

Fundamental Optics Principles

Vergence, reflection, refraction, and lenses

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LEARNING OBJECTIVES

1. Point sources of light, vergence, and collimation
2. Reflection and refraction
3. Snell's Law and the index of refraction
4. Lenses, focal points, and lens power

CONTENTS

1. **Point Sources & Vergence:** How light spreads and how we measure it in diopters
2. **Collimation:** Parallel light, zero vergence, and optical infinity
3. **Reflection:** Angle in equals angle out, from the normal
4. **Refraction:** Snell's Law and the index of refraction
5. **Applications:** Lenses, mirages, fishing, and rainbows
6. **Lenses & Focal Points:** Plus and minus lenses, $P = 1/f$, and $V = U + P$

KEY FORMULAS

Vergence

$$V = \frac{1}{d(\text{m})}$$

Optical infinity

$$6 \text{ m} = 20 \text{ ft} \Rightarrow V \approx 0$$

Reflection

$$\theta_i = \theta_r$$

Snell's Law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Index of refraction

$$n = \frac{c}{v}$$

Lens power

$$P = \frac{1}{f(\text{m})}$$

Vergence equation

$$V = U + P$$

How to use this handout: follow along during the lecture, write in the note space beside each topic, then try the practice worksheet.

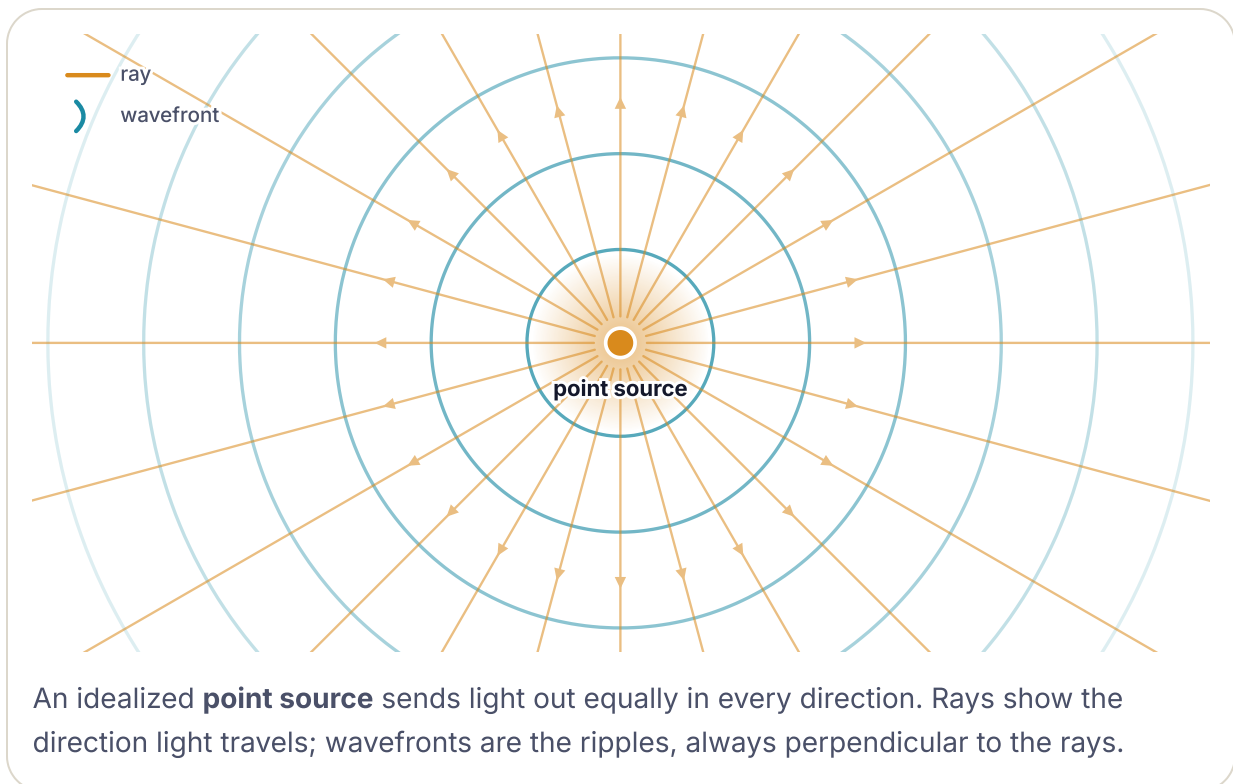
Point Sources & Vergence

Point Sources of Light

- If we imagine a small, powerful source of light, we get the physical idealization of a **point source**.
- Light leaves a point source equally in every direction.
- We can describe that light two ways: as **rays** streaming outward, or as **wavefronts** rippling outward.

Takeaway: A point source is an idealized, infinitely small light source radiating in all directions.

NOTES

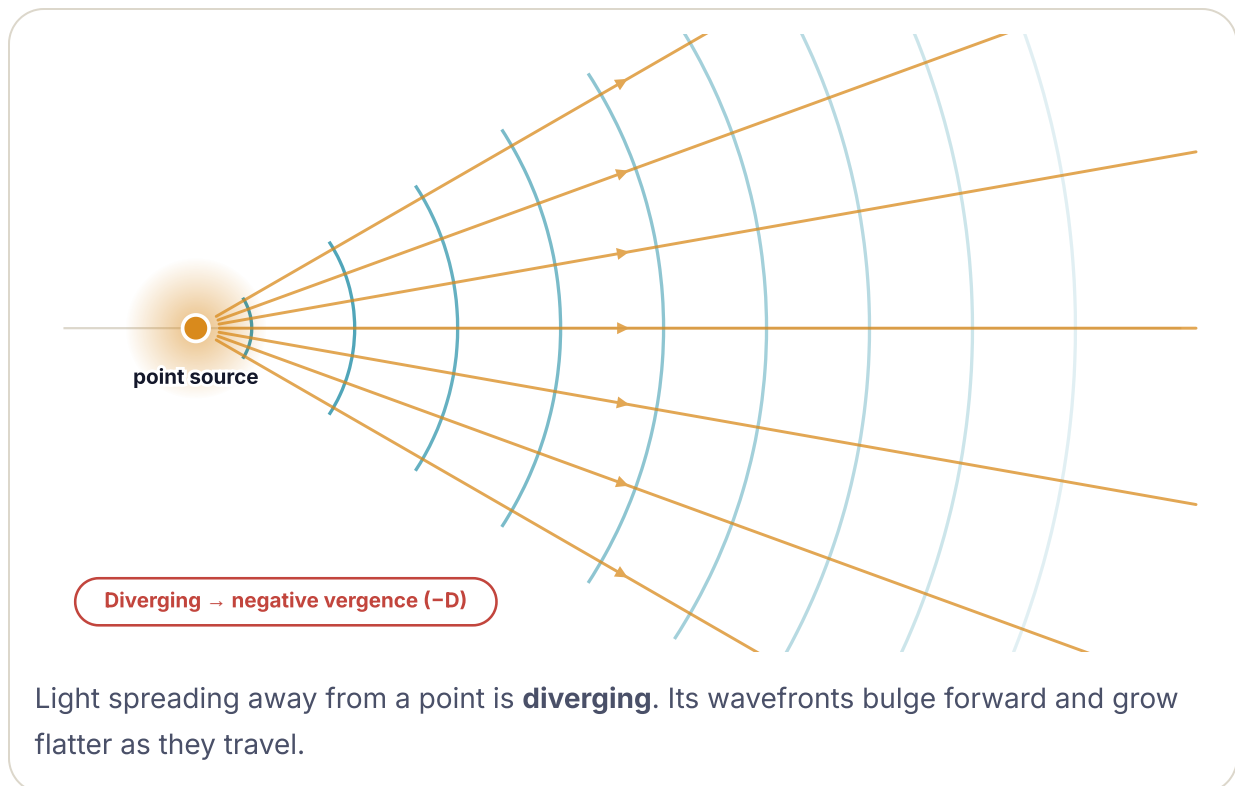


Divergence

- From a point source, light **diverges**: rays stream outward, like light from the sun, while waves ripple outward.
- The farther the light travels, the larger and flatter its wavefronts become.

Takeaway: Diverging light spreads apart as it travels away from its source.

