Leaving Cert Physics Notes

Higher Level

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Chapter 4

Light 1: Geometrical Optics

'Do not read so much; look about you and think of what you see there.'

—Richard Feynman *(1918-1988)*

4.1 Reflection

Light is a form of energy which travels at the constant speed of $c = 3 \times 10^8 \mathrm{ms}^{-1}$.

All objects fall into one of the following categories:

1. *Luminous:* emit their own light.

2. *Non-luminous:* reflect light which falls on them.

We know that light is a form of energy because otherwise the principle of conservation of energy would be violated:

1. Other forms of energy are required to produce light. Think of the electrical $\rightarrow$ light conversion in the lightbulb.

2. Light can be converted into other forms of energy. Think of the solar panel or the Crookes' radiometer.

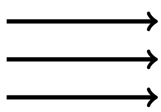
We know that light travels in straight lines because:

1. Shadows (the principle behind the operation of sundials).

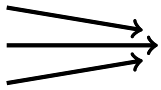
2. The 'cardboard hole' demonstration.

A *light ray* is a straight line showing the direction in which light is travelling. A number of rays together are referred to as a *beam.*

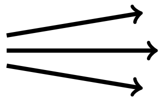
1. *Parallel beam:* all of the light rays are parallel.



2. *Converging beam:* all of the rays appear to be approaching a common point of intersection.



3. *Diverging beam:* all of the rays appear to be emanating from a single point.



Reflection of light: is the bouncing of light off an object.

There are two types:

1. *Diffuse reflection:* if the surface on which the light shines is rough (as are most surfaces), then the reflected light is scattered in all directions.

2. *Regular reflection:* if the surface on which the light shines is silvered and polished smooth, then the light is reflected in a regular manner (,i.e. all of the reflected rays have commom characteristics).

Terminology associated with reflection:

1. *Incident ray:* the name given to the ray approaching the mirror.

2. *Reflected ray:* the name given to the ray leaving the surface of the mirror.

3. *Point of incidence:* the name given to the point at which the ray strikes the mirror.

4. *Normal at the point of incidence:* the name given to an imaginary line which passes through the point of incidence, and is perpendicular to the surface of the mirror.

5. *Angle of incidence:* the name given to the angle between the incident ray and the normal at the point of incidence.

6. *Angle of reflection:* the name given to the angle between the reflected ray and the normal at the point of incidence.

The Laws of Reflection of Light:

1. The incident ray, the normal at the point of incidence and the reflected ray all lie in the same plane.

2. The angle of incidence is equal to the angle of reflection.

$$i = r$$

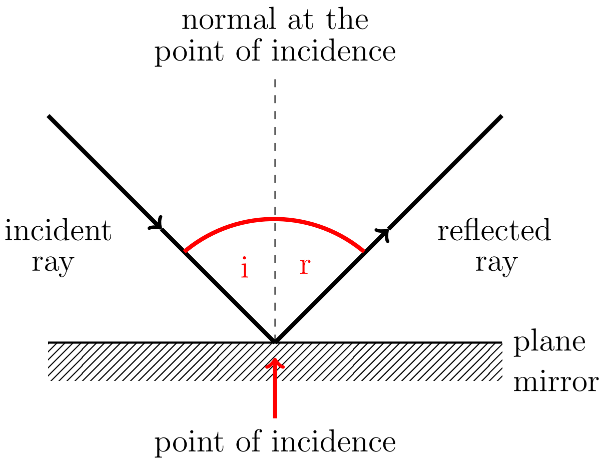


Figure 4.1: Reflection

Mirrors can be used to form images, of which there are two types:

1. *Real images:* are formed by the actual intersection of light rays.

   Such images can be located on a screen or by the method of 'no parallax' (see below).

2. *Virtual images:* are formed by the apparent intersection of light rays.

   Such images can never be formed on a screen, but they can be located by the method of 'no parallax'.

A virtual image in a plane mirror is:

1. On the perpendicular from the object to the mirror.

2. The same distance behind the mirror as the object is in front.

Lateral inversion: in a mirror all reflected objects are inverted from right to left. (e.g. mirror writing: the word 'ambulance' on the front of ambulances).

The apparent movement of one object relative to another due to the motion of the observer is called *parallax*. The object that is furthest away appears to move with the observer.

State of No Parallax: if there is no parallax between two objects, then they must be in the same line and the same distance from the observer.

4.2 Spherical Mirrors

Spherical mirrors are so-called because the material from which they are made forms part of the surface of a sphere.

There are two types of spherical mirror:

1. **Concave mirror:** the reflecting surface is located on the 'inside bend'.

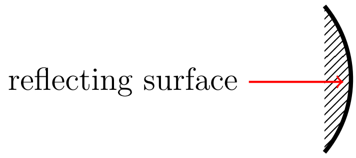


Figure 4.2: Concave Mirror

2. **Convex mirror:** the relecting surface is located on the 'outside bend'.

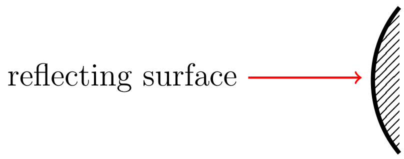


Figure 4.3: Convex Mirror

Terminology associated with spherical mirrors:

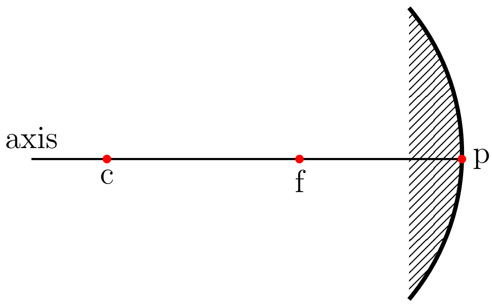


Figure 4.4: Standard Concave Mirror

1. *Centre of curvature:* is the centre of the sphere from which the mirror is made. Denoted by C.

2. *Pole:* is the centre of the spherical mirror. Denoted P.

3. *Principal axis:* is the straight line joining the pole to the centre of curvature. Also referred to simply as the 'axis'.

4. *Focus/focal point:* is the point midway between the centre of curvature and the pole. Denoted F.

5. *Focal length:* is the distance between the focus and the pole. Denoted f.

Magnification: is the ratio of the height of the image to the height of the object. Denoted m.

$$m = \frac{\text{height of image}}{\text{height of object}} = \frac{\text{image distance}}{\text{object distance}}$$

$\therefore$

$$m = \frac{v}{u}$$

Reflection of Light From a Concave Mirror

The laws of reflection of light apply also to spherical mirrors.
For reflection in concave mirrors, the normal at the point of incidence will always pass through the centre of curvature. Then, simply solve the problem or refer to standard cases.

Concave mirror: special cases

1. *Strikes pole, equal angles:* a ray that strikes the pole is reflected at an equal angle with the axis.

