

PhysicsKIT

4STEM

WAVES

Lesson Plan
Emphasys Centre



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1. Lesson Plan: WAVES

Calculating the distance between objects, using sensors.

1.1 Short description

In this module, you will learn about waves and the differences between their types. Also, the theory of how waves travel and behave when travelling through different mediums will be explored. The learning material will cover wave equations, longitudinal waves, transverse waves, as well as their properties, similarities and differences. Along with the teaching material, you will find some experiments that you can perform using the Raspberry Pi and various other sensors. In addition, resources, references and other useful material have been included at the end of the chapter to improve your learning and understanding of the topic. By the end of this module, you should have a basic understanding of the field of waves and the theory around them.

1.2 Learning objectives and links to curriculum

The main learning objectives of this lesson are:

- Understand the behaviour of waves when travelling through different mediums.
- Recognise and analyse different types of waves.
- Understand wave equations.
- Building a system of sensors, connected with the Raspberry Pi.
- Use a programming code in Python to do some experiments.
- Analyse and compare the results of the experiments.

The domains/topics to which this lesson plan can be linked are:

- Informatics / Informatics: processing units and peripherals, interfaces, programming language and main coding structures
- Technology: electronics, open-source hardware and software
- Mathematics: the calculation procedure (equations)
- Physics: Waves (types, analysis)

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1.3 Duration

The duration of this lesson plan is estimated to be about 135 mins, i.e. three didactic periods.

- 45 minutes – Introduction to waves and their equivalent equations.
- 45 minutes – Explanation of the components used and how the code works.
- 45 minutes – Experiments and results.

2. Lesson Plan

The lesson plan is divided into three phases, which are the introduction, preparation and conclusion. As a follow-up, there is also an optional exercise at the end.

2.1 Introduction

Waves exist all around us, yet when people are asked to name a few examples of waves most of them can only name sound waves and microwaves. But what exactly is a wave to begin with?

Waves are a form of disturbance that travels from one location to another. They transfer energy and information, but without transferring matter.

Did you know that Wi-Fi uses radio waves to transmit information between the router and your phone?

However, not all waves work in the same way. Some waves can travel long distances, some waves can travel short distances and some can only be detected or produced by using special scientific equipment.

The teacher or educator of this module can use the learning material and must cover the following topics:

- What is a wave
- Types of waves
- Anatomy of waves
- Properties of waves
- Wave equations
- Reflection, Refraction and Diffraction

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Types of Waves

Transverse Waves

Transverse waves can be best described as waves that vibrate or oscillate at right angles of the direction in which the wave or energy is moving.

Examples: Light waves, water waves (ripples), S-waves from earthquakes.

Longitudinal Waves

Longitudinal waves are the opposite of Transverse, as their vibration and oscillations are along the direction in which the wave or energy is moving.

Examples: Sound waves, Compression waves.

The following diagram (Figure 1) visually demonstrates the differences between the two waves by using a slinky coil.

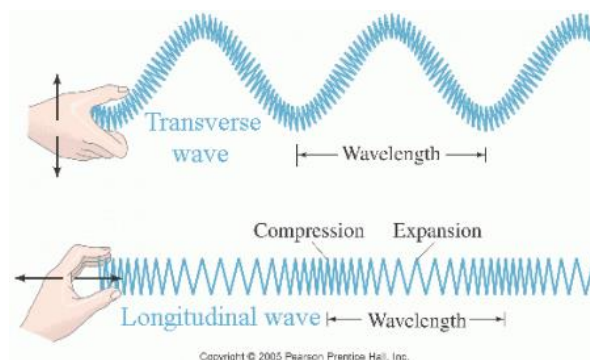


FIGURE 1

The anatomy of Waves

The three main properties of waves are amplitude, wavelength, and frequency. To be able to further explain these terms, it's important to first identify some waves elements that appear on graphs.

