Nature of Light

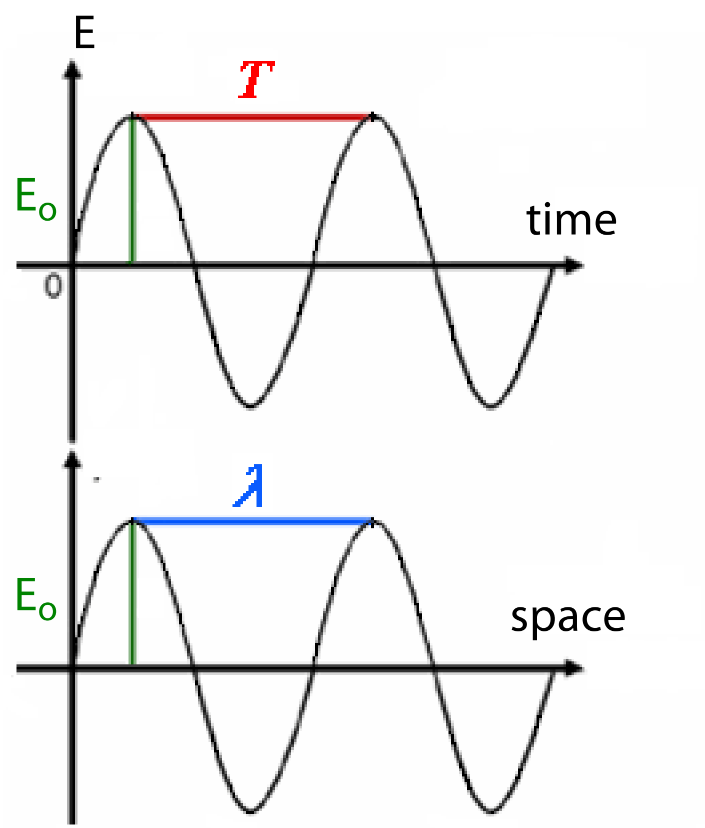
Light can be described as a traveling electromagnetic wave

$$E(r, t) = E_o \sin(k \cdot x - \omega \cdot t + \phi)$$

$\omega = 2\pi \cdot f$ angular frequency

$f = 1 / T$ frequency

$k = 2\pi / \lambda$ wave number



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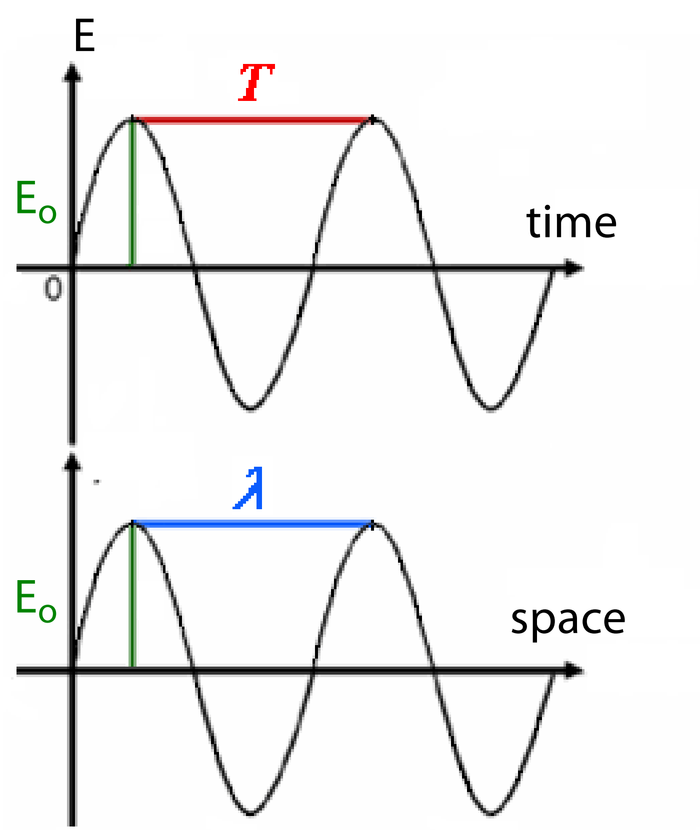
which is a solution to the wave equation:

$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}$$



c = speed of light in vacuum

$$c = f \cdot \lambda = \omega / k$$

$$I = \text{Intensity} = (c \cdot \varepsilon_o \cdot n / 2) \cdot |E|^2$$

Nature of Light

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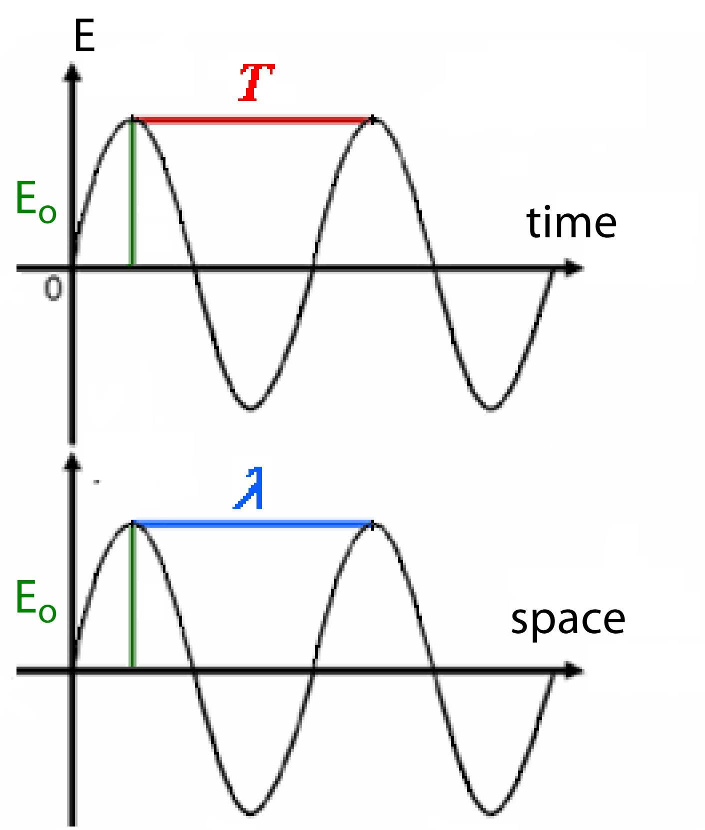
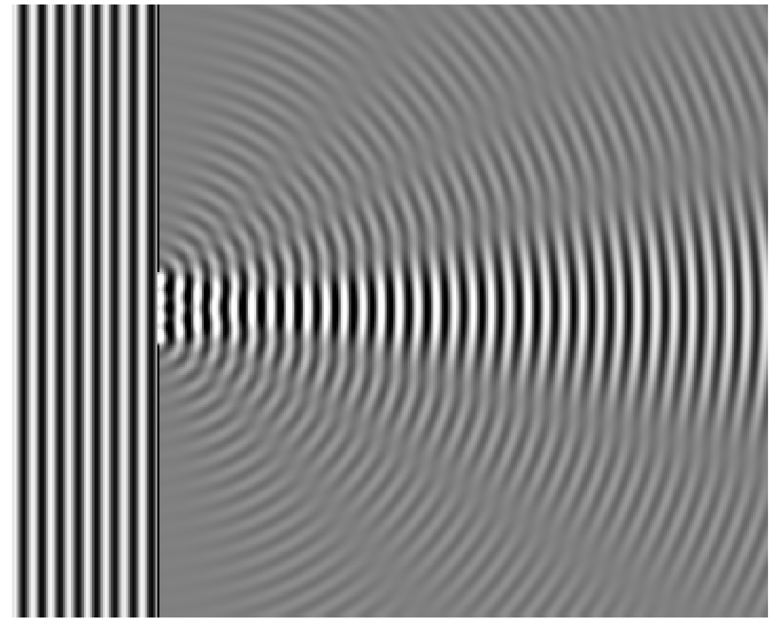
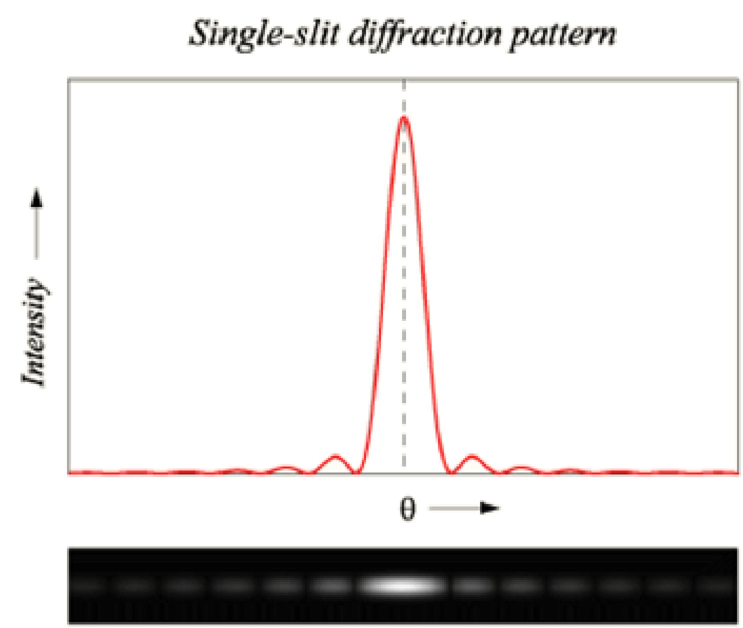
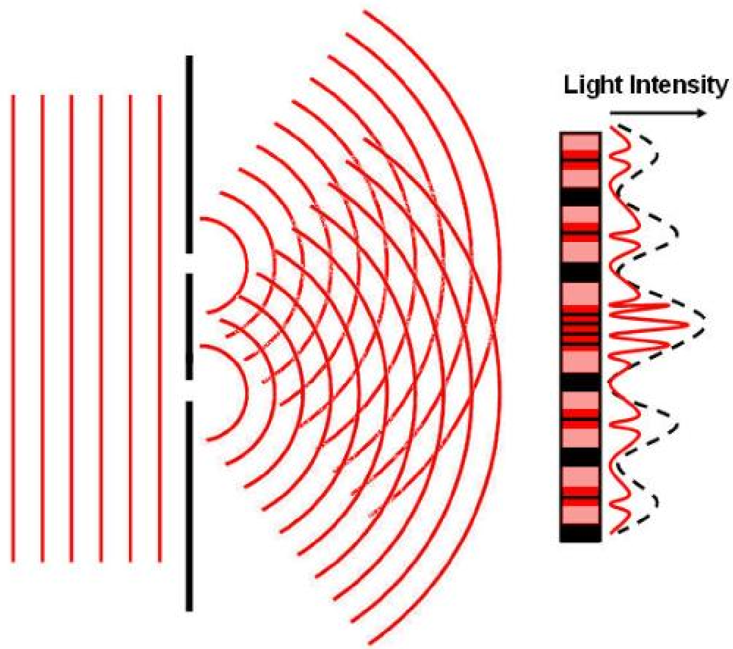




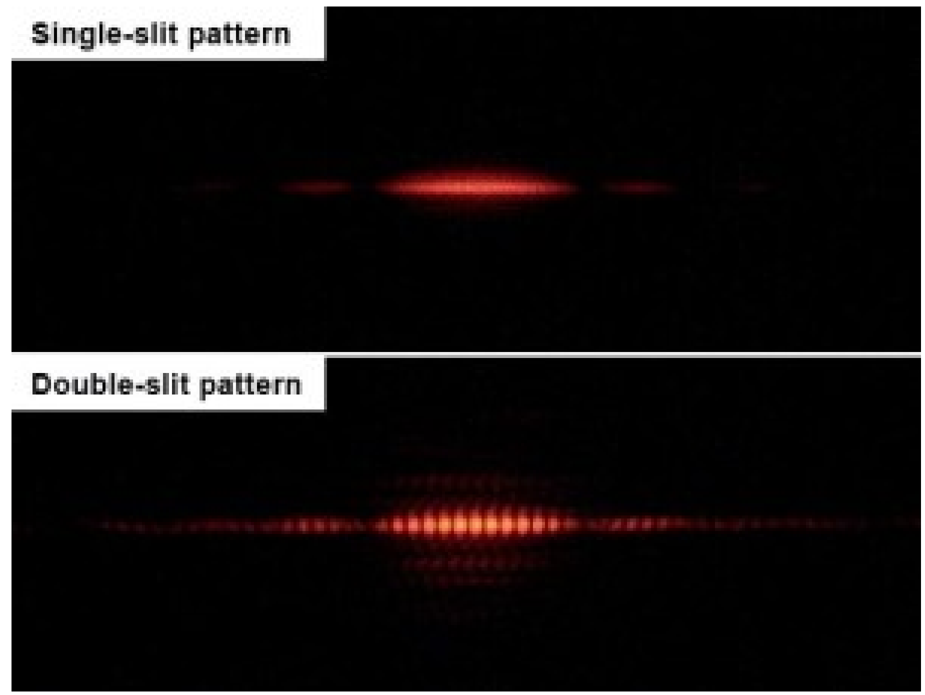


Nature of Light

Light can be described as an traveling electromagnetic wave

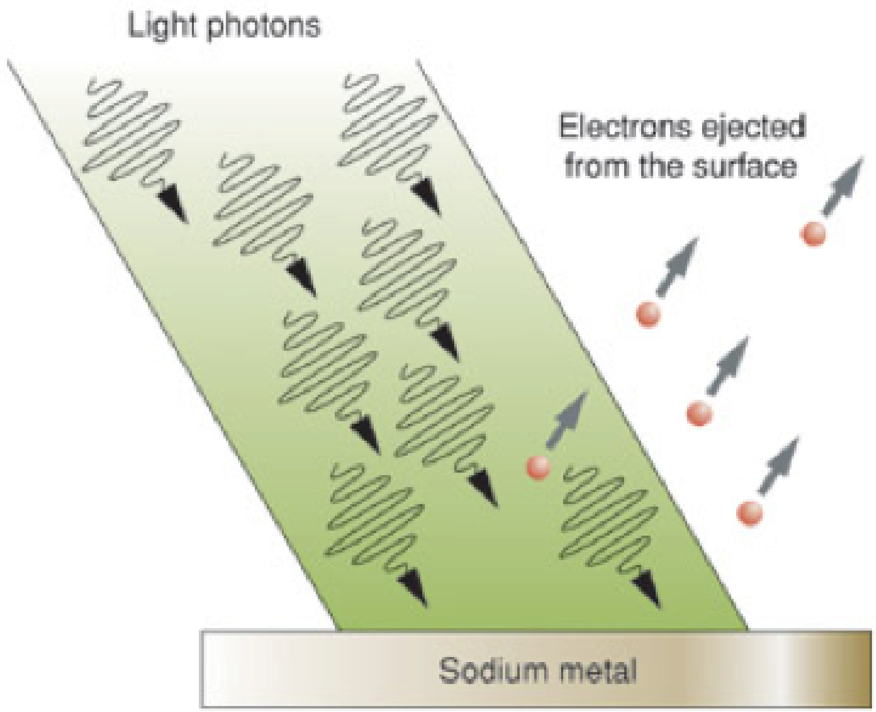


Double Slit
Diffraction Experiment



Nature of Light

Light can be described as discrete particles (photons)



Photoelectric Effect

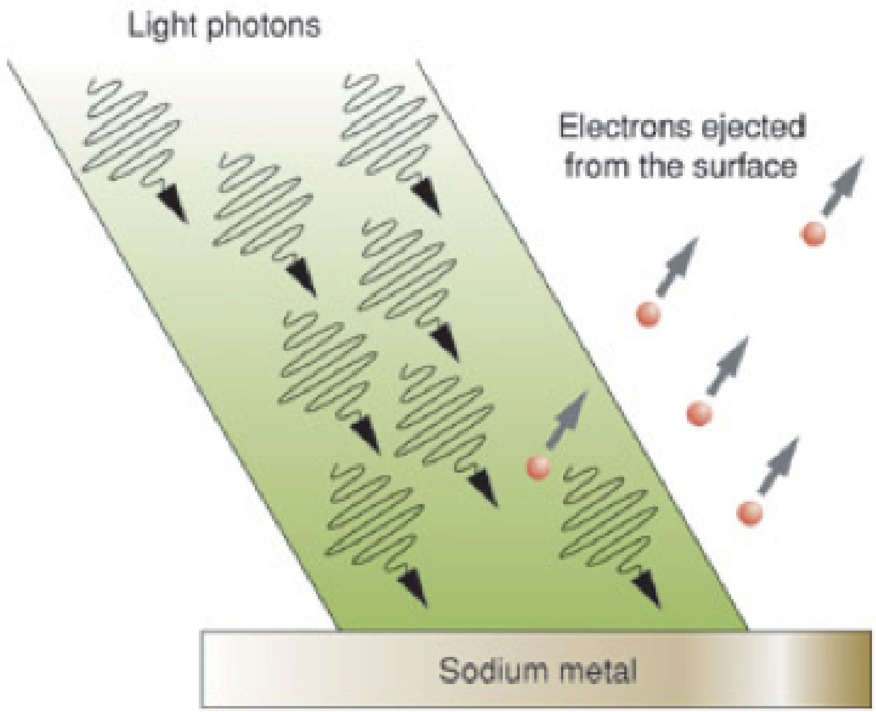
Albert Einstein, 1905

(Nobel Prize 1921)

(Image taken from LLNL website)

Nature of Light

Wave - Particle Duality



Photoelectric Effect
Albert Einstein, 1905
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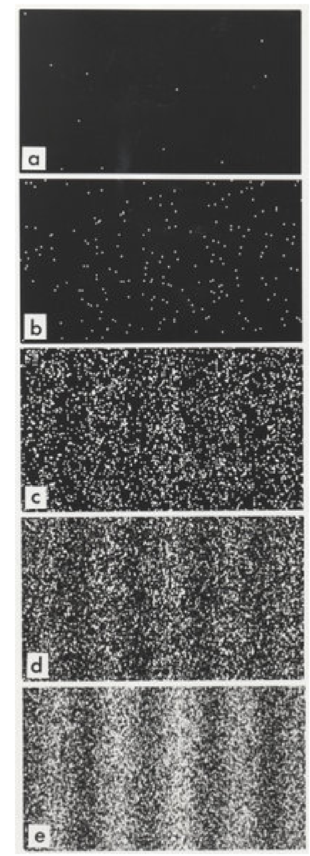
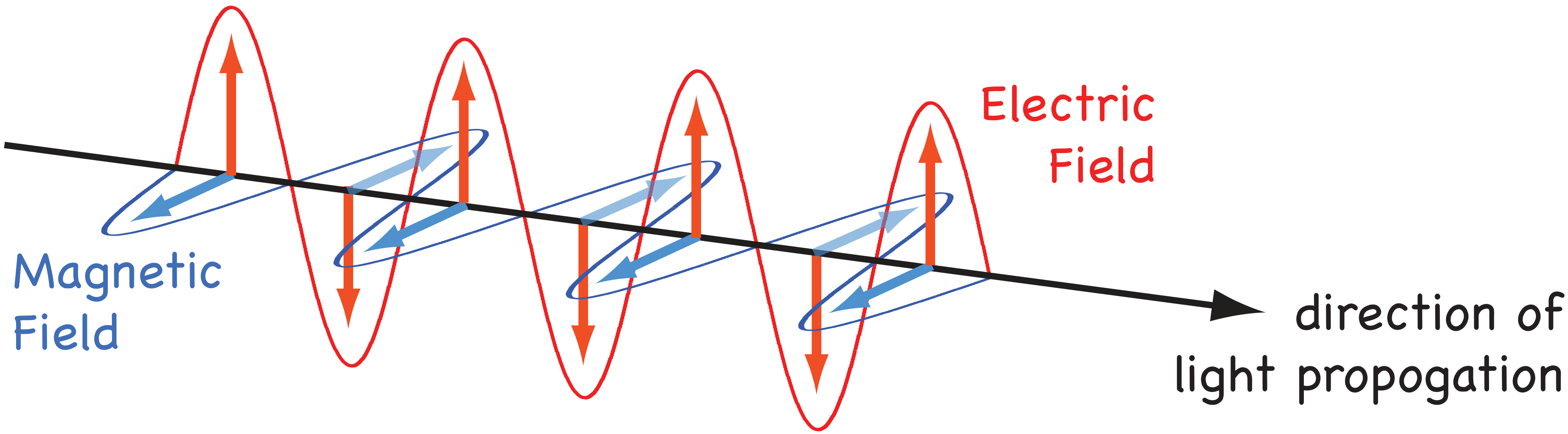


Young's
Double Slit Experiment

Light is an Electromagnetic Field

We will discuss electromagnetic fields
in more detail when we cover Ch. 24



For now, the important point is that we can treat light as a transverse wave : as the light propogates forward, the electric field oscillates perpendicular to that direction of oscillation.

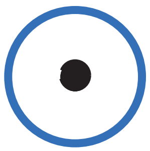
We will deal only with the electric field and completely ignore the magnetic field for now.

Huygen's Principle (from Ch.25)

A conceptual way to look at wave propogation

Huygen's Principle (from Ch.25)

A conceptual way to look at wave propogation



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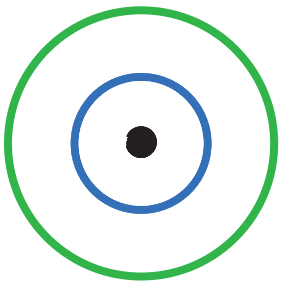

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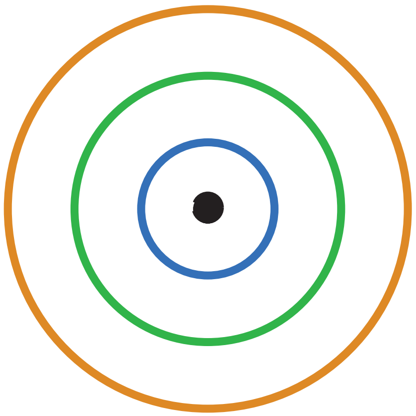

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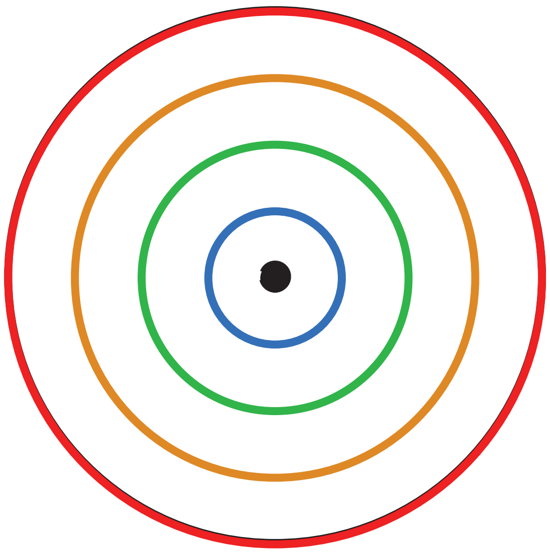

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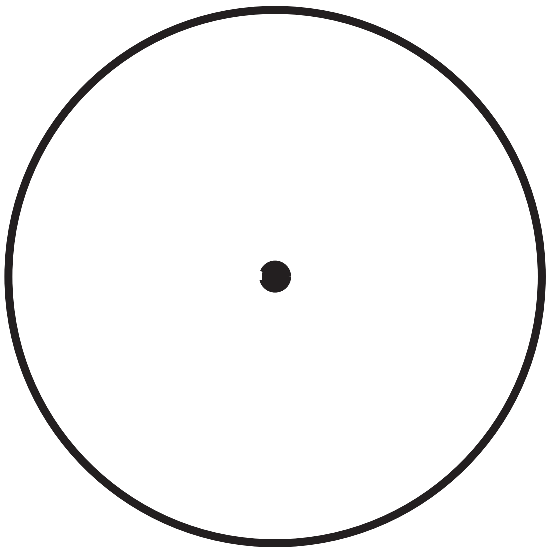

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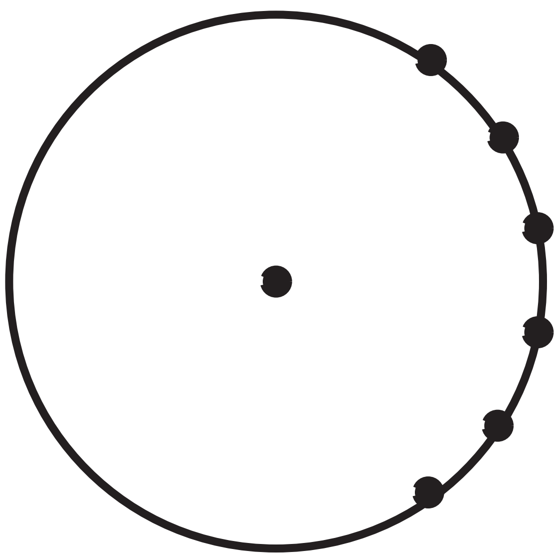

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Every point on a particular wavefront can be considered a "new source" of small spherical "wavelets".

Huygen's Principle (from Ch.25)

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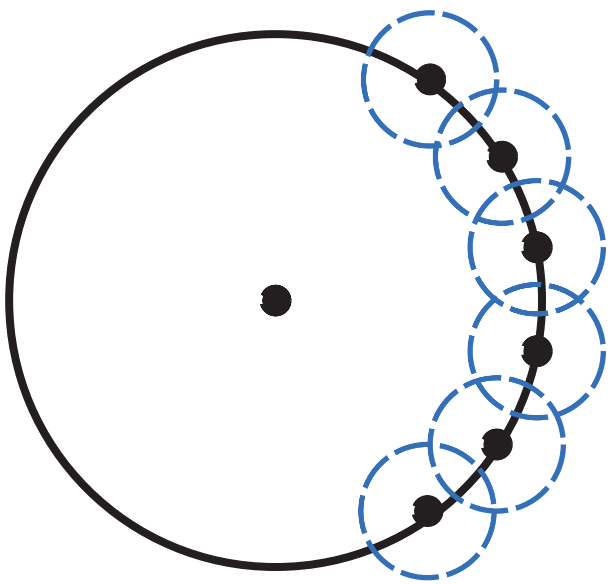

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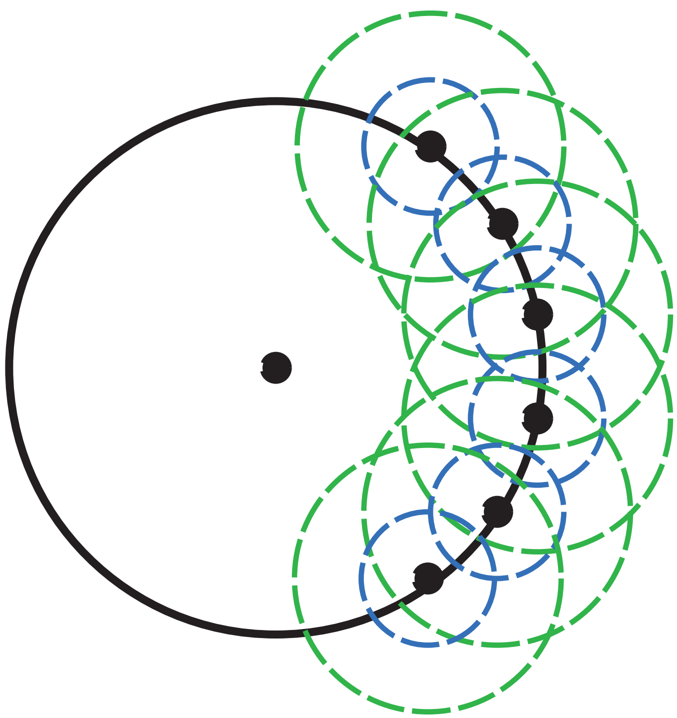

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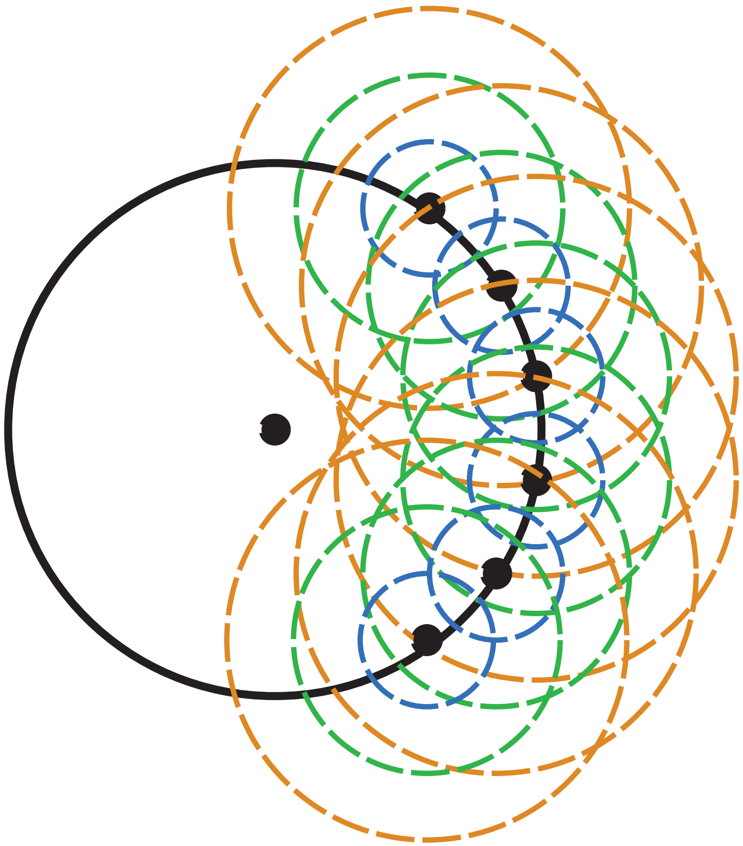

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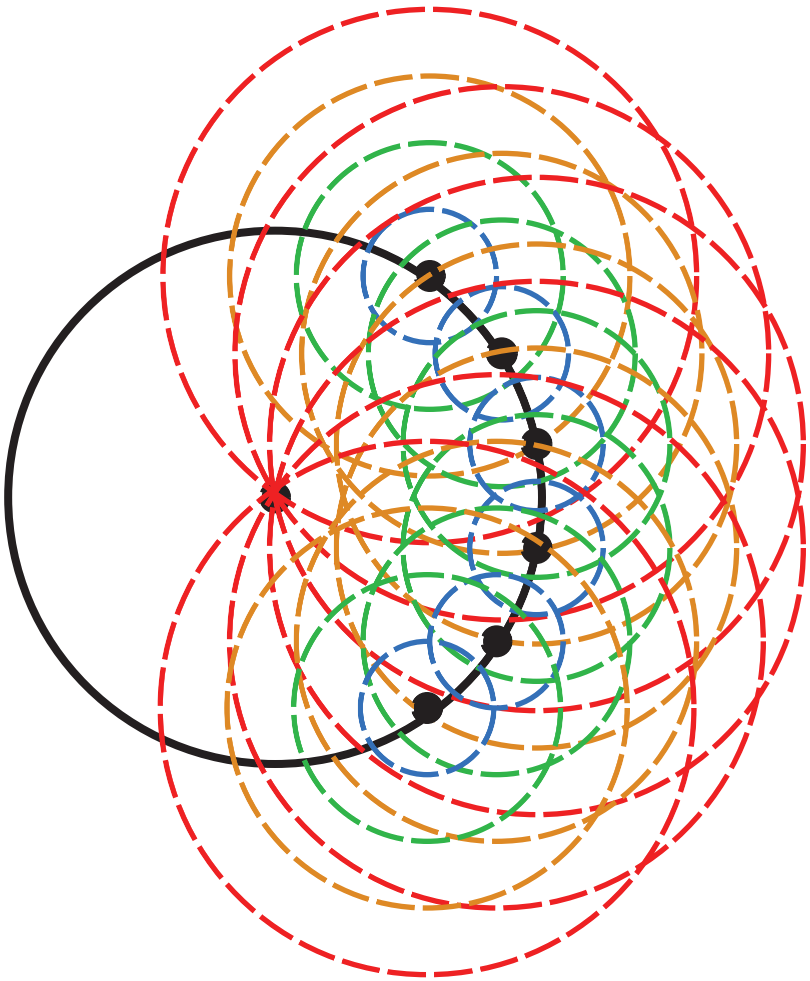

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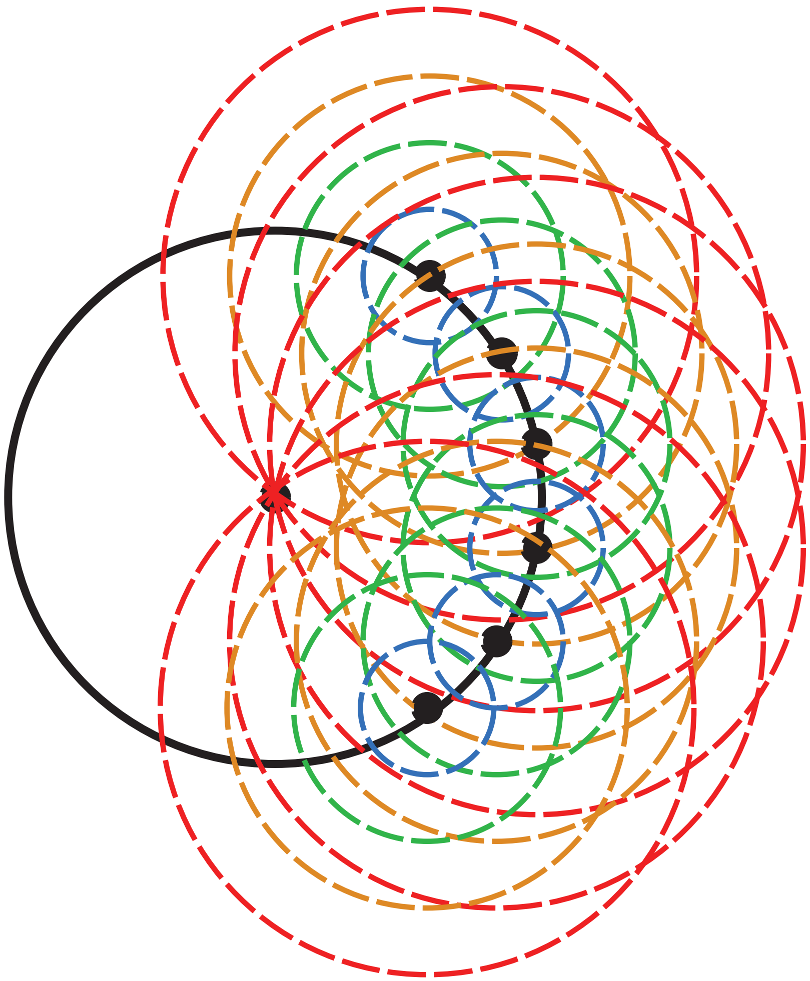

Huygen's Principle:

Every point on a particular wavefront can be considered a "new source" of small spherical "wavelets".

As the wavelets propogate outward, the curve that runs tangent to these wavelets defines the new wavefront.

Huygen's Principle (from Ch.25)

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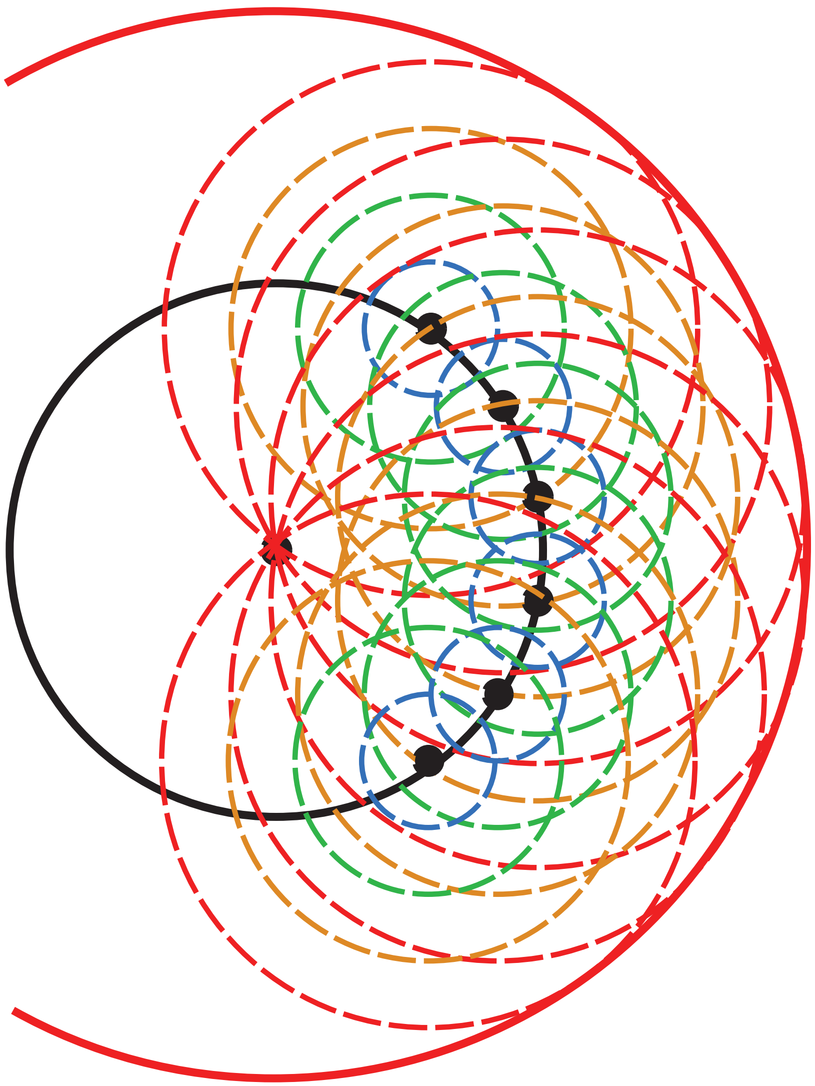

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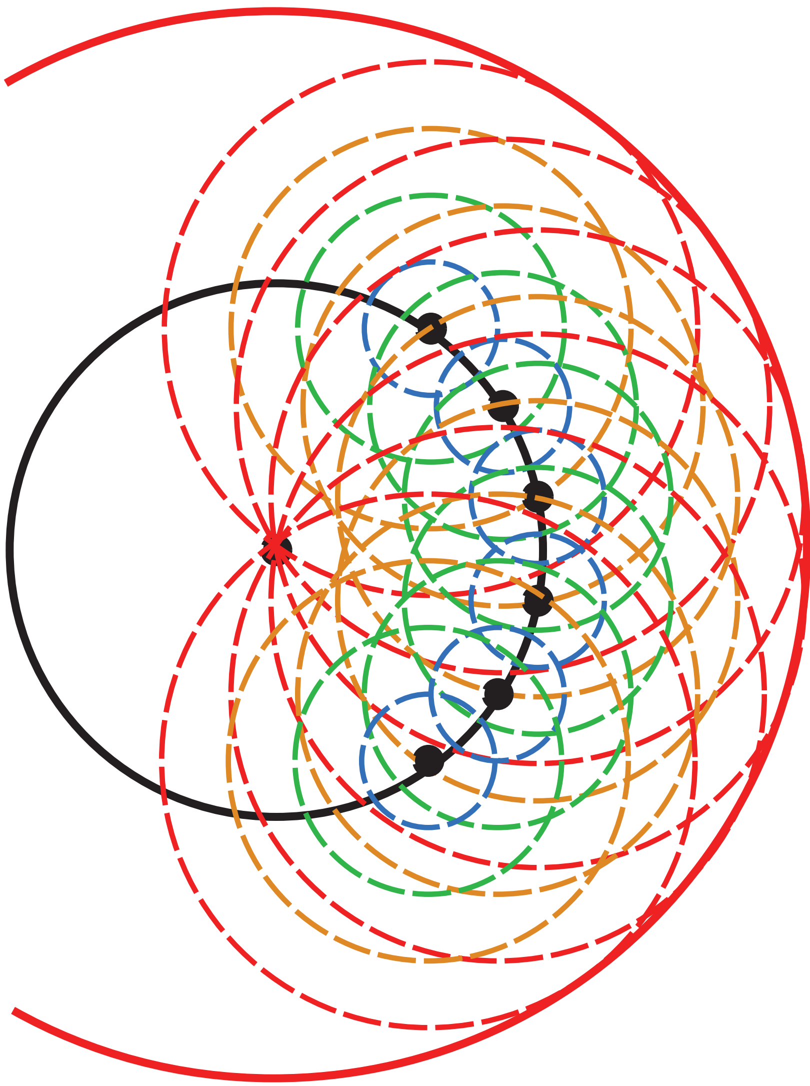

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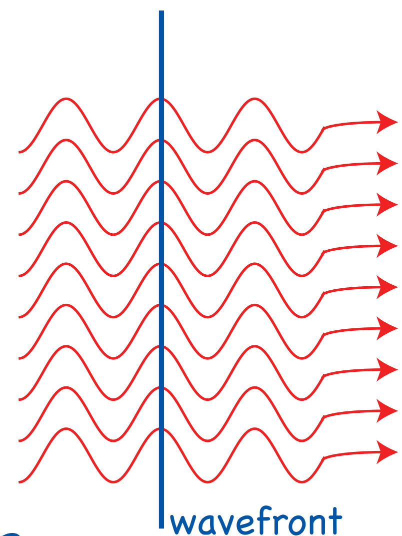

Note : A wavefront is defined by the line (or curve) that connects the points of constant phase in a wave.

example : a line through the peaks of a set of sine waves

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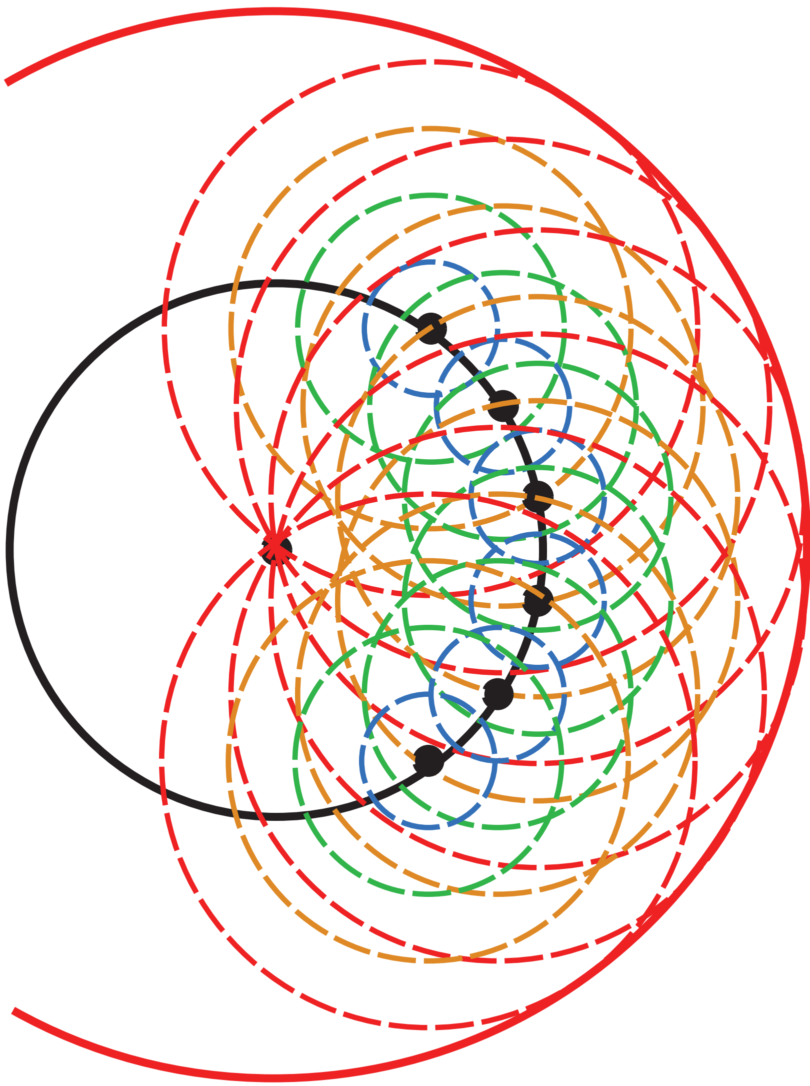
A conceptual way to look at wave propogation



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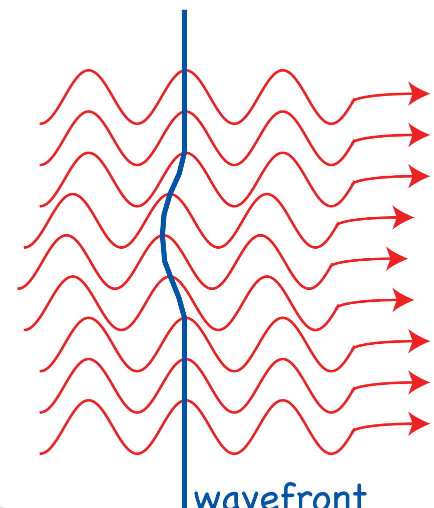
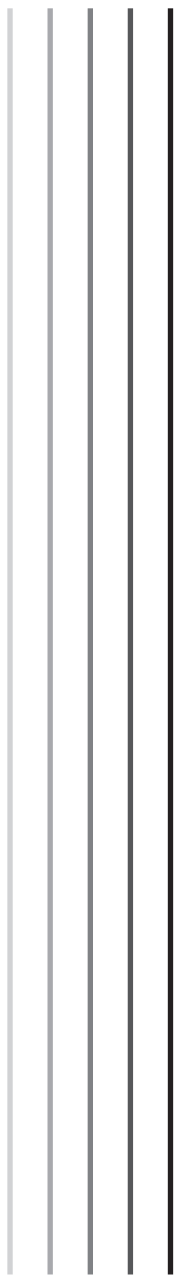


example : a line through the peaks of a set of sine waves

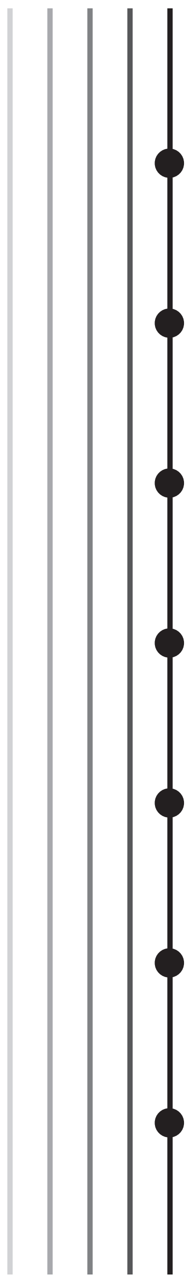
This may seem like a lot of effort to get a trivial result, but this same method will allows us to examine situations like diffraction andrefraction at an interface (Ch 25)

Huygen's Principle (from Ch.25)



Consider if we (somehow) have a wavefront that is completely straight? (We call this an "infinite plane wave" because in 3D space the straight wavefront is a giant flat sheet.

