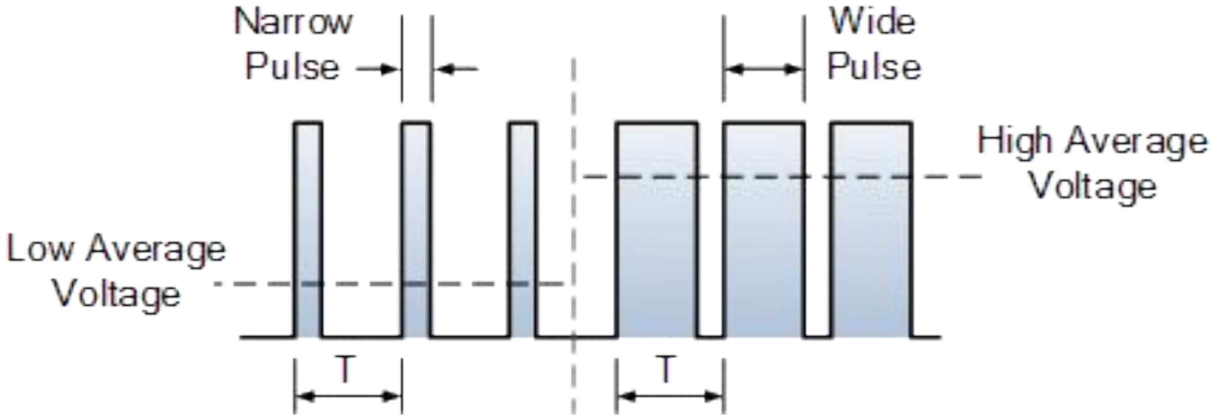
Application in an automobile

- When accelerator pedal is pressed in an automobile throttle valve opens wider allowing more air to go in the engine providing larger energy.
- Precise control of throttle valve can be obtained by using feedback
- Two potentiometers are used. One to sense the pedal position and the other to sense throttle valve

Feedback control



Pulse width modulation



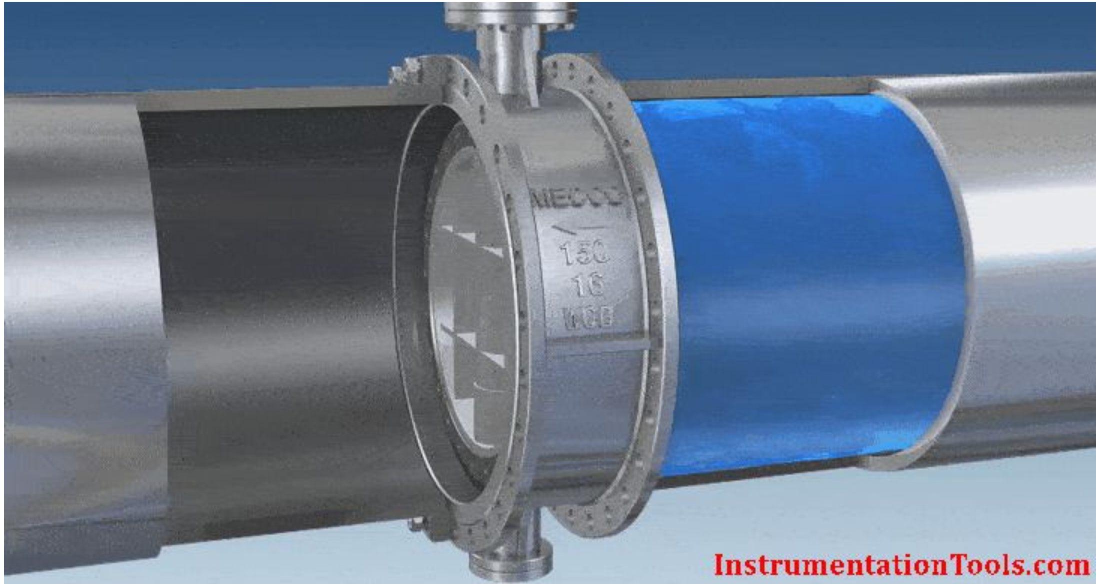
More efficient than using a DC amplifier

$$f = \frac{1}{T}$$

Typical values

from $200\,Hz$ *to* $500\,Hz$

Throttle valve



Throttle valve angle and Potentiometer output

$$V_{out} = \frac{V_{cc} \times \theta}{\theta_{\max}}$$

At 0 degrees the throttle valve is closed. At 90 degrees it is fully open.

$$V_{out} \; ranges \;\; from \; 0 \; to \frac{V_{cc} \times 90}{\theta_{\max}}$$

Pedal angle and Potentiometer output

$$V_{out} = \frac{V_{cc} \times \theta}{\theta_{\max}}$$

At 0 degrees the accelerator is un-pressed. At 45 degrees it is fully pressed.