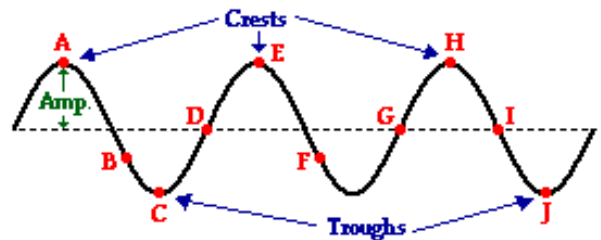


FIGURE 2

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The example above (figure 2), is an example of a transverse wave. The horizontal dotted line at the centre of the diagram represents point zero and at that point, the wave reaches equilibrium (also known as rest position). Points A, E and H are what is known as crests, which translates to the maximum positive point on the graph, whereas points C and J which show the maximum negative point on the graph are known as Troughs. Alternatively, they are sometimes referred to as maxima (crest) and minima (trough) and the point where the gradient on the graph changes is known as the turning point (in figure 2 that would be points A, C, E, H, J).

Properties of Waves

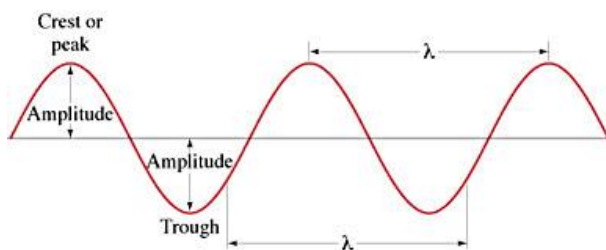


FIGURE 3

Amplitude

The maximum amount of displacement is known as amplitude. It is usually symbolized using the capital letter A. It can be measured by calculating the change in value from the point of equilibrium and the peak of the wave. To better understand this, you can think of it by using music as an example. In sound waves, the higher the amplitude, the higher the loudness and therefore the louder the music.

Wavelength

The wavelength as the name suggests is the length of one full wave. It is the distance between two consecutive crests or troughs. In order to calculate the value of half a wavelength, it would be the distance between a crest and the next available trough or vice versa. It is symbolized using the Greek letter lambda (λ). Two examples of wavelengths can be found in figures 3 and 4.

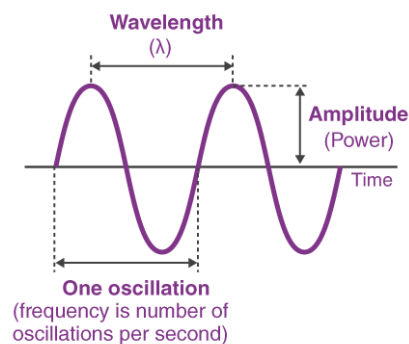


FIGURE 4

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Frequency

The amount of time it takes for one oscillation to occur is known as the frequency of the wave. Frequency (f) is measured using hertz (Hz), which translates to the wave's rate (how many waves per unit time). Frequency is also known as the number of oscillations per unit time (waves per second). For example, a wave source that can create 10 complete waves each second has a frequency of 10 Hz.

Did you know? The audible human spectrum is between 20 Hz – 20 kHz (value may slightly vary per person).

Tip: 1 kHz = 1000 Hz

Oscillation

A complete oscillation occurs when a wave begins from its resting position and then returns to it (Figure 4). The time for one oscillation is referred to as the Period (T). The period and frequency are reciprocal of each other.

$$Period = \frac{1}{Frequency}$$

OR

$$Frequency = \frac{1}{Period}$$

FIGURE 5

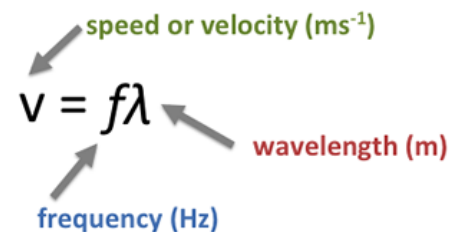
Wave Equations

Speed

Now that we have looked at different elements associated with waves, let's take a look at how these elements relate to each other. As you may know from other modules, Speed = distance / time. This equation applies to waves as well but you might be thinking "how can I find the speed if I don't know the distance? Is distance related to waves? We didn't learn anything about distance". That is true, but also wrong at the same time. We did not mention distance, but we did talk about wavelength and frequency which can help us derive it.