Huygen's Principle (from Ch.25)



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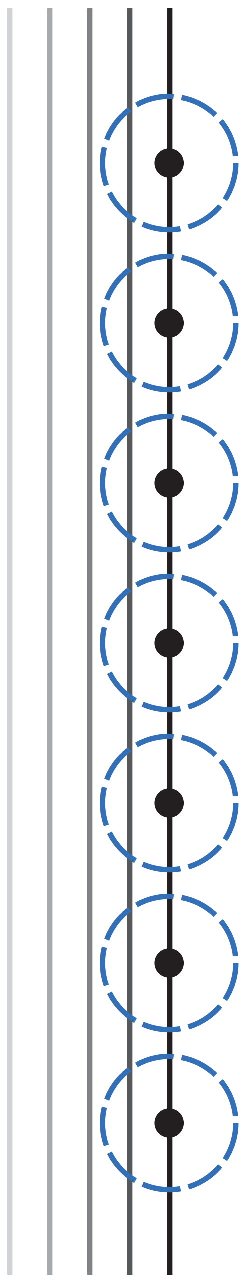

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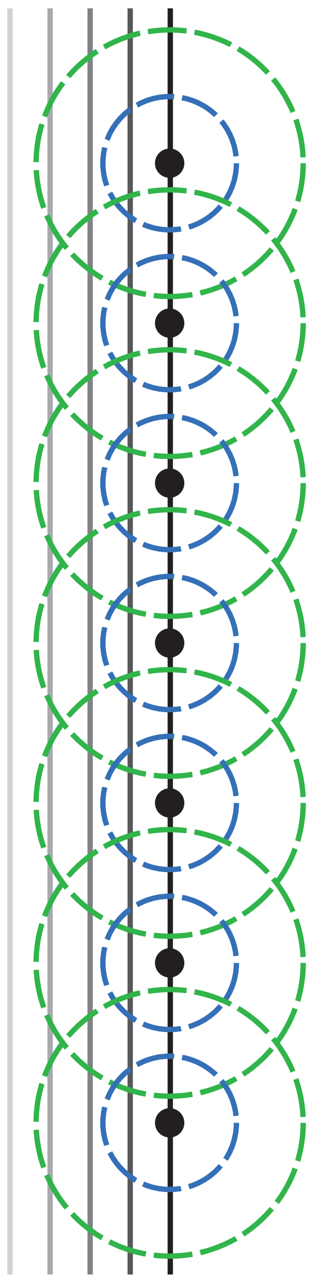

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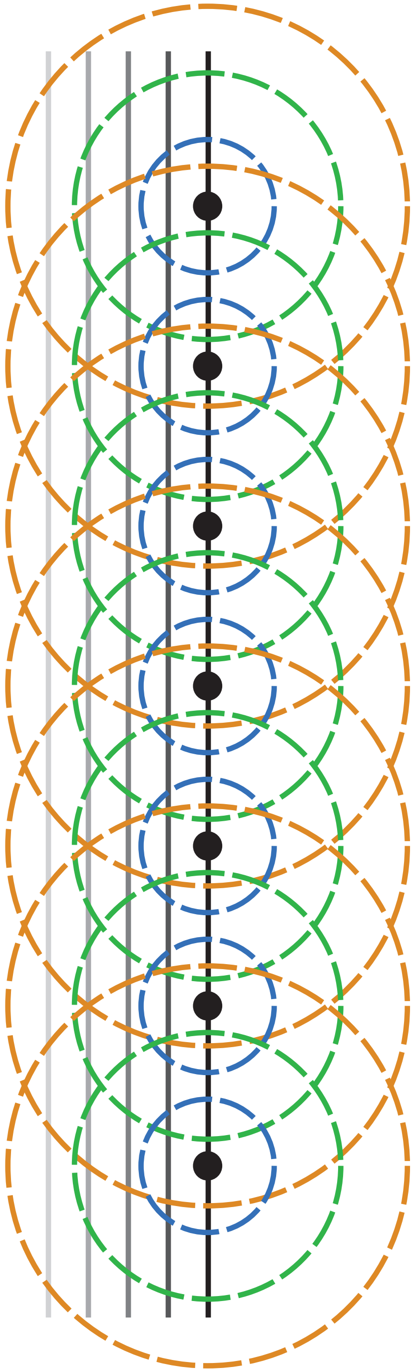

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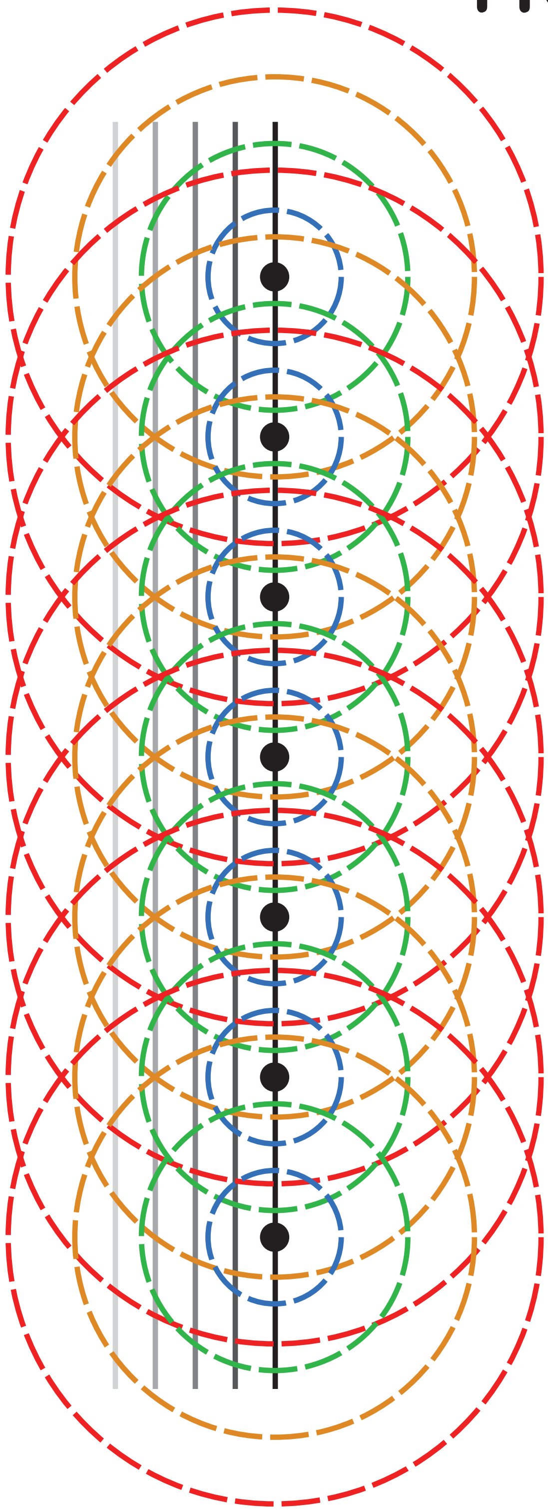

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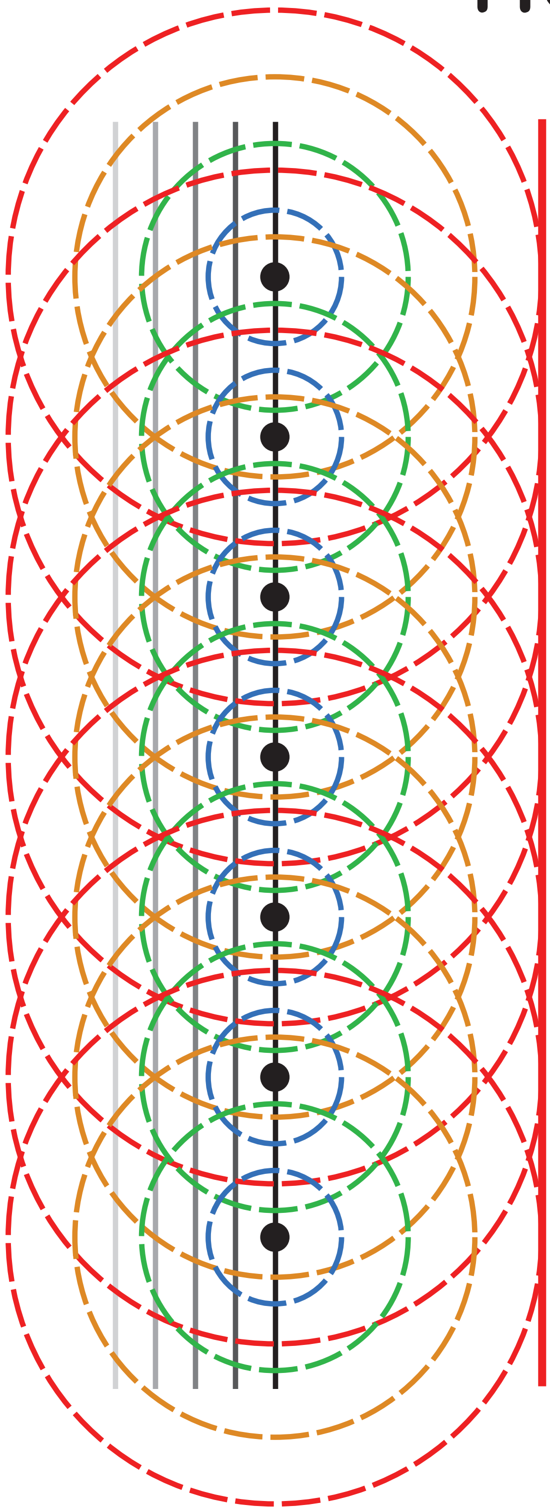

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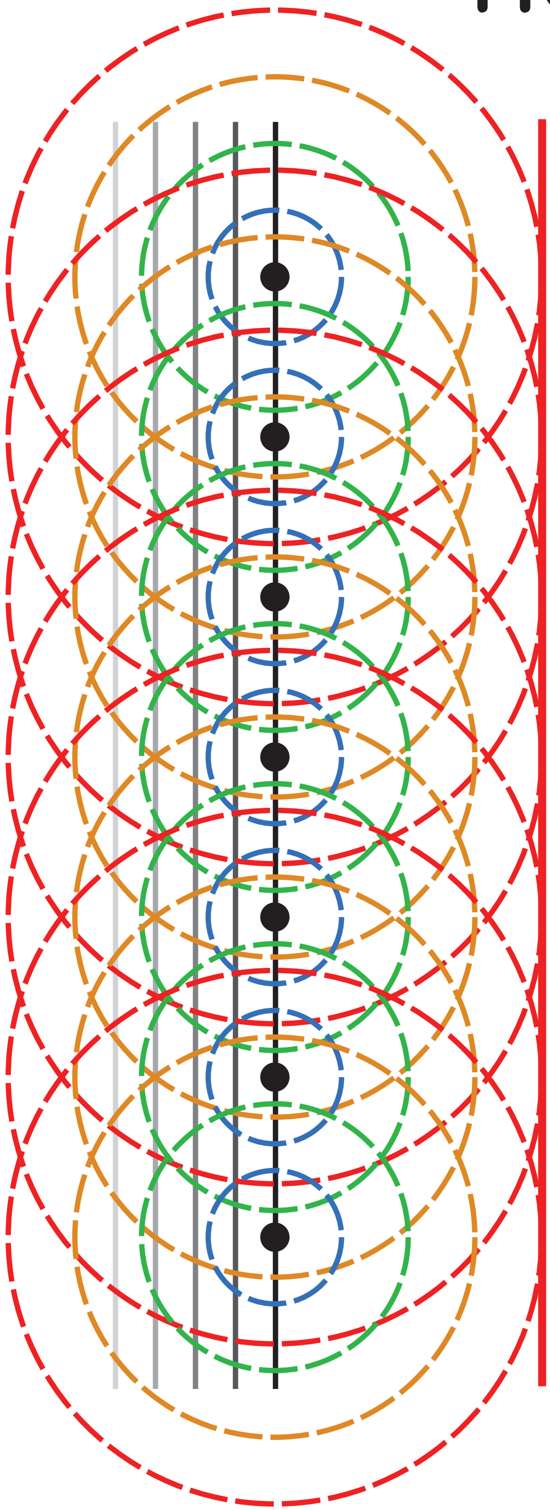

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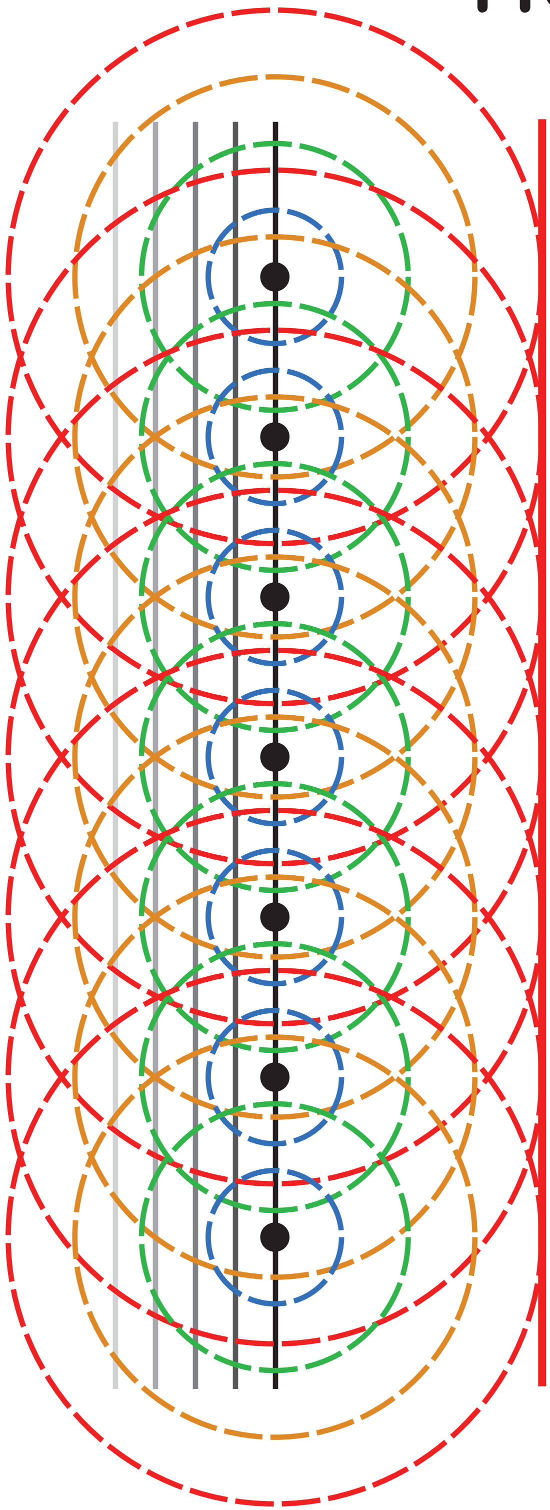
The tangent to the Huygen wavelets traces out another infinite plane wavefront.

Huygen's Principle (from Ch.25)



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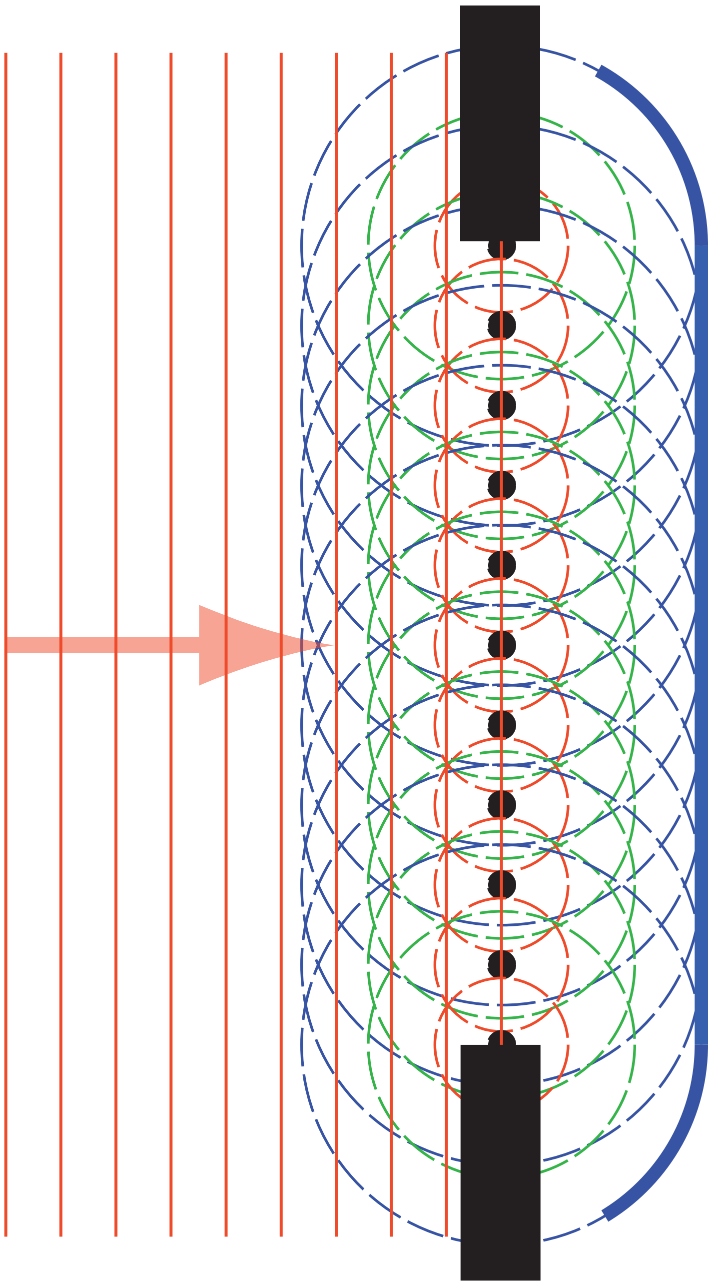
The tangent to the Huygen wavelets traces out another infinite plane wavefront.

How do we get an "infinite plane wave" to start with? Well, in reality we can never really get a truly infinite plane wave, but if we look at the light from a distant star, the radius of curvature of the wavefront is so large, that over any small area (say, this room), the wavefront appears flat, and seems to extend to infinity

Diffraction



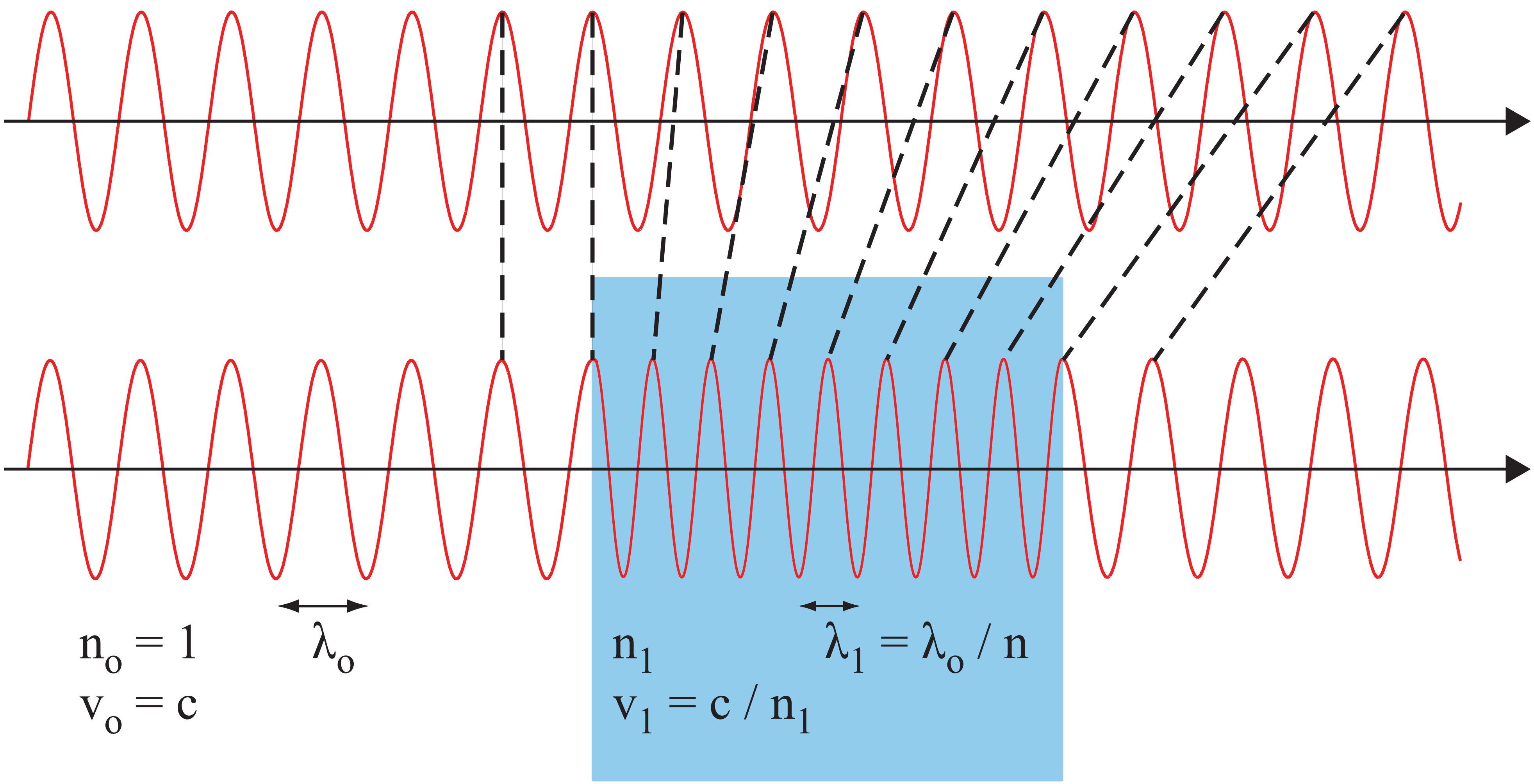
When we pass an [infinite] wave past a barrier (for example, through a hole) we break the symmetry of the Huygen wavelets near the edges.

As a result, waves diffract (bend) as they pass through small openings.

How small is small?
Diffraction becomes appreciable when the opening get to be approximately the same size or smaller than a wavelength of the wave passing through it.

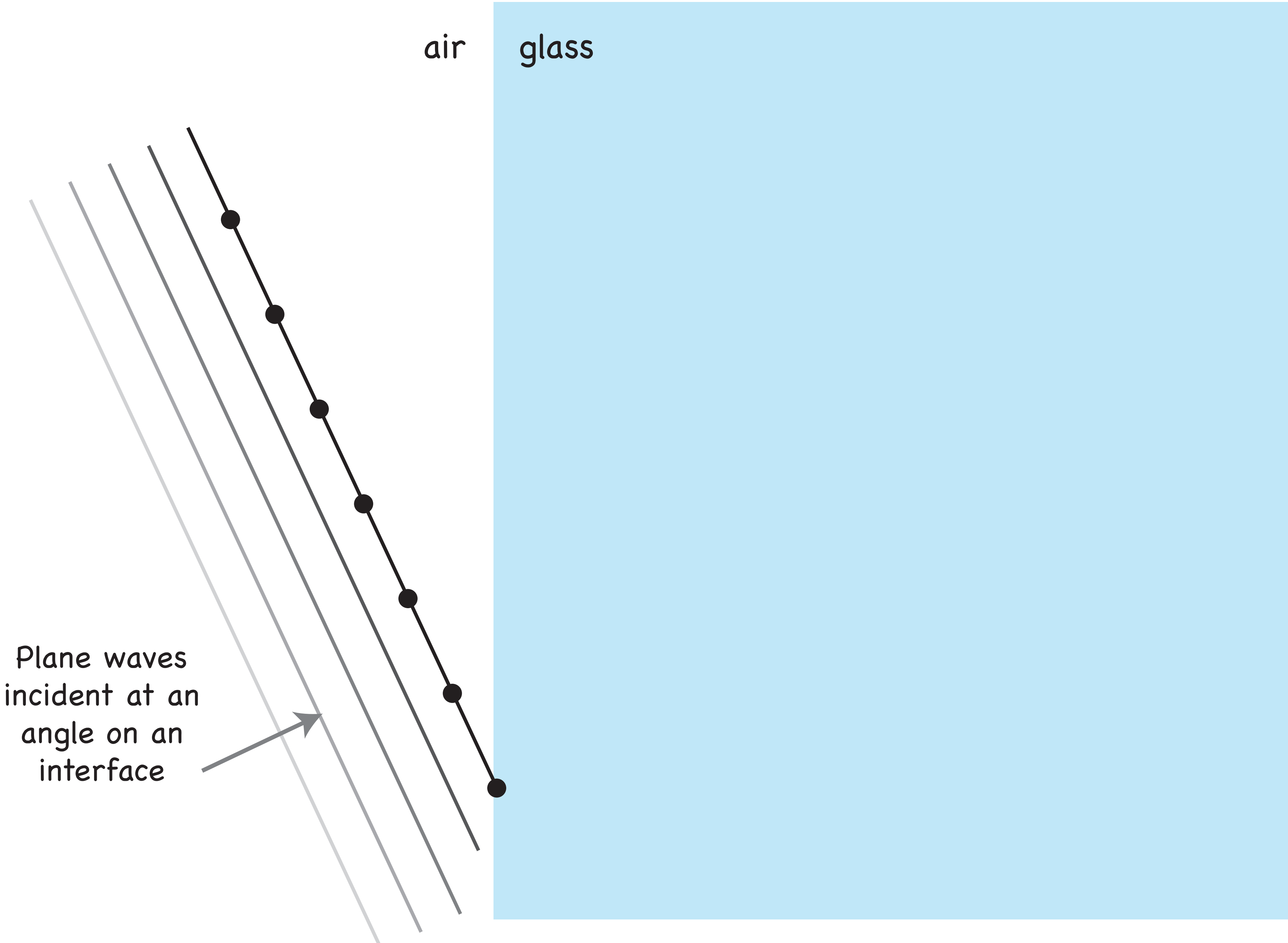
Index of Refraction

Light travels slower in materials with higher refractive index



$$\text{Index of Refraction : } n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v}$$

Huygen's Principle



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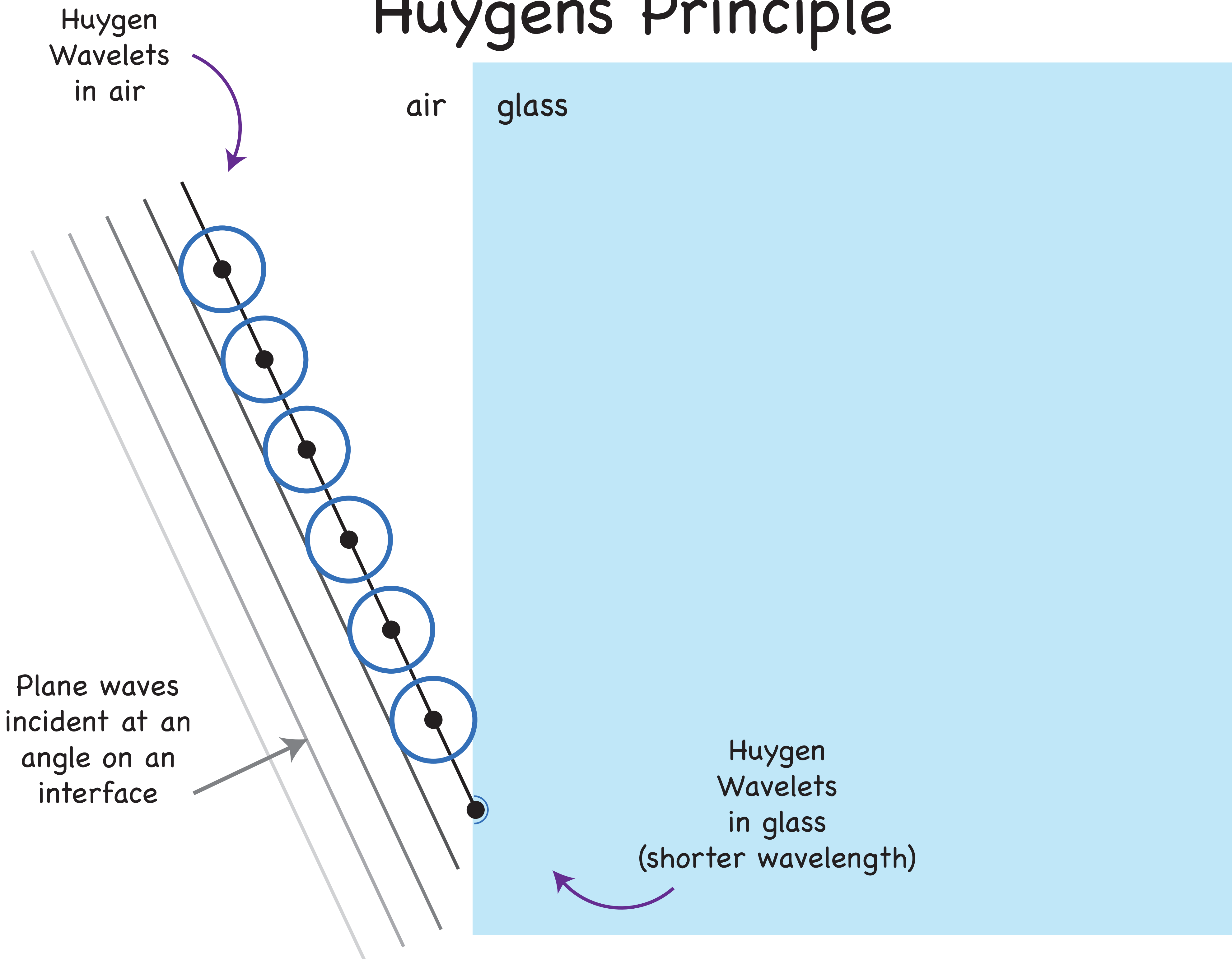

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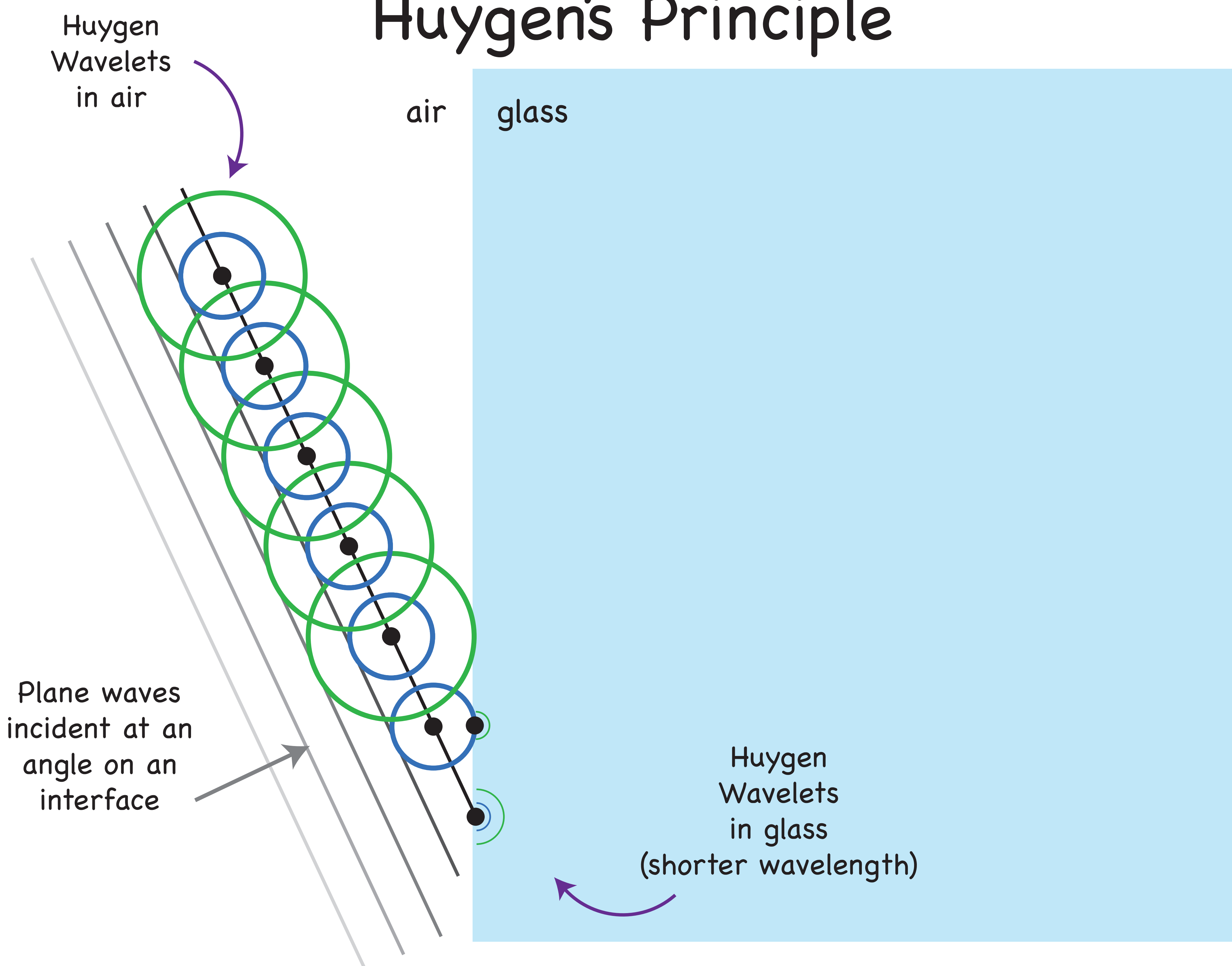

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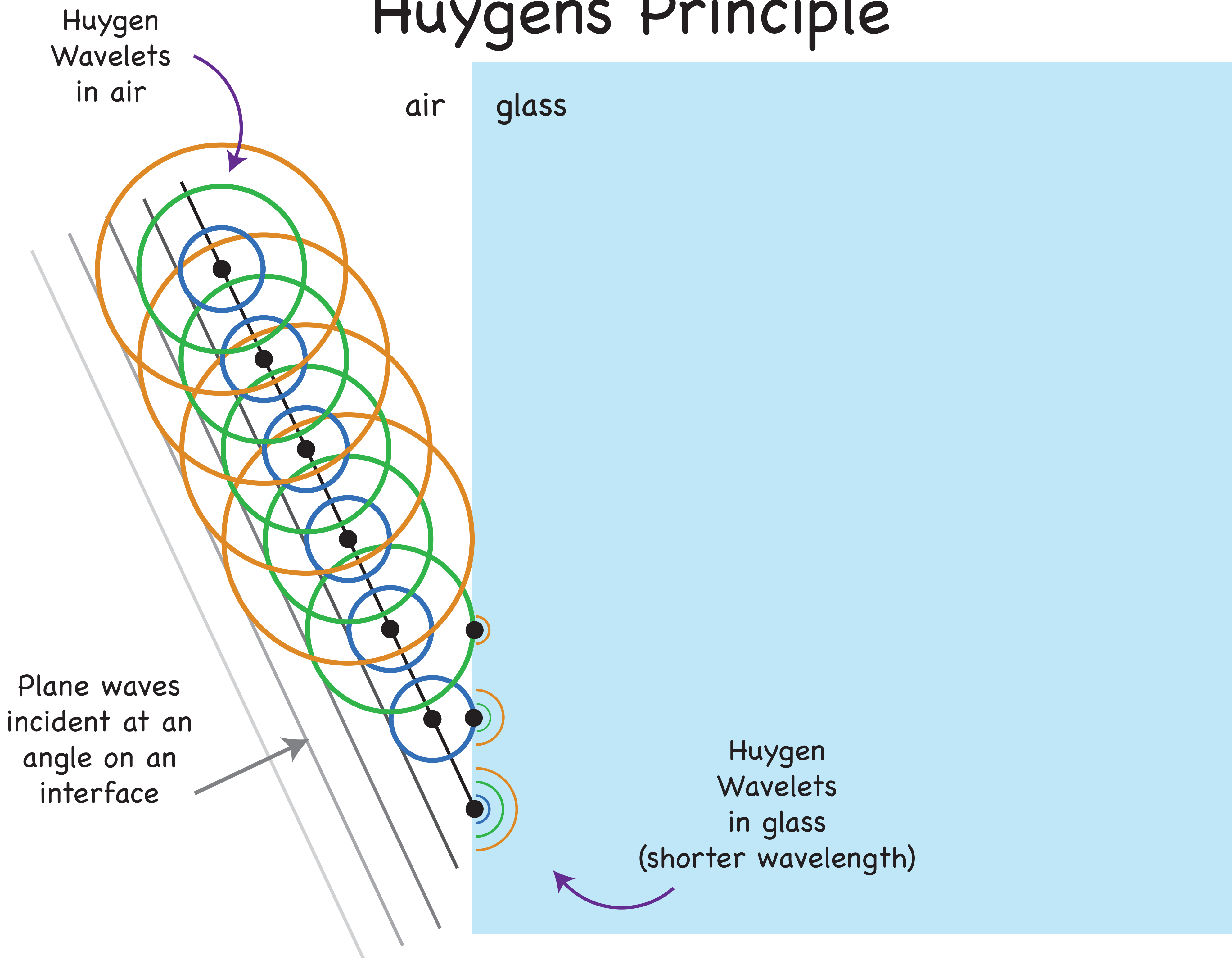

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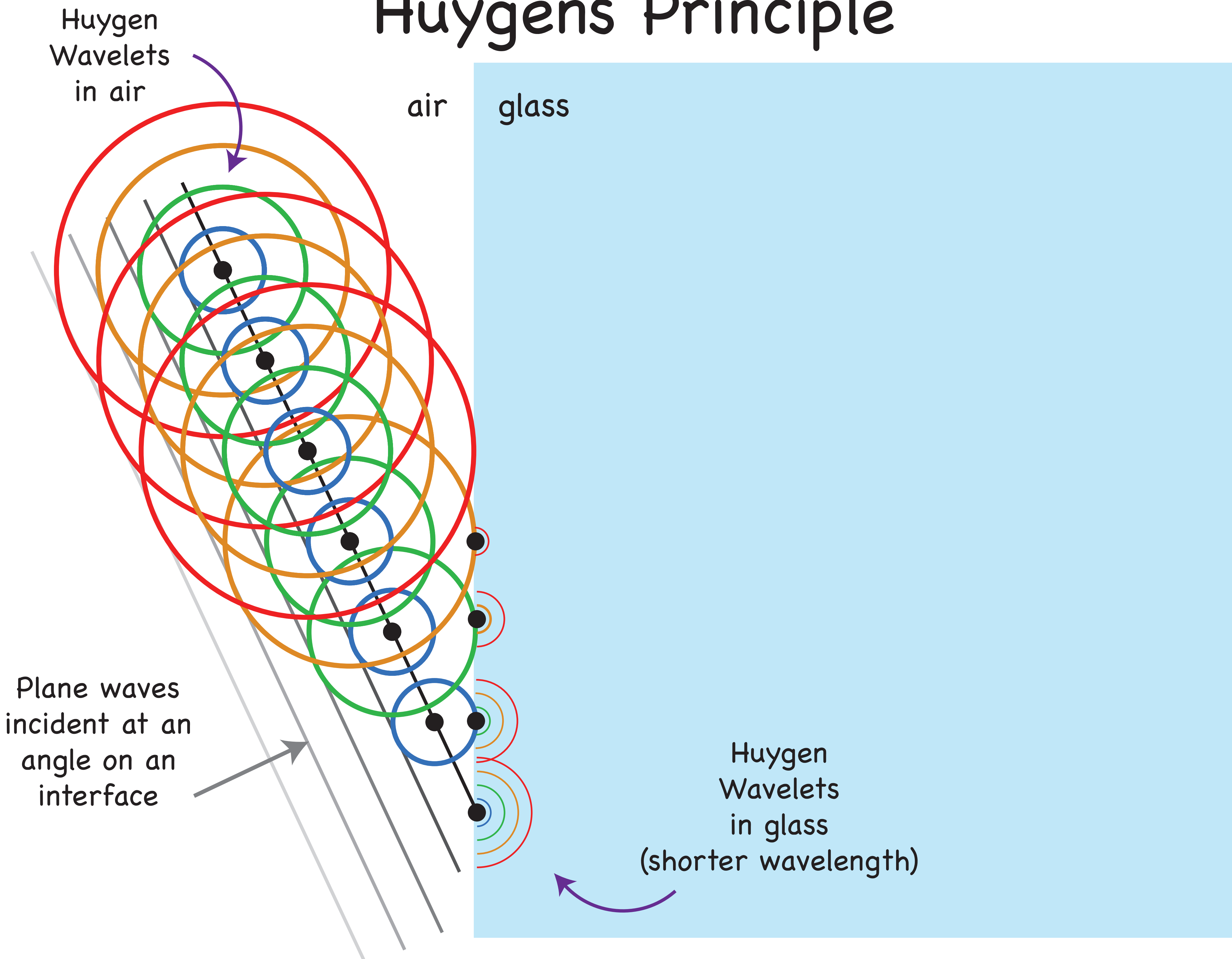

