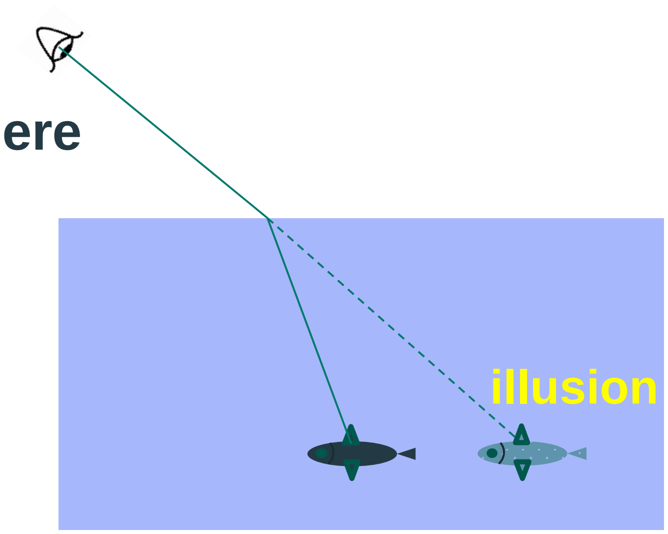
Refraction
&
The Invisibility Cloak

M. Dowlut

Hunting Fish

Where will you aim your spear if you are fishing?

- ❑ At the fish
- ❑ Close to the fish, as it looks bigger
- ❑ Close to the fish as there is no fish there



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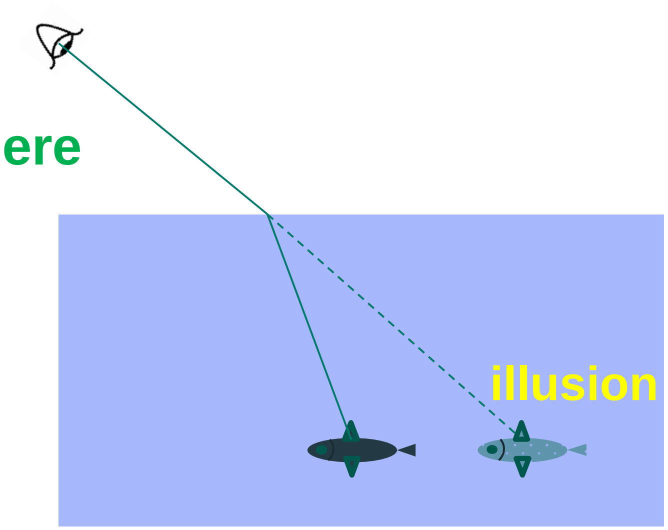
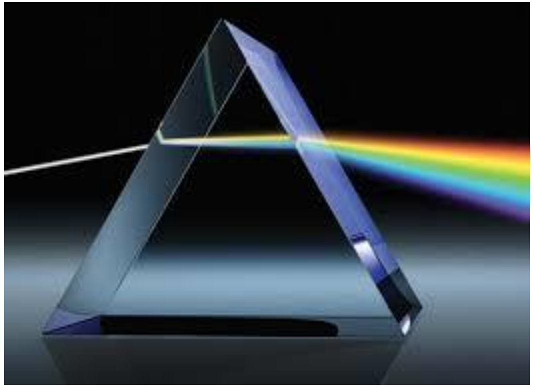
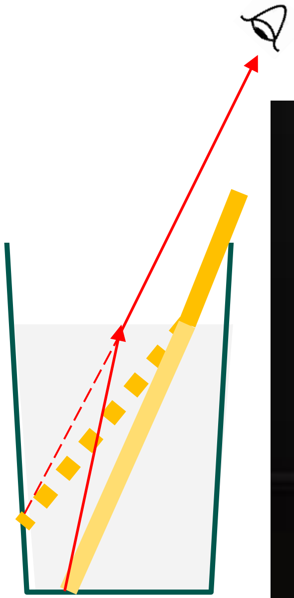


Phenomenon Associated with Refraction



Credit: https://www.britannica.com/science/refraction



Refraction of Light

Light travels in straight lines but appears to bend when it travels into a different medium (substance or matter). This is due to a change in speed of light.