NOTES

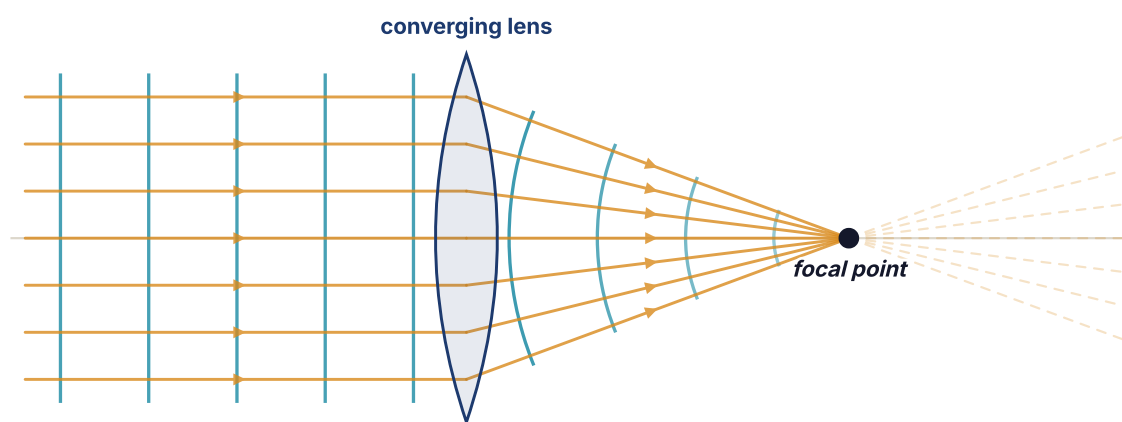


Convergence

- Using lenses or other means, light can be condensed to focus back onto a point. This is the meaning of **convergence**.
- Converging wavefronts shrink as they close in on the focal point.

Takeaway: Converging light comes together toward a point of focus.

NOTES



Converging – positive vergence (+D)

A converging (plus) lens bends parallel rays toward a single point. The wavefronts after the lens curve inward and shrink into the **focal point**.

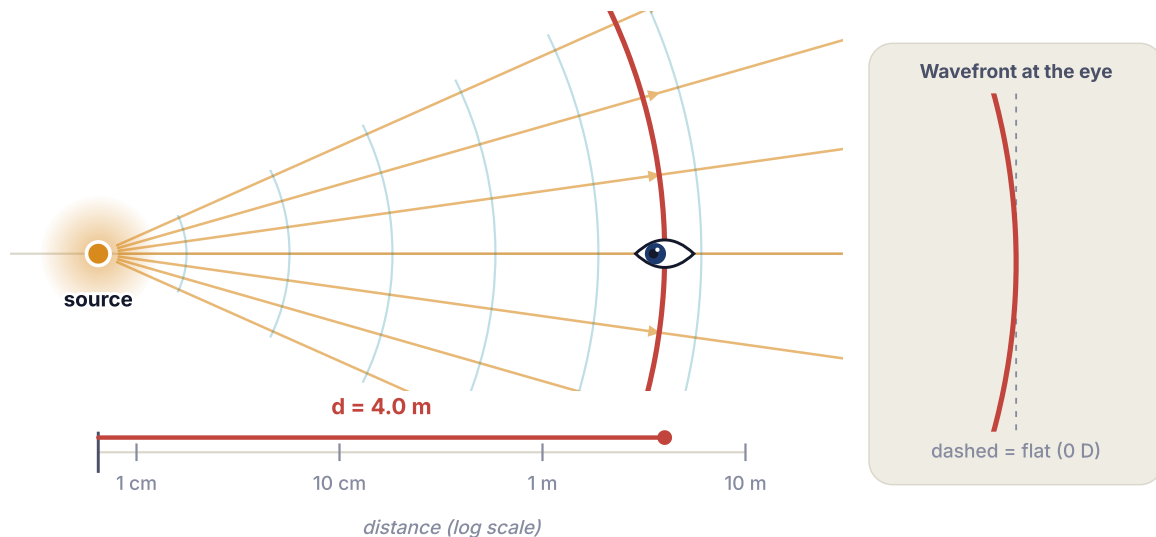
Measuring Divergence

- Sometimes we need to know how far light has diverged from its source.
- Taking the reciprocal of the distance (in meters) from the source to the observer gives a unit called the **diopter (D)**.
- By convention, divergence is **negative** and convergence is **positive**.
- *Example:* a source 4 m away gives the observer $-\frac{1}{4\text{ m}} = -0.25\text{ D}$ of divergence.

$$V = \frac{1}{d(\text{m})}$$

Takeaway: Vergence in diopters = $1 \div \text{distance in meters}$. Diverging light is negative.

NOTES



$$V = -\frac{1}{d} = -\frac{1}{4.00\text{ m}} = -0.25\text{ D}$$

VERGENCE

-0.25 D

Vergence is the reciprocal of the distance (in meters) to the point light is diverging from or converging to. Closer to the point means more curved wavefronts and larger vergence.

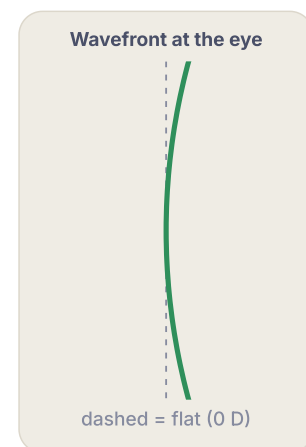
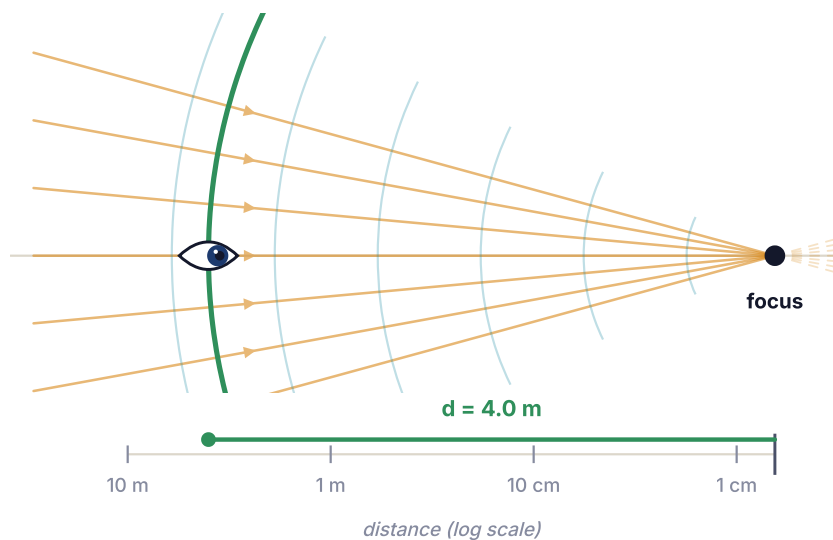
Measuring Convergence

- Diopters measure convergence too, only with a positive sign instead of negative.
- *Example:* if a lens focuses light to a point 4 m away, the light leaving the lens has **+0.25 D** of convergence.

$$V = +\frac{1}{d} = +\frac{1}{4\text{ m}} = +0.25\text{ D}$$

Takeaway: Converging light is measured in positive diopters.

NOTES



$$V = +\frac{1}{d} = +\frac{1}{4.00\text{ m}} = +0.25\text{ D}$$

VERGENCE

+0.25 D

Vergence is the reciprocal of the distance (in meters) to the point light is diverging from or converging to. Closer to the point means more curved wavefronts and larger vergence.