Remember? Frequency is the number of oscillations per unit time and wavelength is the length of one full wave.

Therefore, if we know how many waves there are in a second, and the length of each wave, then we can calculate the distance by multiplying the two. Since frequency is calculated per second, X divided by 1 is still X. This means that by simply multiplying the frequency and the wavelength we can get the speed of a wave (Figure 6).



$$v = f\lambda$$

FIGURE 6

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Tip: Wavelength is measured in metres and speed in m/s. However, if the value of the wavelength is in cm, you might have to give the speed in cm/s or make adjustments to your calculations.

Distance

One of the first things we learn in physics is that we can calculate the distance between two objects by multiplying speed and time.

$$\text{Distance} = \text{speed} * \text{time}$$

Waves can be used to calculate the distance between two objects. Since we already know how to calculate the speed of a wave, all we need to do is multiply it by the time it takes for it to reach an object.

Reflection, Refraction and Diffraction

Reflection

When a wave hits an object it cannot pass through, it is reflected on the object's surface. The angle at which the wave hits the barrier is calculated at 90° from the object's surface from the direction the wave came from and it is called the angle of incidence (i). When the wave is reflected, it is reflected at an angle exactly the same at the angle of incidence and it is known as the angle of reflection (r). Figure 7 demonstrates an example of how a wave gets reflected on a flat surface. The arrows on the diagram show the travelling direction of the wave. As you can see the angle of incidence and the angle of reflection are exactly the same.

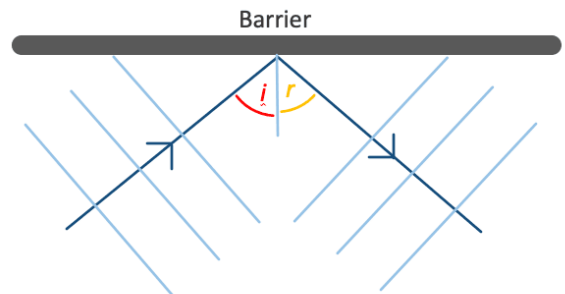


FIGURE 7

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Did you know? In the case of a perfect mirror, the light will be reflected perfectly. Shiny objects shine because they have smooth surfaces and can reflect light waves in the same directions. Whereas uneven/rough objects disperse the waves in different directions which can make objects appear dull. This process is also known as diffuse reflection (Figure 8). When you wax a car, it appears shinier because the wax fills in the small holes on its surface and makes it smoother, causing less light diffusion.

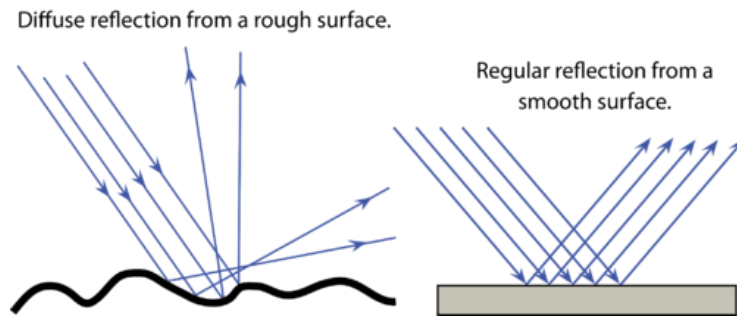


FIGURE 8

Refraction

Waves that enter an object undergo what is called refraction. Refraction is simply the change of direction at which the wave is travelling when it enters a medium. However, the speed of the wave might also be affected as the wavelength of the wave might increase or decrease depending on the medium at which is travelling. The faster the wave is travelling, the bigger the wavelength, but if the wave is slowed down, its wavelength will decrease. Keep in mind that depending on the barrier or medium the wave comes in contact with, it is possible for partial reflection to occur during refraction and vice versa. Figure 9 illustrates this case and it also shows how a ray of light changes direction as it enters and exits a medium.