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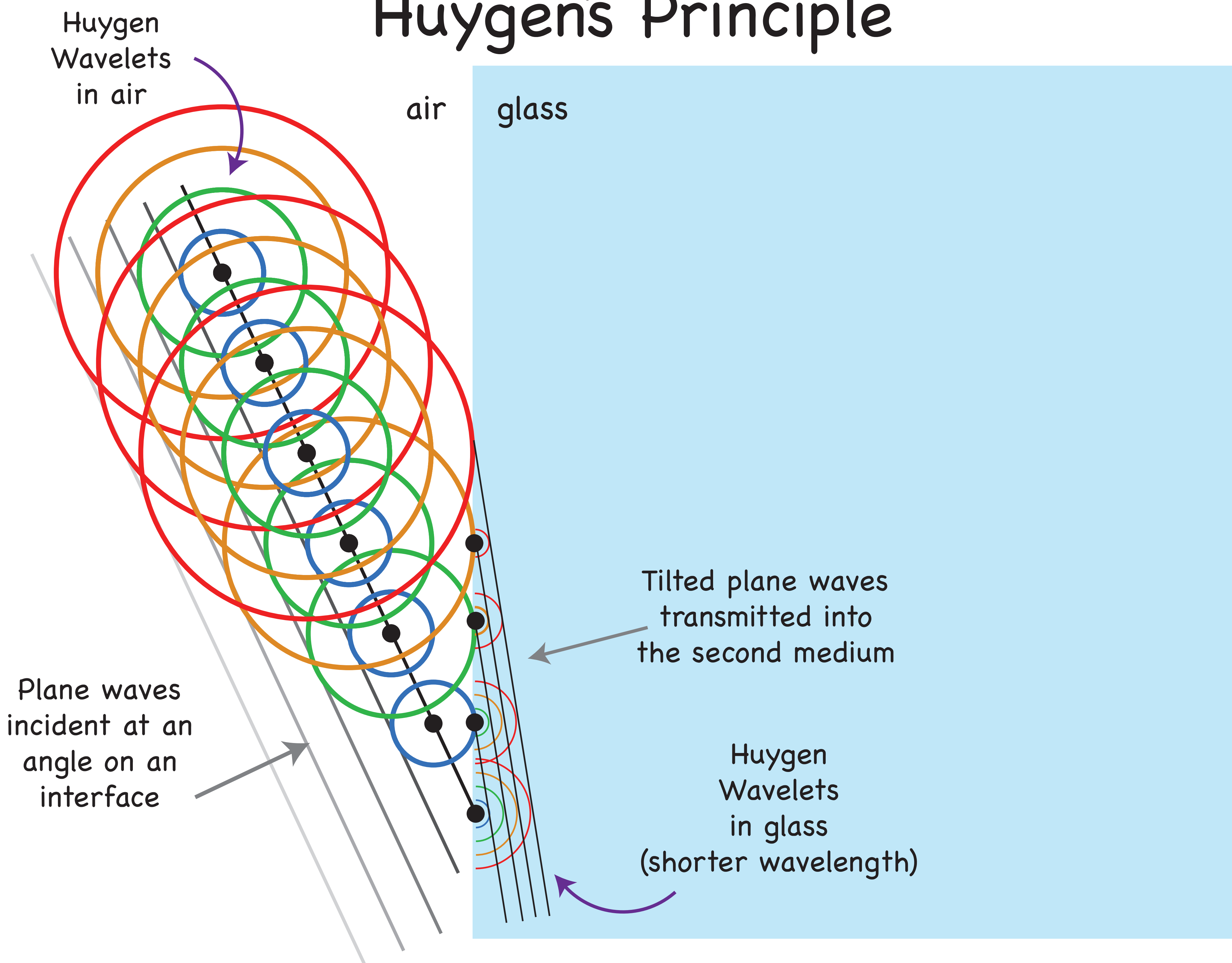

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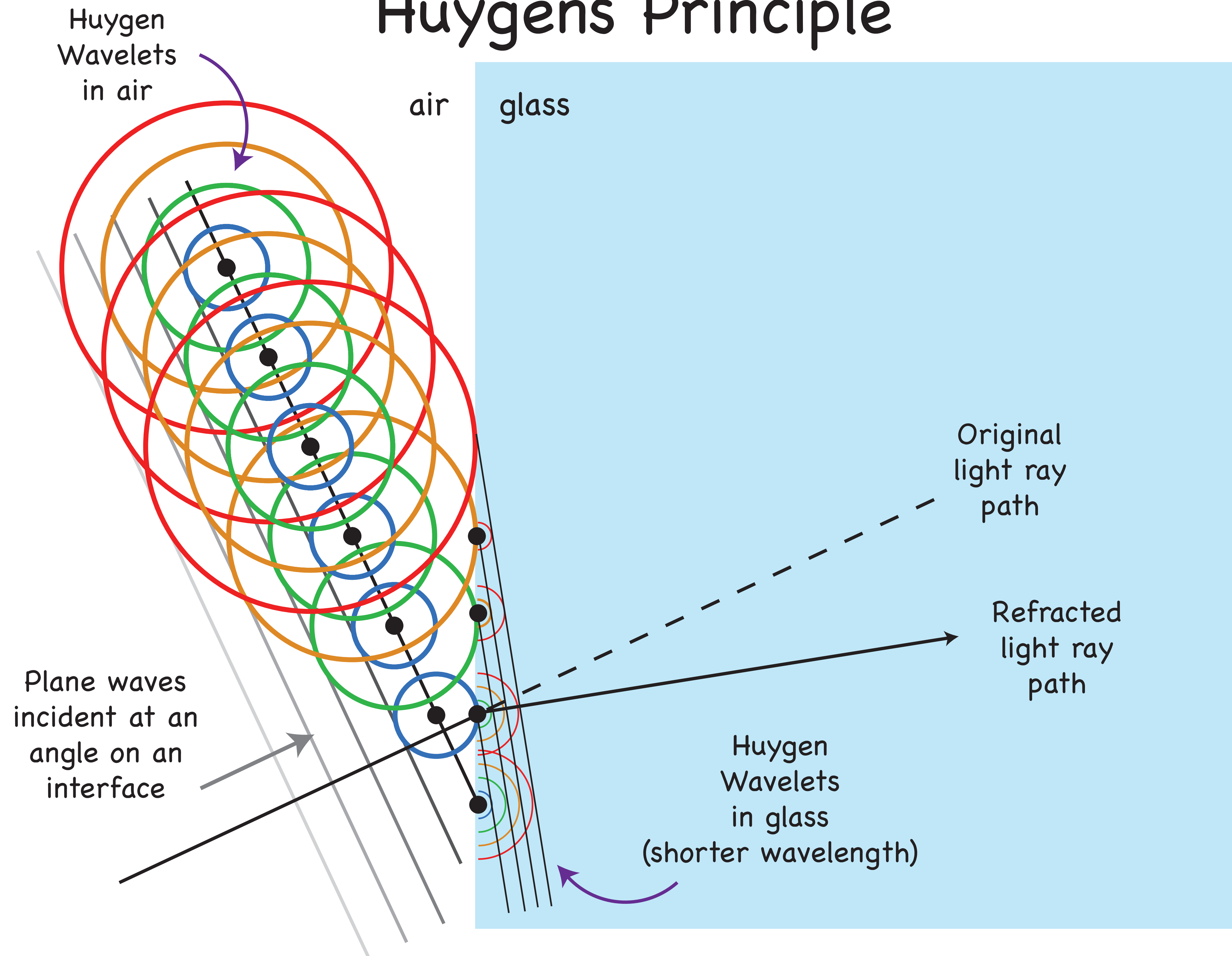


Approximations

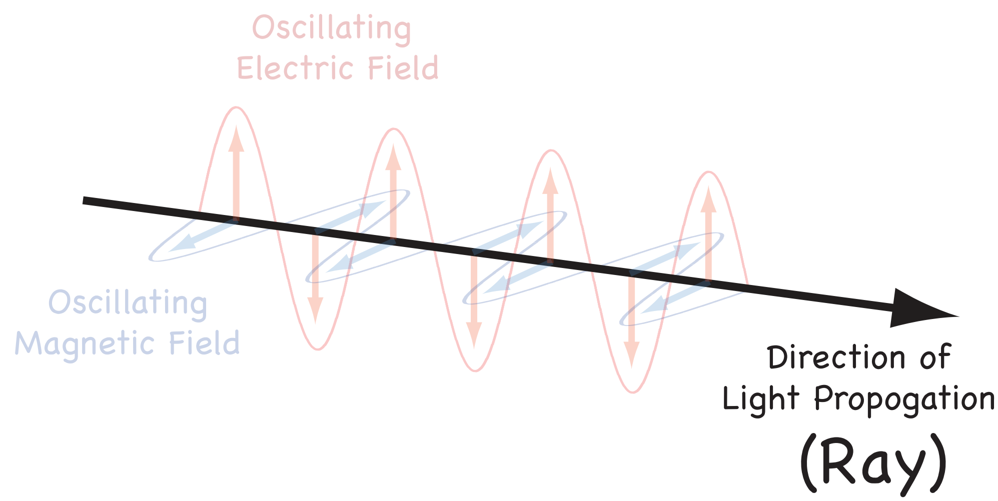
Brutalizing optics into 4 limiting regimes

- Ray (Geometric Optics) : $\lambda \rightarrow 0$
- Paraxial Approximation : $\theta \ll \pi / 2$
- Thin Lens Approximation : lens thickness $\rightarrow 0$
- Lossless Approximation : scatter, absorption $\rightarrow 0$

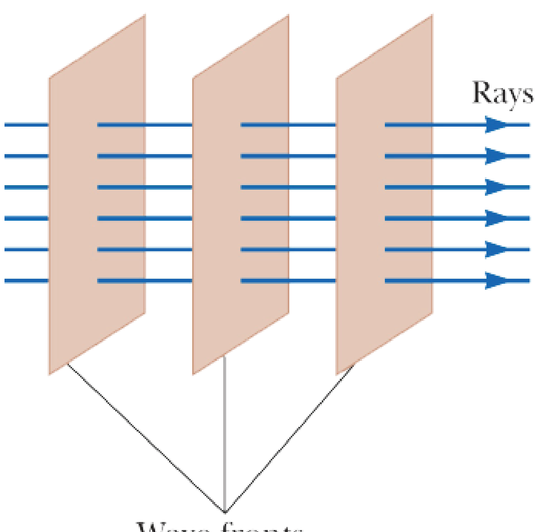
Ray Model / Geometric Optics

Assumes that ($\lambda \ll d$) so that we can ignore diffraction effects

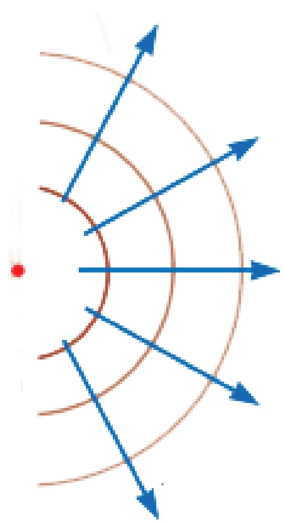
We will take our electromagnetic wave and strip it down to the ray (arrow) that points in the direction of the wave propogation.



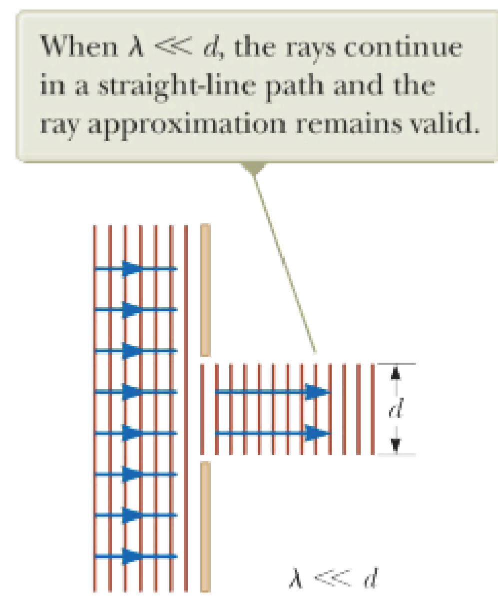
The light rays are straight lines that are perpendicular to the wave fronts



Plane Wave Fronts



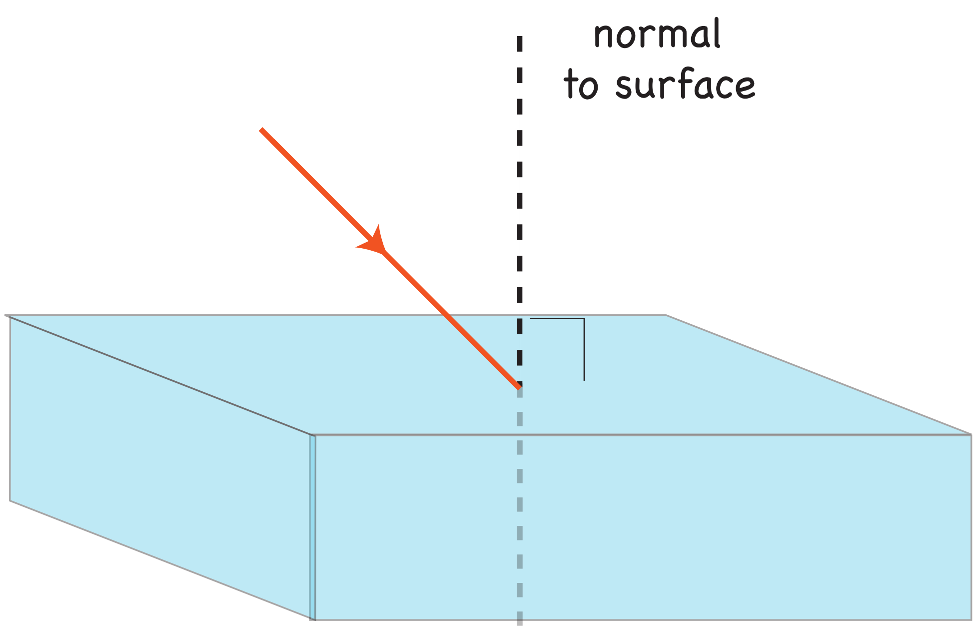
Spherical Wave Fronts

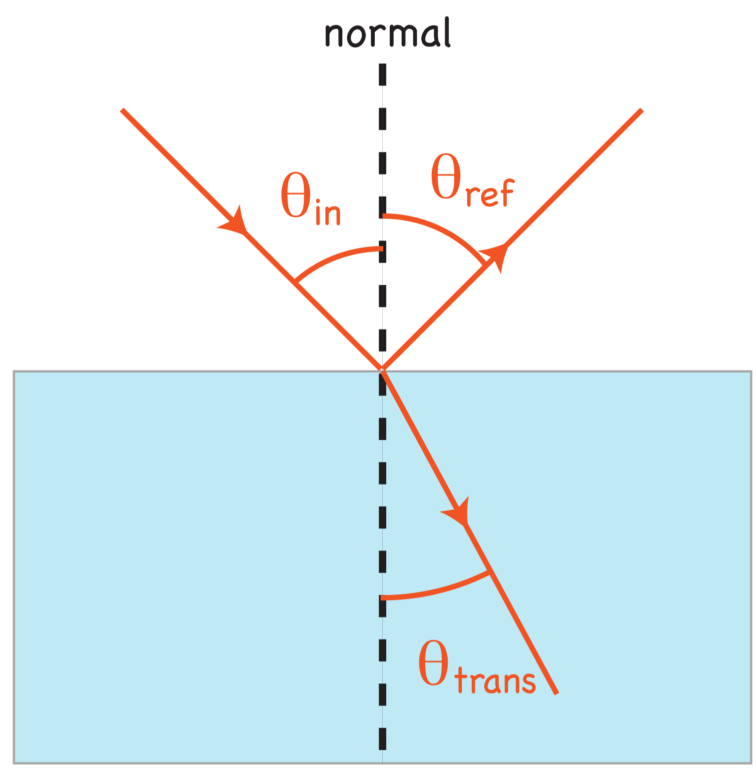


In the ray optics limit, we ignore diffraction.

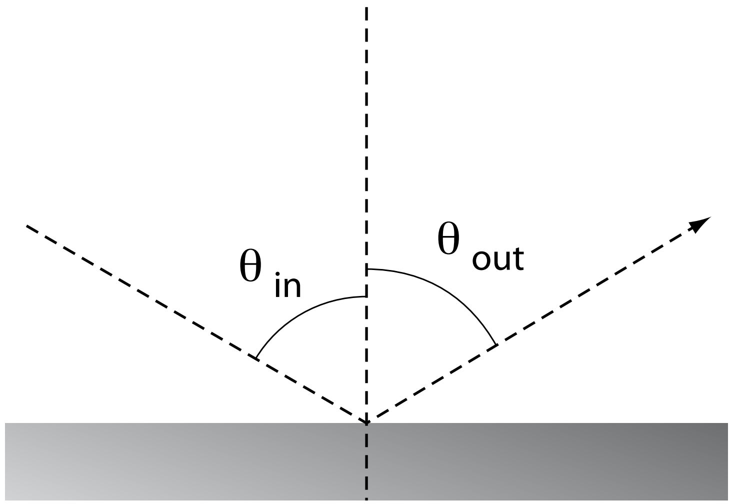
Rays : The Rules

- A geometric ray will move in a straight line as long as the medium does not change.
- When a geometric ray arrives at an interface between two different materials, it can reflect or refract to a new angle
- When dealing with interfaces, the angle of a geometric ray is always taken with respect to the "normal to the surface" (an imaginary line that is perpendicular to the surface)

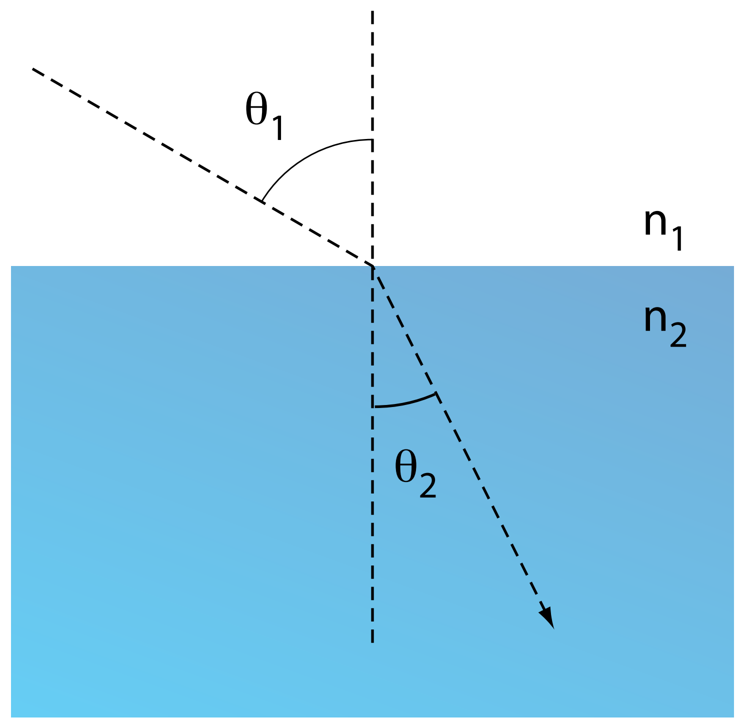




Laws of Reflection and Refraction



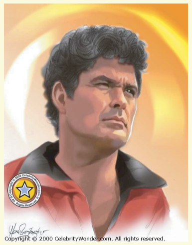
Laws of Reflection : $\theta_{in} = \theta_{out}$



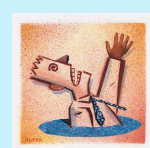
Snell's Law : $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$

Snell's Law

Fermat's Principle Derivation : Principle of Least Time



What path should the lifeguard take to minimize the time to reach the drownng victim?



Snell's Law

Fermat's Principle Derivation : Principle of Least Time

What path should the
lifeguard take to minimize
the time to reach
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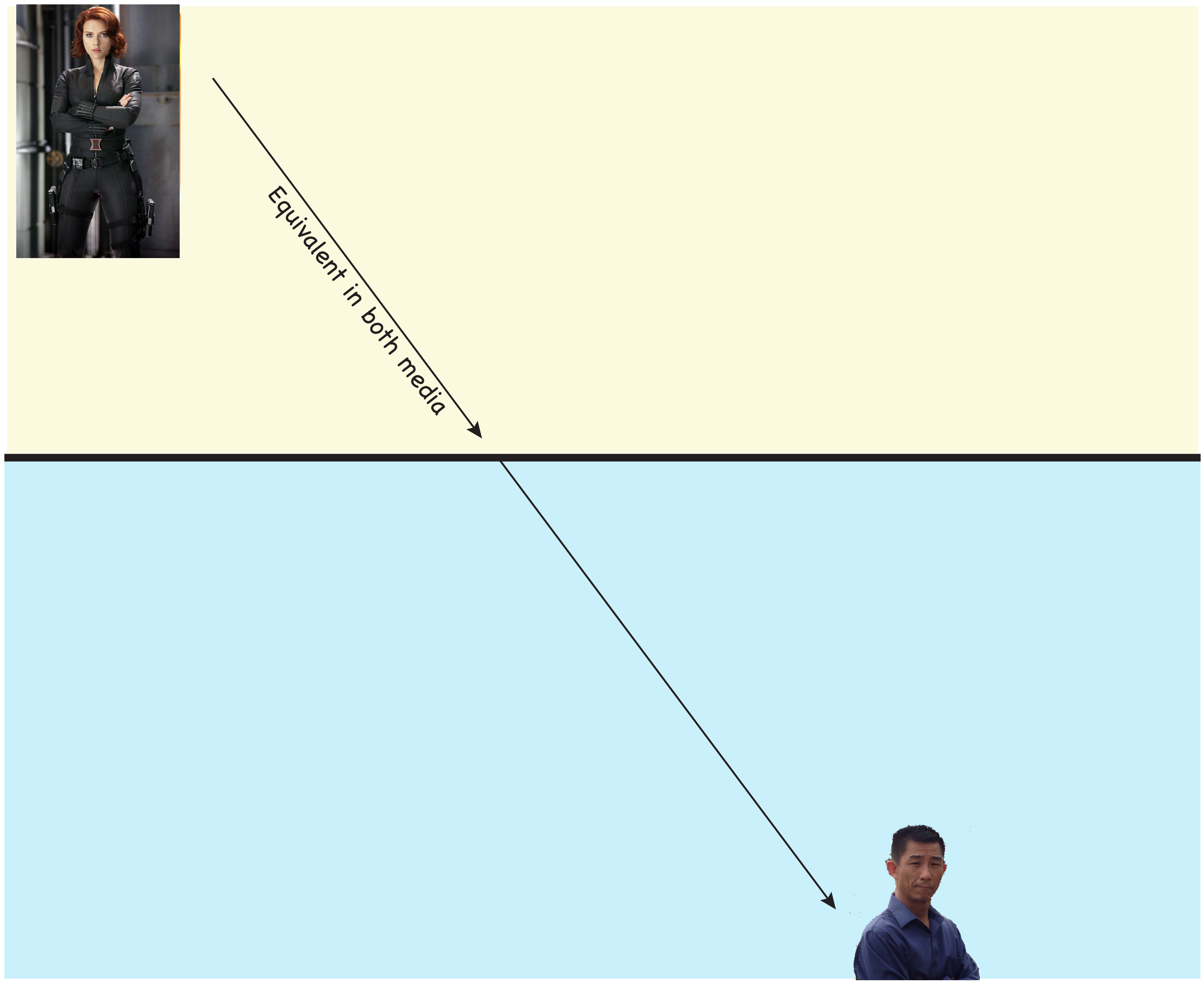

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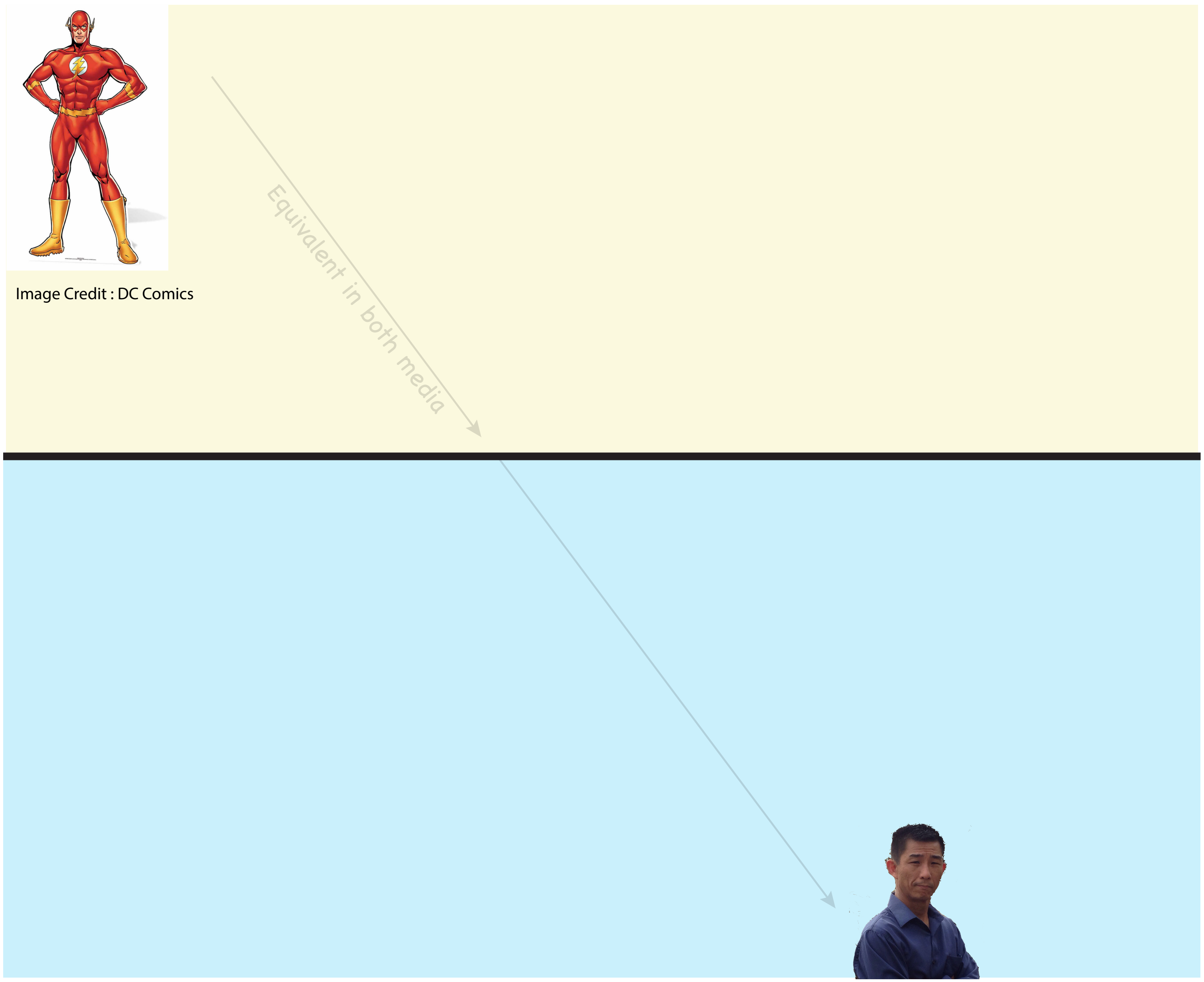
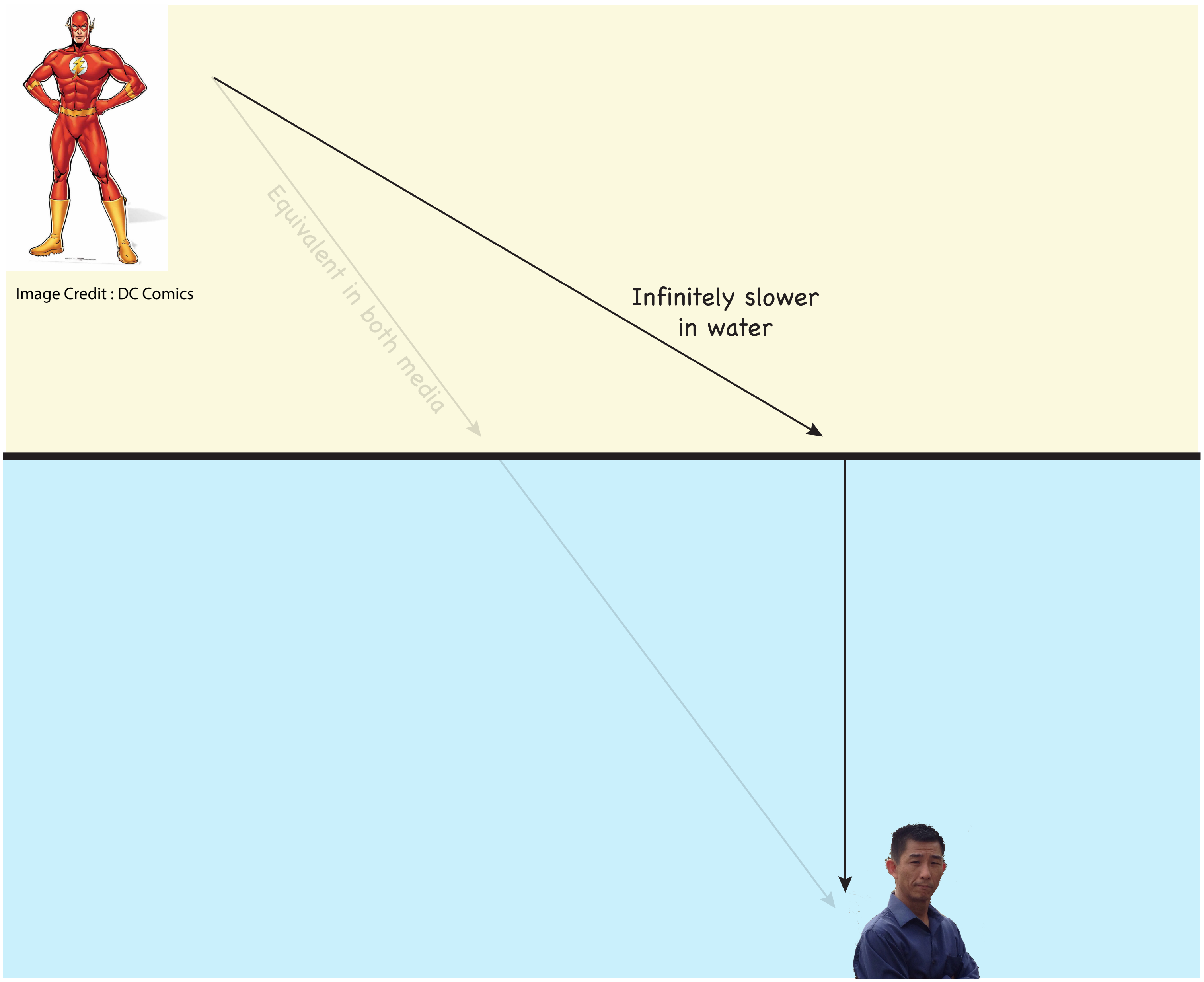


Image Credit : DC Comics

Snell's Law

Fermat's Principle Derivation : Principle of Least Time



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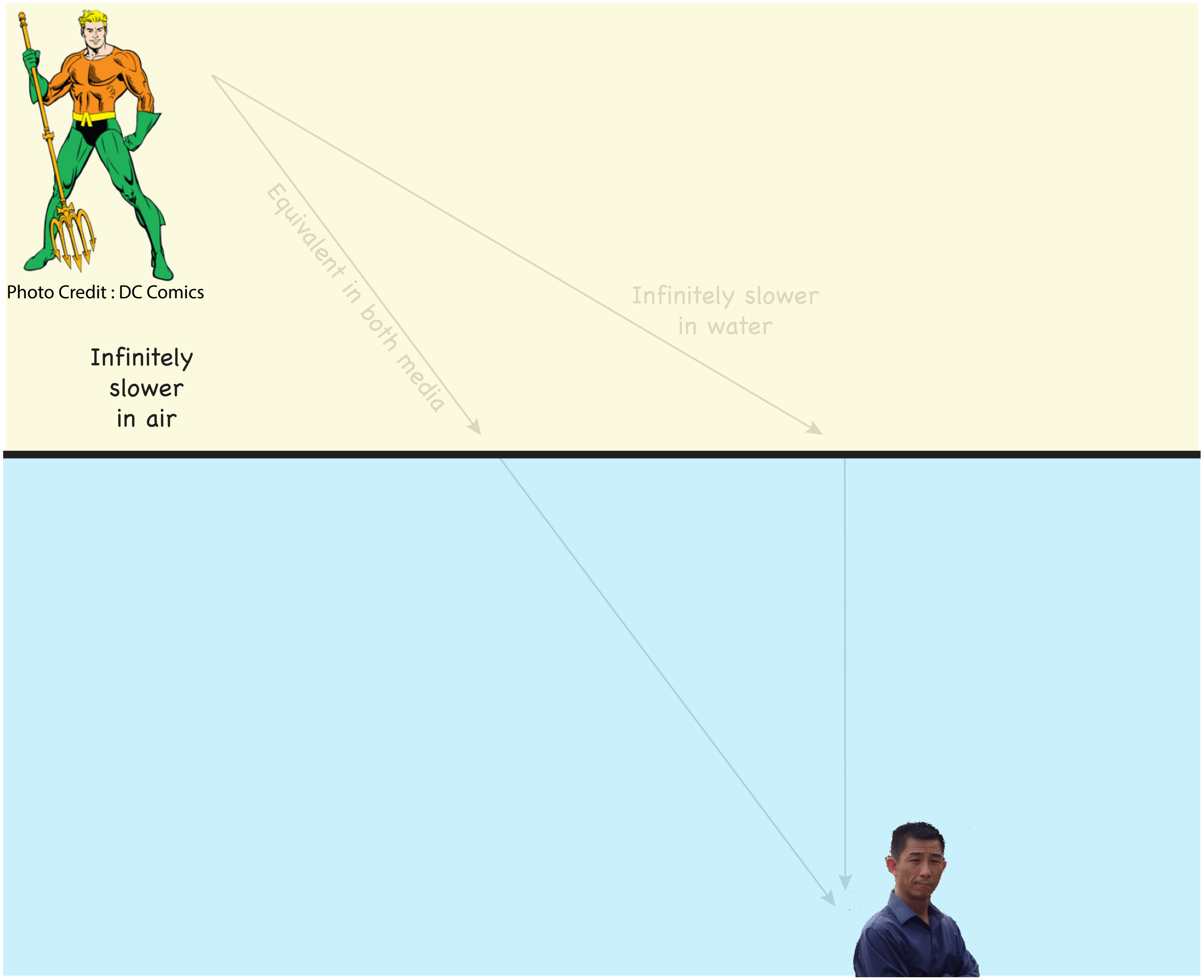

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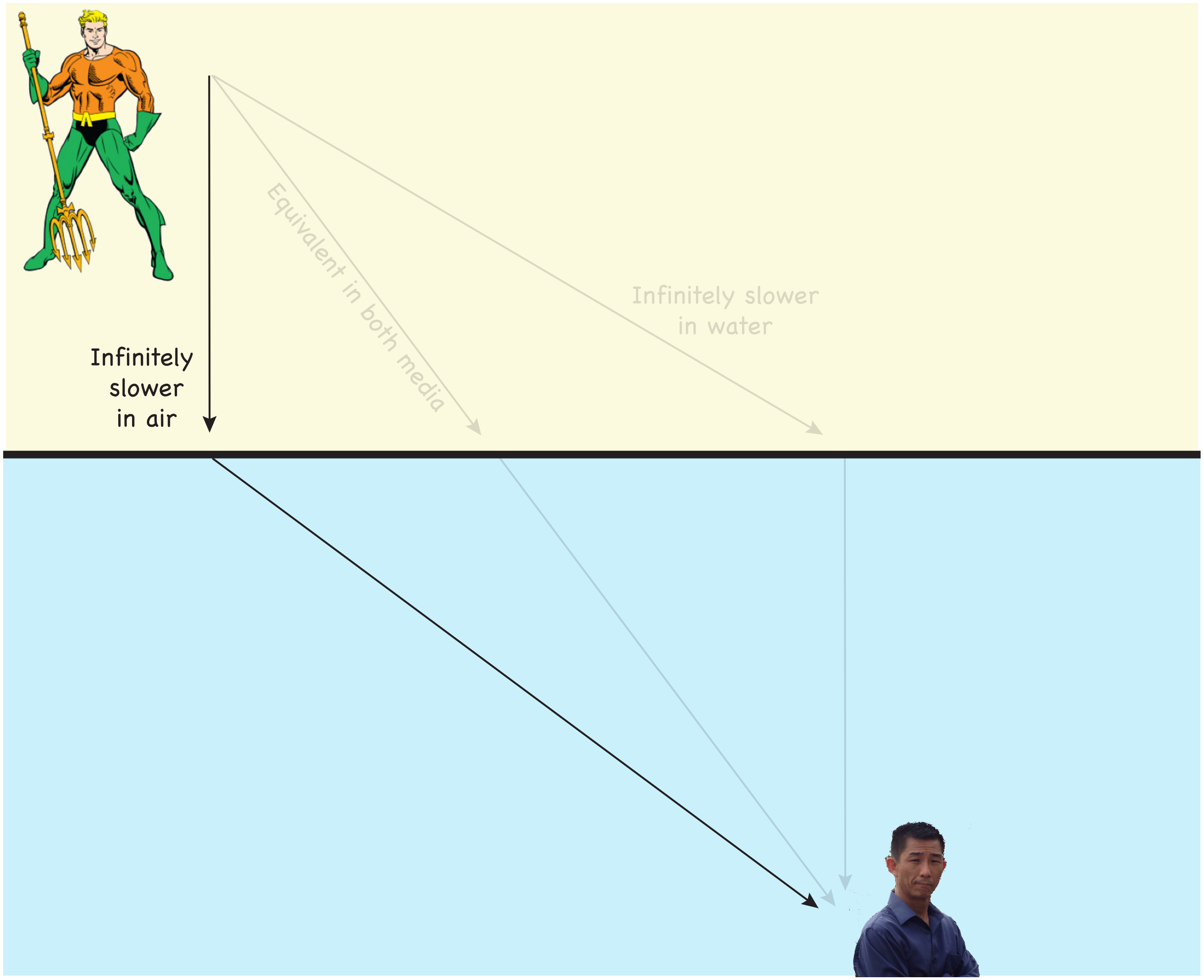

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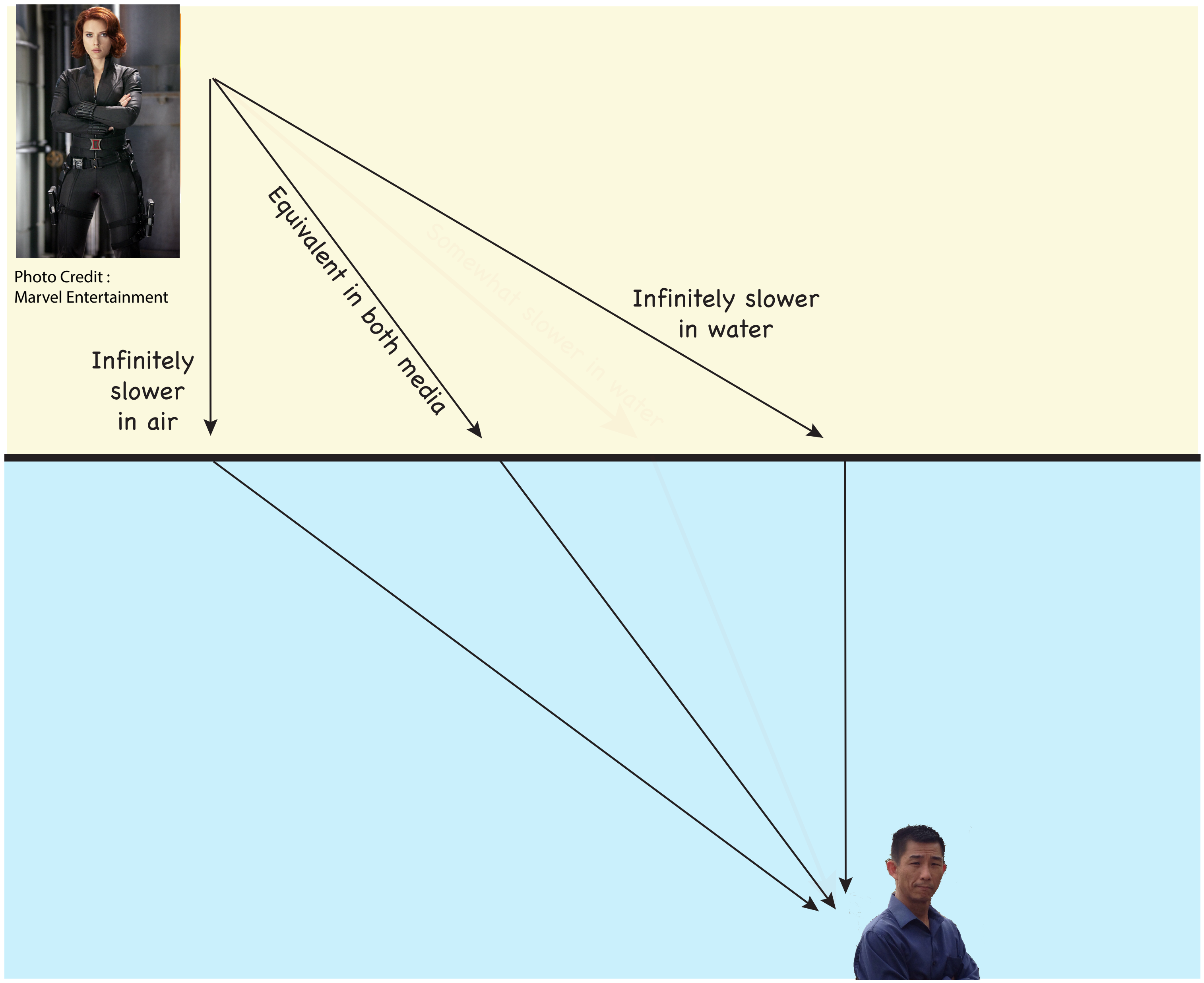