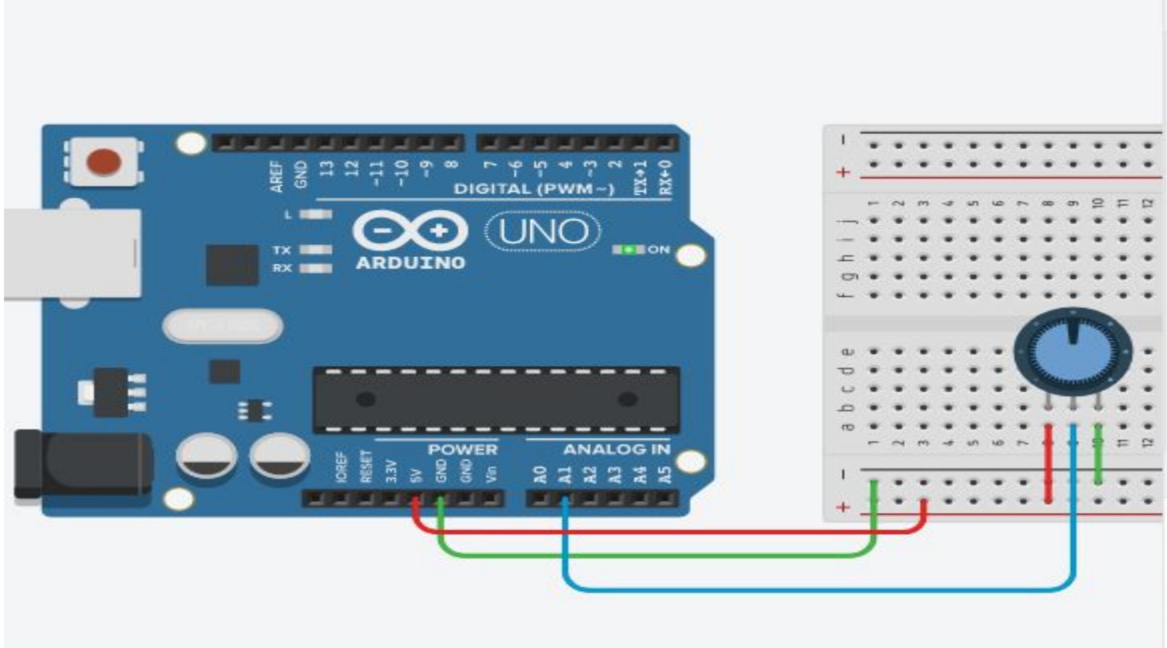
$$V_{out} \text{ ranges from } 0 \text{ to } \frac{V_{cc} \times 45}{\theta_{\max}}$$

So if $\theta_{\max}$ *is same for throttle valve pot and Pedal pot, for zero error you need twice the supply voltage for Pedal Potentiometer*

Angle measurement using arduino Exercise 9.1

- Interface a potentiometer to Arduino in Tinkercad using analog input pin.
- Note that potentiometer goes from zero degrees to 270 degrees.
- Write the program to read the input from the potentiometer and display the angle on serial monitor

Angle measurement




```cpp
// C++ code
//
float(A);
float(V);
void setup()
{
  Serial.begin(9600);
}

void loop()
{
  V = analogRead(1);
  A = (270*V/1023);
  Serial.println(A);
}
```

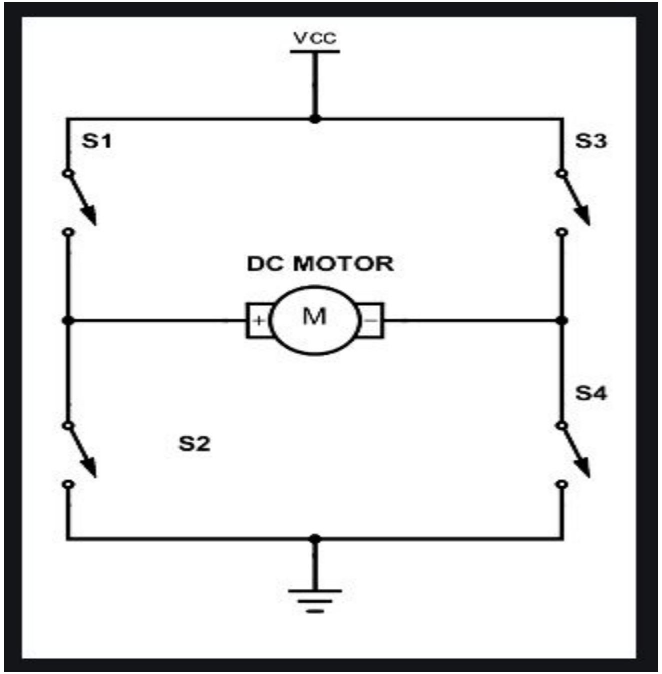
Serial Monitor

```
134.87
134.87
134.87
134.87
134.87
134.87
134.87
```

DC motor control using Arduino

- A dc motor is interfaced to Arduino
- The speed of the dc motor will depend on the applied voltage
- Direction of the rotation will depend on the direction of current through the winding.
- Direction of rotation can be reversed using a H bridge

H bridge



S2, S3 open
S1, S4 closed
Current flows from left to right
S2,S3 closed
S1, S4 open
Current flows from right to left
reversing the direction of rotation

H Bridge IC

The spinning direction of a motor can be controlled by applying either a logic HIGH(5 Volts) or logic LOW(Ground) to these pins. The below chart illustrates how this is done.

