

Unit 13: Geometric Optics

Unit 13 covers how light behaves when it meets a boundary between materials and when it passes through lenses or reflects off mirrors. It includes the law of reflection, refraction and Snell's law, total internal reflection, dispersion, thin lenses, and mirrors, held together by the sign conventions that make every image calculation work.

AP Physics 2

Geometric Optics

About 15 minutes to read

How to use this guide

Read it in order the first time because the topics build on each other. Reflection and refraction set the rules that lenses and mirrors then use, and the sign conventions introduced with thin lenses apply unchanged to mirrors. The worked examples recompute every number step by step, so copy that habit on your own paper.

After the first read, use the trap boxes and the tables to review the distinctions that exam questions test most often. Sign conventions cause more lost points in this unit than any forgotten equation, so give them extra attention. Finish with the practice questions, then complete the recall check on the last page out loud and note any items you cannot explain yet.

What this unit is worth. Geometric Optics is about 12 to 15 percent of the AP Physics 2 exam, one of the heaviest units on the test. It rewards careful bookkeeping. The thin lens equation is short, but every symbol carries a sign, and the exam tests whether you track them.

13.1 Reflection

Light travels in straight lines until it meets a surface. The **law of reflection** says the angle of incidence equals the angle of reflection, written $\theta_i = \theta_r$. Both angles are measured from the **normal**, the line perpendicular to the surface at the point where the ray strikes. The incident ray, the reflected ray, and the normal all lie in the same plane.

A **plane mirror** forms an image with four dependable characteristics. The image is **virtual**, meaning no light actually passes through the image location. Your brain traces the reflected rays backward and concludes they came from behind the mirror. It is **upright** and the **same size** as the object, it sits the **same distance behind the mirror** as the object sits in front, and it is **laterally reversed**, so left and right appear swapped.

Trap. Angles in optics are measured from the normal, not from the surface. If a problem says a ray strikes a surface at 30° to the surface, the angle of incidence is 60° . Convert before you use the angle in any equation.

13.2 Refraction and Snell's Law

When light crosses into a material where it travels at a different speed, it bends. This bending is called **refraction**. The **index of refraction** of a material is $n = c / v$, where $c = 3.00 \times 10^8$ m/s is the speed of light in vacuum and v is the speed of light in the material. Because light slows down in any material, n is always greater than 1. Air is about 1.00, water is 1.33, and typical glass is around 1.52.

Snell's law relates the angles on the two sides of a boundary: $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Here θ_1 is the angle in the first medium and θ_2 is the angle in the second medium, and both are measured from the normal. When light slows down entering a higher- n material, it bends toward the normal. When it speeds up entering a lower- n material, it bends away from the normal.

A worked example, recomputed fully. Light in air ($n_1 = 1.00$) strikes water ($n_2 = 1.33$) with an angle of incidence of 40° from the normal. From Snell's law, $\sin\theta_2 = n_1 \sin\theta_1 / n_2 = (1.00)(\sin 40^\circ) / 1.33 = 0.6428 / 1.33 = 0.4833$, so $\theta_2 = 28.9^\circ$. The ray bends toward the normal because it slowed down. The speed of light in the water is $v = c / n = (3.00 \times 10^8 \text{ m/s}) / 1.33 = 2.26 \times 10^8 \text{ m/s}$.

Trap. Keep each index matched with its own angle: n_1 goes with θ_1 , n_2 with θ_2 . The most common Snell's law error is swapping the ratio and computing $\sin\theta_2 = (n_2 / n_1) \sin\theta_1$, which gives an angle larger than the incident one when the light actually slowed down. If your refracted angle bends the wrong way, check the ratio.

13.3 Total Internal Reflection

When light travels from a higher- n medium toward a lower- n medium, Snell's law makes the refracted angle larger than the incident angle. At one particular incident angle, the refracted ray would run exactly along the boundary, with $\theta_2 = 90^\circ$. That angle is the **critical angle** θ_c . For any incident angle larger than θ_c , there is no refracted ray at all. Every bit of the light reflects back into the first medium, which is **total internal reflection**.