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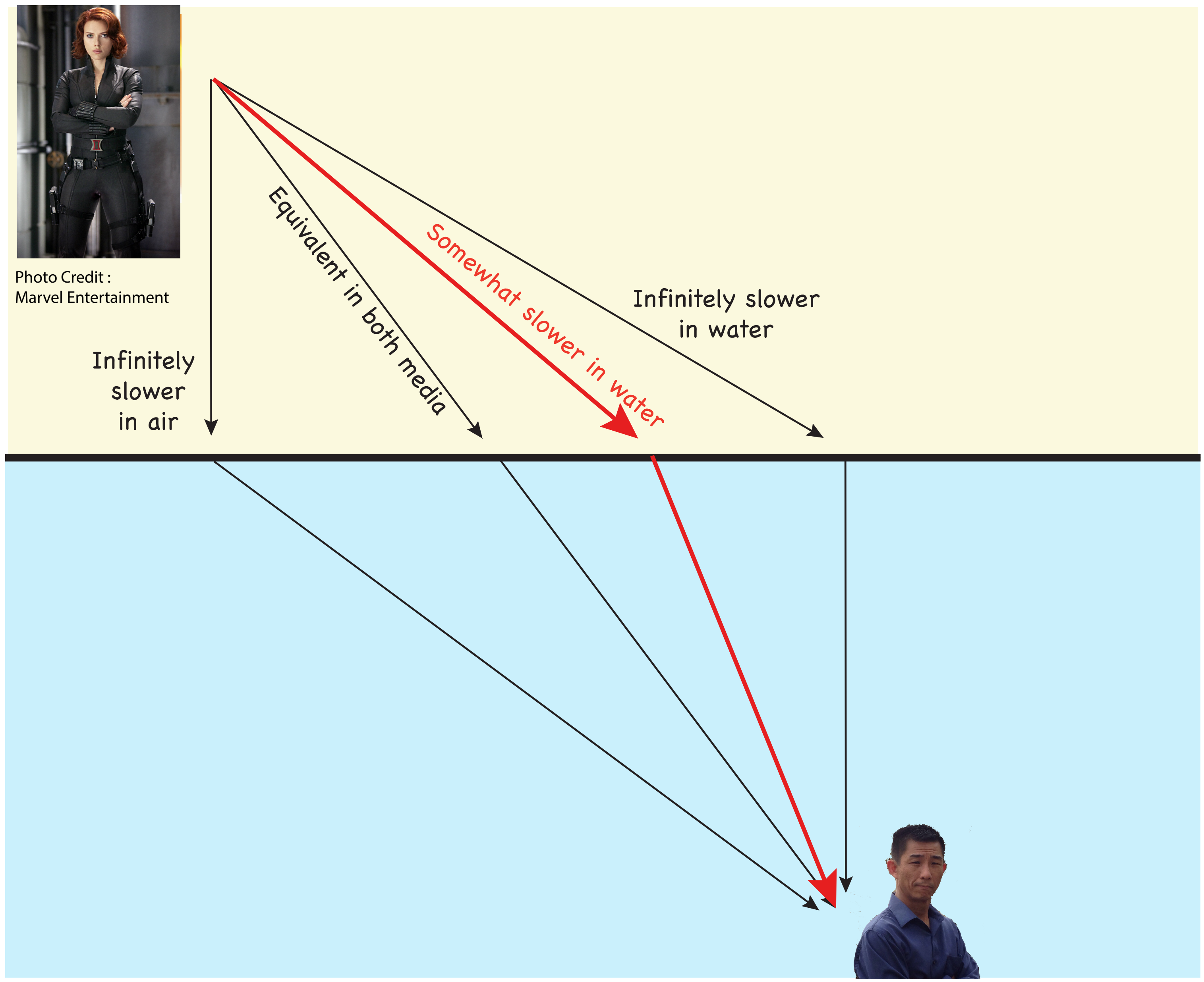

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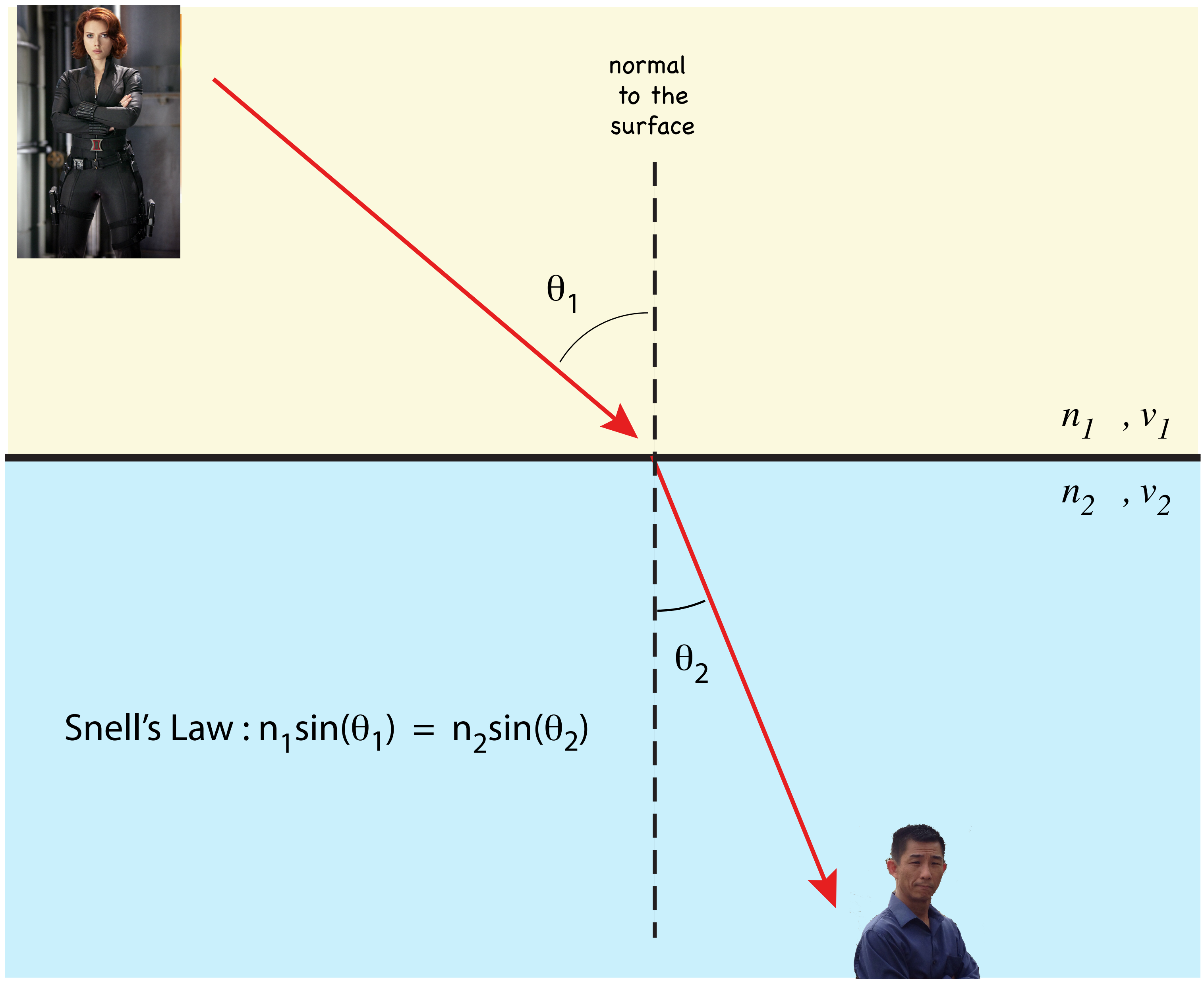

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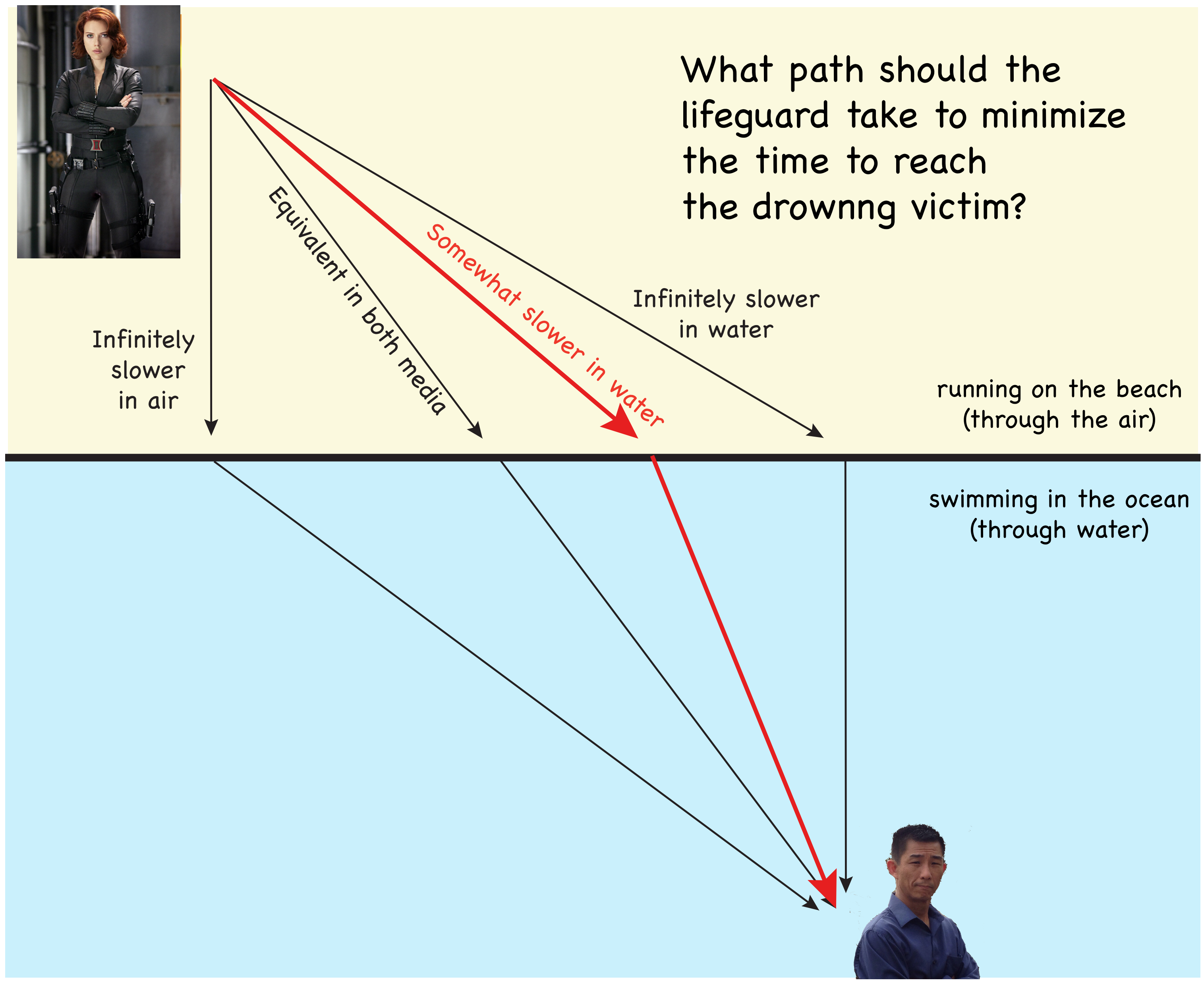
Fermat's Principle Derivation : Principle of Least Time

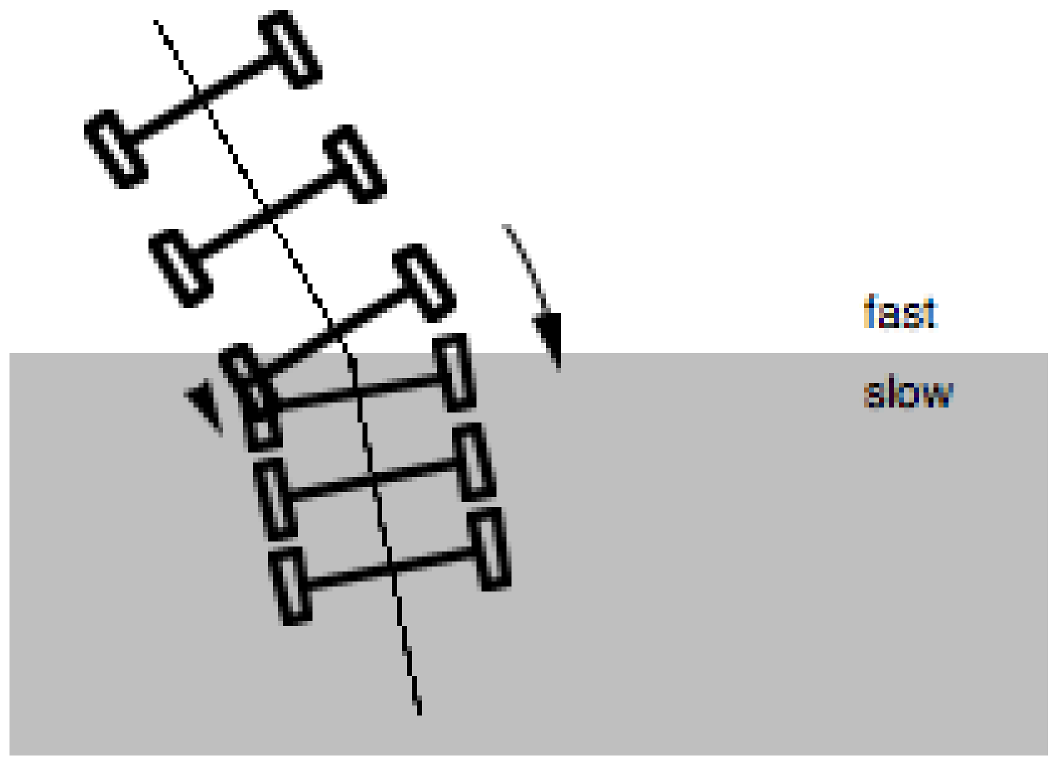


Snell's Law

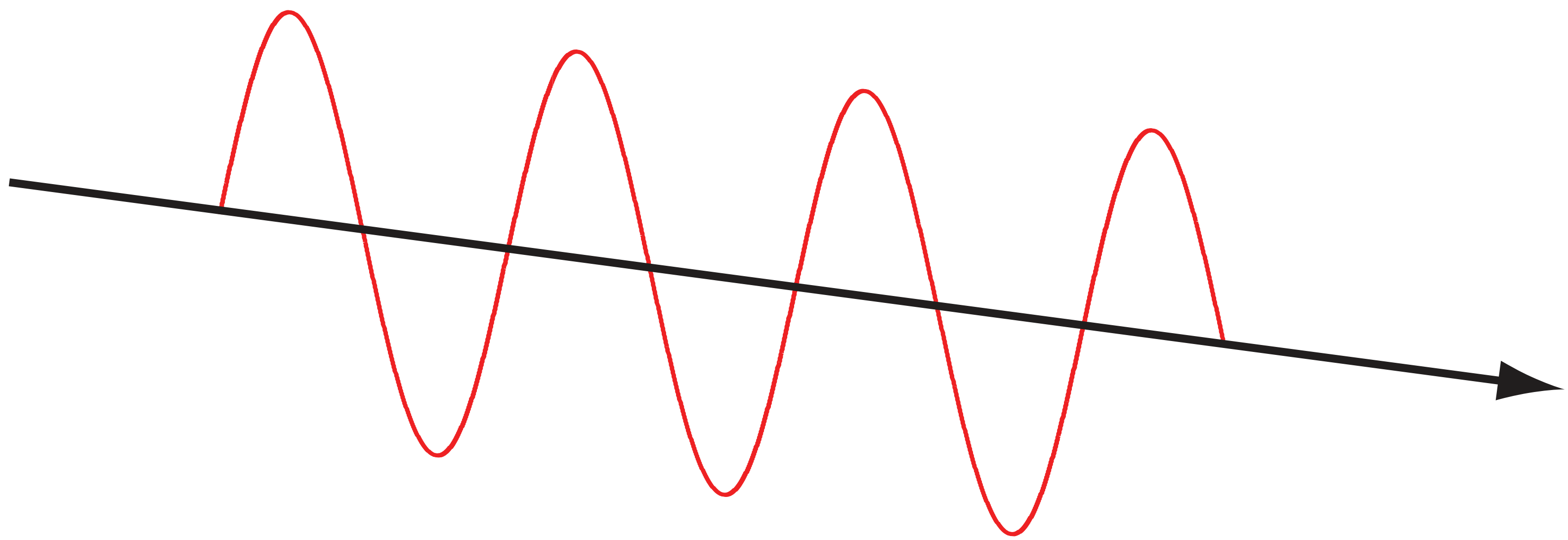
One final (easy way) to think about (and remember) Snell's law

Consider a dumbell or car axle rolling on pavement at an angle towards a patch of of mud.

When the first wheel hits the mud, it slows down, but the other wheel is still on the fast pavement, and causes the trajectory of the axle to tilt towards the normal to the interface.



Linearly Polarized Light



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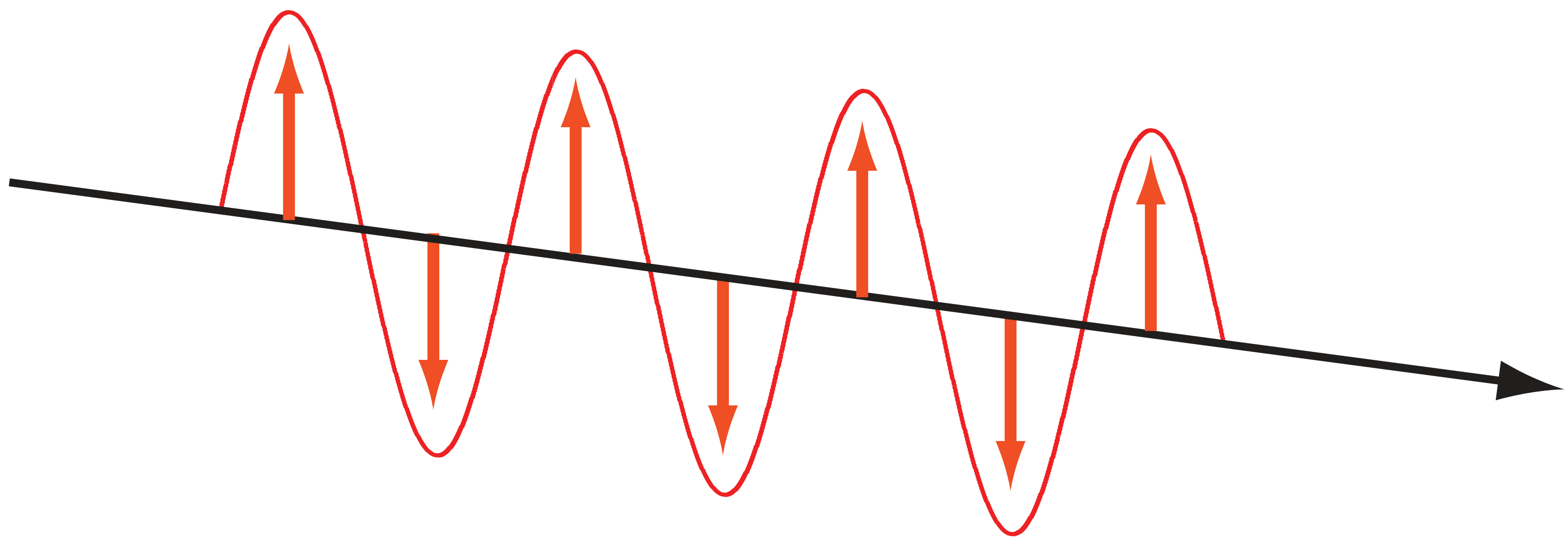

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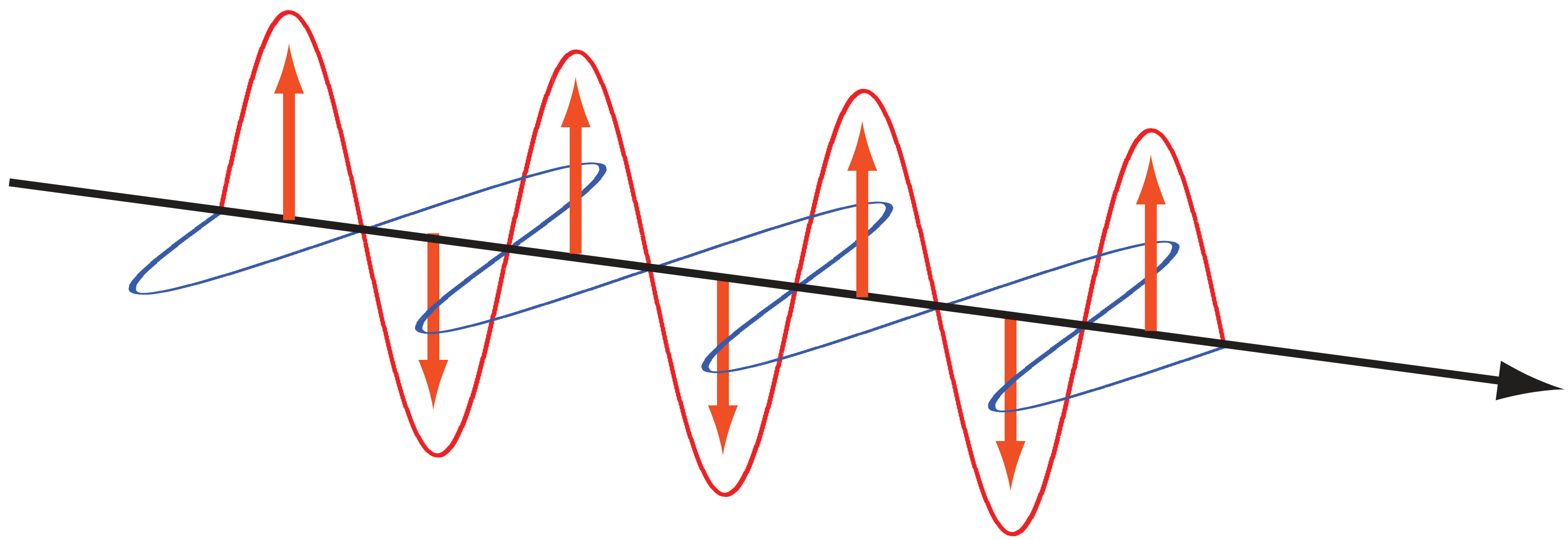

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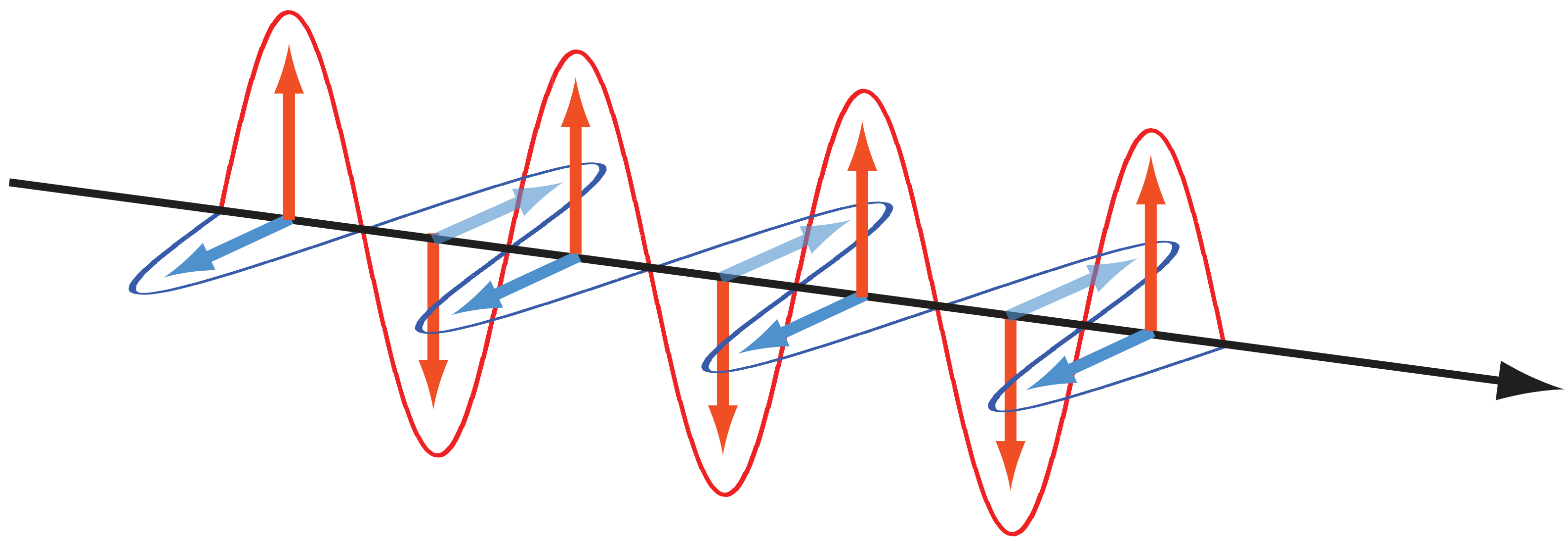

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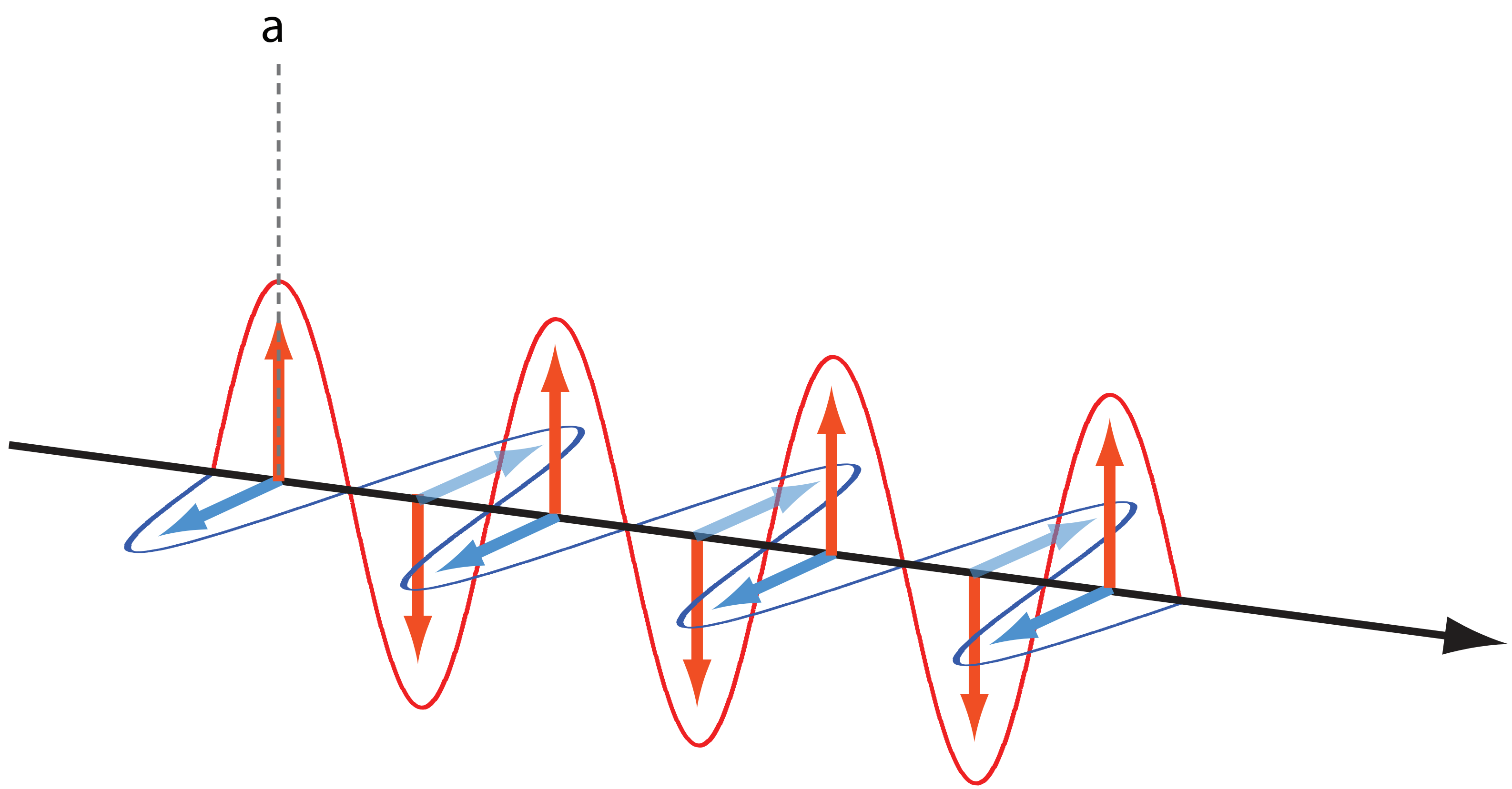
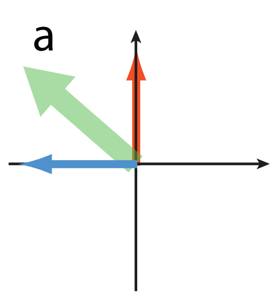
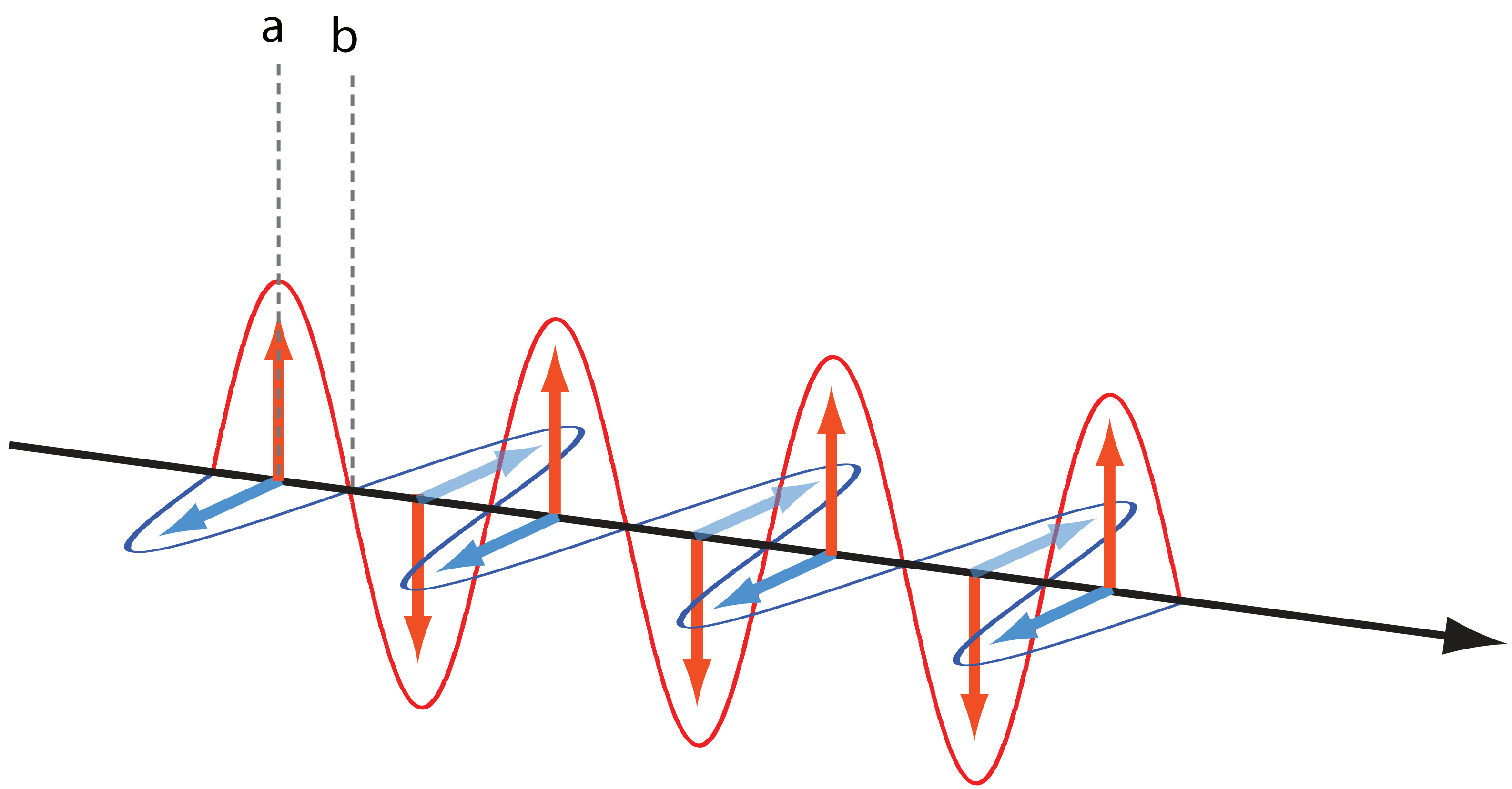
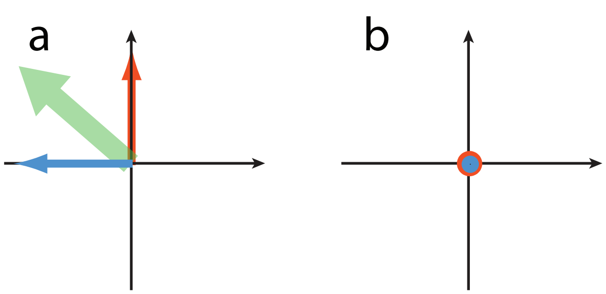




Linearly Polarized Light





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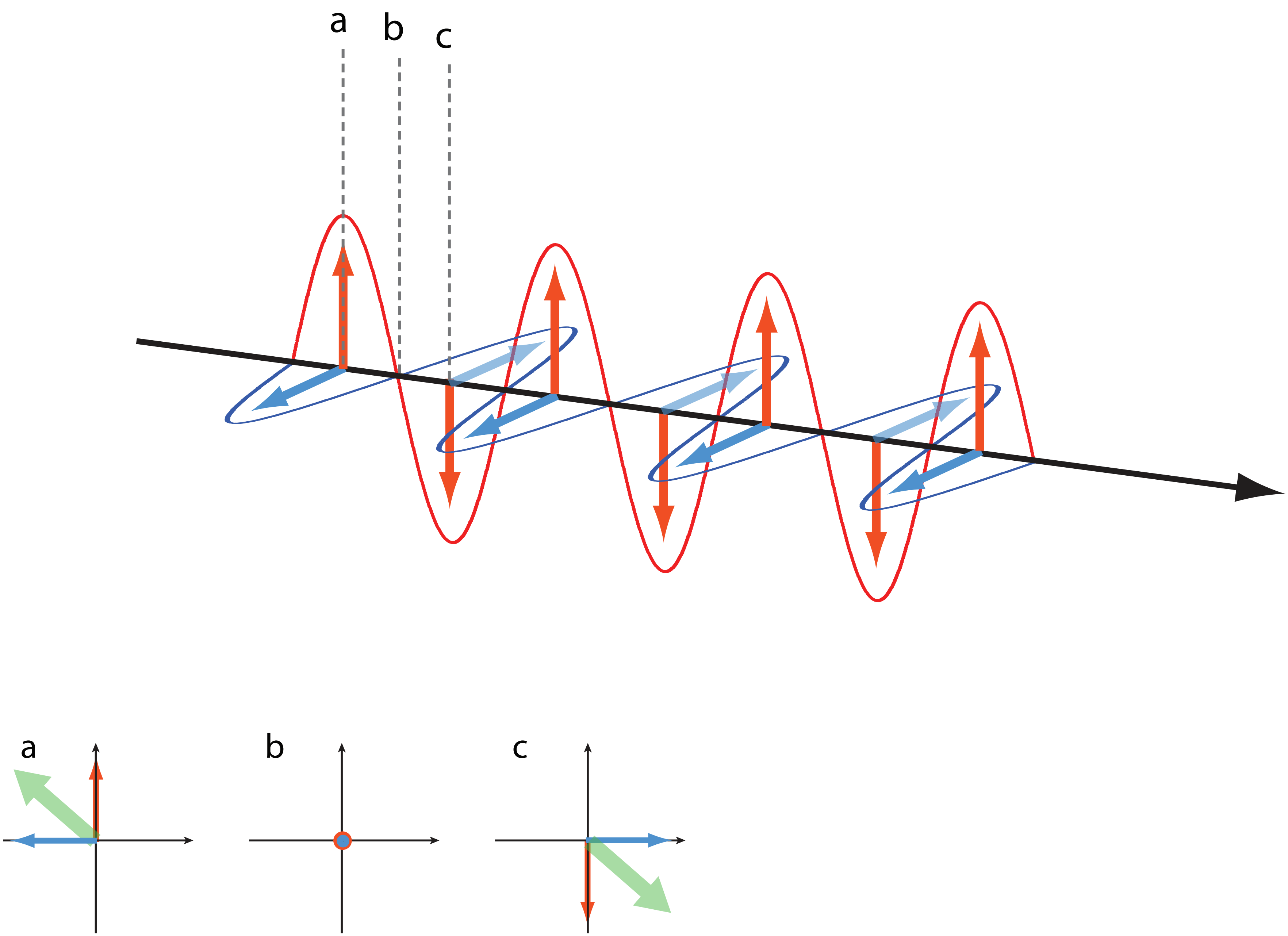

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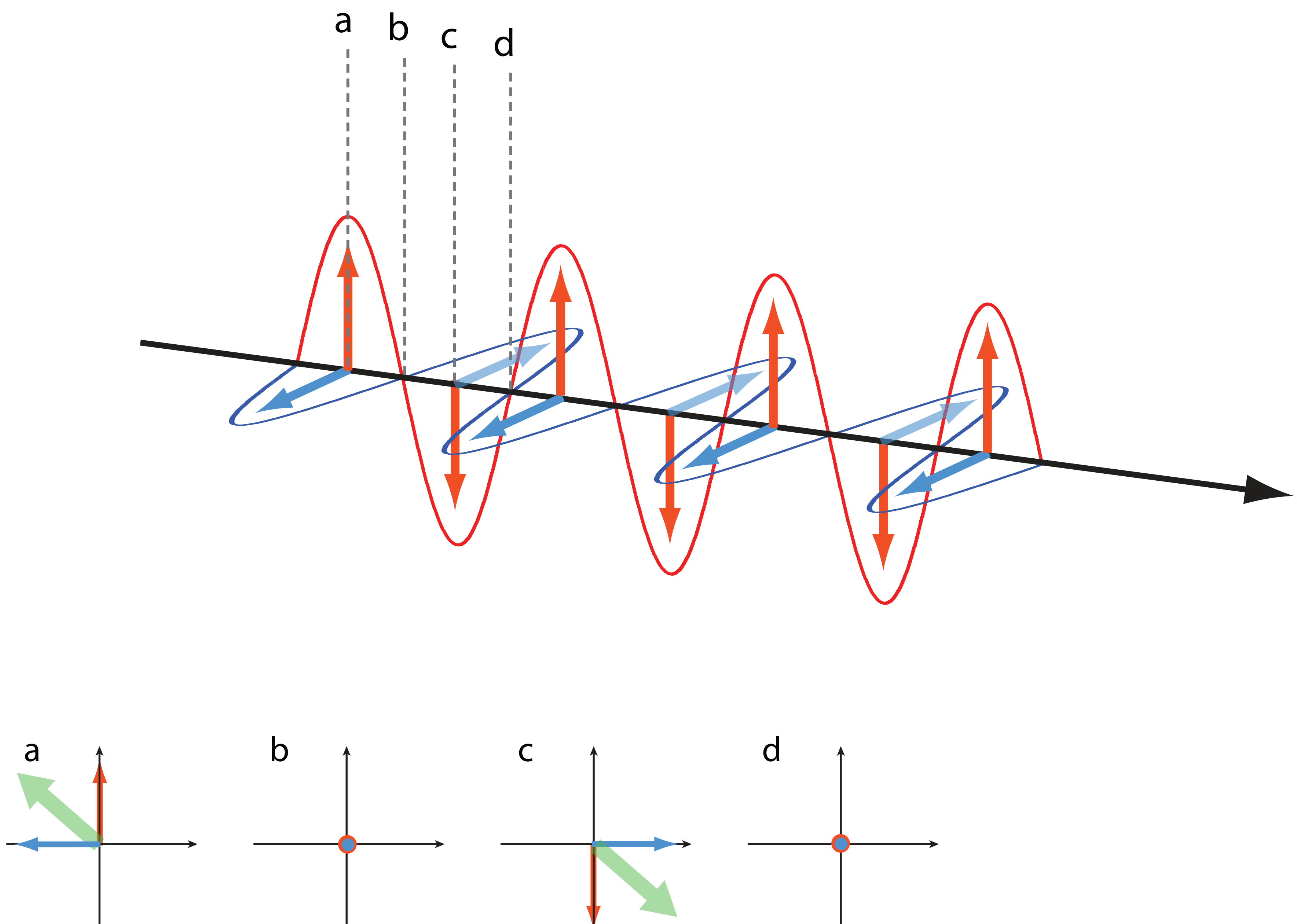

