Scientific Theory of Invisibility Cloaking

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Introduction

Invisibility Cloaking is a scientific theory where objects can be hidden from sight. The first thing that comes to my mind when I hear the word invisibility is probably the fictitious Harry Potter, but surprisingly, Invisibility Cloaking was scientifically proven by Ulf Leonhardt [1] and John Pendry [2] in 2006. To make an object invisible, a cloaking device is placed around it. A cloaking device is made of artificially structured metamaterials, which are composed of metals and plastic [3]. The cloaking device bends the light rays ensuring that they come in and leave the cloak in the same direction. In this paper, when I refer to an object becoming invisible, it means that the object cannot be seen, but it still exists in space, therefore, making the object hidden. This paper consists of the following topics of Invisibility Cloaking: (1) background theory, (2) optical media, (3) cloaking devices, (4) light trajectories, (5) conclusion, and (6) outlook.

Background Theory

To understand Invisibility Cloaking, we need to learn how vision works and how we can see objects. As shown in Figure 1a, when light rays hit any object, the light rays will reflect back, allowing our eyes to see the object. Therefore, as shown in Figure 1b, to make the object invisible, every light ray needs to bend around the object and not hit our eyes. If we do not see the object, the object has become invisible.

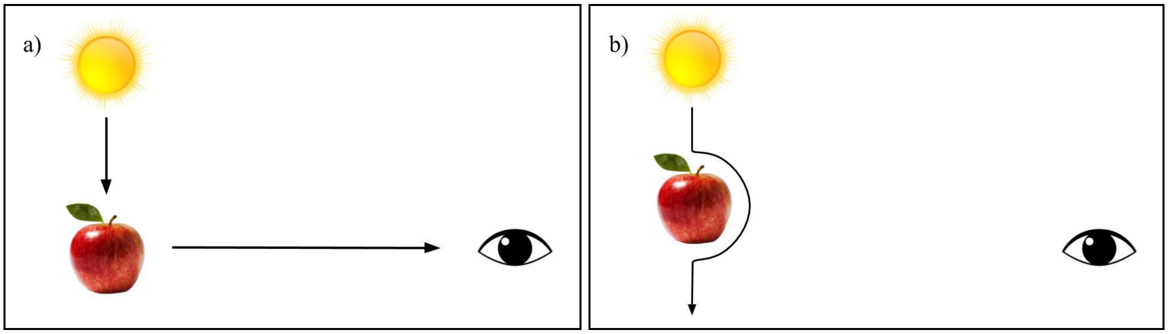

Figure 1: (a) Light reflected off the apple (b) Light bent around the apple

Optical Media

How do we bend light to make an object invisible? Using optical media, light has the property to bend around an object. Optical media are transparent materials where each medium has a specific refractive index. The refractive index depends on the speed of the light in that medium. To solve for the refractive index (n), we use the equation $n = c/v$, where c is the speed of light in a vacuum ($3 \bullet 10^8$ m/s) and v is the speed of light in the medium. For example, in air, the speed of light (v) is $3 \bullet 10^8$ m/s meaning that refractive index (n) is 1. In water, the speed of light (v) is $2.26 \bullet 10^8$ m/s hence the refractive index (n) is 1.33. The changing refractive indices result in the bending of light. Two examples of light bending are a straw in a cup of water looking broken and a mirage between the road and sky. One way to bend light is by using lenses, which are specialized optical devices. The most common example of lenses are glasses. The glasses act as a lense to bend light rays, allowing people to see better.

The bending of light is governed by Snell's Law when light travels from one medium to another. Snell's Law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$, describes the ratio between the angle of incidence and angle of refraction Figure 2 shows an example of Snell's Law between air and water. In this example, n_1 is the refractive index of air, n_2 is the refractive index of water, θ_1 is the angle of incidence, and θ_2 is the angle of refraction. Snell's Law governs the path the light ray takes through different materials (air to water in this example). The light ray entering the medium is called the Incident Ray (shown in blue). When it hits the surface between both media and enters the second medium, it is called the Refracted Ray (shown in green). The light ray gets refracted due to the sudden change in media and the angles at which it hits the surface. While Snell's Law governs the path the light ray takes through two media, Fermat's principle governs how the light ray bends when the medium changes gradually. Fermat's principle states that the path taken by a ray between two points, A and B, should take the least amount of time possible [4].