Setting $\theta_2 = 90^\circ$ in Snell's law gives $n_1 \sin\theta_c = n_2 \sin 90^\circ = n_2$, so $\sin\theta_c = n_2 / n_1$. Two conditions must both hold. First, the light must go from higher n to lower n , so $n_1 > n_2$. Second, the incident angle must exceed the critical angle, so $\theta_1 > \theta_c$.

A worked example. For light inside glass ($n_1 = 1.52$) heading toward air ($n_2 = 1.00$): $\sin\theta_c = 1.00 / 1.52 = 0.6579$, so $\theta_c = 41.1^\circ$. Any ray inside the glass that strikes the boundary at more than 41.1° from the normal reflects entirely back into the glass. For comparison, water ($n = 1.33$) to air gives $\sin\theta_c = 1.00 / 1.33 = 0.7519$, so $\theta_c = 48.8^\circ$.

Trap. Total internal reflection cannot happen when light goes from lower n to higher n , no matter how large the incident angle is. Check the direction first. A question that sends light from air into water at a steep angle is testing whether you notice the direction makes total internal reflection impossible.

13.4 Dispersion

The index of refraction of a material depends slightly on the wavelength of the light. In glass, shorter wavelengths experience a slightly larger n than longer wavelengths, so violet light bends more than red light when it refracts. White light passing through a prism spreads into a spectrum for this reason, with violet deviated the most and red the least. Dispersion is qualitative on the exam. You need the idea that n varies with color and that shorter wavelengths bend more, not a formula.

13.5 Thin Lenses

A **converging lens** is thicker in the middle than at the edges. It bends rays that arrive parallel to the axis so they meet at a **focal point** on the opposite side of the lens. A **diverging lens** is thinner in the middle. It spreads parallel rays apart so that they appear to come from a focal point on the same side as the incoming light. The **focal length** f is the distance from the lens to the focal point.

Two equations describe every thin lens image. The **thin lens equation** is $1/f = 1/d_o + 1/d_i$, where d_o is the object distance and d_i is the image distance. The **magnification** is $m = h_i/h_o = -d_i/d_o$, where h_o and h_i are the object and image heights. The minus sign in the magnification is part of the equation, not optional.

Sign conventions (AP convention: real is positive)

Learn this table before doing a single calculation. It is the same for lenses and mirrors, and it is where most points are lost.

QUANTITY	POSITIVE MEANS	NEGATIVE MEANS
f	Converging lens or concave mirror	Diverging lens or convex mirror
d_o	Real object (always, for the objects on this exam)	Not used on this exam
d_i	Real image: opposite side of a lens from the object, or in front of a mirror	Virtual image: same side of a lens as the object, or behind a mirror
m	Upright image	Inverted image
$ m $	> 1 enlarged, < 1 reduced, $= 1$ same size	Size comes from $ m $ only, never from the sign

Read an answer in this order. The sign of d_i tells you real or virtual. The sign of m tells you upright or inverted. The size of $|m|$ tells you enlarged or reduced. A **real image** is formed where light rays actually converge, so it can be projected on a screen. A **virtual image** is formed where rays only appear to converge, so you see it by looking through the lens or into the mirror, but no screen will catch it.

Trap. Decide the sign of f from the lens type before you touch the equation. A diverging lens always has negative f . Forgetting that minus sign flips the image distance and the magnification, and every conclusion drawn from them.

Worked Lens Examples

Example 1: converging lens, real image. A converging lens has $f = +10$ cm. An object is placed at $d_o = +30$ cm, which is beyond twice the focal length. Solve the thin lens equation for d_i : $1/d_i = 1/f - 1/d_o = 1/10 - 1/30 = 3/30 - 1/30 = 2/30 = 1/15$, so $d_i = +15$ cm. The positive sign means a real image, 15 cm from the lens on the opposite side from the object.