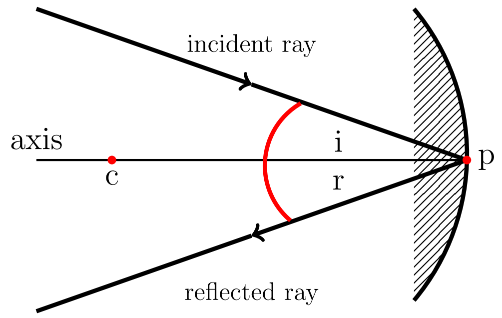


Figure 4.5: Strikes Pole, Equal Angles

2. *In through C, out through C:* a ray which passes through the centre of curvature and then strikes the mirror is reflected back along its own path.

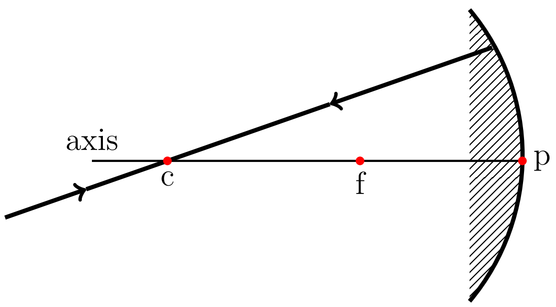


Figure 4.6: In Through C, Out Through C

3. *In parallel, out through F:* a ray which comes in parallel to the axis passes through the focus after reflection at the mirror.

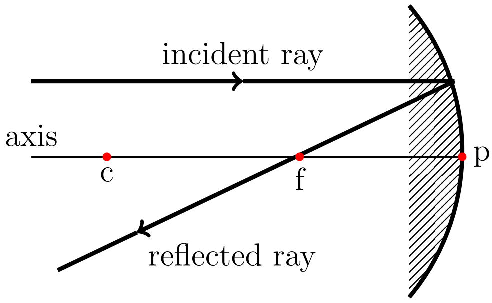


Figure 4.7: In Parallel, Out Through f

4. *In through F, out parallel:* a ray which passes through the focus and then strikes the mirror is reflected out parallel to the axis.

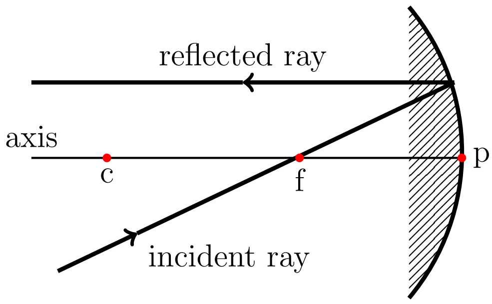


Figure 4.8: In Through f, Out Parallel

For a concave mirror:

- If the object is *outside the focus* the image is *real* and located *in front* of the mirror.
- If the object is *inside* or *at the focus* the image is *virtual* and is located *behind* the mirror.

Image of a Distant Object in a Concave Mirror:
If an object is a *large distance* from a concave mirror, then the image is *real* and located at the *focus*. This is because light from any point on a distant object arrives as a beam of *parallel light*.

Formula for a Concave Mirror:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f} \qquad \text{real image}$$

$$\frac{1}{u} - \frac{1}{v} = \frac{1}{f} \qquad \text{virtual image}$$

Reflection of Light From a Convex Mirror

The laws of reflection of light apply also to spherical mirrors.
For reflection in convex mirrors, the normal at the point of incidence is the line joining the point of incidence to the centre of curvature of the mirror. $(i = r)$

Convex mirror: special cases

These are very similar to what happens with a concave mirror. The only difference is that light rays which are reflected in a convex mirror can never *actually* pass through C or F. A ray that comes in as if to hit C will be reflected back along its path as if it came out through C. A ray that goes in parallel will come out as if it has passed through F. A ray that goes in as if it will hit F will come out parallel.

For a convex mirror:

- The image is always *virtual* and located behind the mirror.
- The image is always *diminished*. The nearer the objext is to the mirror the bigger the image.

Formula for a Convex Mirror:

$$\frac{1}{u} - \frac{1}{v} = -\frac{1}{f}$$

Real is Positive - Virtual is Negative Rule:

All distances to real objects and images are positive, while all distances to virtual objects and images are negative. Also, the focal length of a concave mirror is positive, while the focal length of a convex mirror is negative.

Hence, the formula for concave and convex mirrors can be summarised in one formula as follows:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

where:

- u is always $+$
- v is $+$ for a real image
- v is $-$ for a virtual image
- f is $+$ for a concave mirror
- f is $-$ for a convex mirror.

Comparison and Properties of Real and Virtual Images:

REAL	VIRTUAL
can be formed on a screen	cannot be formed on a screen
rays of light actually intersect where image is formed	rays of light appear to intersect where image is formed
all images in concave mirrors are real, except when the object is placed inside f	all images in convex and plane mirrors are always virtual

4.2.1 How Images Are Formed in Concave Mirrors

In all that follows, the black and green lines represent two distinct light rays which is the minimal amount required for the formation of an image. The blue arrow ↑ represents the object, and the red arrow ↑ the image formed as a result of reflection in the mirror.

1. When the object is outside C, the image is:

   (a) real;

   (b) inverted;

   (c) diminished;

   (d) formed between C and f.

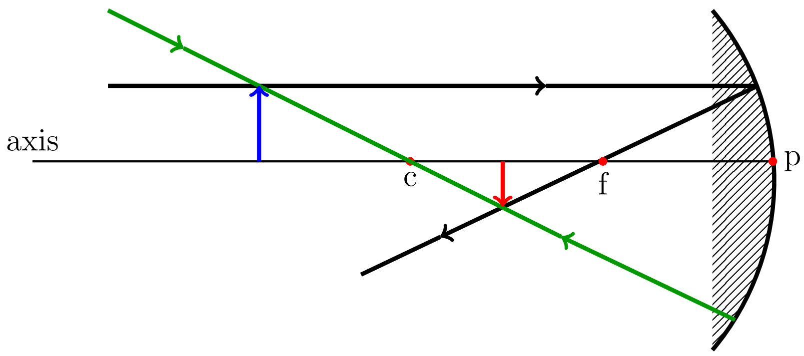


Figure 4.9: Object Outside C

2. When the object is at C, the image is:

   (a) real;

   (b) inverted;

   (c) the same size as the object;

   (d) formed at C.

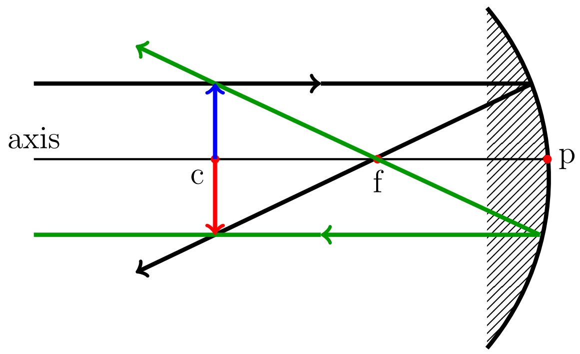


Figure 4.10: Object at C

3. When the object is between C and f, the image is:
   (a) real;
   (b) inverted;
   (c) magnified;
   (d) formed outside C.