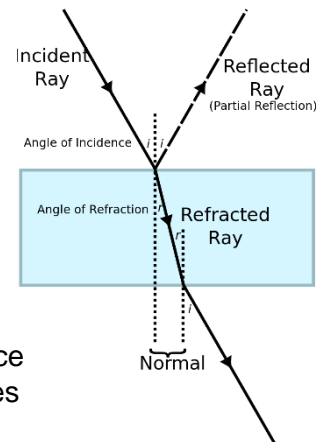


FIGURE 9

Did you know? The reason you cannot hear people clearly when you are underwater in a swimming pool is because the sound waves are affected by refraction.

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Diffraction

Diffraction is defined as a spreading wave around an obstacle. It occurs when a wave passes by an obstacle or opening that is smaller or the same size as the wavelength. According to Huygens' principle, when the wave passes through the obstacle, we can see on the other side bright and dark fringes spread across the screen, in a wide area bigger than the area of the normal wave. Diffraction can be performed with one slit, two slits or multiple slits. In real life, diffractions can occur in the sea when water is passing from a small gap and we can see circle waves, or when the clouds block the sun and crepuscular rays are created.

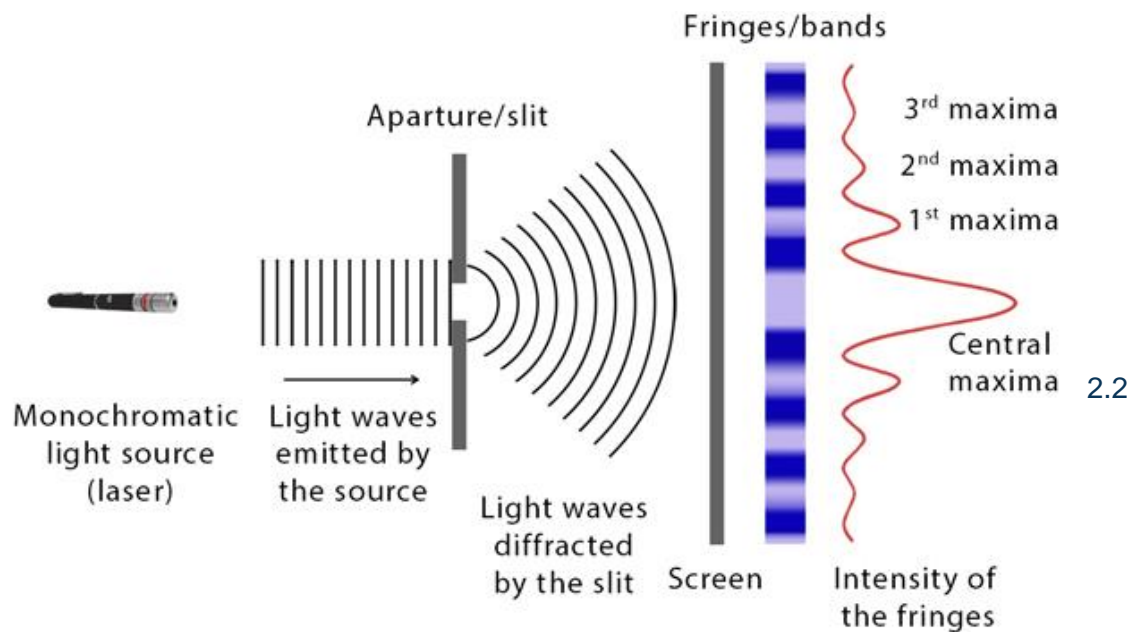


FIGURE 10

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Preparation

This section will provide the hardware setup as well as the coding in order to connect and program using Python an ultrasonic sensor for measuring the distance from an object. We will learn how to connect the HC-SR04 ultrasonic sensor to the GPIO pins and measure the distance by using the speed at which sound waves travel. Apart from the sensor, a few jumper wires, a GPIO Extension board and a breadboard, no other tools are needed.

