

PhysicsKIT
4STEM

CONSERVATION OF ENERGY AND MOMENTUM

Lesson Plans
Pistes-Solitaires



Co-funded by the
Erasmus+ Programme
of the European Union

This project has been funded with support from the European Commission.

Project N°: 2020-1-FR01-KA201-080433

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1. Lesson Plan: Conservation of energy and momentum

1.1 General information

This module proposes an introduction to the concepts of conservation of energy and momentum. Energy is, like the principles and concepts presented in this curriculum, very important when it comes to the knowledge of our universe.

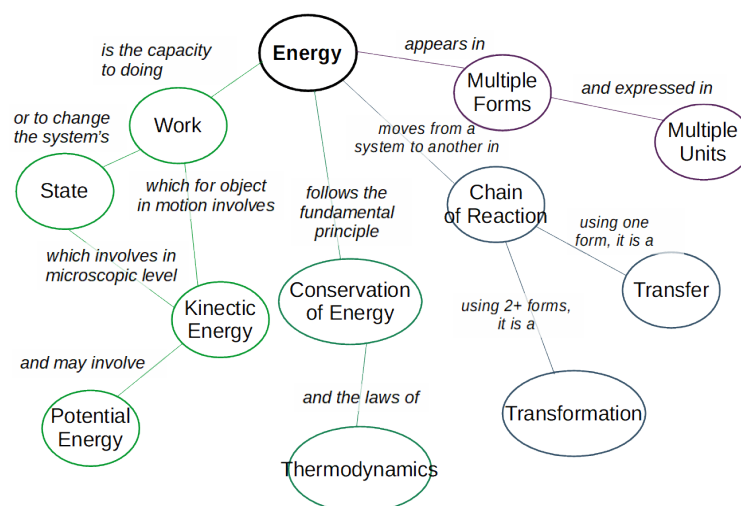
Universe is indeed composed of matter and energy. In one hand, matter is concrete and visible, formed by atoms and has a mass. We observe it with our own eye, with a microscope when it is too small or with a telescope when it is too far. In the other hand, even if we feel what the energy is, we never observe it, only its effect on our environment. Like the wind: we can't see it, but we feel it when it blows against our cheek, we see it when it blows in the trees and their leaves move. Energy is defined by the capacity to change the state of a system. This can be about the system's velocity, temperature, stretching, wave emission... the modification will alter any physic properties of the system. Again, if we feel the wind, it is because it changes the state of our cheek by applying a pressure; if we see it, it is because the leaves gain in motion.

1.2 Short description`

People know a lot of transformation of energy examples without really understanding them: the photosynthesis by the plants, when you turn on a light bulb, when you use a dynamo, when you watch television, when you use your computer or your optical fiber internet connection. This module will propose simple but essential activities to understand these concepts that are essential in this field of study, to allow young students to improve their knowledge and to encourage them to continue to discover their own pathway within science (Image 1).

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IMAGE 1: MINDMAP OF ENERGY AND THE CONCEPTS AROUND IT



1.3 Learning objectives

The main learning objectives of this lesson are:

- To understand the definition of energy, the different forms it can take
- To understand the transfer and transformation of energy, its conservation laws
- To have a better understanding of the concept of energy transformation
- To recognise different types of energies.
- To understand equations of kinetic and gravitational energy.
- To building a system of sensors, connected with the Raspberry Pi.
- To use a programming code in Python to do some experiments.
- To analyse and compare the results of the experiments.

1.4 Links to curriculum

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: Energy (types, analysis)

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1.5 Materials required

The following materials will be required for the different experiments

EXPERIMENT 1

The objective of this experiment is to understand what energy is and observe some types of it.

For this experiment we will need:

- Different beads like marbles, steel beads, paper beads (could be other objects like different coins or dice...)
- Semolina (or something that can print easily like modeling clay or flour)
- Tray
- Meter
- A Weight scale (optional)

EXPERIMENT 2

This experiment is a representation of energy conservation. By playing with the elements, students will understand how the energy is distributed.