Now the magnification: $m = -d_i/d_o = -15/30 = -0.5$. The negative sign means inverted, and $|m| = 0.5 < 1$ means reduced. If the object is 4.0 cm tall, the image height is $h_i = m \cdot h_o = (-0.5)(4.0 \text{ cm}) = -2.0$ cm. The minus sign records the inversion, and the image is 2.0 cm tall. Summary: real, inverted, reduced.

Example 2: converging lens, virtual image. The same lens, $f = +10$ cm, but now the object is at $d_o = +5$ cm, inside the focal length. Then $1/d_i = 1/10 - 1/5 = 1/10 - 2/10 = -1/10$, so $d_i = -10$ cm. The negative sign means a virtual image, 10 cm from the lens on the same side as the object. You see it by looking through the lens, the way a magnifying glass works.

The magnification is $m = -(-10)/5 = +2$. The positive sign means upright, and $|m| = 2$ means enlarged. A 4.0 cm object gives an 8.0 cm tall upright image. Summary: virtual, upright, enlarged.

Trap. A negative image distance is a valid answer, not a mistake to fix. It describes a virtual image you see by looking through the lens. Students who flip the sign to make it positive turn a correct calculation into a wrong description of the image.

13.6 Mirrors

A **concave mirror** curves inward like the inside of a spoon. It converges reflected rays to a real focal point in front of the mirror, so f is positive. A **convex mirror** curves outward. It diverges reflected rays so they appear to come from a focal point behind the mirror, so f is negative.

Mirrors use the same two equations as lenses: $1/f = 1/d_o + 1/d_i$ and $m = -d_i/d_o$. The sign conventions carry over with one change of scenery. A positive d_i means a real image located in front of the mirror, on the same side as the object, where the reflected light actually travels. A negative d_i means a virtual image behind the mirror surface, where no reflected light goes.

Worked example: concave mirror. A concave mirror has $f = +15$ cm. An object is placed at $d_o = +45$ cm in front of it. Then $1/d_i = 1/15 - 1/45 = 3/45 - 1/45 = 2/45$, so $d_i = +22.5$ cm. The positive sign means a real image, 22.5 cm in front of the mirror. The magnification is $m = -22.5/45 = -0.5$, so the image is inverted and reduced. A 6.0 cm tall object gives an image 3.0 cm tall and upside down. Summary: real, inverted, reduced, in front of the mirror.

Trap. A convex mirror can never form a real image, and a diverging lens can never form a real image either. Their focal lengths are negative, and with a positive object distance the equation always returns a negative d_i . If your calculation gives a real image for one of these, you dropped the minus sign on f .

13.7 Ray Diagrams

A ray diagram traces a few special rays to locate an image. Learn the path of each ray in words, because exam questions describe diagrams without showing them. In every diagram, solid lines are real light paths and dashed lines are backward extensions that your brain follows. An image forms where rays actually meet (real) or where their extensions meet (virtual).

Converging lens, object outside the focal length. Three principal rays: (1) a ray arriving parallel to the principal axis refracts through the lens and passes through the focal point on the far side; (2) a ray through the center of the lens continues straight without bending; (3) a ray through the near focal point refracts through the lens and emerges parallel to the axis. The refracted rays intersect on the far side, marking a real, inverted image.

Converging lens, object inside the focal length. The same three rays, but after refraction they spread apart on the far side. Extend them backward with dashed lines to the object's side, where the extensions meet. That meeting point is a virtual, upright, enlarged image.

Diverging lens. Three principal rays: (1) a ray arriving parallel to the axis refracts so that its backward extension passes through the near focal point, while the ray itself bends away from the axis; (2) a ray aimed at the center of the lens continues straight; (3) a ray aimed at the far focal point refracts and emerges parallel to the axis. The backward extensions meet on the object's side, always giving a virtual, upright, reduced image.

