

PHOTONICS WORKSHOP
POLARIMETER

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PROPERTIES OF THIS WORKSHOP

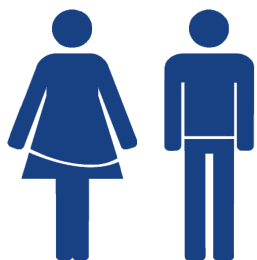
Summary:



In this project we'll use the phenomenon of polarisation of light to determine the concentration of sugar in an aqueous solution.

To achieve this, we'll construct a small detection instrument using several electronic components, including a laser, a servomotor, a photoreistor, a power supply module and an OLED display. All will be hooked up on a breadboard and encased within a wooden box which we'll build with a laser cutter.

In the end, we can measure the concentration of sugar in a solution (like ice tea) and find out how unhealthy our nutrition really is!



TARGET AUDIENCE:

Students (15-18 years old)

SUGGESTED TIME PLANNING: (Total: 4h)

Timing in minutes	Activity
25 min	Understanding the polarization and the working principle
15 min	3D printing
20 min	Constructing the casing
20 min	Making the sample chamber
60 min	Implementing the electronics
30min	Putting everything together
70 min	Testing



TOOLS:



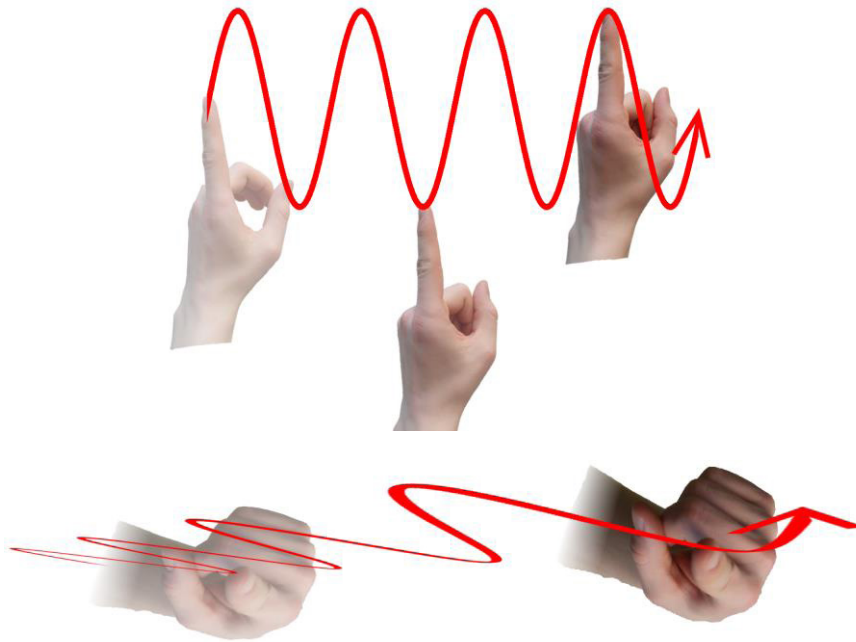
ESTIMATED COST:

€ 30

Step 1: What is polarisation?

Light is composed of electromagnetic waves that propagate in space.

Try to trace the path of a single light wave with your hand. You will find that there are different directions in which the wave can oscillate. It might go up and down or it might go back and forth – or maybe something in between:

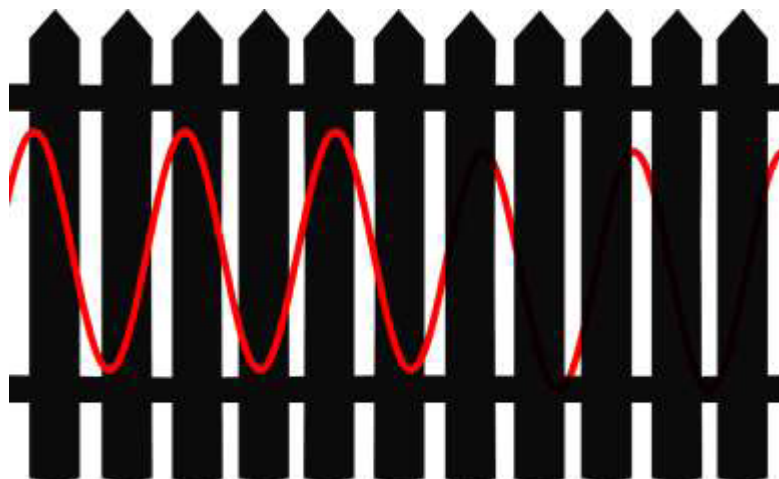


This phenomenon is called **polarisation**. The plane in which a wave oscillates is called a plane of polarisation.

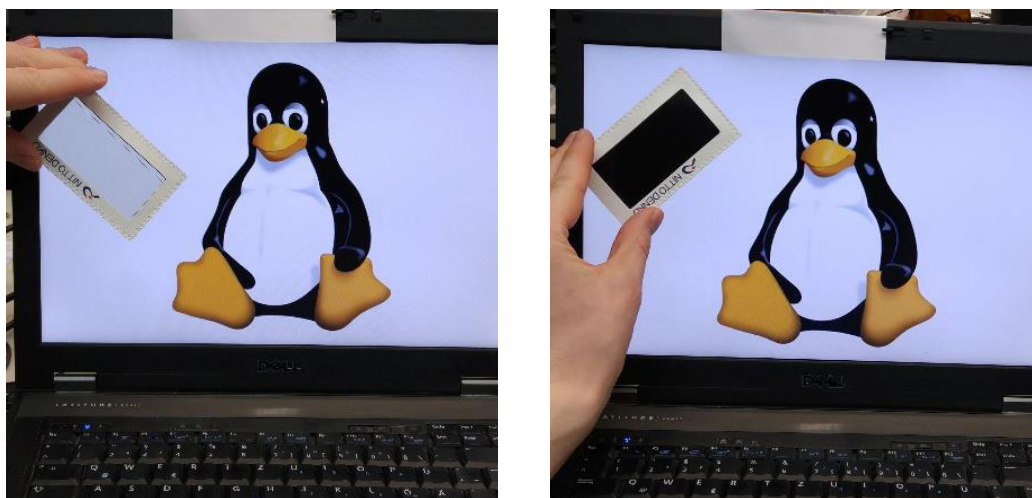
If all waves coming from a light source share the same plane of polarisation (that is, all oscillate in the same direction) the light is said to be **linearly polarised**.

Typical gadgets which emit linearly polarised light are, for example, lasers and LCD displays. But most light we deal with in our daily life is not linearly polarised – instead, all the individual light waves have a different plane of polarisation. In this case we call the light **unpolarised**.