For this part we will need:

- Raspberry Pi 3 (RPI)
- Jumper wires (male-to-male and female-to-male)
- SG90 Servo Motor
- Breadboard + T-Cobbler
- LEDs
- 3V DC Motor
- L293D control chip
- rotary encoder
- motor
- buttons
- resistances
- computer and its connectics to the raspberry (code)

1.6 Duration

Introduction: 45-60 minutes

Experiment 1: 45-60 minutes

Experiment 2: 45-60 minutes

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2 Lesson Plan

If the lesson is not enough, please refer to the “professor module” where the “principles”, types of energy and examples are more detailed.

2.1.1 Introduction

There are two big categories of energy: energy based on motion and energy based on potential energy, that is, energy that is stored and is waiting to be released. Within those two, we find different forms of energy that we will look at in more detail (image 2):

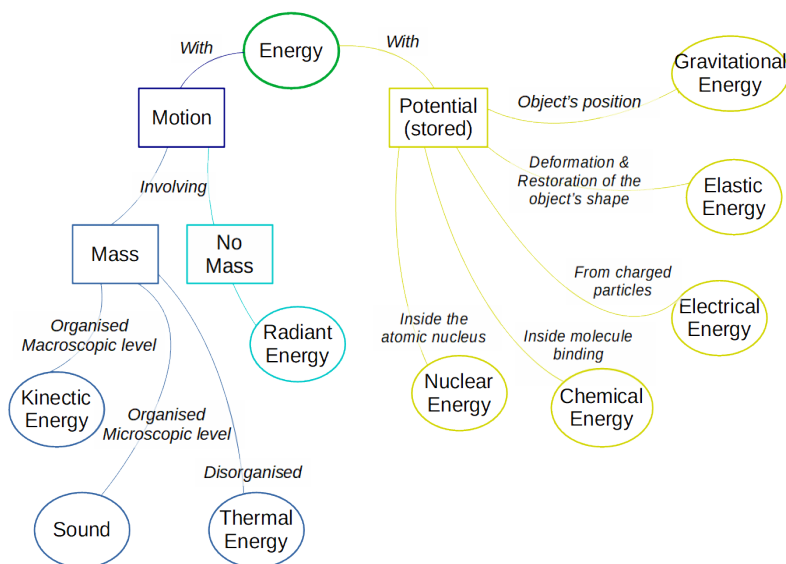


IMAGE 2: MINDMAP OF THE DIFFERENT FORMS OF ENERGY

MECHANICAL ENERGY/MOTION ENERGY

An object in movement, be it macroscopic or microscopic, has energy. If the movement involves mass, is macroscopic and is organized, then this type of energy is called kinetic energy. If it is microscopic, then we’re talking about sound; if it is microscopic and disorganized, it’s thermal energy. And finally, a movement without a mass involved is radiant energy.

- The macroscopic **kinetic energy** is the easiest energy to observe. It depends on the mass and the speed of the object, following this equation:

$$KE = \frac{1}{2} m \cdot v^2$$

where KE is kinetic energy measured in J, m is mass measured in Kg and v is velocity of the object measured in m/s.

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So, the heavier and the faster the object is, the more the object gains in KE. But this energy is only obtained when the object or the system is in movement. Otherwise, the KE is null.

KE can be further divided into rotational KE which is the energy given to an object spinning around an axis. It follows this equation: $K_{Er} = \frac{1}{2} I \cdot \omega^2$ where K_{Er} is the rotational KE (in J); ω is the angular speed in rad/s; I is the rotational mass of inertia also called the angular mass (in Kg/m^2) for which the calculation depends on the form of the object.

- **Thermal Energy** is also informally called heat. It is another form of KE but we are looking at it on a different level: thermal energy is the result of the total microscopic KE of particles inside an object, a liquid or a gas. Because the molecules of solid objects cannot go around, the only way to move and create heat is to vibrate. Therefore, when you rub your hands, the molecules on the surface of the skin start vibrating, creating some energy that will be dissipated by heat.
- **Sound** is also a microscopic movement of molecules but organized, in wave form. When a collision occurs, one part of the energy is lost in sound. When an object flies, we can hear it. During its flight, the object impacts air molecules and makes them vibrate faster. The vibration propagates until reaches our eardrum and therefore, at a macroscopic level we heard a sound.
- **Radiant Energy** is based on wave movement without a mass, like electromagnetic waves or radiation. This energy is found in the warmth of sunlight or fire; by heating food in the microwave. This energy transmission occurs without involving mass. However electromagnetic radiation is also made of individual particles called photons. When the light travels, it has no mass and reaches the speed of light; when the light collides with the matter, it loses its velocity and then an electron is ejected out of the matter. This is light's duality: a wave without mass and, at the same time, particles with mass.