Concave mirror. Three principal rays: (1) a ray arriving parallel to the axis reflects through the focal point in front of the mirror; (2) a ray through the focal point reflects parallel to the axis; (3) a ray striking the vertex, the center point of the mirror surface, reflects with equal angles, $\theta_i = \theta_r$. The reflected rays meet in front of the mirror for a real image.

Convex mirror. Two useful rays: (1) a ray arriving parallel to the axis reflects so that its backward extension comes from the focal point behind the mirror; (2) a ray aimed at the focal point behind the mirror reflects parallel to the axis. The extensions meet behind the mirror, always giving a virtual, upright, reduced image.

Trap. A dashed intersection is a virtual image, never a real one. Drawing backward extensions that meet behind a mirror or on the object's side of a lens and then calling the image real is the diagram version of misreading a negative d_i .

Comparing the Four Devices

DEVICE	F SIGN	CAN IT MAKE A REAL IMAGE?	IMAGE TYPES POSSIBLE
Converging lens	+	Yes, when $d_o > f$	Real and inverted when the object is outside f (reduced if $d_o > 2f$, enlarged if $f < d_o < 2f$); virtual, upright, and enlarged when $d_o < f$
Diverging lens	-	Never	Always virtual, upright, and reduced
Concave mirror	+	Yes, when $d_o > f$	Real and inverted when the object is outside f ; virtual, upright, and enlarged when $d_o < f$
Convex mirror	-	Never	Always virtual, upright, and reduced

Notice the pattern. The two devices with negative f , the diverging lens and the convex mirror, behave identically: virtual, upright, reduced, every time. The two with positive f behave identically too, with the object position relative to f deciding between a real inverted image and a virtual upright one. Memorizing the pattern beats memorizing four separate lists.

Confusions That Cost Points

PAIR	HOW TO KEEP THEM STRAIGHT
d_i sign vs image reality	Positive d_i means real, negative means virtual. The sign is the answer, not an error to correct.
m sign vs image size	The sign of m gives orientation only: negative is inverted, positive is upright. Size comes from $ m $.
Angle from the normal vs from the surface	Snell's law and the law of reflection both use the normal. Convert a surface angle by subtracting from 90° .
TIR direction vs TIR angle	High-to-low n is necessary but not enough. The incident angle must also exceed θ_c .
Converging device vs guaranteed real image	A converging lens or concave mirror makes a virtual image when the object sits inside the focal length. Check d_o against f .

Practice Questions

Original questions written for this guide in the style of the AP exam. Answers and explanations are on the next pages, so complete the questions before checking them.

1. A ray of light in air ($n = 1.00$) strikes a glass surface ($n = 1.50$). The angle of incidence is 30° , measured from the normal. What is the angle of refraction?

1. 19.5° , measured from the normal
2. 30° , measured from the normal
3. 48.6° , measured from the normal
4. 19.5° , measured from the surface

2. Which of the following situations can produce total internal reflection?

1. Light travels from glass ($n = 1.52$) to water ($n = 1.33$) with an angle of incidence of 30°
2. Light travels from water ($n = 1.33$) to air ($n = 1.00$) with an angle of incidence of 30°
3. Light travels from water ($n = 1.33$) to air ($n = 1.00$) with an angle of incidence of 60°
4. Light travels from air ($n = 1.00$) to water ($n = 1.33$) with an angle of incidence of 60°

3. A converging lens has a focal length of $+20$ cm. An object is placed 30 cm from the lens. What is the image distance, and what kind of image forms?

