CPS Lecture 3: Sensors and Actuators

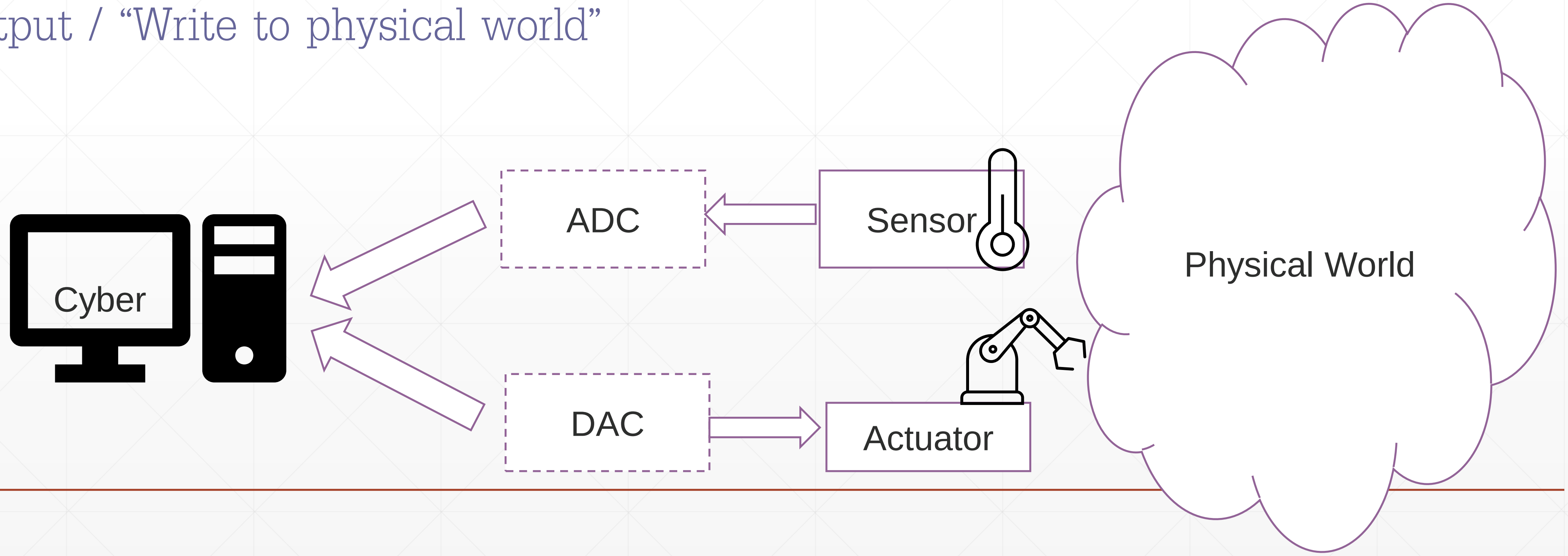
Semester 1-2022

Objectives

- To familiar with sensors sand actuators, and their applications
- To learn how to use ultrasonic sensors.

What is a sensor? An actuator?

- A sensor is a device that measures a physical quantity
- Input / “Read from physical world”
- An actuator is a device that modifies a physical quantity
- Output / “Write to physical world”



Sensors and Actuators – The Bridge between the Cyber and the Physical

- **Sensors**
- Cameras
- Accelerometers
- Gyroscopes
- Strain gauges
- Microphones
- Magnetometers
- Radar/Lidar
- Chemical sensors
- Pressure sensors
- Switches
- …

- **Actuator**
- Motor controllers
- Solenoids
- LEDs, lasers
- LCD and plasma displays
- Loudspeakers
- Switches
- Valves
- …

- **Modelling Issues**
- Physical Dynamics
- Noise
- Bais
- Sampling
- Interactions
- Faults
- …

Quantity being Measured	Input Device (Sensor)	Output Device (Actuator)
Light Level	Light Dependant Resistor (LDR) Photodiode Photo-transistor Solar Cell	Lights & Lamps LED's & Displays Fiber Optics
Temperature	Thermocouple Thermistor Thermostat Resistive Temperature Detectors	Heater Fan
Force/Pressure	Strain Gauge Pressure Switch Load Cells	Lifts & Jacks Electromagnet Vibration
Position	Potentiometer Encoders Reflective/Slotted Opto-switch LVDT	Motor Solenoid Panel Meters
Speed	Tacho-generator Reflective/Slotted Opto-coupler Doppler Effect Sensors	AC and DC Motors Stepper Motor Brake
Sound	Carbon Microphone Piezo-electric Crystal	Bell Buzzer Loudspeaker

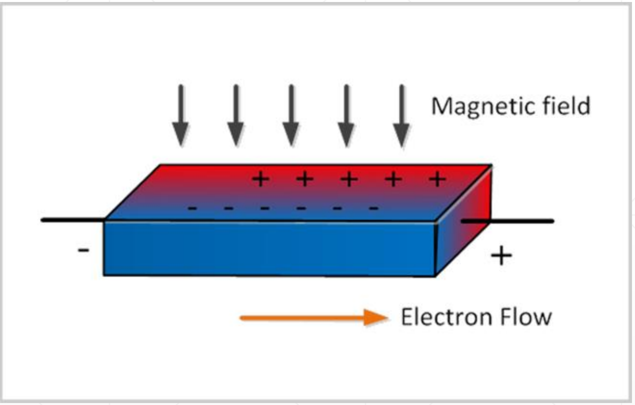
Source: https://www.electronics-tutorials.ws/io/io_1.html

Sensors or Reading Physical World

- Sensors can be designed for virtually every physical and chemical quantity, including
  - Weight, velocity, acceleration, electrical current, voltage, temperatures, chemical compounds, etc.
- Many physical effects are used for constructing sensors.

  Example:

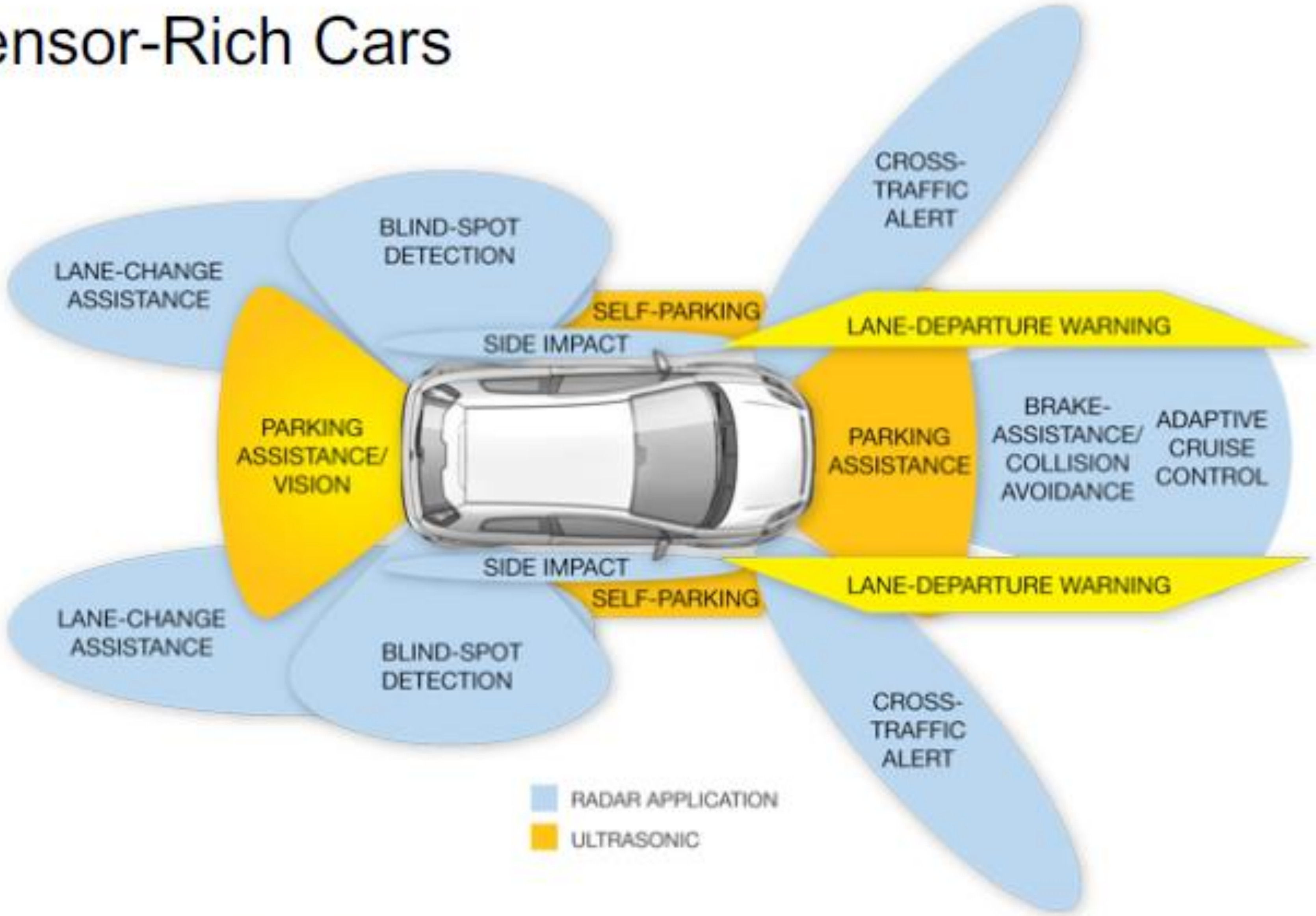
  Law of induction (generation of voltages in a magnetic field),



