LASER CLASSROOM

Bringing STEM to light®

BIG IDEAS

- Explain and demonstrate the Rochester Cloak at an advanced level.

WHAT YOU'LL NEED

- 2 Lenses: 50mm diameter, 150mm focal length (f_1)
- 2 Lenses: 50mm diameter, 50mm focal length (f_2)
- 4 Lens holders
- 1 Red LASER pointer
- A ruler
- A sheet of graph paper
- A long flat surface (table)
- Masking tape (optional)
- Double-sided tape (optional)

ADVANCED: INVISIBILITY

To be invisible is a dream as old as human history. Not only does it have far-reaching applications for medical science and the military, but opens doors we don't even know are there yet. The technique you'll be exploring in this activity is one of many ways that researchers have tackled the problem of making the visible less so. It turns out that Harry Potter's invisibility cloak in no longer as magical as you might think…

ELECTROMAGNETIC RADIATION

All visible light is a form of electromagnetic radiation. It falls within the electromagnetic spectrum, which also includes microwaves, radio waves, x-rays and infrared light.

Electromagnetic waves consist of an electric field and a magnetic field. Each of these components is a transverse wave (Act 9), transverse meaning a point on the wave moves up and down, not forwards and backwards. The direction of this up-and-down movement is called the polarization of the wave.

The electric and magnetic fields in an electromagnetic wave are polarized perpendicular to one another, as shown in *Figure 1*. The polarization of each is also perpendicular to the direction of propagation, or the direction in which the wave itself is moving as a whole.

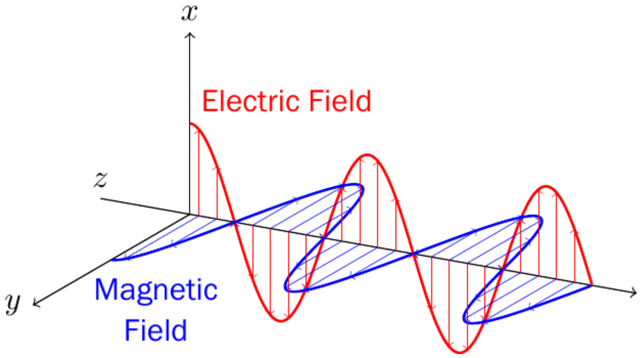

Figure 1: Electromagnetic Wave

PERFECT INVISIBILITY

An object can be made invisible by something called a “cloaking device” or a cloak. In order for something to be considered a perfect cloaking device, it needs to meet a certain set of requirements.

Firstly, the perfect cloak should be able to render any object invisible. This means that not only should the object disappear from view, but the background behind the object needs to be visible as if the object were not there at all. The background must be the same size, color and in the same place as it would be if the cloak and hidden object weren’t there.

Secondly, an observer should not know that the cloak itself is there. This is the more difficult of the two requirements. The cloak itself should be invisible; looking at it should be just the same as looking at a volume of air.

HISTORY OF INVISIBILITY

One of the oldest stories about invisibility is the invisibility cap used by the hero Perseus in Greek mythology to slay the monstrous Medusa. This story went on to influence Celtic and Norse mythology, and legend has it that one of King Arthur’s most prized possessions was an invisibility cloak. Even German fairy tales make mention of a Tarnkappe; an invisibility cap owned by a dwarf king.

The fascination extended into the modern age, with H.G. Well’s book The Invisible Man where a scientist obsessed with optics changes his body’s refractive index to that of air. In other words, his body reflected and absorbed no light, and so he was invisible. Other authors were less forthcoming with scientific explanations for their uses of invisibility, leaving the workings of things like Harry Potter’s invisibility cloak and the titular ring from the Lord of the Rings to the realm of imagination.

TRANSFORMATION OPTICS

In 2006, two research teams simultaneously published their findings in the prestigious journal Science on a method of invisibility called “transformation optics”. They had created the first fully functional invisibility cloak which could hide microwaves from detection.