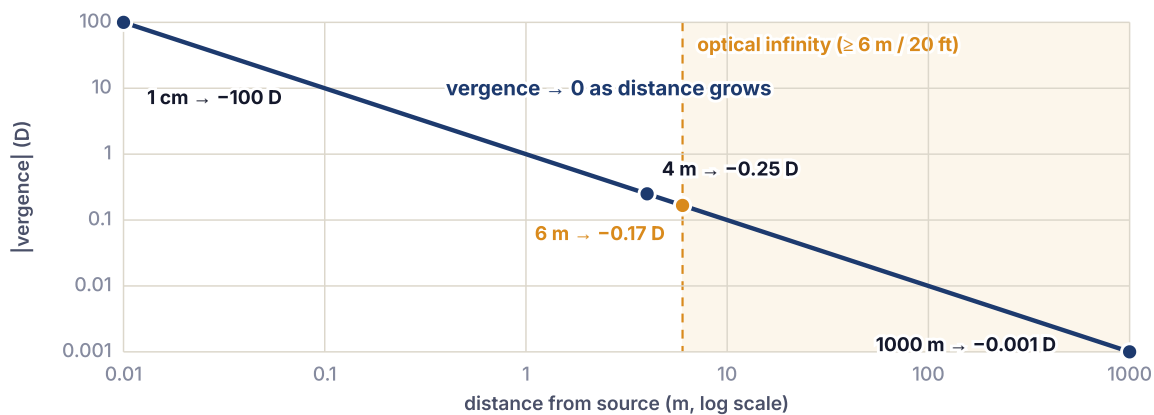
Collimation

Collimated Light

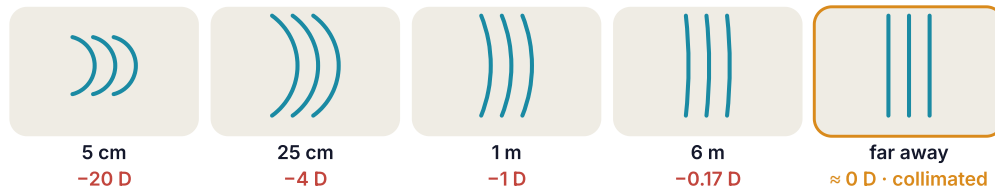
- As light travels away from its source, it diverges less and less.
- At 1 cm from a point source the light diverges by $1/0.01 = 100 \text{ D}$; at 1000 m it diverges by only $1/1000 = 0.001 \text{ D}$.
- Far from its source, light is considered **collimated**: its rays are parallel to each other.
- Collimated light has **zero vergence**.

NOTES

Takeaway: Collimated light has parallel rays and zero vergence.



Wavefront shape at each distance



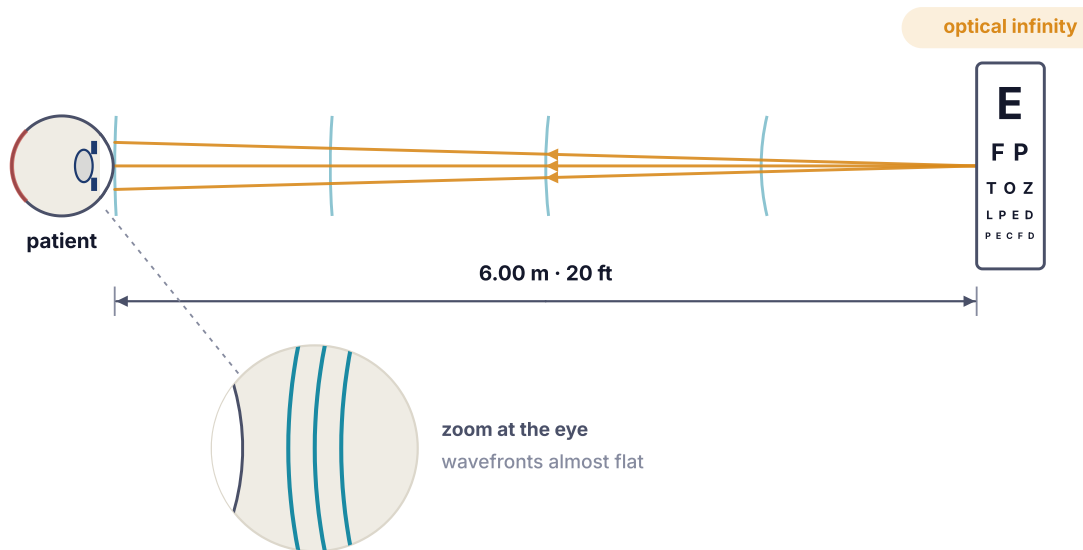
Vergence falls off as $1/\text{distance}$. Beyond about 6 m it is so small that the light is treated as collimated.

Optical Infinity

- When examining patients, we need collimated light to measure prescriptions.
- We treat light as collimated beyond a certain distance. In optometry, that distance is **20 feet (6 meters)**, known as **optical infinity**.
- The true vergence at 6 m is only $-1/6 \approx -0.17$ D, small enough to treat as zero.

NOTES

Takeaway: Optical infinity = 6 m (20 ft). Light from there is treated as collimated.



VERGENCE AT THE EYE

$$V = -\frac{1}{d} = -\frac{1}{6.00 \text{ m}} = -0.17 \text{ D}$$

$\approx$ TREATED AS 0: OPTICAL INFINITY

-0.17 D

At 6 m (20 ft) light from the chart reaches the eye with only -0.17 D of vergence, close enough to parallel that we treat it as coming from **optical infinity**.

Reflection

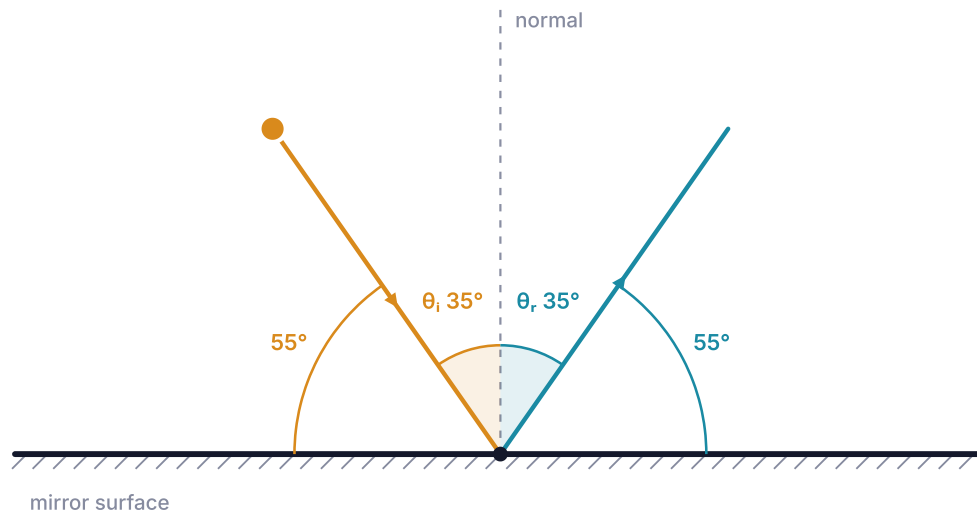
Reflection

- When light passes from one medium toward another, some of it bounces off the second medium. This is **reflection**.
- For example, light in air hitting a still surface of water partially reflects off it.
- Light leaves a surface at the **same angle** it approached, measured from the **normal** (the line perpendicular to the surface).

$$\theta_{\text{incidence}} = \theta_{\text{reflection}}$$

Takeaway: Angle of incidence = angle of reflection, both measured from the normal.

NOTES



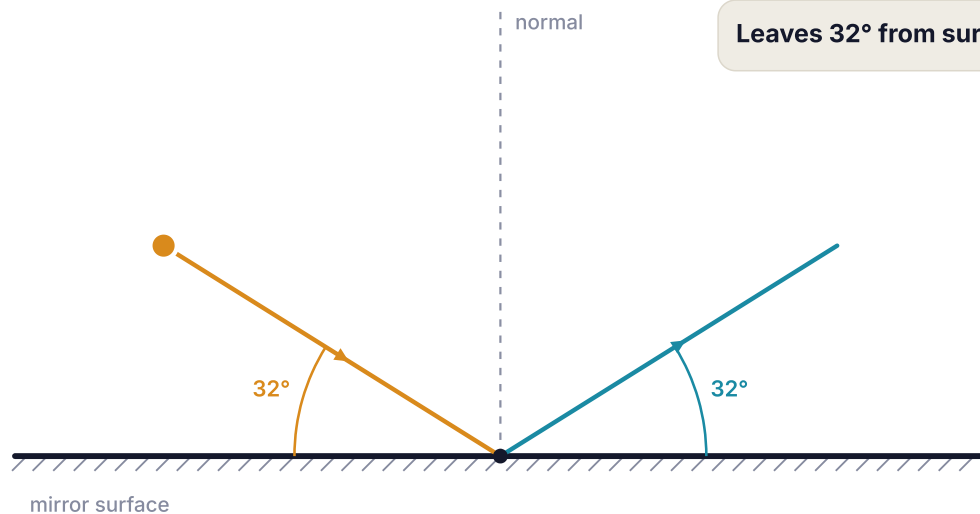
Drag the light source. The angle of reflection always equals the angle of incidence, both measured from the normal.

Worked example 1: Predicting Reflection

- A ray approaches a mirror at 32° from the mirror's surface. At what angle does it leave, relative to the surface?
- Solution:** by the law of reflection, the light leaves at 32° from the surface.

Takeaway: If the angle is given from the surface, the reflected angle from the surface is the same.