Using special polarisers we can filter light according to its polarization. A polariser is an object that only lets through light waves with a certain plane of polarisation – all the other waves are blocked. This way, you can compare it with a picket fence which would only let through items oscillating in the direction of the pickets:



You can try this out with a polariser sheet and an LCD display (i.e. a laptop, TV, smartphone). Just hold the polariser in front of the display and rotate it. As the LCD emits linearly polarised light, the light is only let through when the orientation of the analyzer and the plane of polarisation match. If you turn the analyzer by 90° , you will notice that nearly all the light is blocked:



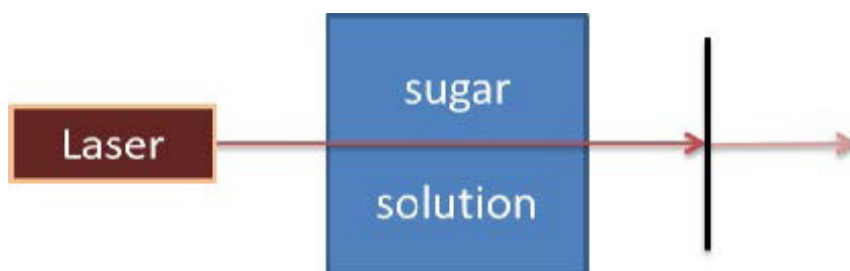
Working principle

Besides LCDs, many lasers belong to the group of components that emit linearly polarized light. So you might place a polarizer in front of a laser and see that, again, the light is only let through when the polarizer is properly aligned to match with the plane of polarization. In the following picture, this is not the case – the light is absorbed entirely:



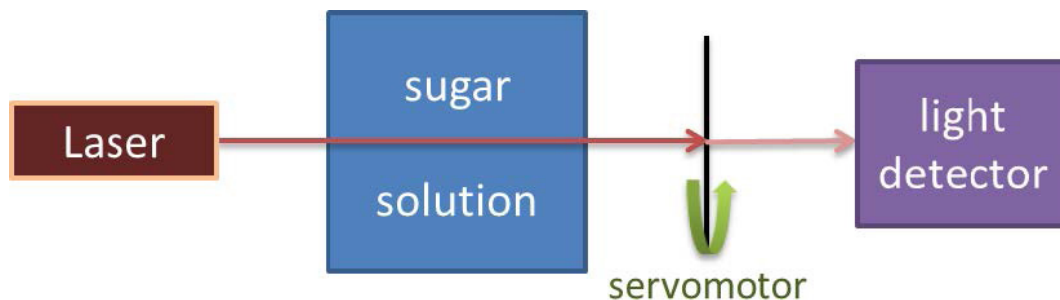
Now comes the interesting part: There are materials which rotate the plane of polarization of the light that goes through them. These substances are called optically active. Among these substances is sugar.

Now, if you place a sugar solution between the laser and the polarizer, the plane of polarization will be rotated. Because of that, the plane of polarization of the light beam and the orientation of the polarizer will now match (at least in part) and a portion of the light will be transmitted:



The following figure outlines the working principle of the polarimeter which we are going to con-

struct in this workshop. On the one side, there is a laser that emits a narrow light beam through a jam jar filled with an aqueous solution with sugar. This beam then goes through a polarizer which can be rotated by a servomotor. If you do so, the intensity of the light that is let through will differ depending on the angle of rotation. Thus, the light detector on the other side of the apparatus will detect a different signal for each angle: If the orientation of the (rotated) polarizer and the plane

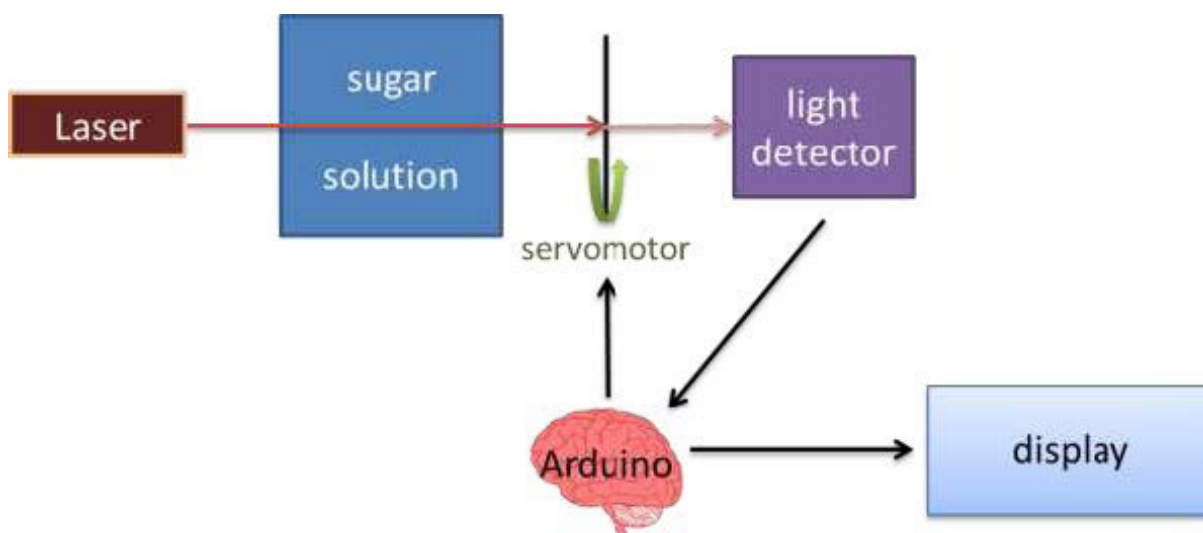


of polarization match, the signal will be maximal. If not, the signal will decrease.

Thus, by changing the orientation of the polarizer with the servomotor we'll obtain different values for the light intensity. The rotation angle with the highest light intensity is the angle by which the plane of polarization is rotated inside the sugar solution. This angle can then be traced back to the sugar concentration.

Now, how does all of this work in more detail? In order to control the different electronic components, we'll use a microcontroller. You can think of a microcontroller as a brain that can take up the information from peripheral sensors (in this case, a light detector) and process it. It can also control other elements. Here, it regulates the angle of a servomotor. In the end, the result will be shown on a small display.

To keep things easy, we'll use an Arduino Nano. This is a small circuit board with a microcontroller on top of it. As the power supply and the connection with the PC is organized via a common USB interface, it's easy for us to program the Arduino and to fuel it while running.



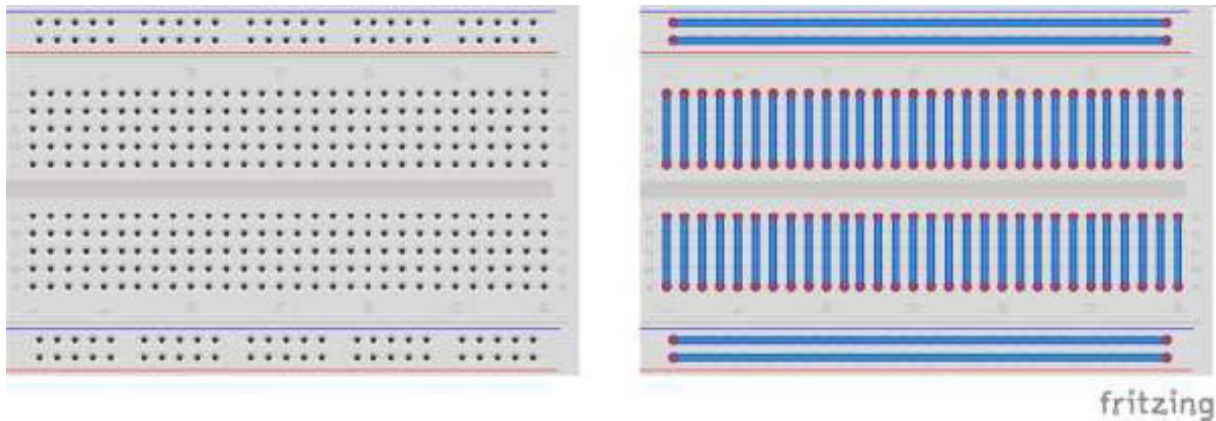
The light detector we'll use is a photoresistor. A photoresistor is in fact a small resistor (like you've seen in school) which changes its resistance depending on the intensity of light that shines upon it. By reading out the resistance (using a so called voltage divider), we'll learn about the amount of light that is let thorough the polarizer.

As display, we'll employ a small Organic Light Emitting Diode (or OLED for short). Nowadays, this technology is also used in some modern smartphones and TV sets.

