PHABLABS 4.0

PHOTONICS WORKSHOP

PLAYING WITH LIGHT

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PROPERTIES OF THIS WORKSHOP

SUMMARY:

Discover, measure, have fun and play with light and photonics! Make a small kit with laser-cut and Plexiglas to experiment and play with the strange properties of light, from refraction to total reflection, from lenses to prisms, and play with the photonics billiards.

TARGET AUDIENCE:

Young students (15-18 years old)

SUGGESTED TIME PLANNING: (Total: 1h)

Timing in minutes	activity
0 - 15	Introduction
15 - 30	Lasercutting
30 - 60	Fabricating the kit and playing with light

TOOLS:

Laser Cutter

WEBLINK:

All needed files for lasercutting andWemos can be found on:
http://www.phablabs.eu/workshop/playing-lenses
or via the QR code.

Step 1: reflection and refraction of light

1.1 The speed of light

The light propagates in vacuum at the constant speed of c = 299 792 458 m/s (generally approximated at c ≈ 300 000 000 m/s). This means that a ray of light takes only a little more than one second to travel from Earth to Moon.
According to relativity nothing can move faster than light in vacuum. But in other transparent media the light travels at slower speeds, for example in water the speed of light is about $v_{water} \approx$ 225 407 000 m/s, in glass $v_{glass} \approx$ 197 231 000 m/s, in plexiglass $v_{plexy} \approx$ 201 203 000 m/s.

1.2 The refractive index

The ratio between the speed of light in vacuum and in a different medium is called refractive index. This number indicates how much the light is slower in the considered medium with respect to the vacuum. For example, the refractive index in water is $n_{water} = c/v_{water} \approx 1.33$, in glass $n_{glass} = c/v_{glass} \approx 1.52$, in plexiglass $n_{plexy} = c/v_{plexy} \approx 1.49$.

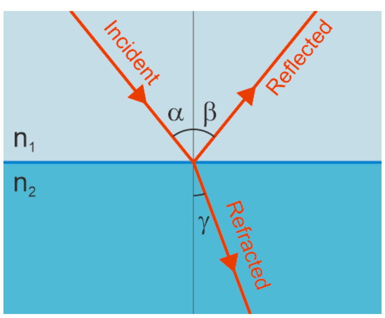
1.3 Reflection and refraction

In crossing the boundary surface between two transparent materials with different refractive index a ray of light is subject to reflection and refraction:

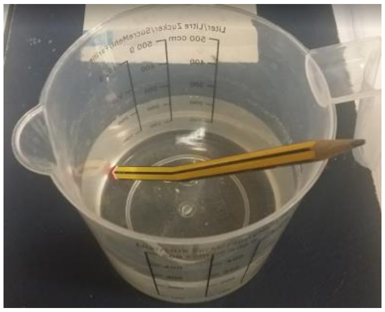
(a) Reflection: part of the light is reflected back, with a reflection angle β identical to the angle of incidence α (see the figure below), $\alpha = \beta$;

(b) Refraction: part of the light crosses the boundary and it is deviated, with a final refraction angle γ (see the figure below) related to the incident angle α by the "Snell law":

$$\frac{sin\alpha}{sin\gamma} = \frac{n_2}{n_1}$$

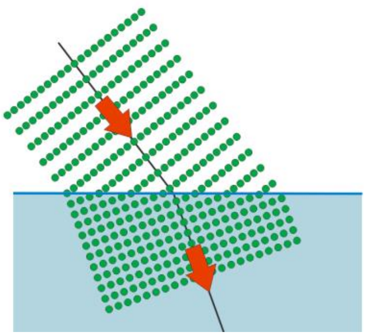


This effect can be observed, for example, with pencil immersed in water that appears to be "broken" because of the refraction between water and air.



1.4 Explaining refraction

Refraction is due to the variation of the speed of light in the passage between the two media. Just to give an intuitive illustration, imagine light as a military column marching lined up by rows. When the soldiers enter in the region where they must slow down, they deviate from the original direction in order to maintain the line with their faster comrades (see the illustration).

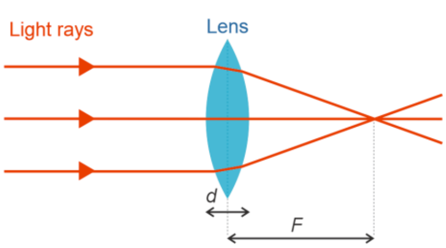


In a similar way a tank turns by slowing down one track with respect to the other.