Table 1. Speed of Light in Various Media

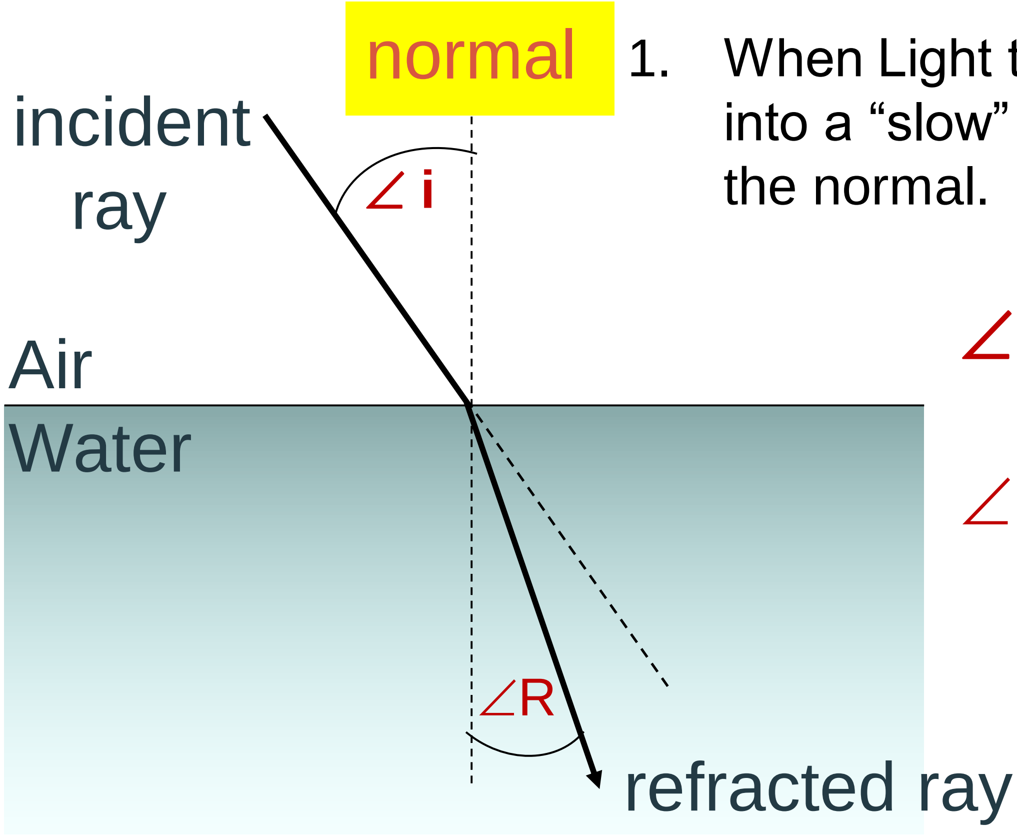
Fastest

Slowest

Media	Speed
Vacuum	3.00 $\times 10^8$ m/s
Air	Close to vacuum
Water	2.26 $\times 10^8$ m/s
Glass	1.97 $\times 10^8$ m/s
Ruby	1.70 $\times 10^8$ m/s
Diamond	1.24 $\times 10^8$ m/s

Credits:
1.Nelson: Science Perspectives 10; Neslon Education Ltd (2010)
2. Nelson: Science Connections 10: Neslon Education Ltd (2011)

Rules of Refraction



1. When Light travels from a "fast" medium into a "slow" medium, light bends <u>toward</u> the normal.

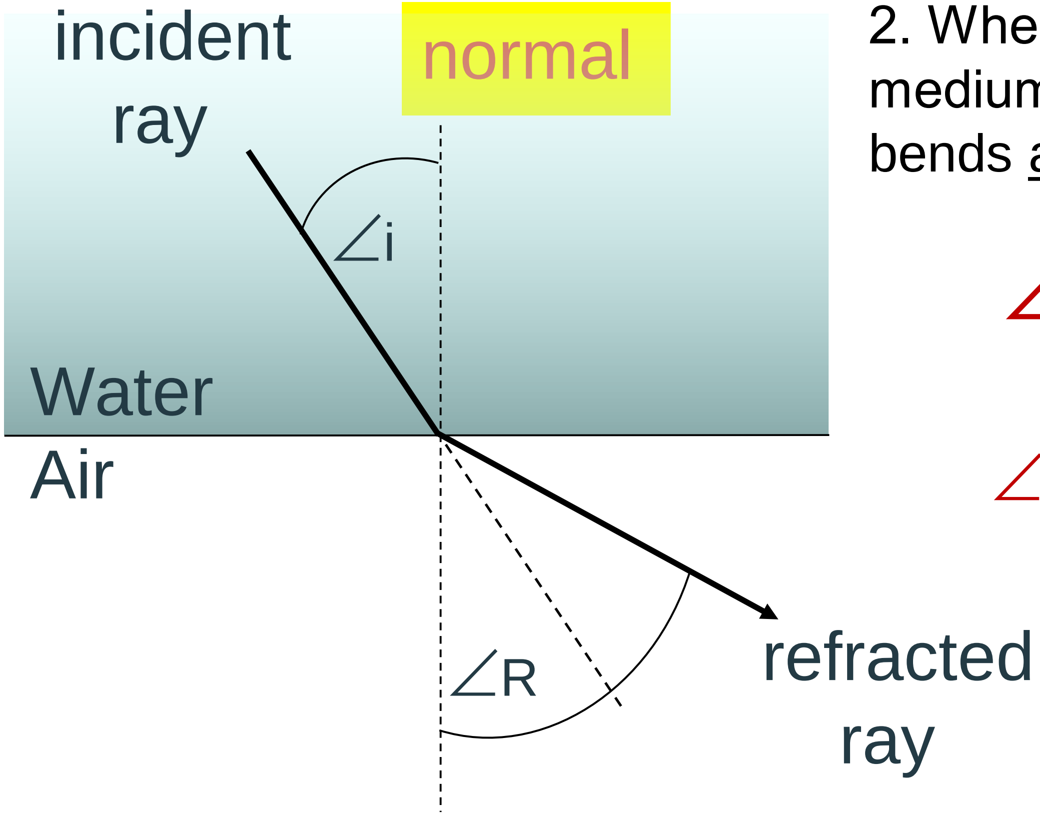
∠i = *angle of incidence (angle between the incident ray and the normal)*