Some words on electrical circuitry

Constructing an electric circuit means connecting different components together so the electrical current can flow between them. For this, we may use cables – however, when we have too many of them, things get a little messy. This is where a solderless breadboard comes in handy.

This is a board with quite a lot of tiny little metal holes in which you can stuff the pins of the components you want to hook up. The holes are ordered in rows and columns, like in the left figure:

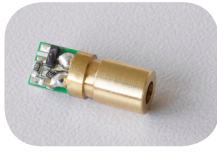


Some of the holes are conductively connected with each other. These are the holes that lie under the same blue strip in the right figure. The two long strips on either the top and on the bottom of the board usually supply the voltage for the system, whereas the strips that are vertically aligned are used to connect the different components with each other.

Step 2: Parts list

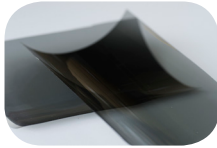
Collect all materials for each participant.

Photonics Parts:

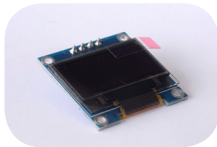


Simple diode laser

40 pieces



Linear polarising sheet (4 x 2.5cm) roll



OLED display

40 pieces



Acrylic glass

Additional components:

- *MDF sheet thickness 3mm (600 250mm)
- *Plastic filament
- *transparent adhesive tape
- *wood glue
- *bell wire
- *pipe, outer diameter ca.20 mm, inner diameter ca. 16 mm
- *seal rings for pipe
- *sugar



Electronic Parts:



Jumper cables (male to male) & Jumper cables (female to male) 120 pieces & 160 pieces



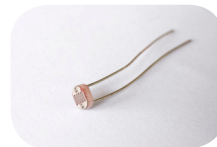
Arduino nano

40 pieces



Resistor 3.9 kOhm

40 pieces



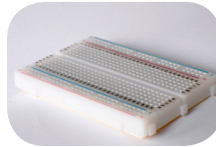
Photoresistor

40 pieces



Servomotor SG90

40 pieces



Solderless breadboard

40 pieces

The photonics parts can be bought by [EYESTvzw](https://www.eyestvzw.com).
The electronic parts can be bought by [Fablabfactory](https://www.fablabfactory.com).

Step 3: Using the 3D printer

First, we'll use a 3D printer to make some additional parts that will be attached to the polarimeter:

- a clamp for the OLED display in order to be fixed firmly on the casing
- a lever for the small laser to properly adjust its beam on the photosensor
- two caps for the sample chamber so that the liquid doesn't leak

Make sure the 3D printer is switched on and there is enough plastic filament. Now, load the file Polarimeter_parts.stl with the parts into the 3D printer and start the print job. The printing process may take a while – meanwhile, you can proceed to the next steps.

We also provide the STEP file Polarimeter_parts.stp for you to load into a CAD software if you should ever desire to change the 3D model, i.e. if your pipe for the sample chamber is bigger than the one we used.

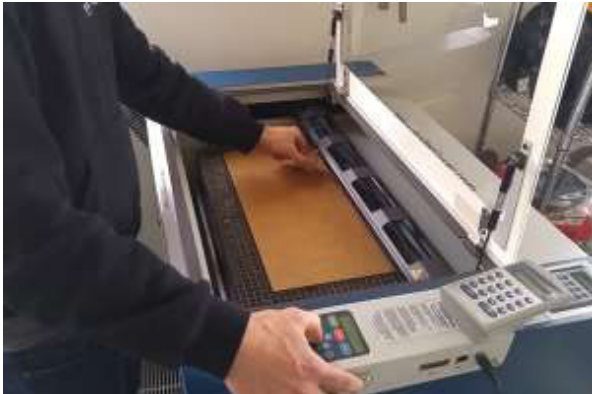
Step 4: Cutting the wooden parts and assembling the box

In this step we'll be using a laser cutter machine. Make sure you've understood all necessary security regulations. Especially, it's important to keep the laser casing shut during operation!

Take an appropriate plywood sheet (at least 600x250 mm with 3 mm thickness) and put it into the laser cutting machine. We provide a file with the designed pattern: Polarimeter_Casing.pdf. Make sure you have the appropriate laser parameters set! For plywood with a thickness of 3 mm processed by a 40 W CO2 laser we determined the following parameters to be optimal:

- Speed: 65%
- Power: 90%
- Pulse frequency: 500 Hz

Adjust the sheet within the laser cutter and let the process start:

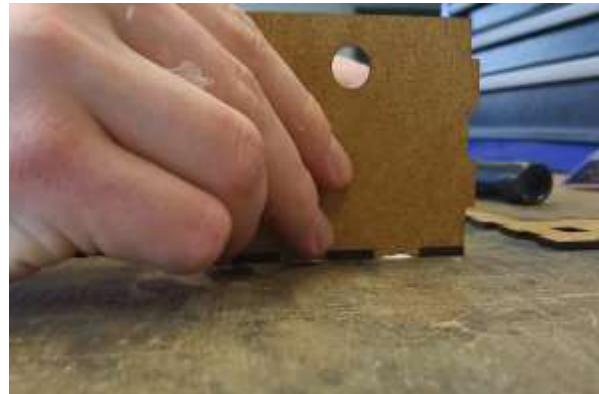


Step 5: Gluing the wooden parts together

Now, the laser head will cut out the parts from the plywood sheet. Once done, take the parts out of the machine and try to stick them together so that they will form the two boxes we want to construct (see figure below):



Once you know which parts belong together, glue the different parts together. Please note: The topmost lid of the bigger of the two casings must not be glued to the rest as we will have to embed the electronics later.

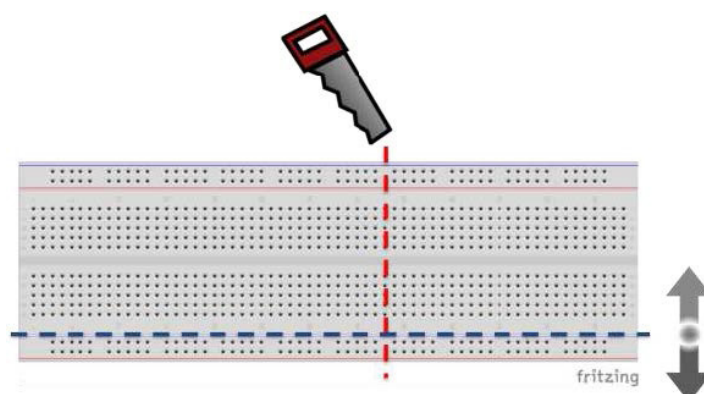


Now the glue will need some time in order to get dry and hard. Meanwhile we can proceed to the next steps.

Step 6: Splitting the breadboard

Your breadboard is probably too big to fit into the polarimeter casing. In order to circumvent this problem you will have to saw up your breadboard into several smaller pieces of which you will use one to include it into your system.

Take a saw and saw off a piece with a width of not more than 7 cm length. You should also remove one bus piece (the one with the red and blue/black strip) – this can simply be accomplished by breaking it from the rest of the breadboard.