1.5 Lenses

The deflection of light rays thanks to refraction is the basic concept for the manufacturing of lenses, fundamental elements for a large number of applications: eyeglasses, photo and video cameras, microscopes, telescopes, laser cutting, but also eyes and eyesight etc.

In the following scheme it is illustrated the working principle of a biconvex lens, capable to concentrate parallel light rays into a focus point.



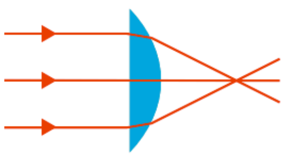
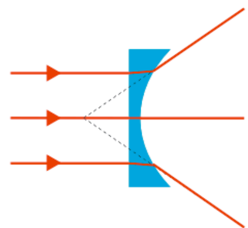
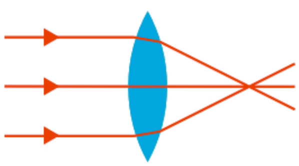
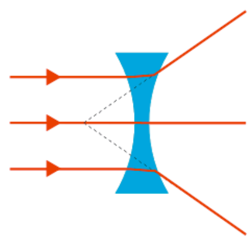
Parallel rays coming from infinity and perpendicular to the lens (for example from a laser or from the sunshine) are concentrated at a distance F (focal length) from the lens. For any lens the focal length F is given by the formula:

$$\frac{1}{F} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2} - \frac{(n-1)d}{n\,R_1R_2}\right)$$

where

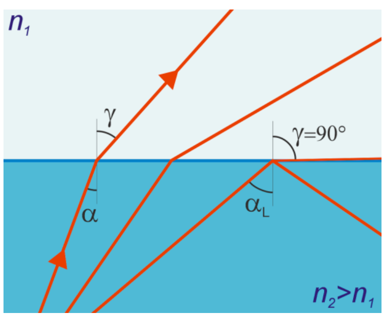
- n is the refractive index of the lens material
- R_1 is the radius of curvature (with sign) of the lens surface closer to the light source
- R_2 is the radius of curvature (with sign) of the lens surface farther from the light source
- d is the thickness of the lens

In the following scheme are summarized different kind of lenses:

Plano-convex  $R_1 = \infty, R_2 > 0$	Plano-concave  $R_1 = \infty, R_2 < 0$
Biconvex  $R_1 > 0, R_2 > 0$	Biconcave  $R_1 < 0, R_2 < 0$

1.6 Total internal reflection

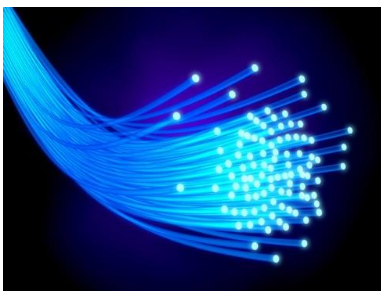
The total internal reflection is an interesting phenomenon related to the crossing of light between different transparent media.
In the passage from higher to lower refractive index (for example from water to air) a light ray diverges (see figure below).

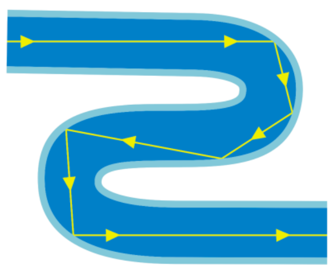


There is a limit condition for which the emerging refraction angle is parallel to the border surface ($\gamma = 90°$), and this corresponds to a limit incident angle $\alpha_L = \arcsin(n_1/n_2)$. For $\alpha > \alpha_L$ all the incident light is totally reflected back.
This phenomenon can be experimented underwater by observing the reflection of the seabed looking at the surface of the water (see the figure).

1.7 Optical fibers

Nowadays fastest communications (telephones, internet etc.) are guaranteed by optical fibers. Optical fibers are essentially flexible glass wires within which the light is transmitted by total internal reflection.