Source: wikipedia

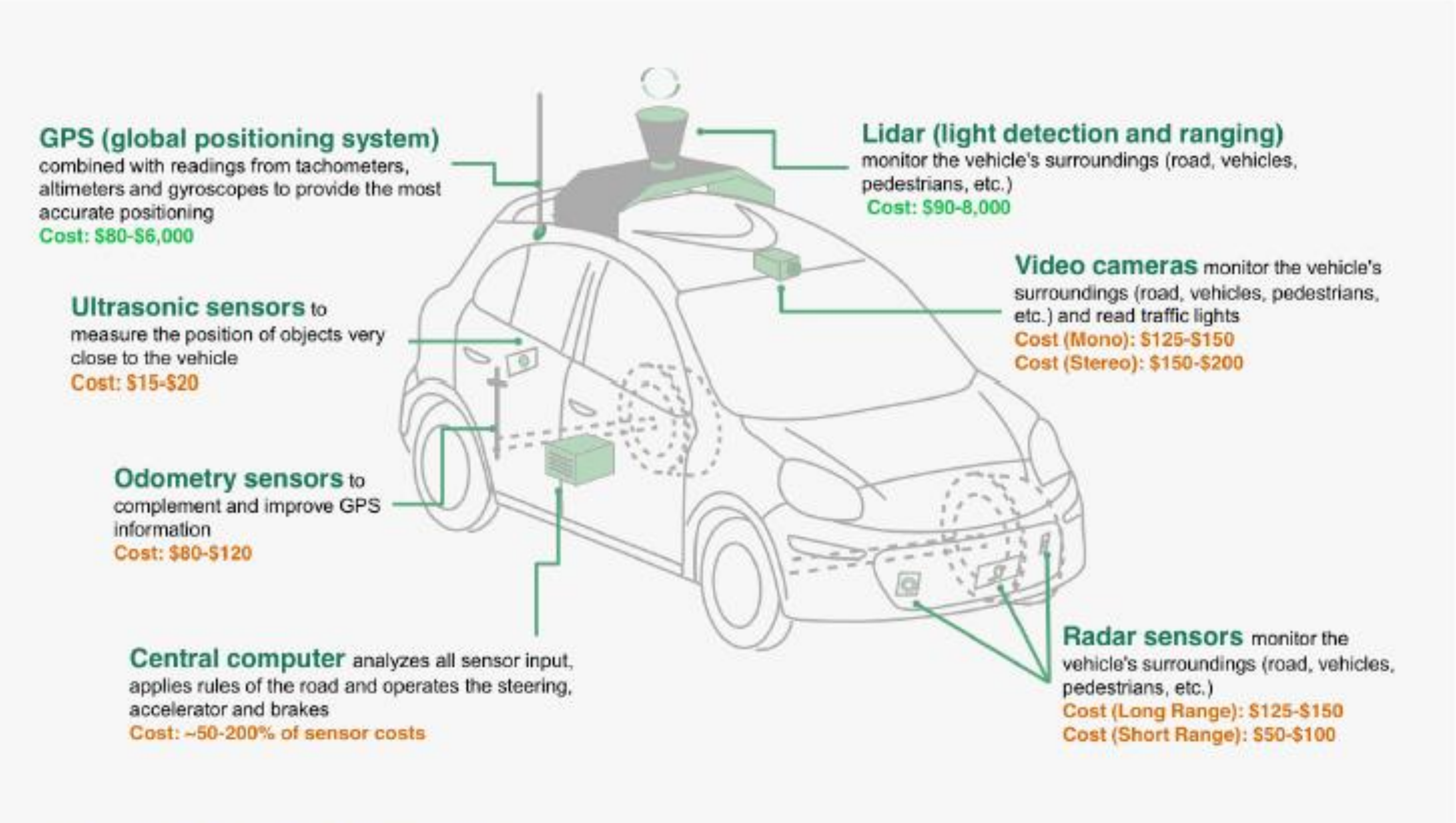
Source: [3]

Sensor-Rich Cars

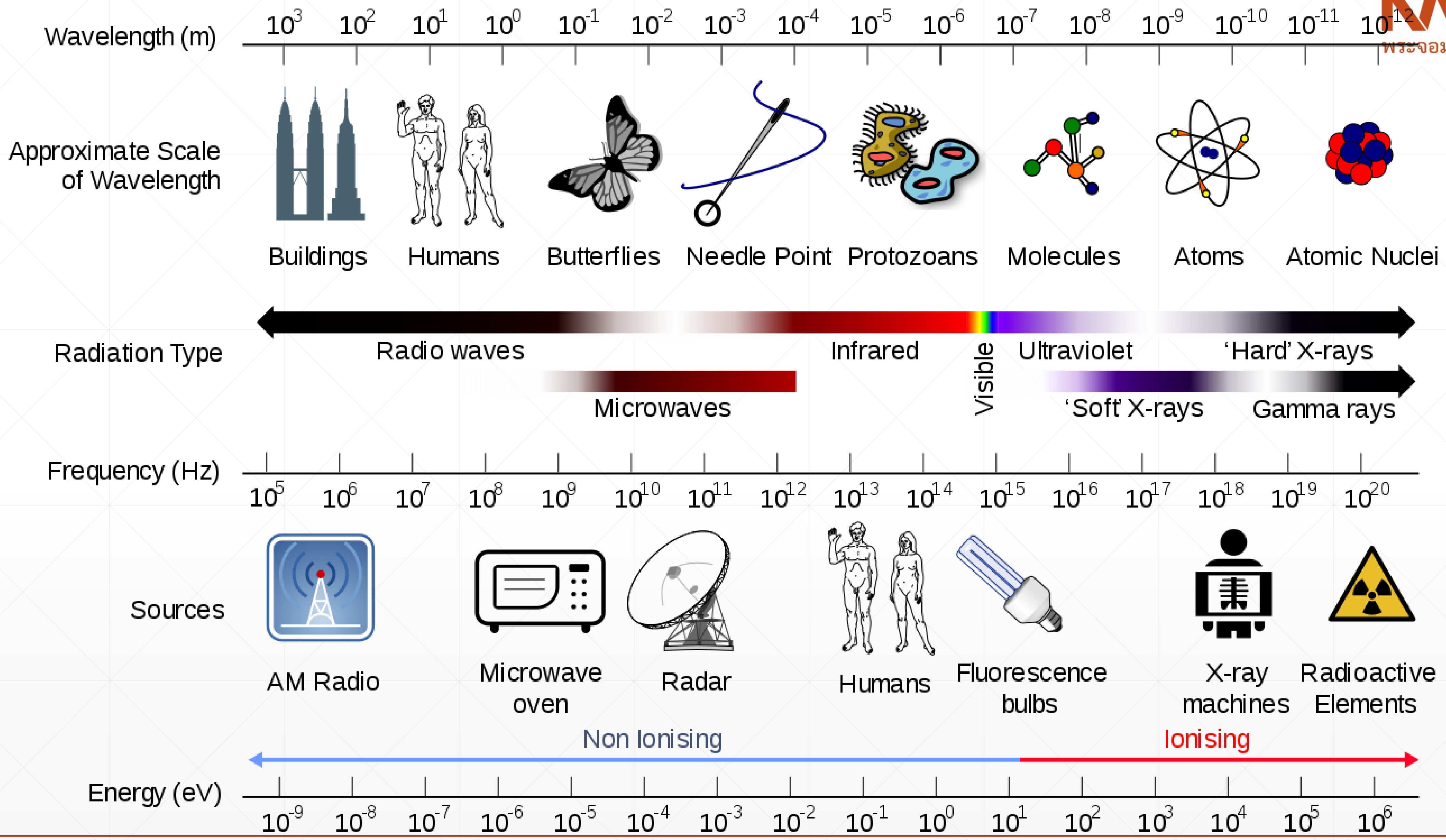


Source: Analog Devices

Sensor-Rich Cars



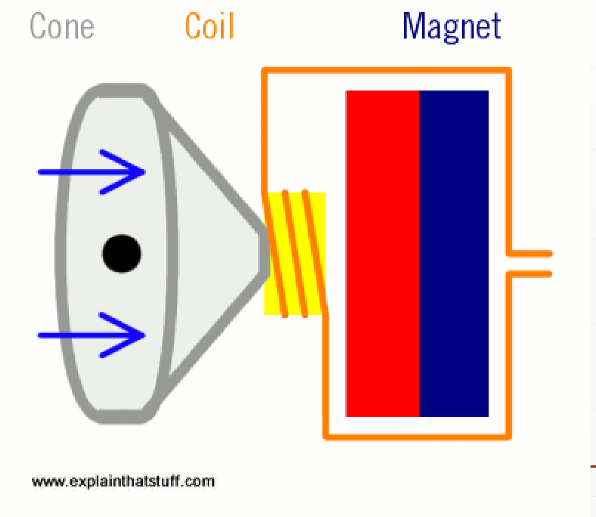
Source: Wired Magazine


Wavelength (m)
10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Radiation Type
Radio waves
Microwaves
Infrared
Visible
Ultraviolet
'Soft' X-rays
'Hard' X-rays
Gamma rays
Frequency (Hz)
10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Sources
AM Radio
Microwave oven
Radar
Humans
Fluorescence bulbs
X-ray machines
Radioactive Elements
Non Ionising
Ionising
Energy (eV)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Source: Wiki

Actuator or Controlling the Physical World

- An actuator converts the electric signal such as voltage or current to an action that effects the physical world.
- Physical laws and phenomena are used for designing actuators
- Example: Speaker converts the changes of electric current into the changes in magnetic field which occurs the vibration of sound.



Magnetometers

A very common type is the Hall Effect magnetometer.

Charge particles (electrons, 1) flow through a conductor (2) serving as a Hall sensor. Magnets (3) induce a magnetic field (4) that causes the charged particles to accumulate on one side of the Hall sensor, inducing a measurable voltage difference from top to bottom.

The four drawings at the right illustrate electron paths under different current and magnetic field polarities.

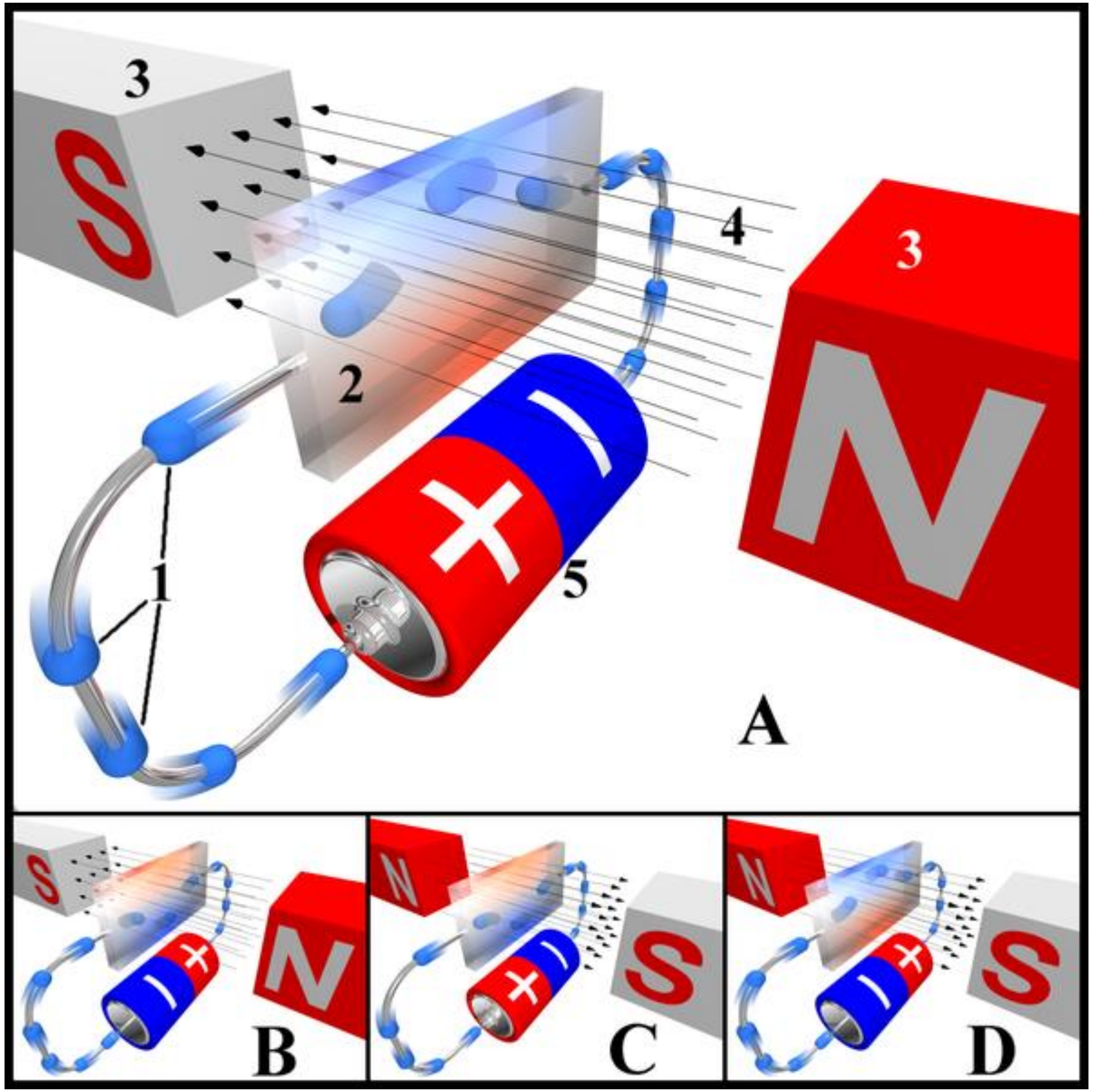


Image source: Wikipedia Commons

Edwin Hall discovered this effect in 1879.