The approach relies on the use of metamaterials: artificial matter which does not interact with electromagnetic waves the same way natural matter does. Most optical devices interact mainly with the electric field component of an electromagnetic (EM) wave, which causes familiar optical phenomena such as refraction. These metamaterials, on the other hand, interact with both the electric and magnetic fields. We thus call transformation optics full field cloaking, because it hides the entire EM-wave.

One of the advantages of the method of transformation optics is that one can engineer various types of metamaterials that each interact uniquely with EM-radiation and thereby produce different effects at each wavelength. While visible light has not yet been cloaked using this method, it may very well be on the horizon. Another strength of this method of cloaking is that it is omnidirectional - it doesn’t matter from which direction you look at the cloaked object, it remains hidden.

RAY OPTICS CLOAKING

Transformation optics method endeavours to cloak the entire electromagnetic wave, which involves considering the electric and magnetic field, along with a host of other properties. This can be quite a complicated procedure, which is why it isn't yet possible to cloak visible light. The ray optics cloaking is a simplification of the transformation optics process and considers only the direction and power of the EM-wave.

Think of the ray diagrams you draw in class to describe optic systems. The lines representing light waves don't show us how the electric or magnetic fields behave; instead, we care only about the overall direction of propagation of the wave. Ray optics cloaking seeks to prevent the light from interacting with the object it wishes to cloak in the first place. If the light does not reflect off the object, we won't see it.

When the ray optics cloaking method was first conceived, there were a number of problems. The magnification of the background was not be perceived to be1, but, slightly larger. The cloak was also unidirectional, i.e. the object would only be cloaked from one specific direction. If you moved even slightly from the perfect line of sight, the object would become visible, or the background so distorted that it becomes obvious that a cloak was present.

PARAXIAL RAY OPTICS CLOAKING

In the special case where the incident (or incoming) light rays are parallel to the vertical axis of the lens, paraxial ray optics cloaking can be implemented. This case tends to occur when a background is relatively close to the lens, not giving the light much time to diverge before entering the lens. Paraxial ray optics cloaking has proved the most successful of the ray optics cloaking methods to date, producing results with a magnification of 1 and limited multi-directionality. The Rochester Cloak we'll be building is an example of paraxial ray optics cloaking.

CONVEX LENSES & FOCAL LENGTHS

Key to the operation of the Rochester Cloak is knowing the focal length of a convex lens precisely. A convex lens is any optically transparent material that is uniformly thicker in the middle than at the ends. This shape causes light rays entering the lens to refract towards the normal perpendicular to the surface of the lens at any given point, as shown in *Figure 2*.

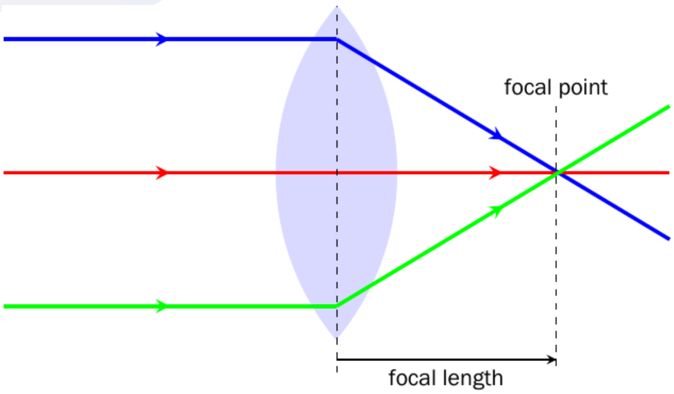

Figure 2: Focal Length of Refracted Rays

All rays entering a convex lens perpendicular to the axis of the lens will refract and meet at a single point. This point is called the focal point of the lens. The distance between the centercentre of the lens and the focal point is called the focal length of the lens.

It is crucial to realise realize that not every convex lens has the same focal length. Thinner convex lenses typically have longer focal lengths. This is because the thicker the lens usually is, the more it bends the light, so the closer the focal point is to the lens.