∠R = *angle of refraction (angle between the refracted ray and the normal)*

∠i is greater than ∠R

Credit: Nelson: Science Connections 10: Neslon Education Ltd (2011)

Rules of Refraction



2. When Light travels from a "slow" medium into a "fast" medium, light bends away from the normal.

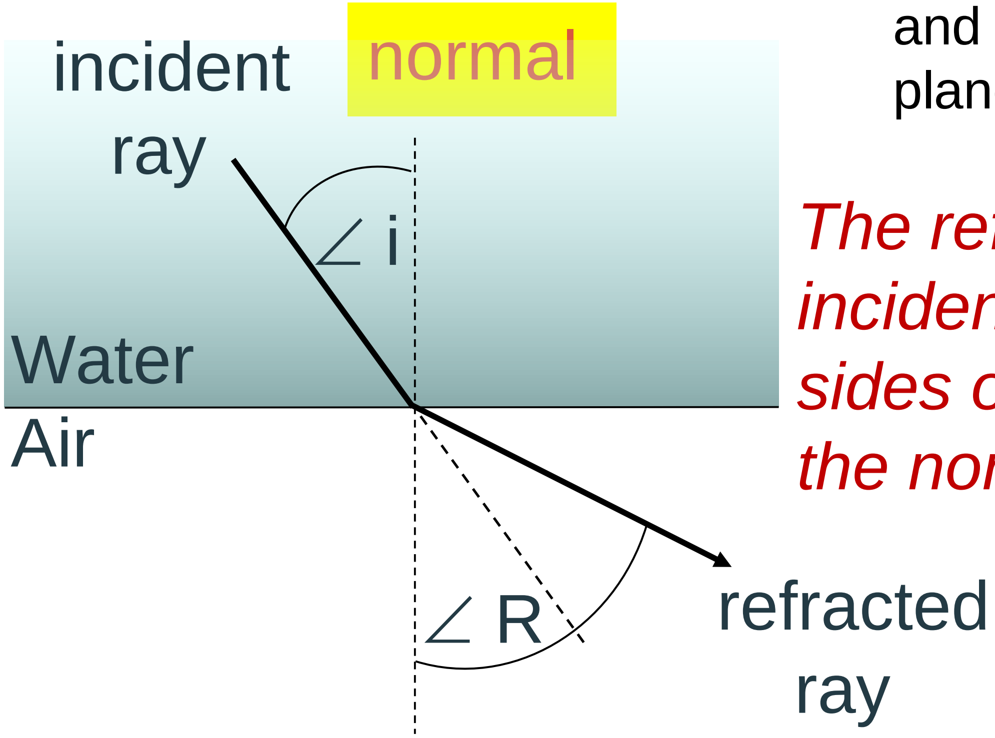
∠**i** = *angle of incidence (angle between the incident ray and the normal)*

∠R = *angle of refraction (angle between the refracted ray and the normal)*

∠i **is smaller than** ∠R

Credit: Nelson: Science Connections 10: Neslon Education Ltd (2011)

Rules of Refraction



3. The incident ray, the refracted ray and the normal all lie in the same plane.

The refracted ray and the incident ray are on opposite sides of the boundary and the normal.

Credit: Nelson: Science Connections 10: Neslon Education Ltd (2011)

Index of Refraction

The **ratio** between the 2 speeds is the same as the ratio between the angle of incidence and angle of refraction.

$$n = \frac{c}{v} = \frac{\sin \angle i}{\sin \angle R}$$

where

n = index of refraction (it is a physical constant)
c = speed of light in vacuum
v = speed of light in medium
NOTE: "n" must always be a value ≥ 1 because "c" will always be larger than "v"

Sample Problems (Use table 1 from slide 5)

Problem 1:
Determine the index of refraction for ruby.

$$n = \frac{c}{v} = \frac{3.00 \times 10^8 \text{ m/s}}{1.70 \times 10^8 \text{ m/s}} = 1.8$$

Problem 2:
Determine the index of refraction for diamond.