POTENTIAL ENERGIES

Each object of the Universe is a tank of energy waiting to be used. A 'potential to do work' is locked until the energy is released.

- **The gravitational potential energy** is the capacity to produce work depending on the position of the object in the gravitational field.

PE = m.g.h where PE is gravitational potential energy in J; m is mass in Kg; h is height in m; g is the gravitational acceleration in m/s^2 . The last one is a constant representing the potential of motion near the surface ($\sim 9.8 \text{ m/s}^2$ on Earth).

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The higher and the larger an object is, the more PE it possesses. Moreover, the gravity of the system modulates this energy. For example, the acceleration given to an object on the moon ($\sim 1.6 \text{ m/s}^2$) is smaller and on Jupiter ($\sim 24.8 \text{ m/s}^2$) is greater than on Earth.

- **Chemical energy** is the potential energy inside molecules whose atoms can be combined differently. A chemical reaction is the destruction of chemical bonds or the creation of new ones. When chemical bonds are created, energy is dissipated; when they are broken energy is needed.
- **Nuclear energy** is the energy stored inside the nuclei of atoms. A nucleus is composed of protons and neutrons which are bound to each other by strong forces while high repulsion occurs between the protons (due to their positive charges). The energy contained inside a nucleus can be estimated with the following equation:

$E = \Delta m \cdot c^2$ where E is the nuclear binding energy in eV; Δm is the difference between the sum of all the individual part constituting the nucleus (protons and neutrons) and the mass of the nucleus; c is the speed of the light in m/s

- **Elastic potential energy** is the energy given by the deformation of an elastic object, springs are a good example of this. It depends on the objects deformation capacity and the distance stretched, following this equation:

$PE = \frac{1}{2} k \cdot x^2$ where PE is potential energy in J; k is elastic or spring constant in N/m; x is the displacement of the spring, in other word the distance stretched, in m

Elastic/spring constant is the force necessary to deform the elastic object by a certain length. It depends on the shape and the material. The higher the number is, the more resistant the spring will be and the more force should be applied to deform it.

$PE=0$ when the spring is not stretched. It is given energy when it is stretched or compressed. A spring can maintain compression or stretching for extended periods in time without dissipating energy. When all the energy is dissipated, its initial shape or starting length is restored (if not, it is not an elastic object).

- **Electrical potential energy**, especially in a capacitor (electrical storage as batteries), is the energy given by the arrangement and the motion of charges (usually electrons) in electrical and magnetic fields (**See Chapter 2.4.1 of Module 2**). Electrical energy moves from one point to another, being held in the movement of electrical charges. However, it is difficult to store electricity in large quantities.

TRANSFER

Energy is in motion and it's essentially invisible. We can only see the effects of energy on our environment. We often observe its transfer from one system to another. Like we cannot see the wind, but air molecules are moving which will move leaves in trees via a chain reaction. Another example from daily life is cycling. To ride a bike, the cyclist applies forces on the pedals which turn and cause the chain to move and the wheel to rotate. All the energy used to trigger the wheel's rotation was based on kinetic energy.

TRANSFORMATION

Energy can also be stored, waiting to be released. Energy has many faces as we describe it in the preceding section. When it changes from one form of energy to another we call it transformation. Let's focus and explore this idea in the following example:

- A **bike dynamo (image 3)**: from muscles to the lamps. Potential chemical energy contained in the ATP molecules in the body allowed muscles to function and produce linear KE (the foot pulls the pedal). After a chain reaction of KE, the wheels turns, and the bike moves. On the wheels, we often find a bottle dynamo, an electrical generator that converts mechanical energy to electrical potential energy. Then electrical energy is transformed to radiant energy (light) and heat, and the lamp lights up.



IMAGE 3: BOTTLE DYNAMO MOUNTED ON A BICYCLE.
(IMAGE

FROM: https://en.wikipedia.org/wiki/Bottle_dynamo#/media/File:Fahrrad-Detail-23.JPG)

2.1.2 Preparation

Preparation [that can be done by the students themselves]

First, fill the tray with semolina. Then place a meter or a ruler where its 0 is align with the semolina surface.