THE ROCHESTER CLOAK

The Rochester Cloak is the first perfect paraxial ray optics cloak, developed by Professor John Howell and his doctoral student Joseph Choi at the University of Rochester. It uses four converging lenses to redirect light from the background behind a cloaked object in such a way that it never comes in contact with the object, and the viewer sees only the background as it would be if the object were not there.

The Rochester Cloak consists of two pairs of convex lenses, each pair having a different focal length. The lenses are set up in a straight line, with the thicker lenses in the middle and the thinner lenses on the ends. The thin lenses have focal length f_1, and the thick lenses focal length f_2.

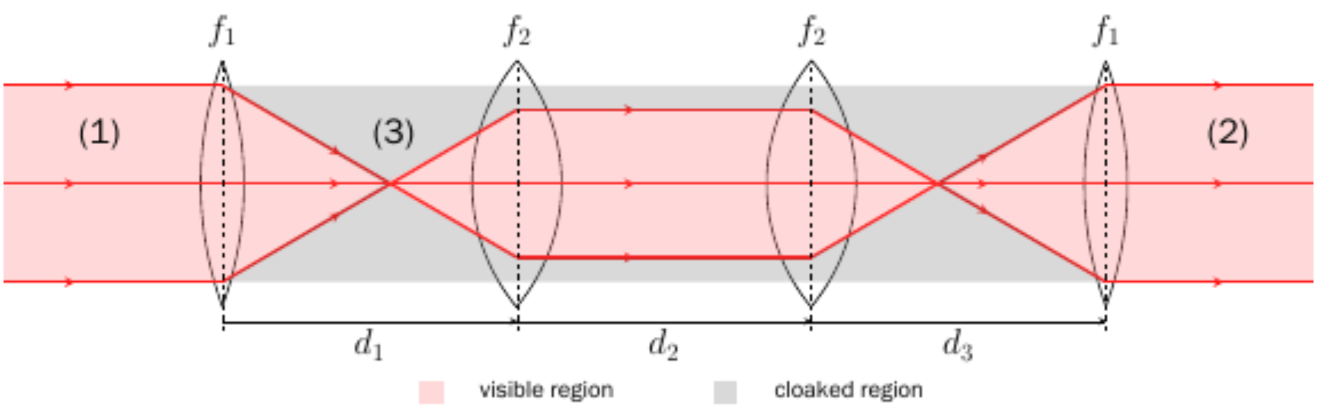

Figure 3: Ray Optics of a Rochester Cloak

The optimal distances between the lenses are calculated using the formulas:

$d_1 = d_3 = f_1 + f_2$ and $d_2 = 2f_2\frac{(f_1 + f_2)}{(f_1 - f_2)}$

Consider the Rochester Cloak illustrated in *Figure 3*. Light reflected off or created by the background enters the first lens from point (1). It is refracted inwards and converges before entering the second lens. The grey shaded area denoted by (3) is completely avoided by the light waves; that is, any an object placed in the shaded region would not interact with and henceor obstruct light from the background. The grey shaded areas are called cloaked regions, and form a donut shaped volume of invisibility around the central axis of the lenses.

Following the red light rays through the system of lenses, you'll see that they emerge at (2), where the viewer is standing. This observer will hence see only the background, and no light from the cloaked regions whatsoever. Any object placed in the cloaked regions becomes are therefore invisible to a viewer looking through the lenses!.

WHY THE SPACING MATTERS

It's important that the spacing between lenses is very precise in order for the Rochester Cloak to work. This is because the device depends entirely on using the lenses' focal lengths to make sure the light bends around the cloaked regions.

Consider the rays moving between the first two lenses, as shown in *Figure 4*. The rays moving in from the left pass through the first lens with focal length f1 and converge to the focal point of the first lensshown.