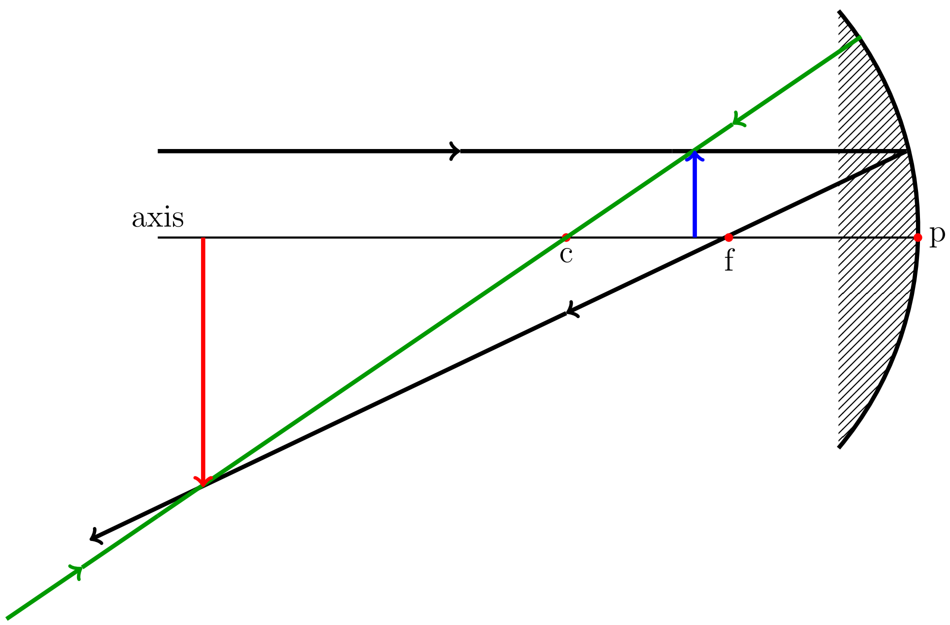


Figure 4.11: Object Between C and f

4. When the object is at f, the image is formed at infinity. This means that the rays are parallel so they never meet to form an image[1]

[1]Parallel lines do actually meet at infinity; for instance, train tracks appear to converge at the horizon. See projective geometry for more on this.

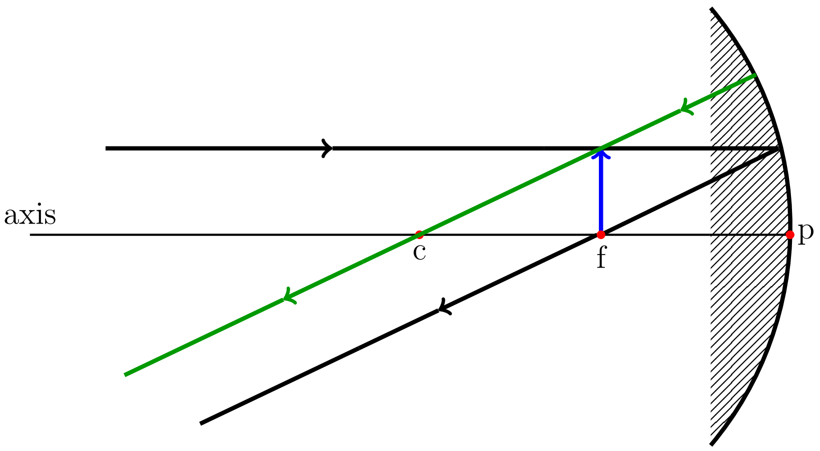


Figure 4.12: Object at f

5. When the object is inside f, the image is:
   (a) virtual;
   (b) erect;
   (c) magnified;
   (d) formed behind the mirror.

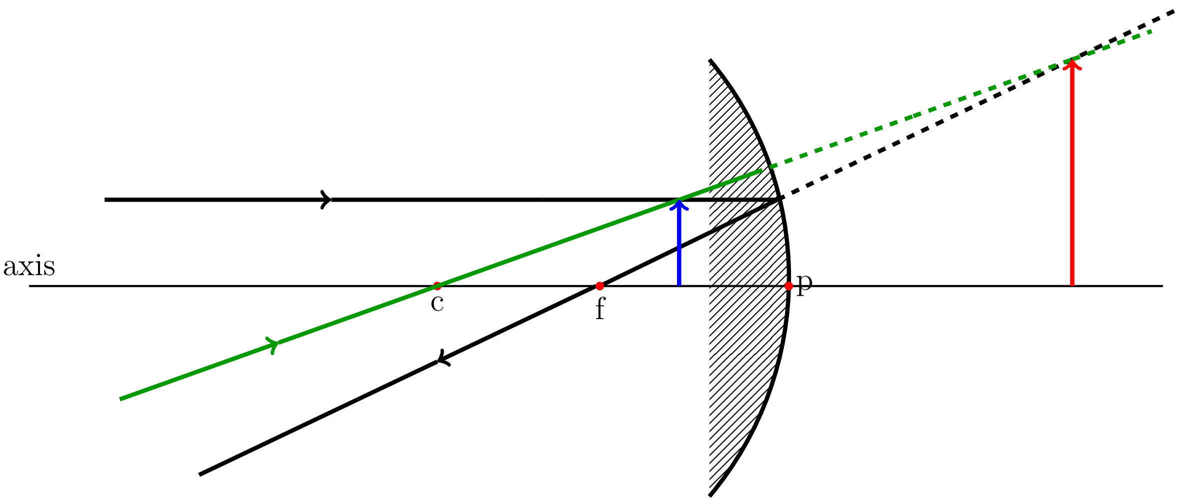


Figure 4.13: Object Inside f

4.2.2 How Images Are Formed in Convex Mirrors

The notation is as above, and there is only one case to consider as reflection only occurs when the object is located on the side of the mirror opposite f and C. The image is:

1. virtual;

2. erect;
3. diminished;
4. formed behind the mirror.

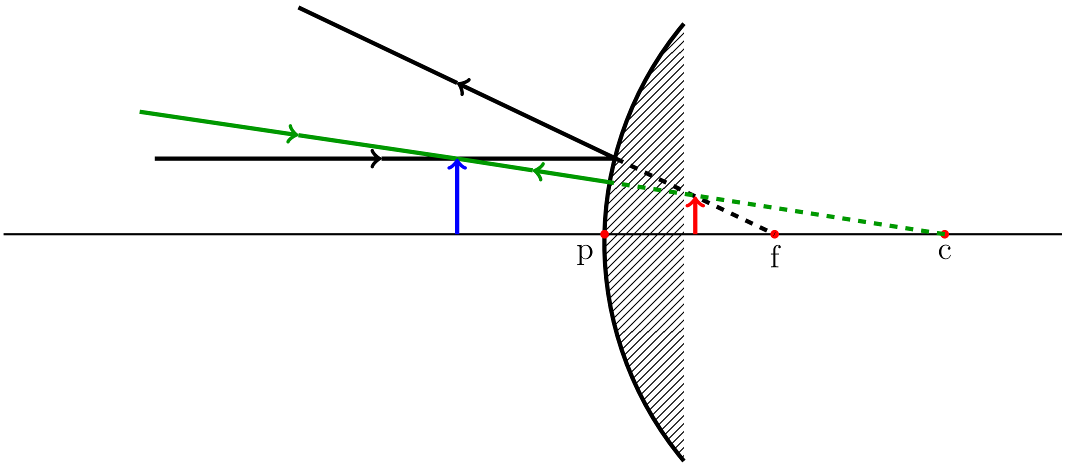


Figure 4.14: All Images in a Convex Mirror

4.3 Refraction

Refraction: is the bending of a ray of light as it passes from one transparent medium to another.