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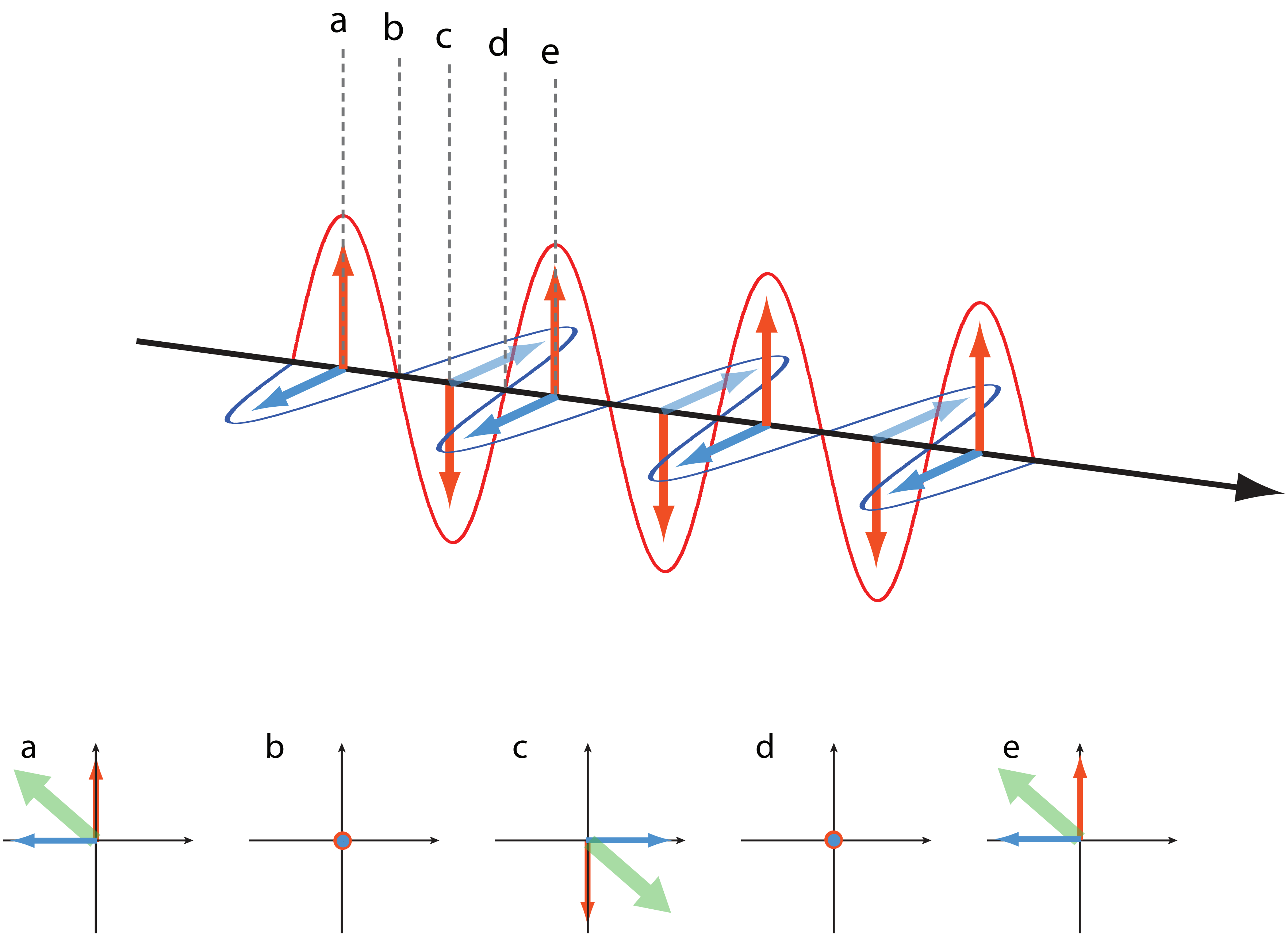
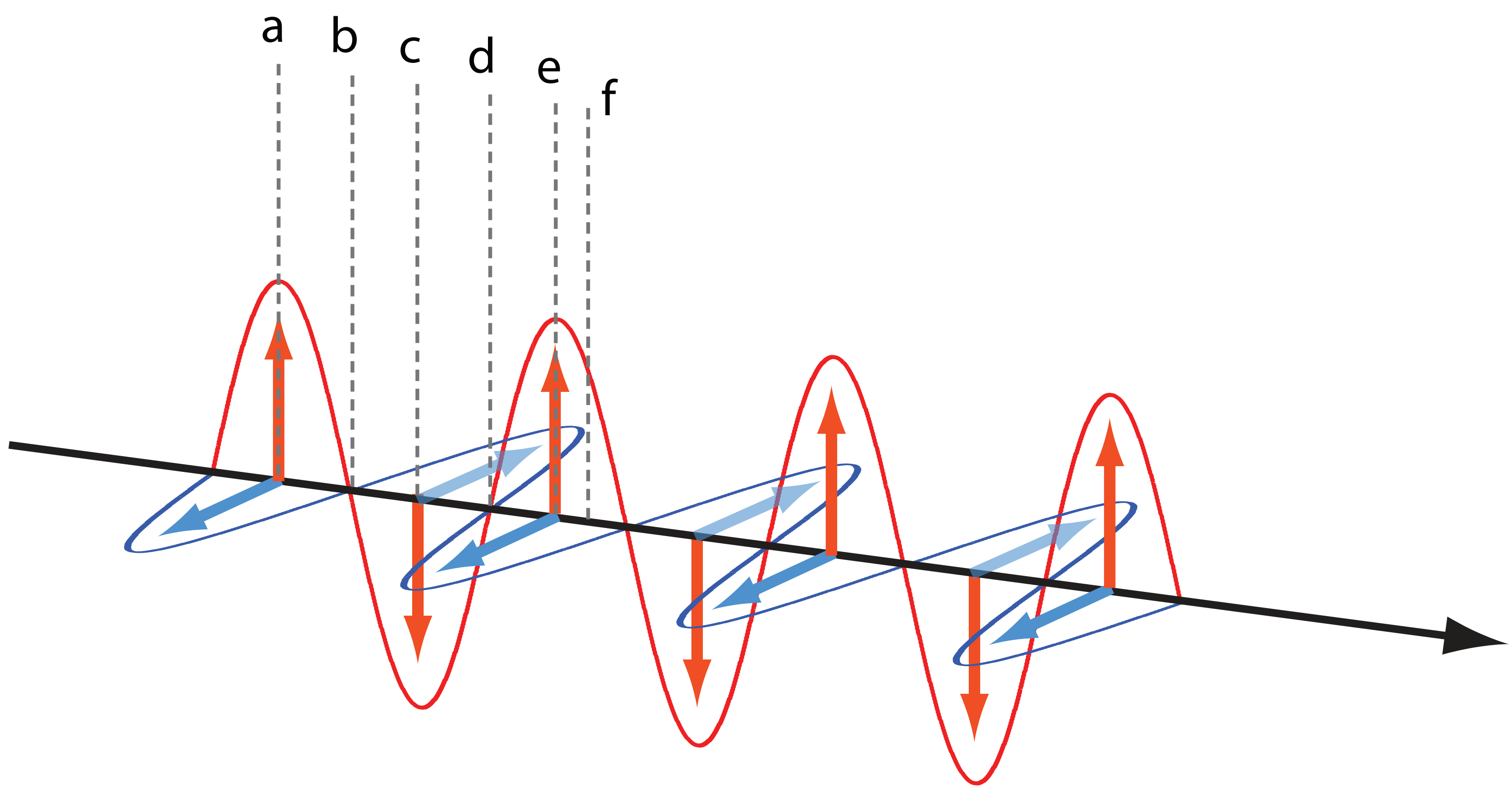
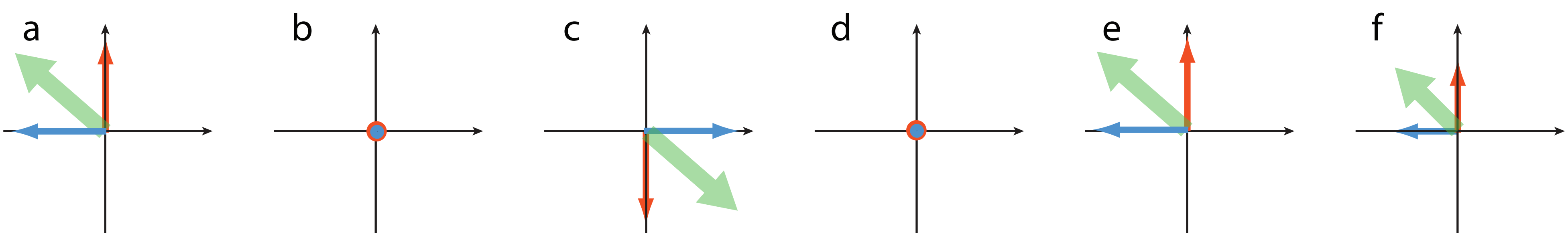
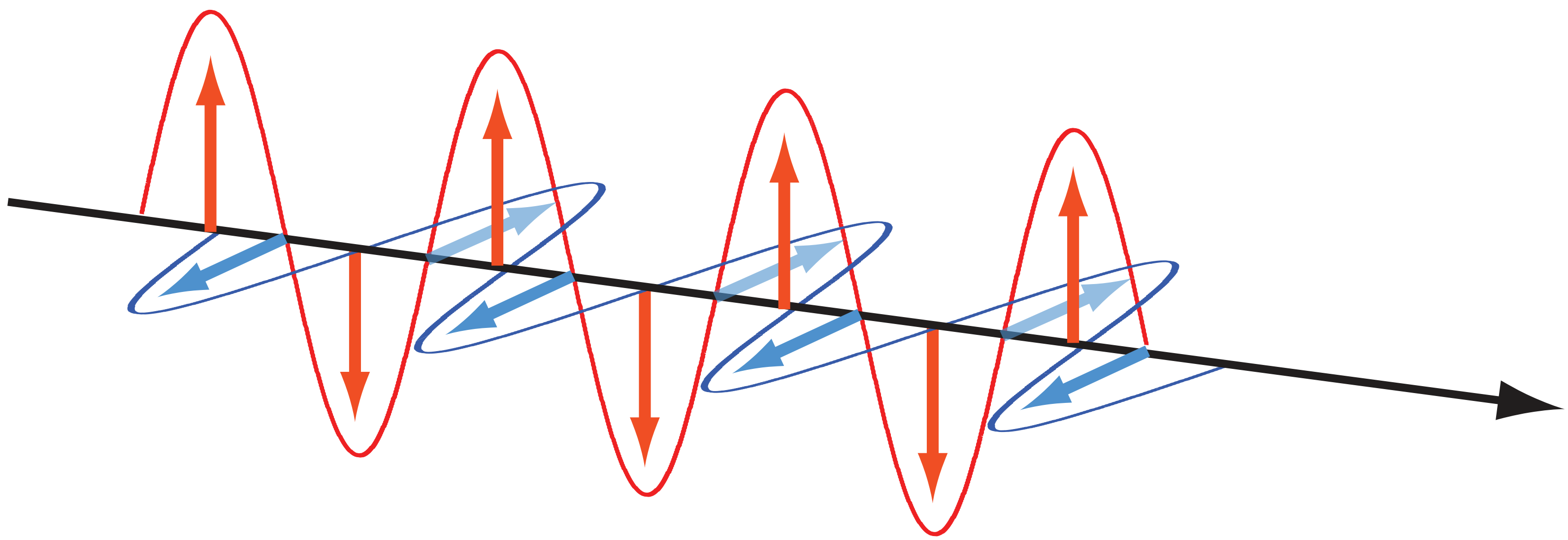


Linearly Polarized Light

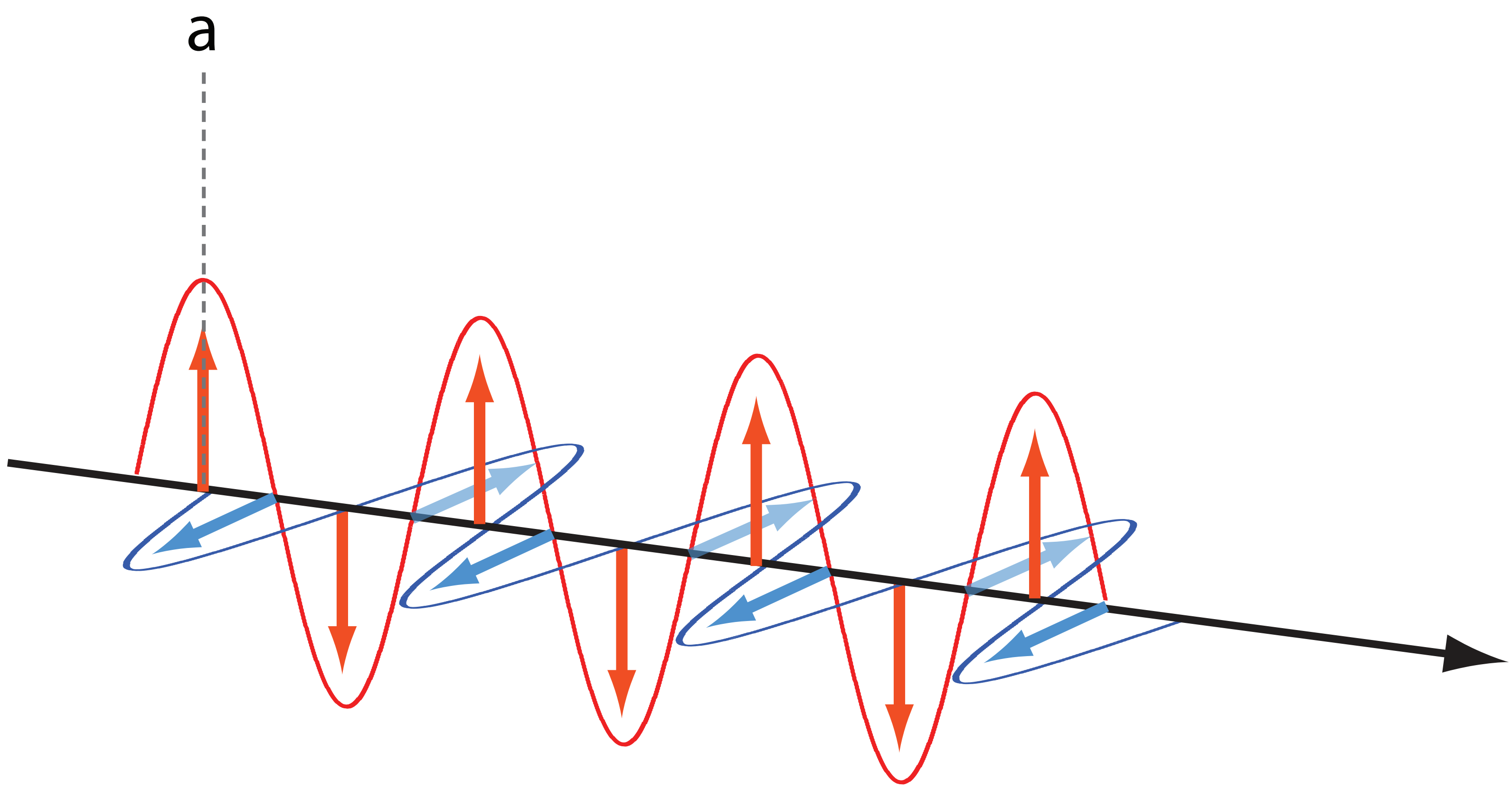


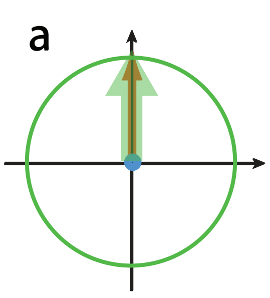


Circularly Polarized Light



Circularly Polarized Light





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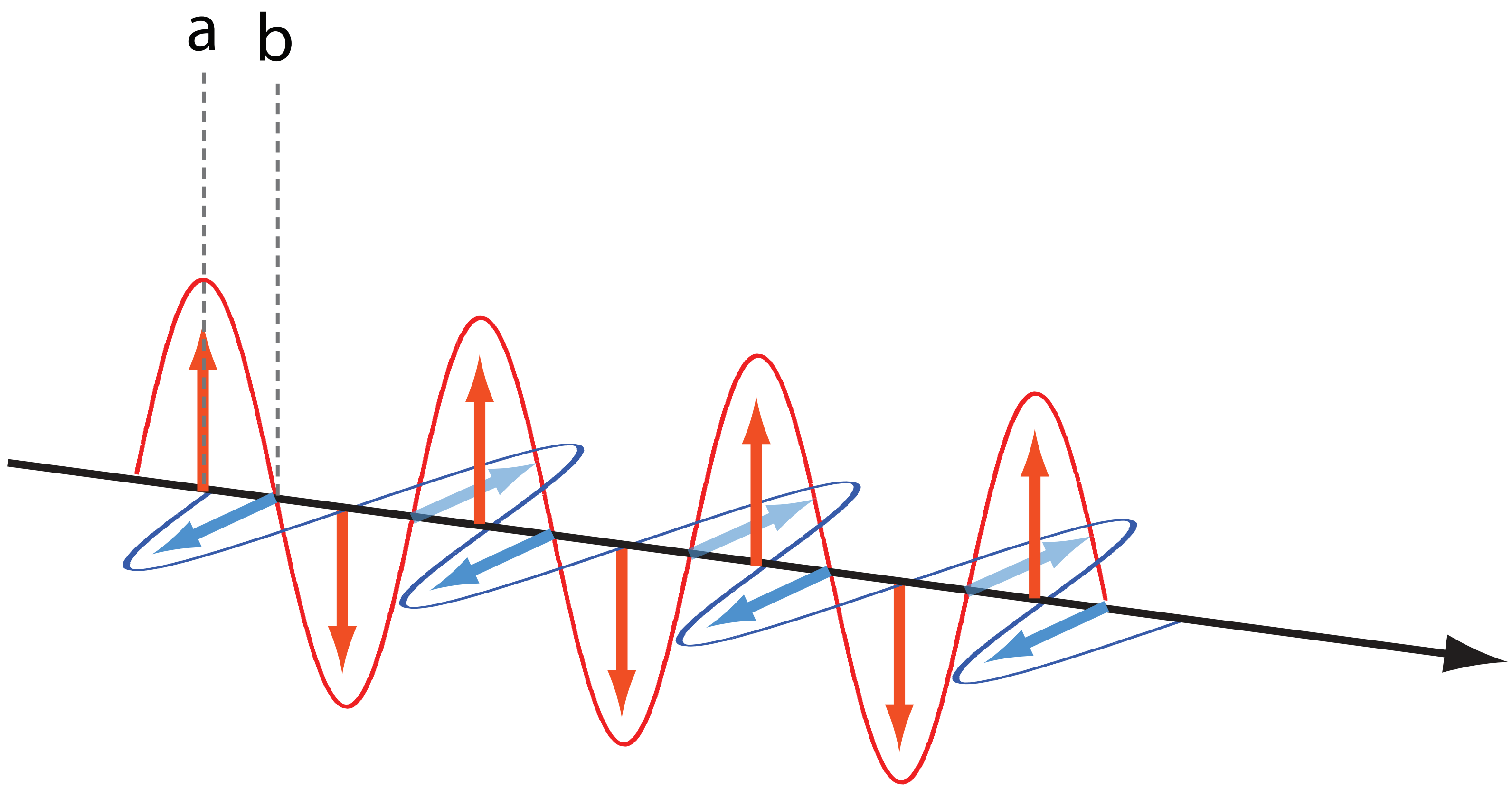

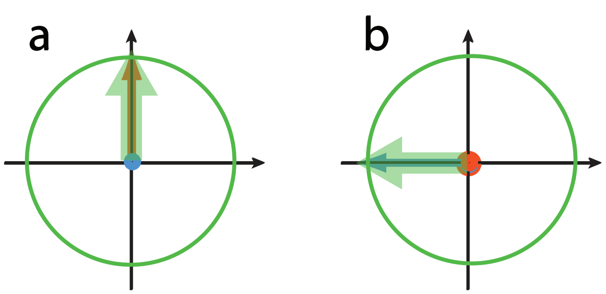

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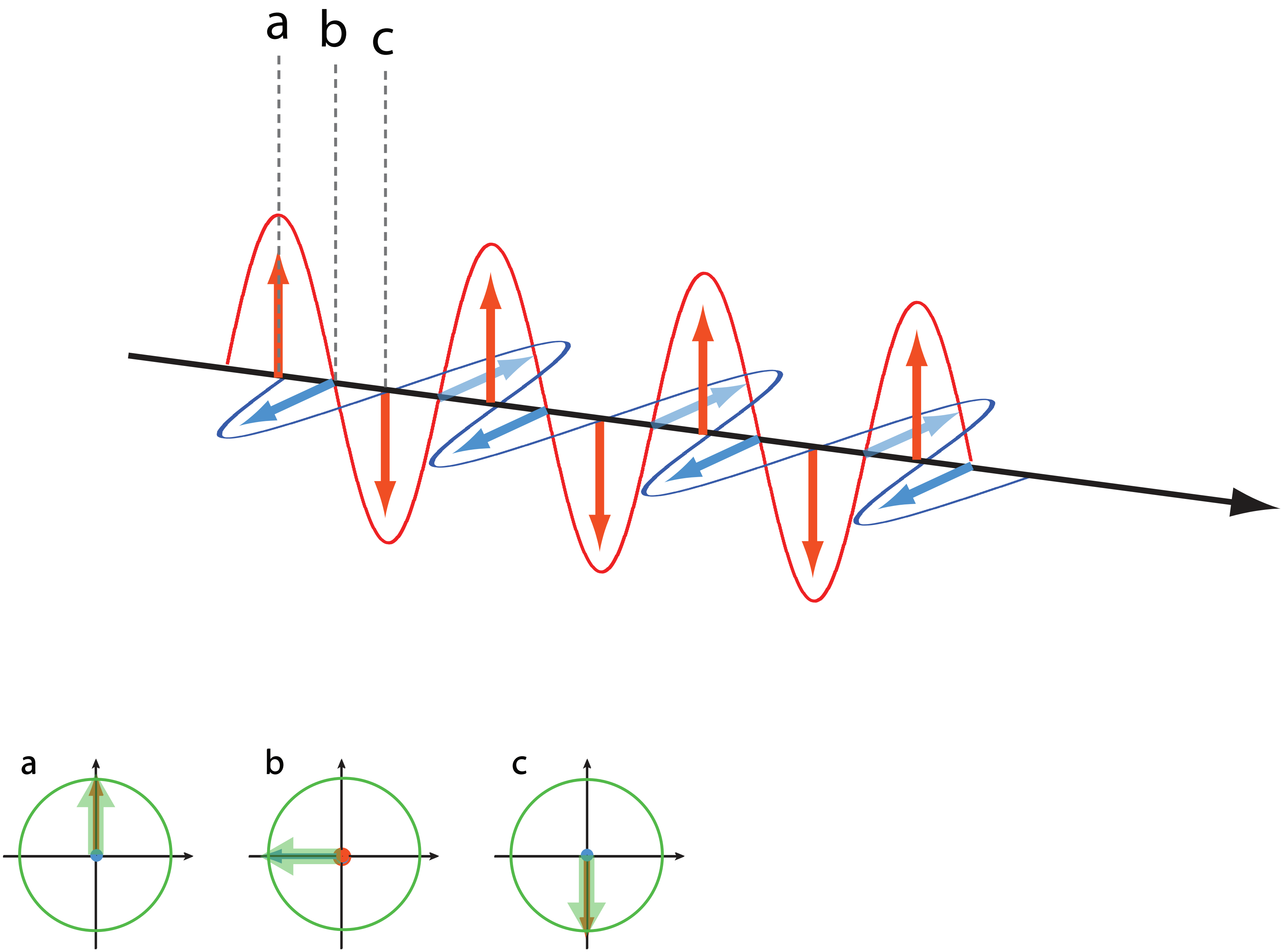

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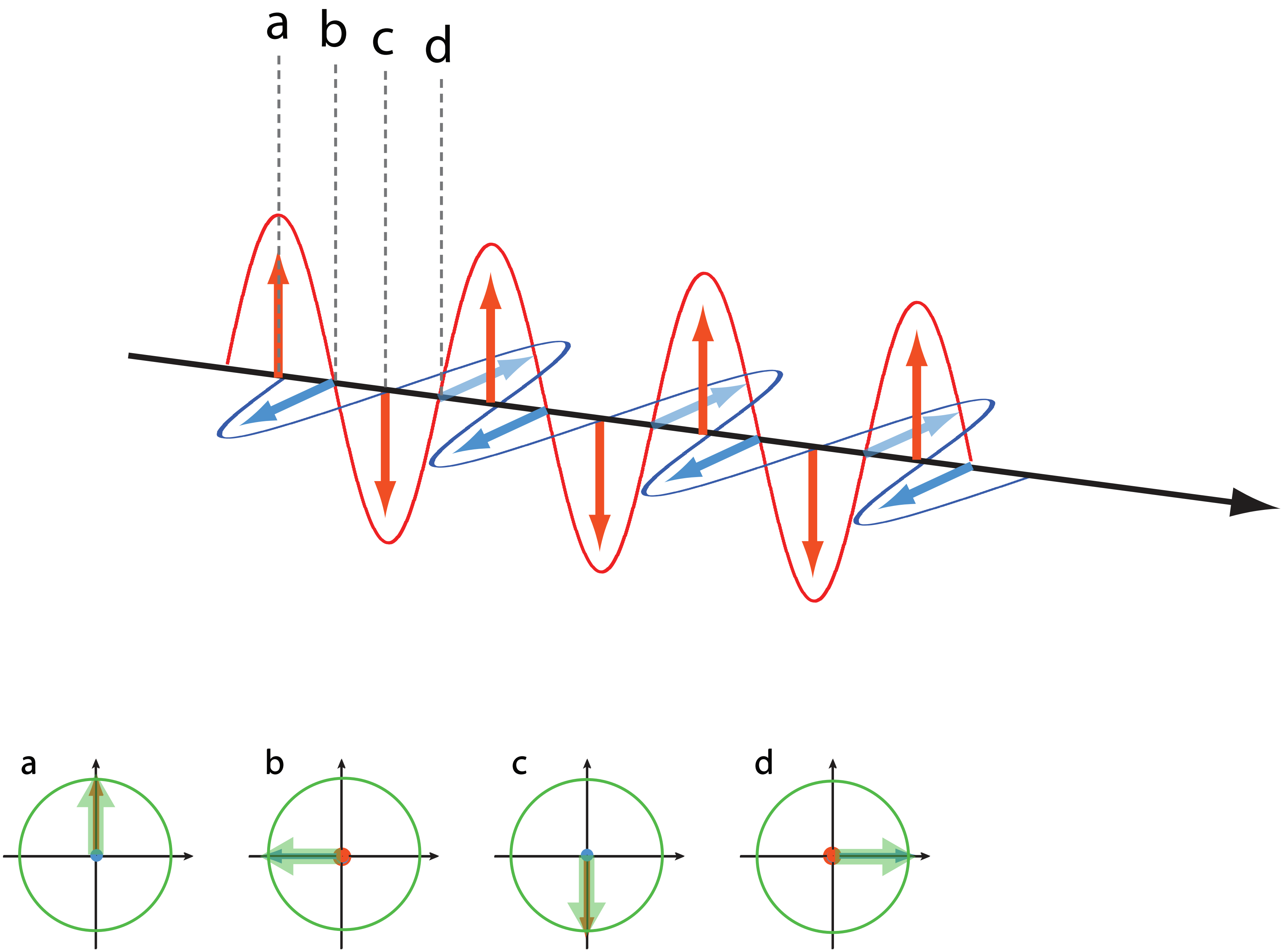

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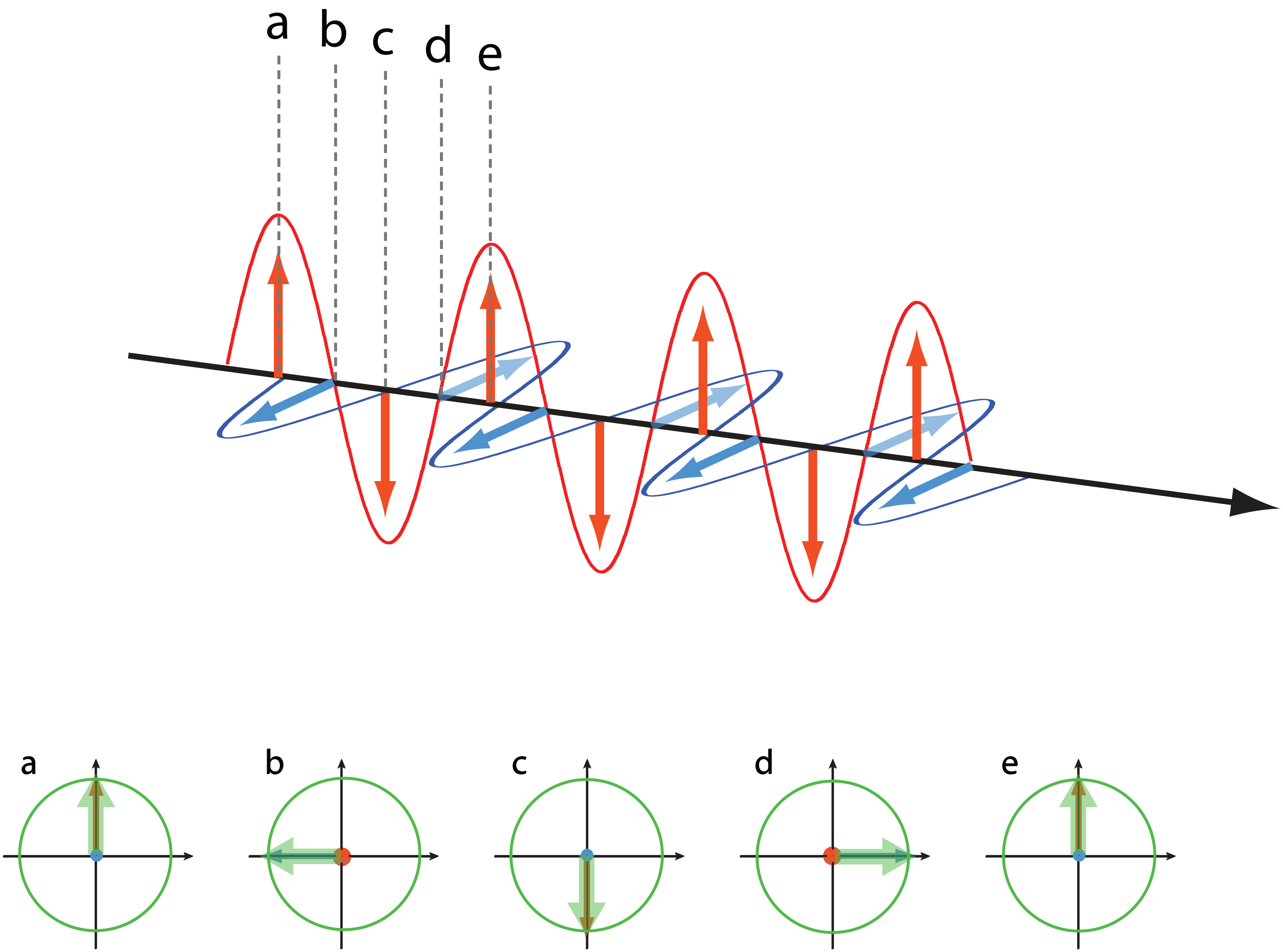

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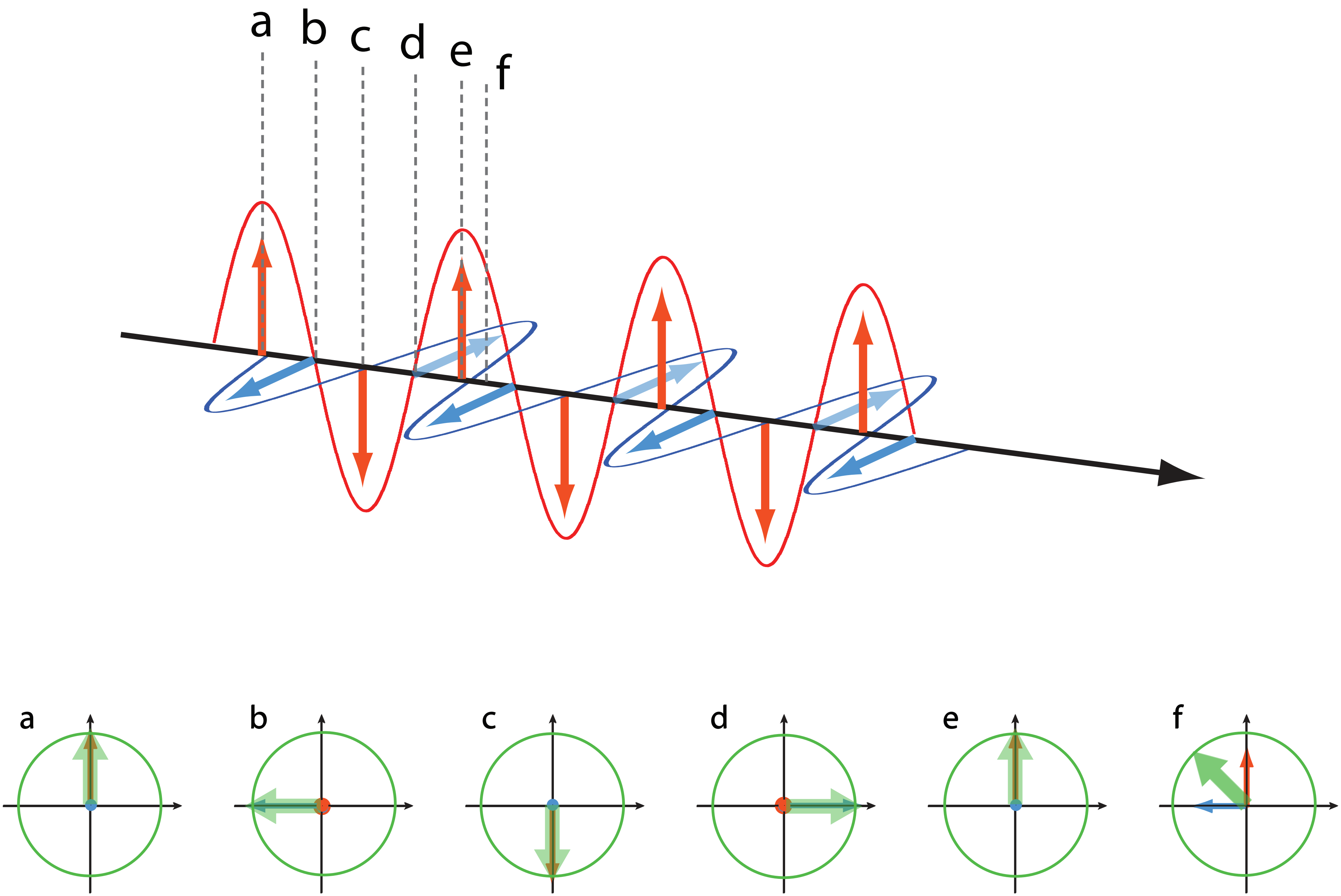
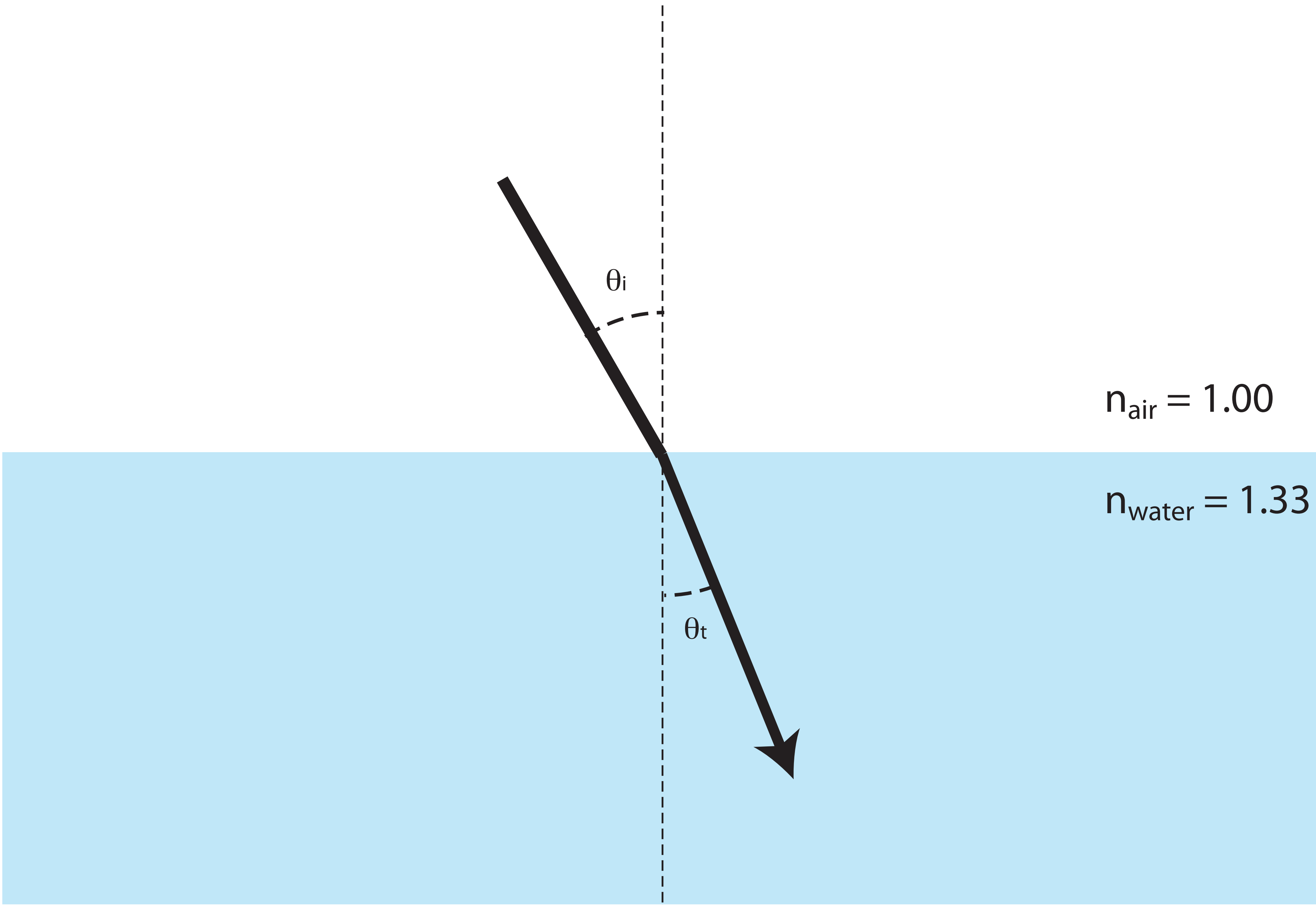


Reflection & Refraction



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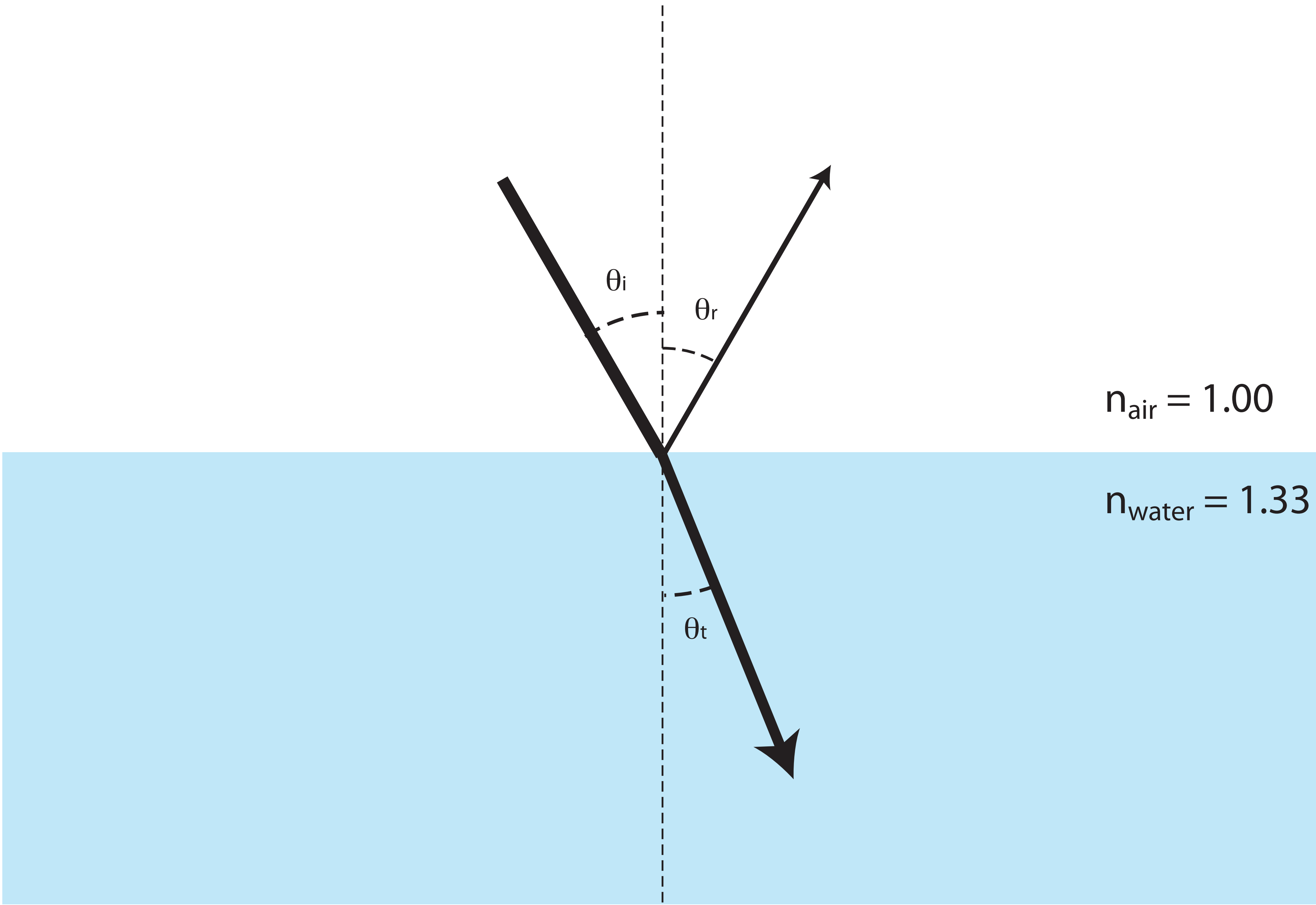
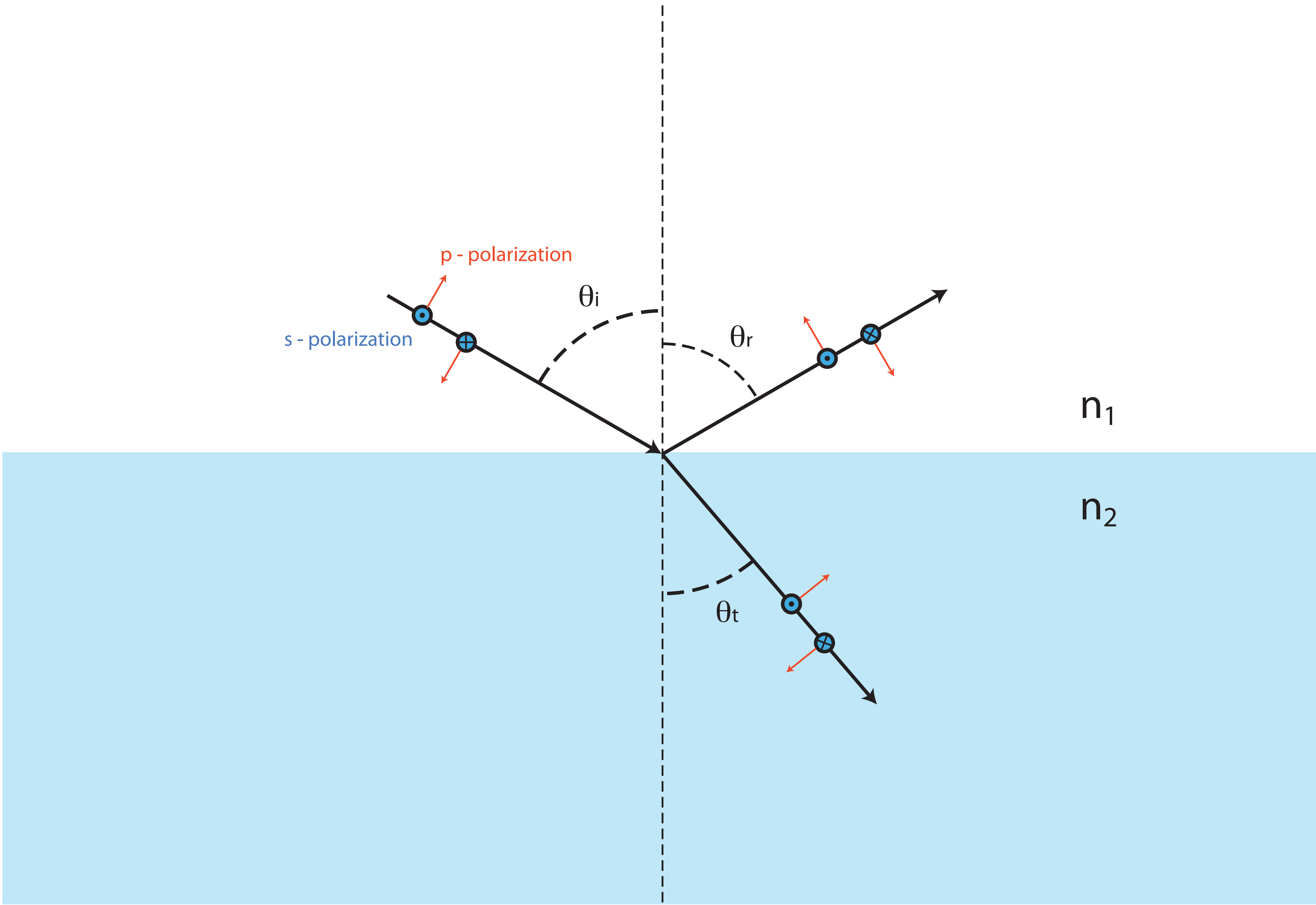