NOTES



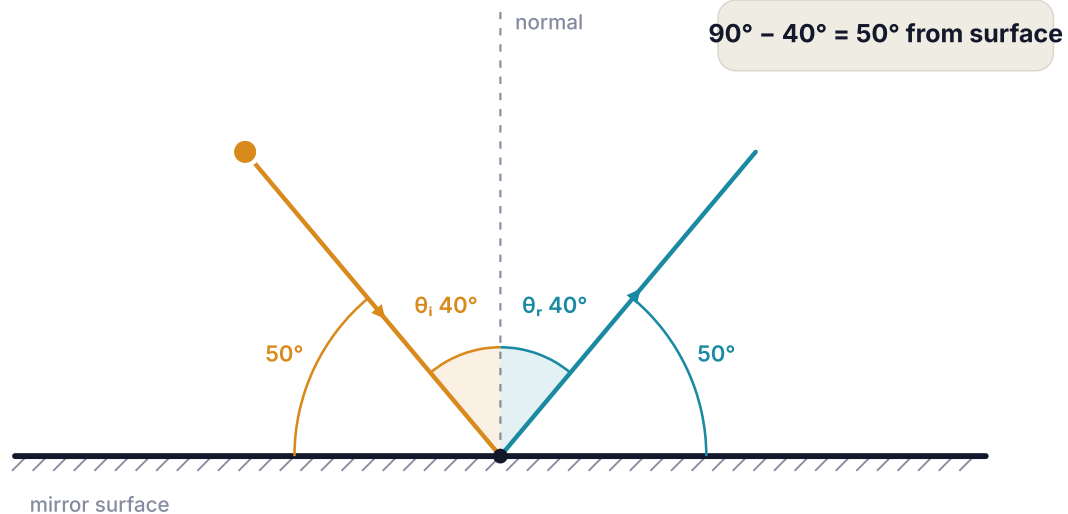
Worked example 1: the ray arrives 32° from the mirror's surface.

Worked example 2: Predicting Reflection

- A ray approaches a mirror at **40° from the normal**. At what angle does it leave, relative to the mirror's *surface*?
- Solution:** the normal is 90° from the surface, so $90^\circ - 40^\circ = 50^\circ$ from the surface.

Takeaway: Angle from surface = $90^\circ - \text{angle from normal}$.

NOTES



Worked example 2: the ray arrives 40° from the normal. The normal is 90° from the surface.

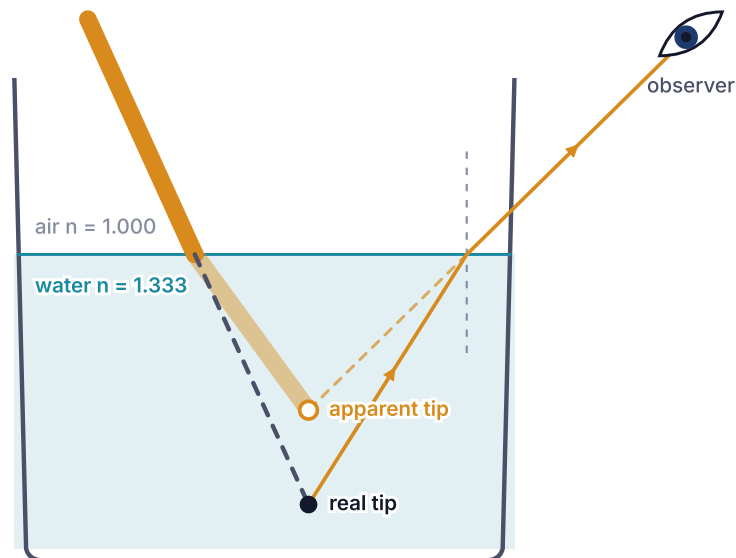
Refraction

Refraction

- When light enters one medium from another, the second medium often bends its path. This is **refraction**.
- For example, light traveling from water into air bends, so a straw in a glass looks broken at the surface.

Takeaway: Refraction is the bending of light as it passes from one medium into another.

NOTES



Light from the submerged tip bends away from the normal as it leaves the water. Your brain traces it back in a straight line, so the tip looks higher than it really is.

Snell's Law

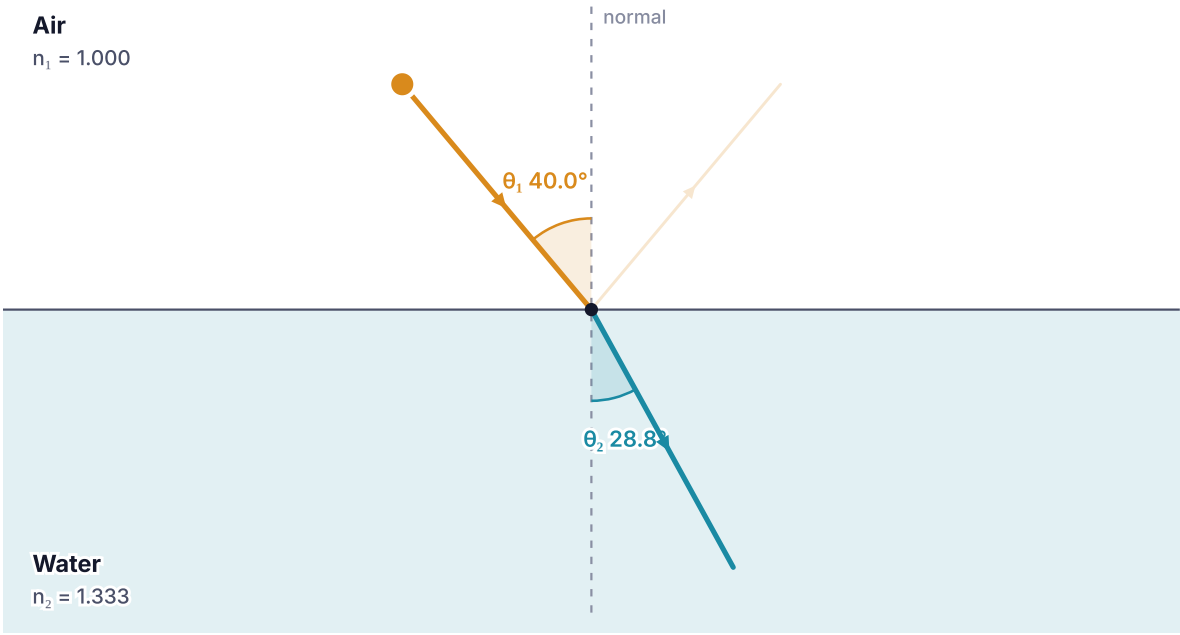
- Predicting refraction is a little more complicated than predicting reflection.
- Measured from the normal, the sine of the angle of incidence times that medium's index of refraction equals the sine of the angle of refraction times its index.
- Entering a higher index, light bends **toward** the normal. Entering a lower index, it bends **away**.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

NOTES

Takeaway: Snell's Law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$ (angles from the normal).

Air
 $n_1 = 1.000$



Water
 $n_2 = 1.333$

$\theta_1 40.0^\circ$

$\theta_2 28.8^\circ$

normal

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$
$$1.000 \times \sin 40.0^\circ = 1.333 \times \sin 28.8^\circ \quad (\text{both sides} = 0.643)$$

Index of Refraction

- An **index of refraction** is a physical property of a pure medium that helps predict how much light bends passing between media.
- Air has an index of 1.000; water has an index of 1.333.
- Formally, it is the ratio of the speed of light in a vacuum to the speed of light in that medium.

NOTES

$$n = \frac{c}{v} \quad n_{\text{water}} = \frac{c}{v_{\text{water}}} = 1.333$$

Takeaway: $n = c / v$. Light is slower in media with a higher index.

Vacuum

$$n = 1.000 \cdot 3.00 \times 10^8 \text{ m/s} \cdot 100\% c$$

Air

$$n = 1.000 \cdot 3.00 \times 10^8 \text{ m/s} \cdot 100\% c$$

Water

$$n = 1.333 \cdot 2.25 \times 10^8 \text{ m/s} \cdot 75\% c$$

Crown glass

$$n = 1.523 \cdot 1.97 \times 10^8 \text{ m/s} \cdot 66\% c$$

Diamond

$$n = 2.417 \cdot 1.24 \times 10^8 \text{ m/s} \cdot 41\% c$$

start

finish

Positions after the same amount of time: light in vacuum has reached the finish line.
Speed in a medium is $v = c / n$.