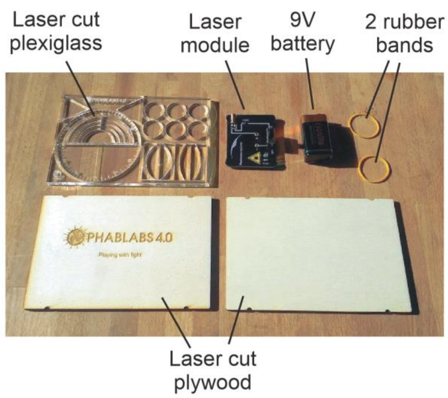




Step 2: Part list

Components needed to carry out the workshop:

- Plexiglass sheet for laser cut (5 mm thick, at least 15 cm x 10 cm)
- Plywood sheet for laser cut (4 mm thick, at least 16 cm x 21 cm)
- 1 laser module
- 1 9V battery
- 2 rubber bands



Detail of the laser module in the correct position:

Laser Safety Rules

The laser beam can be dangerous for eyes. Please, follows these rules:

1. Act cautiously and responsibly! Do Not only think of your own safety but also that of others.
2. Never direct the laser beam or its reflection in anyone's face, including your own. Take precautions and think ahead to ensure that this cannot happen accidentally. Act responsibly!
3. The laser beam should always remain parallel to the table surface and must never leave the table boundaries. Make sure that the beam and its reflections are stopped before they reach the table edge
4. The laser itself, all components in the beam path and beam stoppers have to stand stable.
5. While the laser is on, the space within 10 cm above the table top is the laser zone. The laser beam and its reflections must not leave the laser zone! On the other hand, your eye absolutely must stay out of this zone – that is, in almost all cases, well above it.
6. Before you switch on the laser, ensure that there are no reflective items in the laser zone.
7. If you put anything into, or remove anything from, the laser zone – especially objects in the beam path! – make sure that reflections from their surface are always pointing downwards, towards the table.
8. If you see a laser beam or reflection of a beam on someone: warn him or her.
9. Act responsibly!

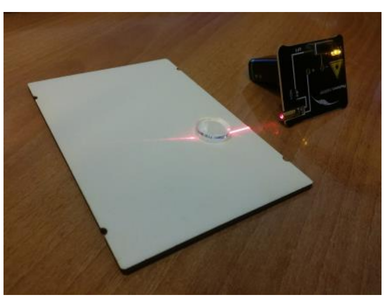
<u>**Step 3: Realization**</u>

1) Realize the optical kit by laser cutting and engraving of a 5 mm thick plexiglass sheet (about 25 minutes required by a Trotec Speedy 100 Laser Cut machine) according to the project file ***light_kit_plexy.svg***

2) Realize the casing by laser cutting and engraving of a 4 mm thick plywood sheet (about 10 minutes required by a Trotec Speedy 100 Laser Cut machine) according to the project file ***light_kit_plywood.svg***

3) Remove all the elements from the plexiglass sheet. If necessary, remove the protective film from the plexiglass elements.

4) Put the desired transparent element(s) on the plywood base, place the laser module close to the base (as illustrated in the figure), switch it on and hit the element with the beam.



To pack away the kit easily:

1) place the plexiglass frame on the plywood base.

2) insert the transparent elements in the frame.

3) cover the frame with the plywood cover.

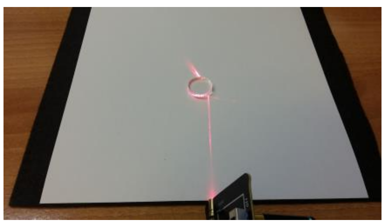
4) Fix the package with the two rubber bands.

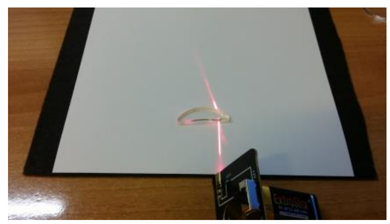
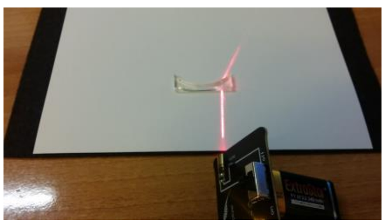
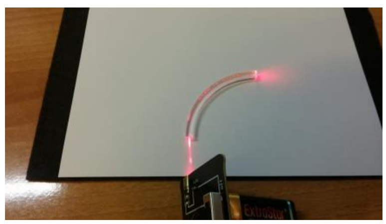
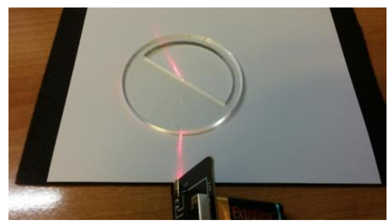
Step 4: Activities

Use the kit of transparent elements and the laser module to play, experiment and measure light phenomena with a series of hands-on activities. Here there are some examples.