If you desire to use some equation, the students will need the weight of the objects. If you do not know them, you can do it before or let them weigh the objects by themselves.

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If the weigh is too small, you will need several identical objects. Then divide the weigh by the number of objects.

The pictures of the experiment are available here:

http://www.wikidebrouillard.org/wiki/Des_cratères_d%27énergie. The step by step is written in French.

2.1.3 Investigation

The goal of the experiment is to drop an object from a given height (like a marble), to change the parameters of the experiment (another height or the same height with another beads) and then to observe the consequences on the semolina.

Different parameters can be measured as the height of dropping, the weight of the dropped objects, the speed (so the time of dropping to be able to calculate it), the size of the crater.

Observation

Choose a height (ex. 10 cm above the semolina surface). Drop a marble. Do not remove it yet. Drop a bead. Notice anything? Write all the observation possible (size of the crater, the sound emitted).

Change the height. Does it change something?

What are the different types of energy you are seeing in this experiment (or you can guess) ?

The student can fill a table to help them to report their observation. Examples:

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Height (ex. 10 cm)	Object 1 (ex. Small marble)	Object 2 (ex. Big marble)	Object 3 (ex. Paper bead)	Object 4 (ex. metal bead)
Weight				
Size of the crater				
Speed *				
Sound heard? (Y/N)				

* the speed should be the same. You can use the several dropping to obtain a mean about the speed.

Height	10 cm	20 cm	10 cm	20 cm
Objects:	(ex. Small marble)	(ex. Small marble)	(ex. metal bead)	(ex. metal bead)
Weight				
Size of the crater				
Speed *				
Sound heard? (Y/N)				

* the speed should be the same. You can use the several dropping to obtain a mean about the speed.

Calculation/Analysis

If you know the weight (or at least attribute one arbitrarily to each different object), it will be possible to calculate the kinetic energy ($KE = 1/2 m \cdot v^2$) and the potential gravitational energy ($PE = mgh$)

2.1.4 Conclusion

At the end of the experiment, the students have explored different types of energy: potential gravitational energy, sound, kinetic energy (and also probably heat which would be minimal).

They should arrive at the conclusion that the heavier the bead is, the louder the sound and bigger the crater will be. And the higher the dropping is, the louder the sound and bigger the crater will be.

2.2.1 Conservation of Energy: Law

Energy is ruled by a fundamental principle: "Energy can neither be created nor destroyed". In other words, in an isolated system, energy does not appear or disappear; it remains constant by changing its form.

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CONSERVATIVE FORCES

When only conservative forces are applied in a system, mechanical energy is the sum of kinetic and potential energy following this equation:

$E = KE + PE$ where E is the mechanical energy; KE is the kinetic energy and PE is the potential gravitational energy (all in J)

This equation could also be written as:

$E \sim \frac{1}{2}mv^2 + m \cdot c^2$ where E is the rest mass energy in J; m the mass of the object in kg; c is the speed of light in m/s; v is the speed of the object in m/s

NON-CONSERVATIVE FORCES

If non-conservative forces, like air resistance, enter into the system, it could be seen as not applying the conservative energy law. However, at the level of particles, air friction results in the heating of particles. The application of the energy conservation is translated by the 1st law of thermodynamics that follow this equation:

$E_t = E_i + W + Q$ where E_t is the total of mechanical energy of a system; E_i is the initial energy of a system; W is the work done by or on the system; Q is the heat added to, or removed from, the system (all in J)

In summary, mechanical energy is converted in work or/and heat. But be aware that all work can be turned into heat but not all heat can be turned into work. This is the 2nd law of thermodynamics principle.

A WORD ABOUT MOMENTUM

Momentum is a mass in motion (**See Chapter 2.4.3 of Module 2 for details**). So, the mass has potential energy and because of its motion it possesses mechanical energy too. With all this energy, momentum is also subjected to the conservative law.

2.2.2 Preparation

This experiment is a representation of energy conservation. By playing with the elements, students will understand how the energy is distributed.