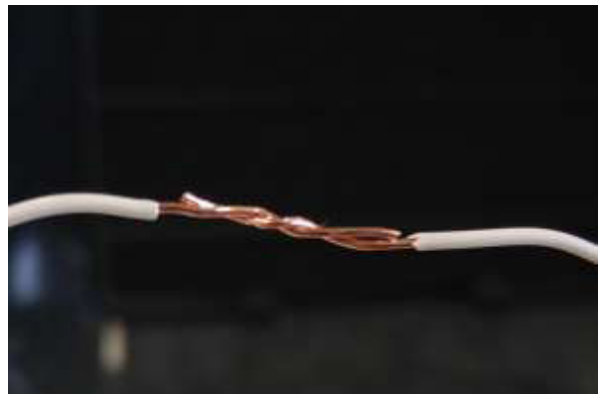
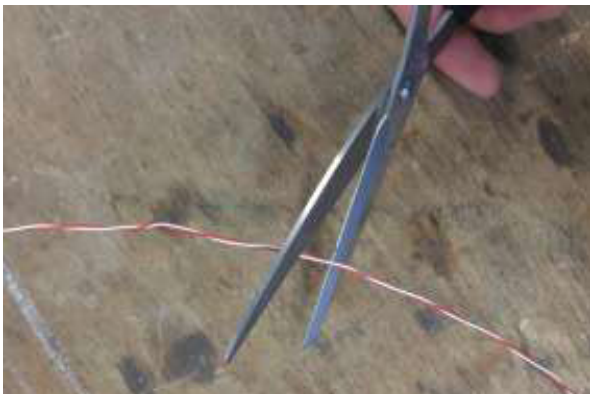


Step 7: Soldering

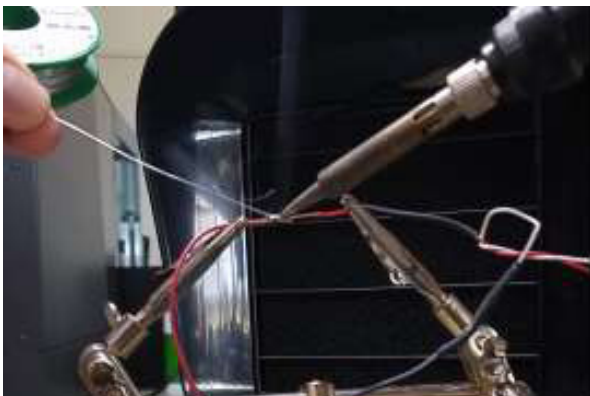
Now we will create some electric connections using soldering. Heat up a soldering iron – this may take a few minutes. Please be careful with the hot iron.

The small laser will come with two connection cables: a black one and a red one. As these cables are quite short we will have to extend them. We do this by soldering them to some bell wire (or any other suitable wire). This wire must be longer than the sample chamber created previously. For a chamber length of 70 cm we might take a wire of approximately 100 cm.

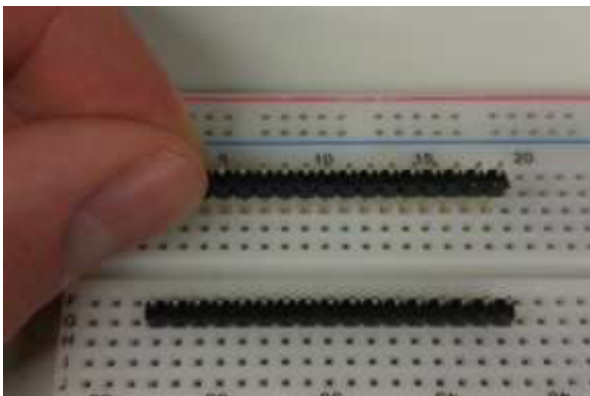
Cut the bell wire to the desired length and strip it at each side. Put a heat shrink tube on each fibre of the bell wire and twist each fibre around its corresponding connection cable of the laser.



Then, solder the two fibres together and move the shrink tube so it covers the uncoated metal. You can let it shrink using fire or your soldering iron.



When it is delivered to the customer, the Arduino Nano is not connected to any pins. In order to fix it on the breadboard, we'll have to solder the Arduino to the pin heads first. In order to do so, insert the pin heads into the breadboard and put the Arduino on top of it. Then start soldering.



Be careful not to create any solder bridges as those can compromise the functionality of your polarimeter or even damage the Arduino. If unsure, use a multimeter to measure the resistance between two pins. It should be a high value (at least 1 MΩ).

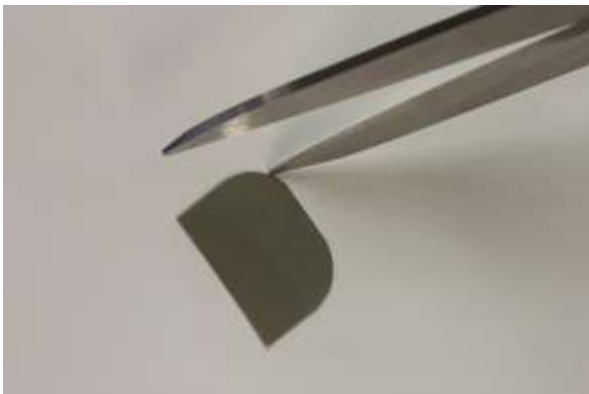
Step 8: Preparing the polarizer

First of all, keep in mind that our servomotors are rather cheap. Applying too much pressure on the rotor may cause harm to the servo. You should avoid doing so.

The servo comes with a small attachment to be pinned onto the rotor. We will glue a polarizer foil onto the attachment so that the polarizer will be rotated.



Cut out a small piece from the polarizer foil. In our case a rectangle of 4cm x 2.5cm was sufficient. Additionally, we rounded up two corners to ensure that the polarizer can be turned freely above the ground of the casing. Glue the attachment to the polarizer, either by using double-sided tape or normal adhesive.