NB No refraction occurs if the ray strikes the second medium at right angles.

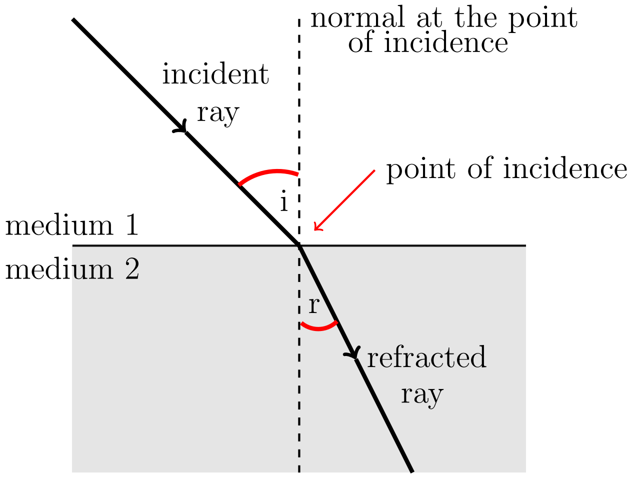


Figure 4.15: Refraction

Terminology associated with refraction:

1. *Incident ray:* the ray of light striking the second medium.

2. *Refracted ray:* the ray of light travelling through the second medium.

3. *Point of incidence:* the point at which the incident ray strikes the secon medium.

4. *Normal at the point of incidence:* the imaginary line through the point of incidence, and perpendicular to the boundary between the two media.

5. *Angle of incidence:* the angle between the incident ray and the normal at the point of incidence. Denoted i.

6. *Angle of refraction:* the angle between the refracted ray and the normal at the point of incidence. Denoted r.

Refraction will only occur if the speed of light in the second medium is different from the speed of light in the first.

- When light travels from a *rarer to a denser* medium it is refracted *towards the normal.*

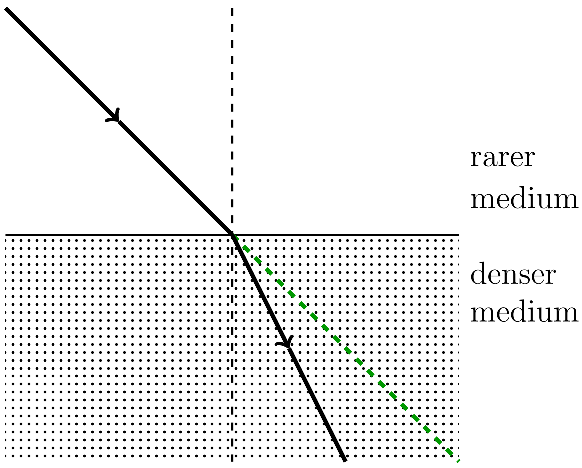


Figure 4.16: Refraction: rarer to a denser medium

- When light travels from a *denser to a rarer* medium it is refracted *away from the normal.*

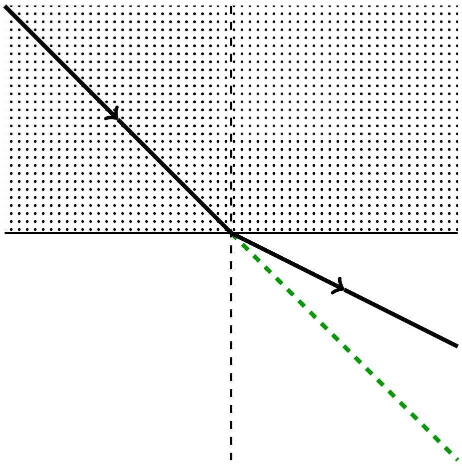


Figure 4.17: Refraction: from a denser to a rarer medium

The Laws of Refraction:

1. The incident ray, the normal at the point of incidence and the refracted ray all lie in the same plane.

2. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant (for the given media in question).

$$\frac{\sin i}{\sin r} = n$$

   where n is constant.

The value of n depends on the two media in question, and it is called the *refractive index between the two media*.

Refractive Index of a Medium: is the ratio of the sine of the angle of incidence to the sine of the angle of refraction when light passes from a vacuum into that medium.

- The bigger the refractive index of a medium the greater the amount by which that medium bends the light for a given angle of incidence.

- n is always 1 or bigger. This is because when light goes from a vacuum into another medium it is always bent towards the normal.

$$r < i \Rightarrow \sin i < \sin r \Rightarrow \frac{\sin i}{\sin r} \geq 1$$

$\therefore$

$$n \geq 1$$

The Refractive Index Between Two Media: is the ratio of the sine of the angle if incidence to the sine of the angle of refraction when light travels from one of those media into the other.

The order in which the light passes through the media is important.

$$ {}_x n_y = \frac{1}{{}_y n_x} $$

It is an experimental fact that a ray of light will retrace its path.

Real Depth and Apparent Depth:
If an object is viewed from air through another medium and the line of view is perpendicular to the surface of the medium:

$$ \text{refractive index of a medium} = \frac{\text{real depth}}{\text{apparent depth}} $$

$\Longrightarrow$

$$ {}_a n_m = \frac{\text{real depth}}{\text{apparent depth}} $$

Refractive Index in Terms of Relative Speeds:
If the speed of light in medium 1 is c_1 and the speed in medium 2 is c_2, then:

$$ {}_1 n_2 = \frac{c_1}{c_2} \Longrightarrow \frac{\sin i}{\sin r} = \frac{c_1}{c_2} $$

- The greater the refractive index the slower the speed of light.

4.3.1 Total Internal Reflection

Critical Angle: when light travels from a **denser to a rarer** medium the angle of incidence whose angle of refraction is 90° is called the critical angle for those two media. Denoted by C.

Total Internal Reflection: when light going from a *denser to a rarer* medium strikes the second medium with an angle of incidence greater than the critical angle, it does not enter the second medium. It is *entirely* reflected back in the denser medium. This is called total internal reflection.

Relationship Between Refractive Index and Critical Angle:
For a ray of light going from a denser to a rarer medium and striking at the critical angle:

$$ {}_x n_y = \frac{\sin C}{\sin 90} = \frac{\sin C}{1} = \sin C $$

If the second medium (the rarer one) is air or a vacuum this equation becomes:

$$ {}_x n_a = \sin C \Longrightarrow_a n_x = \frac{1}{\sin C} $$

$\therefore$

$$ {}_a n_m = \frac{1}{\sin C} $$

where C is the critical angle.

Everyday Phenomena Related to Total Internal Reflection:

- *Snell's window:* if you are underwater and looking upwards, light from outside can only enter the water through a circle of radius r.
- *Safety reflectors:* bicycles and cars contain many tiny right-angled prisms that use total internal reflection to reflect the light back the way it came.