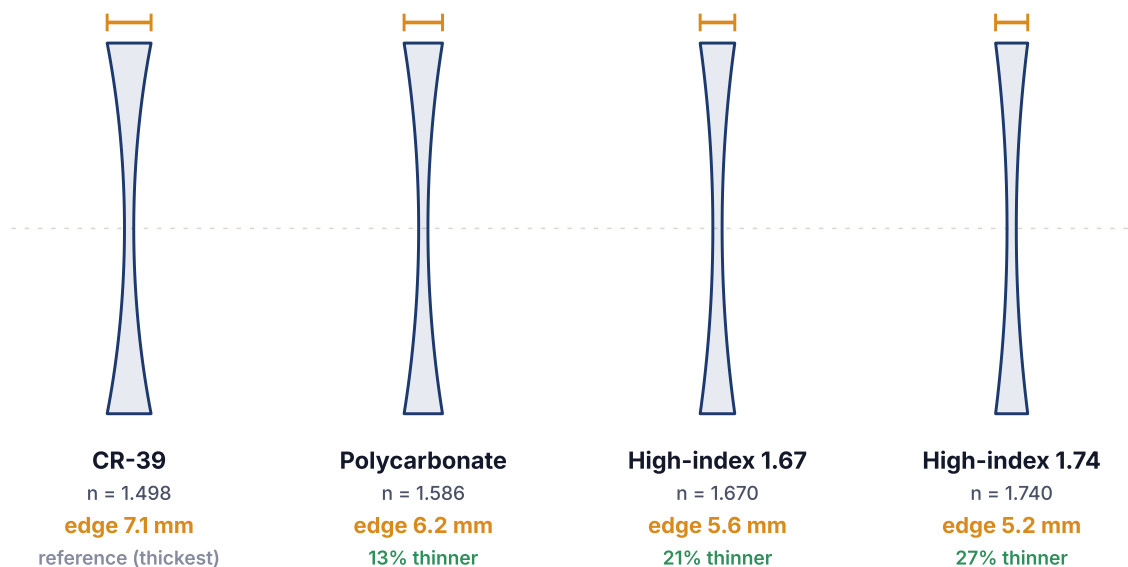
Applications

High-Index Lenses

- High-index lenses are thinner, lighter lenses for people with stronger prescriptions.
- With a higher index than, say, polycarbonate, you need less lens material to bend light the same amount.
- Historically they have drawbacks such as color fringing (chromatic aberration) and other visual aberrations.

NOTES

Takeaway: Higher index → less curvature needed → thinner, lighter lenses.



Same -6.00 D prescription, 60 mm lens, drawn to scale. A higher index needs less curvature for the same power, so the lens is thinner.

Spectacle Materials

- Every spectacle material has its own index of refraction.
- Common and historic types: glass, CR-39, polycarbonate, Trivex, and high-index plastics.

NOTES

Takeaway: Glass, CR-39, polycarbonate, Trivex, and high-index each trade off index, weight, impact resistance, and clarity.

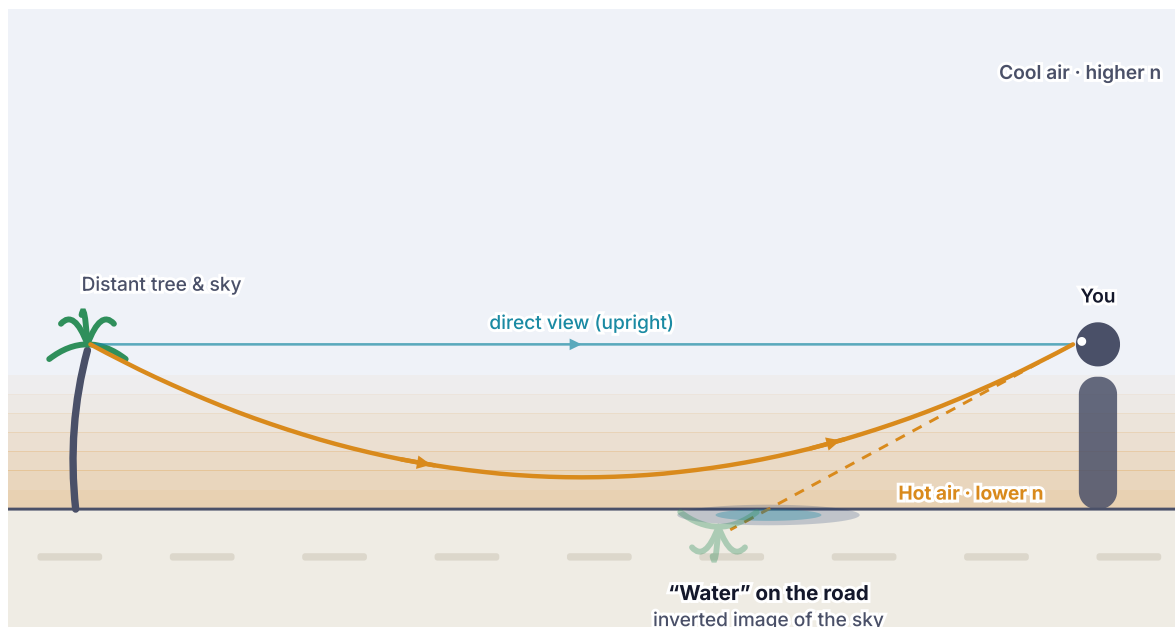
	INDEX N	1.45 – 1.76	ABBE VALUE	
Glass (crown)		1.523		59
Scratch-resistant and optically excellent, but heavy and shatters. The historic standard.				
CR-39		1.498		58
Plastic introduced in the 1940s. Lightweight with great optics; the everyday default.				
Polycarbonate		1.586		30
Highly impact-resistant: the choice for kids and safety eyewear. Lower Abbe value means more color fringing.				
Trivex		1.530		45
Impact-resistant like polycarbonate, but lighter and with better optics.				
High-index 1.67		1.670		32
Thin and light for strong prescriptions, at the cost of more chromatic aberration.				
High-index 1.74		1.740		33
The thinnest common plastic lens, for the strongest prescriptions.				
Typical nominal values; vary by manufacturer. Higher Abbe value = less color fringing (chromatic aberration).				

Mirages

- On a hot desert road you may see an image rising above the road: distorted, wavy, and often looking like water.
- Hot air near the road has a different (lower) index of refraction than the cooler air above it. Light is bent your way, giving a false image.

Takeaway: Mirages come from gradual refraction through air layers of different temperature.

NOTES



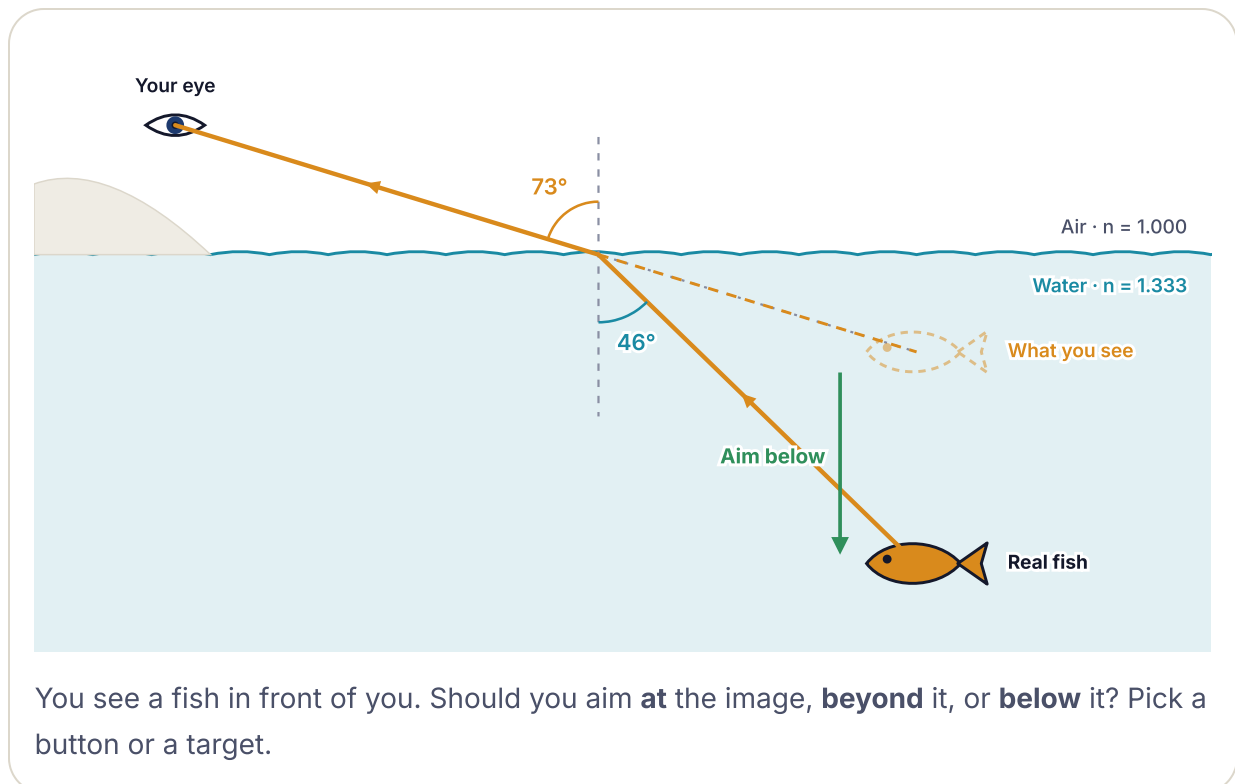
Air just above a hot road is **hotter and less dense**, so it has a **lower index of refraction** than the cooler air above. Light from the sky bends gradually upward toward your eye. Your brain traces it back in a straight line, so you see an inverted image of the sky on the road. It looks like water. (Vertical scale exaggerated.)