Fresnel Equations for Partial Reflection



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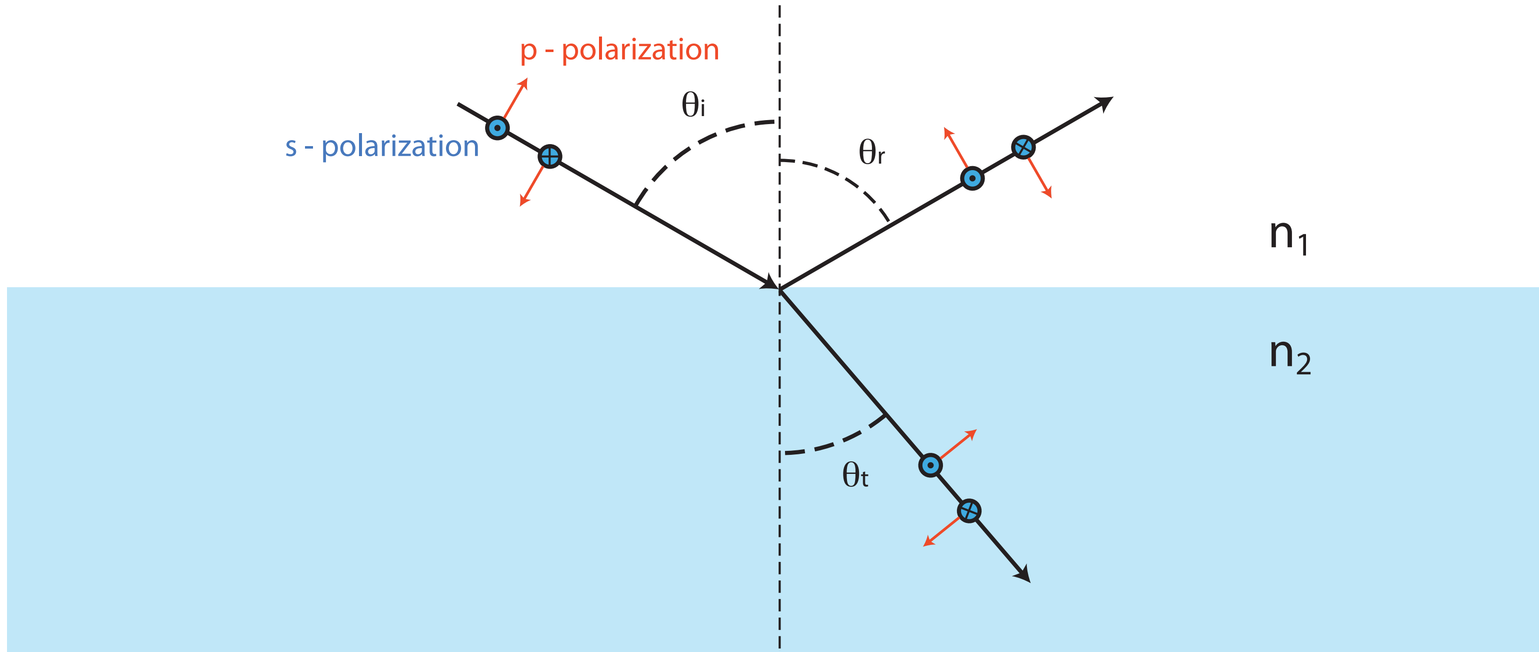
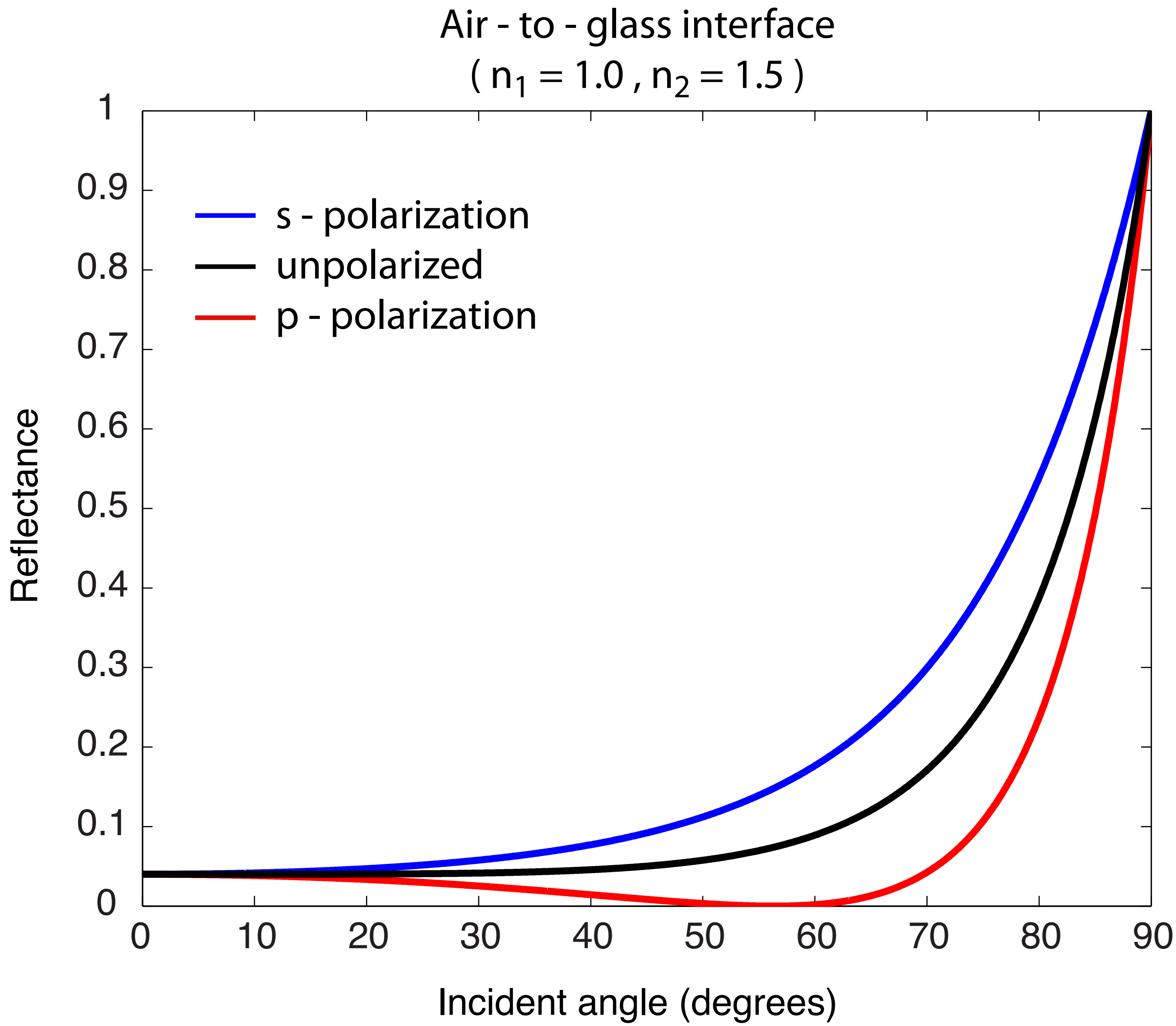
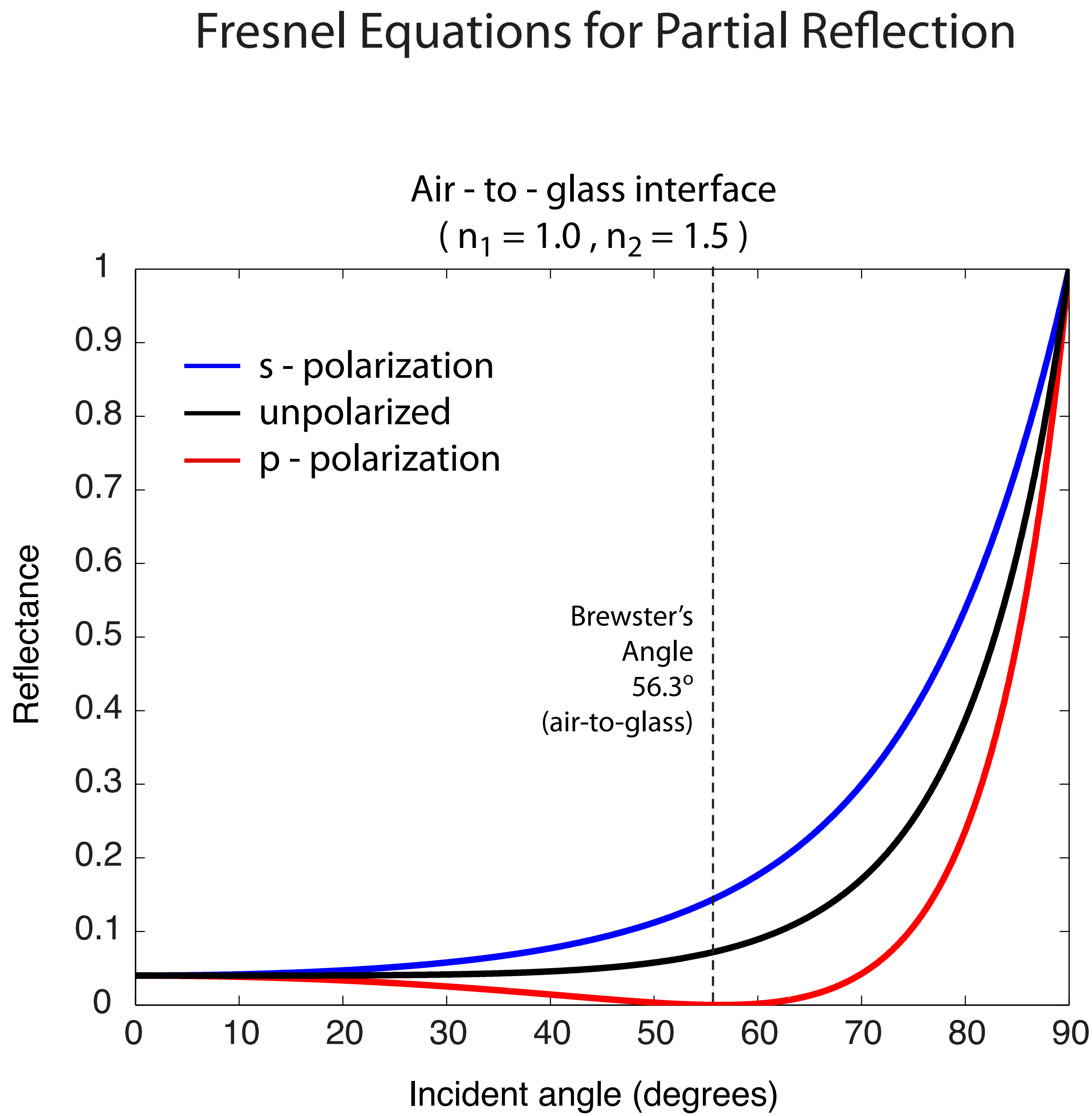


$$R_s = \left| \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right|^2 = \left| \frac{n_1 \cos\theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2}} \right|^2$$

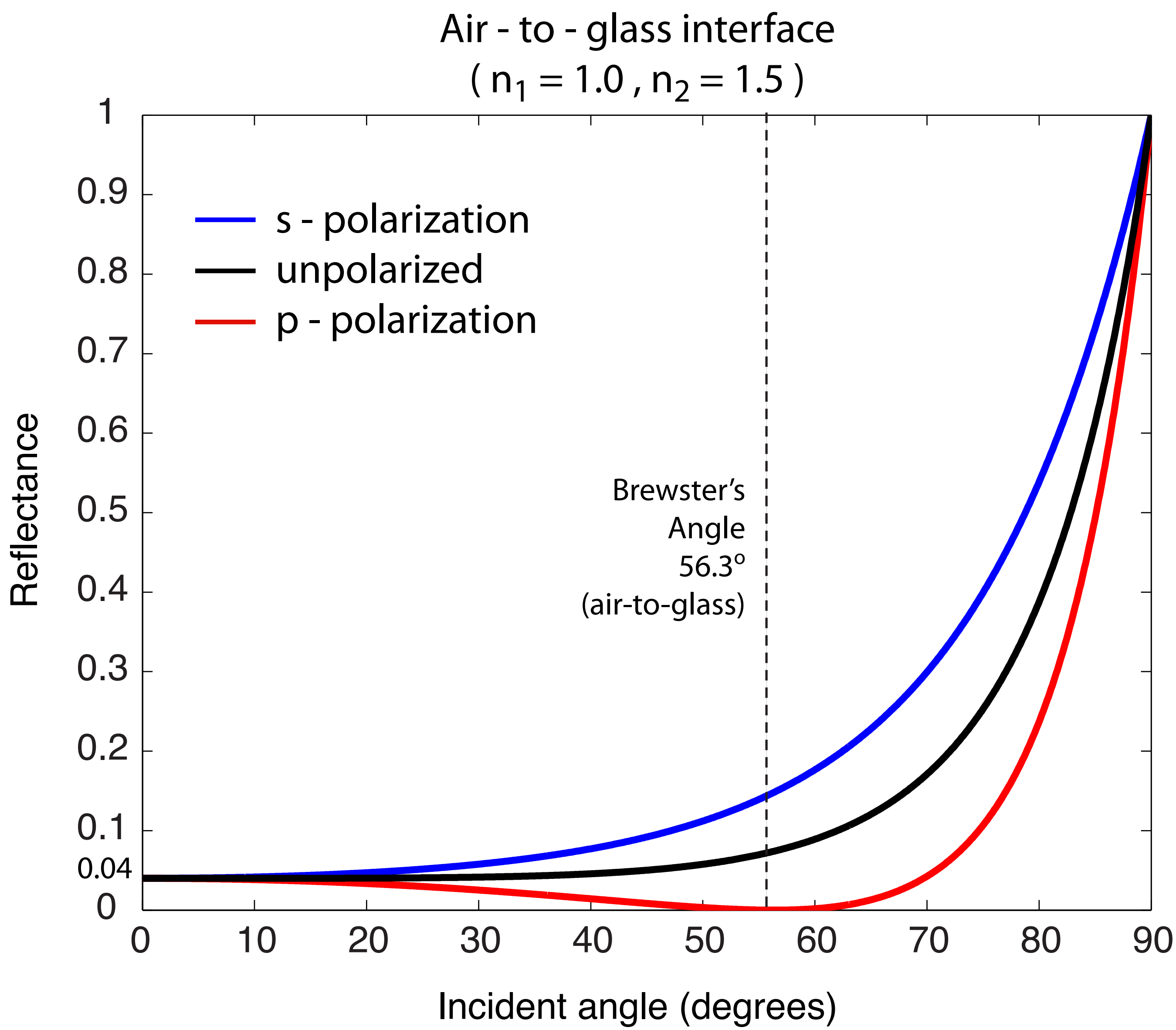
$$R_p = \left| \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2} - n_2 \cos\theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2} + n_2 \cos\theta_i} \right|^2$$

Fresnel Equations for Partial Reflection

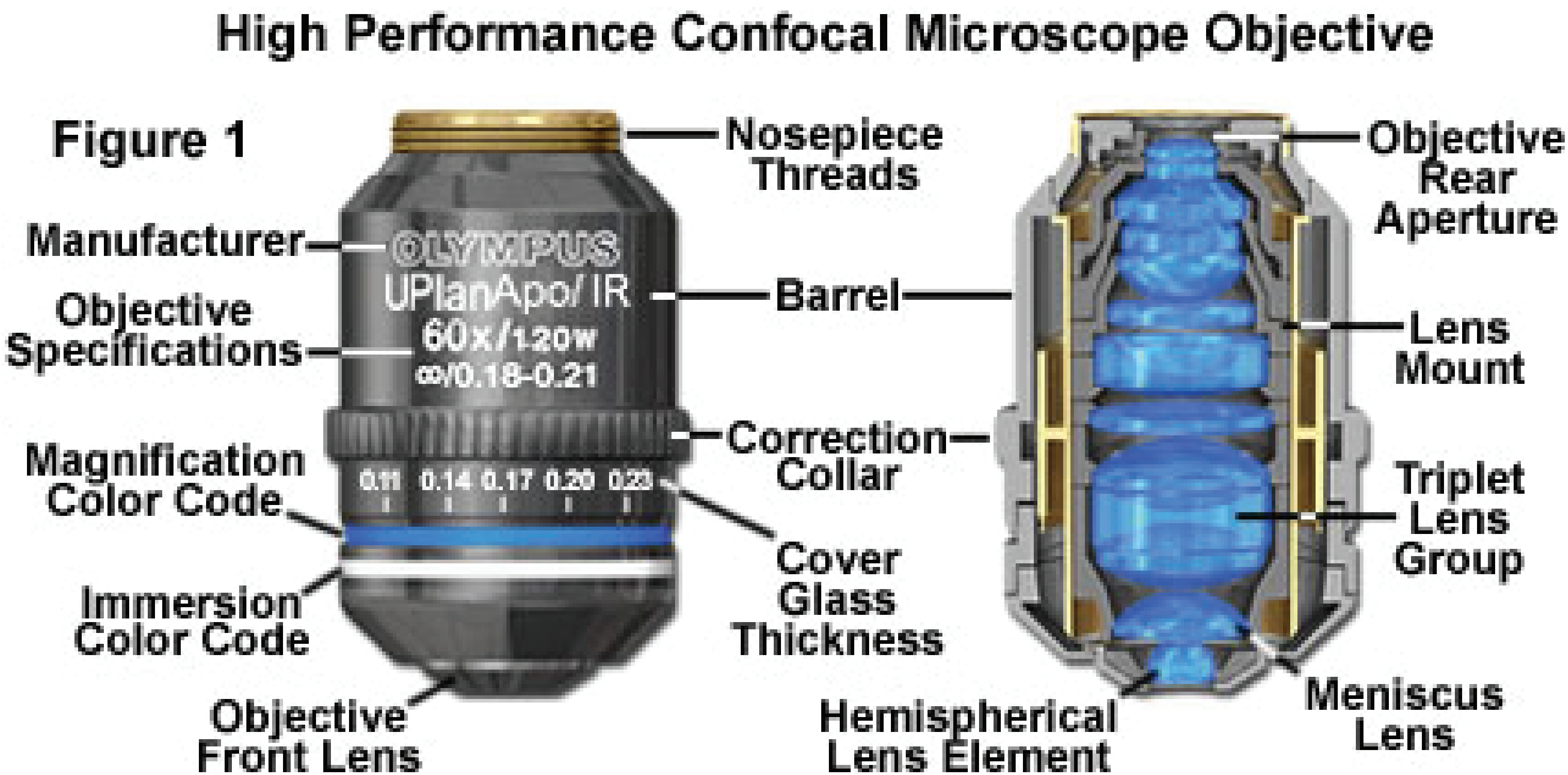



Fresnel Equations for Partial Reflection
Air - to - glass interface
(n1 = 1.0 , n2 = 1.5)
s - polarization
unpolarized
p - polarization
Brewster's
Angle
56.3°
(air-to-glass)
Reflectance
Incident angle (degrees)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90

Fresnel Equations for Partial Reflection



Oh Photon, How do I miss thee? Let me count the ways?



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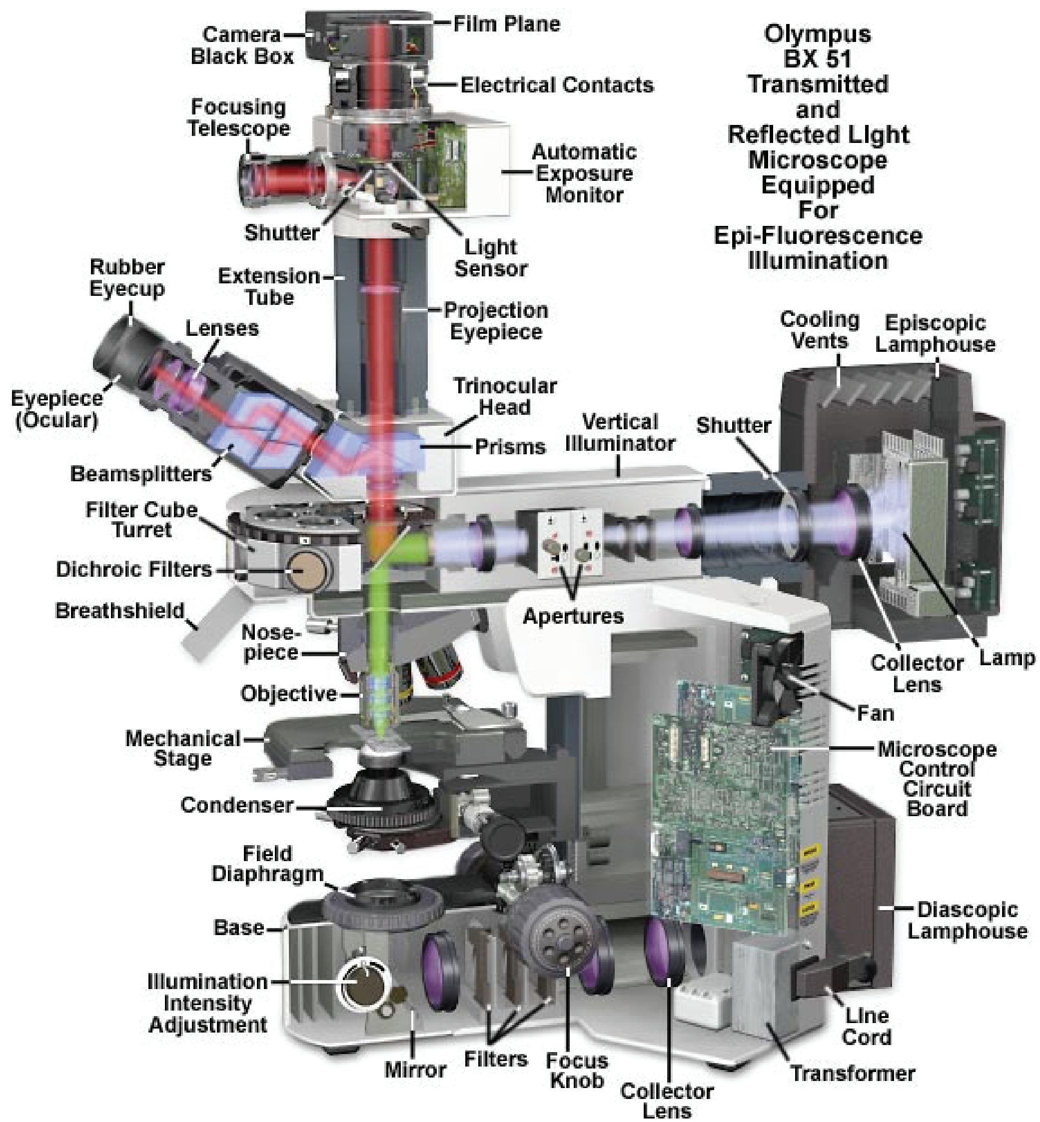

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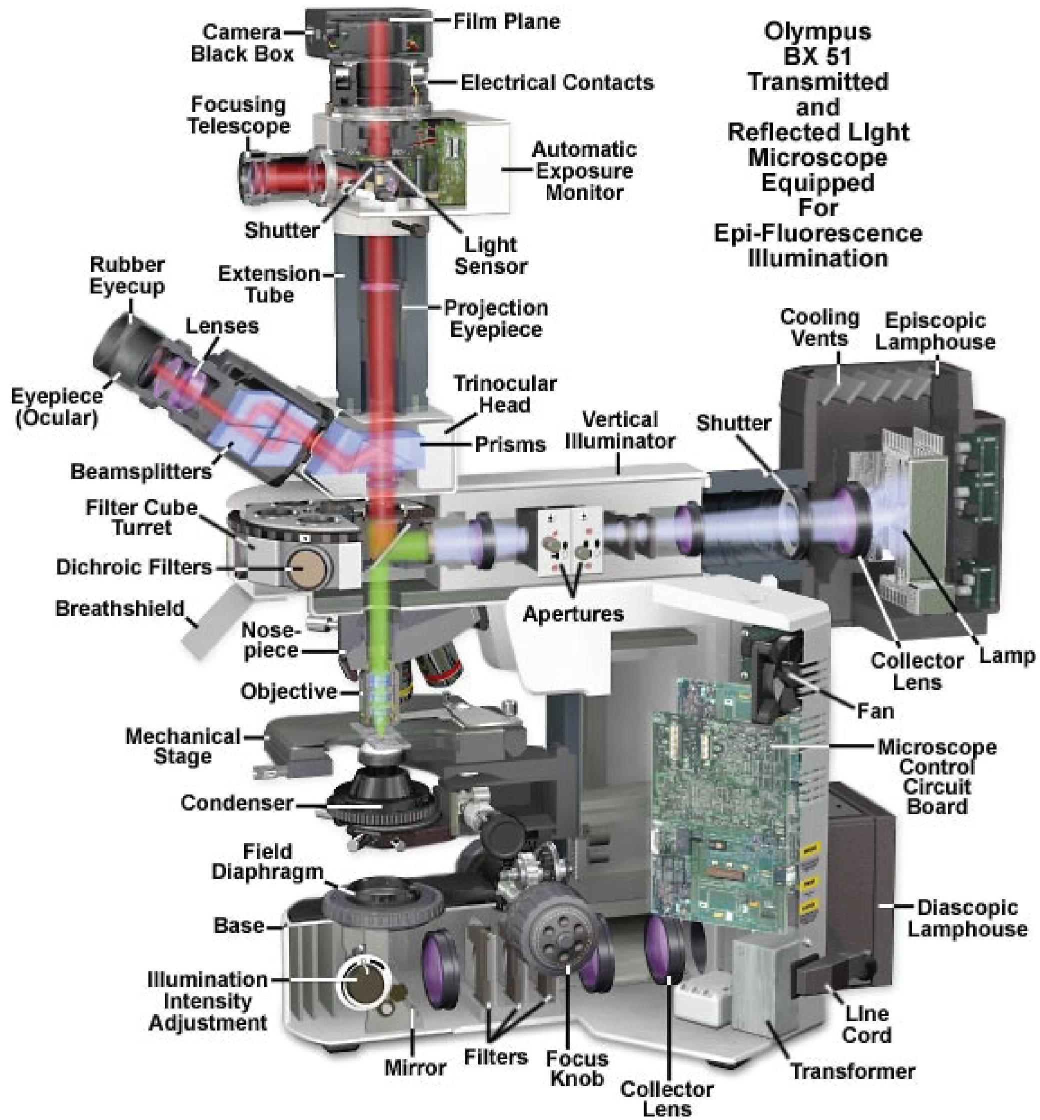

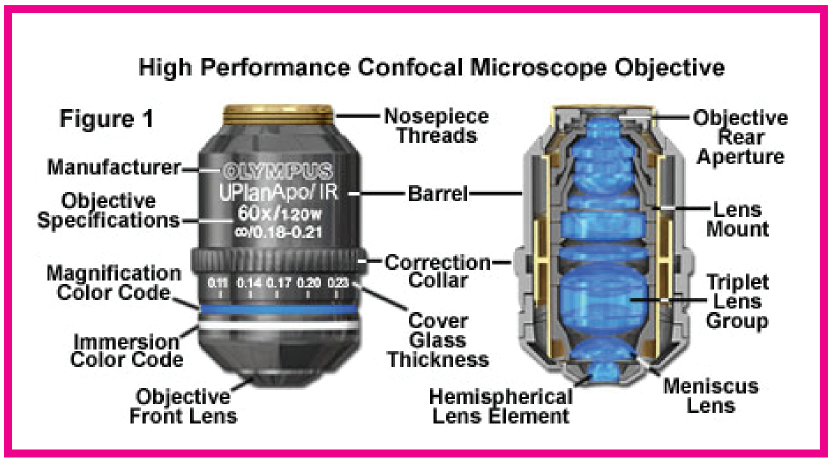

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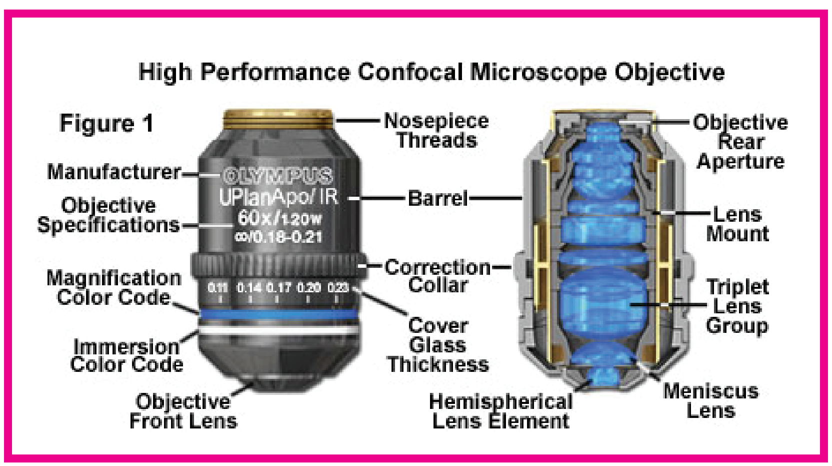

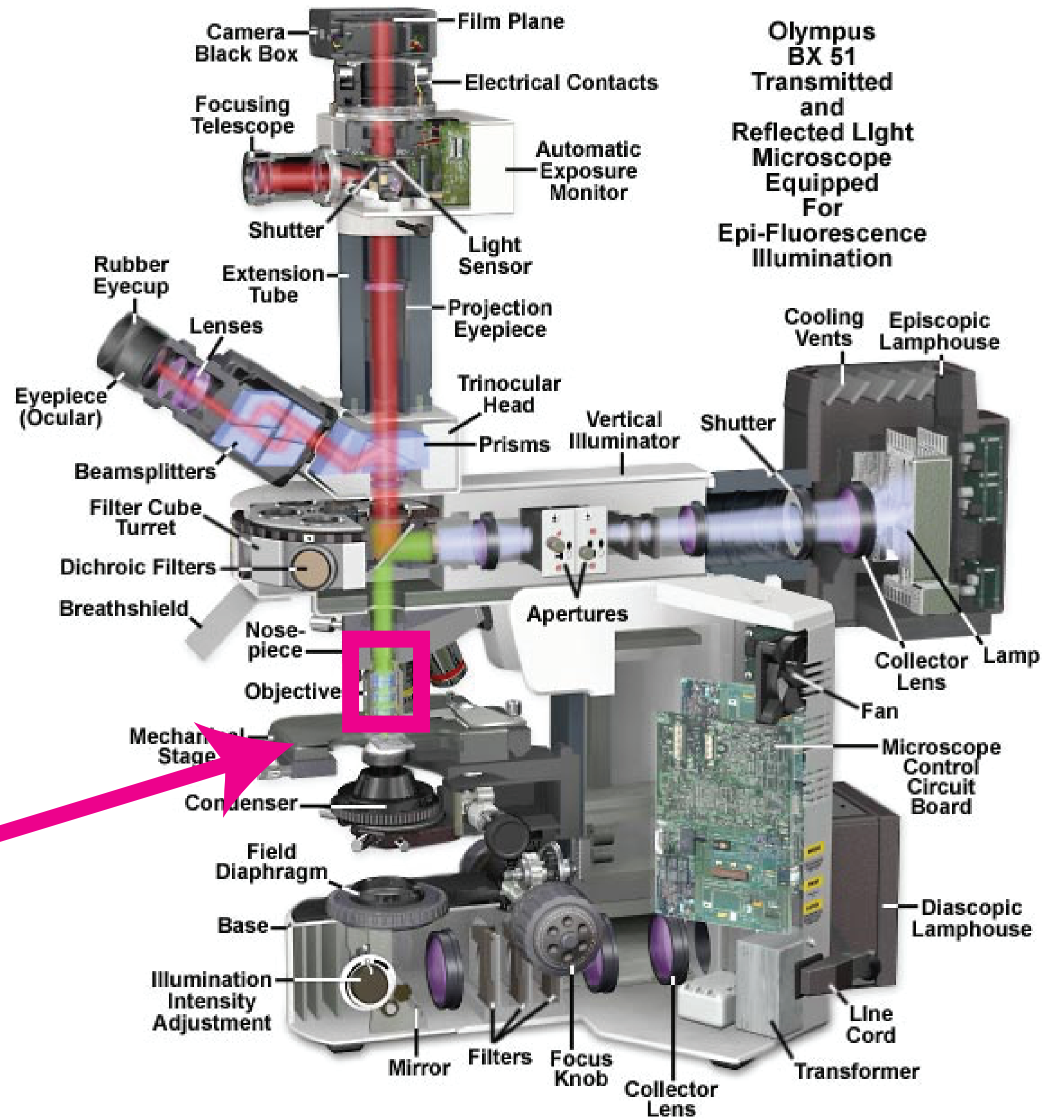

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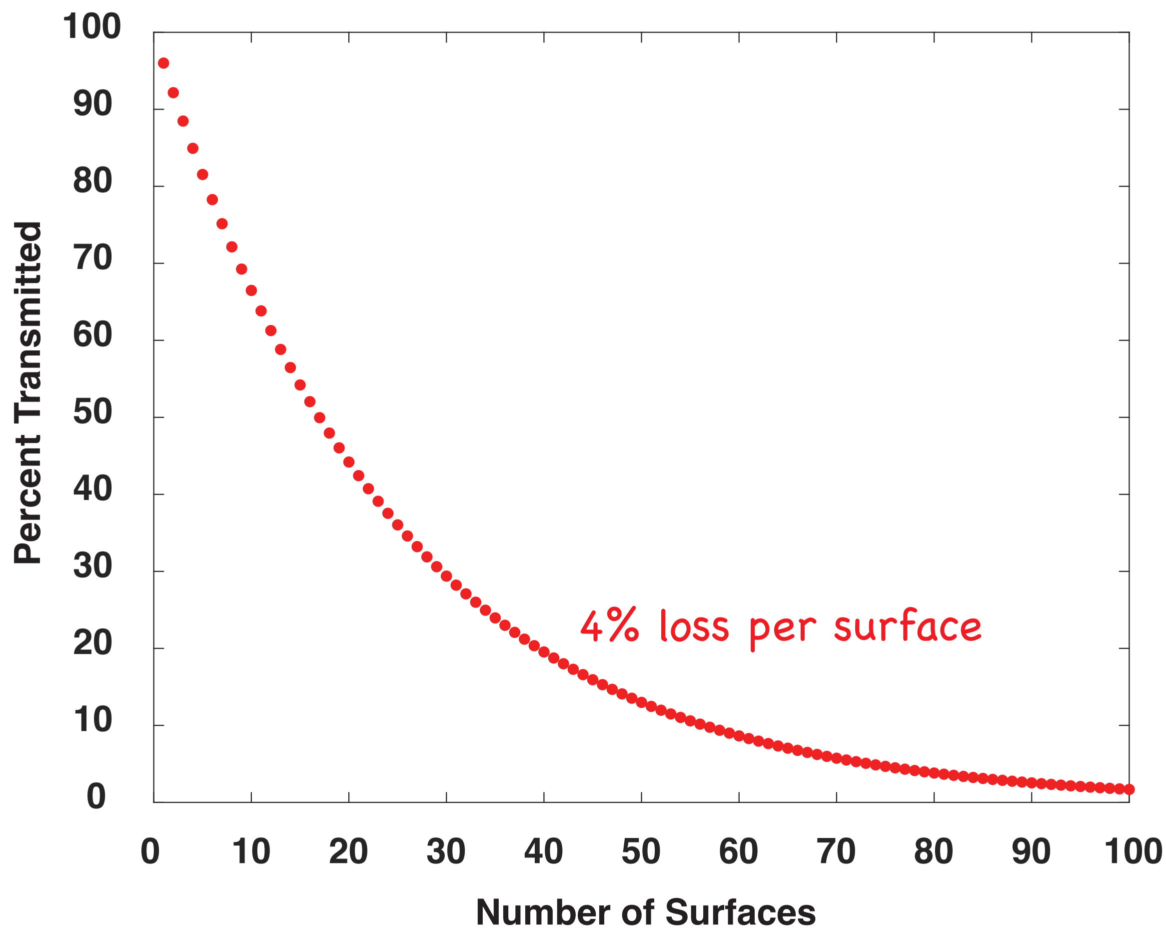

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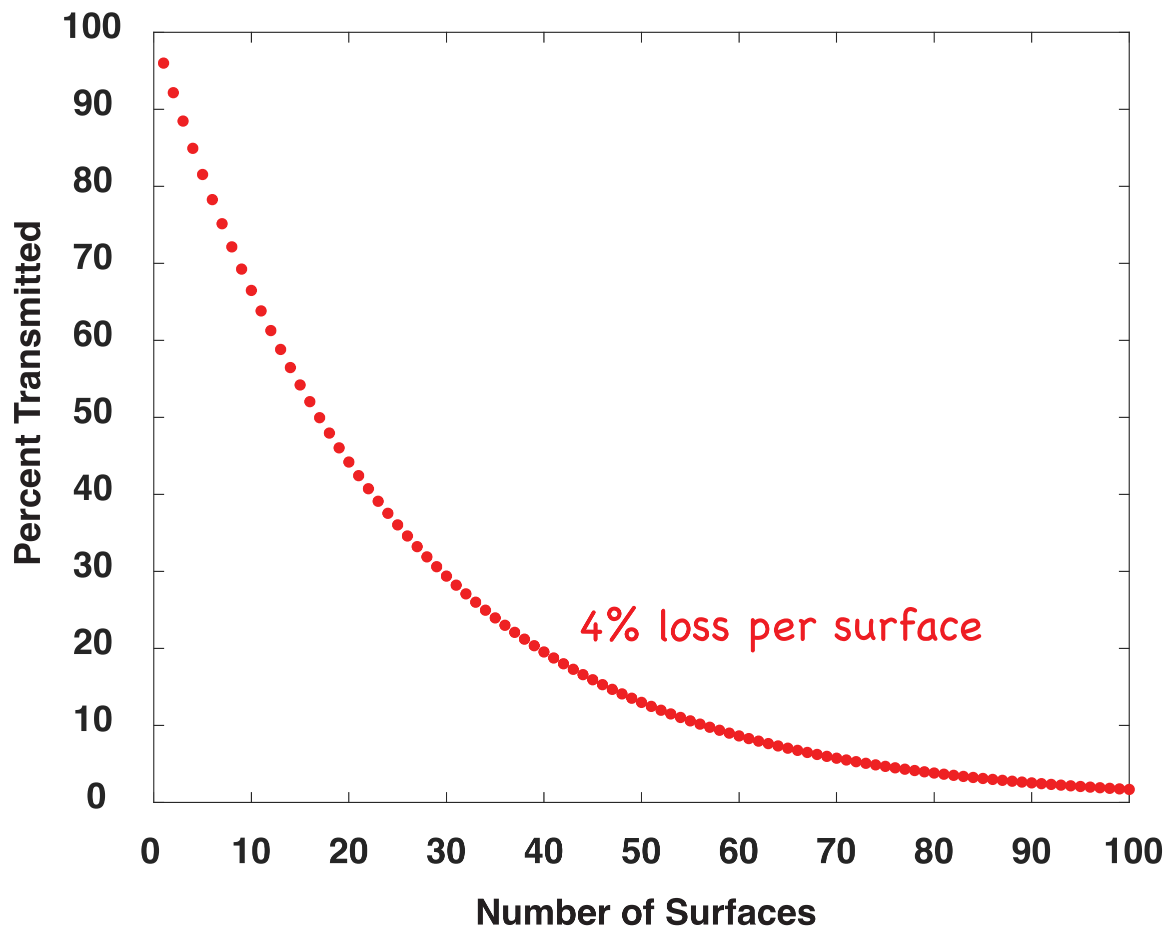

+1			LA1207	N-BK7 Plano-Convex Lens, Ø1/2", f = 100.0 mm, Uncoated	$18.87
+1			LA1207-A	N-BK7 Plano-Convex Lens, Ø1/2", f = 100.0 mm, AR Coating: 350-700 nm	$29.07

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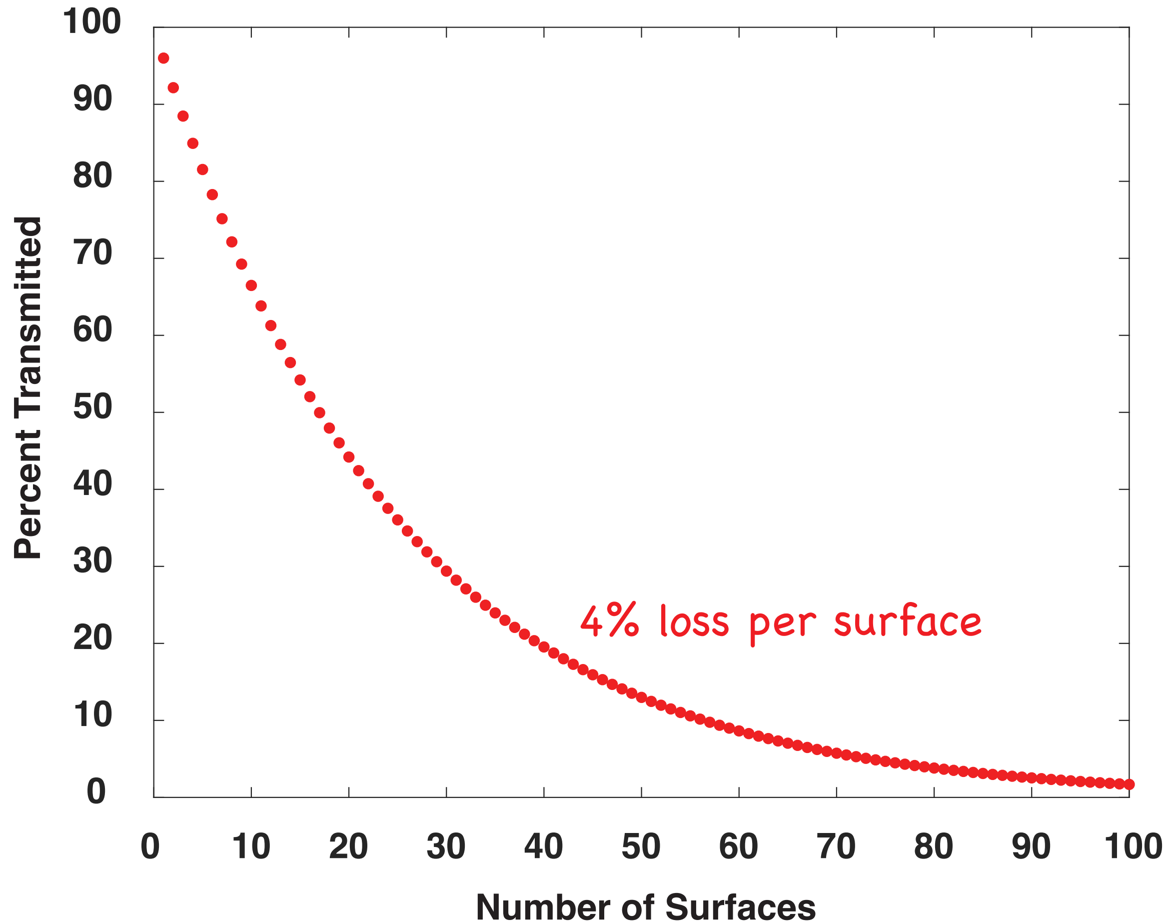

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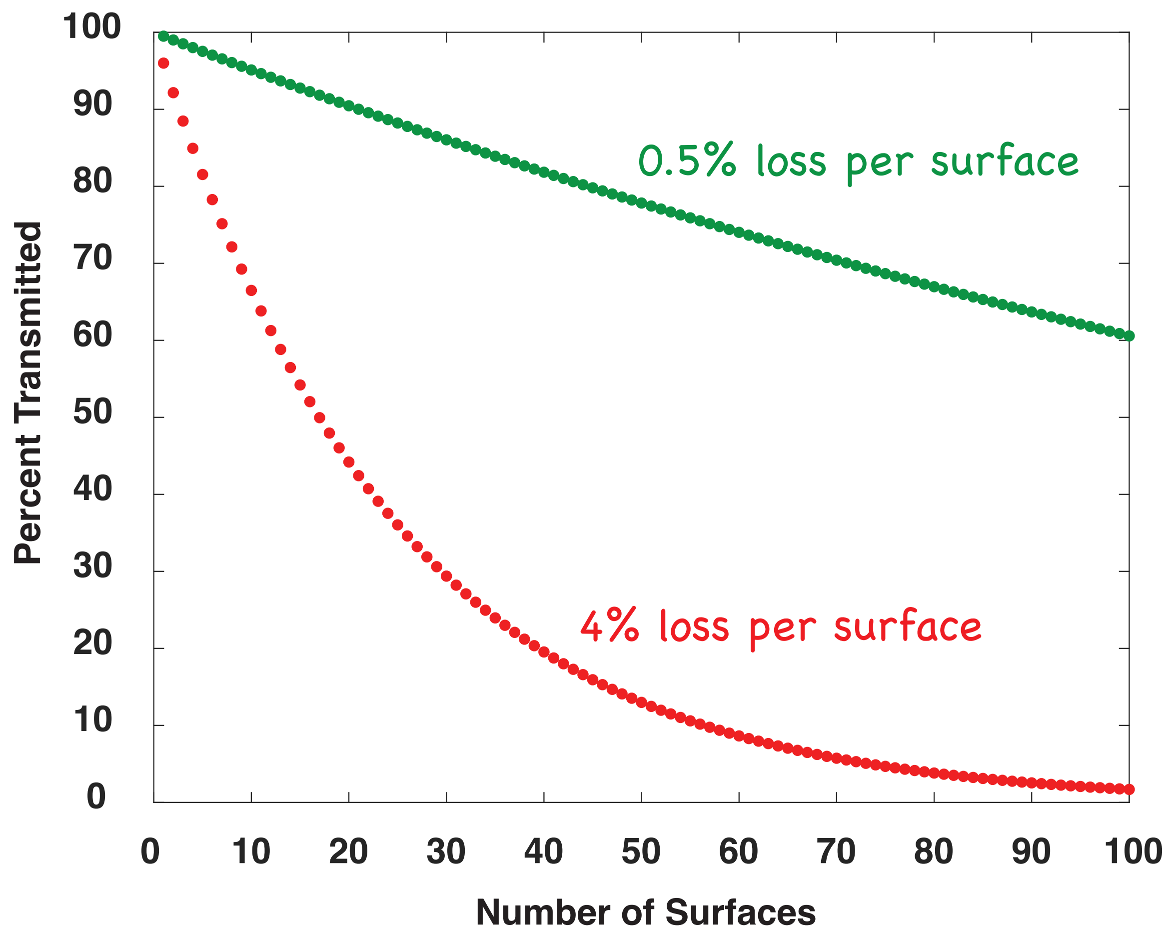
AR Coating Range	350 - 700 nm (-A Coating)
Reflectance over Coating Range (Avg.)	<0.50%

Oh Photon, How do I miss thee? Let me count the ways?