4.3.2 Optical Fibres

Optical Fibre: is a very thin transparent rod (usually of glass) through which light can travel by total internal reflection.

- Note that optical fibres are solid, not hollow.

Transmisssion of Light Through an Optical Fibre:

1. Light enters the fibre and strikes the inside of the fibre at an angle *greater than the critical angle*. Total internal reflection occurs.
2. The ray is reflected to the opposite side and total internal reflection occurs again.
3. This process continues and the light travels through the fibre.

Light can escape from optical fibres in two ways:

1. If an optical fibre is bent through too large an angle, then the ray travelling inside it may strike it at an angle less than the critical angle. If this happens the light will not be totally internally reflected and will leave the fibre.
2. If an optical fibre comes into contact with another fibre (or another part of itself) a ray of light inside it may no longer be travelling from a denser to a rarer medium (e.g. glass $\rightarrow$ glass instead of glass $\rightarrow$ air). Total internal reflection will not then occur and the ray will travel from one fibre into the other.

Prevention:
One method to prevent this occurring is to coat the optical fibre with a layer of glass of lower refractive index. Even if two fibres then come into contact, total internal reflection still occurs as the light is going from a denser to a rarer glass at an angle of incidence greater than the critical angle.

Uses of Optical Fibres:

- Telecommunications (fibre optic broadband).
- Medicine (endoscopes).
- Dentistry.

Advantages of Optical Fibres:

1. Energy losses in optical fibres are much smaller than losses in electrical cables.
2. Optical fibres are much smaller than the electric wires needed to carry the same amount of signals.
3. Interference in optical fibres is much less.
4. Optical fibres are cheaper than copper wires.

Mirages:
The refractive index of air changes slightly with temperature. On a hot day a road will radiate heat upwards causing the layer of air above the road to become less dense with a lower refractive index. The air above this layer remains cool, and thus is more dense with a higher refractive index. Therefore, total internal reflection occurs with the result that an image of the sky is produced as the light is reflected upwards.

The Mechanism of Total Internal Reflecton:
It can only occur in going from a denser to a rarer medium because light is always refracted away from the normal when it enters a less dense medium and towards the normal when it enters a denser medium.
When total internal reflection occurs the light does not leave the medium. It happens as follows:

1. Light is refracted away from the normal because it enters a less dense medium.

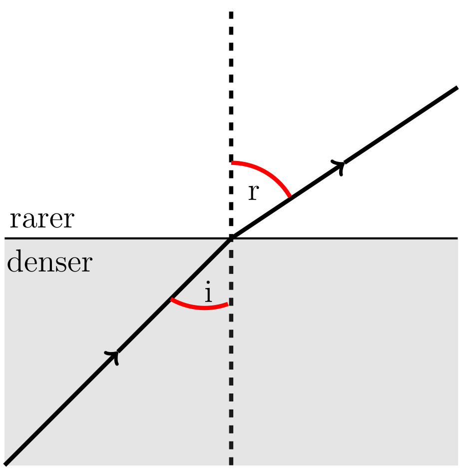


Figure 4.18: Mechanism of Total Internal Reflection (i)

2. At a certain angle of incidence, called the critical angle C, the angle of refraction $= 90°$.

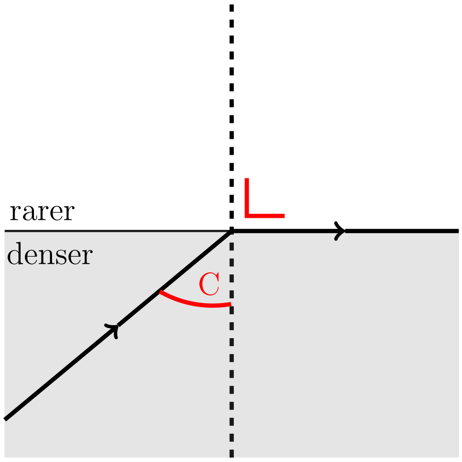


Figure 4.19: Mechanism of Total Internal Reflection (ii)

3. If the angle of incidence is greater than C then total internal reflection occurs. Therefore, angle of incidence = angle of reflection ($i = r$).

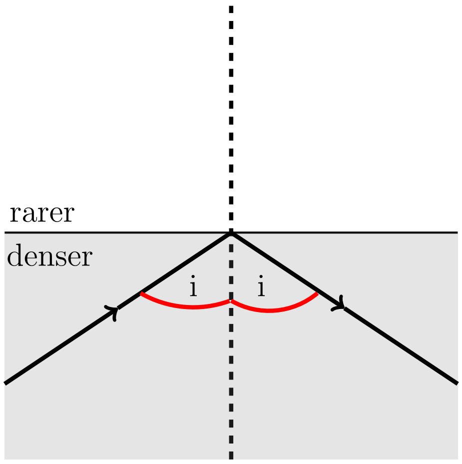


Figure 4.20: Mechanism of Total Internal Reflection (iii)

4.4 Lenses

There are two types of lens:

1. **Convex lens:** a converging lens - ‘middle heavy’.

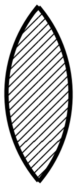


Figure 4.21: Convex Lens

2. **Concave lens:** a diverging lens - 'top-and-bottom heavy'.

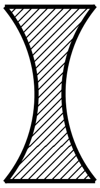


Figure 4.22: Concave Lens

Uses:

- Glasses.
- Cameras.
- Projectors.
- Telecopes.
- Magnifying glasses.

Terminology associated with lenses:

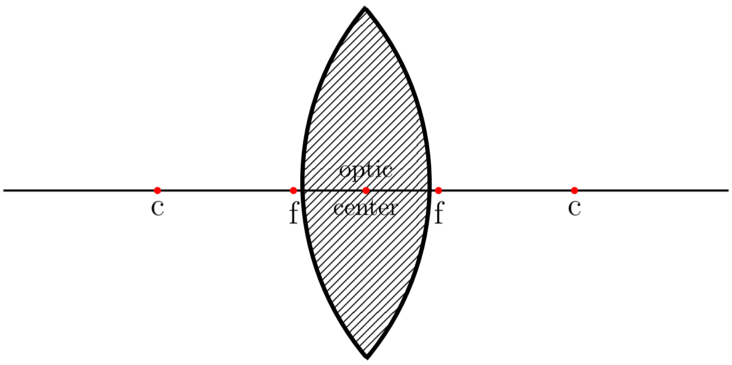


Figure 4.23: Standard Convex Lens

1. *The optic centre:* is the centre of the lens.

2. *The principal axis/axis:* is the imaginary line through the optic centre which is at right angles to the face of the lens.

3. *Focus of a convex lens:* the point at which light rays converge after striking a convex lens parallel to the axis.

4. *Focus of a concave lens:* the point from which light rays appear to diverge after rays of light strike a concave lens parallel to the axis.