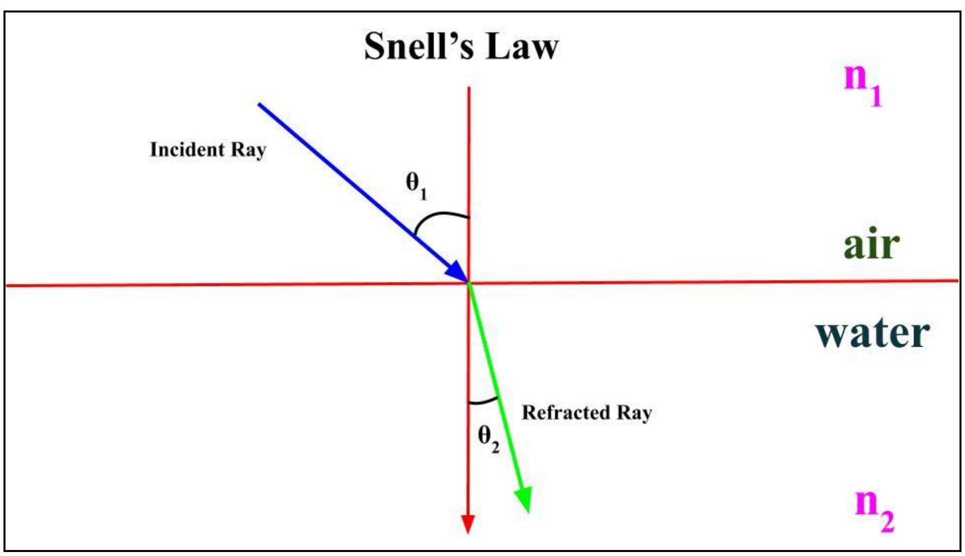

Figure 2: Snell's Law

Cloaking Devices

Using Fermat's principle, in 2006, two physicists, Professor Ulf Leonhardt and Sir John Pendry, proposed the usage of cloaking devices to bend light to make an object appear invisible. When a cloaking device is placed around an object, a container is formed around it. Light is an electromagnetic wave which bends in such a way that it travels around the container. Then, light leaves the cloaking device by propagating in the same direction it entered the cloak. The light propagates around the cloak and does not hit the object, therefore making the object invisible. When the object is invisible, we are able to see whatever is hidden behind the object but not the object itself.

How does the cloaking device bend light around the object? Cloaking devices are made of artificially engineered metamaterials, which are composed of circuits. As shown in Figure 3, the circuits are made of metals and plastic. The circuits in the metamaterials produce an electromagnetic field, which makes an optical medium where each layer in that medium has a different refractive index. Some layers have a higher refractive index than other layers, and as stated in Fermat's principle, light rays will bend around the cloak to optimize the time it takes to travel through the medium. This scientific theory has also been proven by an experiment done in 2006 [3].

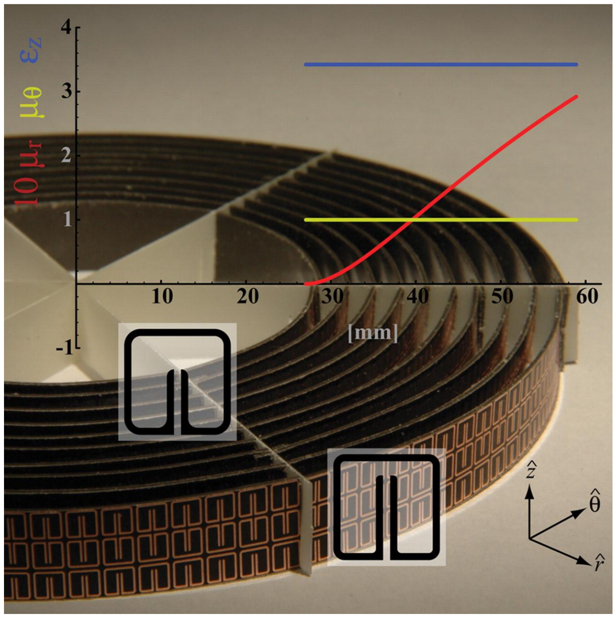

Figure 3: Metamaterial Cloaking Device in the 2006 Experiment [3].

Light Trajectories

To illustrate how Invisibility Cloaking works, Figure 4a shows a visual animation created in a computational tool called Wolfram Mathematica [5]. The chamber, where an object can be invisible to the naked eye, is shown within the blue circle. The cloaking device made of metamaterials is shown in the orange area between the green and blue circles. The cloaking device bends the light rays, shown in red, around the cloak, making the object invisible. After a light ray emerges from the cloaking device, it regains its original direction and its path is restored. As shown in Figure 4b, the light ray appears to have propagated in a straight line through empty space, creating an illusion that there is nothing present. These figures have been produced using the proposal in Ref. [2].

