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Science Investigation

Year 9 - 10

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Science Investigation

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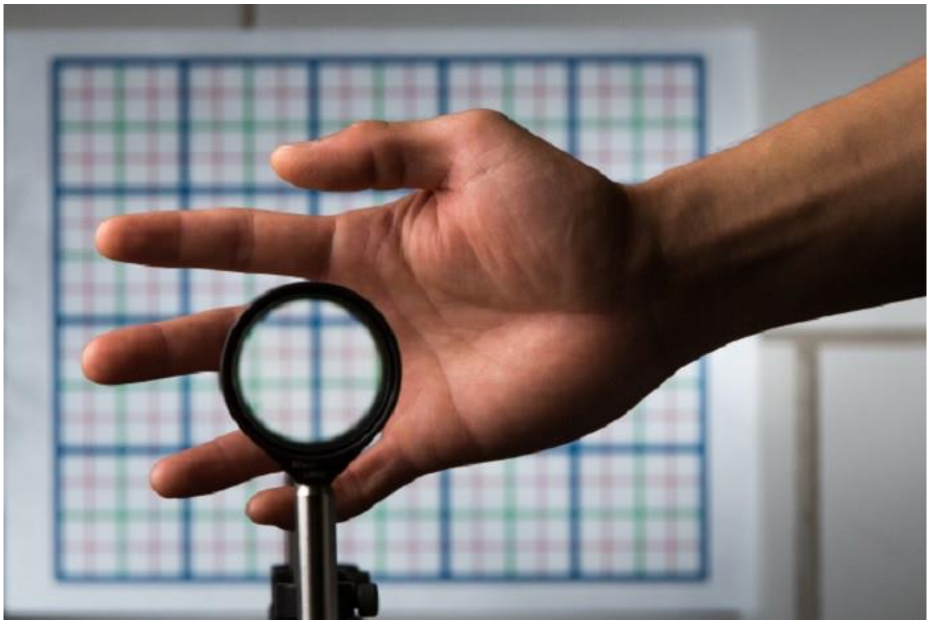
Bending Light to Disappear: An Investigation into Optical Cloaking



https://www.ibtimes.co.uk/us-scientists-invent-harry-potter-style-invisibility-cloak-1467499

WORD COUNT: 2200 (Excluding, caption, tables, references and logbook)

INTRODUCTION

Invisibility is a fascinating area that has inspired many books and movies. My experience with invisibility has mostly been watching this in movies. I first saw invisibility happen in one of my favorite Marvel movies, Avengers, when Nick Fury says, "Lets vanish" and the huge battleship starts to really vanish and disappear in the sky. More recently, I've seen invisibility happen when Harry Potter uses his invisibility cloak and when Sue Storm (Invisible Woman) from Fantastic Four, disappear at will. My research has shown there are three scientific ways using which we can achieve invisibility and the examples from movies mentioned above might all be actually possible. (Public Intelligence 2019)

Invisibility can be achieved through the following three methods: Camouflage, Transparency and Cloaking.

- Camouflage: Animals like chameleons and stick insects disguise themselves from taking the shapes and colors of objects in their surroundings. Used by military for their uniform and stealth planes.
- Transparency: Works by modifying the speed of light. Transparency is obtained by surrounding a particle by layers made of transparent substances like glass.
- Optical cloaking: The hidden object is enclosed by a cloaking device – a transparent shell that guides light around the object as if the light would go through empty space. The experiment I'm doing is a type of partial cloaking.

(Public Intelligence 2019)

BACKGROUND

Fermat’s Law of Optics and Law of Refraction

Optical cloaking uses a device modifies the light waves such that detecting the hidden object is impossible. Rochester cloak is a simplified method of optical cloaking using the Fermat’s principle of optics, first proposed by the French mathematician Pierre de Fermat in 1662. The principle states that light waves of frequency will only follow the fastest route when travelling from one point to another. Fermat's law has been used to obtain the law of reflection and refraction. Refraction is the bending of light; when light travels from one medium to another, it bends. (GoPhotonics 2023)

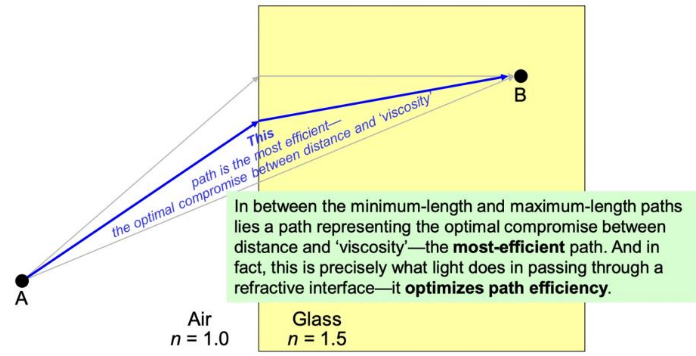


Figure 1 Fermat's law of optics and refraction (American Academy of Ophthalmology n.d.)

Optical illusions caused by bending of light

The bending of light as it passes through different mediums Is the cause of many optical illusions. The most famous natural examples of this are mirages. Mirage is an optical illusion that causes the eye to see an image of an object that does not actually exist. The illusion convinces the eye that what we see is a real object, even though it is not real at all. (The Britannica 2025)

In 2006, Prof Ulf Leonhardt and Prof John Pendry independently presented their proposals in the same journal (Science) to bend light by using artificial means. Pendry’s team proposed that light can be made to flow around an object, the way water does, by enveloping the object in a metamaterial cloak. (BBC News 2026) Leonhardt considered his proposal to be like a mirage, where light bends around an object in such a way that is leaves the object the same way that it initially hits. Then the observes gets the illusion that there is nothing there. (Basu 2009) Some articles I have read compare this to the way invisibility is achieved in the movie Predator, which I haven’t seen but now I plan to.

Rochester Cloak Technique

Metamaterials are highly complex devices to attain invisibility. The method proposed by both researchers was to use special materials, called metamaterials. These are artificial materials with special properties that are either not available or not easily obtainable in nature. (Liu 2013)

The technique explored for this experiment is basically using off-the-shelf lenses to achieve a similar, if partial effect of invisibility. In 2014, Prof Josh Howell and his PhD student Joseph Choi, from the University of Rochester, developed a device using 4 standard lenses. The device used standard lens ray optics to allow an object to appear invisible, leaving the background undisturbed. The other devices can cause the background to shift a lot, making it obvious that there is a device present. Rochester cloak technique claims to both cloak and object and leave the background undisturbed. Rochester cloak can also be scaled up as large as the size of the lenses, which means that large objects can also be cloaked. (Barnstone 2014)

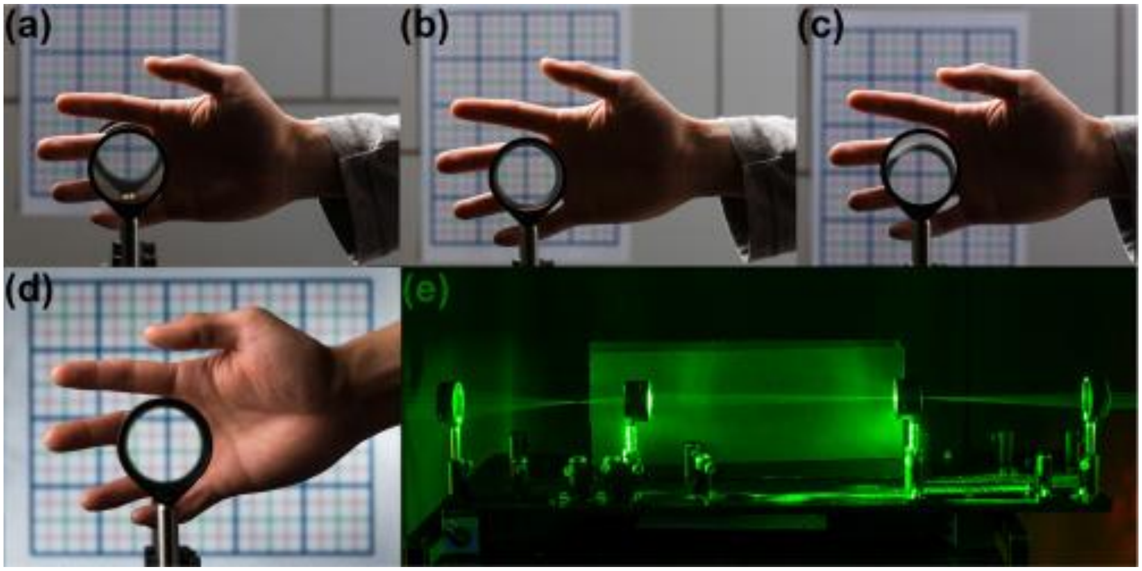


Figure 2 Rochester Cloak Experiment (Barnstone 2014)