Before we begin the experiments, some background knowledge of the electronics we'll be using is required. First of all, a Raspberry Pi is an open-source, fully functional, credit card-sized computer made by the Raspberry Pi Foundation.

The Raspberry Pi has 40 open GPIO pins which will be used for connecting and controlling electronics and sensors. GPIO stands for "General Purpose Input/Output" which means that these pins send and receive electrical signals to control hardware or read sensor data.

Secondly, we use Python to program these sensors. Python is an object-oriented programming language. No prior knowledge in programming is required as the programs we will create are very simple and use the simplest of Python commands.

Now let us dive into the experiments.

Experiments – Measuring Distance with an ultrasonic sensor

For this experiment we will need:

- Raspberry Pi 3 (RPi)
- 1 GPIO Extension Board
- 1 Full+ Breadboard
- 1 Ultrasonic Sensor – HC SR04
- 4 Jumper Wires (Male to Female)

The HC-SR04 Ultrasonic Sensor uses SONAR (Sound Navigation and Ranging) to determine the distance of an object. This technique is also what bats use and enables them to 'see'. The particular sensor offers excellent contactless distance detection with high accuracy (an accuracy of 3mm) from 2cm to 400cm. This sensor is widely used in a variety of applications that require distance measurement or object detection.

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The HC-SR04 Ultrasonic sensor is a four-pin module with the pin names Vcc, Trigger, Echo, and Ground, as shown below:

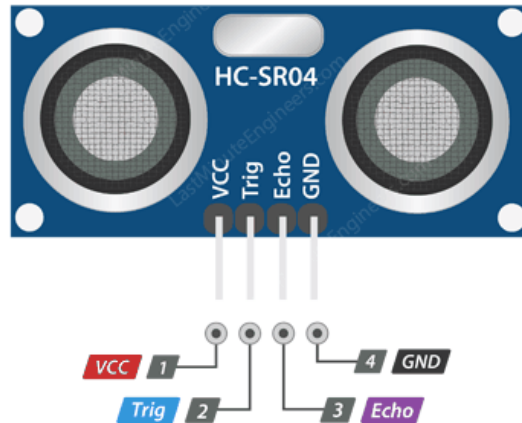


FIGURE 11

- VCC is the power supply for HC-SR04 Ultrasonic distance sensor which we connect the 5V pin on the Raspberry Pi.
- Trig (Trigger) pin is used to trigger the ultrasonic sound pulses.
- Echo pin produces a pulse when the reflected signal is received. The length of the pulse is proportional to the time it took for the transmitted signal to be detected.
- GND should be connected to the ground of Raspberry Pi.

How it will work in theory:

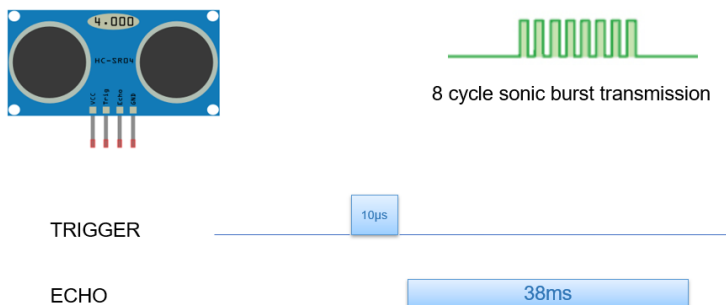


FIGURE 12

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When a pulse of at least 10 μs (10 microseconds) in duration is applied to the Trigger pin, the sensor responds by emitting an eight-pulse sonic burst at 40 KHz. This 8-pulse pattern distinguishes the device's "ultrasonic signature," allowing the receiver to distinguish the transmitted pattern from ambient ultrasonic noise. The eight ultrasonic pulses travel away from the transmitter through the air. Meanwhile, the Echo pin is set to HIGH to begin forming the echo-back signal.