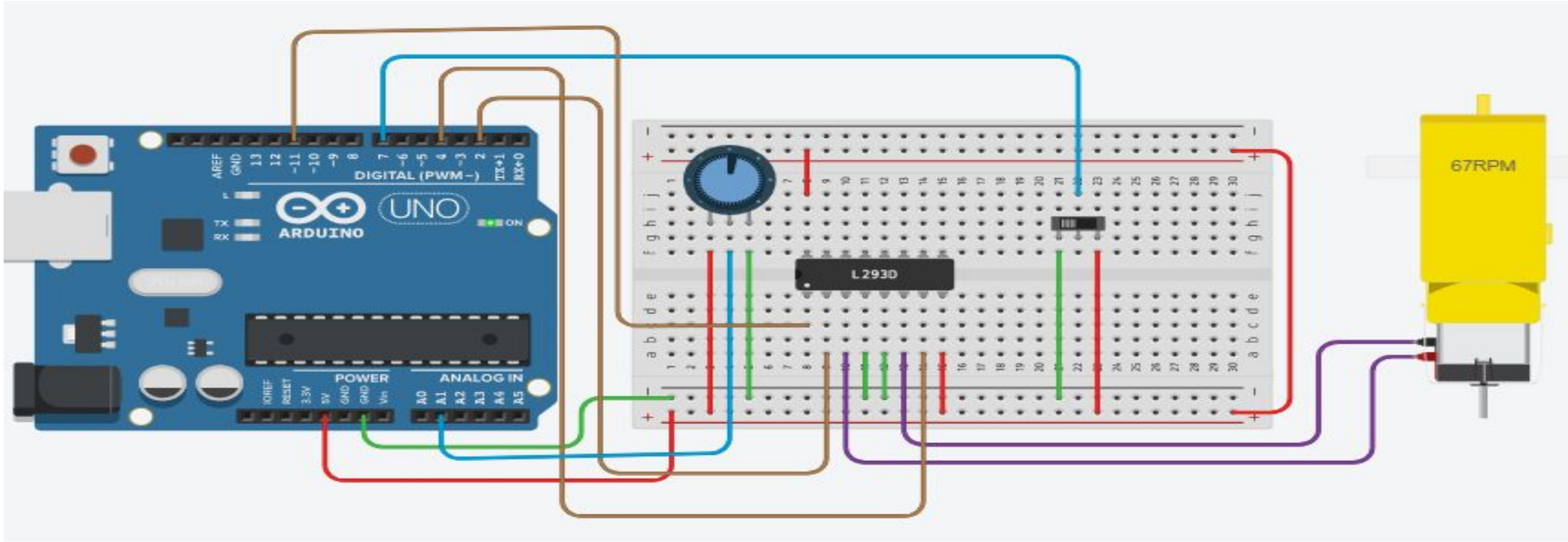
IN1	IN2	Spinning Direction
Low(0)	Low(0)	Motor OFF
High(1)	Low(0)	Forward
Low(0)	High(1)	Backward
High(1)	High(1)	Motor OFF

This can control two motors
Vcc1 should be +5 volts. This is used for logic circuits.
Voltage to Vcc2 is for the motor. This can have values from 4.5 volts to 36 volts.
Out1 and Out2 go to motor terminals.
IN1 and IN2 control direction of rotation as follows
When ENA is high the motor runs. When it is low the motor stops. So if a PWM waveform is connected to ENA speed can be

Exercise 9.2

- Design the hardware and software interface to arduino for direction and speed control of a dc motor. (Use hobby gear-motor in Tinkercad)
- Use a potentiometer and an analog input pin to provide a variable voltage to the Arduino. In the program scale this so as to generate a PWM signal of variable duty cycle to be connected to Enable pin.
- Use a slide switch to generate a digital input. If this is high motor should run in one direction. Otherwise in the

Hardware interface



```
float x; float y;
void setup()
{
  pinMode(11, OUTPUT);


   pinMode(4, OUTPUT);
   pinMode(2, OUTPUT);
}


void loop()
{
  if (digitalRead(7) == HIGH)
  {

else
  {
  digitalWrite(4,LOW);
  digitalWrite(2,HIGH);
  }
  x = analogRead(A1);
  y = x*255/1023 ;
  analogWrite(11,y);
}
```

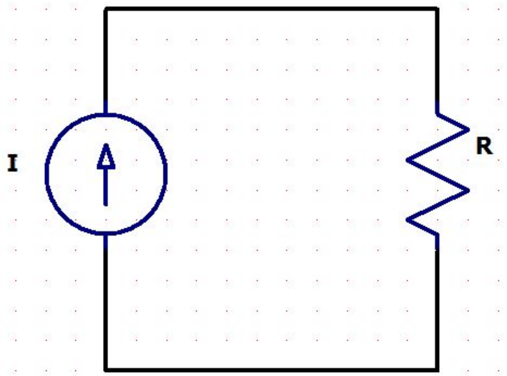
SENSORS, INSTRUMENTS AND EXPERIMENTATION

10 Temperature Detectors

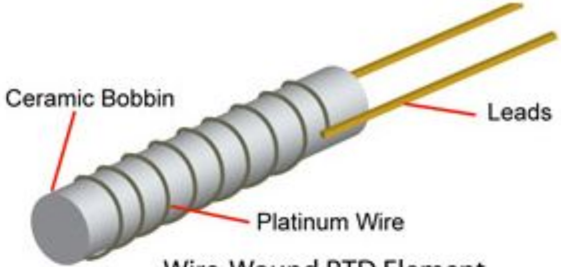
By Ashok Ranade

Resistance temperature detectors (RTD)