In a Rochester cloak experiment, the invisibility affect only works if you look directly into the lenses down the center. This, in effect, means that the object is the first device that can do 3D continuous multidirectional cloaking for light in the visible spectrum. This is unlike other cloaking devices that work fine when you look at an object straight on but if you move even a little, the object becomes visible.

THEORY AND HOW IT WORKS

Rochester cloak can work with 2,3 or 4 lenses. In this experiment, the scenario explored is by making use of 4 lenses. This is the simplest one as per the researchers and one that have suggested in their press release. For the experiment, 2 pairs of lenses are required. Each pair has a different focal length. Theoretically, any two focal lengths would work. The set up looks as below, where f_1 and f_2 are the two focal lengths. (Hager--Barnard n.d.)

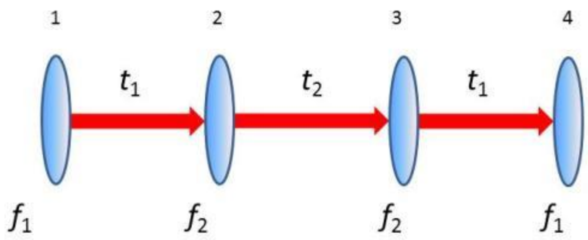


Figure 3 Rochester cloak experimental setup (Hager--Barnard n.d.)

The distance between the lenses can be calculated as below: From (Wizards of Wright 2018)

$$t_1 = f_1 + f_2 \qquad \textit{Equation 1}$$

$$t_2 = 2f_2\frac{f_1+f_2}{f_1-f_2} \qquad \textit{Equation 2}$$

The image below shows the visible and invisible regions.

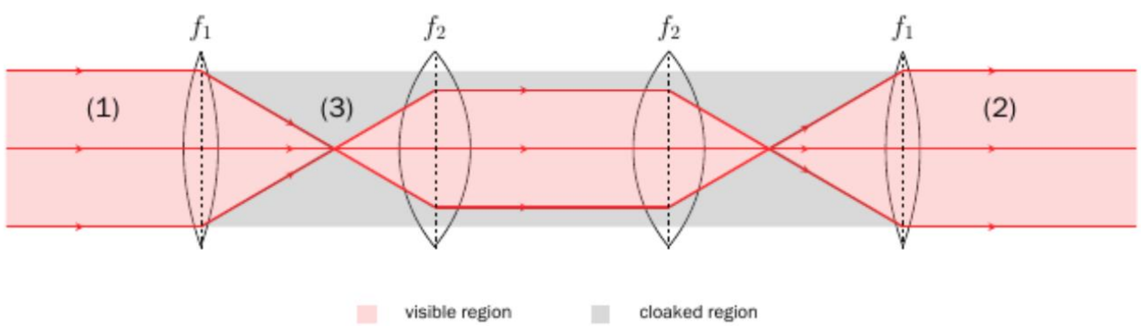


Figure 4 Rochester cloak: visible and cloaked regions (Wizards of Wright 2018)

METHOD

Experimental Setup

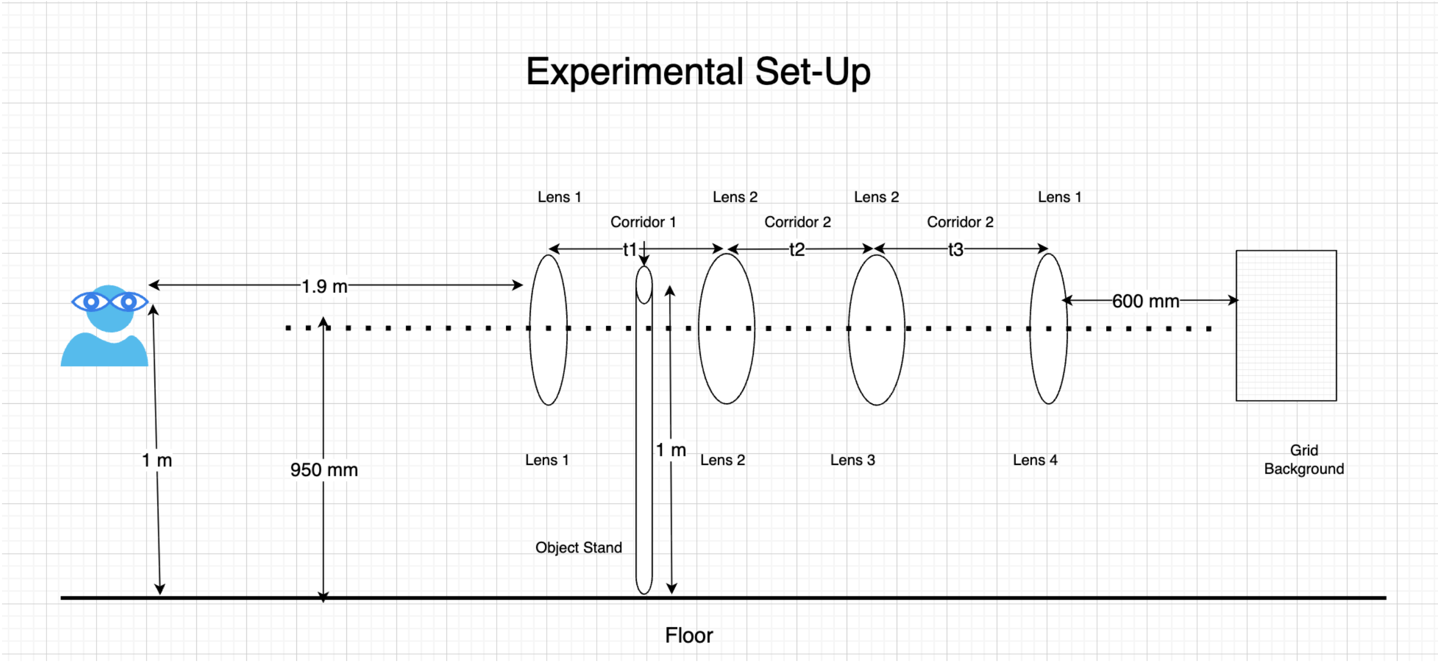


Figure 5 Experimental Setup

AIM: The investigation tests two parts of a 4-lens optical cloaking system (shown above):

First how the ratio of the outer and inner lens Focal lens, affects the length of the cloaked corridors and second, how does the cloaking change when the lenses are moved away from their correct position

HYPOTHESIS 1: As the focal length ratio (f_1: f_2) increases, the length of each of the cloaked corridors also increases

- $C_{1\text{-}2}$, $C_{2\text{-}3}$, and $C_{3\text{-}4}$ increase

HYPOTHESIS 2: As the two outer lenses are symmetrically moved both inward and outward from the original positions, the length of each of the cloaked corridors decreases.