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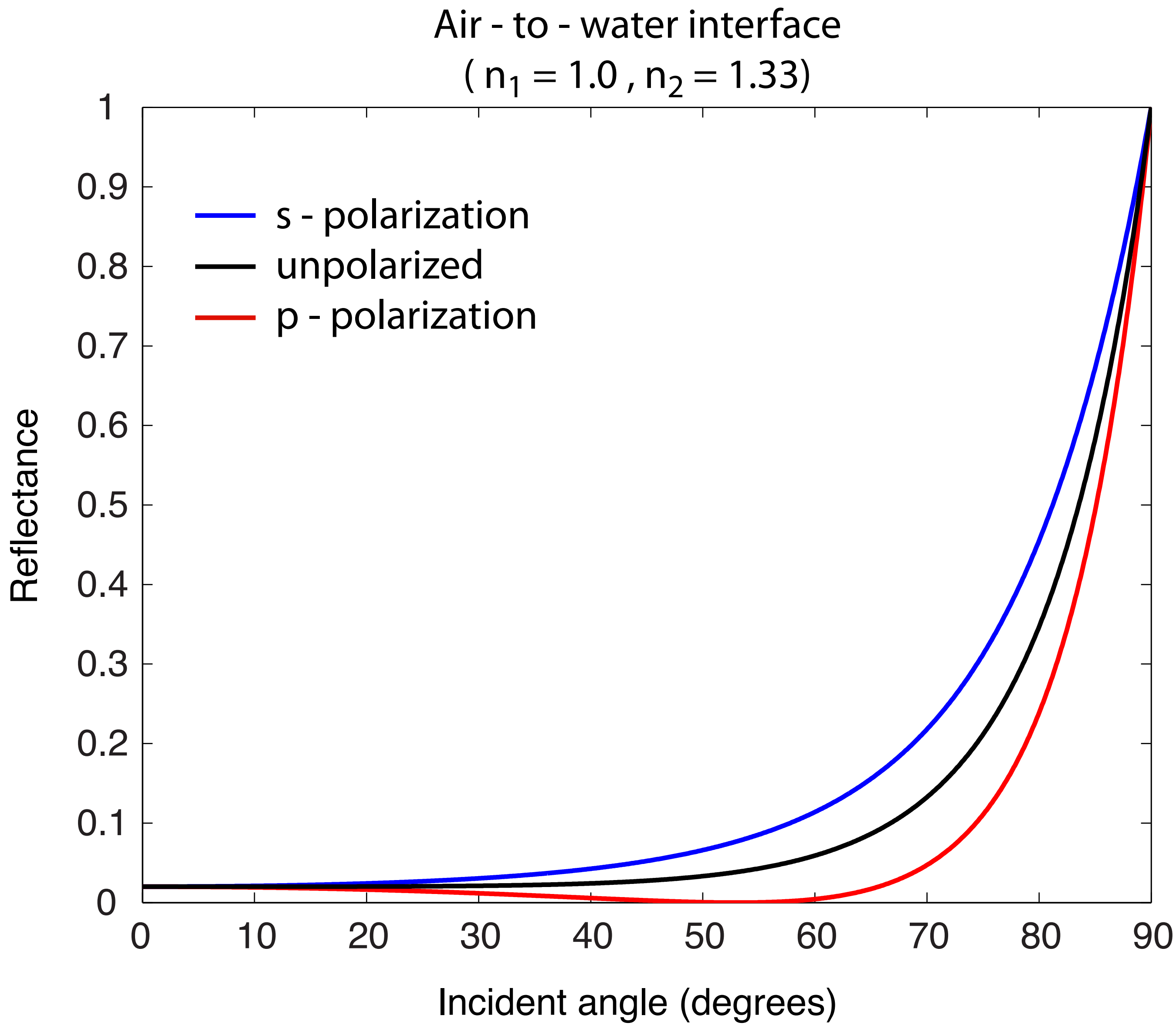
Fresnel Equations for Partial Reflection



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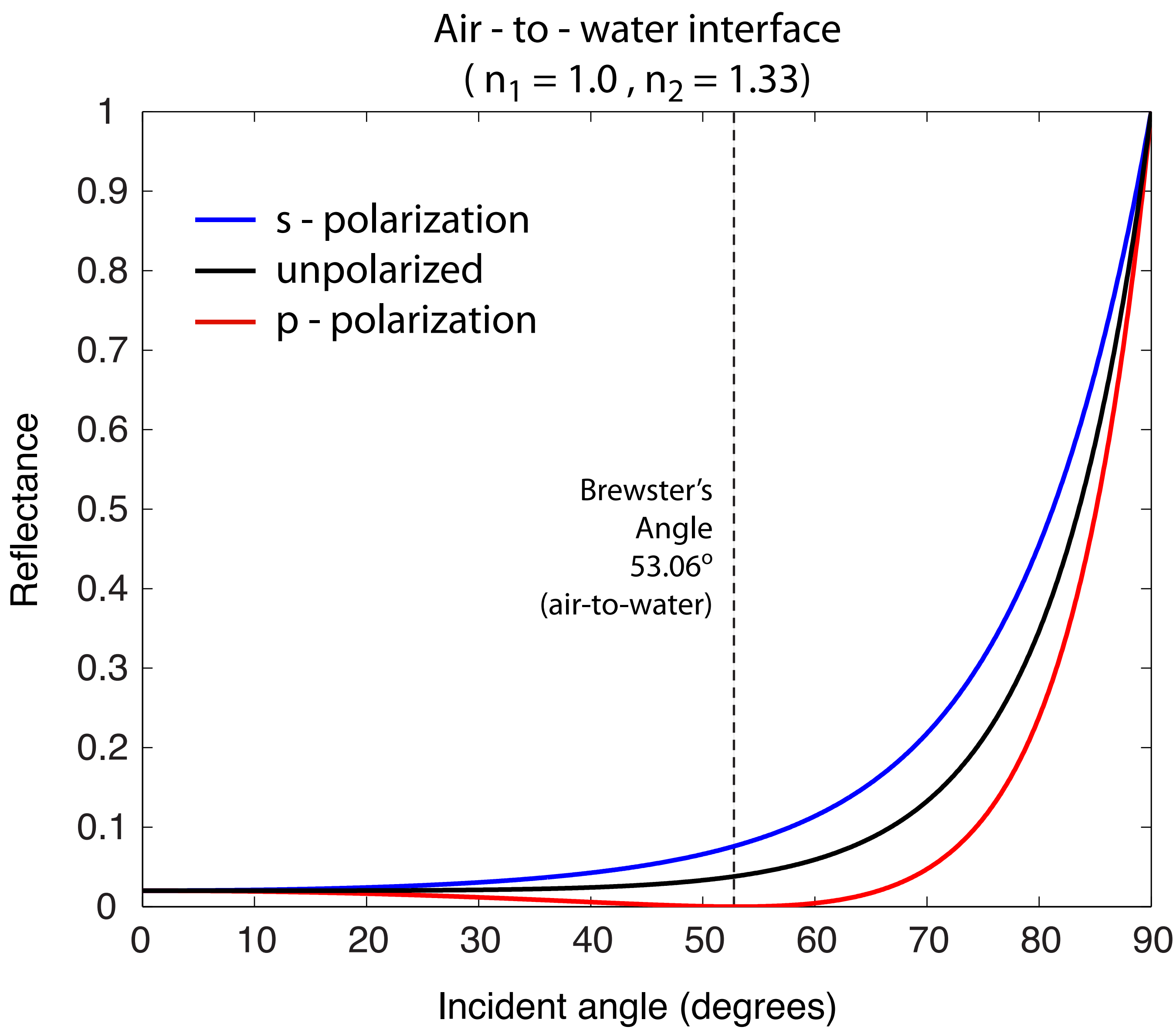
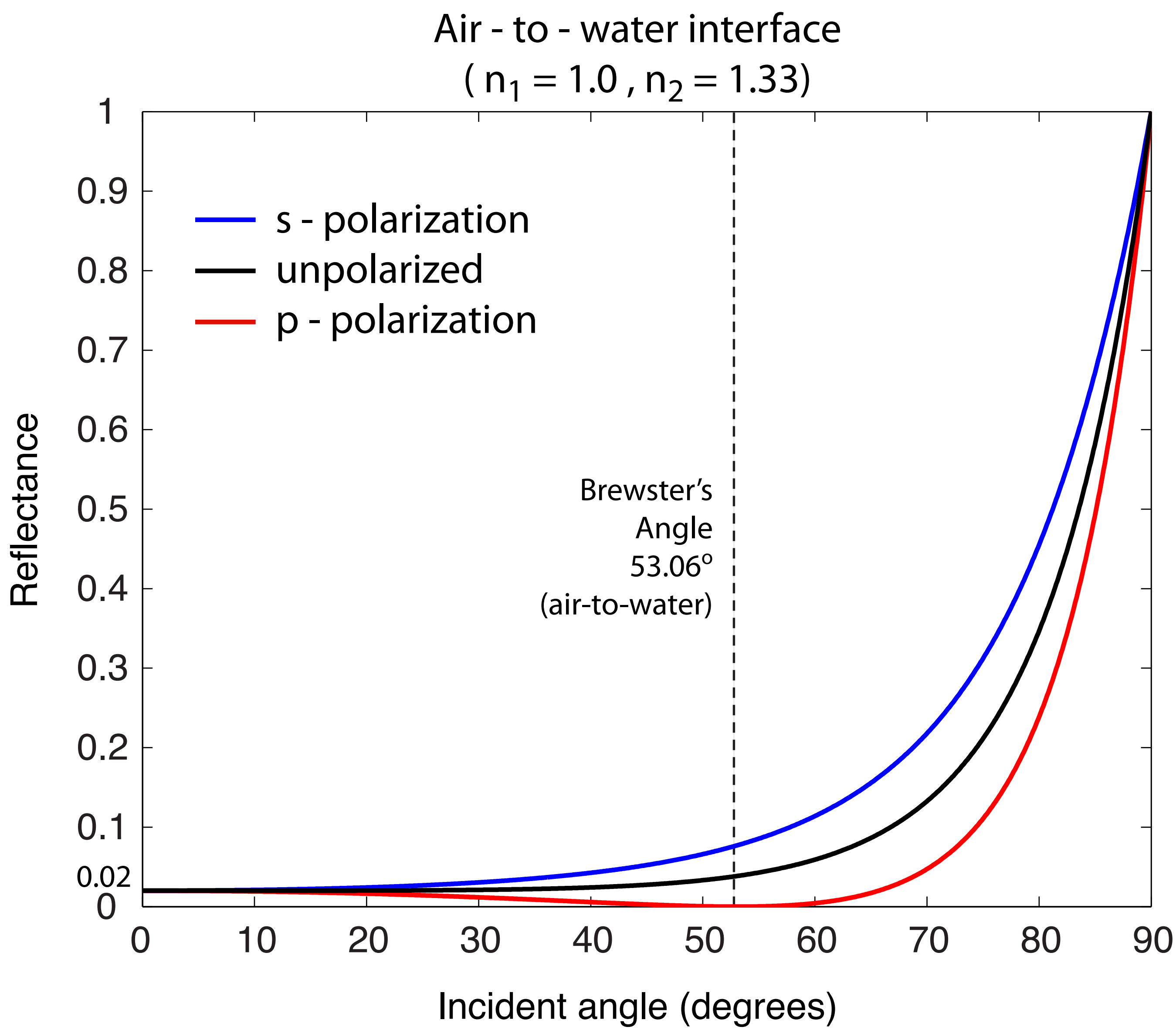
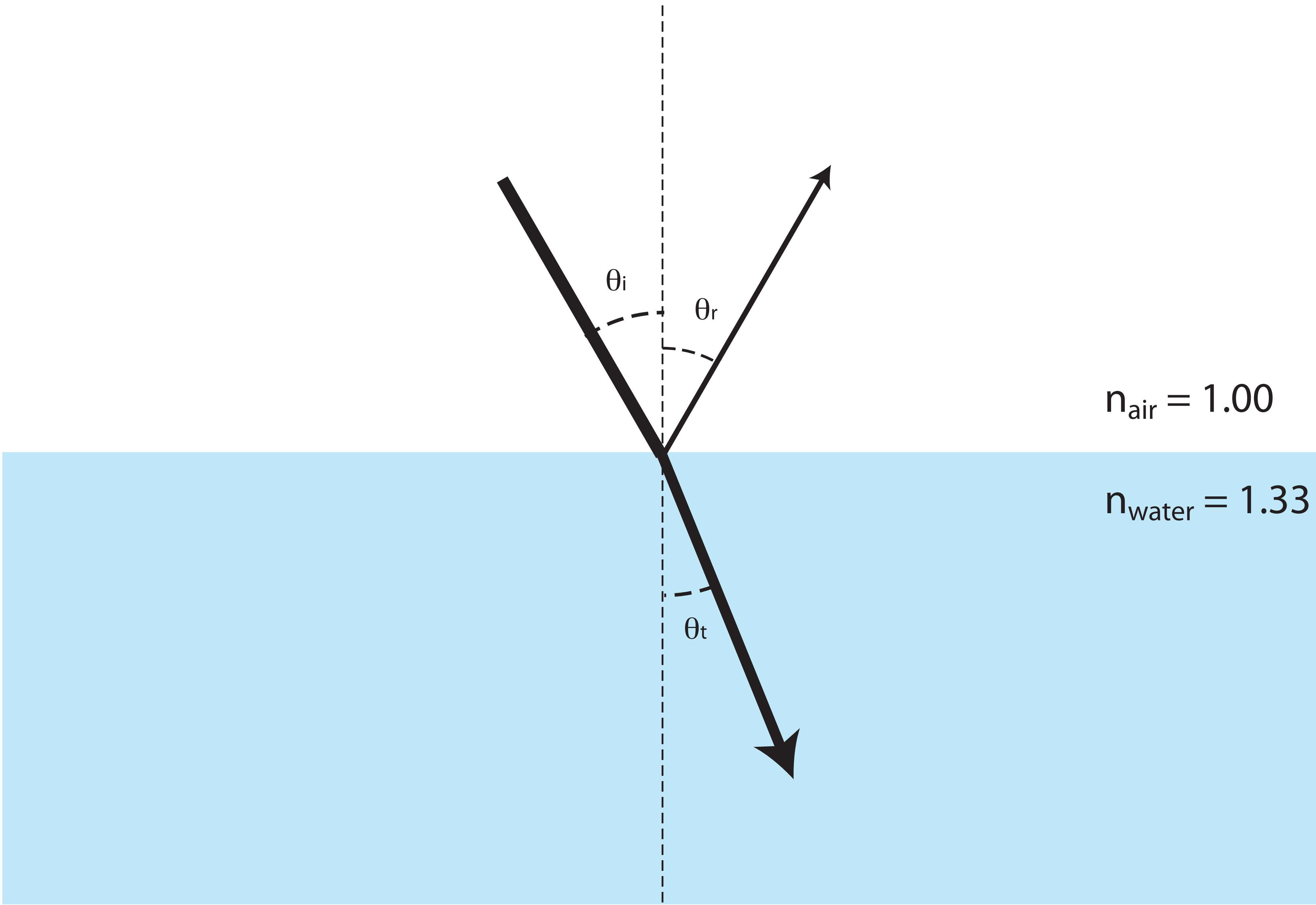
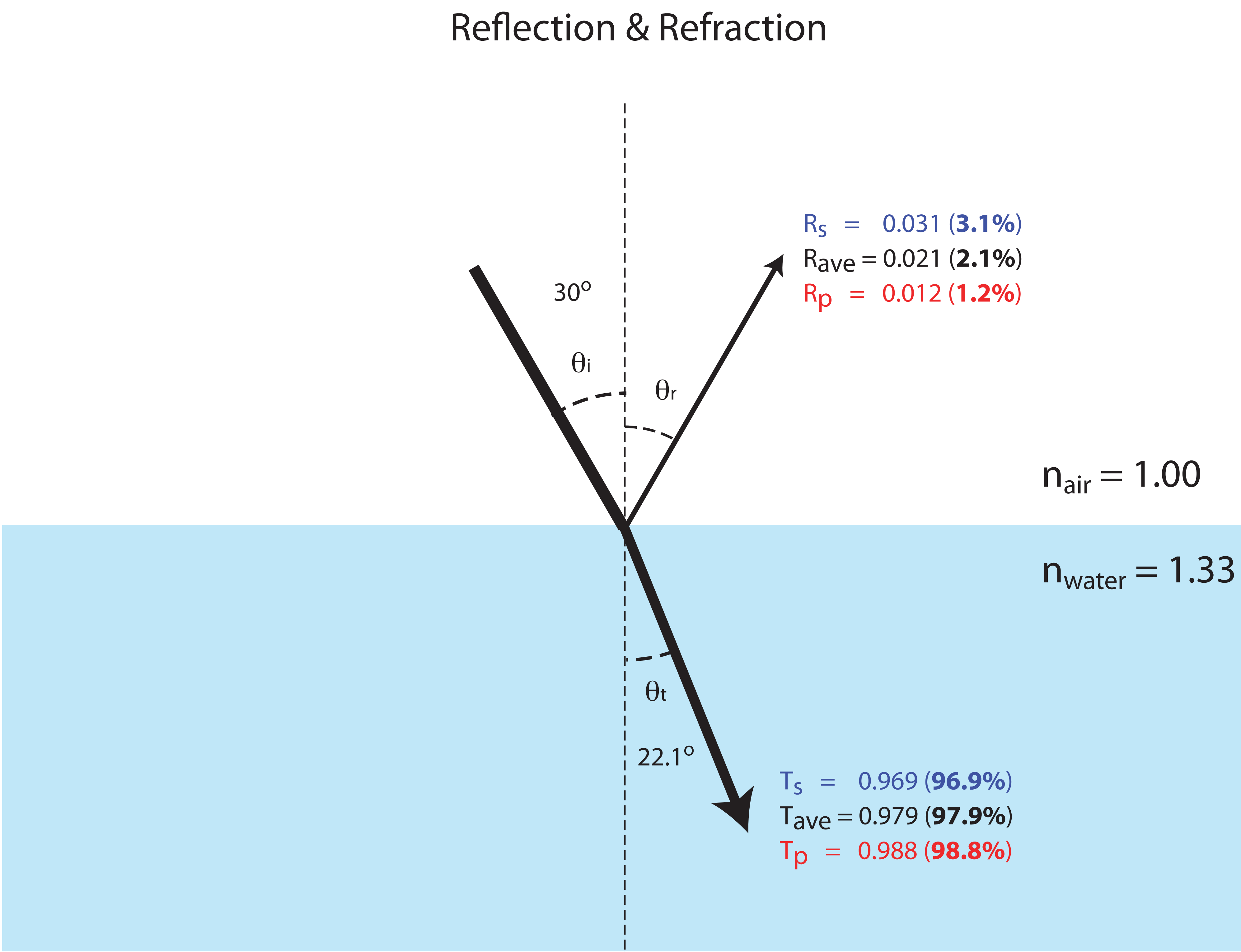


Fresnel Equations for Partial Reflection

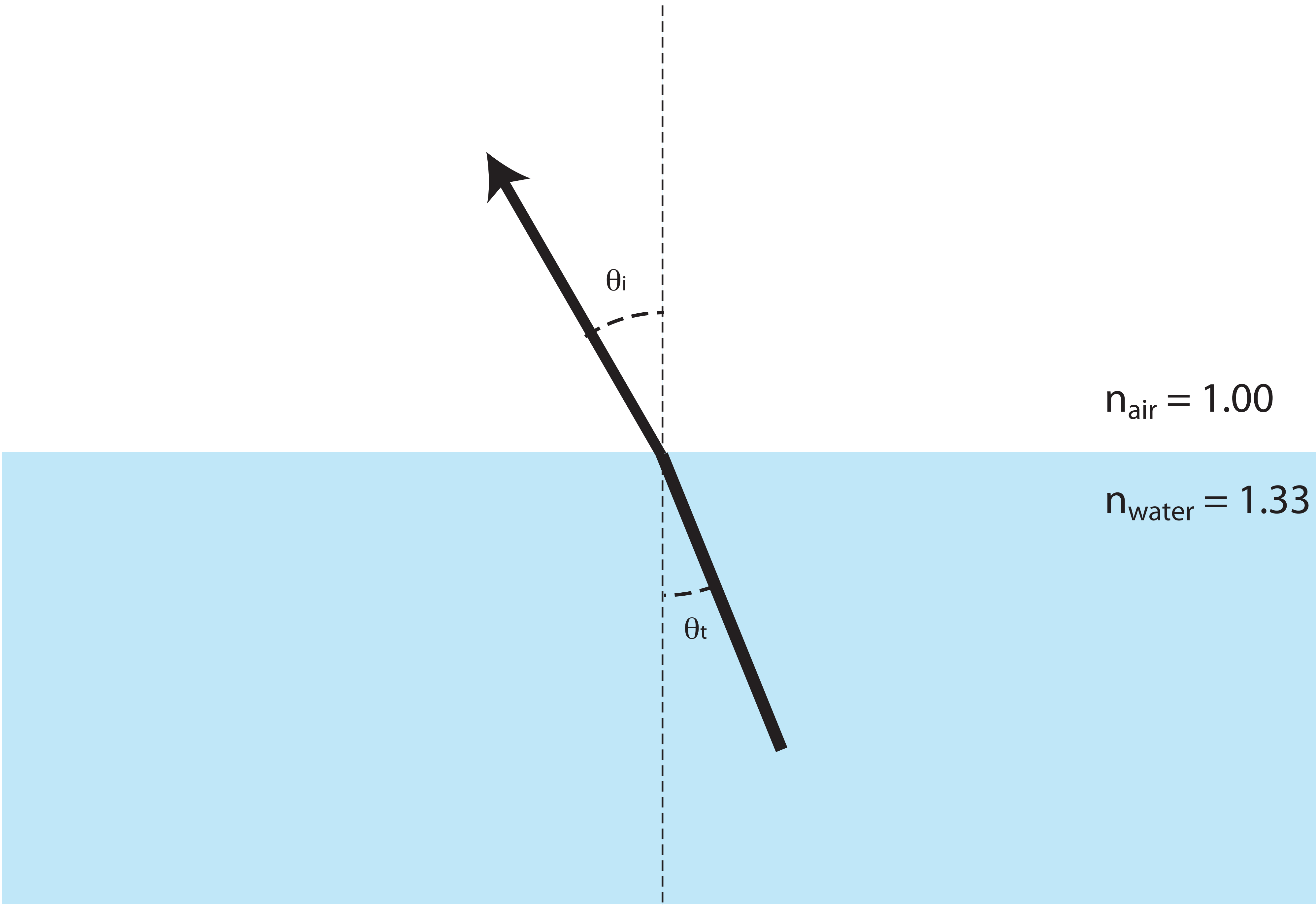


Reflection & Refraction

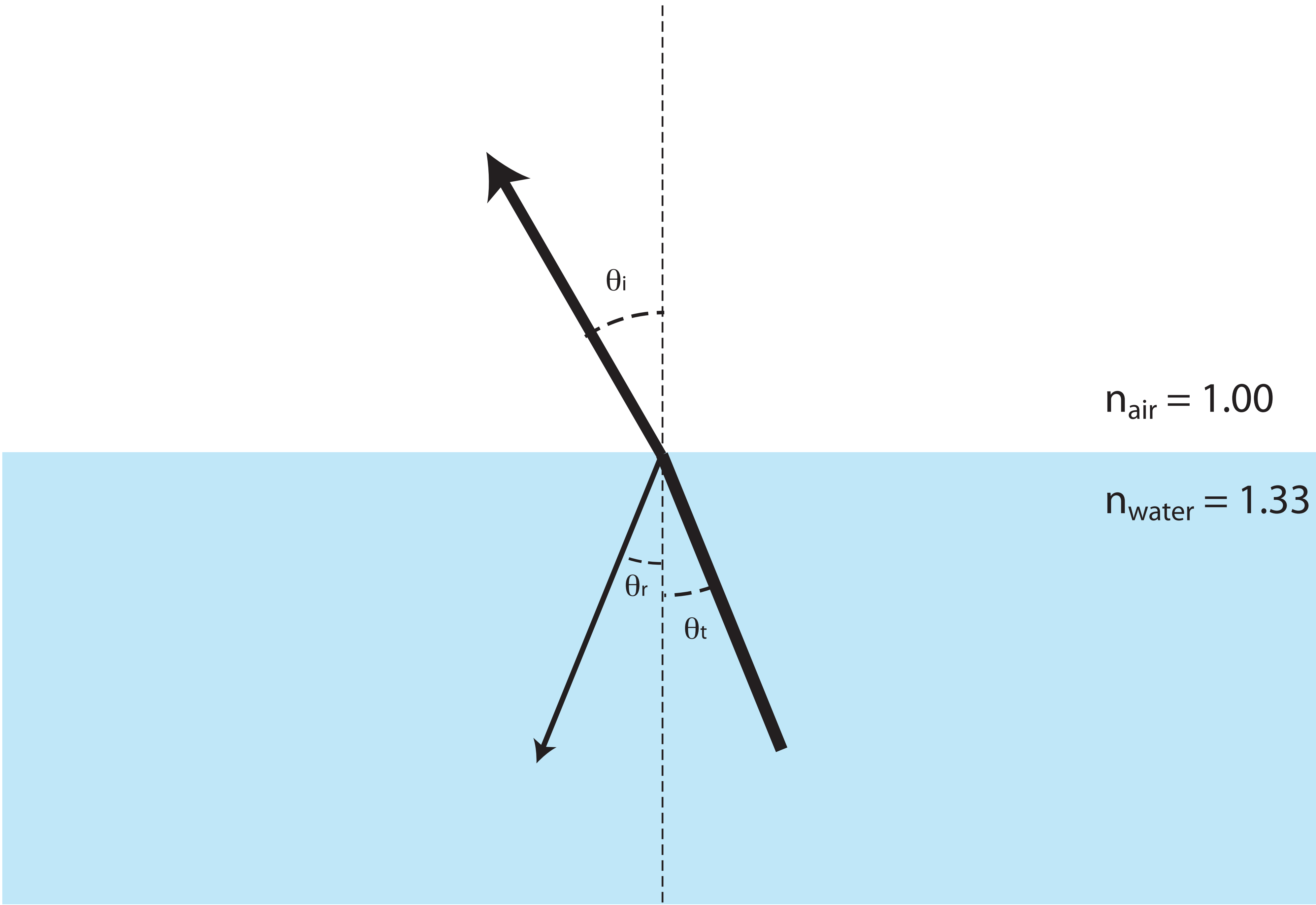


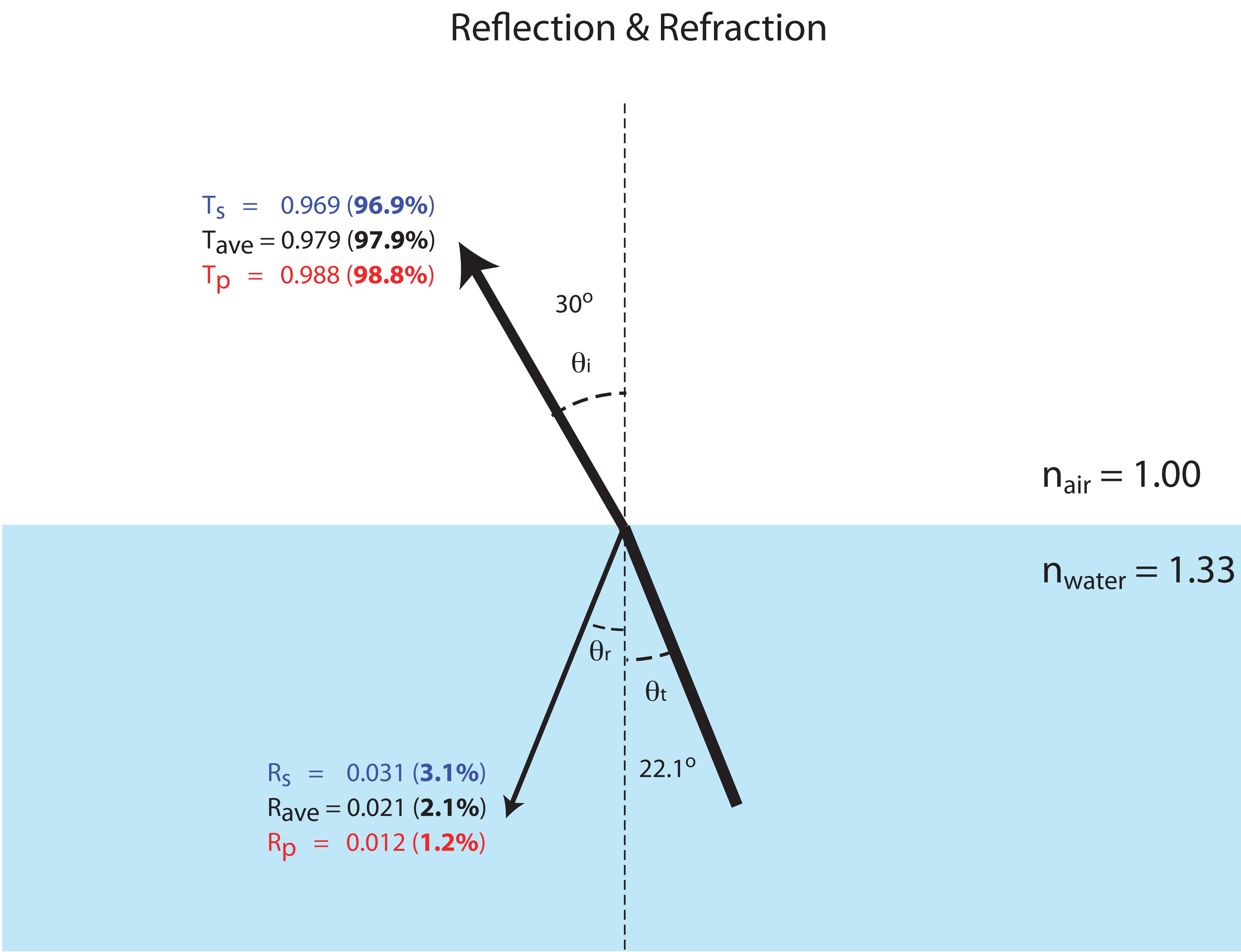

Reflection & Refraction
30°
θi
θr
Rs = 0.031 (3.1%)
Rave = 0.021 (2.1%)
Rp = 0.012 (1.2%)
nair = 1.00
nwater = 1.33
θt
22.1°
Ts = 0.969 (96.9%)
Tave = 0.979 (97.9%)
Tp = 0.988 (98.8%)

Reflection & Refraction



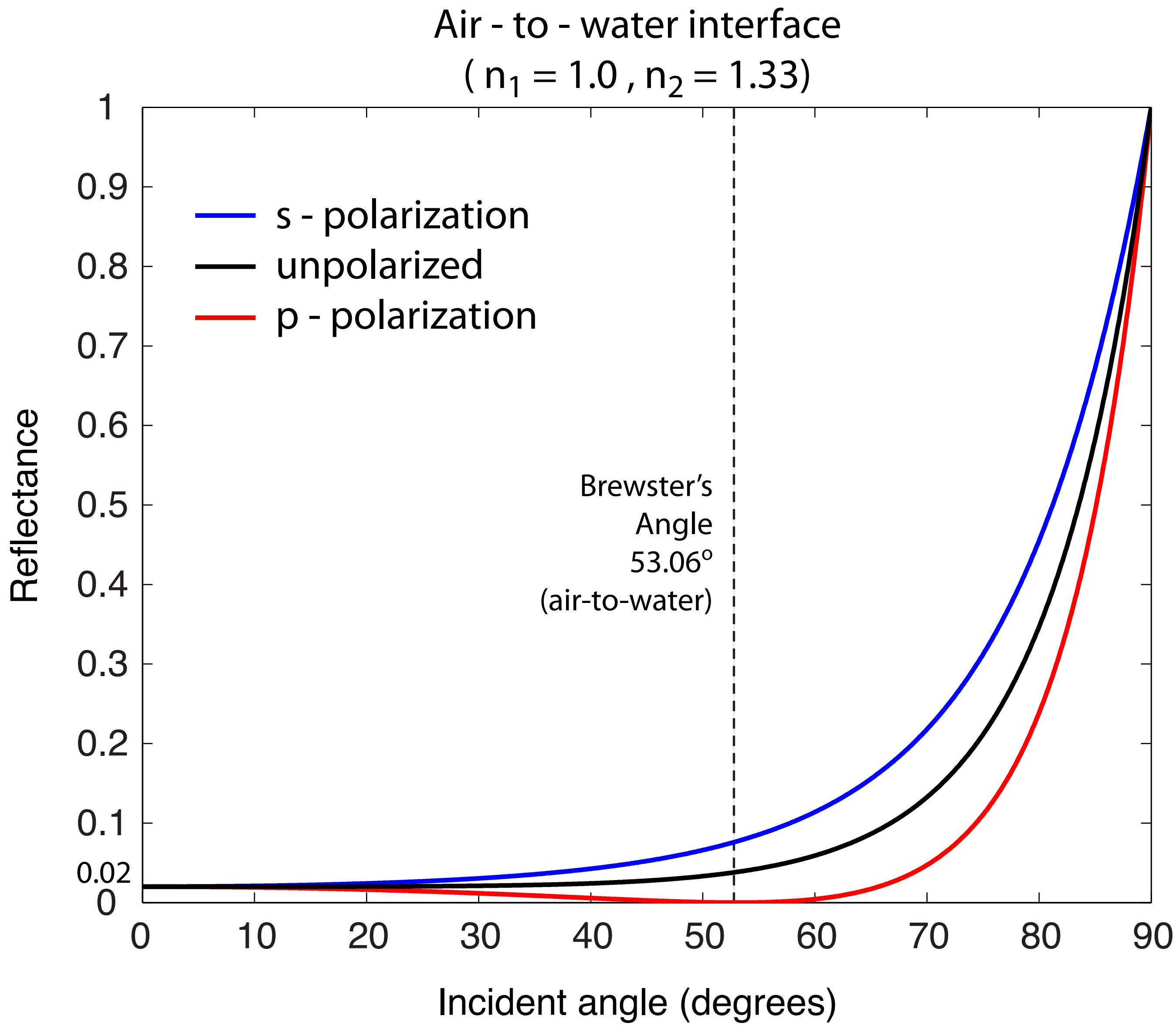
Reflection & Refraction



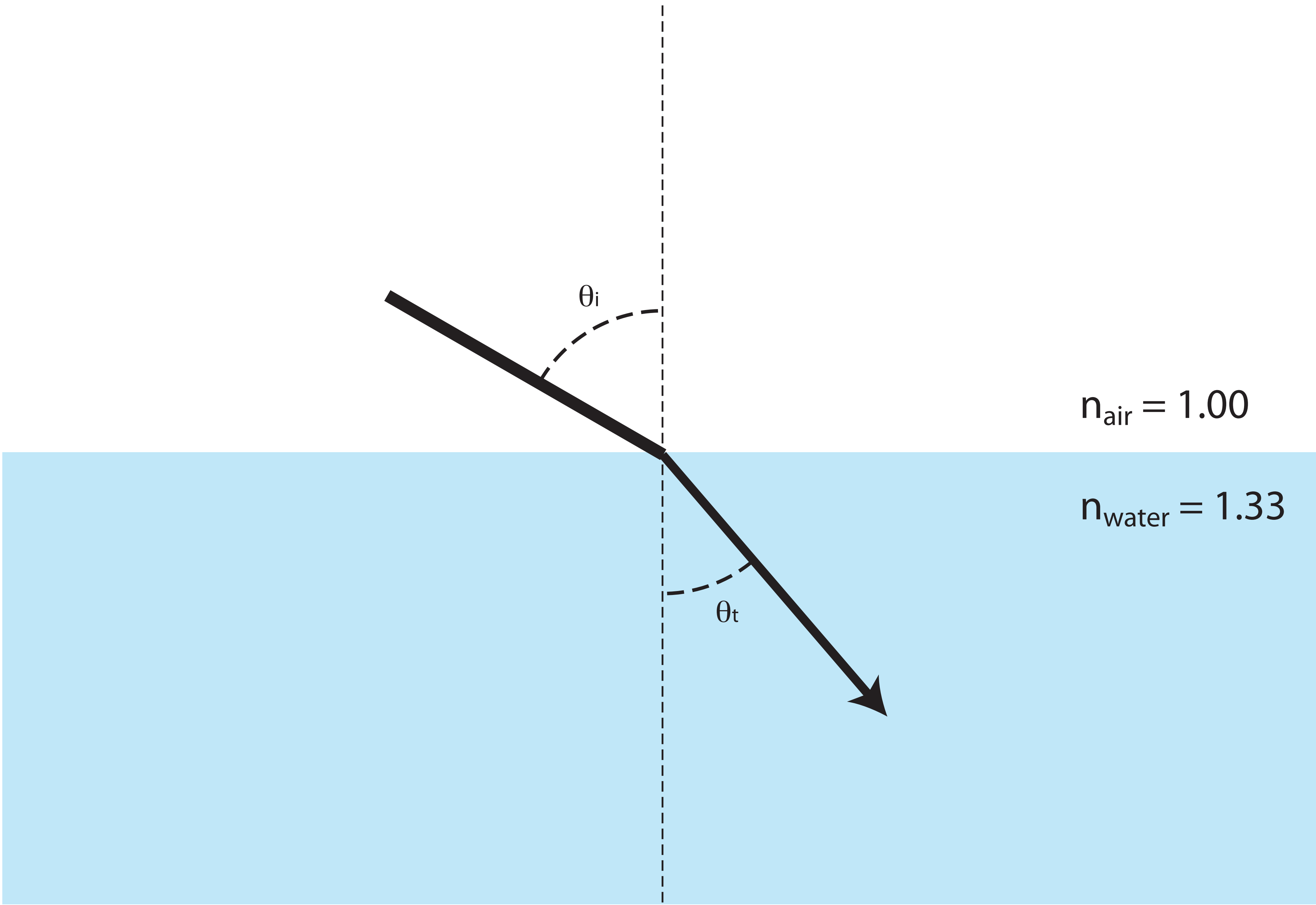


Reflection & Refraction
Ts = 0.969 (96.9%)
Tave = 0.979 (97.9%)
Tp = 0.988 (98.8%)
30o
θi
nair = 1.00
nwater = 1.33
θr
θt
22.1o
Rs = 0.031 (3.1%)
Rave = 0.021 (2.1%)
Rp = 0.012 (1.2%)

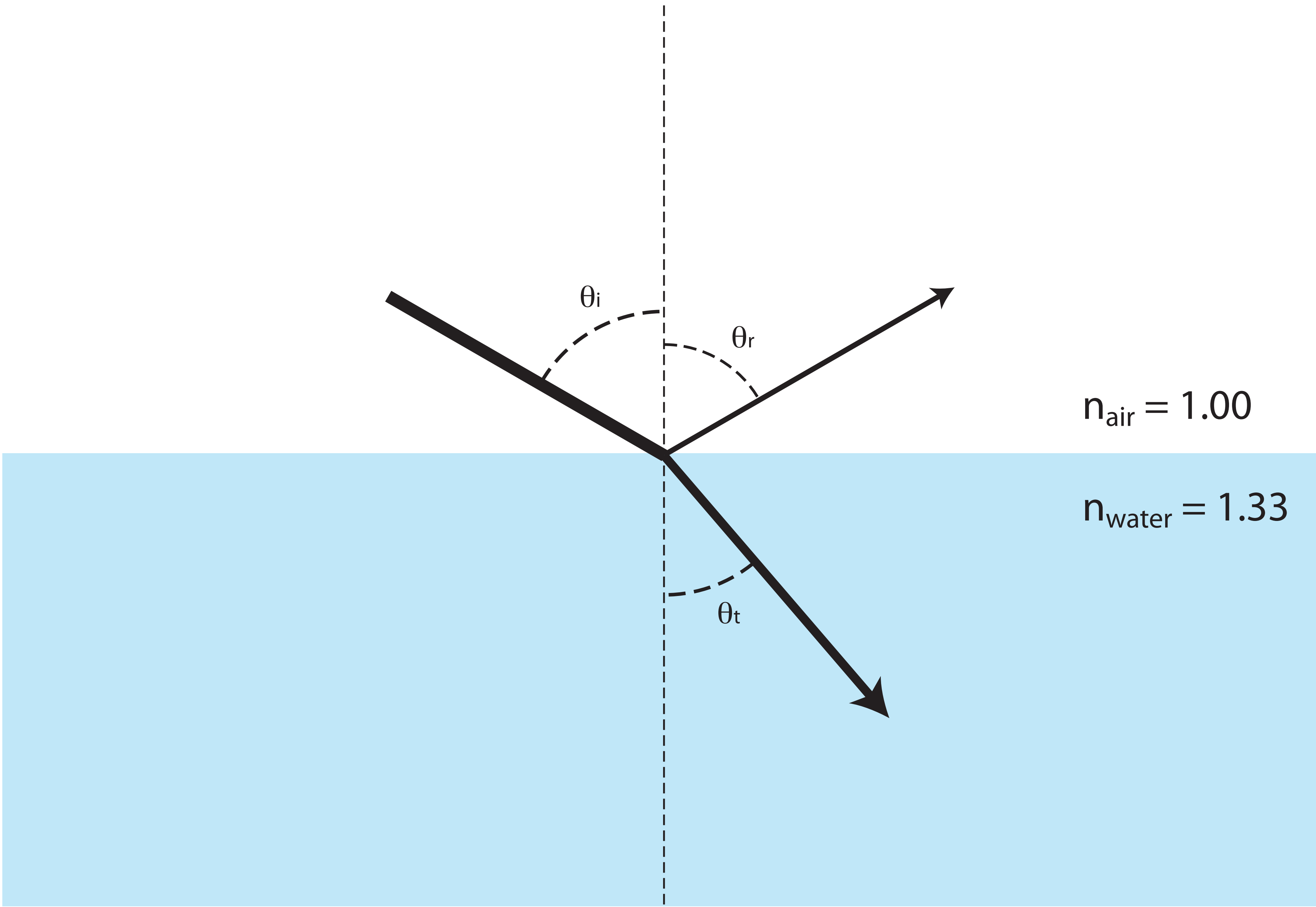
Fresnel Equations for Partial Reflection