If those pulses are not reflected back, the Echo signal will timeout and return LOW after 38 mS (38 milliseconds). As a result, a 38 mS pulse ensures that there is no obstruction within the sensor's range. In the other case where those pulses are reflected back, the Echo pin goes LOW as soon as the signal is received and results in a pulse with a width ranging from 150 mS to 25 mS, depending on the time it took to transmit the signal. We then can use this pulse to calculate the distance since we know the speed of sound.

The Ultrasonic transmitter and receiver are formed by two eye-like projects on the front of the module. The one acts as a transmitter and sends out 40 KHz ultrasonic sound pulses, which travels through the air and is reflected back towards the sensor when it encounters any material. The other acts as a receiver and detects this reflected wave. After receiving the reflected wave, it produces an output pulse whose width can be used to determine the distance the pulse travelled.

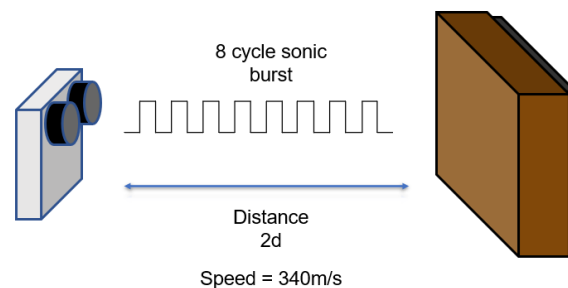


FIGURE 13

The sensor is based on a simple well-known formula:

$$\text{Distance} = \text{Speed} \times \text{Time}$$

Since we know that our wave is moving with the speed of sound which is 340m/s and since we have the value of time, we can easily calculate the distance.

*We have to convert the speed of sound into $\text{cm}/\mu\text{s}$ in order to calculate the distance ($0.034 \text{ cm}/\mu\text{s}$)

*Our Distance parameter is twice the size we want to calculate ($2d$) because the single comes and goes twice.

$$2d = 0.034 \times \text{Time}$$

$$d = 0.017 \times \text{Time}$$

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How it will be connected:

Back to our experiment, we need to connect the sensor with the GPIO pins of our Raspberry Pi. To do that, we need to plug four wires from the ultrasound sensor pins into the GPIO board as shown below:

- The VCC will be connected to the 5V pin (# 2 or # 4)
- Trig will be connected to GPIO 23 (#16)
- Echo will be connected to GPIO 24 (#18)
- GND will be connected to the GROUND pin (#6,9,14,20,25,34,39)

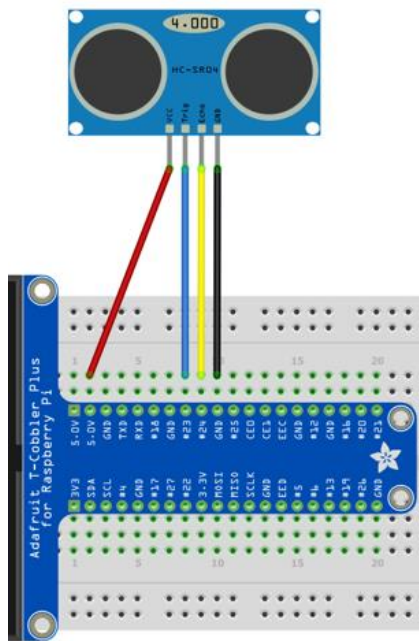


FIGURE 15

	Pin No.		
3.3V	1	2	5V
GPIO2	3	4	5V
GPIO3	5	6	GND
GPIO4	7	8	GPIO14
GND	9	10	GPIO15
GPIO17	11	12	GPIO18
GPIO27	13	14	GND
GPIO22	15	16	GPIO23
3.3V	17	18	GPIO24
GPIO10	19	20	GND
GPIO9	21	22	GPIO25
GPIO11	23	24	GPIO8
GND	25	26	GPIO7
DNC	27	28	DNC
GPIO5	29	30	GND
GPIO6	31	32	GPIO12
GPIO13	33	34	GND
GPIO19	35	36	GPIO16
GPIO26	37	38	GPIO20
GND	39	40	GPIO21