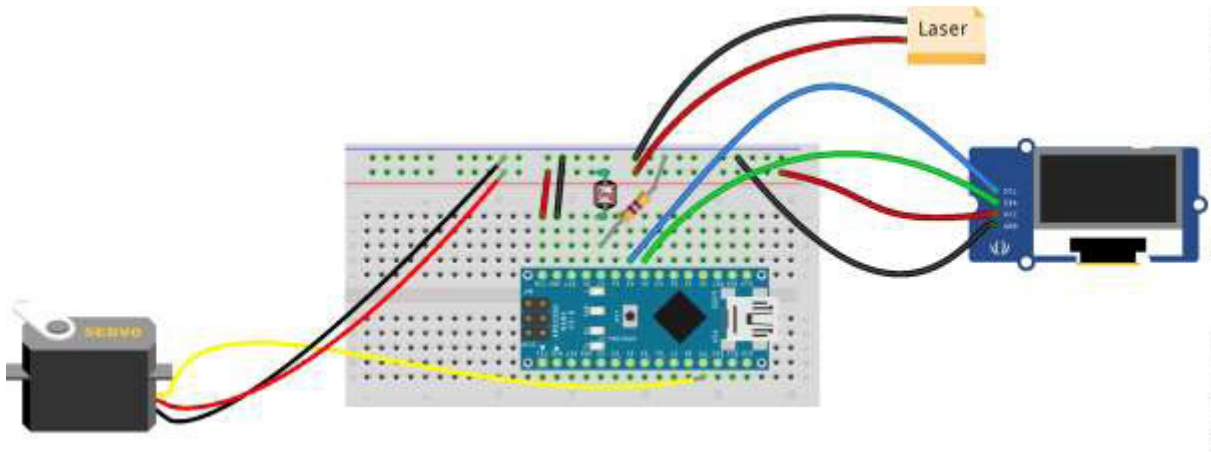


Step 9: Hook up the electronic components

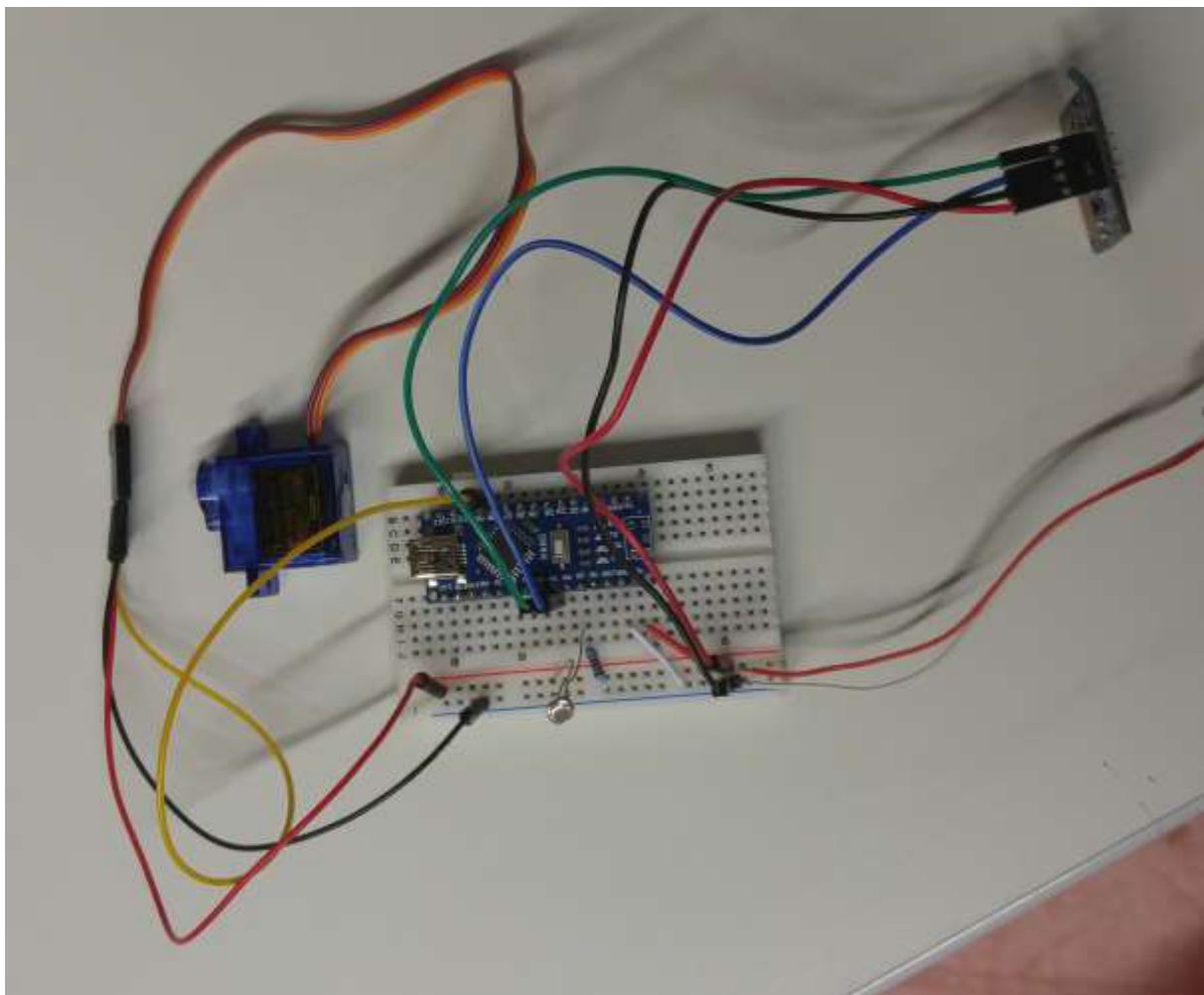
In this step, we'll connect the different electronic components with each other. First place the Arduino on the breadboard and connect the other components accordingly. The scheme below can be taken as a good example. In particular, the following connections have to be made:

Arduino pin	Connect with....
A4	OLED SDA
A5	OLED SCL
A7	1 st pin of photoresistor 1 st pin of 2k resistor
D9	Signal cable of servomotor (usually the one with the brightest colour - for black-red-yellow, it would be the yellow one)

VIN	<p>Jumper cable to the red bus strip of the breadboard, connect via this strip:</p> <ul style="list-style-type: none"> - VIN cable of the servomotor (usually red) - red cable of the laser - VCC cable of the OLED - 2nd pin of the photoresistor
GND	<p>Jumper cable to the blue bus strip of the breadboard, connect via this strip:</p> <ul style="list-style-type: none"> - GND cable of the servomotor (usually black) - black cable of the laser - GND cable of the OLED - 2nd pin of 2k resistor



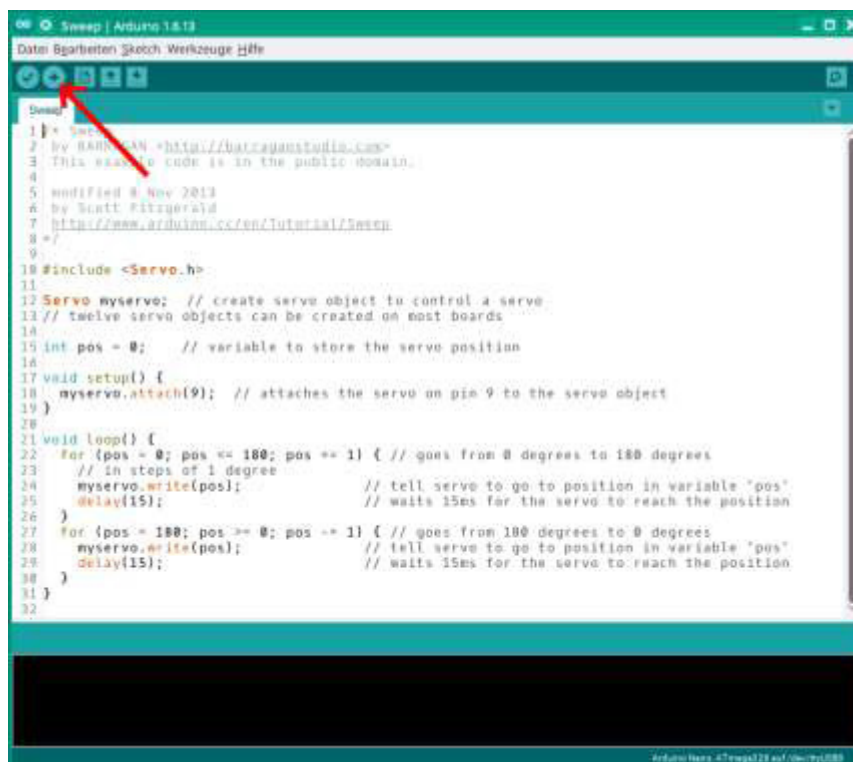
After you've finished, check if all is set up correctly. Observe the polarity of the external devices: If you swap VCC and GND, you might damage them. In the end it might look like this:



Step 10: Program the Arduino

So far we have connected the Arduino to the required components. Now we have to tell it what to do with them. This process is called **programming**.