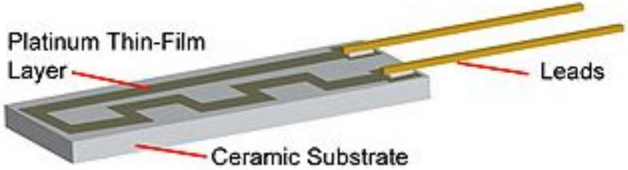
- RTD is a resistance which depends on temperature
- RTDs can be made with both positive and negative temperature coefficients.
- To develop a voltage proportional to temperature a cu[illegible] equired



Platinum RTDs



Wire-Wound RTD Element



Thin-Film RTD Element

Platinum has high resistivity

1.06×10^{-7} ohm-meter at 20^{0}C

$R_T = [R_o + (\alpha R_o \Delta T)]$

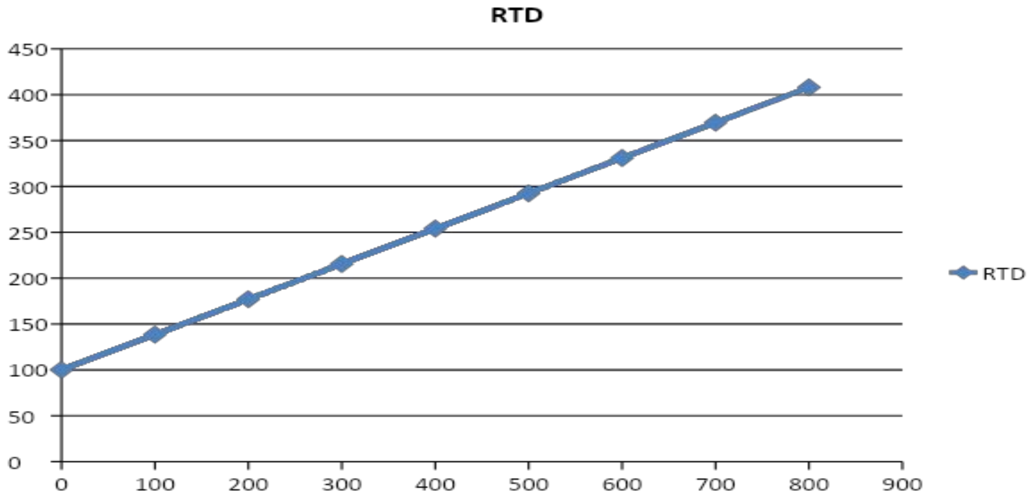
$\alpha = 0.00385\ \Omega/\Omega/°C$ at 0°C

A typical value $R_0 = 100$ ohms

Approximate relationship

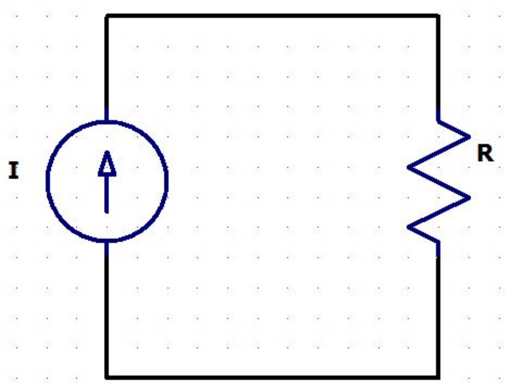
T	0	100	200	300	400	500	600	700	800
RTD	100	138.5	177	215.5	254	292.5	331	369.5	408