1. 12 cm from the lens; real, inverted, and reduced
2. 60 cm from the lens on the same side as the object; virtual and upright
3. 60 cm from the lens on the opposite side from the object; real, upright, and enlarged
4. 60 cm from the lens on the opposite side from the object; real, inverted, and enlarged

4. A concave mirror forms an image with an image distance of -12 cm. What does the negative sign tell you?

1. The calculation must be wrong, because image distances are always positive
2. The image is virtual and located 12 cm behind the mirror
3. The image is real and located 12 cm in front of the mirror
4. The image is inverted

5. A diverging lens has a focal length of -15 cm. An object is placed 30 cm from the lens. What are the image distance and the magnification?

1. $d_i = -15$ cm, $m = -0.5$; the image is virtual, inverted, and reduced
2. $d_i = -7.5$ cm, $m = +0.25$; the image is virtual, upright, and reduced
3. $d_i = -15$ cm, $m = +0.5$; the image is virtual, upright, and reduced
4. $d_i = +30$ cm, $m = -1$; the image is real, inverted, and the same size as the object

6. An object is placed in front of a convex mirror. Which statement about the image must be true?

1. The image is real
2. The image is virtual, upright, and smaller than the object
3. The image is inverted
4. The image distance is positive

7. In a ray diagram for a converging lens, one principal ray starts out parallel to the principal axis. After passing through the lens, this ray

1. continues parallel to the principal axis
2. passes through the center of the lens
3. reflects back toward the object
4. passes through the focal point on the opposite side of the lens

8. White light shines through a glass prism and spreads into a spectrum. Which color is deviated the most, and why?

1. Violet, because violet light experiences a slightly larger index of refraction in glass
2. Red, because red light has the highest frequency of the visible colors
3. All colors deviate by the same amount, because Snell's law uses a single index for glass
4. Violet, because violet light travels faster through glass than red light does

Answer Key

- 1. A.** From Snell's law, $\sin\theta_2 = (n_1 / n_2) \sin\theta_1 = (1.00 / 1.50)(\sin 30^\circ) = (0.6667)(0.5) = 0.3333$, so $\theta_2 = 19.5^\circ$ from the normal. B assumes the light does not bend at all. C inverts the index ratio, computing $(1.50 / 1.00)(\sin 30^\circ) = 0.75$, which gives 48.6° ; that ratio would bend the ray away from the normal even though the light slowed down. D confuses the reference line: the computed 19.5° is measured from the normal, and the angle from the surface would be $90^\circ - 19.5^\circ = 70.5^\circ$.
- 2. C.** Total internal reflection needs light going from higher n to lower n with an incident angle above the critical angle. For water to air, $\sin\theta_c = 1.00 / 1.33 = 0.7519$, so $\theta_c = 48.8^\circ$, and 60° exceeds it. D fails the direction condition: going from air to water, the refracted ray always exists. A has the right direction but the wrong angle: for glass to water, $\sin\theta_c = 1.33 / 1.52 = 0.875$, so $\theta_c = 61.0^\circ$, and 30° is below it. B has the right direction but 30° is below the water-to-air critical angle of 48.8° .
- 3. D.** From $1 / d_i = 1 / f - 1 / d_o = 1 / 20 - 1 / 30 = 3 / 60 - 2 / 60 = 1 / 60$, $d_i = +60$ cm. The positive sign means a real image on the opposite side from the object. The magnification is $m = -60 / 30 = -2$, so the image is inverted and enlarged. A adds $1 / d_o$ instead of subtracting it, giving $1 / 20 + 1 / 30 = 5 / 60$ and $d_i = 12$ cm. B misreads the positive image distance as a virtual image on the object's side. C forgets the minus sign in $m = -d_i / d_o$ and calls the image upright.
- 4. B.** For a mirror, a negative image distance means a virtual image behind the mirror surface, 12 cm back. C treats the minus sign as meaningless and describes a real image. D confuses the meaning of the signs: the sign of d_i tells you real or virtual, while orientation comes from the sign of m (here $m = -(-12) / d_o$ is positive, so the image is upright). A is the reflex to "fix" a negative answer; a negative d_i is a valid result that describes a virtual image.