Spear-Fishing

- You see a fish directly in front of you. Should you aim your spear *at* the image, *beyond* it, or *below* it?
- Answer: below the image.** Water's index is greater than air's, so light from the fish bends at the surface, making the fish appear higher than it really is.

Takeaway: Objects under water appear shallower than they are; aim below the image.

NOTES

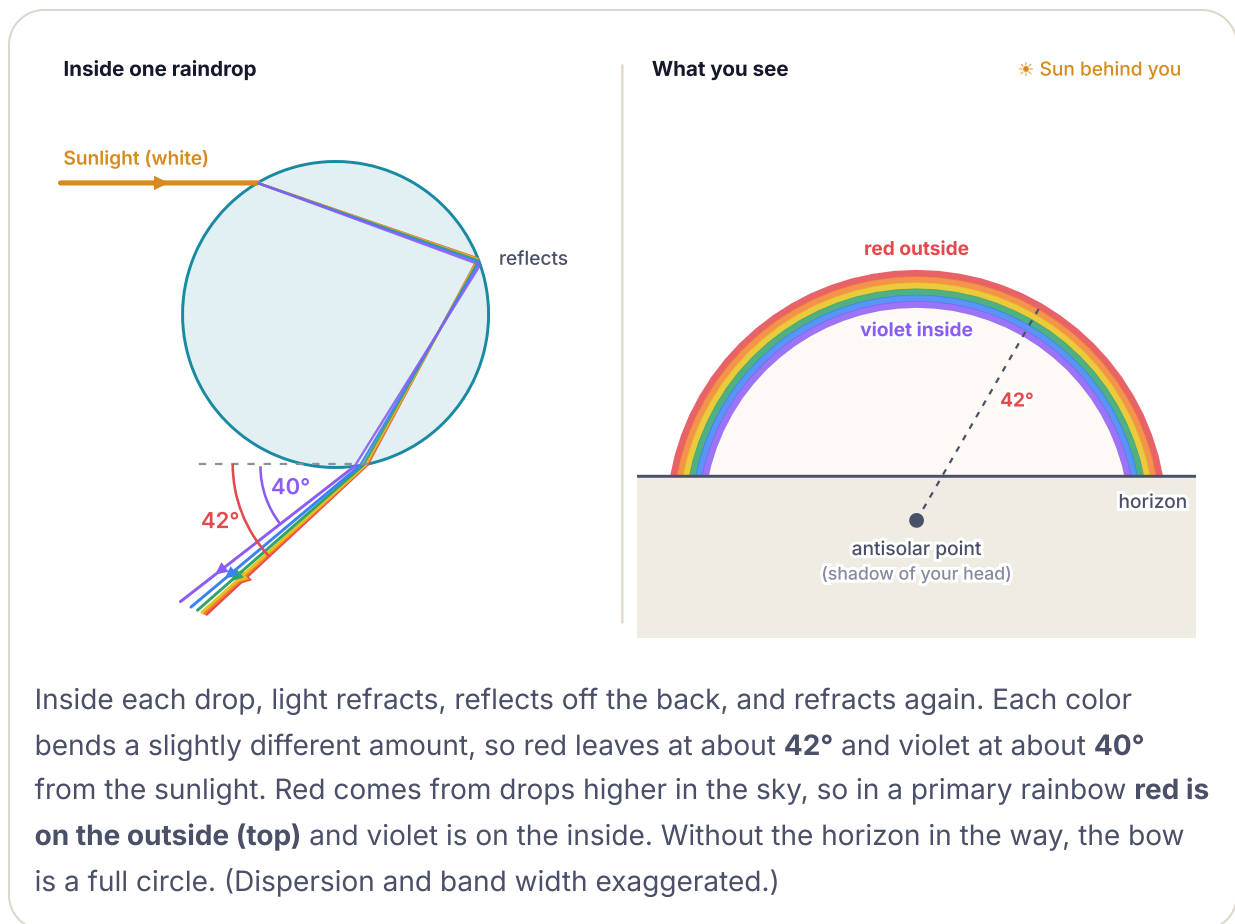


Rainbows

- Each falling raindrop acts a bit like a prism (we will study prisms in more detail later).
- Different colors have slightly different indices of refraction in water, so each drop spreads white light into colors: **dispersion**, a form of chromatic aberration.
- Red is bent least, so it exits at a slightly larger angle ($\approx 42^\circ$) than violet ($\approx 40^\circ$). Across the sky, **red appears on the outside (top)** of the bow and violet on the inside.
- Rainbows would be complete circles if not for the horizon, as seen from aircraft or in a moonbow.

NOTES

Takeaway: Dispersion in raindrops separates colors; red is on the outside of a primary rainbow.



A detour: Iris: from rainbows to eyes

NOTES



Iris (Ἴρις): Greek goddess of rainbows, and the namesake of...

=



...the **human iris**, the colored ring of the eye.