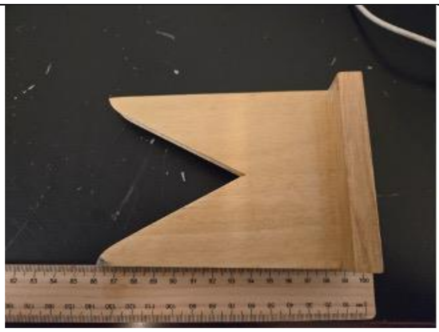
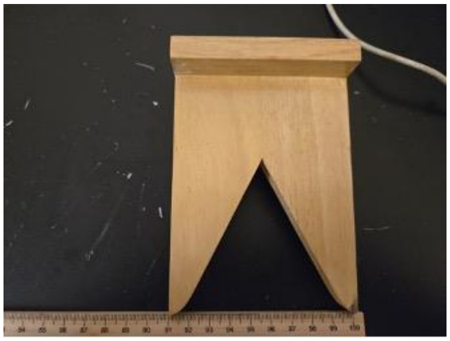
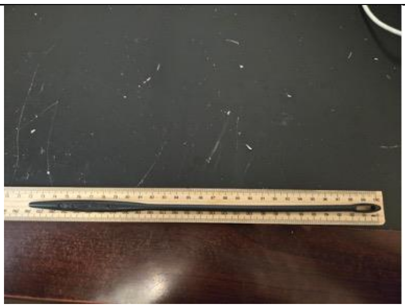
- $C_{1\text{-}2}$, $C_{2\text{-}3}$, and $C_{3\text{-}4}$ decrease

DEPENDENT VARIABLES (What do we measure?)
Length of the cloaked region • $C_{1\text{-}2}$: between lenses 1 and 2 • $C_{2\text{-}3}$: between lenses 2 and 3 • $C_{3\text{-}4}$: between lenses 3 and 4

INDEPENDENT VARIABLES (what do we change?)	
Hypothesis 1	Focal length of the outer lenses f_1 (150mm, 200mm, 250mm, 300mm)
Hypothesis 2	The outer lenses are each moved by 10mm, 20 mm, and 30 mm outward as well as inward

CONTROLLED VARIABLES (What stays the same for both experiments)	
• Same observer - Me • Object used for showing cloaking – the same knitting needle • The height at which the knitting needle was inserted • Background – same grid paper set up • Lighting condition and system set up – same room	
Controlled variables **(specifically for Hypothesis 1)**	• Focal length of the inner lens f_2 • Distance of the observer from Lens 1 • Distance of the grid paper background from Lens 4
Controlled variables **(specifically for Hypothesis 2)**	• Focal length of the lens f_1 (150mm) and f_2 (50mm) • Distance between inner lenses (t2)

Materials

2 lenses each of (diameter 50 mm) and focal lengths: • 50 mm • 150 mm • 200 mm • 250 mm • 300 mm	• Grid Background • Lens Cleaner • Measuring tape • Blue Tack
4 lens stands	 
1 Knitting Needle (object used for cloaking)	
Materials for stand: • 2 Pillar Candles Height = 140 cm • Lego Bricks 4 x 2 (4 pieces), Height = 1 cm each	

Set up Images

Figure 6 Actual experiment setup – Top View

Figure 7 Actual experiment setup – Front View

Figure 8 Object (Knitting needle) visible

Figure 9 Object (Knitting needle) cloaked partially

Steps for doing Experiment 1 for Hypothesis 1

1. First the Correct Values of t1, t2, t3 for each lens combination of lens was calculated. (F_2 = 50 mm; The combination is formed by pairing F_2 with the following F_1 values: 150 mm, 200 mm, 250 mm, 300 mm)
2. The 4-lens system was set up using the calculated distances for the first lens combination, as shown in **Error! Reference source not found.**
3. The viewer (Me) was positioned at a fixed height (1 m from the ground) and fixed distance (1.9 m from lens 1).
4. The grid paper was kept at a fixed distance (500 mm) from lens 4.
5. The object mounted on a stand was moved along each corridor until it appeared or disappeared from view and the approximate position was noted.
6. The stand was then moved in 5 mm increments around this approximate position to get the exact point where the object changed between visible and hidden. This gave the correct measurement with an error of $\pm$5 mm
7. Step 6 was repeated 3 times to find the cloaking corridor (for each start and end points). Then the distance between the two points was recorded as the corridor length.
8. The lens system was rebuilt for the other F_1-F_2 combinations and steps 5 to 7 were repeated for each combination.
9. All the results were recorded in the raw data table for Hypothesis 1 (shown in Appendix 1)

Steps for doing Experiment 2 for Hypothesis 2

10. The first combination was the starting point; lenses 2 and 3 were fixed at their correct positions throughout this experiment.
11. Steps 5 to 7 were repeated at the original distances to find the cloaking corridor widths.
12. Lenses 1 and 4 were moved inward by 10 mm each.
13. Steps 5 to 7 were repeated to find the new corridor widths.
14. Steps 12 and 13 were repeated, when lenses are moved inward by 20 mm and 30 mm.
15. The the lenses were brought back back to the original position.
16. Steps 12 and 13 were then repeated after moving each lenses outward by 10 mm, 20 mm and 30 mm each.
17. All the results were recorded in the raw data table for Hypothesis 2 (shown in Appendix 1)

Fair testing statement

In both parts of this investigation, only one thing was changed at a time, so the test stayed fair. In experiment 1 for hypothesis 1, only the Focal length ratio was changed, and the lens spacing was recalculated correctly for each ratio. In experiment 2 for hypothesis 2, only the positions of the outer lens were changed. The space between inner lenses, and focal lengths were kept the same. Each condition was tested 3 times to check whether the results were consistent and there was no major mistake.

RESULTS

Results from Experiment 1 for Hypothesis 1

Raw result are in Appendix 1:

Ratio: F1/F2	t1 = t3 (mm)	t2 (mm)	C1-2 Cloaking Corridor (mm)	C2-3 Cloaking Corridor (mm)	C3-4 Cloaking Corridor (mm)
3	200	200	87	90	130
4	250	167	104	79	140
5	300	150	144	70	192
6	350	140	155	67	240