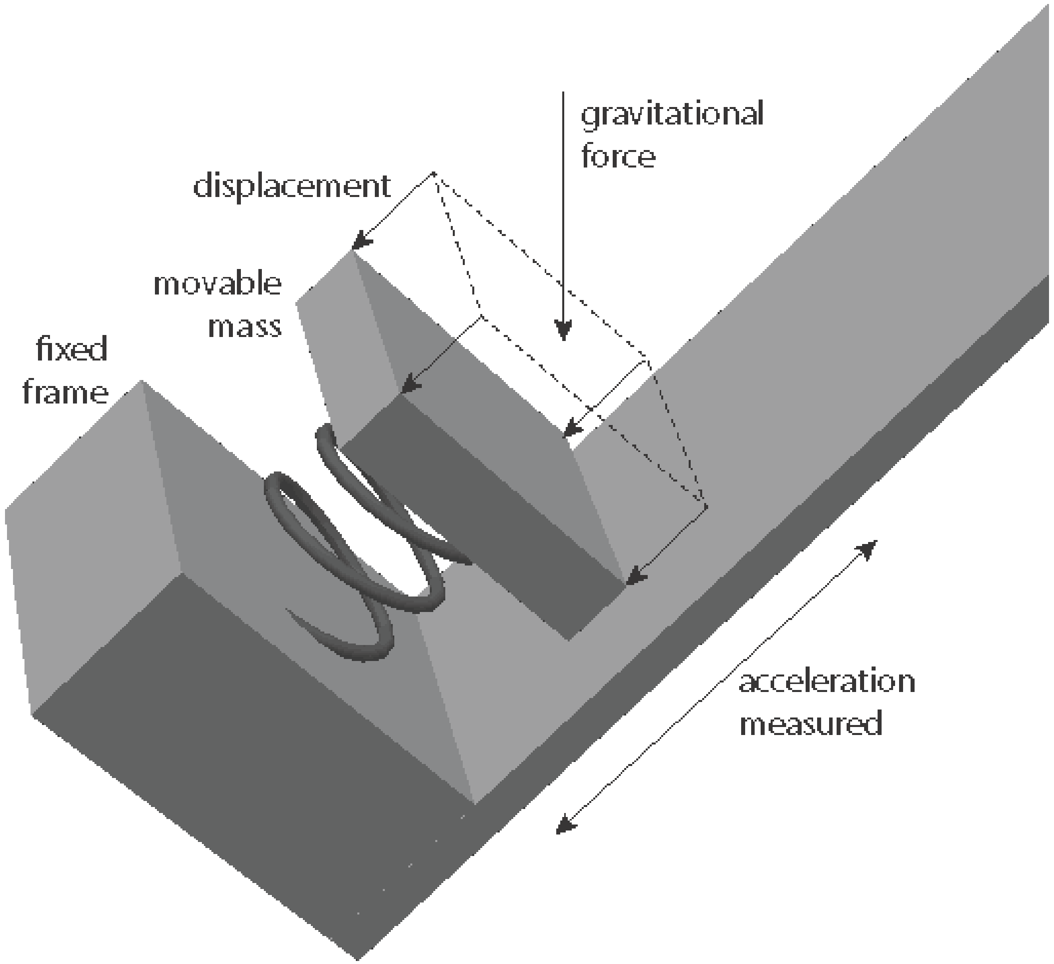
What is Hall Effect and How Hall Effect Sensors Work

Accelerometers

The most common design measures the distance between a plate fixed to the platform and one attached by a spring and damper. The measurement is typically done by measuring capacitance.

Uses:

- Navigation
- Orientation
- Drop detection
- Image stabilization
- Airbag systems

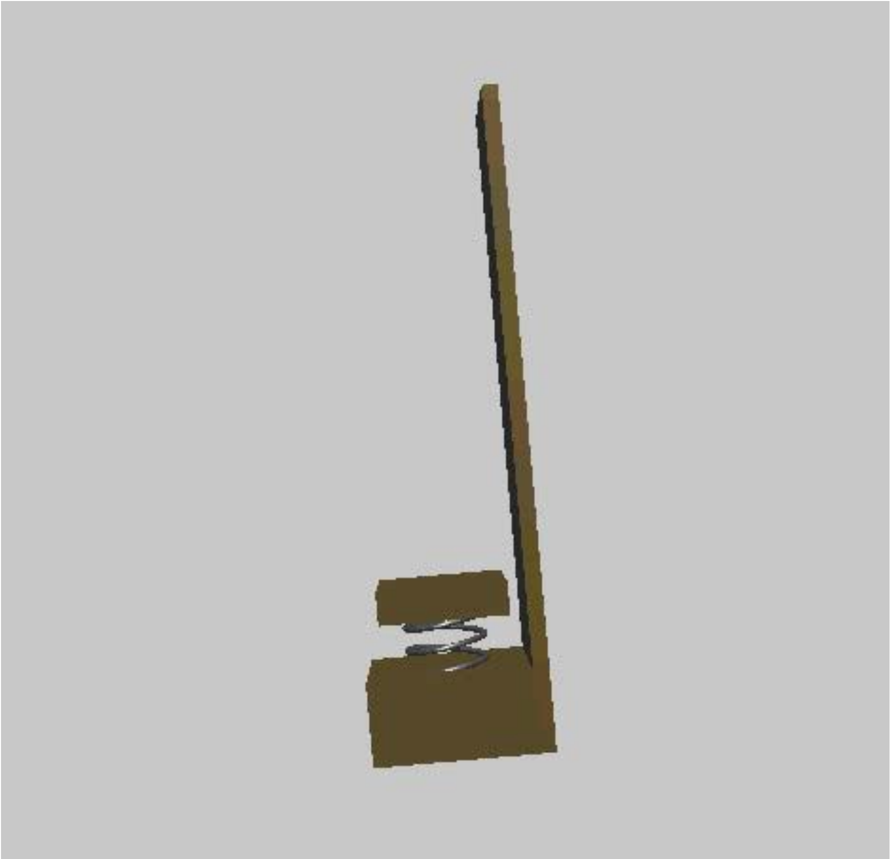


Spring-Mass-Damper Accelerometer

By Newton's second law, F=ma.

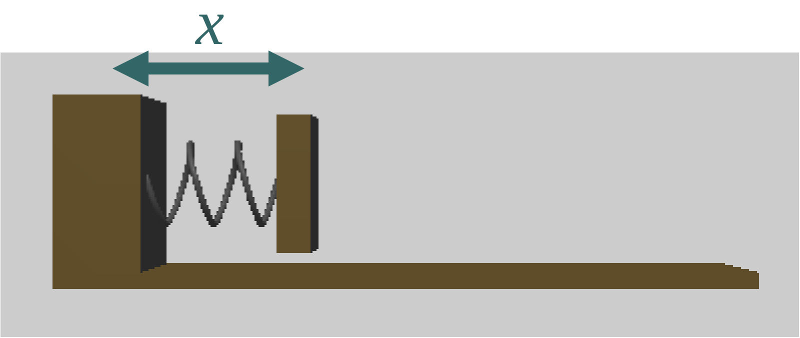
For example, F could be the Earth's gravitational force.

The force is balanced by the restoring force of the spring.



Spring-Mass-Damper System

- mass: M
- spring constant: k
- spring rest position: p
- position of mass: x
- viscous damping constant: c



Force due to spring extension:

$$F_1(t) = k(p - x(t))$$

Force due to viscous damping:

$$F_2(t) = -c\dot{x}(t)$$

Newton's second law:

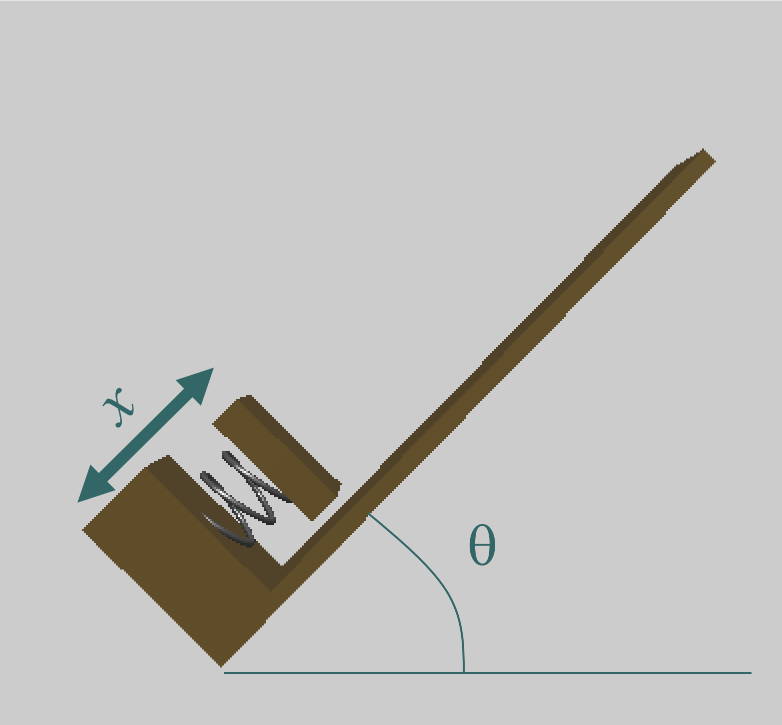
$$F_1(t) + F_2(t) = M\ddot{x}(t)$$

or

$$M\ddot{x}(t) + c\dot{x}(t) + kx(t) = kp.$$

Exercise: Convert to an integral equation with initial conditions.

Measuring tilt



Component of gravitational force in the direction of the accelerometer axis must equal the spring force:

$$Mg\sin(\theta) = k(p - x(t))$$

Given a measurement of x, you can solve for θ, up to an ambiguity of π.