Lenses & Focal Points

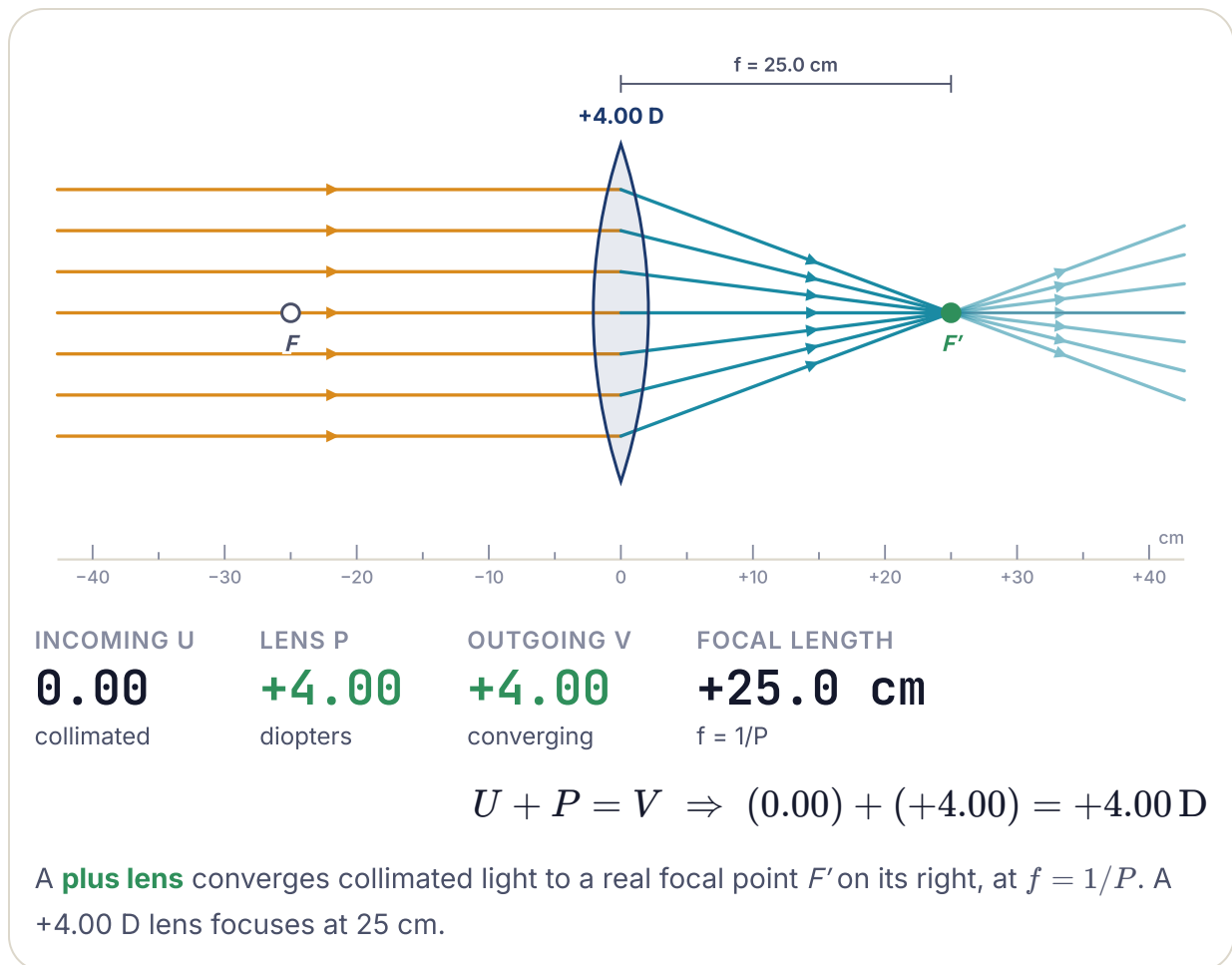
Positive Lenses & Focal Points

- A lens that converges light to a point is a **positive lens**. By convention its focal point is placed to its **right**.
- Example:* a lens that converges collimated light to a point 25 cm away is a **+4.00 D** lens, because $1/0.25 \text{ m} = 4 \text{ D}$.

NOTES

$$P = \frac{1}{f(\text{m})}$$

Takeaway: Positive lenses converge light; $P = 1/f$.

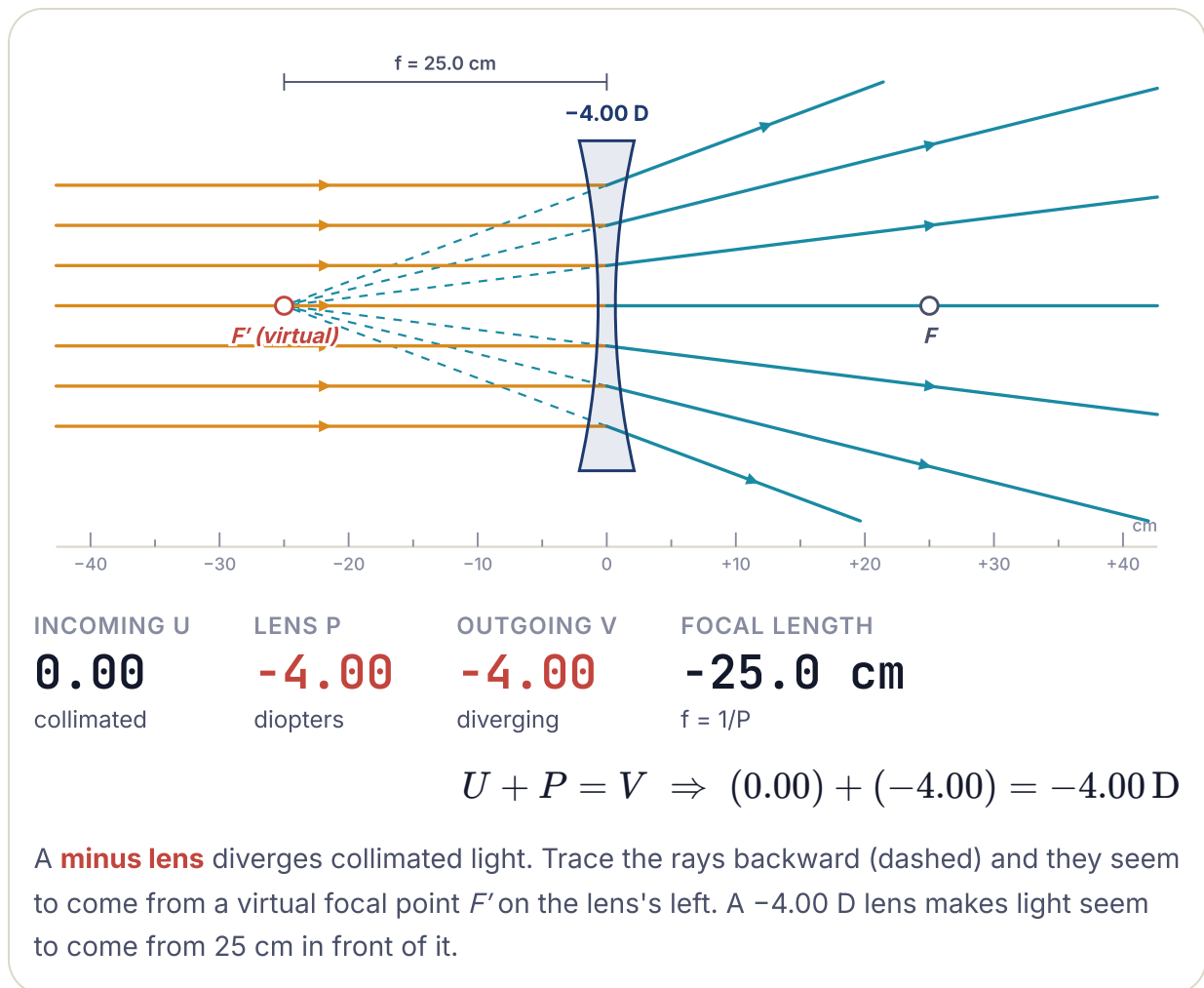


Negative Lenses & Focal Points

- A lens that diverges light is a **negative lens**. By convention its focal point is placed to its **left**.
- Instead of a real focus, a negative lens makes collimated light appear to diverge from a point a certain distance in front of the lens.
- Example:* if the light seems to come from 25 cm before the lens, it is a **-4.00 D** lens, because $1/-0.25 \text{ m} = -4 \text{ D}$.

NOTES

Takeaway: Negative lenses diverge light from a virtual focal point.