5. C. The focal length is negative for a diverging lens: $1/d_i = 1/f - 1/d_o = -1/15 - 1/30 = -2/60 - 2/60 = -4/60$, so $d_i = -15$ cm. Then $m = -(-15)/30 = +0.5$, giving a virtual, upright, reduced image. D forgets that f is negative and uses $+15$ cm, which gives $d_i = +30$ cm and a real image that a diverging lens can never form. A gets d_i right but drops the minus sign in the magnification formula, calling the image inverted. B substitutes the focal length in place of the object distance, computing $-1/15 - 1/15 = -2/15$.

6. B. A convex mirror has a negative focal length, so with a positive object distance the image distance always comes out negative: the image is virtual, behind the mirror. The magnification $m = -d_i/d_o$ is then positive (upright) and less than 1 (reduced). A is impossible; a convex mirror never forms a real image. C contradicts the positive magnification. D contradicts the sign convention: d_i is negative for every convex mirror image.

7. D. A ray parallel to the principal axis is one of the principal rays for a converging lens, and it refracts through the focal point on the far side. A describes no bending at all. B describes a different principal ray, the one through the center of the lens. C confuses lenses with mirrors; lenses refract, they do not reflect the ray back.

8. A. Dispersion happens because the index of refraction depends on wavelength: shorter wavelengths see a slightly larger n in glass, so violet bends the most. B gets the frequency order backward; red has the lowest frequency of the visible colors. C ignores the wavelength dependence of n that causes dispersion in the first place. D reverses the physics: the larger index for violet means it travels slower through the glass, not faster.

When you check your answers, note which distinction each miss came from. Make a flashcard for that distinction and drill it spaced out over the next few days instead of rereading the whole section. If you missed one of these questions, the same distinction is worth practicing again in Rycal, where the Geometric Optics deck has flashcards for it and more practice questions use the same kinds of traps.

One-Page Recall Check

Say each answer out loud before you look back, and mark the ones you cannot finish. Anything you cannot say out loud yet belongs in your flashcard deck. In Rycal, add those items to the Geometric Optics deck and let spaced review bring them back over the next few days.

- State the law of reflection and explain how the angles are measured.
- Describe the image formed by a plane mirror: type, orientation, size, and location.
- Write Snell's law and define the index of refraction.
- Work the air-to-water refraction example from scratch: $n_1 = 1.00$, $n_2 = 1.33$, $\theta_1 = 40^\circ$, and find θ_2 .
- State both conditions for total internal reflection and write the critical angle formula.
- Compute the critical angle for light going from glass ($n = 1.52$) to air.
- Explain dispersion and say which visible color bends the most in glass.
- Write the thin lens equation and the magnification equation, including the minus sign.
- State the full AP sign convention for f , d_o , d_i , and m .
- Work the converging lens example from scratch: $f = +10$ cm, $d_o = 30$ cm. Find d_i and m and describe the image.
- Explain what changes when the object is placed inside the focal length of a converging lens.
- Describe the image a diverging lens always forms and the image a convex mirror always forms.
- Work the concave mirror example from scratch: $f = +15$ cm, $d_o = 45$ cm.
- List the three principal rays for a converging lens and the three for a concave mirror.

Where to go next. Turn every missed item above into flashcards and drill them spaced out over several days rather than in one sitting. In Rycal, open the Geometric Optics deck under AP Physics 2. The deck covers the terms in this guide, and its practice questions target the same traps named here. If you have a test date, add it in the Test Planner. You can also start your next review with a Brain Dump, then check what you missed against this guide.

Key terms for this unit

Law of reflection, Angle of incidence, Normal, Plane mirror, Virtual image, Real image, Index of refraction, Snell's law, Total internal reflection, Critical angle, Dispersion, Converging lens, Diverging lens, Focal point, Focal length, Thin lens equation, Magnification, Sign convention, Concave mirror, Convex mirror, Principal ray.

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