Difficulties Using Accelerometers

- Separating tilt from acceleration
- Vibration
- Nonlinearities in the spring or damper
- Integrating twice to get position: Drift

Given a measurement x of acceleration over time,

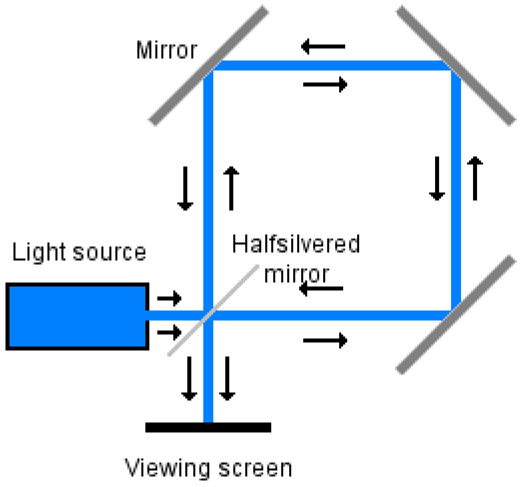
$$p(t) = p(0) + \int_0^t v(\tau) d\tau,$$

$$v(t) = v(0) + \int_0^t x(\tau) d\tau.$$

Position is the integral of velocity, which is the integral of acceleration. Bias in the measurement of acceleration causes position estimate error to increase quadratically.

Measuring Changes in Orientation: Gyroscopes

A gyroscope (from Ancient Greek γῦρος gûros, "circle" and σκοπέω skopéō, "to look") is **a device used for measuring or maintaining orientation and angular velocity**. It is a spinning wheel or disc in which the axis of rotation (spin axis) is free to assume any orientation by itself.



Optical gyros: Leverage the Sagnac effect, where a laser light is sent around a loop in opposite directions and the interference is measured. When the loop is rotating, the distance the light travels in one direction is smaller than the distance in the other. This shows up as a change in the interference.

Inertial Navigation Systems

Dead reckoning plus GPS.

Combinations of:

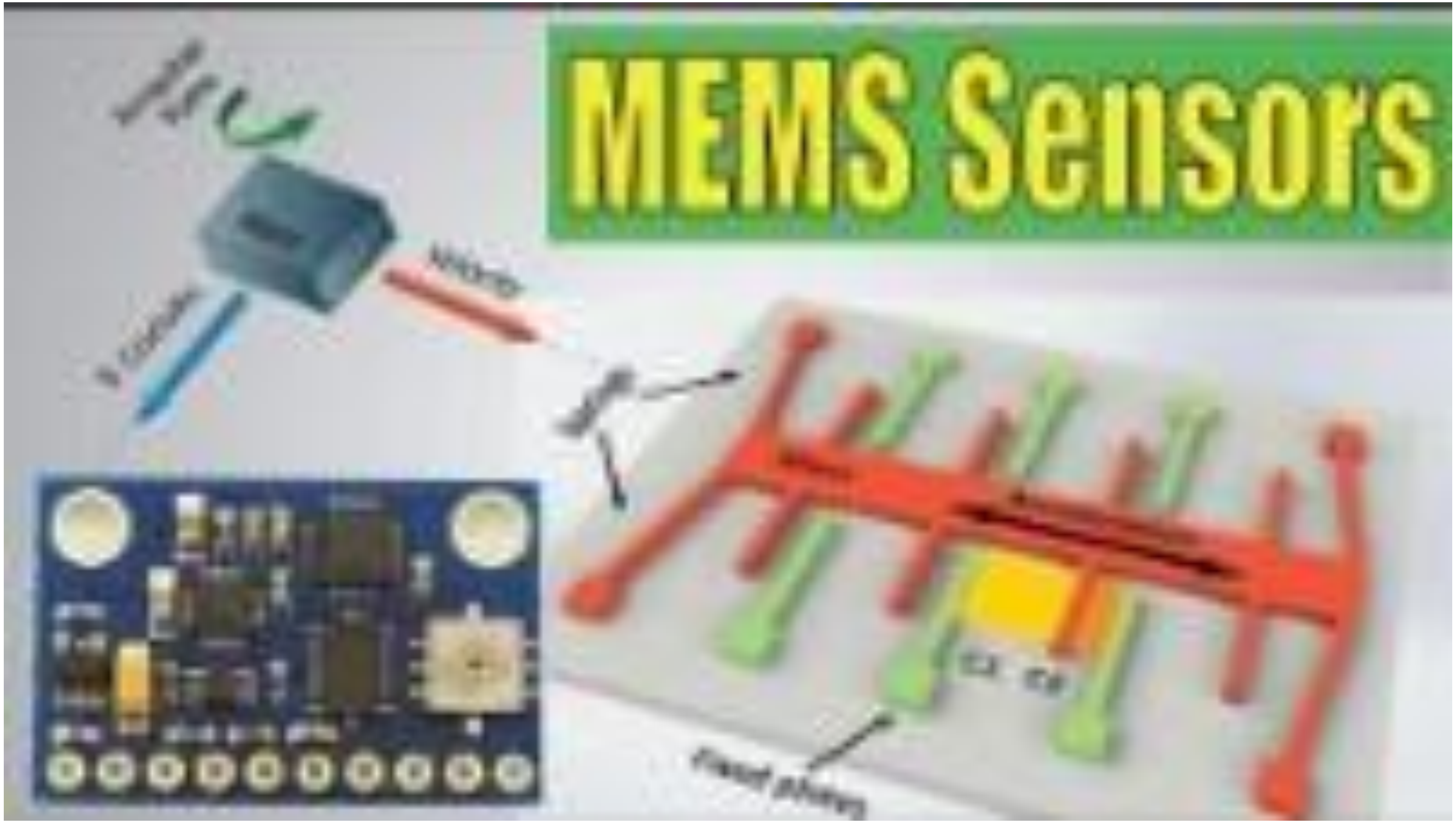
- GPS (for initialization and periodic correction).
- Three axis gyroscope measures orientation.
- Three axis accelerometer, double integrated for position after correction for orientation.

Typical drift for systems used in aircraft have to be:

- 0.6 nautical miles per hour
- tenths of a degree per hour

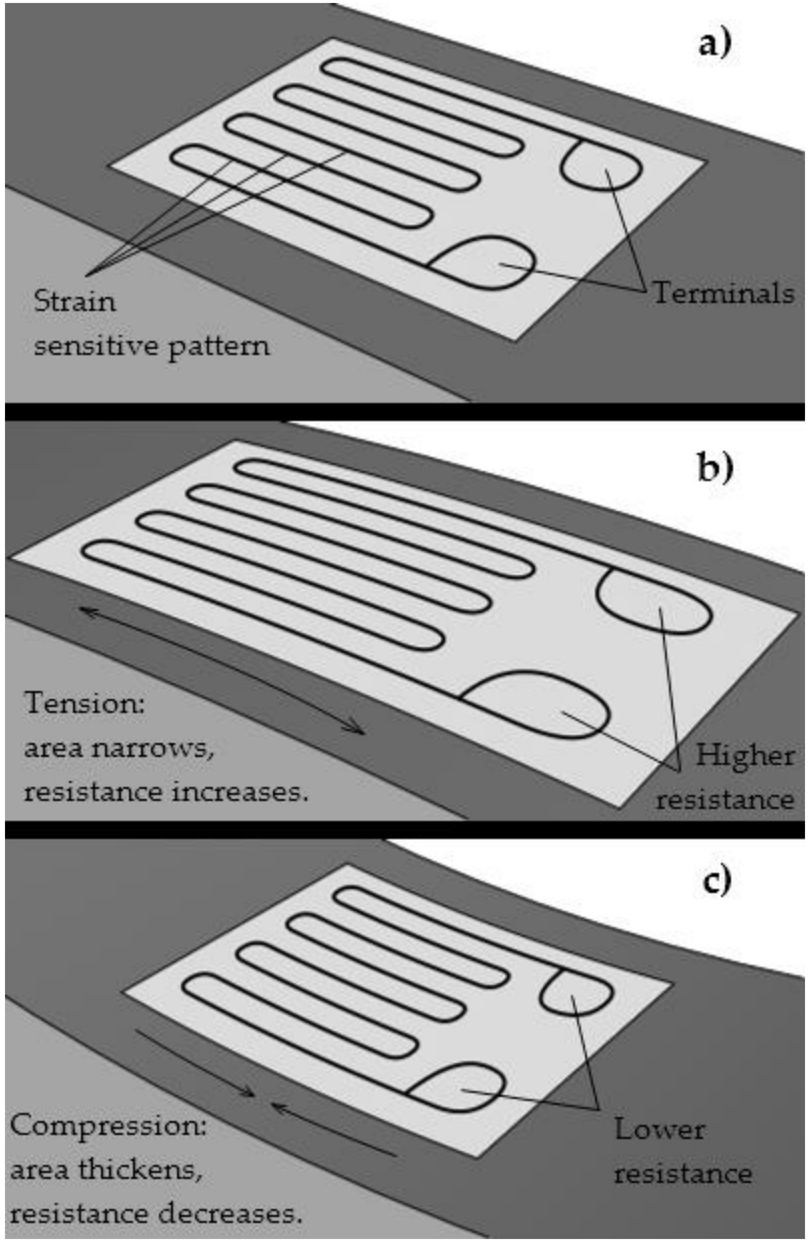
Good enough? It depends on the application!

How MEMS Accelerometer Gyroscope Magnetometer Work & Arduino Tutorial



Strain Gauges

Mechanical strain gauge used to measure the growth of a crack in a masonry foundation. This one is installed on the Hudson-Athens Lighthouse. Photo by Roy Smith, used with permission.



Images from the Wikipedia Commons

IoT, Industry 4.0, Machine-to-Machine (M2M), The Fog

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- Today, sensors and actuators are often packaged with microprocessors and network interfaces, enabling them to appear on the Internet as services.
- The trend is towards a technology that deeply connects our physical world with our information world through such smart sensors and actuators.
- Some technologies for interfacing to sensors and actuators have emerged that leverage established mechanisms originally developed for ordinary Internet usage.
- Representational State Transfer (REST) architectural style: a sensor or actuator may be accessible via a web server

Models of Sensors and Actuators

- Having a good model of a sensor or actuator is essential to effectively using it.
- Linear and Affine Models
- Range and Dynamic Range
- Quantization and Sampling
- Faults in Sensors

Linear and Affine Models with Noise

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- Suppose that a physical quantity $x(t)$ at time t is reported by the sensor to have value $f(x(t))$, where $f : \mathbb{R} \to \mathbb{R}$ is a function.
- Linear Model $f(x(t)) = ax(t)$
- Affine Model $f(x(t)) = ax(t) + b$
- Affine Sensor Model $f(x(t)) = ax(t) + b + n$

  where a is sensitivity, b is bias and n is noise.
- **Sensitivity** specifies the degree to which the measurement changes when the physical quantity changes

Range and Dynamic Range

- Range

$$f(x(t)) = \begin{cases} ax(t) + b & \text{if } L \leq x(t) \leq H \\ aH + b & \text{if } x(t) > H \\ aL + b & \text{if } x(t) < L, \end{cases}$$

where L, $H \in \mathbb{R}$, $L < H$ are the low and high end of the sensor range.

- Dynamic Range

$$D = \frac{H - L}{p}, \qquad D_{dB} = 20 \log_{10}\left(\frac{H - L}{p}\right)$$

- The precision p of a sensor is the smallest absolute difference between two values of a physical quantity whose sensor readings are distinguishable.