Resistance in ohms



Temp in ^{0}C

Temperature calculation



T

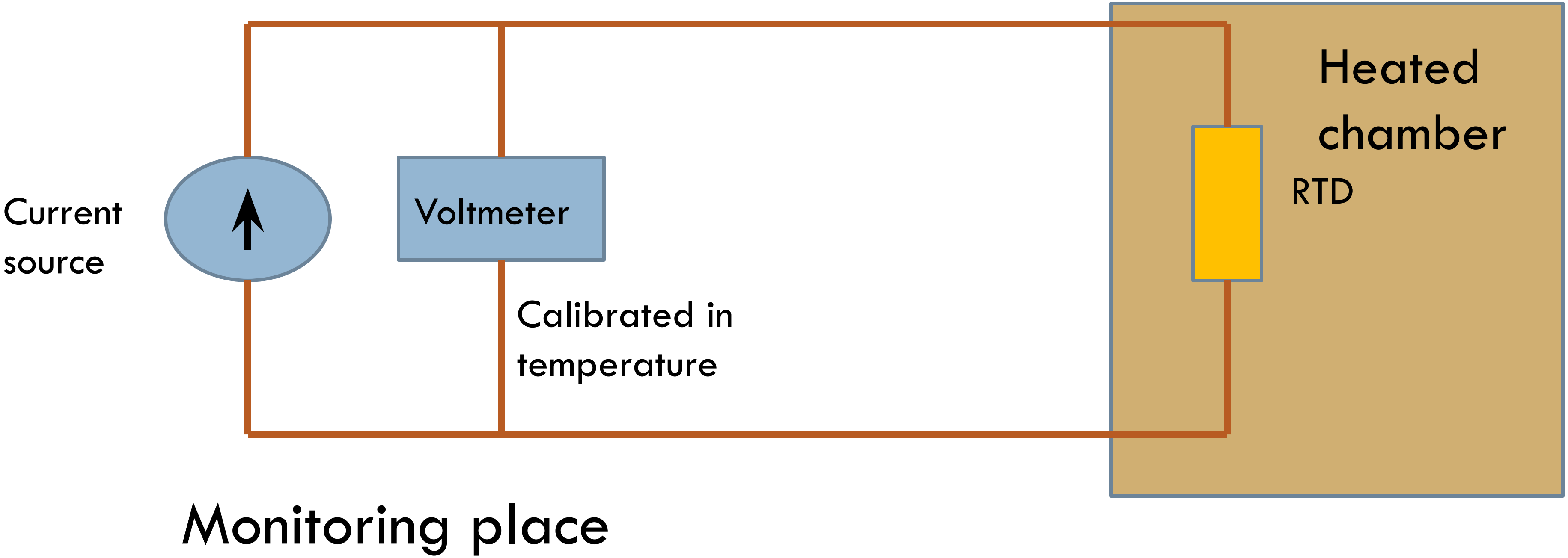
RTD

$$R_T = R_0 + R_0 \times \alpha \times T$$

$$V_T = IR_T = IR_0 + IR_0 \alpha T$$

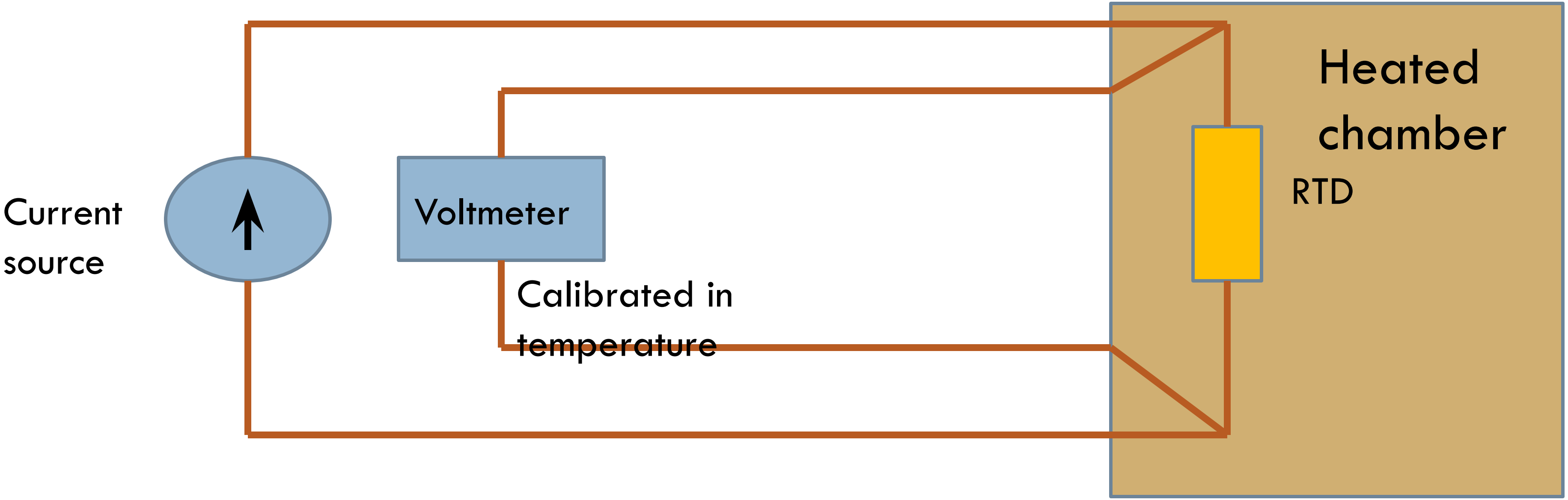
$$T = \frac{1}{\alpha}\left(\frac{V_T}{IR_0} - 1\right)$$

Line resistance effect



If the distance between monitoring place and the chamber is large line resistances will cause error

4-Wire RTD measurement



Monitoring place

Voltmeter has large resistance so very little current flows through measurement wires

Resistance as a function of temperature

- A better approximation is

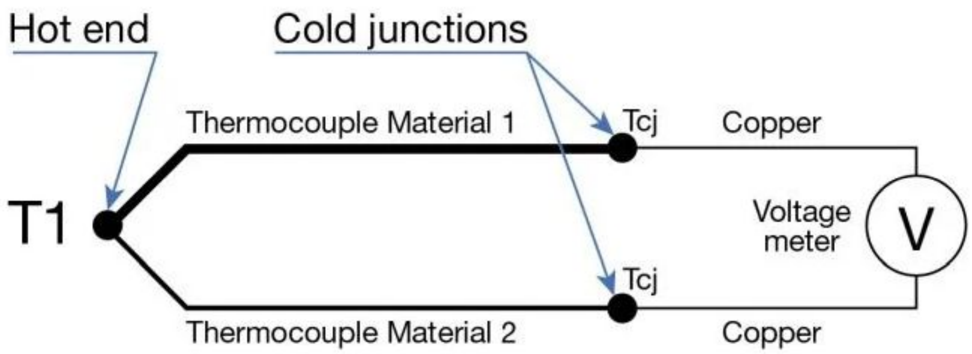
$R = R_0(1 + AT - BT^2 - CT^3)$

$A = 3.6962 \times 10^{-3}$; $B = 5.8494 \times 10^{-7}$

$C = 4.2325 \times 10^{-12}$

Thermocouples

- Thermocouple is basically a junction of two dissimilar metals and gives a voltage depending on the temperature of the junction
- Discovered by Thomas Seebeck in 1821