FIGURE 14

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When our circuit is ready, we can start writing our program in Thonny Python (IDLE) which will control the Ultrasonic Sensors. We open Thonny Python, and we save our file as *ultra.py*. Then we will need to write the following program:

```
#####
#Give access to the GPIO pins
import RPi.GPIO as GPIO
#Give access to the time module
import time

#Set the board numbering scheme starting from 1 to 40(top left is 1 and
top right is 2)
GPIO.setmode(GPIO.BOARD)
#The location of the trigger pin
trigPin = 16
#The location of the echo pin
echoPin = 18
#This is the maximum measuring distance in centimeters which the sensors
can measure
maxDistance = 400

#Calculate timeout according to the maximum measuring distance/ the time
which the sensor will stop waiting for a signal if the distance from an
object is larger than the maximum
timeOut = maxDistance*58.82

#Get the pulse time of a pin under timeOut
def pulseIn(pin,level,timeOut):
    time0 = time.time()
    while(GPIO.input(pin) != level):
        if(time.time() - time0) > timeOut*0.000001):
            #Return 0 if the time is greater than the timeout time
            return 0
    time0 = time.time()
    while(GPIO.input(pin) == level):
        if(time.time() - time0) > timeOut*0.000001):
            #Return 0 if the time is greater than the timeout time
            return 0
    #Calculate the pulse time
    pulseTime =(time.time() - time0) * 1000000
    return pulseTime
```

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```

#Get the measurement results of ultrasonic module in centimeters
def getResponse():
    #Set trigPin to output 10us at HIGH level
    GPIO.output(trigPin,GPIO.HIGH)
    #Wait for 10us
    time.sleep(0.00001)
    #Set trigPin to output at LOW level
    GPIO.output(TrigPin.GPIO.LOW)
    #Store the pulse time of echoPin
    pingTime = pulseIn(echoPin,GPIO.HIGH,timeOut)
    #Calculate the distance with sound speed 340m/s
    distance = pingTime * 340.0 / 2.0 / 10000.0
    return distance

def setup():
    print('The Ultrasonic Sensor program is starting...')
    #Use Physical GPIO numbering
    GPIO.setmode(GPIO.BOARD)
    #Set trigPin to OUTPUT mode
    GPIO.setup(trigPin, GPIO.OUT)
    #Set echoPin to INPUT mode
    GPIO.setup(echoPin, GPIO.IN)

def main_loop():
    while(True):
        #Get the distance from an object
        distance = getResponse()
        #Print the distance
        print("The distance is : %.2f cm"%(distance))
        time.sleep(0.5)

if __name__ == '__main__':
    setup()
    try:
        main_loop()
    except KeyboardInterrupt:
        #Release the GPIO resources.
        GPIO.cleanup()