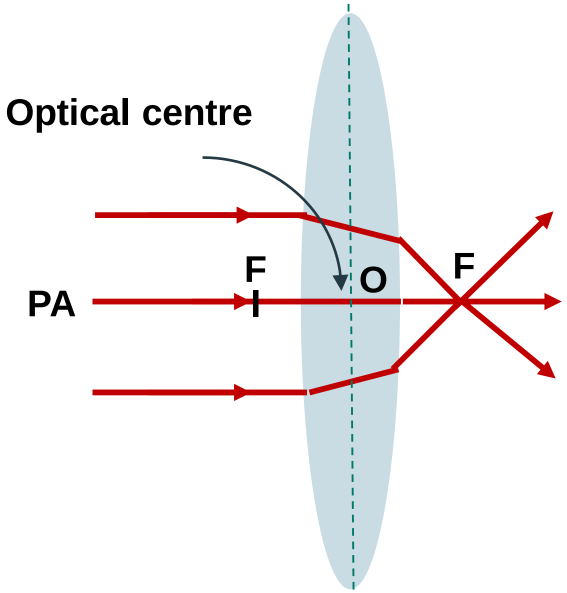
$$n = \frac{c}{v} = \frac{3.00 \times 10^8 \text{ m/s}}{1.24 \times 10^8 \text{ m/s}} = 2.4$$

Refraction in Lenses: What is a lens?

Lens is a transparent object that causes light rays to bend or refract

There are **<u>two types of lenses</u>**:

1. ***Converging or convex lens***:The converging lens is thicker in the middle and is thinner at the edges. The refracted rays come together (converge) at a point called **the focus (F)**.



Terminologies in Optical Lenses

Primary Focus or Primary Focal Point (F) is the point through which light rays parallel to the principal axis
(i) converge through a converging lens
(ii) appear to diverge after going through the diverging lens

Optical Center (O) is the point at the center of the lens

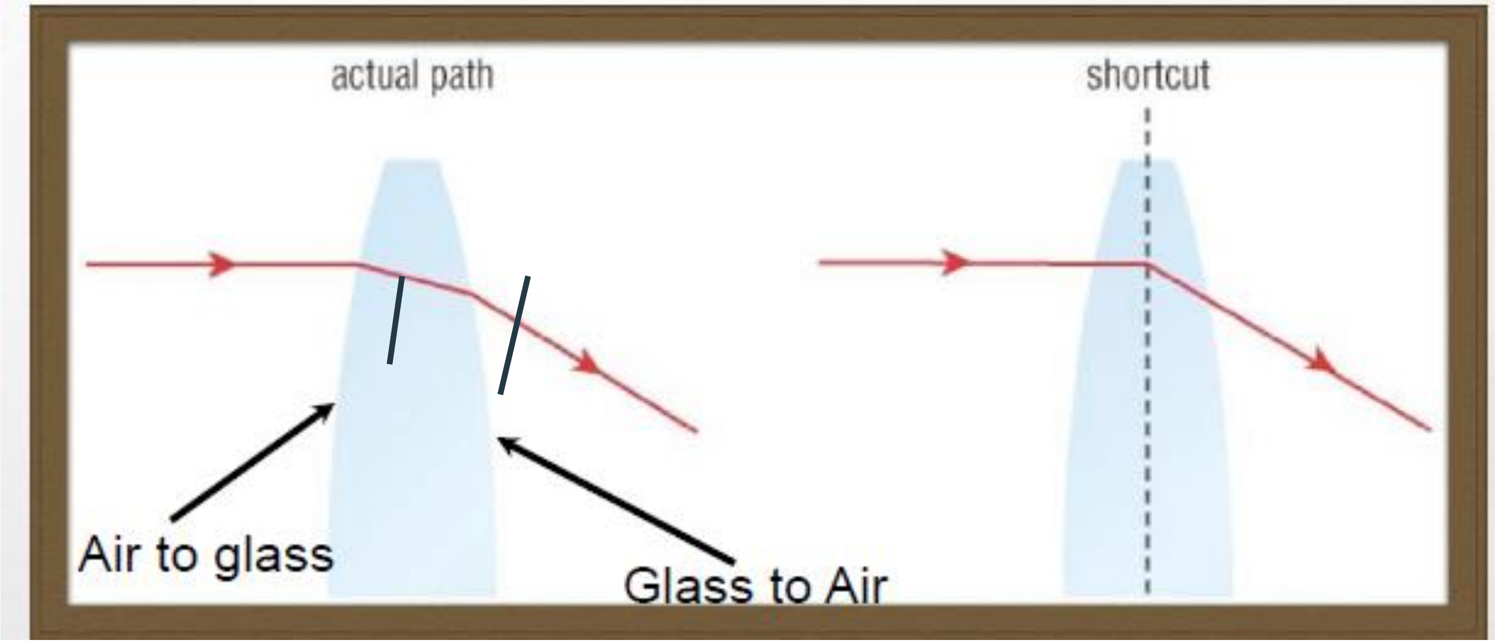
Principal Axis (PA) is the line through the optical center and the focus on either side