5. *Focal length:* the distance from the focus to the optic centre,

Notes:

1. There is a focus at each side of the lens.

2. Each focus is the same distance from the optic centre.

Magnification: is the ratio of the height of the image to the height of the object. Denoted m.

$$m = \frac{\text{height of image}}{\text{height of object}} = \frac{\text{image distance}}{\text{object distance}}$$

$\therefore$

$$m = \frac{v}{u}$$

Convex Lenses

Convex lens: special cases

1. *Strikes optic centre, passes straight through:* a ray that strikes the optic centre passes straight through the lens.

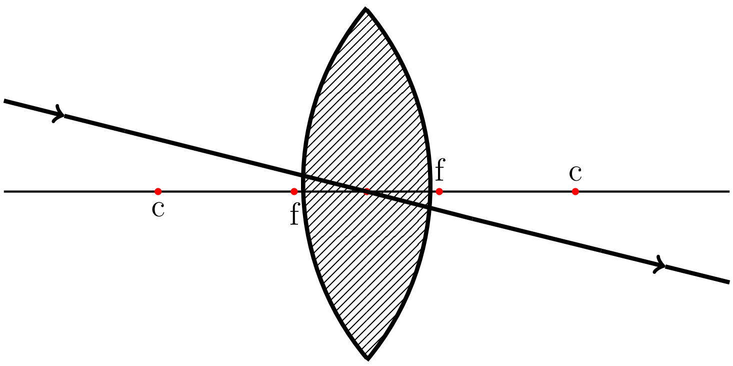


Figure 4.24: Strikes Optic Centre, Passes Straight Through

2. *In parallel out, through F:* a ray which comes in parallel to the axis passes through the focus.

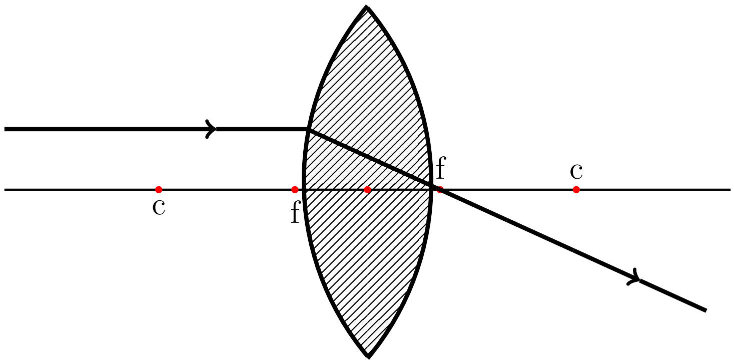


Figure 4.25: In Parallel, Out Through F

3. *In through F, out parallel:* a ray which passes through the focus comes out parallel to the axis.

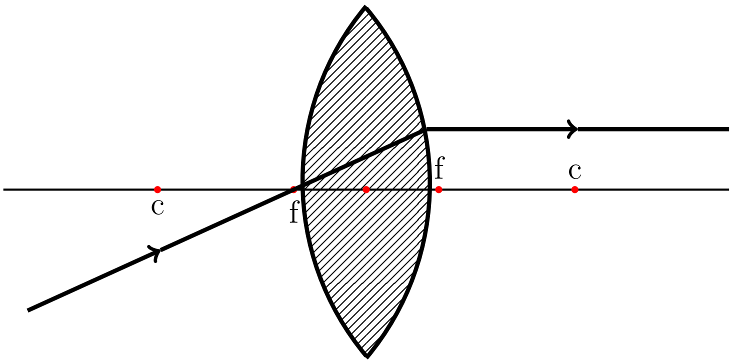


Figure 4.26: In Through F, Out Parallel

For a convex lens:

- If the object is *outside the focus* the image is *real* and located at the opposite side of the lens to the object. The image is *inverted*.
- If the object is *inside the focus* the image is *virtual* and is located at the same side of the lens as the object. The image is *erect*.
- Light from any point on a *distant object* arrives as a beam of parallel light. Hence, the image is *real* and located at the *focus*.

Formula for a Convex Lens:

$$\frac{1}{u}+\frac{1}{v} = \frac{1}{f} \qquad \text{real image}$$

$$\frac{1}{u}-\frac{1}{v} = \frac{1}{f} \qquad \text{virtual image}$$

Concave Lenses

Concave lens: special cases

1. *Strikes optic centre, passes straight through:* a ray that strikes the optic centre passes straight through the lens.

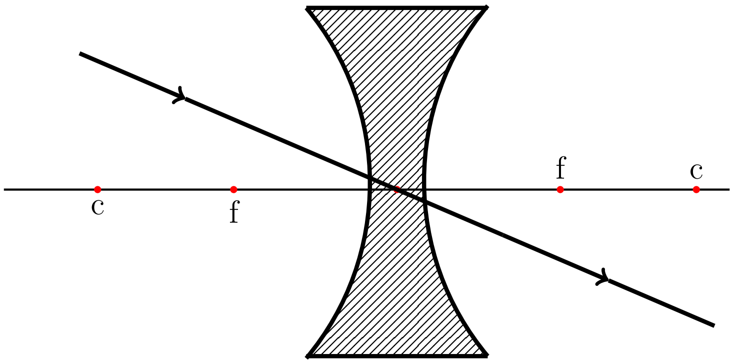


Figure 4.27: Strikes Optic Centre, Passes Straight Through

2. *Heading for F, out parallel:* a ray which comes in heading for the focus leaves parallel to the axis.

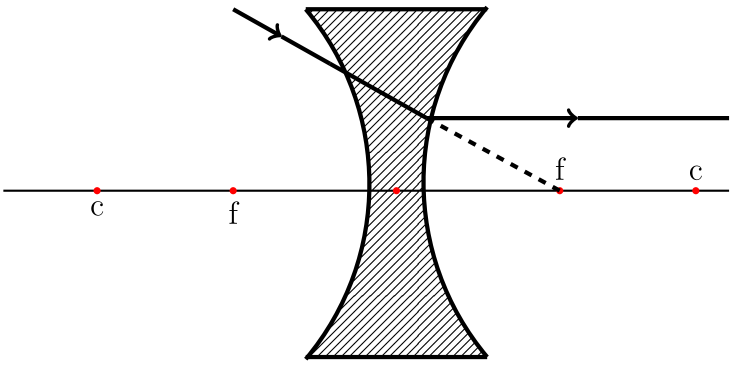


Figure 4.28: Heading for F, Out Parallel

3. *In parallel, out as if from F:* a ray which comes in parallel to the axis leaves as if it came from the focus.

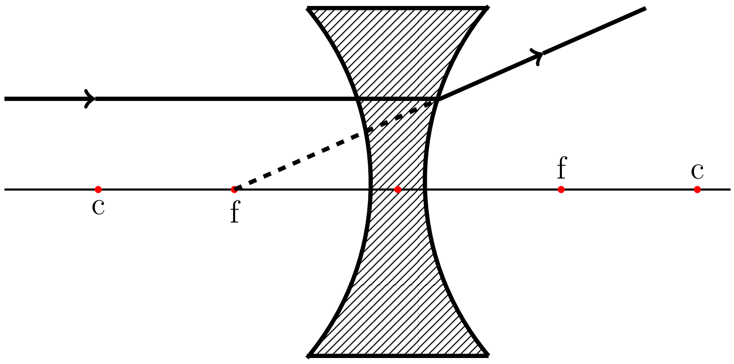


Figure 4.29: In Parallel, Out as if From F

For a concave lens:

- The image is always *virtual* and *erect* and located at the *same side* of the lens as the object.
- The image is always *diminished*. The nearer the object is to the lens the bigger the image.