Types

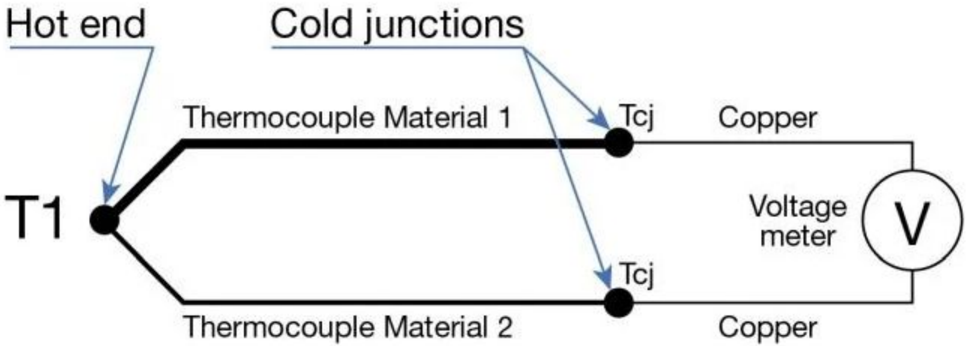
Thermocouple Types			
Type	Conductor Combination	Temperature Range	
		°F	°C
B	Platinum 30% Rhodium / Platinum 6% Rhodium	2500 to 3100	1370 to 1700
E	Nickel-chromium / Constantan	32 to 1600	0 to 870
J	Iron / Constantan	32 to 1400	0 to 760
K	Nickel-chromium / Nickel-aluminium	32 to 2300	0 to 1260
N	Nicrosil / Nisil	32 to 2300	0 to 1260
R	Platinum 13% Rhodium / Platinum	1600 to 2640	870 to 1450
S	Platinum 10% Rhodium / Platinum	1800 to 2640	980 to 1450
T	Copper / Constantan	-75 to +700	-59 to +370

The first metal has +ve polarity

Merits and demerits

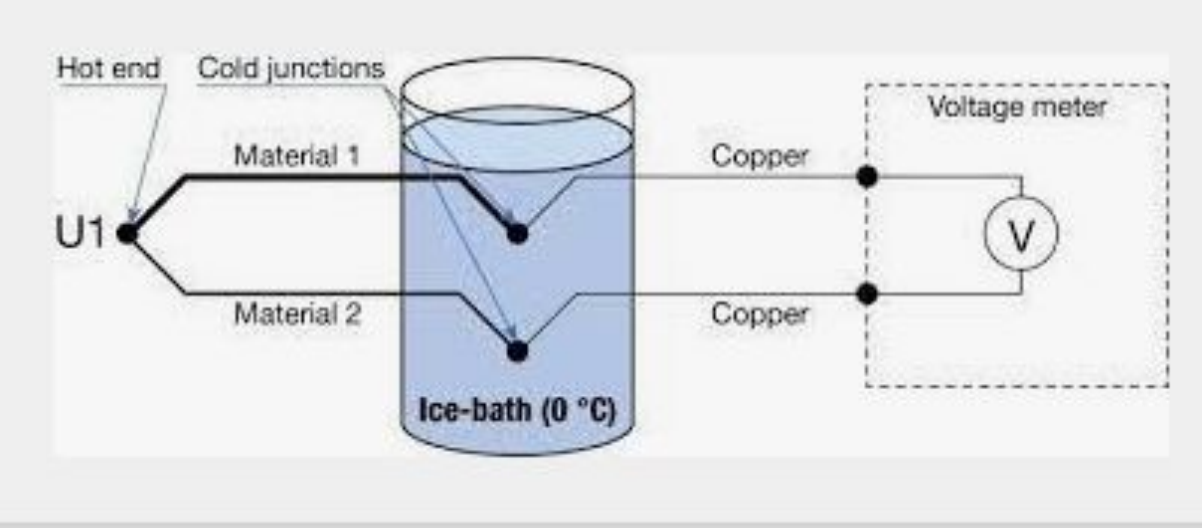
- Much higher temperature range compared to RTD
- Much more rugged
- Non-linear characteristics
- Less accurate.

Reference(Cold) junction



There is one hot junction and two cold junctions. The output voltage is the resultant of all the voltages produced. But if the reference junctions are kept at zero degree centigrade their voltages are zero and the output voltage corresponds to the temperature of hot junction.