1. Make sure an up-to-date version of the Arduino Software is installed on your computer.
2. Connect the Arduino with a PC via the USB cable, if you have not already done so.
3. Open up the Arduino IDE.
4. The editor contains a few lines of code that constitute a little program that actually does nothing. Let's try something a little more elaborate! Click in the menu File->Examples->Servo->Sweep.
5. Now a new window will pop up with more lines of code. If you are familiar with programming, you'll notice two for loops. They basically make the servomotor move forward and backward. To try it out, click on the upload button indicated by the red arrow in the following picture:



```
1 // Sweep
2 // by BARRAGAN <http://barraganstudio.com>
3 // This example code is in the public domain.
4
5 // modified 8 Nov 2013
6 // by Scott Fitzgerald
7 // http://www.arduino.cc/en/Tutorial/Sweep
8 //
9
10 #include <Servo.h>
11
12 Servo myservo; // create servo object to control a servo
13 // twelve servo objects can be created on most boards
14
15 int pos = 0;    // variable to store the servo position
16
17 void setup() {
18   myservo.attach(9); // attaches the servo on pin 9 to the servo object
19 }
20
21 void loop() {
22   for {pos = 0; pos <= 180; pos += 1} { // goes from 0 degrees to 180 degrees
23     // in steps of 1 degree
24     myservo.write(pos);              // tell servo to go to position in variable 'pos'
25     delay(15);                       // waits 15ms for the servo to reach the position
26   }
27   for {pos = 180; pos >= 0; pos -= 1} { // goes from 180 degrees to 0 degrees
28     myservo.write(pos);              // tell servo to go to position in variable 'pos'
29     delay(15);                       // waits 15ms for the servo to reach the position
30   }
31 }
32
```

6. Does the motor move? If not, look at the black command line at the bottom of the window. If it tells you that “the sketch uses” a certain percentage of program memory, then you have succeeded in uploading the program to the Arduino. Hence, the problem should be with your circuit. Check if all connections are correctly built up (according to the scheme in the previous section).
7. Now let's try to feed the Arduino with the polarimeter source code. Click in the menu File -> Open and open the provided file polarimeter.c. As the polarimeter constitutes a more complex apparatus the program contains more than 300 lines of code. If you are curious, the interesting part is at the bottom of the file beginning with the function void measure(void)
8. Click the “Upload” button (like you did for the simple motor program). The process of compiling and uploading may take a while as our program is significantly bigger than the previous one.
9. If the uploading process has finished, the motor should start to move and there should be some output on the OLED. Test the photoresistor by changing the illumination. You may hold a hand in front of it or you can use a lamp. When the system is in the measuring

mode you should be able to trace the degree of illumination in the graph.

10. If something doesn't work, check if the corresponding device is set up correctly. Also consider short circuits. You may also replace a device by another one to make sure that the problem is not caused by a defect.

Step 11: Making the sample chamber

The sample chamber will contain the sugar solution we want to examine. As the laser beam will go through it, it will have to be transparent at two ends. Moreover, the pathlength of the laser beam inside the solution should be sufficiently big in order to obtain a good result. Therefore we'll take a simple tube from the construction market.

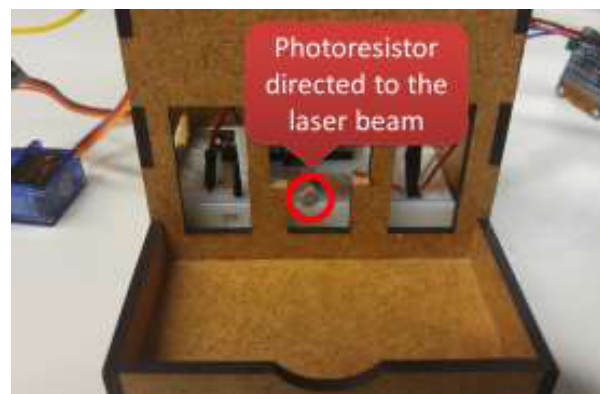
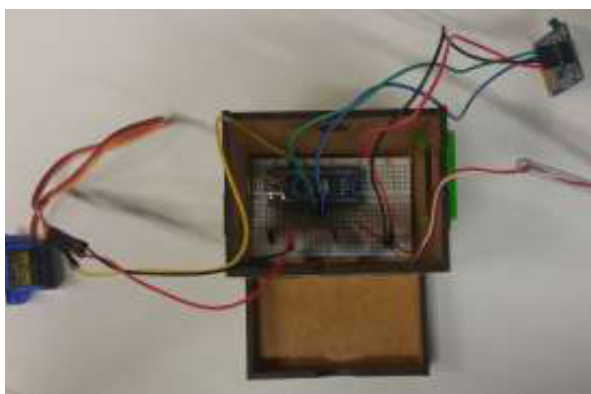
Lay a folding rule beside the pipe and cut off a piece of approximately 70 cm length. Next, we'll make the windows for both ends of the pipe. These will be cut from a sheet of acrylic glass with our lasercutter. You can use the supplied file `Polarimeter_windows.pdf`. We also provide the file `Polarimeter_windows.svg` for you to easily edit the cutting pattern.



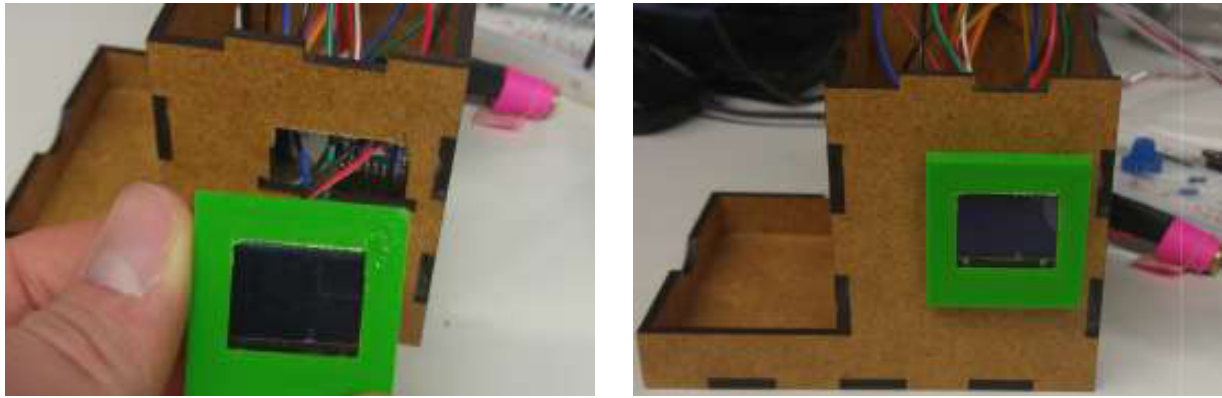
By now, the 3D printer should have finished making the desired parts for the polarimeter. Take the two caps for the sample chamber, lay a seal ring inside and put the caps on either end of the pipe. You should be able to look through the chamber from one end to the other.

Step 12: Embedding the electronics into the housing

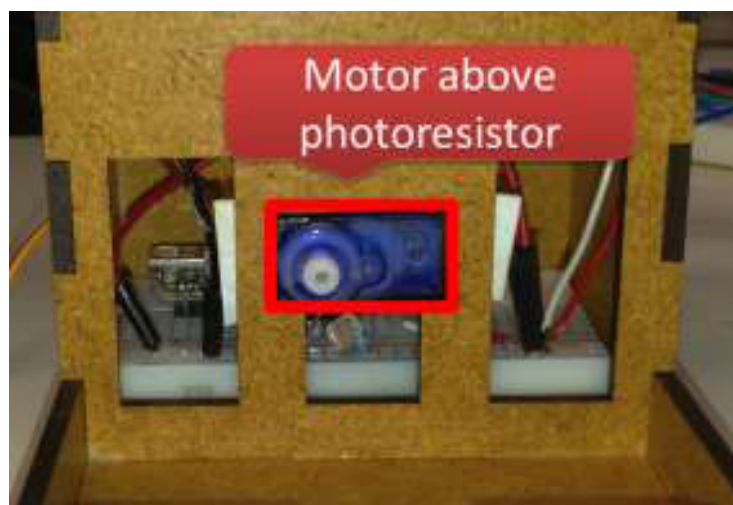
Now that you know that the electronic parts are working together, disconnect the USB cable from the Arduino and lay the breadboard inside the bigger one of the two wooden boxes we constructed in steps 2 and 3. Bend the photoresistor so that its sensor head is directed towards the central opening of the casing. (Make sure that the two pins do not touch each other – or else the sensor won't work!)