Formula for a Concave Lens:

$$\frac{1}{u} - \frac{1}{v} = -\frac{1}{f}$$

4.4.1 How Images Are Formed in Convex Lenses

1. When the object is outside C, the image is:

   (a) real;

   (b) inverted;

   (c) diminished;

   (d) formed between C and f.

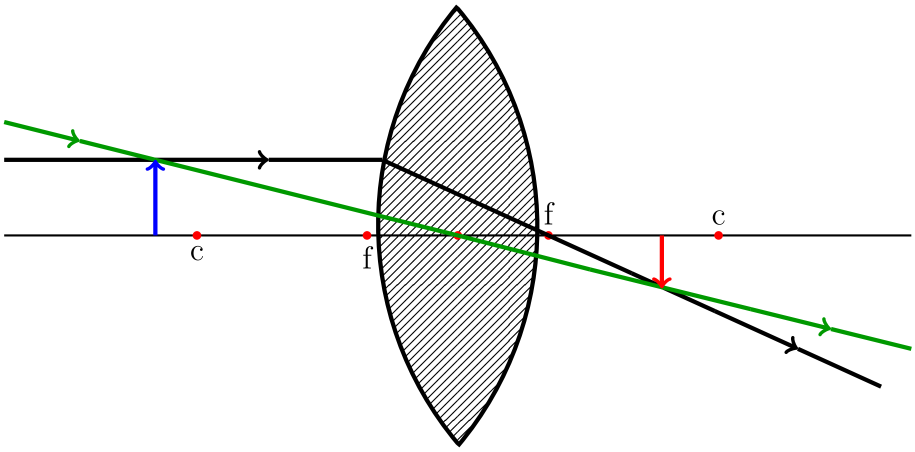


Figure 4.30: Object Outside C

2. When the object is at C, the image is:
   (a) real;
   (b) inverted;
   (c) the same size as the object;
   (d) formed at C.

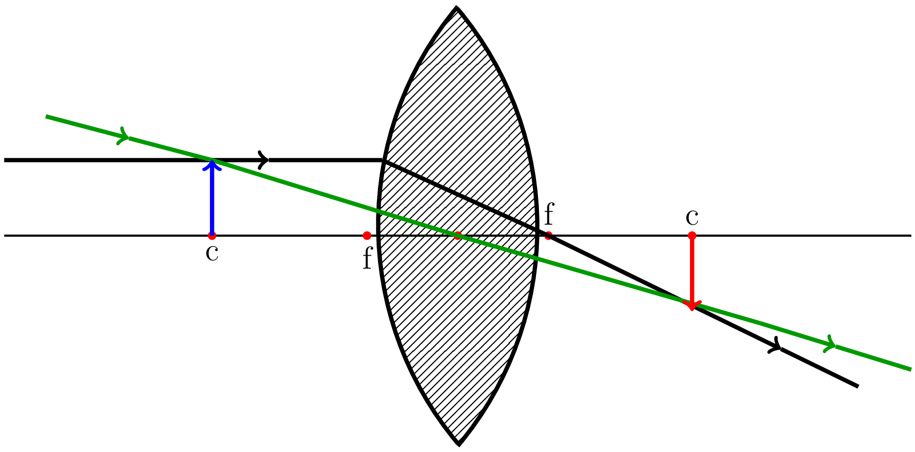


Figure 4.31: Object at C

3. When the object is between C and f, the image is:
   (a) real;
   (b) inverted;
   (c) magnified;
   (d) formed outside C.

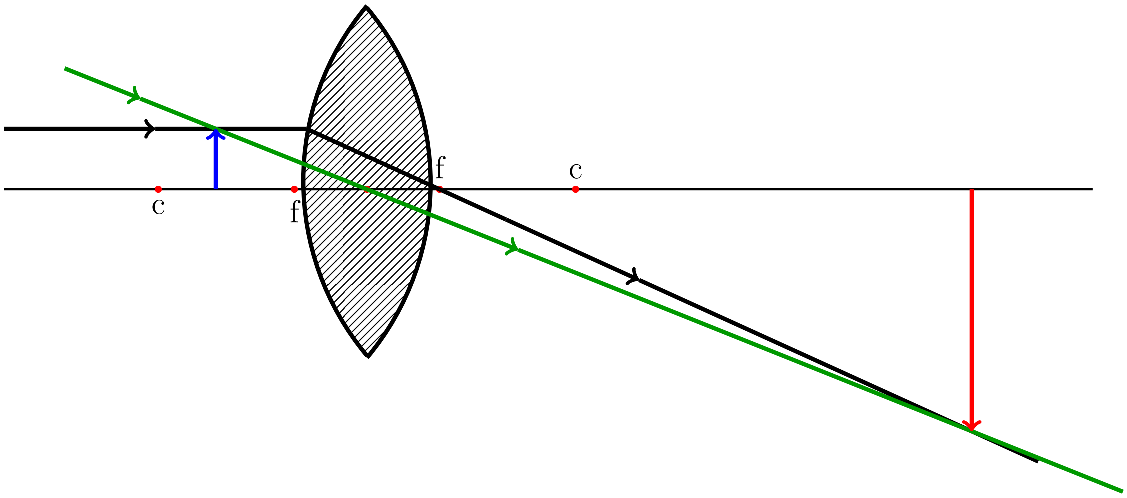


Figure 4.32: Object Between C and f

4. When the object is at f, the image is formed at infinity.

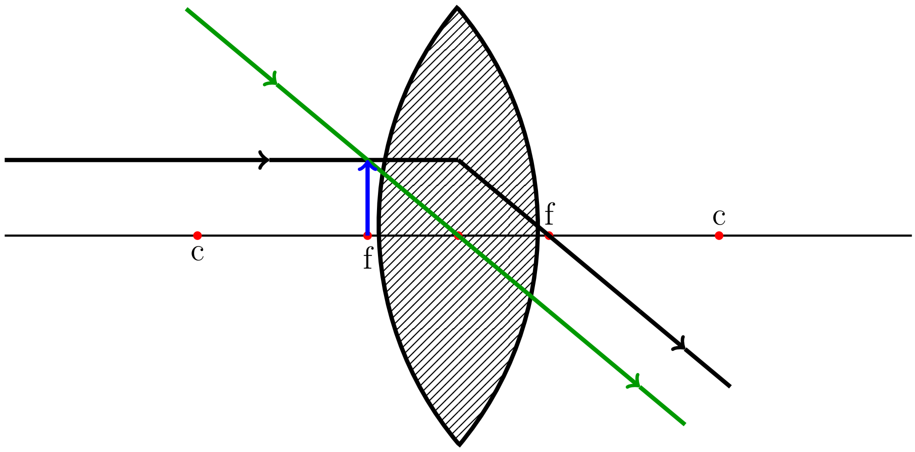


Figure 4.33: Object at f

5. When the object is inside f, the image is:

   (a) virtual;

   (b) erect;

   (c) magnified;

   (d) formed on the same side of the lens as the object.