Table 1 Average length of cloaking corridors for Experiment 1

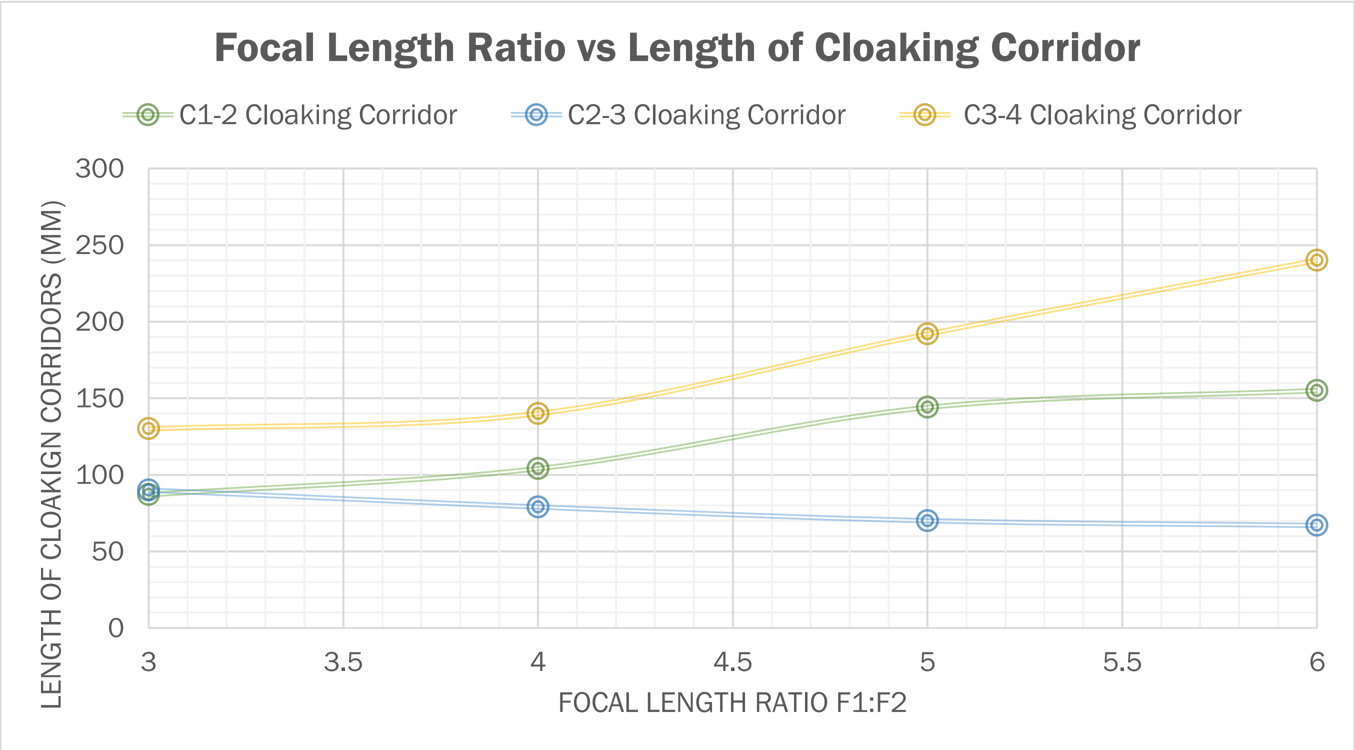


Figure 10 Focal length ratio vs average length of cloaking corridors

Results from Experiment 2 for Hypothesis 2

Note: in calculations, moving inward was taken as positive and moving outward was taken as negative. This was just to show the differences in the direction of moving lenses and the change in t1 and t3.

Displacement from original position (mm)	t1 = t3 (mm)	t2 (mm)	C1-2 Cloaking Corridor (mm)	C2-3 Cloaking Corridor (mm)	C3-4 Cloaking Corridor (mm)
30	170	200	45	120	100
20	180	200	50	110	40
10	190	200	80	120	40
0	200	200	87	90	130
-10	210	200	90	90	130
-20	220	200	105	100	135
-30	230	200	105	110	150

Table 2 Average length of cloaking corridors for Experiment 2

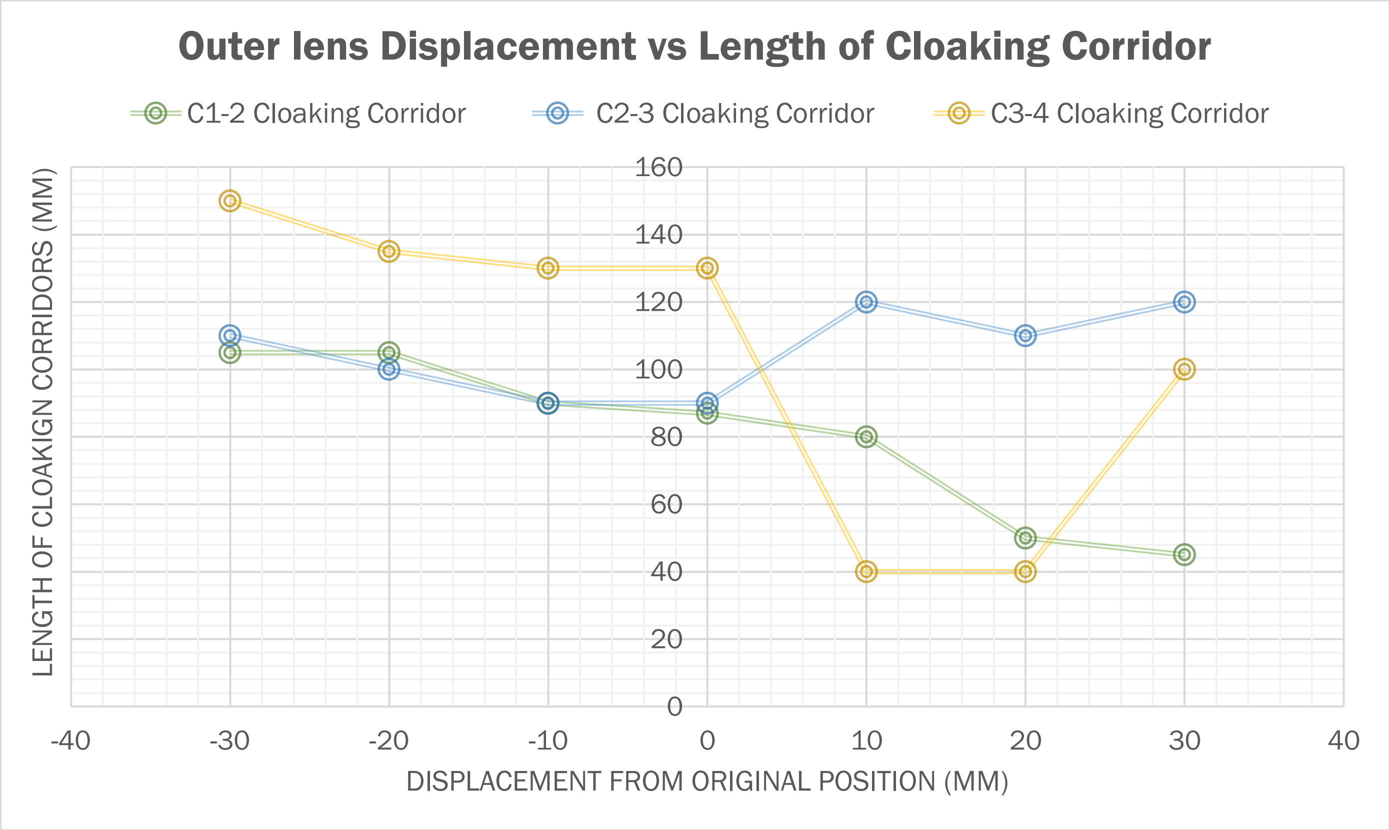


Figure 11 Displacement of outer lenses vs average length of cloaking corridors

RISK REVIEW

Possible Risks	Likelihood of risk	Severity of Risk	Control measures
Lens falling off the table	Medium	High	Change the position of the stand at the middle of the table.
Lens falling off the stand	Medium	Medium	Use blue tack to stick the lens on the stand.
Back pain from sitting at the same position for a long time	Medium	Low	Take some breaks between the readings.
Eye strain from looking at the lenses for a long time	Medium	Low	Take some breaks between the readings.
Cutting the finger while using the measuring tape	High	Medium	Use a glove in one of the hands while using the measuring tape. If possible, use the long ruler.

Table 3 Review of risks

DISCUSSION

Results for Hypothesis 1

Hypothesis 1: As the focal length ratio (f_1: f_2) increases, the length of each of the cloaked corridors also increases: $C_{1\text{-}2}$, $C_{2\text{-}3}$, and $C_{3\text{-}4}$ increase

This is true for both $C_{1\text{-}2}$ and $C_{3\text{-}4}$. Both these increased as the ratio increased as shown in Table 1 and Figure 10

But the hypothesis was not true for $C_{2\text{-}3}$. This length actually decreased as the ratio increased.

I found out why this was the case. When we were calculating the spaces between the lenses, t2 (the length between the two inner lenses) actually decreased as the F_1 increases. So, it makes sense that the cloaking corridor in this region also decreased.