Quantization

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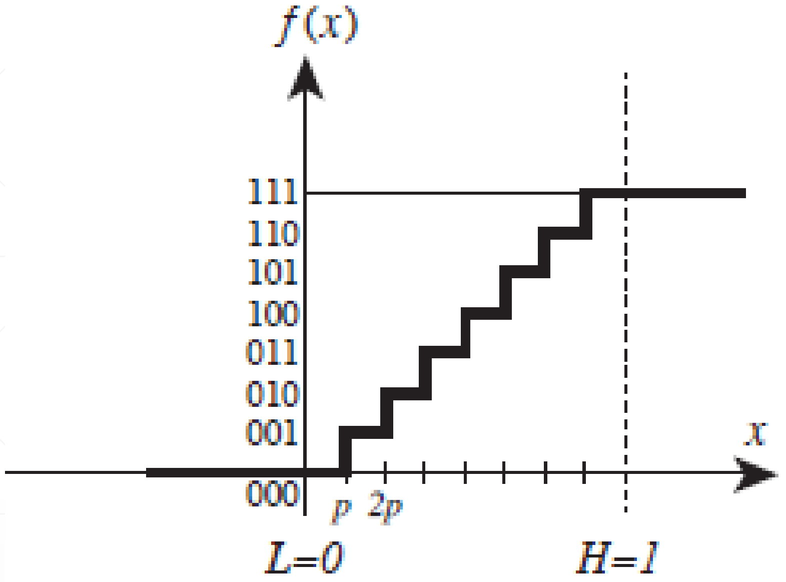
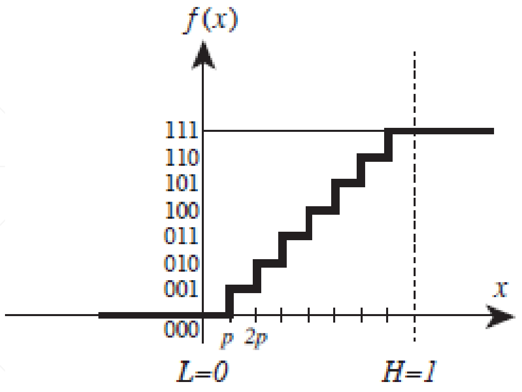
- The actual physical quantity may be represented by a real number $x(t) \in \Re$, but for each such $x(t)$, the sensor must pick one of the 2^n numbers to represent it.
- This process is called quantization.
- For an ideal digital sensor, two physical quantities that differ by the precision ***p*** will be represented by digital quantities that differ by one bit, so precision and quantization become intertwined.



A digital sensor represents a physical quantity using an *n*-bit number, where n is a small integer.
There are only 2^n distinct such numbers, so such a sensor can produce only 2^n distinct measurements.

Example

- The low end of the measurable range is L = 0, and the high end is H = 1. The precision is p = 1/8, because within the operating range, any differ by more than 1=8 of a volt will yield different outputs.



- The dynamic range is

$$D_{dB} = 20 \log_{10}\left(\frac{H - L}{p}\right)$$

- In general, an ideal n-bit digital sensor with a sensor distortion function like that shown in Figure will have a precision given by

$$p = (H - L)/2^n$$

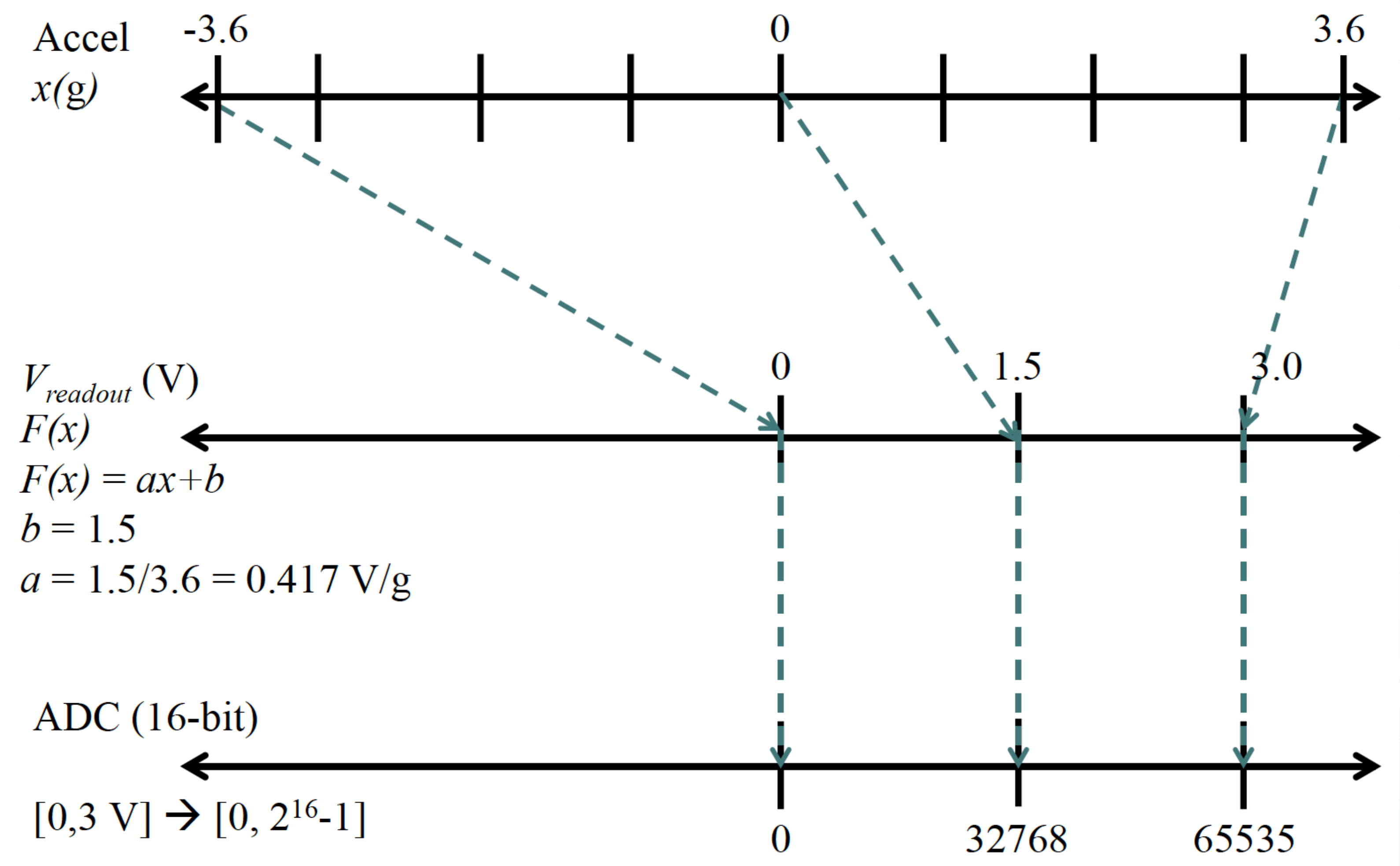
Example

- The dynamic range is

$$D_{dB} = 20\log_{10}\left(\frac{H-L}{p}\right) 20\log_{10}(2^n) = 20n\log_{10}(2) \approx 6n\ dB.$$

- Each additional bit yields approximately 6 decibels of dynamic range.

Bias and Sensitivity



Analog Devices ADXL330 Data Sheet

SPECIFICATIONS

T_A = 25°C, V_S = 3 V, $C_X = C_Y = C_Z$ = 0.1 μF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Inter-Axis Alignment Error			±0.1		Degrees
Cross Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	V_S = 3 V		±0.015		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)	Each axis				
0 *g* Voltage at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		μ*g*/√Hz rms
Noise Density Z_{OUT}			350		μ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz
SELF TEST[6]					

Noise & Signal Conditioning

Parsevals theorem relates the energy or the power in a signal in the time and frequency domains. For a finite energy signal x, the energy is

$$\int_{-\infty}^{\infty} (x(t))^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega$$

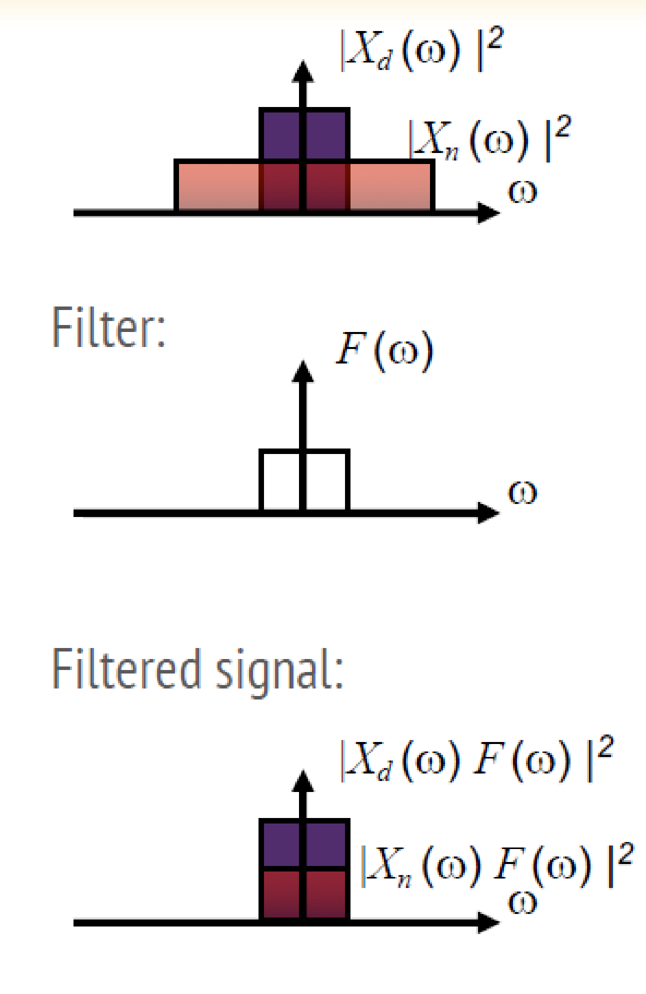
where X is the Fourier transform. If there is a desired part x_d and an undesired part (noise) x_n,

$$x(t) = x_d(t) + x_n(t)$$

then

$$X(\omega) = X_d(\omega) + X_n(\omega)$$

Suppose that x_d is a narrowband signal and x_n is a broadband signal. Then the *signal to noise ratio* (SNR) can be greatly improved with filtering.