Calibration



Polynomial for J thermocouple

$$T = a_0 + a_1 v + a_2 v^2 + a_3 v^3 + a_4 v^4 + a_5 v^5$$

$T = -0.048868252 + 19873.14503\ v - 128614.5353\ v^2 + 11569199.78\ v^3 - 264917531.4\ v^4 + 2018441314\ v^5$

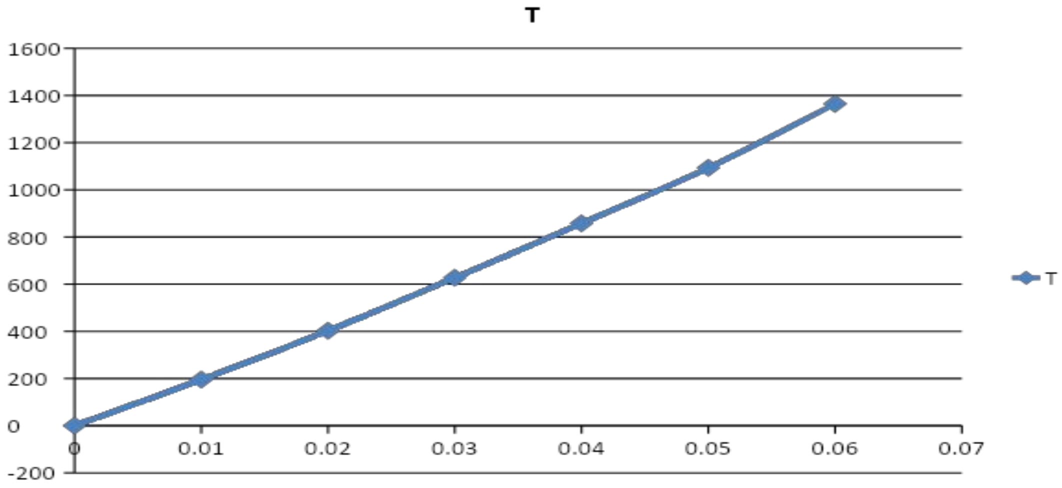
Polynomial for J thermocouple

$$T = a_0 + a_1 v + a_2 v^2 + a_3 v^3 + a_4 v^4 + a_5 v^5$$

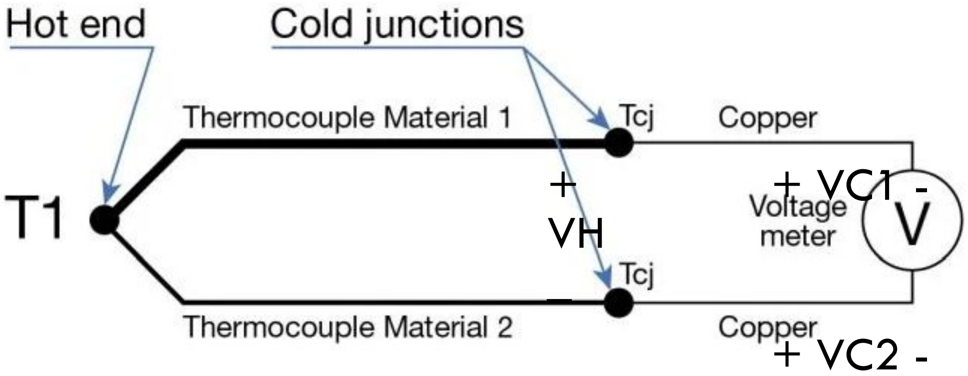
v	0	0.01	0.02	0.03	0.04	0.05	0.06
T	-0.05	194.9	402.6	627.2	858	1093	1364

V in volts

T in degrees C



Reference junction compensation



+

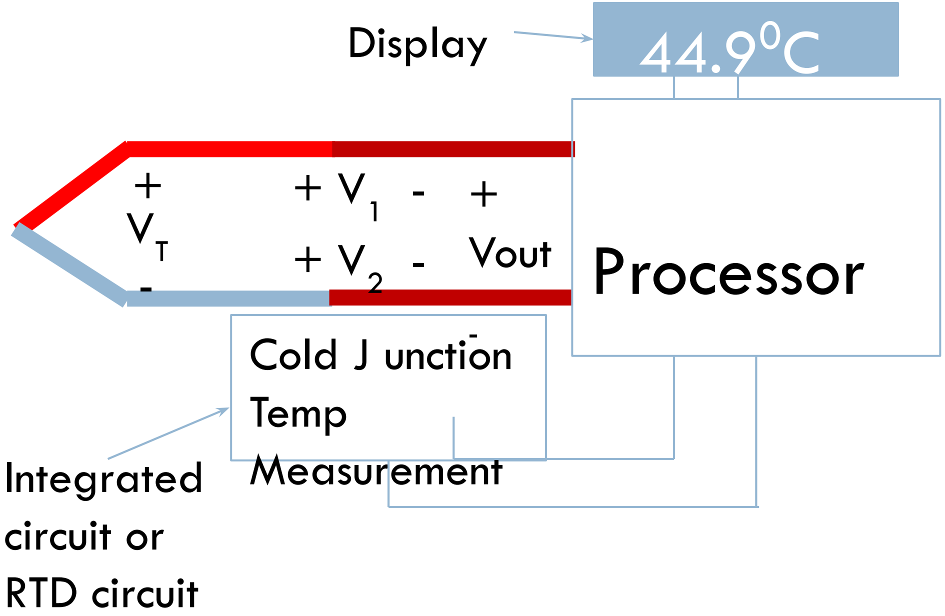
-

The temperature of the reference junction is regulated at some convenient value. Hence VC1 and VC2 are known .V is measured. Note that polarities shown are assumed polarities. They could be different for different type of junctions.