4.1 Guess & Try

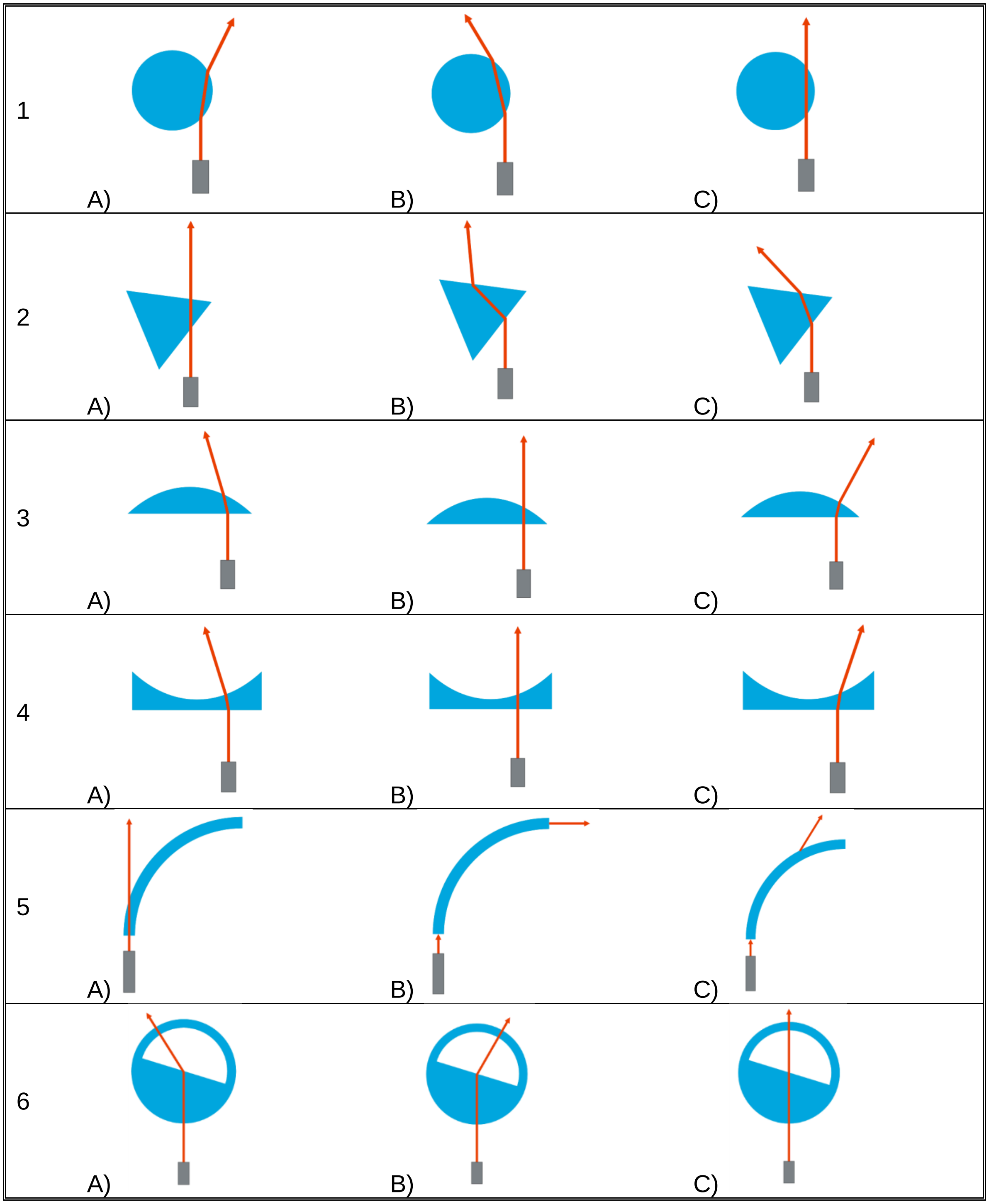
In this first activity the participants have to respond to a quiz, trying to guess the behavior of the laser beam when encounters different transparent elements. Once answered, the participants can find by themselves the right solutions by experimenting the different conditions (see the following figures).