Secondary Focus or Secondary Focal Point (F') is the focus on the same side as the incident rays

Focal Length (f) is the distance between the optical centre and the primary focal point (or secondary focal point)

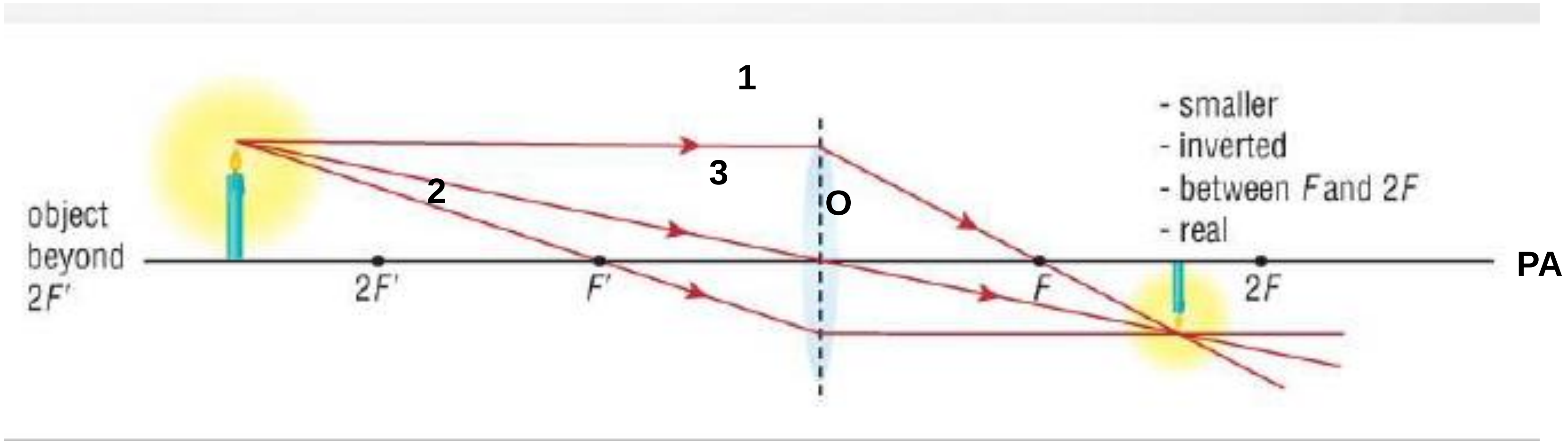
Credit: Nelson: Science Connections 10: Neslon Education Ltd (2011)

Refraction on Converging Lens



Light undergoes bending twice (picture 1) when it travels from air through the lens and from the lens to outside. In picture 2, we usually just draw the center of the lens as it is thin and depict one refraction as occurring at the center.

Rules for Location of Image in a Converging Lens



1. A ray parallel to the principal axis is refracted through the principal focus (F)
2. A ray through the secondary focus (F')is refracted parallel to the Principal axis(PA).
3. A ray through the optical centre (O) continues through without any refraction.

Credit: Nelson: Science Perspectives 10; Neslon Education Ltd (2010)

SALT Characteristics of Image

S: **S**ize of object (smaller or larger)

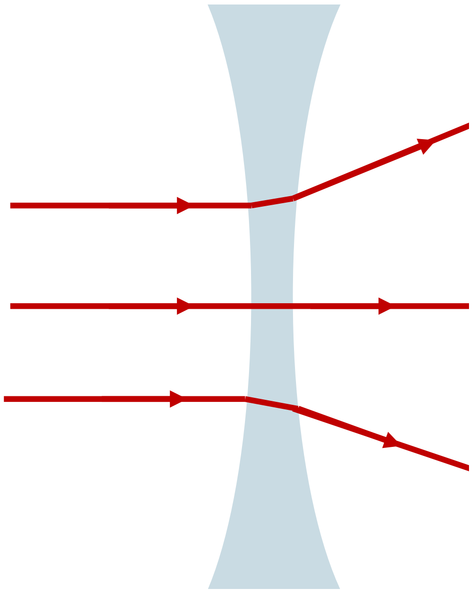
A: **A**ttitude (upright or inverted)