Design Issues with Sensors

- **Calibration**
  - Relating measurements to the physical phenomenon
  - Can dramatically increase manufacturing costs
- **Nonlinearity**
  - Measurements may not be proportional to physical phenomenon
  - Correction may be required
  - Feedback can be used to keep operating point in the linear region
- **Noise**
  - Analog signal conditioning
  - Digital filtering
  - Introduces latency
- **Failures**
  - Redundancy (sensor fusion problem)
  - Attacks (e.g. Stuxnet attack)

Lab 2: Ultrasonic Sensor

Tasks and Assignment

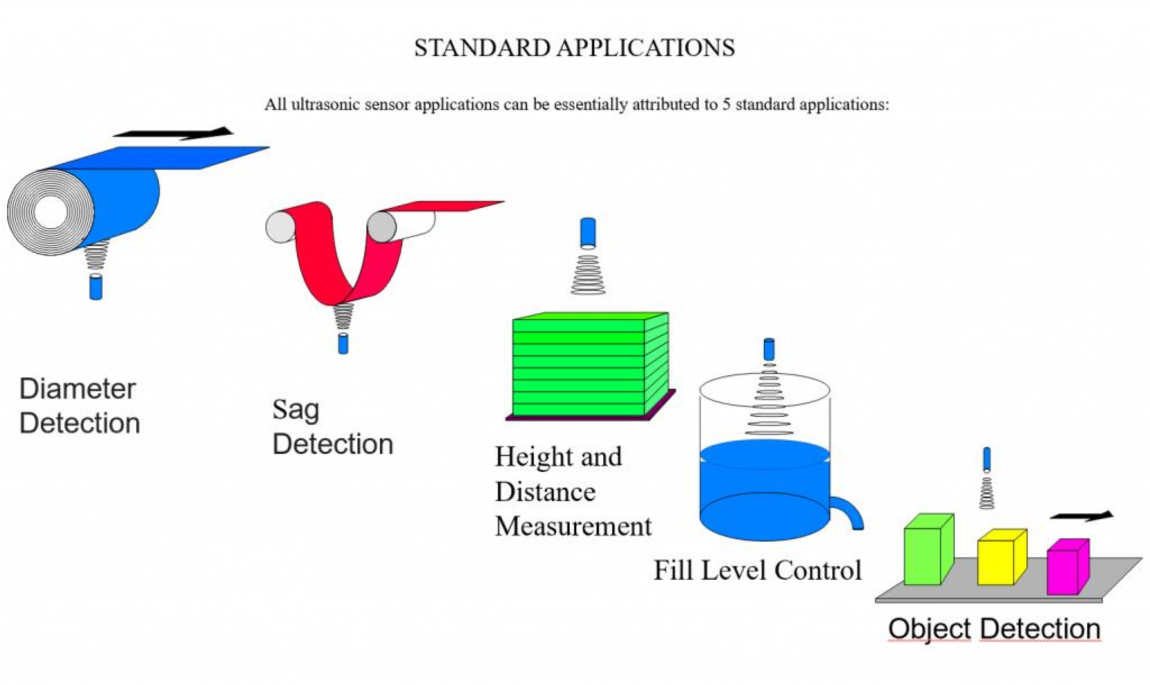
- Task 1: Ultrasonic Sonar HC-SR04-P Setup
- Task 2: Task 2: Showing the Distance in cm
- Lab Assignment:

Components

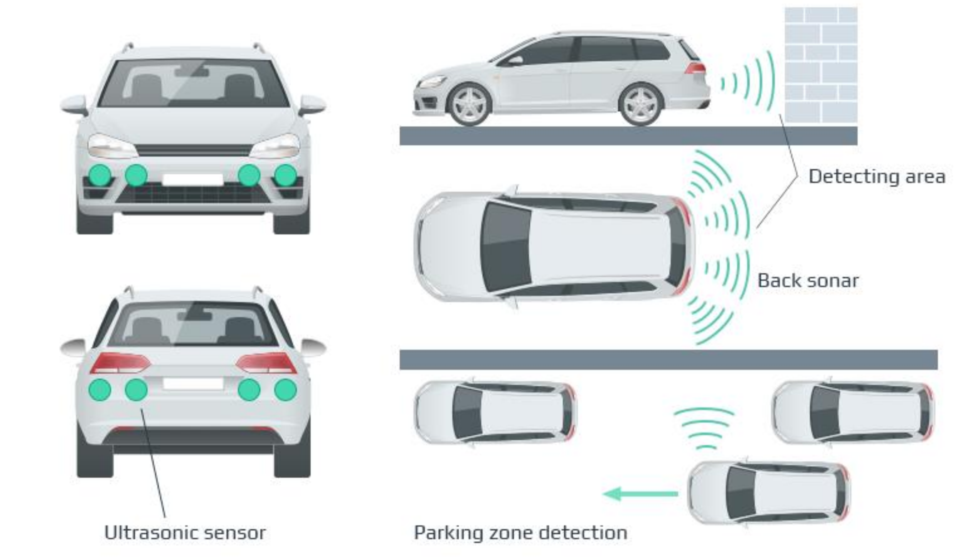
Components	Quatity
Arduino Uno and USB cable	1
Ultrasonic Sonar HC-SR04-P	1
Breadboard	1
Notebook Computer installed Arduino IDE and Python	1

Ultrasonic Sensor Applications

- To measure the level and the distance.
- Quick and easy to implement

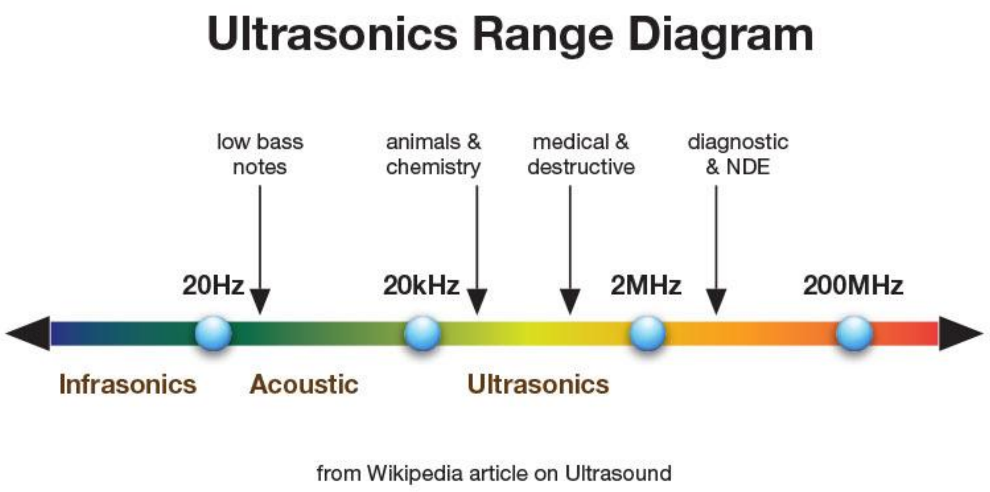


Source: https://www.hoffmann-krippner.com/5-clever-applications-for-ultrasonic-sensors/



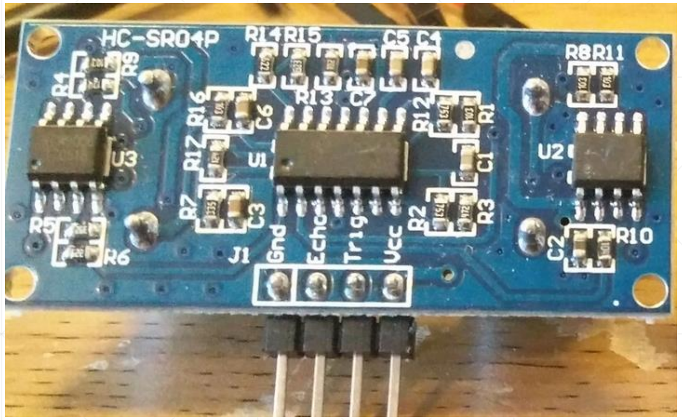
Source: https://www.intellias.com/sensor-fusion-autonomous-cars-helps-avoid-deaths-road/

What is Ultrasound?



- Ultrasound is high-pitched sound waves with frequencies higher than the audible limit of human hearing.
- Human ears can hear sound waves that vibrate in the range from about 20 times a second to about 20,000 times a second.
- However, ultrasound has a frequency of over 20,000 Hz and is therefore inaudible to humans.

Ultrasonic Sonar HC-SR04-P



- HC-SR04-P is a wide voltage working ultrasonic range module. The module dimensions and software are fully compatible with the older version of the HC-SR04.

How Does HC-SR04 (P) Ultrasonic Distance Sensor Work?