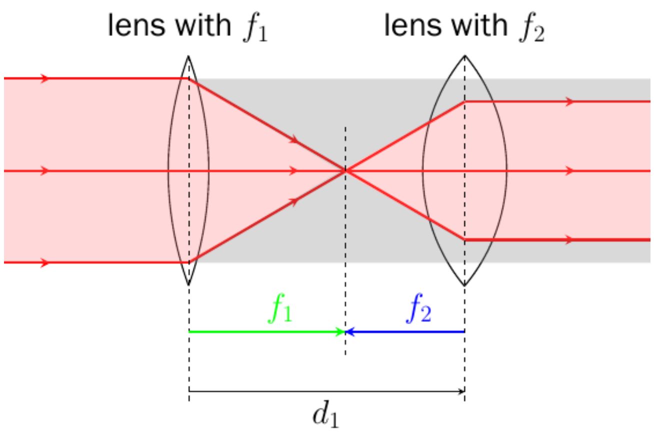

Figure 4: First Two Lenses of Rochester Cloak

Now take a look at the second lens, with focal length f_2. and noticeNotice how the rays emerge parallel from this lens. This is would only be possible if the focal point of f1 was exactly the is exactly a distance of focal length f_2 (the focal length of the second lens) away from the second lens. For the experiment to work, the lenses must be separated by a distance of $f_1 + f_2$.

Imagine tracing the rays backwards from the second lens. The system would work exactly the same way! This is imperative to the working of the Rochester Cloak.

THE FUTURE OF INVISIBILITY

Invisibility has countless possible applications in our current day-to-day. In the field of medical science, invisibility cloaks may could be used by surgeons to see through their own hands as they operate, or into the organs of the patient. With the right cloaking device, Ddoctors could even see unborn babies through their mothers' stomachs in with perfect clarity and to check them for early defects or diseases, all without any discomfort to the mother.

Using invisibility cloaks to mask obstructions between transmission towers could would allow the exchange of radio waves to continue unhindered, leaving us all with better and more reliable cell phone reception.

The development of metamaterials in the pursuit of invisibility opens doors to creating lenses that are stronger than any we've manufactured to date. Scientists may develop lenses that can see microscopic objects, like the inside of a human cell, or even a strand of DNA!

Invisibility cloaks may even be extended to not only cloak electromagnetic waves, but longitudinal waves like sound. It might even dampen the waves produced by an earthquake! The best partexciting aboutaspect of invisibility is that the greatest innovations in the field are still beyond our wildest dreams.

ACTIVITY SHEET: BASIC INVISIBILITY

We're now going to build our own Rochester Cloak!

CALCULATE DISTANCE BETWEEN LENSES

1. Calculate the distance between lenses 1 & 2 and lenses 3 & 4 using the formula: $d_1 = d_3 = f_1 + f_2$ where f_1 and f_2 are focal lengths.
2. Calculate the distance between lenses 2 and 3 using the formula: $d_2 = 2f_2 \frac{(f_1 + f_2)}{(f_1 - f_2)}$ where f_1 and f_2 are focal lengths.

BUILD ROCHESTER CLOAK

1. Place the lenses in the lens holders. Keep track of which lenses have which their focal lengths. **TIP:** If you mix them up, the thicker lens has the shorter focal length (f_2).
2. Stick the sheet of graph paper to the wall on the edgeend of the long surface, or prop it up against a box.
3. Place one f_1 lens at the zero mark. This can be either closest orf furthest from the graph paper; it doesn't matter. You can use a strip of masking tape along the surface to mark off measurements and make sure your lenses are in a straight line. Use the double-sided tape to secure the lens holder in place.
4. Place one f_2 lens distance d_1 from the first lens. Note that you measure from the surface of the lenses, not their centrescenters!
5. Place the other f_2 lens distance d_2 from the second lens. Again, measure from the surface!
6. Lastly, place the other f_1 lens distance d_3 from the third lens.
7. Use the LASER pointer to check that your lenses are aligned. Shine the LASER through the centre of the first lens towards the graph paper. The beam should emerge through all four lenses unchanged: no bigger or blurrier. If the beam is blurry, adjust your lenses until they line up nicely.
8. Stand 2-3 meters from the first lens. You may have to crouch to be on eye-level with the lenses. You should see the graph paper unmagnified through the lenses.
9. Have someone move a pen or other long, thin object between lenses 2 and 3. You should see the object disappear towards the top and bottom of the lenses. See if you can find other areas of invisibility!