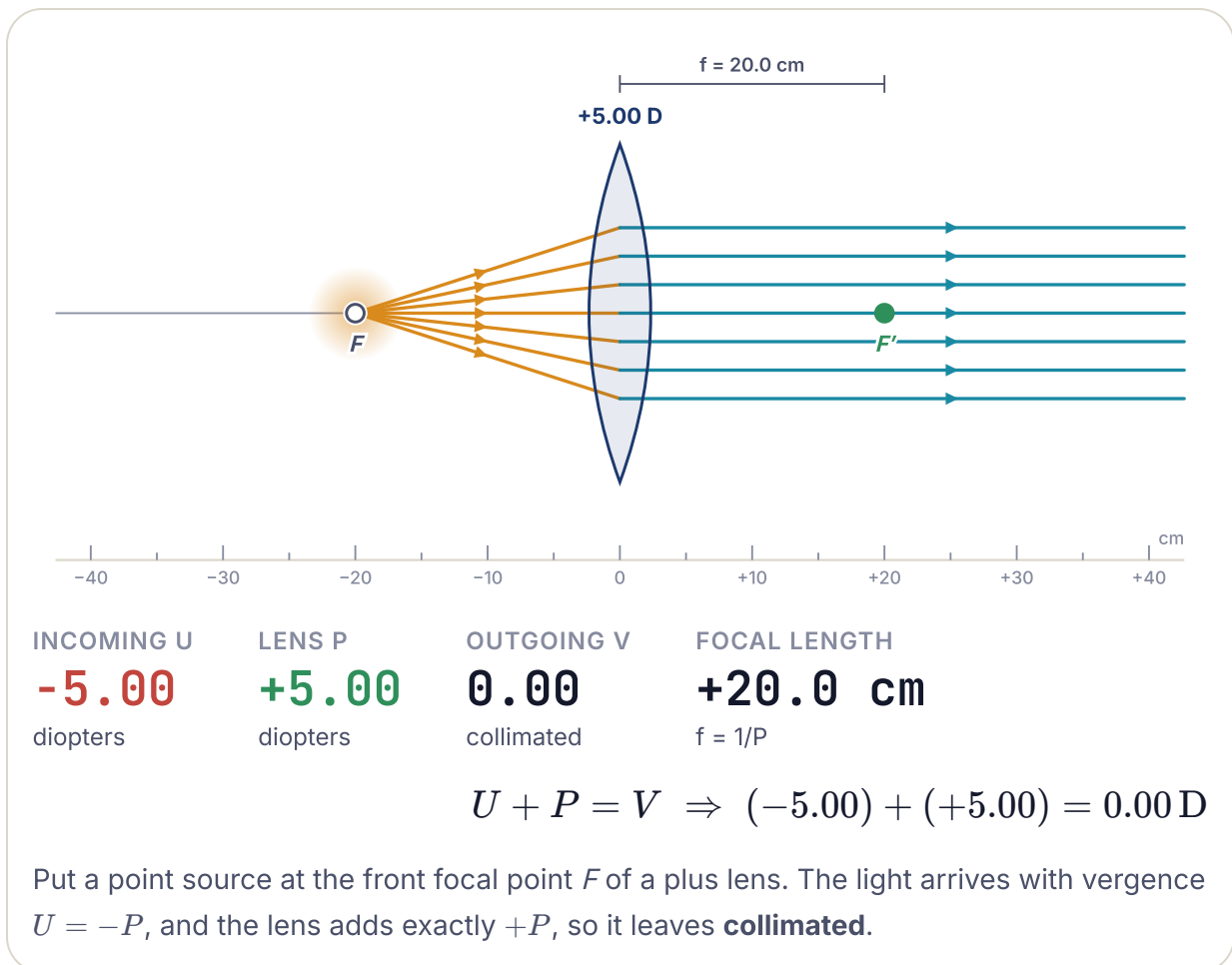
Two Focal Points: Positive Lenses

- Every lens has **two focal points**. For a positive lens, the one on the right is where collimated light focuses.
- The one in front (left) is where a light source produces collimated light beyond the lens.
- *Example:* a light at the front focal point of a +5.00 D lens (20 cm away) reaches the lens with $1/-0.20 \text{ m} = -5 \text{ D}$ of divergence.
- The lens adds +5 D, producing **zero vergence**: collimated light.

NOTES

$$V = U + P = (-5) + (+5) = 0 \text{ D}$$

Takeaway: Exiting vergence = entering vergence + lens power ($V = U + P$).



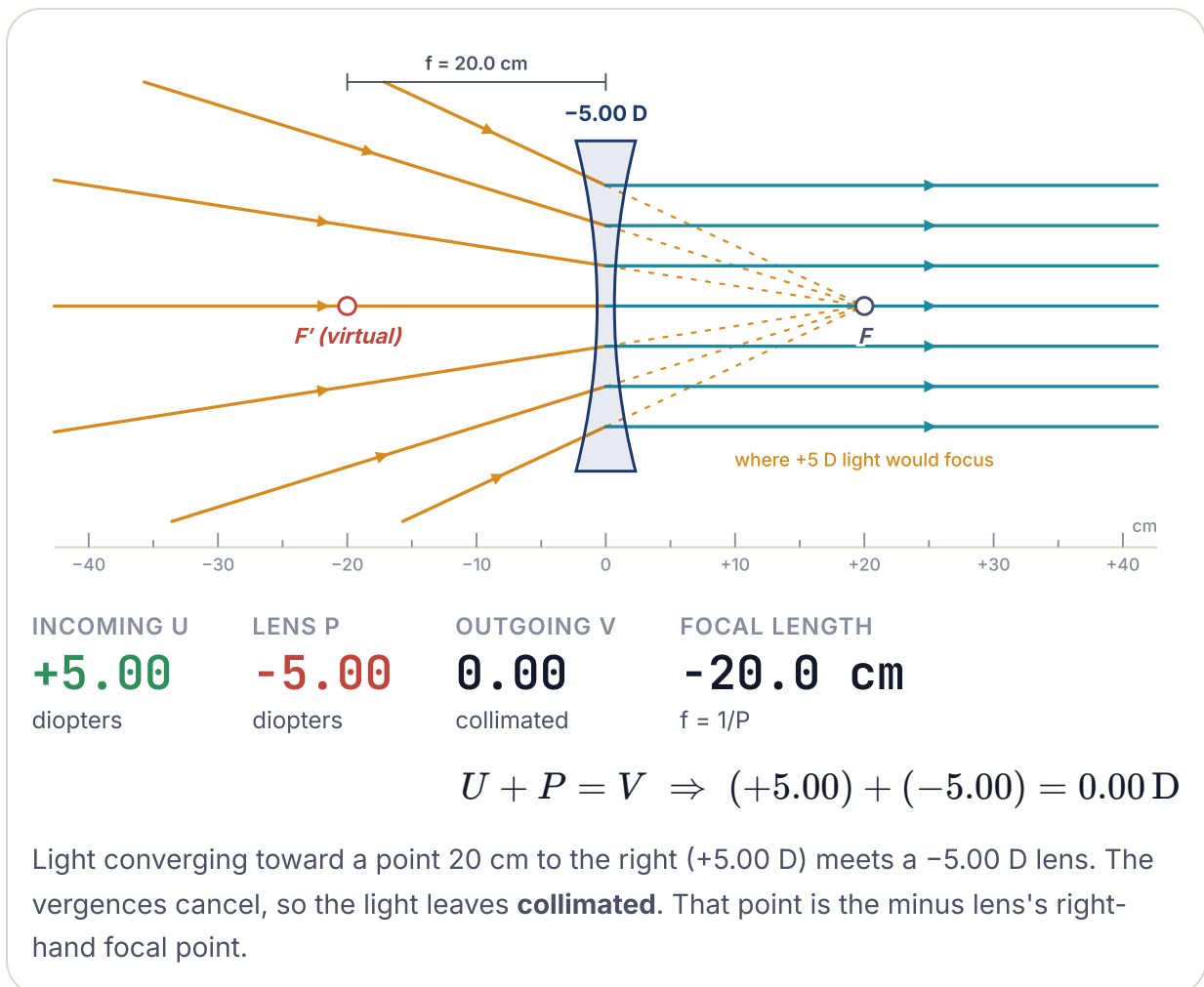
Two Focal Points: Negative Lenses

- For a negative lens, the focal point on the left is the imaginary point from which collimated light appears to emanate.
- The one on the right is where, if converging light were heading toward it, the lens would cancel that convergence.
- Example:* +5.00 D of converging light reaching a -5.00 D lens emerges **collimated**.
- That light would have focused 20 cm right of the lens, so that point is its right-hand focal point.

NOTES

$$V = U + P = (+5) + (-5) = 0 \text{ D}$$

Takeaway: Matching but opposite vergences cancel to collimated light.



Glossary

Point source

An idealized, infinitely small source of light that radiates equally in all directions.

Divergence

Light spreading apart as it travels away from a point. Measured in negative diopters.

Convergence

Light coming together toward a point of focus. Measured in positive diopters.

Vergence

The amount light is converging or diverging at a location: $1 \div \text{distance (m)}$ to the point of origin or focus.

Diopter (D)

The unit of vergence and lens power: the reciprocal of a distance in meters.

Collimated light

Light with parallel rays and zero vergence.

Optical infinity

6 m (20 ft). Light from this distance or farther is treated as collimated in optometry.

Reflection

Light bouncing off a surface, leaving at the same angle (from the normal) at which it arrived.

Normal

The line perpendicular to a surface at the point where light strikes it.

Refraction

The bending of light as it passes from one medium into another.

Index of refraction (n)

The ratio of the speed of light in a vacuum to its speed in a medium: $n = c/v$.

Snell's Law

$n_1 \sin \theta_1 = n_2 \sin \theta_2$. Predicts the angle of refraction.

Critical angle

The angle of incidence beyond which light going into a lower-index medium is totally internally reflected.

Dispersion

The separation of white light into colors because the index of refraction varies with wavelength.

Chromatic aberration

Color fringing caused by dispersion in a lens.

Abbe value

A measure of a material's dispersion. Higher values mean less color fringing.

High-index lens

A lens made of a material with a high index of refraction, letting strong prescriptions be thinner and lighter.

Positive lens

A converging lens; its focal point (for collimated light) is real and to its right.

Negative lens

A diverging lens; collimated light appears to come from a virtual focal point to its left.

Focal point

The point where collimated light focuses (or appears to come from) after a lens. Every lens has two.

Lens power (P)

The vergence a lens adds to light, in diopters: $P = 1/f$.