L: **L**ocation (in front or behind the lens)

T: **T**ype of image (real-can be projected on a screen or virtual-same side as the object)

Diverging Lenses

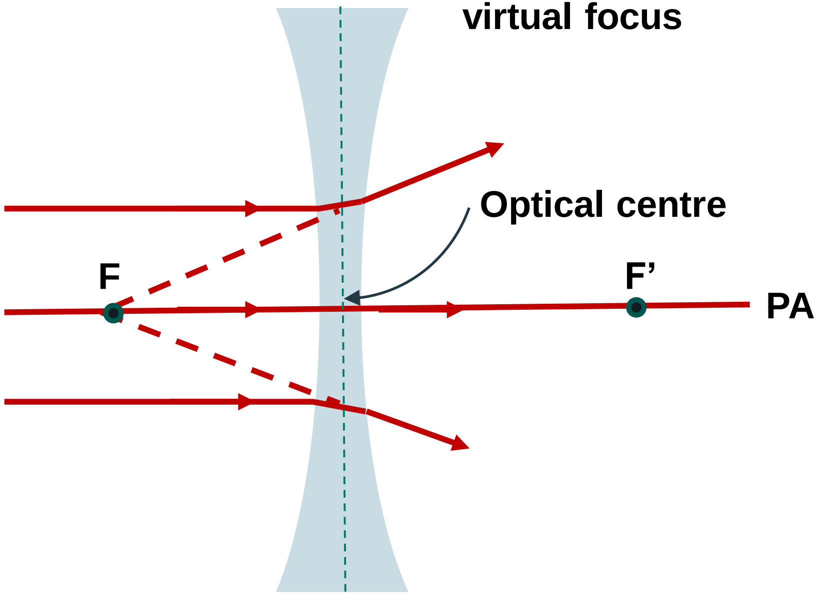
The diverging lens is thinner in the middle and is thicker at the edges. The refracted rays spread apart.



Credit: Nelson: Science Connections 10: Nelson Education Ltd (2011)

Diverging Lenses

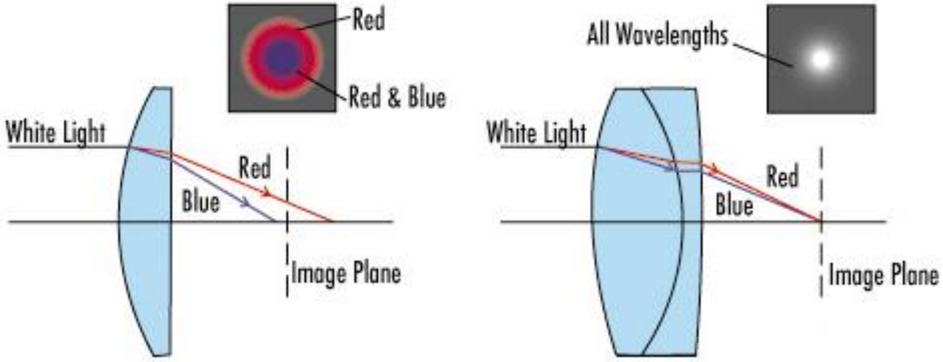
If you want to project
the diverging rays backwards,
it looks as if they come from a
virtual focus



Credit: Nelson: Science Connections 10: Nelson Education Ltd (2011)

Features of Achromatic Lens

- Consist of two optical components, with two different refractive indices
- Reduces the effect of color dispersion and results in a sharper image as lights of different color are brought to a sharper focus as seen in figure below:



Polychromatic Imaging using a Plano-Convex Lens versus an Achromatic Lens

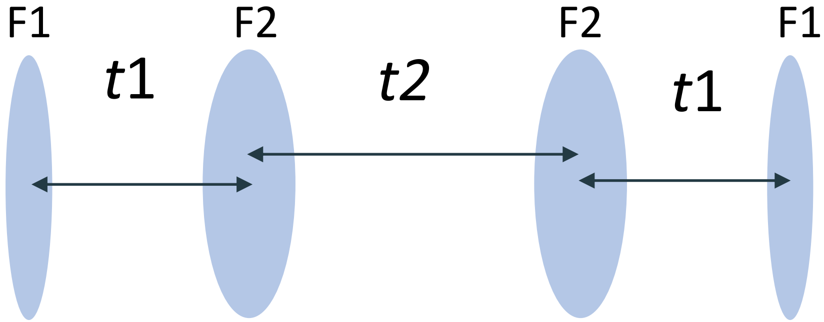
Credit: https://www.edmundoptics.com/resources/application-notes/optics/why-use-an-achromatic-lens/

The Invisibility Cloak

In 1897, H. G. Wells created 'the invisible man'. It took us more than 100 years to make that a reality. A group of scientists from Rochester University took advantage of simple optics that we teach in our schools everyday and made a device of tomorrow, the invisibility cloak.