Results for Hypothesis 2

Hypothesis 2: As the two outer lenses are symmetrically moved both inward and outward from the original positions, the length of each of the cloaked corridors decreases: $C_{1\text{-}2}$, $C_{2\text{-}3}$, and $C_{3\text{-}4}$ decrease

$C_{1\text{-}2}$ - When the lenses move inward, $C_{1\text{-}2}$ increases, but when the distance is outward, $C_{1\text{-}2}$ decreases.

$C_{2\text{-}3}$ - When the lenses move inward, $C_{2\text{-}3}$ slightly increases, but when the distance between the lenses start to increase, $C_{2\text{-}3}$ increases at 10mm length and then stays the same for other two points.

$C_{3\text{-}4}$ - When the lenses move outward, $C_{3\text{-}4}$ decreases based on 30mm point. The other two points in the graph seems like outliers. When the lenses move inwards the $C_{3\text{-}4}$ increases.

Based on the results, the distance increases and decreases in each corridor which makes my hypothesis 2 wrong.

CONCLUSION & FUTURE WORK

This investigation had an aim to test how the Focal length ratio of a 4-lens optical cloaking system affects the width of the cloaked corridor and how sensitive this corridor if the lenses are moved from their originally calculated positions.

The results from experiment 1 partially supported hypothesis 1. As the Focal length ratio increases from 3 to 6, the average length between Lenses 1 and 2 and between Lenses 3 and 4 increased, but the average length between Lenses 2 and 3 decreased.

The results from experiment 2 showed that the system behaved oddly when the outer lenses were moved from their original positions. The hypothesis 2 was proven wrong, but the interesting thing was the trend for change. The average outer cloaking corridor length between Lenses 1 and 2 showed showed a clear trend. When the lenses were brought inward, the cloaking corridor increased and when the lenses were moved inward, the corridor decreased. The average cloaking length between Lenses 3 and 4 potentially also seemed to show a similar trend, but there were two outliers which meant that this result could be confirmed. Interestingly, the average length between Lenses 2 and 3 seem to increase whether the lenses were moved inward or outward.

These conclusions are based on a small number of trials and a viewer-based measurement method. This means that more trials with other observers should be done to confirm these results. Overall, this investigation showed that the basic physics behind the experiment can be repeated using simple inexpensive set-up. However, the practical applications need to consider the sensitivity of the set up.

REFRENCE LIST

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APPENDIX 1

F1 (mm)	F2 (mm)	Ratio: F1/F2	t1 = t3 (mm)	t2 (mm)	C1-2 Cloaking Corridor (mm)				C2-3 Cloaking Corridor (mm)				C3-4 Cloaking Corridor (mm)			
					Corridor Start	Cooridor End	Corridor length	Average Length	Corridor Start	Corridor End	Corridor length	Average Length	Corridor Start	Corridor End	Corridor length	Average Length
150	50	3	200	200	115	200	85		200	290	90		470	600	130	
					115	200	85	87	200	290	90	90	470	600	130	130
					110	200	90		200	290	90		470	600	130	
200	50	4	250	170	145	250	105		340	420	80		530	670	140	
					145	250	105	104	344	420	76	79	540	670	130	140
					150	250	100		340	420	80		520	670	150	
250	50	5	300	150	160	300	140		380	450	70		560	750	190	
					155	300	145	144	380	450	70	70	555	750	195	192
					155	300	145		380	450	70		560	750	190	
300	50	6	350	140	200	350	150		430	490	60		600	840	240	
					190	350	160	155	420	490	70	67	600	840	240	240
					195	350	155		420	490	70		600	840	240	

Table 4 Raw results from Experiment 1 for Hypothesis 1

Displacement from original position (mm)	t1 = t3 (mm)	t2 (mm)	C1-2 Cloaking Corridor (mm)				C2-3 Cloaking Corridor (mm)				C3-4 Cloaking Corridor (mm)			
			Corridor Start	Cooridor End	Corridor length	Average Length	Corridor Start	Cooridor End	Corridor length	Average Length	Corridor Start	Cooridor End	Corridor length	Average Length
0	200	200	115	200	85	87	200	290	90	90	470	600	130	130
			115	200	85		200	290	90		470	600	130	
			110	200	90		200	290	90		470	600	130	
10	190	200	110	190	80	80	270	390	120	120	465	505	40	40
			110	190	80		270	390	120		465	505	40	
			110	190	80		270	390	120		465	505	40	
20	180	200	130	180	50	50	270	380	110	110	455	495	40	40
			130	180	50		270	380	110		455	495	40	
			130	180	50		270	380	110		455	495	40	
30	170	200	135	180	45	45	260	380	120	120	440	540	100	100
			135	180	45		260	380	120		440	540	100	
			135	180	45		260	380	120		440	540	100	
-10	210	200	120	210	90	90	320	410	90	90	490	620	130	130
			120	210	90		320	410	90		490	620	130	
			120	210	90		320	410	90		490	620	130	
-20	220	200	115	220	105	105	320	420	100	100	505	640	135	135
			115	220	105		320	420	100		505	640	135	
			115	220	105		320	420	100		505	640	135	
-30	230	200	125	230	105	105	320	430	110	110	510	660	150	150
			125	230	105		320	430	110		510	660	150	
			125	230	105		320	430	110		510	660	150	

Table 5 Raw results from Experiment 2 for Hypothesis 2

Logbook

10/06/2026

I finally got the lenses, the stands and we had already bought the 1 m ruler. Before starting the full experiment, I wanted to try out whether things really disappear, so I looked at some of the websites and the original from Rochester University to get the set up. I put two 150 mm Focal lenses on the outside stand and 250 mm Focal lens on the inside stands. I put each of the stands exactly 20 cm away. I had taken this information from the NISC Network website because I first wanted to check if the actual experiment worked. I did a couple of tries, but things seem to not be disappearing. I went back and read the experiment details and found that if we look straight down at the centre and the object is also in the centre, it would not be in the cloaking region and would not disappear. But if it is slightly of the centre, it might disappear. I did a couple of tries and asked my parents to put their hand or a pen and check if it disappeared. At first, I did not understand why. But later I realised that I need to keep a high contrast background. For now, I used my bright pink notebook as the background and asked my mum to move a pen between the third and fourth lenses sideways. I found that when the pen was in the centre, it was clearly visible, but when I asked my mum to move it sideways, it started to disappear leaving a sort of hole in the middle. I think I got it, but I probably need to read more to get it exactly like the way the research at Rochester did and made their hands disappear through the hole of the lens. I'll need to do it tomorrow.

11/06/2026

I saw a couple of other videos today to help me understand the experimental set up. I found there were a few problems with yesterday's set up:

- The set up was not fixed, could accidentally bump and move the position of the lenses
- Lens
- Background is supposed to be clear and something that can be used to check the distortion
- The background must be a grid page
- Used the stands right side up and the sides covered the corner of the lens which makes it difficult for this experiment

For fixing the set-up, used my meter ruler (blue tack) to place and space evenly for the light to reflect through the lens. Then I used this to fix the stands, also with the blue tack, so they are not accidentally moved and placed in a straight line.

I decided to turn the stands upside down because it is easier for the lens to get the whole reflection for this experiment. Then I used a small ruler on the back of the stand, to draw two straight lines one in a vertical way and one in a horizontal way using a lead pencil. This gives the centre of the stand, where I fixed the lenses using blue tack.

For the background I used a grid page and glued it onto the tissue box as the background. I used the blu tack stick the tissue box in place and adjusted the background closer. Now I think the tissue box is smaller. I need to use a bigger tissue box to stick the grid page on.

Another issue is that I still need my parents help to hold the objects for this experiment. I'm thinking of some ways to learn how to do this experiment by myself. Will try next build a stand or holder for the objects to disappear. The objects worked this time because they started disappearing in the when it slowly moved slightly on the top. The best object was the lead pencil because I can visibly see if this was disappearing or not through the lens.