Guess & Try quiz

Guess the laser beam behavior in the following cases:



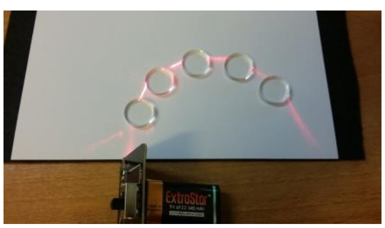
4.2 Try & Play

In this second activity the participants can experiment the behavior of a laser beam in different conditions by using many transparent optical elements with different shapes. For example, it is possible to try the following cases:

a) Reflection and refraction with laser and protractor:
point the laser beam, rotate the protractor in different positions and observe the effects:

b) Refraction in lenses:
move the laser beam perpendicularly to the lens length and observe the effect. Try with different lenses, alone or joined tegether.

c) "Blend" light with a series of circles:

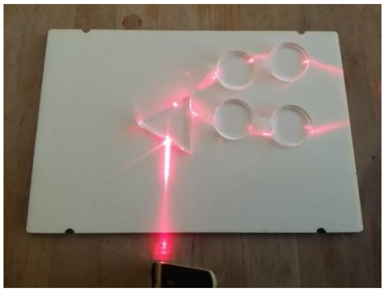


Play: *Challenge other participants: who can use as many disks as possible?*

d) Drive light in a long guide composed by single elements thanks to the total internal reflection (optical fibers principle):

Play: *Challenge other participants: who can create the longest guide?*

e) Split light into two (or more) beams:



f) Scatter the different objects around and hit as many as possible with the laser beam.

Play: *shuffle the transparent elements on the plane and add a target object. Now play to hit the target with the laser beam by using refraction and reflection of light. Challenge other participants.*

4.3 Measure

One of the elements composing the kit is the "protractor", a tool with a graduated scale that allows to study reflection and refraction and to measure incident (α), reflected (β) and refracted (γ) angles in degrees.

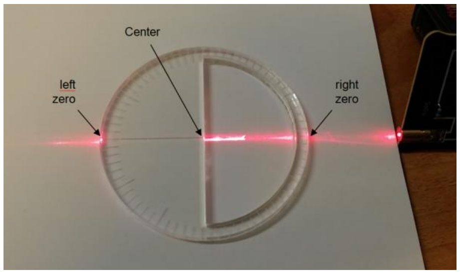
With this element it is possible to estimate the refractive index of plexiglass and verify the Snell law:

$$\frac{sin\alpha}{sin\gamma} = \frac{n_2}{n_1}$$

This can be done in three different ways.

4.3.1 Testing the Snell law with the protractor: from air to plexiglass

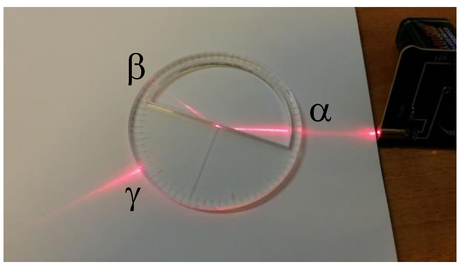
1) First of all, set the system as in the following figure:



The laser beam must:

a) cross the "zero" reference on the right (from the empy part of the protractor, withlight crossing from air to plexiglass);
b) cross the center of the protractor;
c) cross the "zero" references on the left.

2) Turn a little the protractor, still maintaining the laser beam on the center, and read the three angles on the scale:



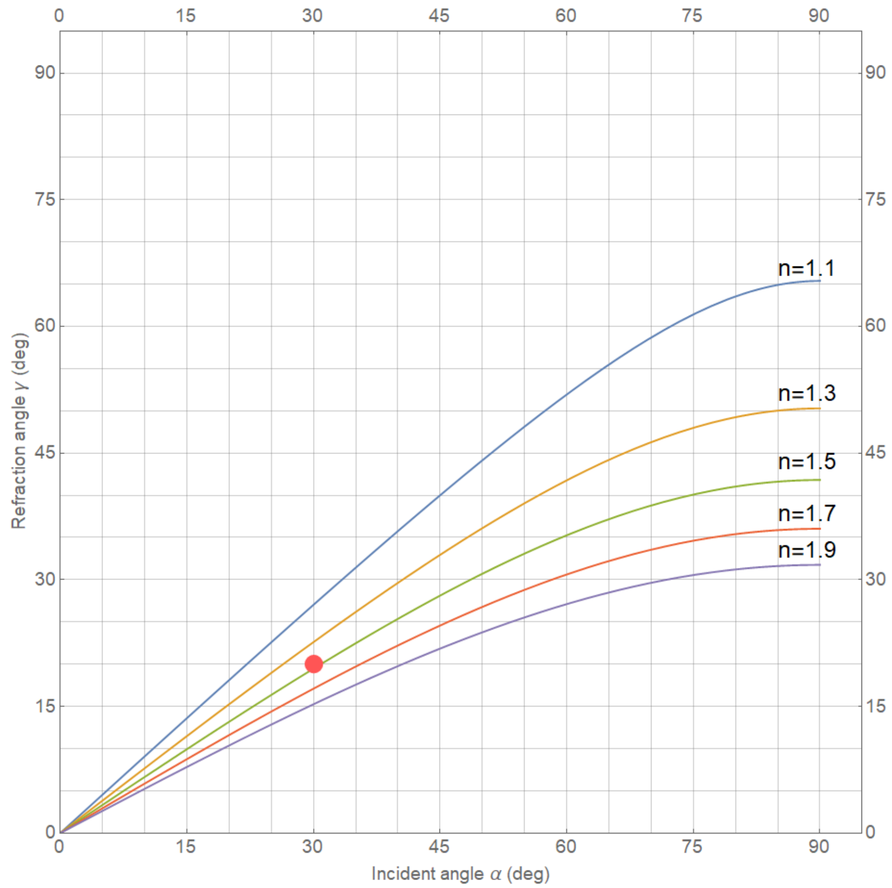
Write the angles on a table:

Incident angle α in degrees	Reflection angle β in degrees	Refraction angle γ in degrees
0	0	0
30°	30°	20°
...	...	...

3) Repeat the measurement for different rotations (still maintaining the empty part facing the laser) and write the obtained angles on the table. Sometimes it will not be possible to see the reflection; in this case write "NA" (Not Available) on the table for the value of the relative angle.

4) Verify that angles α and β are equal (reflection).

5) Report the values of α and γ as points on the following graph (the red point plotted corresponds to $\alpha = 30°$, $\gamma = 20°$).

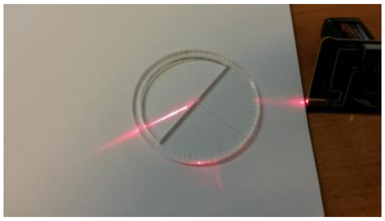


Angles α and γ are linked by the relation $\gamma = \arcsin[sin(\alpha)/n]$ (inverse of the Snell law, where *n* is the refractive index of plexiglass). This relation is plotted in the graph for different values of *n*. If the Snell law is verified the experimental points from the table must be aligned along one of the plotted curves (or along an intermediate one). The corresponding *n* gives an estimation of the correct refractive index. In our case the points will be almost aligned on the *n = 1.5* curve.

Question: *why the points on the graph are scattered?*
Answer: *Every measurement is subject to an error. In this case there is a big error in the measurement of angles.*

4.3.2 Testing the Snell law with the protractor: from plexiglass to air

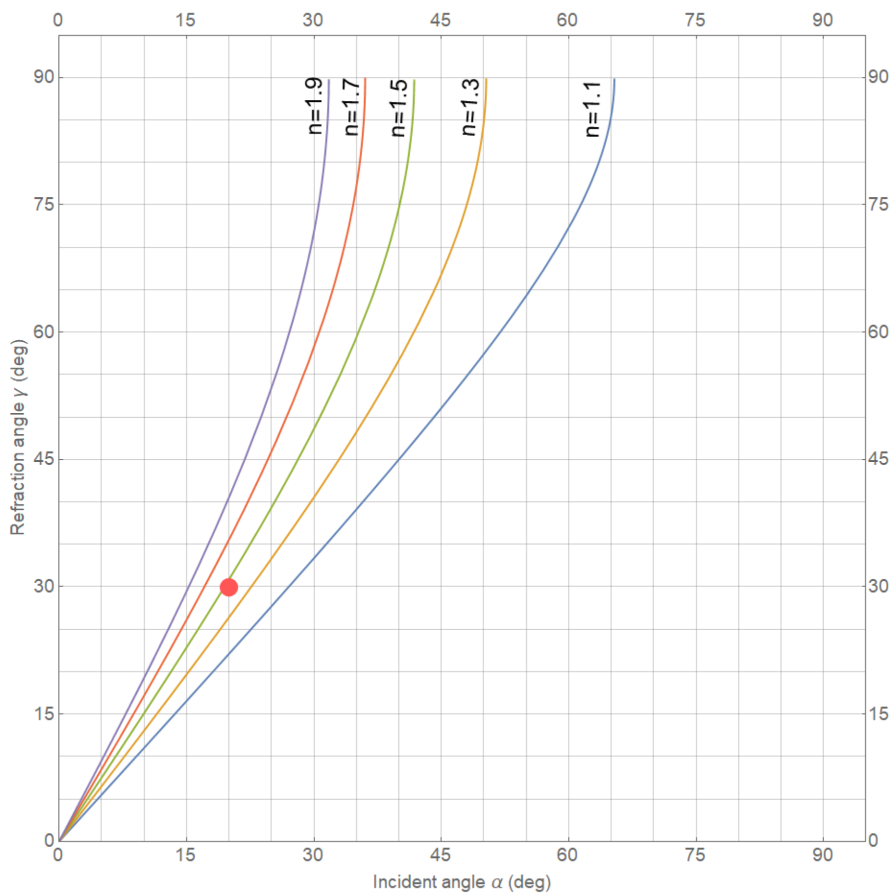
The same measurement can be repeated by placing the empty part of the protractor far from the laser beam (light crossing from plexiglass to air).