Perfect Paraxial versus Common Lenses

Physics is no different. But perfect paraxial lenses provide a continuous viewing angles making the hand appear completely cloaked.



$$t_1 = f_1 + f_2$$

$$t_2 = 2\, f_2\, (f_1+f_2)/(f_1-f_2)$$

Perfect Paraxial: Multidirectional Cloaking

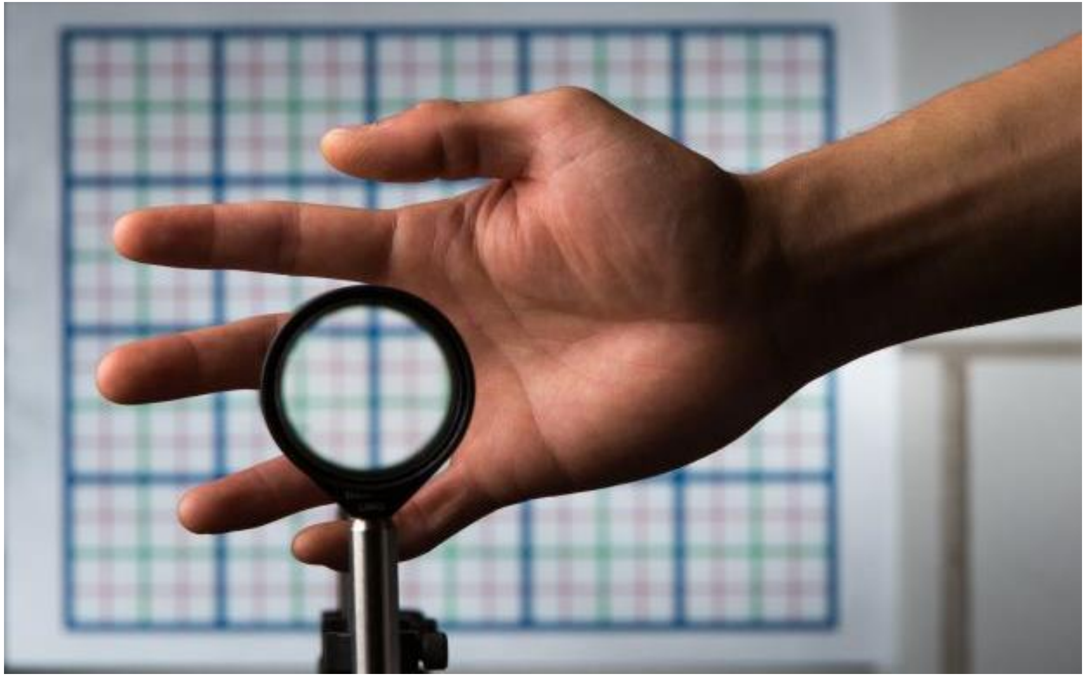
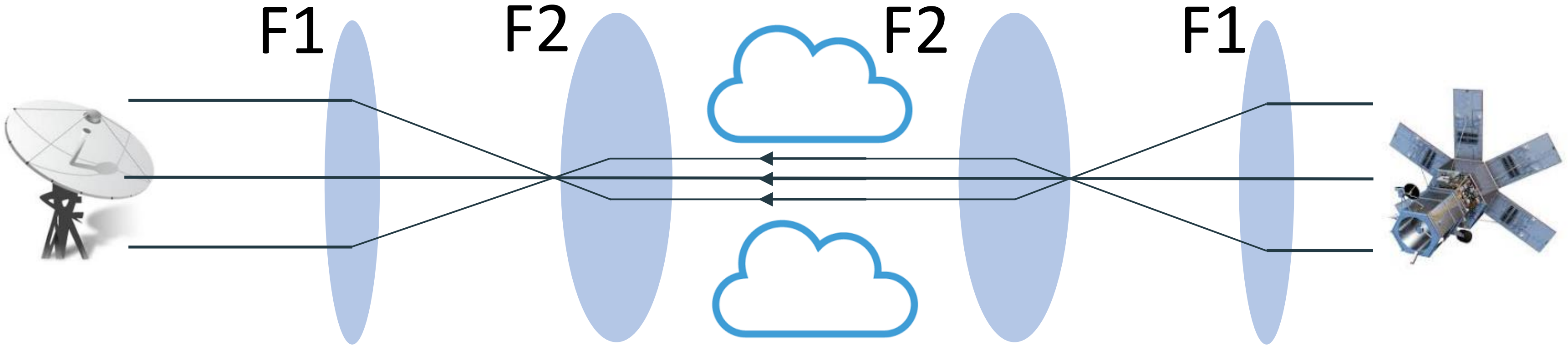


Photo Credit: J. Adam Fenster, University of Rochester

Inventorship Credit: John Howell, University of Rochester

Why Cloaking?