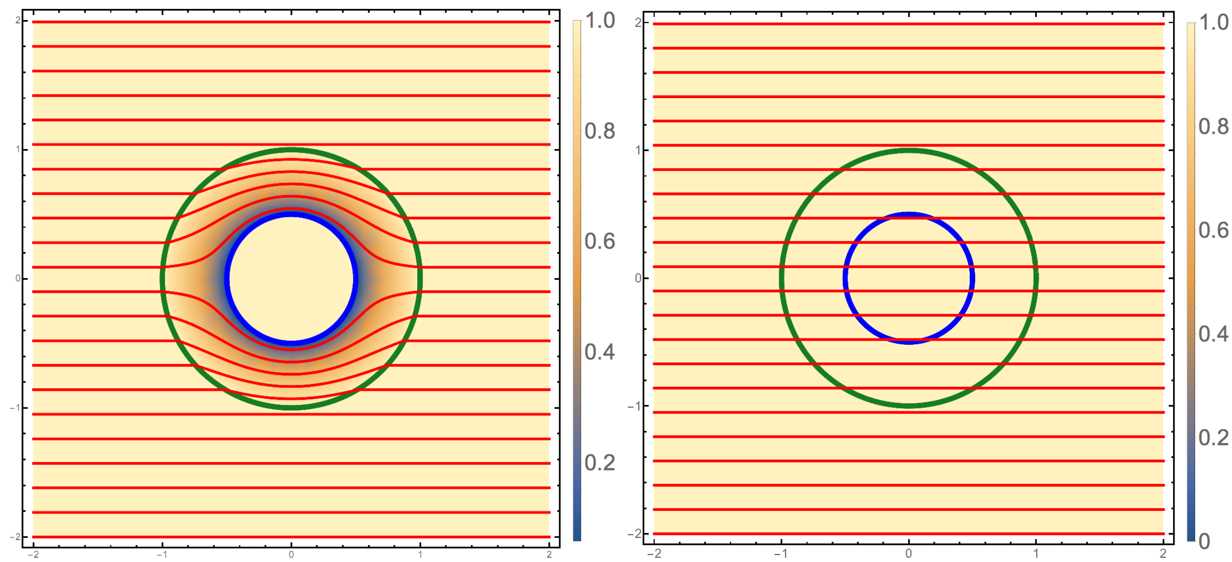

Figure 4: (a) Light rays guided around the object

(b) Light rays appear to pass through empty space

The sudden change in the bending of light is a big challenge for engineers, who are trying to make this cloak a reality. This sudden change requires metamaterials with refractive indices of extreme value. Therefore, I optimized my model, so the changes and distortions of the light rays decrease. This optimized model more gradually changes the bending of light, making the refractive index less extreme. To gradually change the light ray distortions, I have produced an optimized model shown in Figure 5. The original light rays are in red and the optimized light rays are in blue. This optimized model shows the changes from the original model and how it leads to lesser light ray distortions.

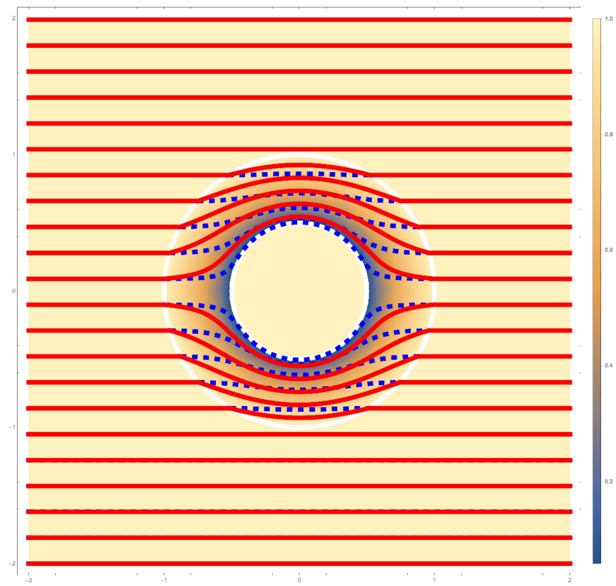

Figure 5: Optimized Model - Light rays (red) vs. Optimized light rays (blue)

Conclusion

So what did we learn about Invisibility Cloaking? We learned that Invisibility Cloaking is a scientific theory where objects can be hidden from sight. When light rays travel in a straight line and hit an object, they reflect back to our eyes allowing us to see the object. When light rays are bent around an object and leave the object in the same direction, the object becomes invisible. For the light rays to bend around an object, there needs to be a cloaking device made of metamaterials. Inside the cloaking device, the object is hidden from sight. Since the rapid change of the bending of light is a challenge, an optimized model must be produced to gradually change the bending of light.

Outlook

While a cloaking device can theoretically make an object invisible, it also has some other practical and beneficial applications. Similar to light waves, the path of seismic waves can be controlled to minimize or deflect earthquake damage. For example, a hospital can be protected during an earthquake by precisely drilling an array of holes at specific angles and depths around it. This could possibly scatter earthquake waves protecting the hospital. Likewise, in the ocean, an oil rig could be protected against damaging ocean waves by placing a patterned structure on the seafloor to avoid a disaster [6]. I cannot wait to see what we scientists can achieve with the scientific theory of Invisibility Cloaking.

References

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