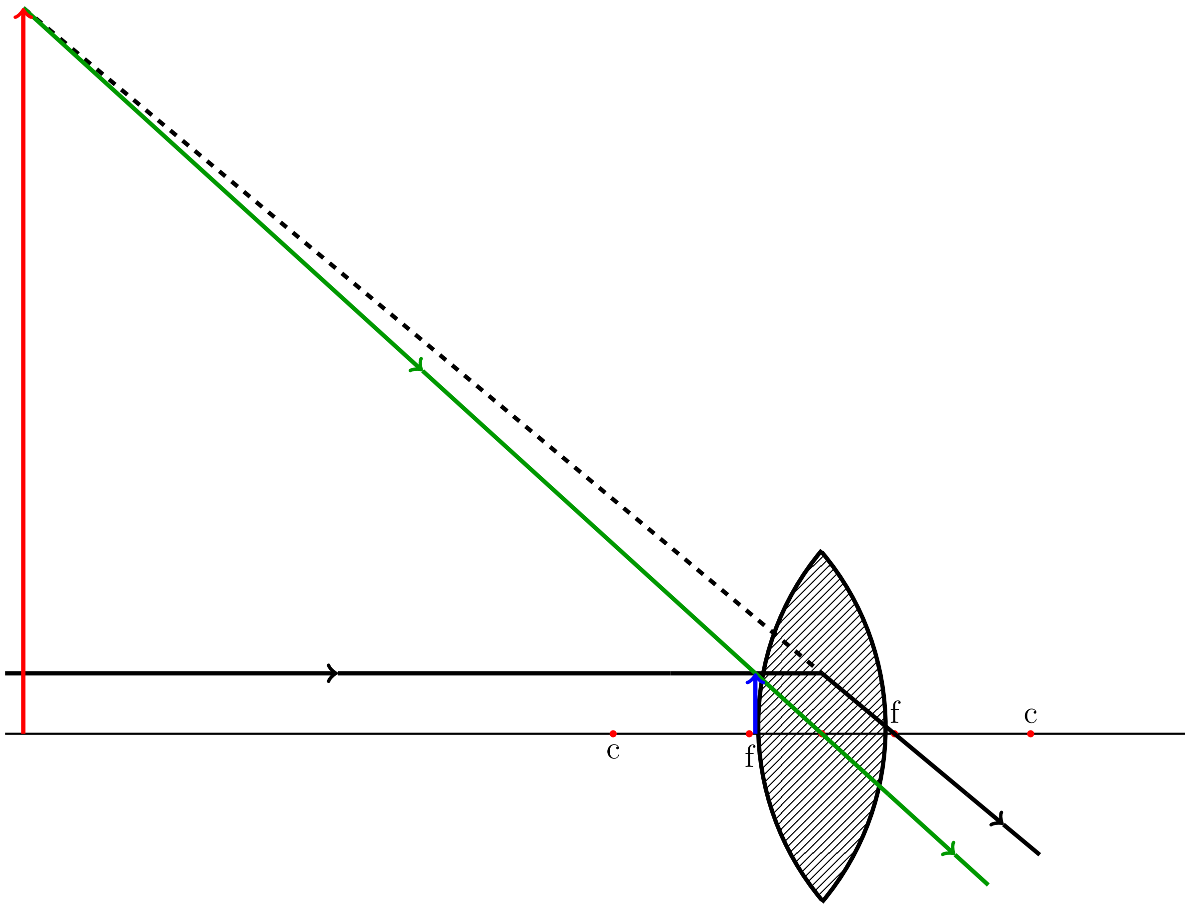


Figure 4.34: Object Inside f

4.4.2 How Images Are Formed in Convex Lenses

In all instances the image is:

1. virtual;
2. erect;
3. diminished;
4. formed inside f.

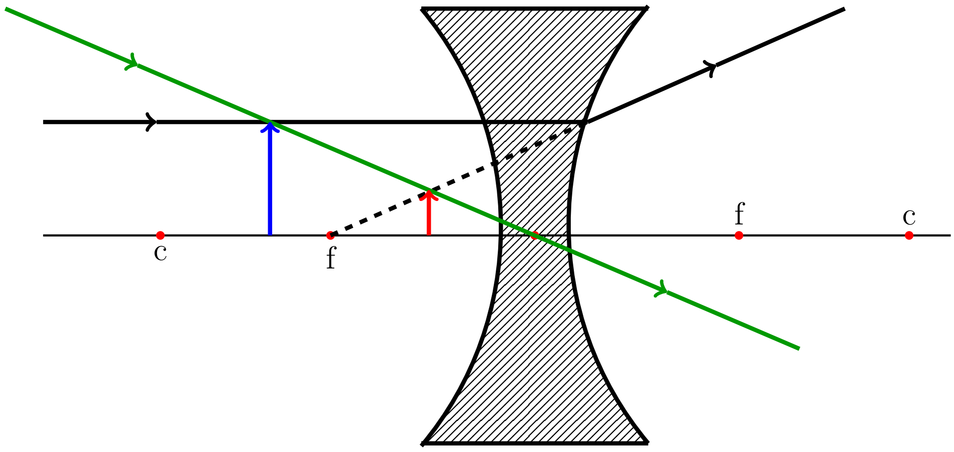


Figure 4.35: All Images in a Concave Lens

Power of a Lens

- For a convex lens: converging power.
- For a concave lens: diverging power.

$$\text{power of a lens} = \frac{1}{\text{focal length}}$$

$\therefore$

$$\boxed{P = \frac{1}{f}}$$

- The power of a convex lens is taken as $+$.
- The power of a concave lens is taken as $-$.

Unit: the per metre m^{-1}.

NB In problems you must convert *cm* to *m* to ensure that the units are correct.

Lenses in Contact

- If two lenses of power P_1 and P_2 are placed in contact, then the power of the composite lens is given by:

$$\boxed{P = P_1 + P_2}$$

- Thus, if two lenses of focal lengths f_1 and f_2 are placed in contact the focal length of the composite lens is giwen by:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \qquad \text{convex lens}$$

$$\frac{1}{f} = \frac{1}{f_1} - \frac{1}{f_2} \qquad \text{concave lens}$$

4.5 The Eye - Biology

The Power of Accommodation of the Eye: is its ability to focus a real image of an object on the retina, whether the object is far from or near to the eye, by changing the shape and hence the focal length of the eye.

The Least Distance of Distinct Vision: is the smallest distance between an object and the eye for which that object can be seen clearly without eye strain.

- When something is at the least distance from the eye it is said to be at the *near point*.
- If the object is within the near point it appears blurred since the lens cannot shorten its focal length to bring its image onto the retina.

Defects of the Eye:

Short-sighted: person can see nearby objects clearly but cannot bring distant objects into focus.

Short-sightedness can be corrected with a *concave lens*.

Long-sighted: person can see distant objects clearly but cannot bring nearby objects into focus.

Long-sightedness can be corrected with a *convex lens*.

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