The next step is to set up the experiment and plan for the hypothesis.

12/06/2026

Today I formally started learning about the basics of the system.

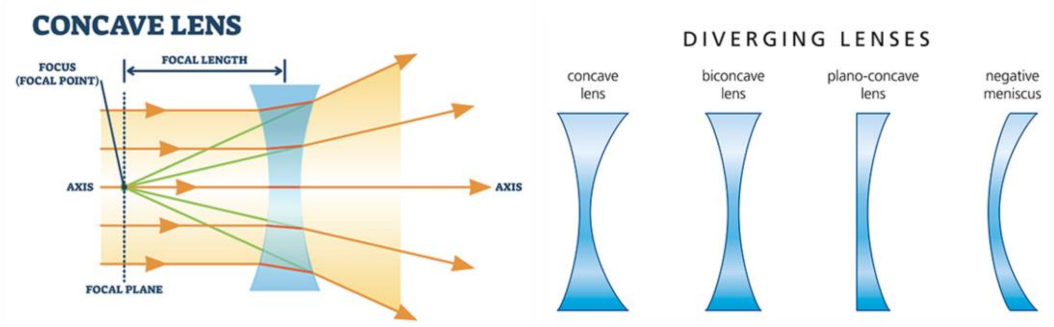
I started with lenses. When I saw the experiment, it focused light at a given spot, because they were convex lenses. This is what I found about convex lenses, which is quite useful and helps me set up my experiment. I also found a useful website that I will use to set up simulations before I actually do the experiment. I think this will help me understand how rays travel and why does the object disappear.

Lenses

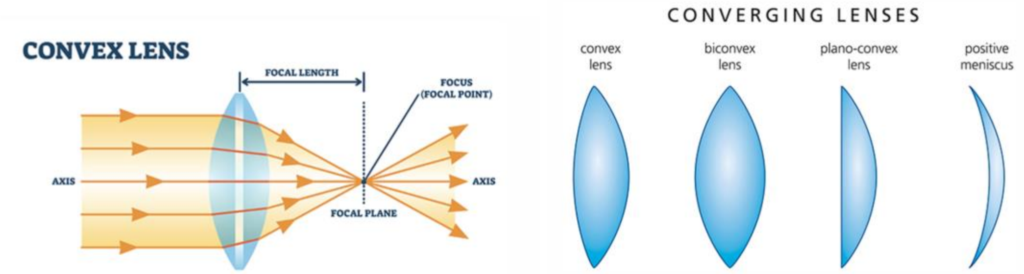
A lens is a curved piece of transparent glass or plastic that refracts light rays. When light rays strike different parts of the lens, they change directions. Depending on the shape of the lens, the light rays either diverge (spread out) or converge (concentrate)

All information on lenses is from (Advanced Optics n.d.)

- <u>Concave Lenses</u> – These lenses are thinner in the middle and thicker at the edges. The image formed by this lens is always smaller than the original. This lens is also called a diverging lens because parallel rays of lights passing through the lens diverge (spread out).



- <u>Convex Lenses</u> -- These lenses are thicker in the middle and thinner at the edges. These lenses can produce both larger and smaller images depending on the distance of the object from the lens. This is also called a converging lens because parallel raise of length passing through the lens converge (brought closer together) smaller

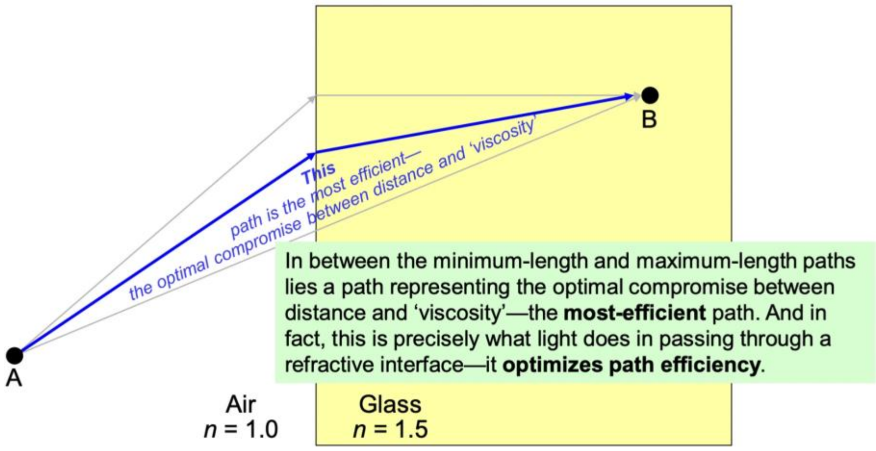


The focal point of a lens is the exact point where parallel raise of light converged (meet) or appear to diverge (spread out) after passing through the glass. The distance from the centre of the lens to the focal point is called the focal length. As light can go through the lens in either direction, there are always two focal points, one on either side of the lens.

Fermat's law and Refraction with an example

Optical cloaking uses a device modifies the light waves such that detecting the hidden object is impossible. Rochester cloak (my experiment) is a simplified method of optical cloaking. Both methods use the Fermat's principle of optics, first proposed by the French mathematician Pierre de Fermat in 1662. In its simplest form, the principle states that light waves of frequency will only follow the fastest route when travelling from one point to another. If more than one path is the fastest, then the light rays will follow all of them. In a medium, in which the speed of light does not change, the fastest path is the same as the shortest distance between the points. Fermat's law has been used to obtain the law of reflection and refraction. Refraction is the bending of light; when light travels from one medium to another, it bends.

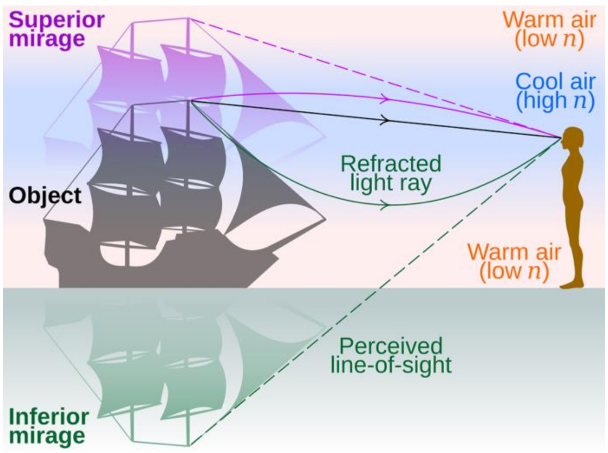
For example, the figure below shows what path light would choose when it goes from air to a more viscous medium like glass. Viscosity is a measure of how much a medium slows down the speed of something, in this case of light. This is measured by a refracted index. The refractive index measures how much the speed of light slows down in a material when entering it from a vacuum or air. The refractive of air is 1 and the refractive of glass is 1.5. This means that the glass slows down the speed of light 1.5 times. So, the light would choose the quickest part, which is a compromise between viscosity giving the fastest time.
Information and image from (American Academy of Ophthalmology n.d.)



Mirages

The oldest and most famous examples of these is travellers seeing a pool of water in the middle of a hot, dry desert but finding that when they rush towards it, there is no such thing, and that it was an illusion. This happens because light refracts as it passes through layers of air that have different temperature and densities,

Information and image from (The Britannica 2025)



Optical illusions (metamaterials)

This theory dealing with techniques to control the follow the light in non-natural ways has now extended to become a new branch of physics called transformation optics – named by Prof. Pendry. The method proposed by both researchers was to use special materials, called metamaterials. These are artificial materials with special properties that are either not available or not easily obtainable in nature. In optics, such materials would have special and changing values of refractive indices that would force light to take a specific desired path. Some concept materials have even been demonstrated such as the 2006 Microwave cloak, the 2011 Carpet Cloak, and 2015 Skin Cloak.