Part #1 – Setting the SG90 Servo Motor

For this part we will need:

- Raspberry Pi 3 (RPi)
- Jumper wires (male-to-male and female-to-male)
- SG90 Servo Motor
- Breadboard + T-Cobbler

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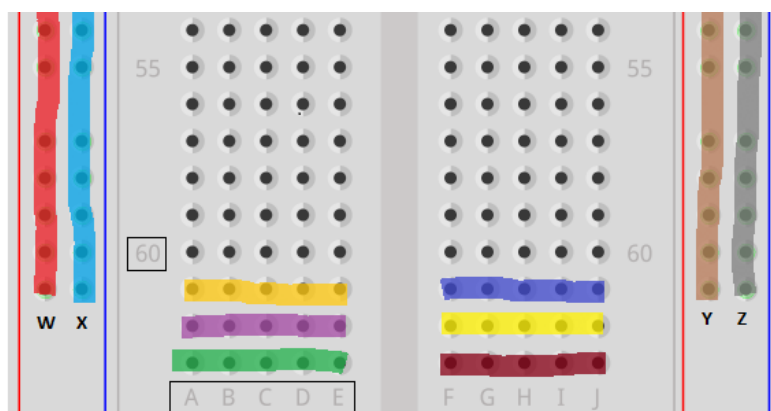


IMAGE 7: HOW THE BREADBOARD IS ORGANISED (IMAGE OBTAINED WITH FRITZING SOFTWARE): THE DIFFERENT UNDERLINED ROWS OR COLUMNS SHOW HOW THE HOLES ARE CONNECTED. THE CONNECTED HOLES OF A ROW HAVE A LETTER (A, B, C, D, E IN ONE SIDE; F, G, H, I, J IN THE OTHER). THERE IS A SEPARATION BETWEEN THE 2 SIDES AND ALSO BETWEEN THE EXTREME COLUMN AND THE INSIDE ROWS. ROWS HAVE ALSO NUMBERS

The breadboard is an extension of the RPi, which allowed us to link more components to it. On the breadboard, you see letters (A, B, C, D, E in one side; F, G, H, I, J in the other) which are all connected in the same row by side. So let's look at the first row: if you put a wire in 1A, 1B or 1C it will be the same as plugging into the GPIO itself. The 2 columns of holes on the outside, without any letter, are connected along the column; on the schematic they are called W, X, Y and Z. The RPi possesses some current entries (3.3V, 5V) and exits (GND). After clipping the RPi we want the entries and exits available along the breadboard so we need to link, using jumper wires, the 3.3V entry (like the first row) to one of the outside column (W) and then the GND exit (row 5) to the next column (X). Do the same with the 5V entry (from row 1 to column Y) and the GND (from row 3 to column Z) exit on the other side.

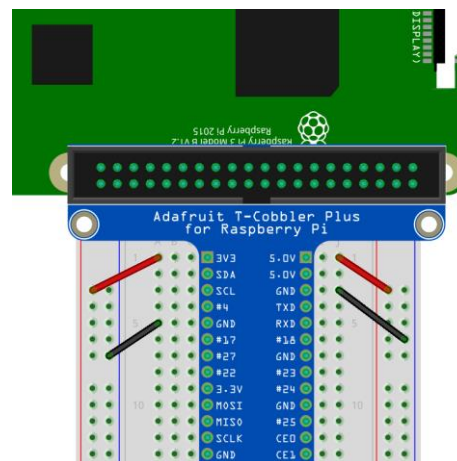


IMAGE 8: HOW TO POWER AND PLACE THE GROUND INTO THE BREADBOARD

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The SG90 Servo comes with three different headers which can be attached on top of its body and can be used to assemble various DIY structures. For this experiment, we will not attach any other object on top. We will just use the one-side header as a gauge.

We need to plug a male-to-male jumper wire into each of the holes on the end of the servo cord, then plug the other side on the breadboard. We'll be sending signals from one GPIO pin (yellow wire) and powering the servo with 5V using another pin (red wire). The third wire is the ground (GND; black wire). So the red wire goes into the Y column, the black wire goes into the Z column and the yellow wire goes into the GPIO pin #18 in our example (J8).