Metamaterial Cloaking

The process of shielding something from view by controlling electromagnetic radiation using transformation optics.

Objects are rendered invisible as the electromagnetic waves are manipulated around them to make them disappear.

Applications

Engineers and physicists (Science Now, 2007) have shown that objects can be hidden by bending of light, sound and water waves.

Antimagnetic cloak can shield an object from a magnetic field.

Potential applications include:

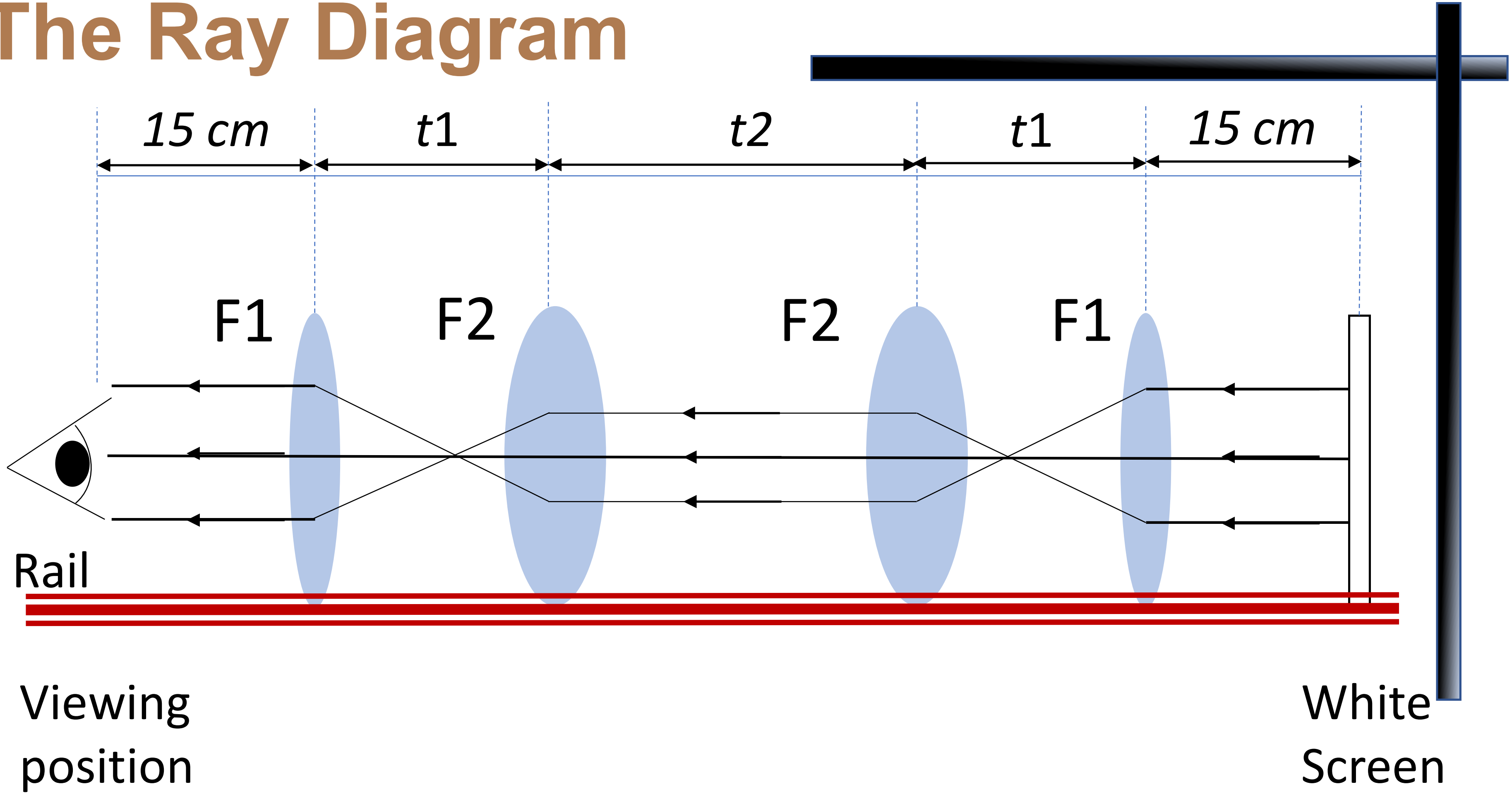
(i) surgeons cutting tissues without seeing their tools

(ii) drivers who can see blind spots without side mirrors

(iii) soldiers can hide from enemies

Credits: https://www.wired.com/2011/09/magnetic-invisibility-cloak/
http://research.ijcaonline.org/volume82/number13/pxc3892289.pdf

The Ray Diagram



Sample Result