Information from (Basu 2009) (Khan 2024) (BBC News 2026) (Liu 2013)

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Information from (Basu 2009) (BBC News 2026) (Hager--Barnard n.d.) (Wizards of Wright 2018) (Barnstone 2014)

Today, I read and experimented with the Rochester Cloaking technique in detail. I read several papers and tried to understand what it meant. It was difficult and my mum and dad helped me understand. I had seen the way it works in videos and had a good idea of how to do the experiment but understanding how the rays moved took some time to understand. The best thing was the optics simulation which helped me understand how the actual system works.

When I saw the experiment, I realised that almost all papers and websites only talked about the formula and how to get the exact points to put the lenses. What I was interested in is what would happen if things changed, where exactly can I place the object (because it was never mentioned and the exact diagram doesn't seem to be accurate). I found an experiment online and played with a few values. Following are the results. I would really like to try and get these results in real time.

I also found that while Rochester cloak was much simpler than using metamaterials, it also had some limitations.

Limitations

According to the researchers, the interesting thing about the Rochester Cloak is that the object is kept hidden even when the viewer moves up to several degrees away from the optimal viewing position. The optics principles used for this technique are called paraxial ray optics. These are simplified way of studying light by only looking at light rays that pass through very near and nearly parallel to the central axis of a mirrors. This is because using the actual refraction by calculating where and how much it bends requires highly complicated mathematics. However, when these angles are small, this complex mathematics can be replaced by simple linear algebra. By using this approximation, we can say that paraxial rays i.e. rays that pass through or near the middle of the lens and parallel to the axis all meet perfectly at a single focal point.

In a Rochester cloak experiment, the invisibility affect only works if you look directly into the lenses down the center. This, in effect, means that the object is the first device that can do 3D continuously multidirectional cloaking for light in the visible spectrum. This is unlike other cloaking devices that work fine when you look at an object straight on but if you move even a little, the object becomes visible.

It must be noted that the Rochester cloak is not perfect. There are 3 specific limitations

- Paraxial rays only: The cloak only works for small angles near the optical axis
- Position of the object: The object must be placed in a specific geometrical region. Because the lenses bend light and send it through the centre of the device, anything that is on and around the axis region cannot be blocked. The cloaked region is basically like a doughnut. The researchers have worked on complicated versions of the simple cloak to solve this problem.
- Edge effects: The cloak also has edge effects, where the viewer can actually see the boundary of the cloaking zone. Researchers have mentioned that this can be reduced when larger lenses are used.

I also learnt a little about invisibility and its types and found that this method fits under the broad category of cloaking. I was a little confused to see why it wasn’t a transparent type of method. But after discussion with, I understand it.

- Invisibility can be achieved through the following three methods: Camouflage, Transparency and Cloaking. Camouflage is the oldest and most natural way of achieving invisibility. Animals like chameleons and stick insects can disguise themselves from taking the shapes and colours of objects in their surroundings. The military also uses camouflage techniques in their uniform and stealth technology like stealth planes.
- Transparency is also a very natural way of becoming invisible substances like glass, air, or plain water become transparent by modifying the speed of glass. This happens because the atoms or molecules of these substances absorb and re-emit light, which takes time. The delay reduces the speed of light, and the refractive index becomes more than one. It is also possible to achieve a refractive index

smaller than 1. Using this method, transparency is obtained by surrounding a particle by layers made of transparent substances like glass. This may be the way both an invisible stealth plane and Harry Potter's cloak might work.

- Optical cloaking is an invisibility technique that works for objects of all types and shapes, but within a given size. In cloaking, the hidden object is enclosed by a cloaking device. This device is basically a transparent shell that guides light around the object as if the light would go through empty space. In this way, the inside of the cloaking device is hidden as is the act of hiding. The experiment I'm doing is a type of partial cloaking.

14/06/2026

Creating hypothesis

Today I started to create the hypothesis.

Still playing with the lenses. I am quite surprised to find that the objects do become invisible, when they are moved between the lenses. But I have so many questions, some of these will become hypotheses – or so my mum tells me.

- I noticed that there are three spaces between the lenses: Lenses 1 and 2, Lenses 2 and 3, and Lenses 3 and 4. My question is does the invisibility happen at all the three spaces? I will call these corridors – because one of the papers I read calls it a corridor. The experiment shows that invisibility should happen at all the three corridors. I tried this and it works!
- But when I was doing the experiment, I found that the objects were invisible for a certain length (depth of cloaked region - corridors) between the lenses.
- I am curious about the length of each corridor and how it changes. Are the lengths of corridors same for all the three spaces between the lenses?
- What happens if I change the focal lengths? I know that this will change the distance between the lenses. Will this also change the length of corridors? Will all the three be impacted by the change?
- Upon researching, I found that there is no actual formula that tells how much this depth is, and how does it change when the focal lengths are changed. This is very exciting to me. I am guessing this is because it is a smaller body of work and has only been explored very basically. I feel I am contributing to an actual real area of research

- Next challenge is how would I measure and show this?
- A discussion with mum was helpful, as I was looking at too many different variables and it was becoming confusing in terms of calculations. She told me to keep thing simple: keep one focal length same and change the other one. And then measure the change in corridors.
- I calculated the focal length ratios and distances between the lenses. The shop I had brought lenses from had only these lenses, so I will work with what I have.
- It seems to be the easiest to keep the focal length of inner lenses constant at the smallest focal length I have (F_2 = 50 mm). This also gives me simple ratios between the lenses (F_1/F_2) as the other lenses I have are 150 mm, 200 mm, 250 mm and 300 mm. Also, the calculations are simple too with these values.

So, my first set of experiments is to find the lengths of invisibility corridors between each of the spaces between the lenses. And then compare how these would change when I change the focal length of outside lenses.

When I calculated the spaces between the lenses, I found that the outer spaces increase as the focal length of outside lens increases. So, I think that the length of invisibility corridor also increases as the focal length of outside lens increases. This is part a of hypothesis 1.

I also found that the space between the inner lenses decreases as the focal length of outside lens decreases. So I think that the length of invisibility corridor also decreases as the focal length of outside lens increases. This is part a of hypothesis 1. This is part b of hypothesis 1

15/06/2026

I have been playing with the lenses but haven't actually recorded any values. I think once I understand the experiment, the actual experiment will only take me a day. But there are so many other questions I have. Understanding how the whole set up works is actually tricky. Also re-creating the set up correctly is important. I don't have the complex lens holders or stand to keep my object moving at same height and move the objects while calculating the distance the object is moved. So, I will have to become creative using the things I have at home.

I have the lens stands (which I have to turn upside down for getting the set up with full lenses) and the lenses. I also have a 1-meter scale making it easy to measure the distance between the lenses. The study table in the library is long and uncluttered, and I can use this to put my experiment set up there. The only risk is the lenses falling and breaking, but we have wooden floors, so there is actually very little risk of lenses smashing. Daisy (my dog) shaking the setup is also a risk.

I tried using a sticky tape to fix the stand on the table, the meter scale on the table (so it doesn't move) and also the lenses on the stand. The meter scale can be fixed, but the stands cannot be fixed using the sticky tape. Mum says what about Blu-tack. I tried and it is great. The set up has fallen a couple of times. But I have lots of Blu-tack to fix both the stands and the lenses.

As I have to mount the lenses on the stand upside down, I have to fix their positions so that all the lenses are exactly in line when I put them up. This was easier when the stands were the right way up, but I'll try my best. I put the stands upside down and find the centre and put some Blue tack on it, as shown. Now I can find the exact centre of the stand for all and can put the lenses at the centre so that they can all be lined up.

I set the stand up, and asked mum to hold a pencil and to check if the stand works and it does!