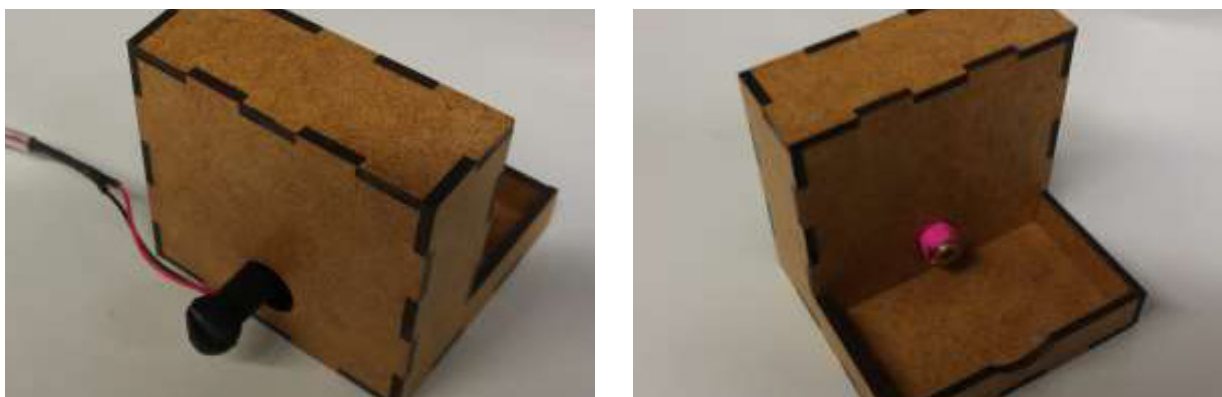
Put the OLED through the corresponding opening, put it inside the plastic clamp and clip the clamp into the opening:



Now, attach the servomotor. You can fix it inside its housing either by using ordinary glue or by using double-sided adhesive tape.



Put the cable for the laser through the opening of the box and stuff the laser itself in the smaller one of the two boxes. Put the laser through the opening in the smaller one of the two boxes. If the laser cannot be properly fastened inside the opening, wrap some thick sticky tape around it. Put the lever on the laser, so you can adjust its beam. Connect the Arduino with the USB cable.

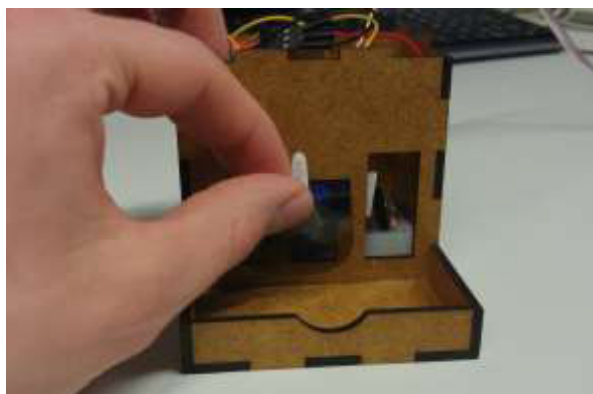


Step 13: Putting the polarizer on the servomotor

In step 9 you glued the polarizer to the attachment of the servomotor. It is this attachment that you will now put onto the servo. Therefore, we have to make sure that the polarizer will be added in the right orientation.

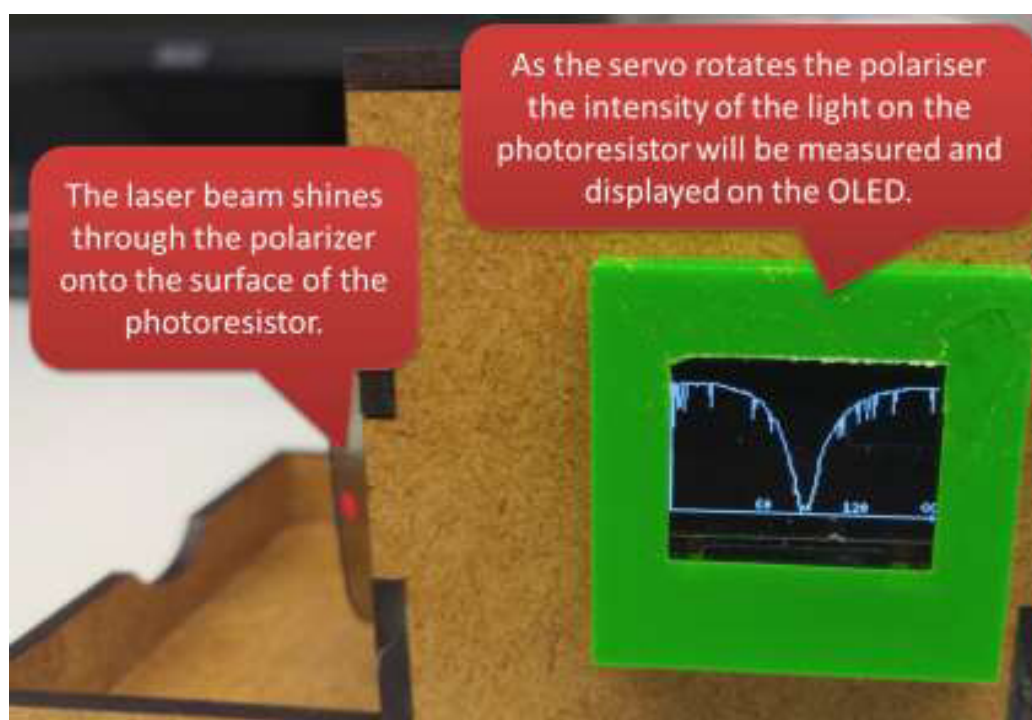
Connect the Arduino with the computer using the USB cable. Start the Arduino IDE and open the file Servo_90deg.c. Click the "Upload" button (just like you did in Step 11). This will make the servomotor move to the position 90°. As we will vary the angle of the servomotor between 0° and 180°, this indicates the central position.

Now, put the attachment onto the rotor of the servo by applying soft pressure:

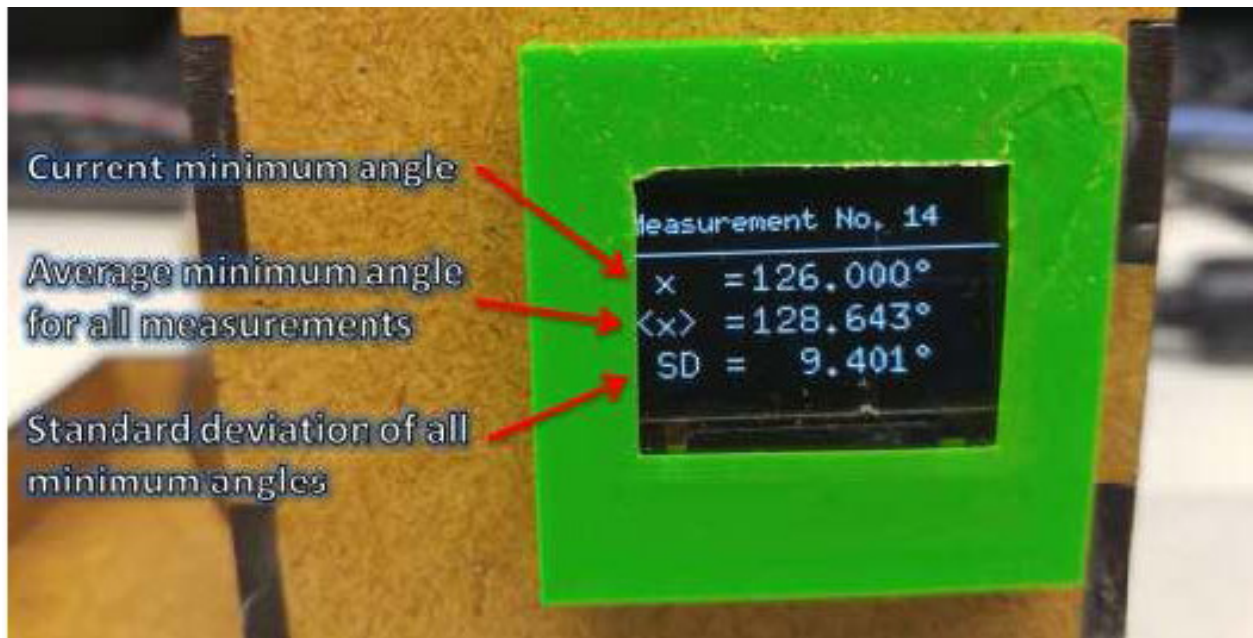


Step 14: Trying it out

Now re-upload the program by following Step 9 (for polarimeter.c only). This turns our machine into a polarimeter again. Adjust the laser so that its beam shines through the polarizer on the sensor head of the photoresistor. If you let the program run through, the OLED will display the light intensity:



The servo rotates the polarizer to different angles (in steps of 1°). After each step the intensity of the transmitted light is measured by the photoresistor and displayed on the OLED. When the plane of polarization of the laser light and the orientation of the polarizer match, then there is an intensity maximum. If they don't match, there is a minimum. So in the end you will get a characteristic curve for the light intensity with a minimum and a maximum. The whole process takes less than one minute. After the servomotor has done a full sweep from 0° to 180° the Arduino will calculate the angle with the smallest intensity. This minimum angle will then be printed out on the OLED as "X". After a few seconds another measurement will start. The results of the measurements are then averaged and printed out as "<X>" together with the standard deviation "SD":

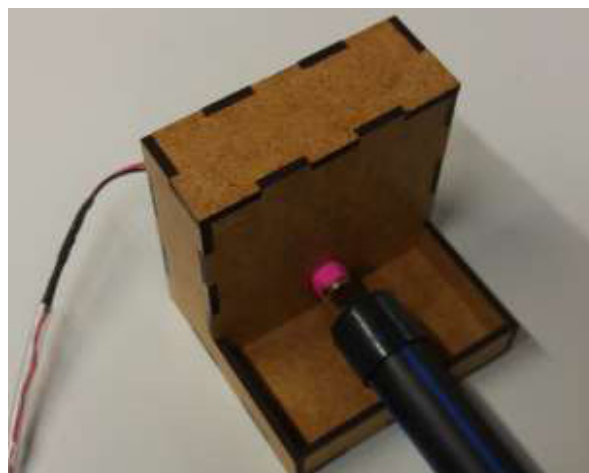


Step 15: Measuring pure water

At first, we'll measure ordinary tap water so we get a reference to compare our sugar results with. Fill the sample chamber to the brim with water using a funnel and close it on both sides. You should now be able to look through the pipe from one end to the other. If not, you should bend it so the light can freely propagate from one side to the other. There should not be big air bubbles, too. If there are, pour some additional water into the chamber.



Lay the chamber onto the round notches of the two wooden boxes as indicated in the following picture:



Next, align the laser so that its beam ends directly upon the surface of the photosensor. This requires some precision as well as patience. It might come in handy to temporarily remove the chamber for the first step of the alignment and to put it back afterwards.

Once everything fits as desired, it's time to measure! Connect the polarimeter with a USB power source (try not to move the polarimeter while doing so) and the process will start. As indicated in Step 12, the relevant quantity is the minimum angle of the transmission graph "X", or even better the average of all minimum angles: "<X>". After the measurement has finished write down the angle for pure water. In the next step, we will compare this angle with solutions with different sugar concentrations.

Attention: If you want to obtain useful results, do not rotate the laser between or during the measurements as this would also rotate the plane of polarisation and would thus influence the minimum angle.

Step 16: Measuring a sugar solution

Now let's see if we obtain a different result if we measure a sugar solution instead of just plain water! We will prepare various solutions with different sugar concentrations using the following dilution scheme:

1. Take a measuring beaker and add 30 sugar cubes (that's 100 g). Pour in 400 ml of water and stir until you obtain a clear solution and no sugar particles can be seen anymore. (Taking hot water might speed up this process.)
2. Pour half the content of the beaker (200 ml) into a glass, a cup or any other container. This solution will be called **S1**. It has a sugar concentration of 250 g/liter. Label the container accordingly.
3. Do not throw away the content of the beaker but fill in plain water until there is again 400 ml liquid inside. Mix well.
4. Pour half of the beaker's content into a container. This solution will then be called **S2**. It has a sugar concentration of 125 g/liter. Label the container accordingly.

Repeat the steps 3 and 4. You will finally obtain the following solutions:

Solution	Sugar concentration	Minimum angle
S1	250 g/liter	...
S2	125 g/liter	...
S3	62.5 g/liter	...
S4	31.25 g/liter	...
S5	15.625 g/liter	...

Pour each solution into the sample chamber and start the measurement process. Write down the minimum angle for each sugar concentration.

You can insert the data into a spreadsheet programme (like Microsoft Excel or LibreOffice Calc) and present it inside a XY chart. Is there a connection between the sugar concentration and the minimum angle?

Step 17: Measuring the sugar concentration of ice tea

Now, we'll examine the sugar concentration of ice tea. Pour ice tea into the chamber and start the measuring process. Be careful not to rotate the laser or else you will influence the quality of the results.

Compare the minimum angle with the results from the previous step. How big is the sugar concentration of ice tea? Have a look at the nutritional values on the packaging to see how good your results are.

Step : End result & conclusions

What we learned?

The participants

- learn about the wave nature of light, especially about the phenomenon of polarisation
- get into contact with the modern field of laser material processing
- learn how to assemble electronic components on a breadboard
- learn about applications of the Arduino platform
- learn how to use a laser cutter to construct a box made of plywood
- learn how to operate a 3D printer
- get a feeling for the sugar concentration of different softdrinks

Concluding thoughts

- According to a guideline by the World Health Organisation the daily intake of free sugar should not exceed 25 g¹. How much ice tea may you drink over the course of a day given this limitation?
- In this workshop we saw that sugar rotates the plane of polarisation. Thus, we could measure the concentration of sugar. Are there other physical phenomena that we might employ to measure the concentration of a given substance (not necessarily sugar)?
- Can you think of other applications for Arduinos / microcontrollers?
- What could you do in order to optimise the polarimeter or the measuring process?
- Could there be a problem if you wanted to examine coke or other drinks with a high light absorption (which are less transparent)? How could you solve it?

Of course, our polarimeter has not yet reached the highest stage of development. There are certain issues:

- Using a solderless breadboard is perfect for developing electrical circuits as you can easily rearrange the components over the board (which is why we used it here). However, those breadboards are often a little instable as cables tend to slip out of their contact points.
One solution might be to fix the pins with some glue. A better solution would have been to use a solderable breadboard where the connections are fixed with a soldering iron. For professional applications where products are made in high quantities, however, it is common practice to design specific circuit boards that are produced in a special process.
- We might use a better servomotor or even a stepper motor to position the polarizer more accurately. Another idea would be to employ a more sensible photosensor or a more powerful laser. However, this is always at a higher financial cost.
- It would be good to integrate an apparatus to better fix the laser so the laser beam won't drift away.

¹ WHO Guideline: Sugars intake for adults and children, 2015



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PHABLABS 4.0 is a European project where **two major trends** are combined into one powerful and ambitious innovation pathway for digitization of European industry:

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