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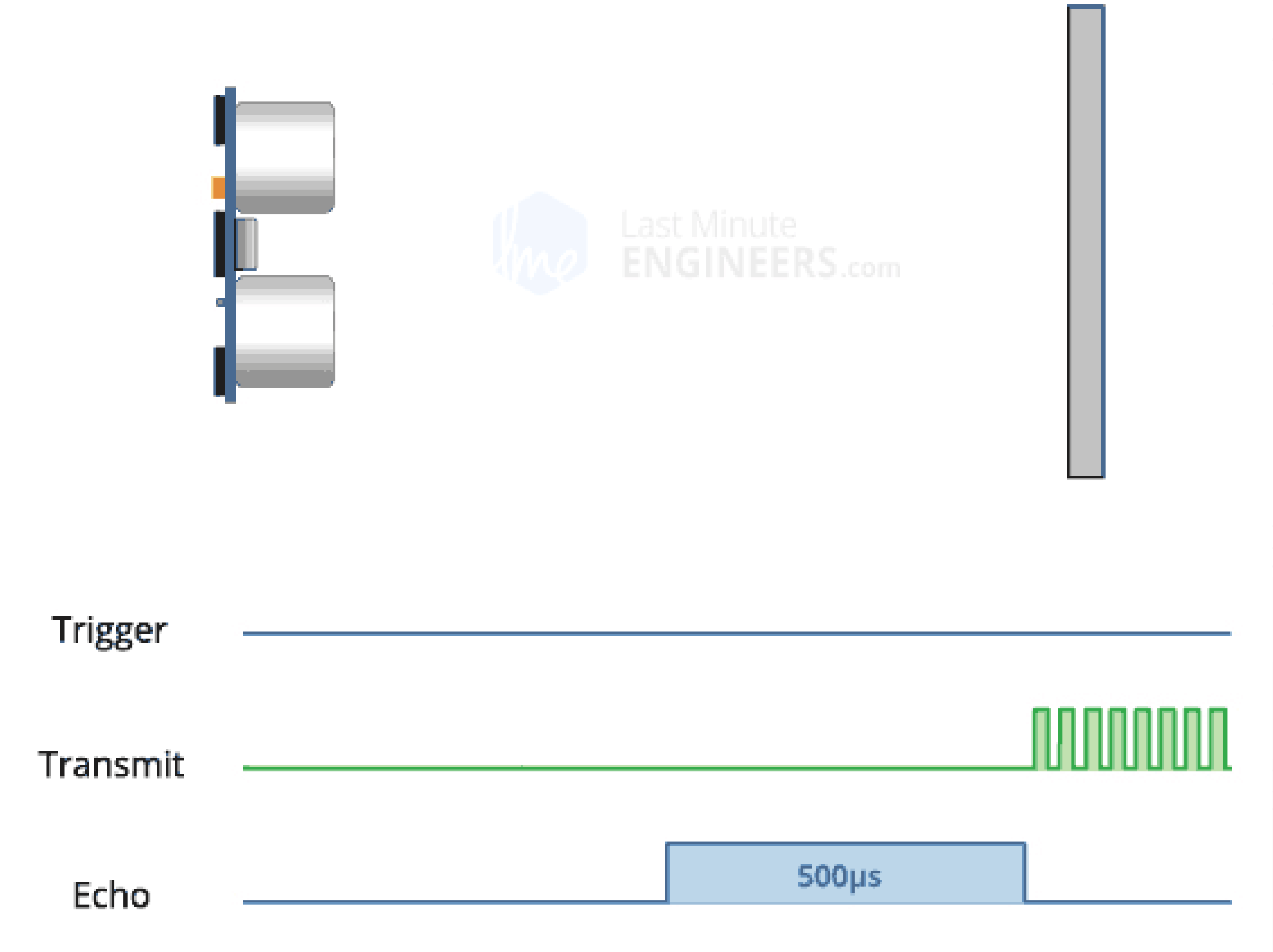
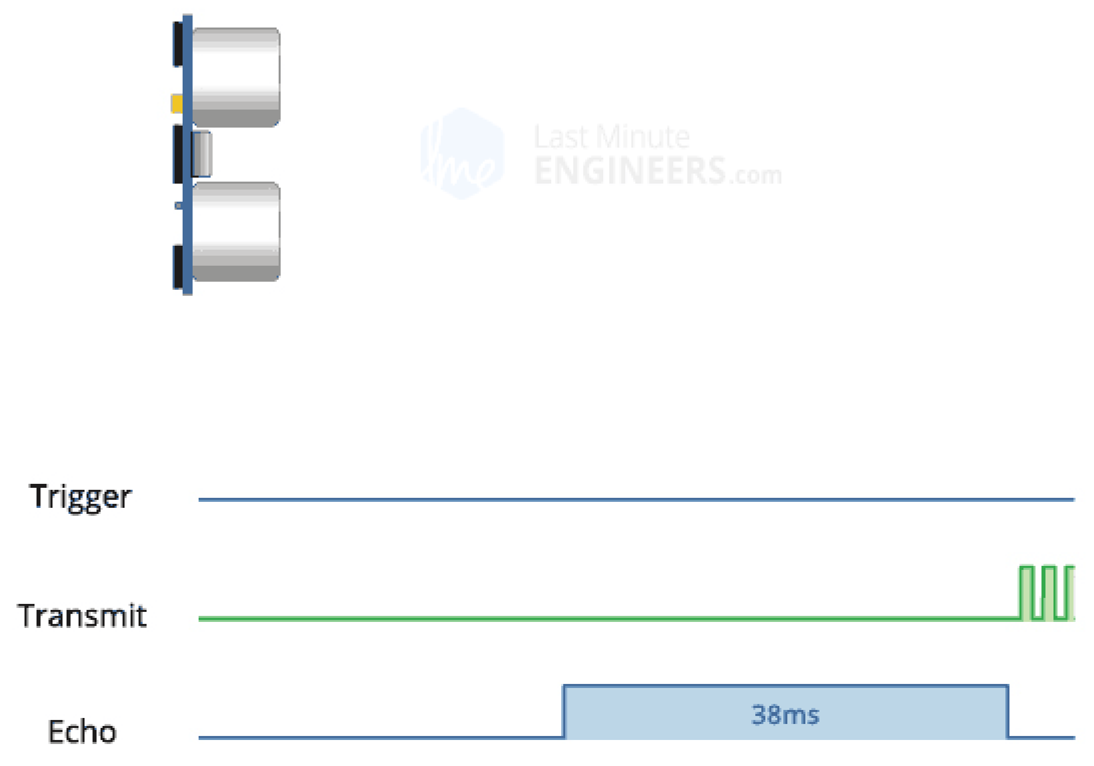
- When a pulse of at least 10 µS (10 microseconds) in duration is applied to the Trigger pin.
- The sensor transmits a sonic burst of 8 pulses at 40 KHz.
- The Echo pin goes HIGH to start forming the beginning of the echo-back signal.
- If those pulses are reflected back the Echo pin goes low as soon as the signal is received.



Source: https://lastminuteengineers.com/arduino-sr04-ultrasonic-sensor-tutorial/

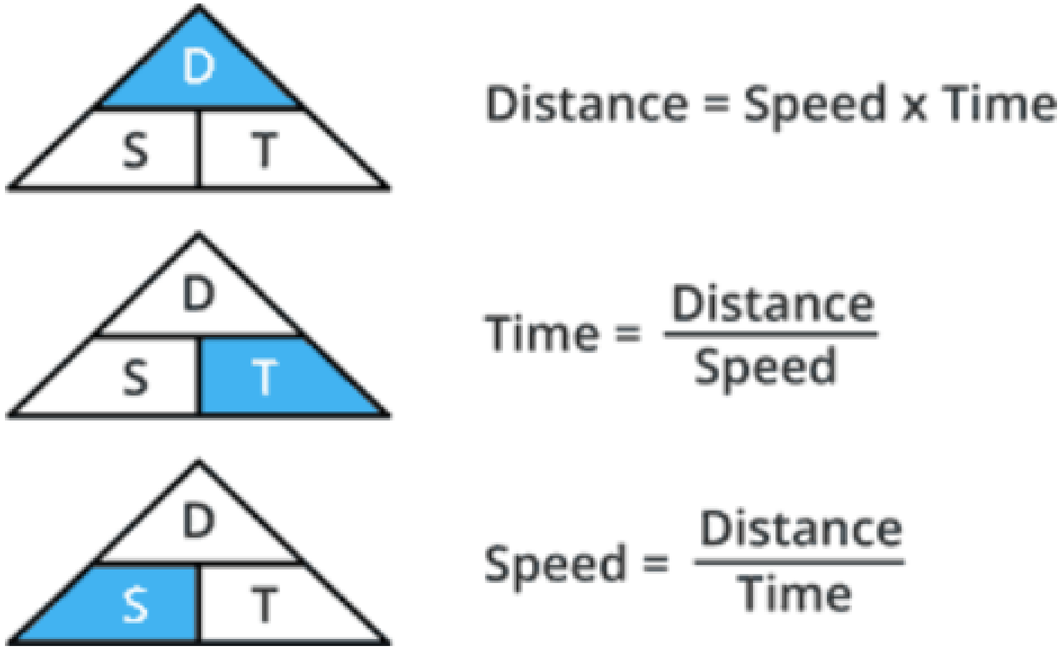
How Does HC-SR04 Ultrasonic Distance Sensor Work?

In case, if those pulses are not reflected back then the Echo signal will timeout after 38 mS (38 milliseconds) and return low. Thus a 38 mS pulse indicates no obstruction within the range of the sensor.



Source: https://lastminuteengineers.com/arduino-sr04-ultrasonic-sensor-tutorial/

Speed, Distance and Time



Altitude	Temperature	m/s	km/h	mph	kn
Sea level	15 °C (59 °F)	340	1,225	761	661
11,000 m−20,000 m (Cruising altitude of commercial jets, and first supersonic flight)	−57 °C (−70 °F)	295	1,062	660	573
29,000 m (Flight of X-43A)	−48 °C (−53 °F)	301	1,083	673	585

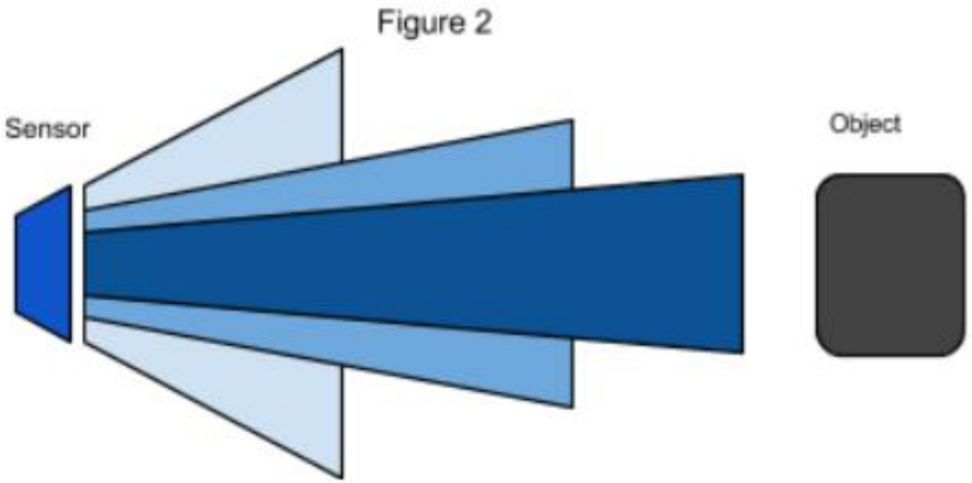
Source: Wikipedia

If time duration = 500 µs at 15’C, what is the distance between the sensor and the object?

The speed of sound depends on a variety of atmospheric conditions, including temperature, humidity and pressure.

Source: https://lastminuteengineers.com/arduino-sr04-ultrasonic-sensor-tutorial/

Ultrasonic Sonar HC-SR04-P



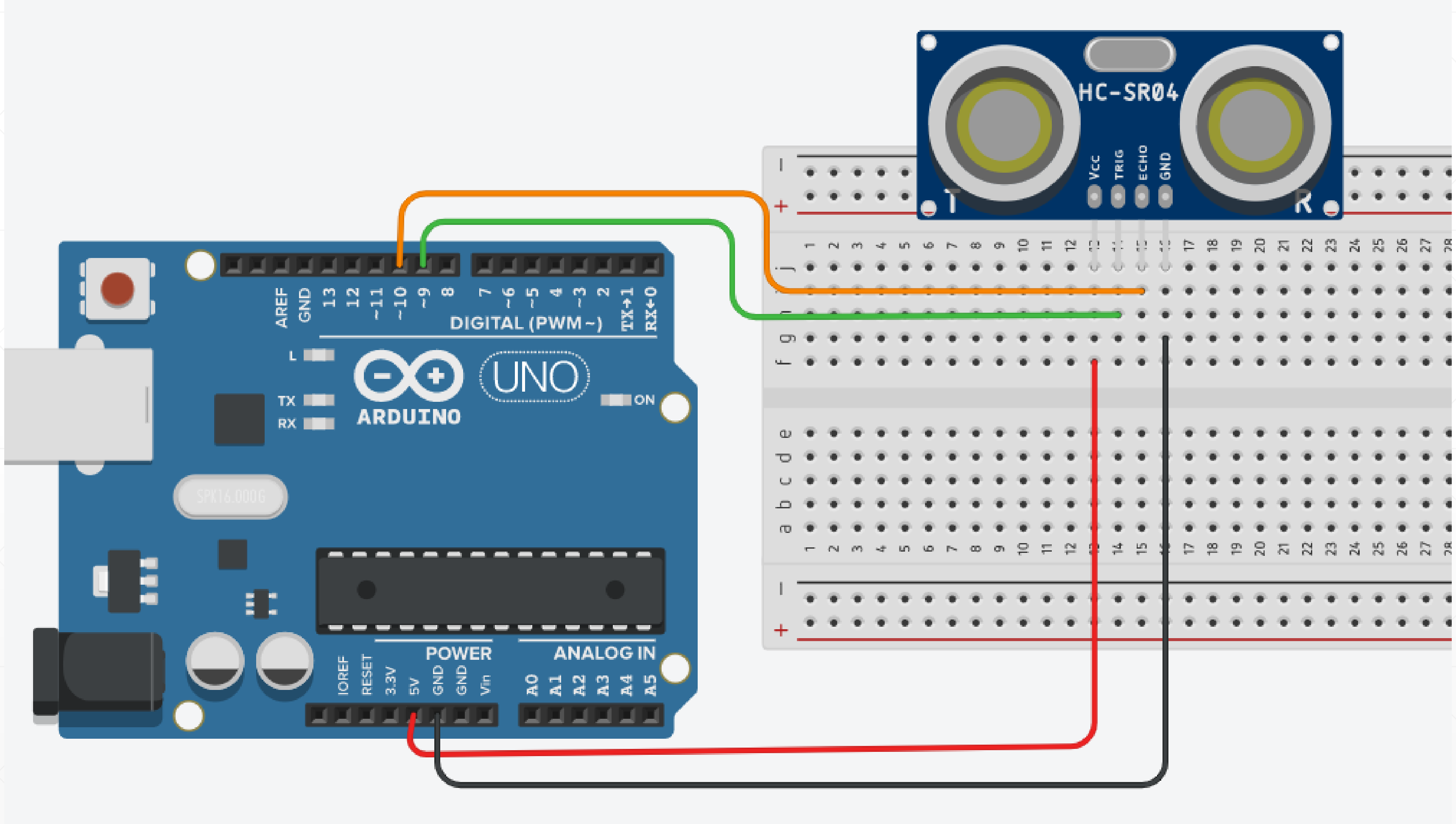
- Ultrasonic sensors have a cone of detection, the angle of this cone varies with distance.
- The ability of a sensor to detect an object also depends on the object’s orientation to the sensor
- If an object doesn’t present a flat surface to the sensor, then it is possible the sound wave will bounce off the object in a way that it does not return to the sensor.