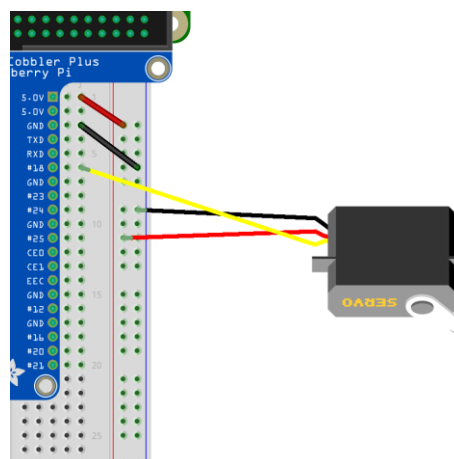


IMAGE 9: CIRCUIT DIAGRAM OF THE BREADBOARD PREPARATION (IMAGE OBTAINED WITH FRITZING SOFTWARE)

Part #2 – Adding LED and buttons

For this part we will need:

- LEDs
- Jumper wires (male-to-male)
- buttons
- resistances

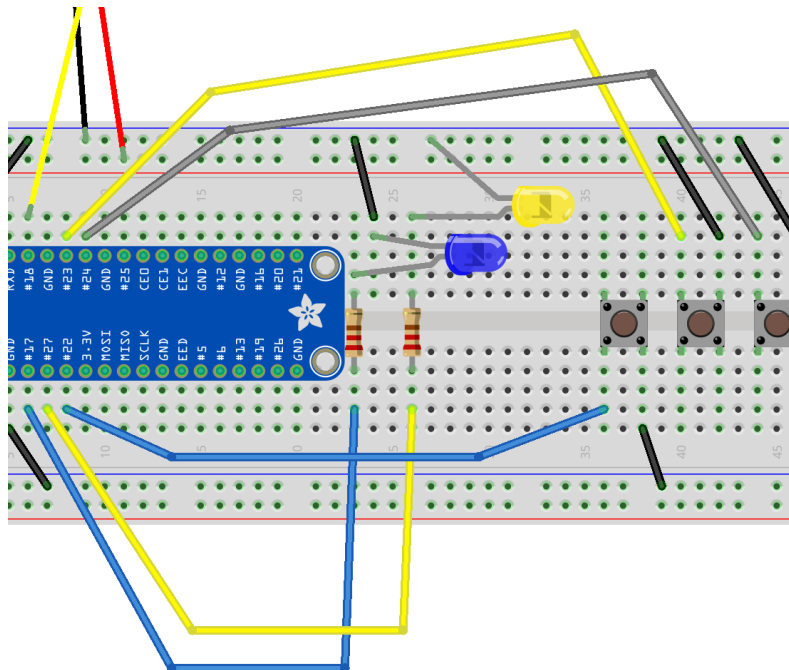
Now, we want to add some components that will be turned on and off. When none of the components are turned on, the gauge (the servomotor) will be at its maximal angle. When they are in use, the angle will decrease. To control each of the components, we will also place some buttons which half its pins on either side, so it runs parallel with the board. One side of buttons needs to be linked to ground (column X or Z) and one GPIO pin (#22, #23 and #24 in our example).

We will also need resistances to avoid a strong current that will break the LED. In our example, we used resistances of 220Ω (red – red – brown marks).

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First place the LEDs, the short leg (cathode) should be plugged in the GND column (Z) and the long leg in the column J26 (see the yellow LED example). If you have difficulties, you can plug the two legs in 2 different rows and link the short leg to the GND column with a jumper wire (see the blue LED example). Then, place one of the pins of the 220Ω resistance in the same row as the long leg of the LED (F26 for the yellow LED) and the other pin on the other side of the breadboard. Finally, we want them to be connected to the GPIO. In our example, we linked the resistance of the yellow LED to the GPIO pin #27 and the one of the blue LED to the GPIO pin #17.

IMAGE 10: CIRCUIT DIAGRAM OF THE PLUGGING OF LEDs AND BUTTONS (IMAGE OBTAINED WITH FRITZING SOFTWARE)



Part #3 – Controlling a small 3V DC Motor with an L293D control chip

For this part we will need:

- 3V DC motor
- L293D control chip

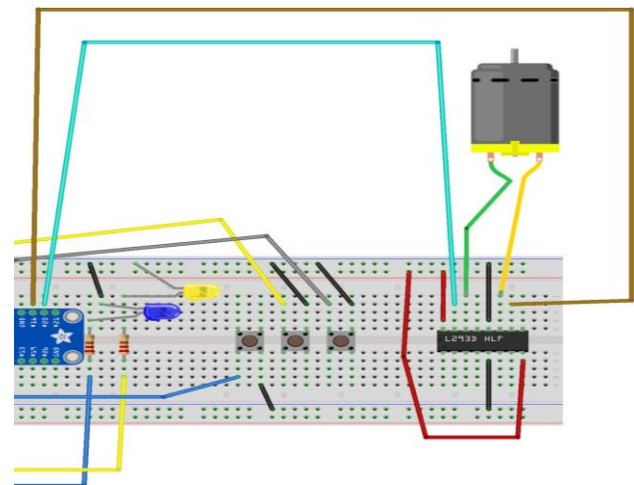
The motor is another component that we want to turn on and off by using the 3rd button. To control the motor, an L293D chip is necessary. Place the chip with half its pins on either side, so it runs parallel with the board. Each side can be used to control and run one motor. In our case, the motor speed will be controlled by the rotary encoder module (see next part).

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Image 11: Pin details of the L293D control chip. Pin 1: sense On/Off motor #1; Pin 2: input for the direction of the motor #1 spinning; Pin 3: output of motor #1; Pin 4-5: ground; Pin 6: output of motor #1; Pin 7: input for the direction of the motor #1 spinning; Pin 8: voltage pin for the motors. It should be comprised between 4,5V and 36V; Pin 9: sense On/Off motor #2; Pin 10: input from the GPIO for the direction of the motor #2 spinning; Pin 11: output of motor #2; Pin 12-13: ground; Pin 14: output of motor #2; Pin 15: input from the GPIO for the direction of the motor #2 spinning; Pin 16: chip power. The tension should be comprised between 4,5V and 7V (image from: <https://microcontrollerslab.com/l293d-motor-driver-ic-introduction-pinouts-example/>)

First, we need to power the chip (Pin 1, 8, 9, 16 of the chip to the 5V/Y column) and place the ground (Pin 4-5 to the X column and Pin 12-13 to the Z column). Then, we plug the outputs of the motor to the pins 11 and 14 of the chip. Now we need to link the raspberry to the chip by using respectively the GPIO pins #16 and #20 with the pins 10 and 15 of the chip.



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IMAGE 12: CIRCUIT DIAGRAM OF THE PLUGGING OF THE DC MOTOR AND ITS L293D CONTROL CHIP (IMAGE OBTAINED WITH FRITZING SOFTWARE)

Part # 4 – Adding the rotary encoder

For this part we will need:

- Rotary encoder
- Jumper wires (female-to-male)

Finally, we will add a rotary encoder which allows us to vary the power given to the components.

The rotary encoder sends a digital signal for each degree of rotation applied to it, clockwise or counterclockwise. It has 5 pins: 2 for the rotary encoder (CLK and DT), one for powering the rotary encoder with 3.3V, the last one (GND) for the ground. In our example we plugged them using female-to-male jumper wires respectively to GPIO pin #6 (B16), GPIO pin #5 (B15), column W, column X.

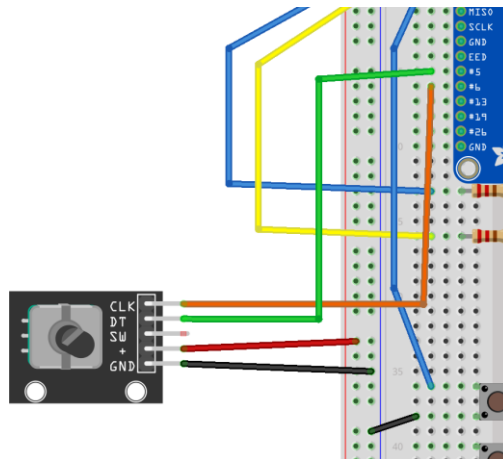


IMAGE 13: CIRCUIT DIAGRAM OF THE PLUGGING OF THE ROTARY ENCODER (IMAGE OBTAINED WITH FRITZING SOFTWARE)

Part # 5 – The code

When our circuit is ready, we can start writing our program in Thonny Python (IDLE).