#####

```

FIGURE 16

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2.3 Lesson Plan

This module demands some theoretical (waves) and practical (Raspberry Pi) knowledge. The teaching material handbook contains everything the teacher needs to complete this module. First, the teacher needs to present the different types of waves (Transverse, Longitudinal).

Then it is important for the students to understand the anatomy of waves and the teacher can present them the attached figure (figure 2) in teaching material. The next step is analyzing the parts of the wave. Before that, students must gain knowledge about amplitude, wavelength, frequency, oscillation. The next step is the equations of waves. Following this, the teacher can show the equations of speed and distance that students will use in their experiments.

The next step is the understanding of reflection, refraction and diffraction. The teacher must explain the difference between the above-mentioned types because students will use three types, some of those methods (reflection) to calculate the distance between two objects.

Following the theoretical part, students can proceed to the experiments. First, the teacher must go through the hardware (RPI) and explain every component that they need for this experiment. Following that, the teacher must demonstrate how it will work in theory, students will have the opportunity to assemble the parts for the experiments. Another important part of this experiment is the code which is run by Raspberry Pi. The teacher can go through the code, explaining what each part does.

The final part of the lesson is the experiment. When everything is set up for the experiments, the students can start running the program and record the results on the monitor. With a measuring ruler, the teacher and students can confirm if the distance measured is correct or not. Students can calculate the accuracy of the sensors and note the results.

In the first experiment, the students must use two objects, which are placed in parallel (see figure). The ultrasonic sensor must be placed on the first object (see the figure in the material handbook).

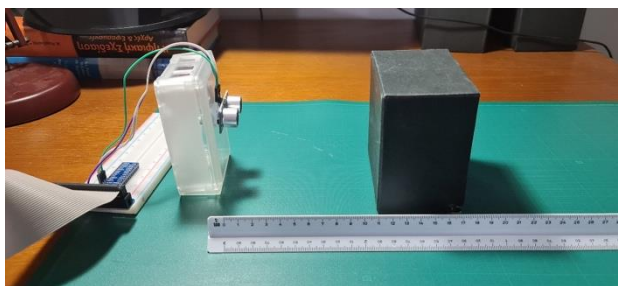


FIGURE 17

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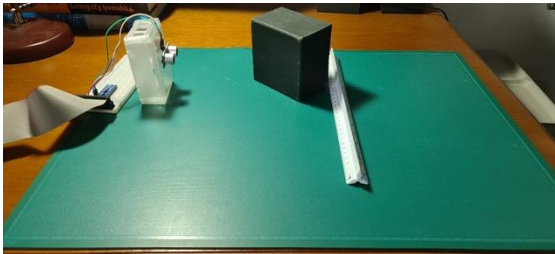


FIGURE 18

In the second experiment, the 2 objects must be placed at an angle of 90 degrees.

In the third experiment, a third object must be placed in parallel with the second object (which is 90 degrees from object one).



FIGURE 19

Students must measure the results of all three experiments and must give a conclusion on how waves react when they meet an object.

After the three experiments, students will collect similar results to the following

	Experiment 1	Experiment 2	Experiment 3
Angle (°)	0 °	45 °	45°
Number of Objects	1	1	2
Distance (cm)	10 - 30 cm	30 cm	30 cm
Accuracy (%)	98%	42.85%	94%

FIGURE 20

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2.4 Conclusion

Students will gain knowledge in the field of waves through the theory and the experiments that have been proposed. The teacher can use both the lesson plan as a guideline and the lesson material to teach this module. Finally, we strongly encourage educators as well as students to self-explore these concepts of physics and find new ways of using the PhysicsKITA and the Raspberry Pi to conduct experiments and learn physics through hands-on educational play.

2.5 Follow-up exercise (Optional)

After finishing this module, the teacher can exercise to see students' progress. During the last teaching period, the teacher can perform a test evaluation for the students, using PhysicsKit4STEAM platform. There are 10 questions to test their knowledge.

3. References or Resources

- Intro to Waves - <https://www.youtube.com/watch?v=aCu4VRKMstA>
- Refraction - <https://www.youtube.com/watch?v=UUc44Vg5pCI>
- Frequency - https://www.youtube.com/watch?v=UPuFx_pVIHU
- Frequency and Wavelength - <https://www.youtube.com/watch?v=KWzyQKcJBYg>
- Reflection - <https://www.youtube.com/watch?v=WDBtOeXUdWQ>
- Ultrasonic sensors - <https://www.youtube.com/watch?v=JNQA3VMFTU>
- Ultrasonic Sensor Projects - <https://www.youtube.com/watch?v=KuTsn66Yf7M>
- <https://components101.com/sensors/ultrasonic-sensor-working-pinout-datasheet>
- <https://lastminuteengineers.com/arduino-sr04-ultrasonic-sensor-tutorial/>

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