Source: https://datasheetspdf.com/pdf-file/1380136/ETC/HC-SR04/1

The specification of HC-SR04-P Ultrasonic Sensor Module

Name	Values
Operating Voltage	DC 3V – 5.5V
Operating Current	2.2 mA @ 3.3V / 2.8 mA @ 5V
Operating Frequency	40 kHz
Max Range	400 cm @ 3.3V/ 450 cm @ 5V
Min Range	2cm
High precision	0.3 cm + 1%
Measuring Angle	< 15’
Trigger Input Signal period	10uS TTL pulse
Dimension	45*20*15mm

Task 1: Ultrasonic Sonar HC-SR04-P Setup



Trigger to Pin 9
Echo to Pin 10

Arduino Code for Reading from Sensor and Sending to Serial

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```
// defines pins numbers
const int trigPin = 9;
const int echoPin = 10;
// defines variables
long duration; // received value from sensor
int SampleTime = 1000; // Sampling Time

void setup() {
  Serial.begin(9600); // Starts the serial communica
  pinMode(trigPin, OUTPUT); // Sets the trigPin as a
  pinMode(echoPin, INPUT); // Sets the echoPin as ar
  pinMode(13, OUTPUT);
}
```

```
void loop() {
  if(Serial.available()>0)
  {
    String incomingBytes = Serial.readString();
    SampleTime = incomingBytes.toInt();
    Serial.println(incomingBytes);
  }

  // Clears the trigPin
  digitalWrite(trigPin, LOW);
  delayMicroseconds(2);

  // Sets the trigPin on HIGH state for 10 micro seconds
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);

  // Reads the echoPin, returns the sound wave travel time in microseconds
  duration = pulseIn(echoPin, HIGH);

  // Prints the distance on the Serial Monitor
  Serial.println(duration);
  delay(SampleTime-1); // Sampling Time
}
```

Test with Serial Monitor and check the number that displays on the monitor by blocking or unblocking an object in front of the sensor. Type 500, 1000, 2000, 4000 in the serial monitor's input, check the changes,

Python Code for Reading the Sensor Data from Arduino Board

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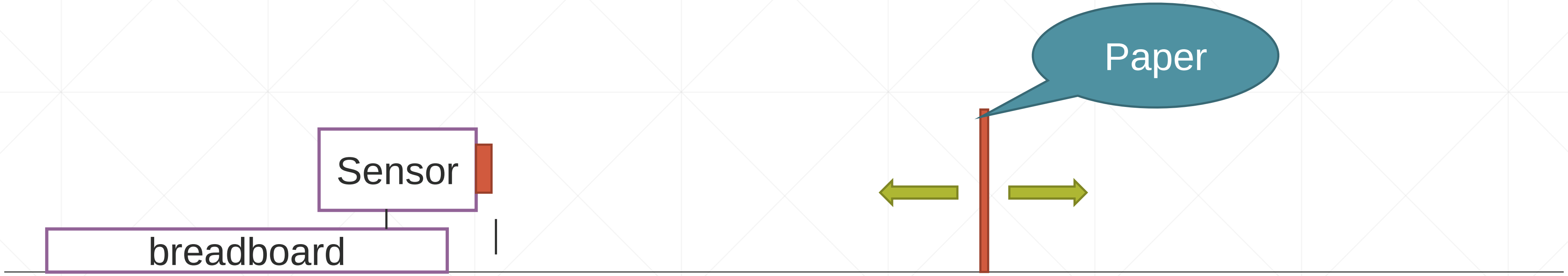
```
import serial
from datetime import datetime
import time
import keyboard

SampleTime = '500' # in milli second

with serial.Serial('COM3',9600) as serArd:
    print(f"The Arduino board is connect through {serArd.port}")
    time.sleep(2)
    serArd.reset_input_buffer()

    if (serArd.writable()):
        serArd.write(SampleTime.encode())
        print(serArd.readline().decode().rstrip())
    while not keyboard.is_pressed('q'):
        if (serArd.inWaiting() > 0):
            #print(serArd.readline())
            rec_time = datetime.now().strftime('%H:%M:%S.%f')
            myData = serArd.readline().decode().rstrip()
            try:
                myData = float(myData)
                print(f"raw data at {rec_time} : {myData}")
            except:
                print("No data")
```

Sampling Time can be changed depend on the applications.

for record the receive time



Q1. Find the minimum number and the maximum number that display on the monitor by placing a piece of paper in front of the sensor.

Q2. Block the sensor totally with the paper and check the number. Why is it so large?

Finding the Speed of Soundwave

- Place an object (a block/box/paper) in front of the sensor at 10 cm distance or (any distance it can be measured).

- Use a scale ruler to get the accurate distance or a paper indicating the distance.
- Run the python program and record the duration data. (Note that you need to record at least 10 measured numbers)

Q3. Compute the speed of sound wave using the average value of the duration data.

Task 2: Showing the Distance in centimeter (cm)

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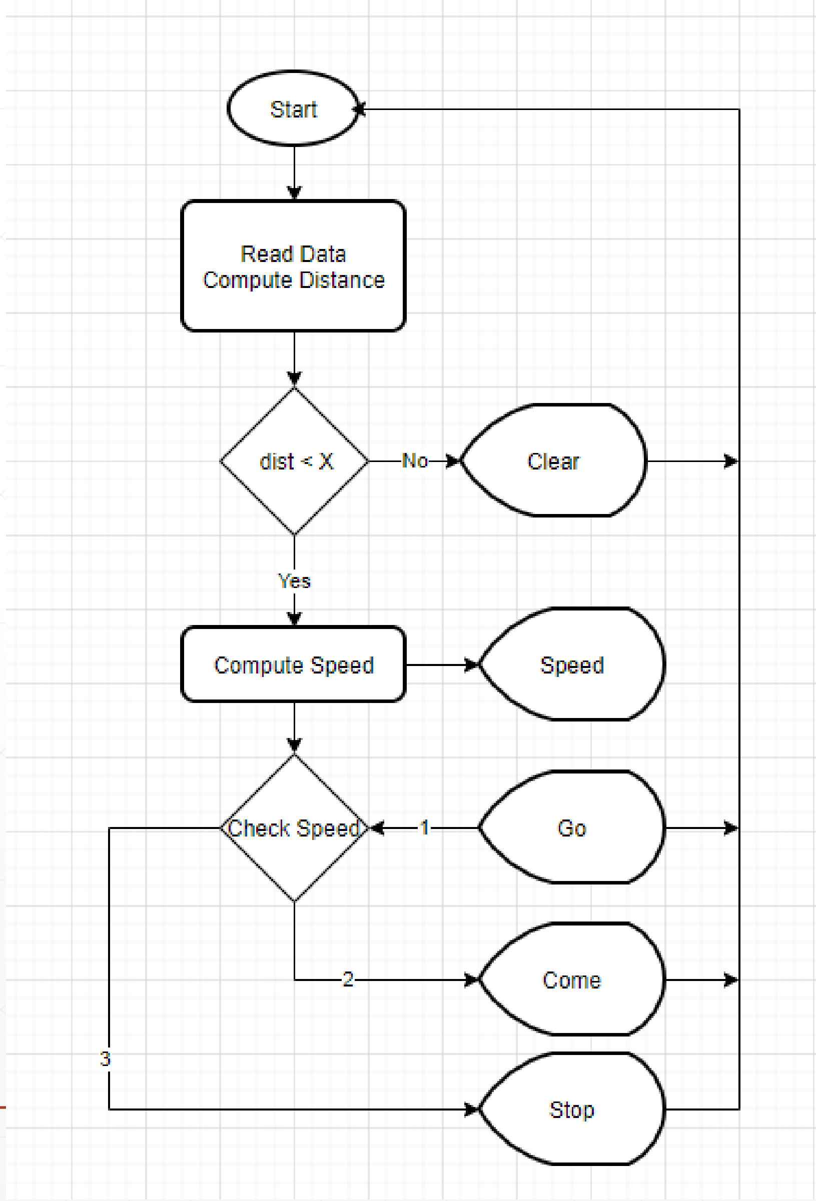
- Modify your python code as follow
  - Define speed of sound (m/s) or (cm/s) or (cm/µs) with the value you calculated in Q3.
  - Convert the duration time to the distance in cm using the speed equation.
  - Display your result like "The distance is 5.80 cm at 16:34:35" at the Console.
- Q4. Find the minimum and maximum distance the system can detect and compare with the max and min range from the specification table.
- If the values of the distance for a fixed object fluctuate, modify your code to generate the stable value.
- Q5. Show your result to the TA Instructors and submit your code online.

Assignment: Movement Detector and Speed System

- Modify both Python and Arduino codes as necessary to do the followings,
  - Check if the object is in front of the sensor or not within the specified distance.
  - If yes,
    - Compute the speed of an object that is moving toward or far away from the system.
    - Display the speed on the console like "The current speed is 3.84 cm/s within 0.50 s".
    - Decide if it is moving toward, far away or stops from the system based on the value of speed and then describe its action on the console as below.
  - If not, just send "Clear" message on the console.
  - Show your result to TA instructions and explain how your program work.

Assignment: Movement Detector and Speed System

Note: it is important to consider the parameters such as the values of distance, speed etc. in making conditional loop. You can define any values to them, but they must be reasonable.



References

- Lee, Edward & Seshia, Sanjit. (2011). Introduction to Embedded Systems - A Cyber-Physical Systems Approach.
- Lecture Note Slides from EECS 149/249A: Introduction to Embedded Systems (UC Berkeley) by Prof. Prabal Dutta and Sanjit A. Seshia
- Lecture Note Slides from Embedded System Hardware by Prof. Peter Marwedel, TU Dortmund University