VH = VC1 + V + VC2

From the characteristics of the thermocouple T1 can be calculated

Automatic junction compensation



The polarities of V_T, V_1 and V_2 depend on the metals

Algorithm

(1) Read V_{out} through an ADC

(2) Read cold junction temperature

(3) Calculate V_1 and V_2

(4) Calculate $V_T = V_1 + V_{out} - V_2$

(5) Calculate the hot junction temperature

(6) Display temperature

(7) Delay

(8) Go to (1)

Temperature sensor TMP 36

Low voltage operation (2.7 V to 5.5 V)
Calibrated directly in °C
10 mV/°C scale factor (20 mV/°C on TMP37)
±2°C accuracy over temperature (typ)
±0.5°C linearity (typ)
Stable with large capacitive loads
Specified −40°C to +125°C, operation to +150°C
Less than 50 µA quiescent current
Shutdown current 0.5 µA max
Low self-heating
Qualified for automotive applications

$$Temp = \frac{(V_0 - 500)}{10}$$

$$Temp\ in\ {}^0C : V_0\ in\ millivolts$$

When Temp = -40^{0}C Vo = 100 mV
When Temp = 125^{0}C Vo = 1750 mV

Exercise 10.1

- Interface the IC TMP 36 to arduino in Tinkercad
- IC has three terminals. Vcc, Ground and Vout
- Use an analog pin to read the output of TMP 36
- Perform necessary calculation to obtain the temperature
- Display the temperature on the serial monitor
- Note that you will see a slider on top of the IC once the simulation has started. This can be used to change the temperature.
- In actual application the temperature is decided by the

Calculation required

- The value read (say, Vd) by the analogRead command will be the digital value ranging from 0 to 1023. And it will be 1023 when the input voltage is 5 volts. So the realtion between Vd and Vo is given by

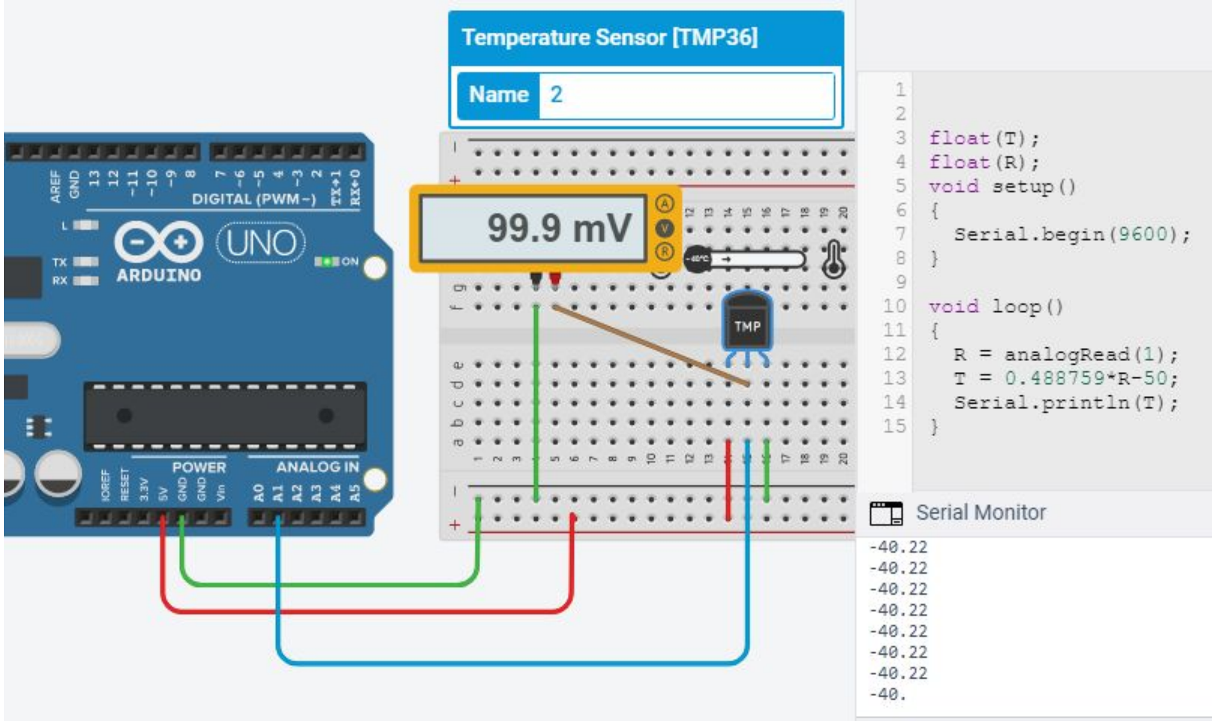
$$V_d = \frac{1023}{5000} \times V_0 \quad : Voltages\ in\ mvolts$$

$$V_0 = \frac{V_d \times 5000}{1023} = 4.88759 \times V_d$$

$$T = \frac{V_0 - 500}{10}$$

$$T = \frac{4.88759 \times V_d - 500}{10} = 0.488759 V_d - 50$$

Solution (Minimum Temperature)



Highest temperature