I am a little disappointed, however. Without a proper set up and seeing that I am only doing it by myself, I would need my parents to hold the object to disappear. Mum also keeps moving the pencil up and down, which is not helpful. It does give me another idea for a hypothesis, but it is more important to make a stand for keeping the pencil. I also think the pencil is too short (that is why mum keeps moving it).

I go into my room to check what is long and thin that can be used as an object whose centre I can show as disappearing. I find a collection of objects, as shown below (a few knitting needles from an old project and a wand). I think the wand is too thick. The brown knitting needle is the same colour as the stands and the grey one is not clearly visible against the grid paper. I think black is the best. It is actually perfect as can be seen below.

16/06/2026

Next for the height of the needle and my biggest challenge. Not only mum holding the object means I am not doing the experiment by myself, but it also means I can't. Also she is not keeping the needle at the same height, meaning it keeps appearing and disappearing. It is an interesting hypothesis to find the height at which an object appears and disappears. I know that the object will definitely be visible at the focal axis (centre line), but it should disappear above an below the axis, also sideways. The invisibility corridor is actually shaped like a doughnut, and it would be interesting to find the diameter of this doughnut.

We have a pair of brand-new unused candles that I thought would be perfect for the experiment. They are identical apart from their colour. Unfortunately, when I put the knitting needle, it sits just at the base of the lenses, which is very disappointing. I didn't know what to do, till I remembered I have several Lego bricks that I can use to increase the height above the candles. I select several pairs, so I can duplicate the height above both the candles. Then I put the knitting needle on it and experimented to see the correct height. The combination below is perfect – I got their after a few tries.

I wanted to put something below the pair of candles, so they could be moved together, but it is too wobbly and messes up with the set up. So I will have to fix the knitting needle and move the candles together. Then measure the top of the candles with the ruler to see if they are both at the same distance from the edge of the stands, to show that they are in a straight line. The advantage is that I reduce the dependency on my parents and can now do most of the experiment by myself with a little bit of running back and forth.

The disadvantage is that the height is now fixed, so I will not be able to test the hypothesis of changing the height of the object or the width of the object, which I was thinking. I will also not be able to measure the radius of the doughnut with this set up, just the length of the corridor itself.

Another limitation is on the approximation of the measurement. When my mum was moving the knitting needle, I was able to get the exact distance of the stand and end of the invisibility corridor in mm. But now I will only be able to move the makeshift stand by 5mm or 10 mm and check if it visible or not. So the accuracy of the length of the corridor will reduce slightly. It will only matter if the change in lengths (when changing focal length) is <10 mm.

I showed my Papa the experiment set up, as he was supposed to help me with it originally. We had a great time moving our heads and trying to make the objects invisible. Papa asked me if there an angle people have to view this? I checked the videos and some websites. The website keeps saying look straight down the length of the lens and that the viewing angle can be move up to 15°. I did think about doing this as my second hypothesis. But I am trying to do this by myself, as much as I can, and also don't have a camera or a specific stand to measure the height, it would be difficult to measure the height of the viewer and effect of change of viewing angle.

The experiment set up is at a height of 1m. interestingly, this is the exact distance at which my eye level is, when I set on the sofa as the viewing stand. This is shown below.

My experiment set up is now complete.

17/06/2026

Start Experiment for Hypothesis 1

I started with the set up. The biggest challenge is going back and forward between the view location and changing the object and then moving back. Given that each has to be done thrice, I have asked mum to help me a little. I first look at the approximate distance where the lenses appears and disappears between each pair of lenses – when mum moves the set up.

Then once I know this approximate corridor, I repeat the experiment 3 times for start and end

18/06/2026

Continue with the Experiment for Hypothesis 1. Completed.

This seems like just one image, so I think I should have another hypothesis.

As the first set up has only a few data points, I was always interested in finding a second hypothesis to check. This is now to do with the sensitivity of the experiment. I know the distance between the lenses are calculated using the formula and as I have now done the experiment multiple time, I know that the distance is correct and invisibility is possible. However, I was curious to understand why this is the case and what would happen if the distances changed. I looked at the original paper, and the maths is too complex to understand. But the simple question I have remains – what happens if the lenses are moved from their position? Would the invisibility corridor disappear? Would it increase or decrease or remain the same?

Upon researching, I found that all the research is focused on repeating with different focal lengths and finding distance but not actually checking if the distances must be exact. There has been no test. I think it is because there are no practical applications yet. But if (as I read) this is used for things like surgery or for camouflaging in real life, the world would not be perfect. What would happen to the invisibility cloak then.

This is an interesting question, but I again got caught by trying to change too many things. I again had a chat with mum, who again told me to make things simple.

I first noted down there are 3 different ways in which I can change the distances between the lenses:

1. Move only one of the middle lenses. While this would keep the length of the system the same, it would change all 3 distances between the system. As per the diagram, both the outer distances are the same, which would not be the case in the new system. The distance between the inner lenses would remain the same.
2. Move both outer lenses. This would change the length of the system and the both the outer distances.
3. Move both the inner lenses. This would keep the length of the system the same. Both the outer distances would change but equal, while the distance between the inner lenses would change.

20/06/2026

Conduct Experiment 2

Upon thinking further, it was easier to just move the outside lenses. It would not disturb the set up too much. The viewing distance is more than 1 m away and the grid is about 500 m away, so changing these distance by a maximum of 30 mm will not impact the results too much. I have also decided to do this for only the original pair of focal lengths (F_2 = 50 mm and F_1 = 150 mm). This is the most common set up and all the distances between the lenses are 200 mm each. It would be interesting to see if the corridor changes and how?

My second hypothesis is if I move the outer lenses simultaneously inward by 10 mm, 20 mm and 30 mm how does the length of each of the invisibility corridor change. Again, if I move the outer lenses simultaneously outward by 10 mm, 20 mm and 30 mm how does the length of each of the invisibility corridor change

21/06/2026

Complete Experiment 2

Do all experiment method calculations and charts

22/06/2026

Complete write up – method, results discussion, conclusion

23/06/2026

Complete risk assessment and write up of conclusion

Insert all images

OSA RISK ASSESSMENT FORM

for all entries in (✓) ☐ Models & Inventions and ☑ Scientific Inquiry

This must be included with your report, logbook or entry. One form per entry.

STUDENT(S) NAME: Mishka Tripathi ID: ______________

SCHOOL: Unley High School

Activity: Give a brief outline of what you are planning to do.

Optical cloaking experiment with lenses and wooden stands

Are there possible risks? Consider the following:

- Chemical risks: Are you using chemicals? If so, check with your teacher that any chemicals to be used are on the approved list for schools. Check the safety requirements for their use, such as eye protection and eyewash facilities, availability of running water, use of gloves, a well-ventilated area or fume cupboard.
- Thermal risks: Are you heating things? Could you be burnt?
- Biological risks: Are you working with micro-organisms such as mould and bacteria?
- Sharps risks: Are you cutting things, and is there a risk of injury from sharp objects?
- Electrical risks: Are you using mains (240 volt) electricity? How will you make sure that this is safe? Could you use a battery instead? **Only batteries can be used for Models & Inventions entries*
- Radiation risks: Does your entry use potentially harmful radiation such as UV or lasers?
- Other hazards.

Also, if you are using other people as subjects in an investigation you must get them to sign a note consenting to be part of your experiment.

Risks	How I will control / manage the risk

(Attach another sheet if needed.)

Risk Assessment indicates that this activity can be safely carried out

RISK ASSESSMENT COMPLETED BY (student name(s)):

Mishka Tripathi

SIGNATURE(S): Mishka Tripathi Digitally signed by Mishka Tripathi Date: 2026.06.24 06:31:16 +09'30'

☑ By ticking this box, I/we state that my/our project adheres to the listed criteria for this Category.

TEACHER'S NAME: ______________________________

SIGNATURE: ______________________ DATE: ______________________