Repeat the measurement for different angles and compile a new table:

Incident angle α in degrees	Reflection angle β in degrees	Refraction angle γ in degrees
0	0	0
20°	20°	30°
...	...	...

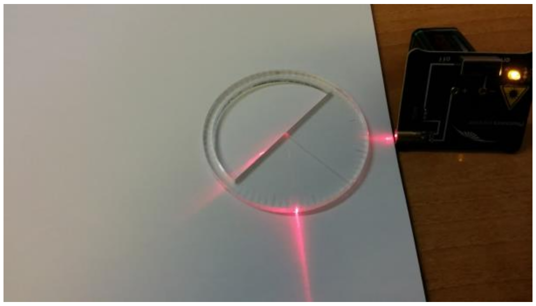
Put the points on the following graph (the red point corresponds to $\alpha = 20°$, $\gamma = 30°$).



Angles α and γ are linked by the relation $\gamma = \arcsin[n\, sin(\alpha)]$ (inverse of the Snell law in this case). This relation is plotted in the graph for different values of *n*. Also in this case, if the Snell law is verified, the experimental points from the table must be aligned along one of the plotted curves (or along an intermediate one). The corresponding *n* gives a new estimation of the correct refractive index. Once again the points will be aligned on the *n = 1.5* curve.

4.3.2 Testing the Snell law with the protractor: total reflection

It is also possible to estimate *n* by considering the total reflection. Rotate the protractor until the refracted beam becomes parallel to the boundary surface (see figure below). The corresponding incident angle is the limit angle α_L.



Since $\alpha_L = \arcsin(1/n)$, we can use α_L to estimate $n = 1/sin(\alpha_L)$.
Obviously the three different estimations must coincide (unless measurement errors).

4.4 Extras

We have proposed a series of possible activities with the kit of transparent elements and the laser module, but it is possible to freely explore and create new activities. For example, you can use the kit to invent new games, challenges, puzzles and solitaires; you can measure the focal length of the different lenses, alone or joined together to form more complex lenses; you can create artistic composition with light, and so on.

Use your creativity and enjoy your light kit!

Step 5: End result & conclusions

What we learned?

- Reflection and refraction of light
- Speed of light and refractive index
- Snell law
- Total internal reflection
- Working principles of lenses, optical fibers and other optical elements
- Fablabs and their capabilities

Concluding thoughts

In this workshop a technology based on light and photonics (laser cut) is used to practically explore fundamental properties of light such as reflection and refraction and possible applications. This is done with a hands on approach based on a "curiosity driven" and "guess and try" exploration, on games and fun, and also on quantitative measurements. The provided kit (which can be taken home by participants) and the acquired experience can be an inspiration for future original explorations and trials.

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:
On the one hand the growing awareness of **photonics** as an important innovation driver and a **key enabling technology** towards a better society, and on the other hand the **exploding network of vibrant Fab Labs** where next-generation **practical skills-based learning** using KETs is core but where photonics is currently lacking.

www.PHABLABS.eu

This workshop was set up by the *Consiglio Nazionale delle Ricerche* in close collaboration with *MUSE FABLAB*.

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