We open Thonny Python, and we save our file as *energy.py*

We need to write the following program:

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```
#####
# little "hacking" to make the servomotor more precise
from gpiozero.pins.pigpio import PiGPIOFactory
import os
os.system("sudo pigpiod 2> /dev/null")

# Importation of libraries
from gpiozero import RotaryEncoder, PWMLED, Button, Servo, Motor
from time import sleep
NB_OF_COMPONENT = 3

# Initialisation of the rotary encoder, 2 LEDs, motor, servomotor
and 3 buttons
# All numbers in bold are corresponding to pins used by each
component (17 <=> 'GPIO17')
rotor = RotaryEncoder(6, 5, max_steps=5)
rotor.steps = -5
led1 = PWMLED(17)
# composant_state equals 0 when the component is turned off, and
it equals 1 when it is turned on
led1_state = 0
led2 = PWMLED(27)
led2_state = 0
motor = Motor(forward=20, backward=16)
motor_state = 0
servo = Servo(18, pin_factory=PiGPIOFactory())
button_led1 = Button(22)
button_led2 = Button(23)
button_motor = Button(24)

# Fonction which convert a value comprised between src_min and
src_max in a value comprised between dst_min and dst_max
# It defaults to a value comprised between -1 and 1 (for the rotary
encoder) and between 0 et 1 (for LEDs and motor)
def scale(val, src_min=-1, src_max=1, dst_min=0, dst_max=1):
    return ((val - src_min) / (src_max - src_min)) * (dst_max -
dst_min) + dst_min

# Give back a value comprised between 0 (all 3 components are
turned on to their maximum) and 1 (all 3 components are turned off)
```

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```
def compute_nrg_left(rotor_value, led1_state, led2_state,
motor_state):
    # According to the value of the rotary encoder, each component
    uses between 0 and 1/3 of energy
    individual_nrg = scale(rotor_value, dst_max=1/NB_OF_COMPONENT)
    total_nrg = individual_nrg * (led1_state + led2_state +
motor_state)
    return 1 - total_nrg

# Fonctions which will be executed if a button is pressed
def button_led1_pressed():
    global led1_state
    if led1_state == 1:
        led1.off()
    # If the state of the component is at 0, then it goes to 1 and
    inversely
    led1_state = 1 - led1_state

def button_led2_pressed():
    global led2_state
    if led2_state == 1:
        led2.off()
    led2_state = 1 - led2_state

def button_motor_pressed():
    global motor_state
    if motor_state == 1:
        motor.stop()
    motor_state = 1 - motor_state

# The 3 preceding fonctions are associated with the 3 buttons
button_led1.when_pressed = button_led1_pressed
button_led2.when_pressed = button_led2_pressed
button_motor.when_pressed = button_motor_pressed

# "try except" allows to try the execution of a piece of code and
to execute another part if an error comes
# Here we try an infinite loop and if there is an error it will be
written on the screen
try:
    # Infinite loop
    while True:
```

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```

    if led1_state == 1:
        led1.value = scale(rotor.value)
    if led2_state == 1:
        led2.value = scale(rotor.value)
    if motor_state == 1:
        motor.value = scale(rotor.value)
    nrj_left = compute_nrj_left(rotor.value, led1_state,
led2_state, motor_state)
    # For this experiment, the minimal value of the servomotor
    is 1, the maximal one is -1 (because the rotation is anticlockwise)
    servo.value = scale(nrj_left, src_min=0, src_max=1,
dst_min=1, dst_max=-1)
    sleep(0.1)
except Exception as e:
    # The error on the screen ("Keyboard interruption" if we stop
    the program with Ctrl + C)
    print(e)

#####
#####

```

2.2.3 Investigation

The servo motor acts as a sensor of the quantity of energy left into the circuit.

What happens when a component (motor or LED) is turned on?

What is the relationship between the rotary encoder and the components?

If the gauge (the servo motor) decreases, what happens to the energy? Is it disappearing?

2.2.4 Conclusion

Each time a component is turned on, the servomotor will decrease its gauge.

Finally, we will add a rotary encoder which allows us to vary the power given to the components. More power will be given, brighter the LED will shine, faster the motor will run and more the angle of gauge (mimicking by the servomotor) will decrease. The conservation of energy is illustrated by adding the energy left in the gauge (the servomotor) plus the transformative energy of the component (light and movement). Whatever the gauge level is, we always have the same amount of energy.

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