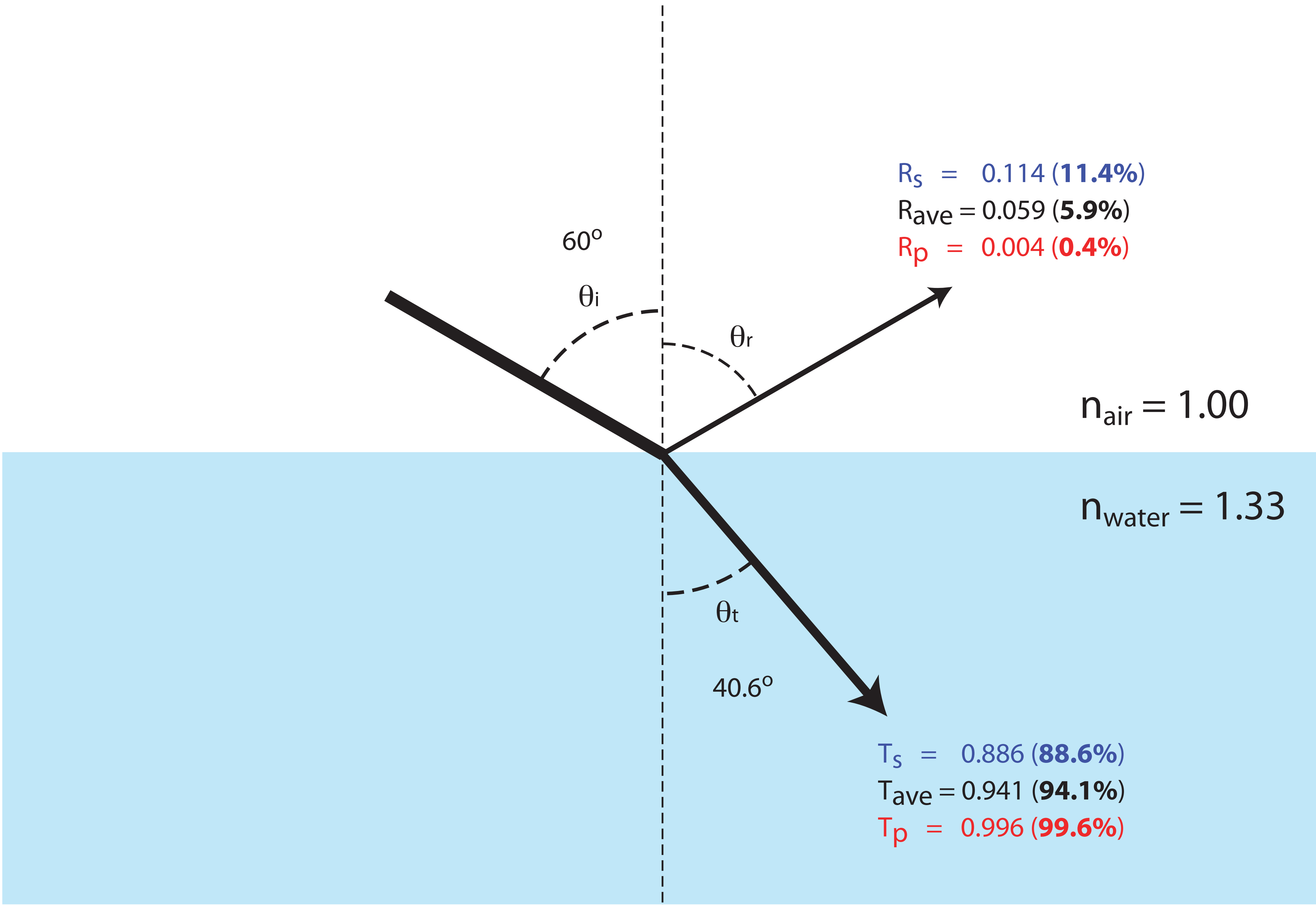
Reflection & Refraction



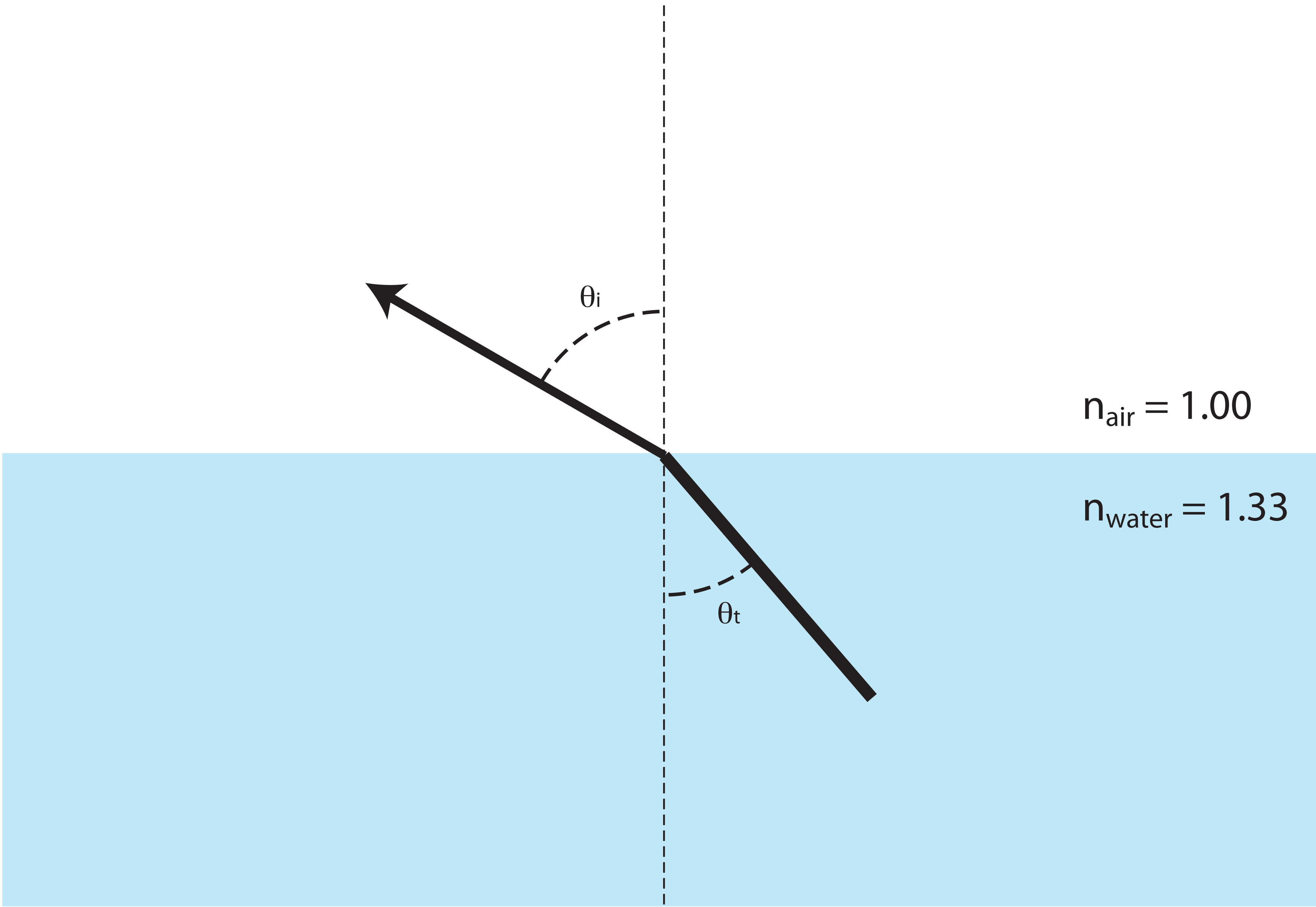
Reflection & Refraction

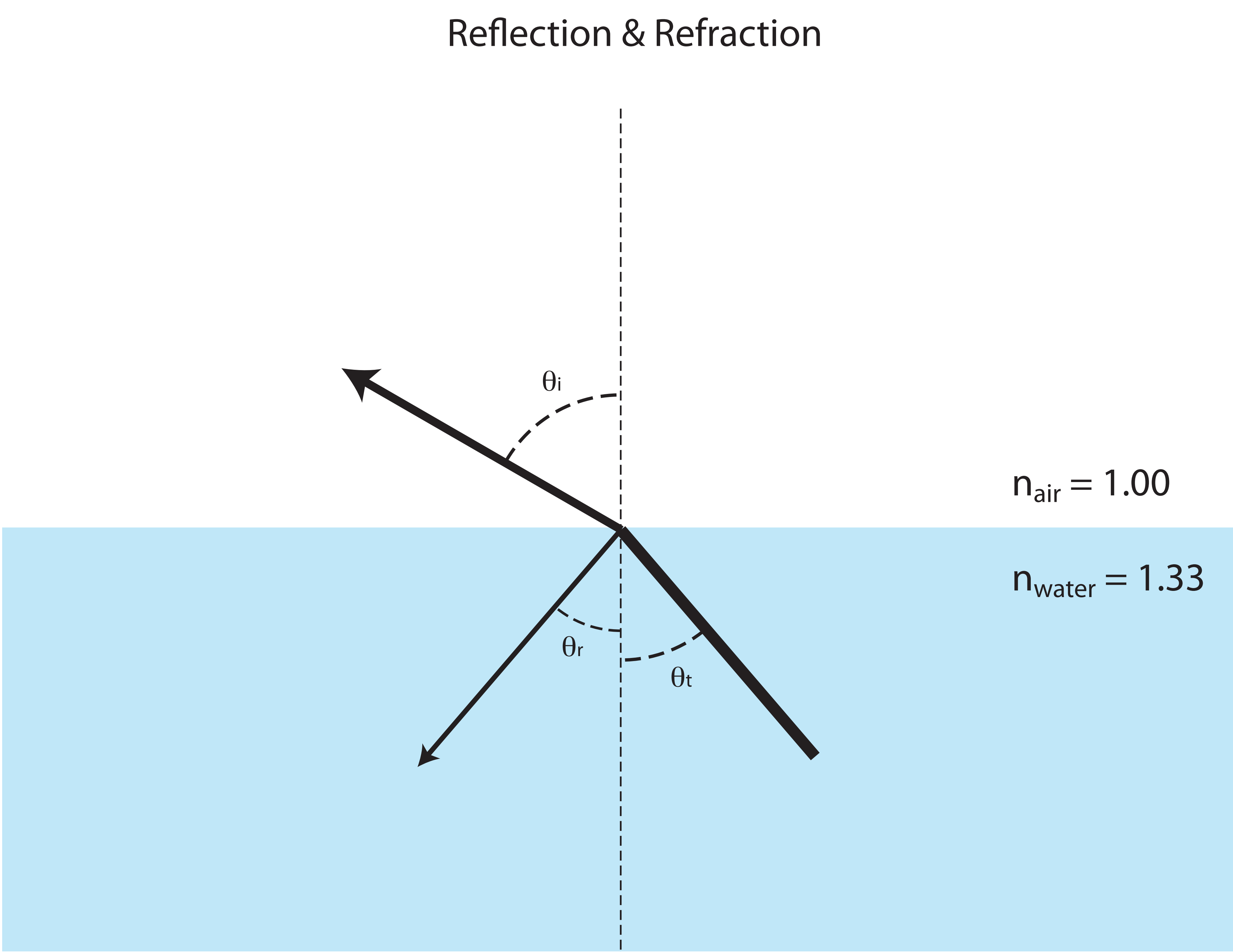


Reflection & Refraction

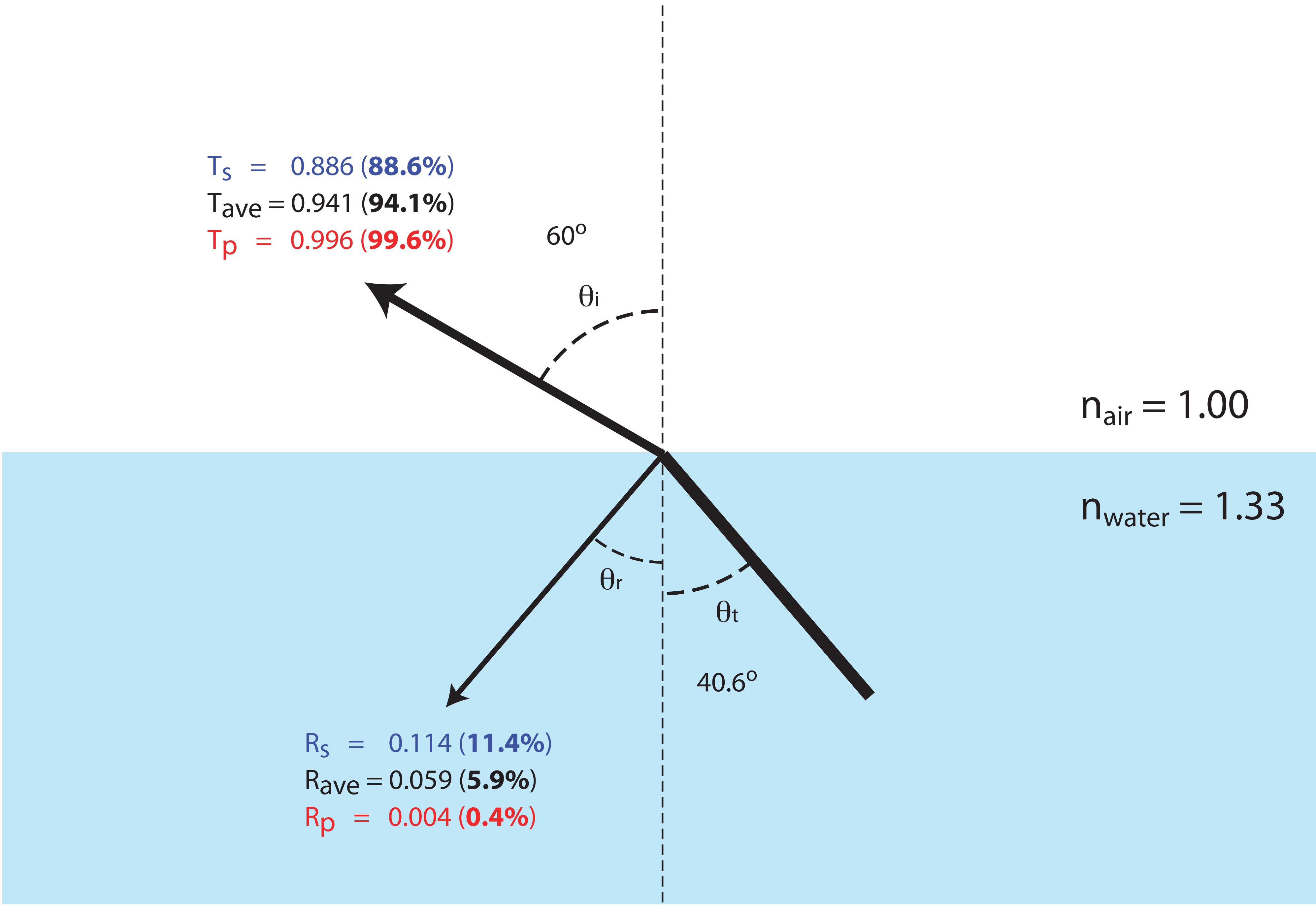


Reflection & Refraction

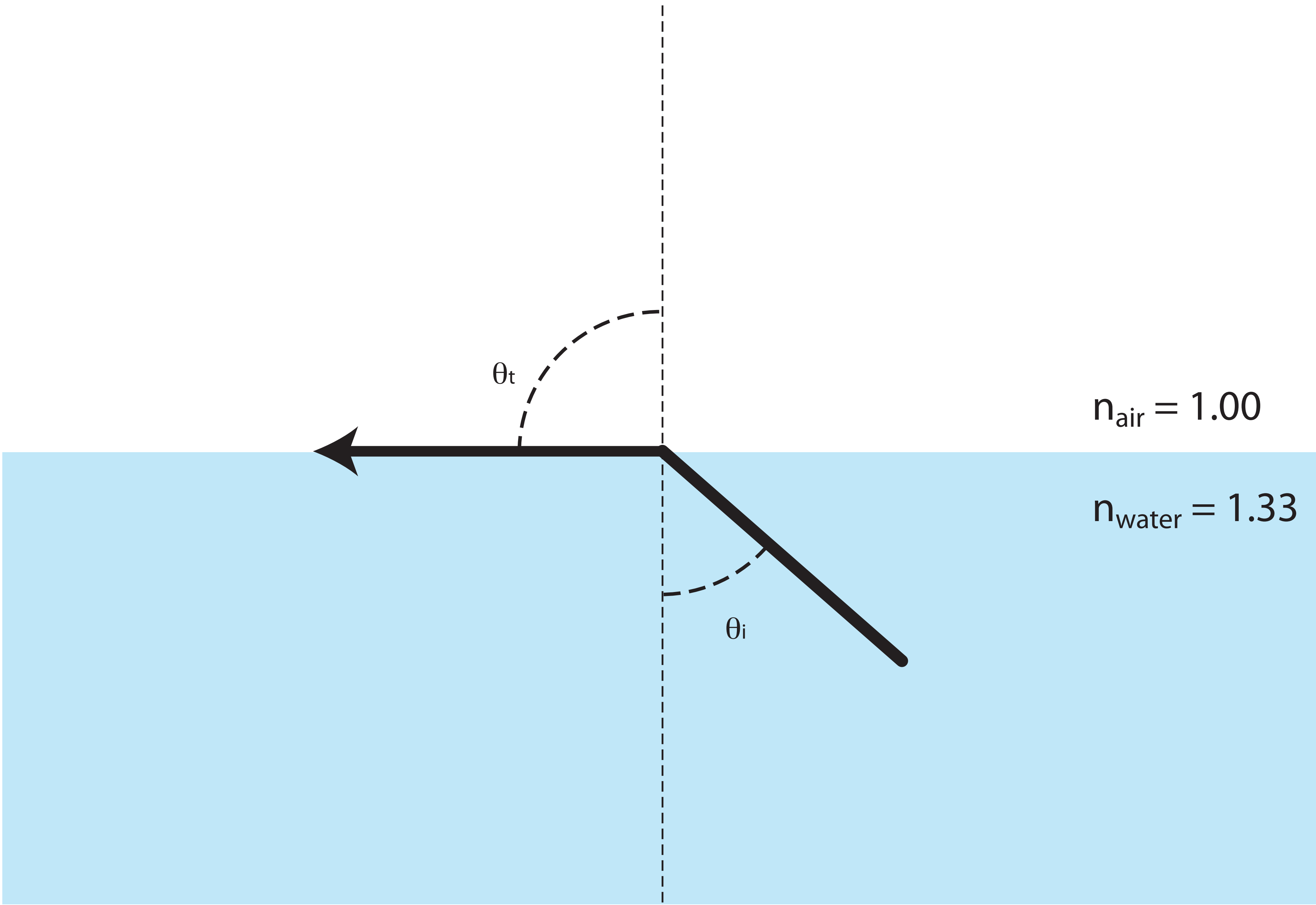



Reflection & Refraction
θi
θr
θt
n_air = 1.00
n_water = 1.33

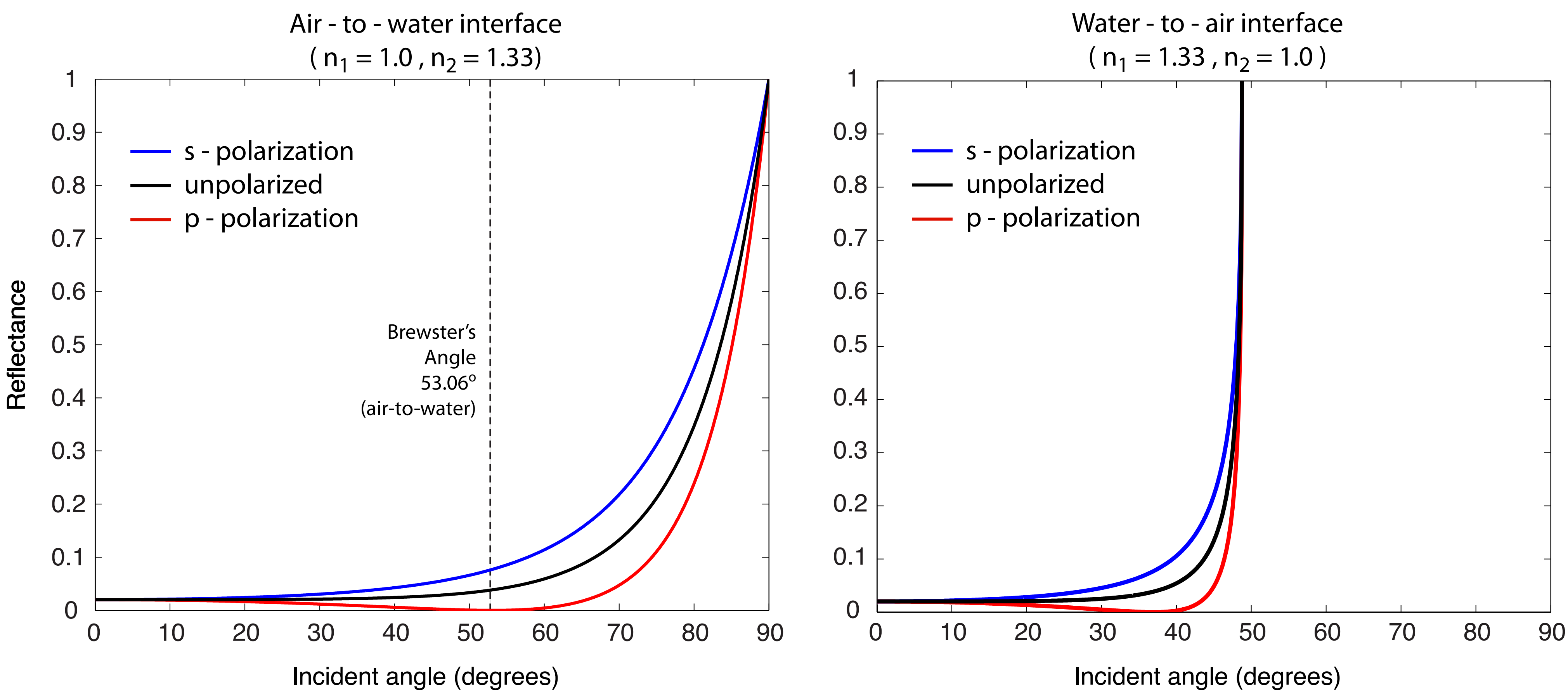
Reflection & Refraction



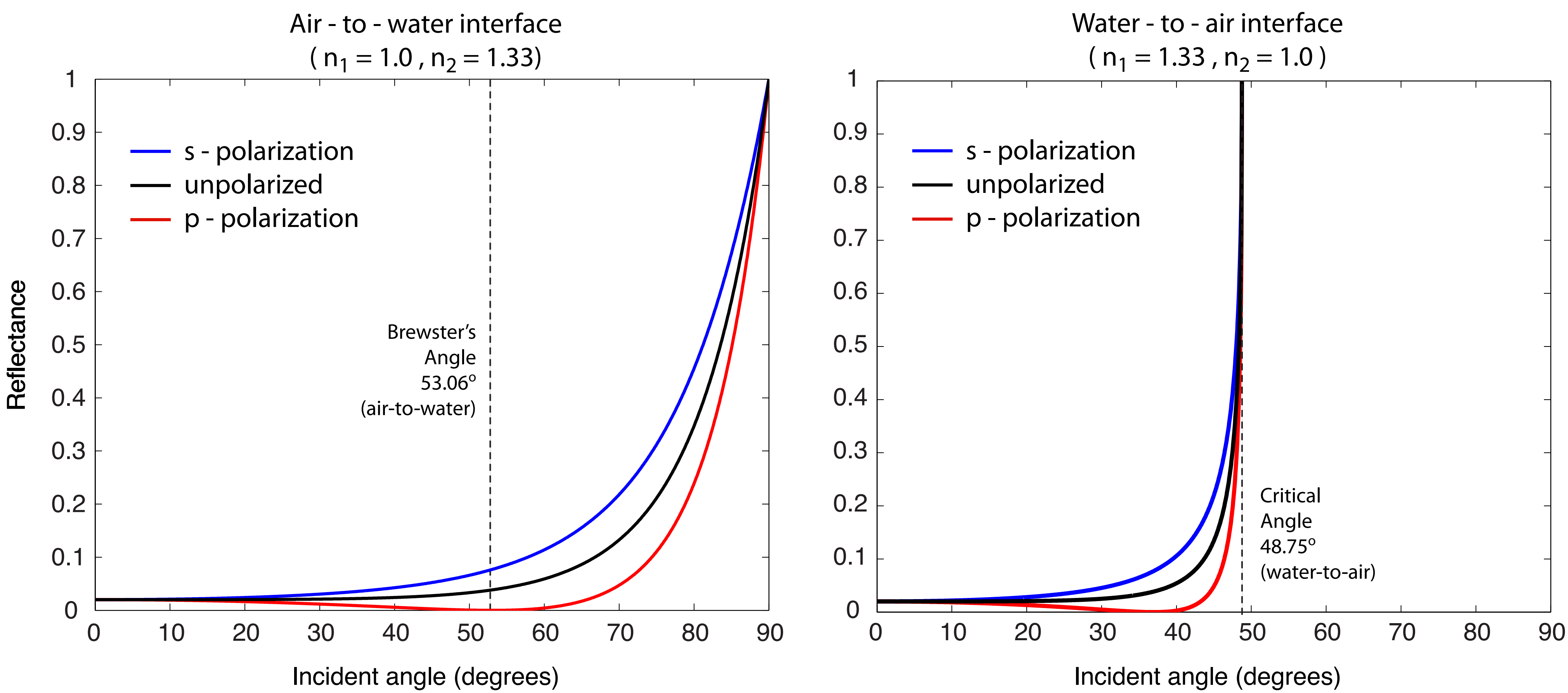
Total Internal Reflection

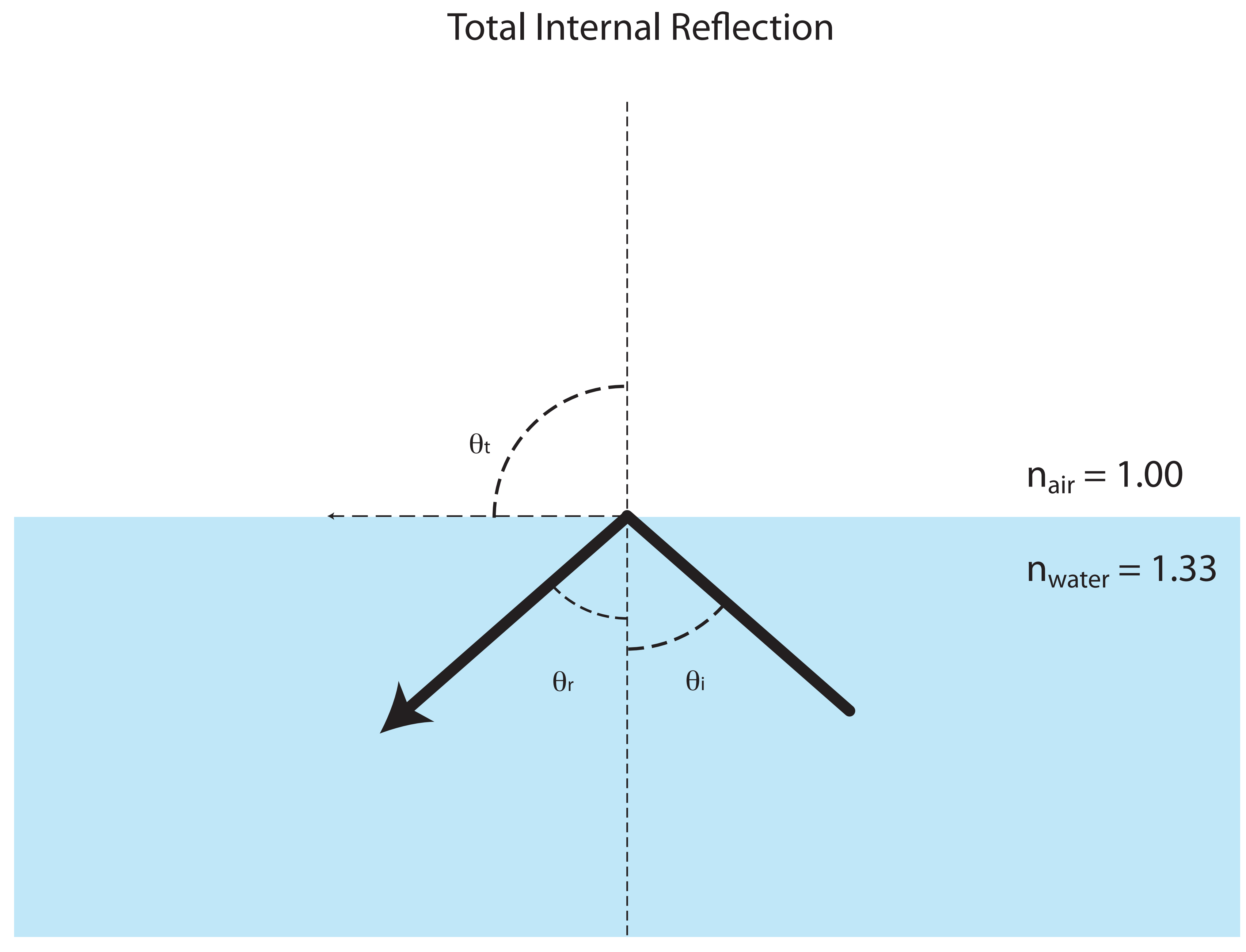


Fresnel Equations for Partial Reflection

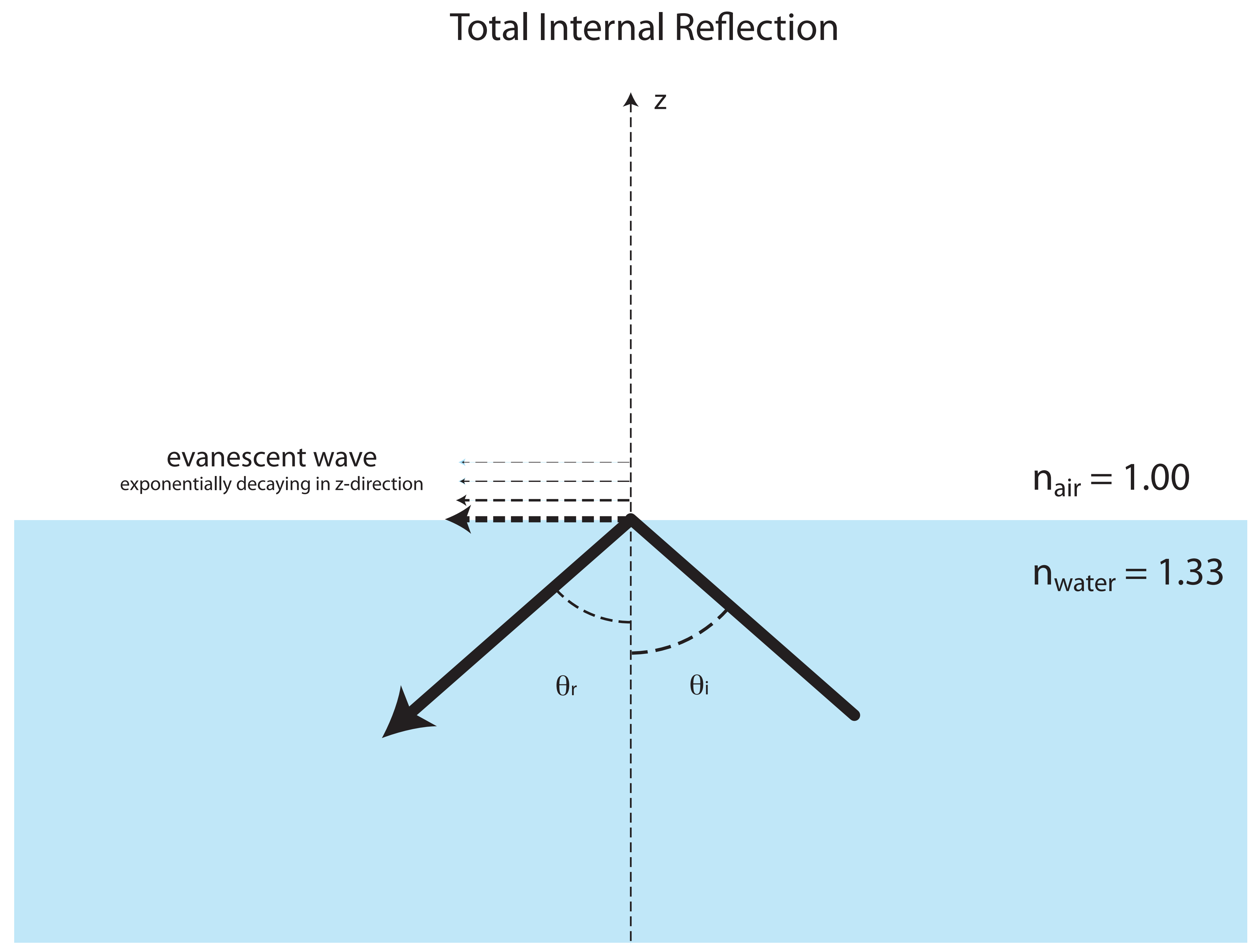


Fresnel Equations for Partial Reflection

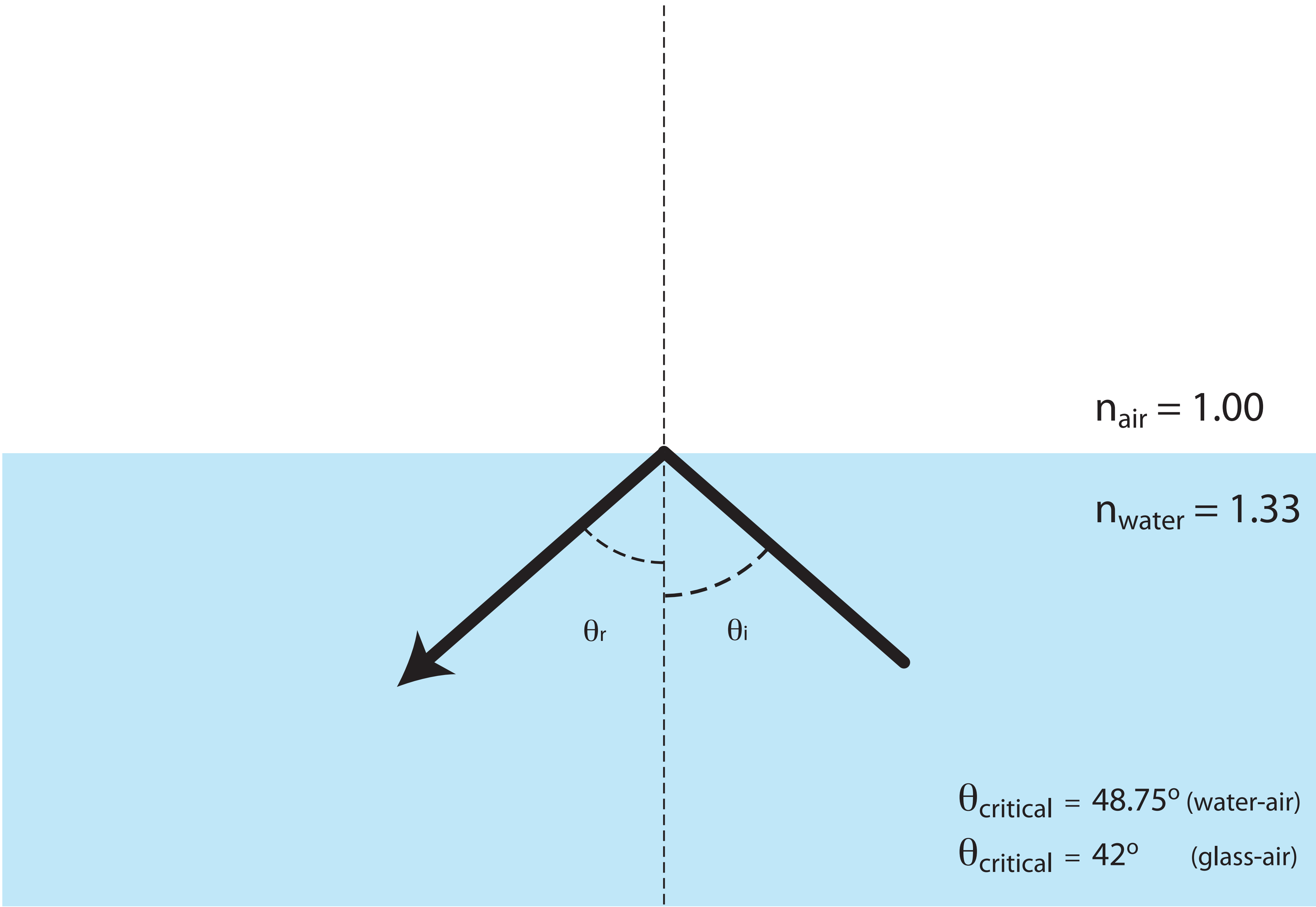




Total Internal Reflection
θt
n_{air} = 1.00
n_{water} = 1.33
θr
θi

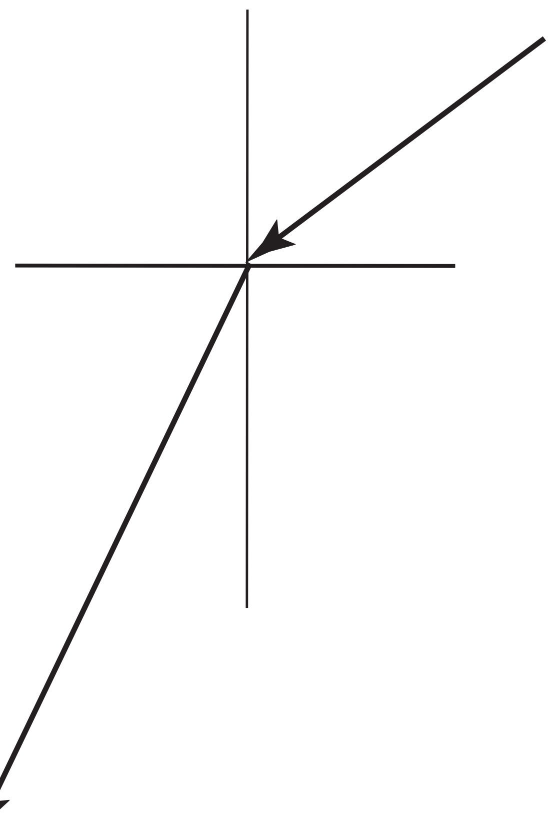

Total Internal Reflection
z
evanescent wave
exponentially decaying in z-direction
$n_{air} = 1.00$
$n_{water} = 1.33$
θ_r
θ_i

Total Internal Reflection



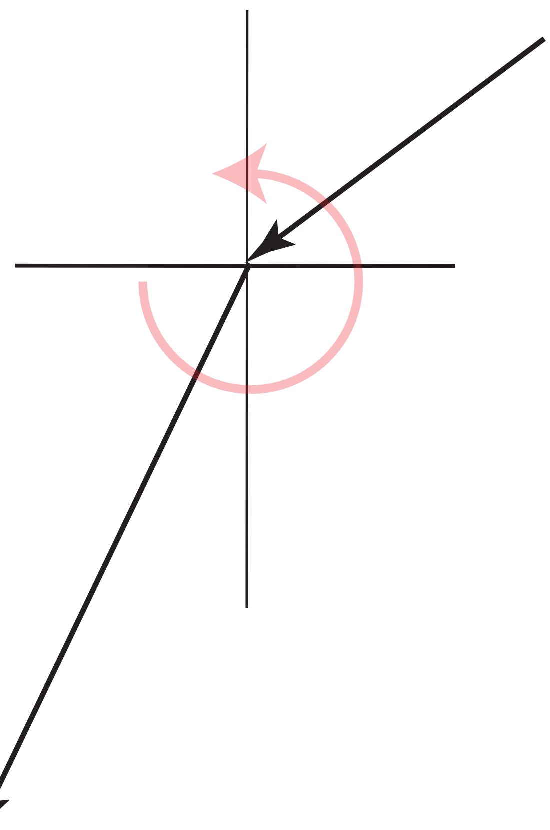
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



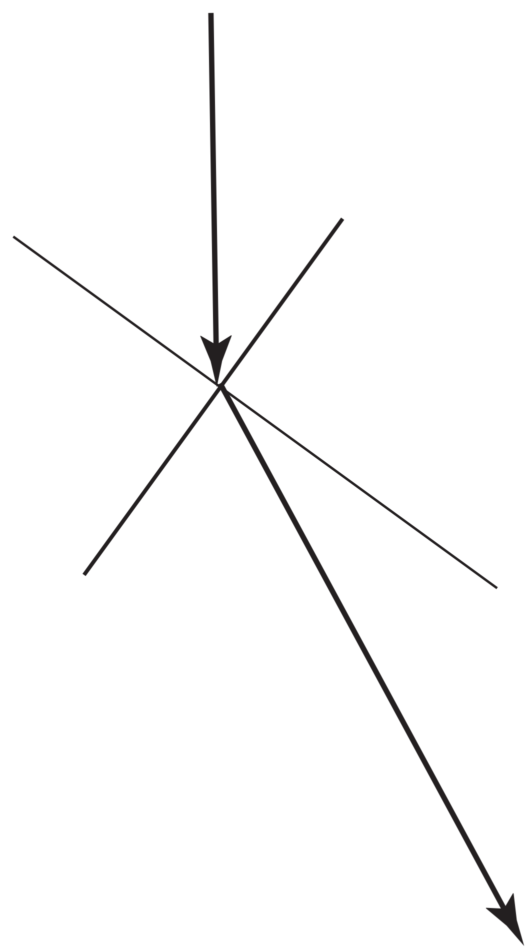
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



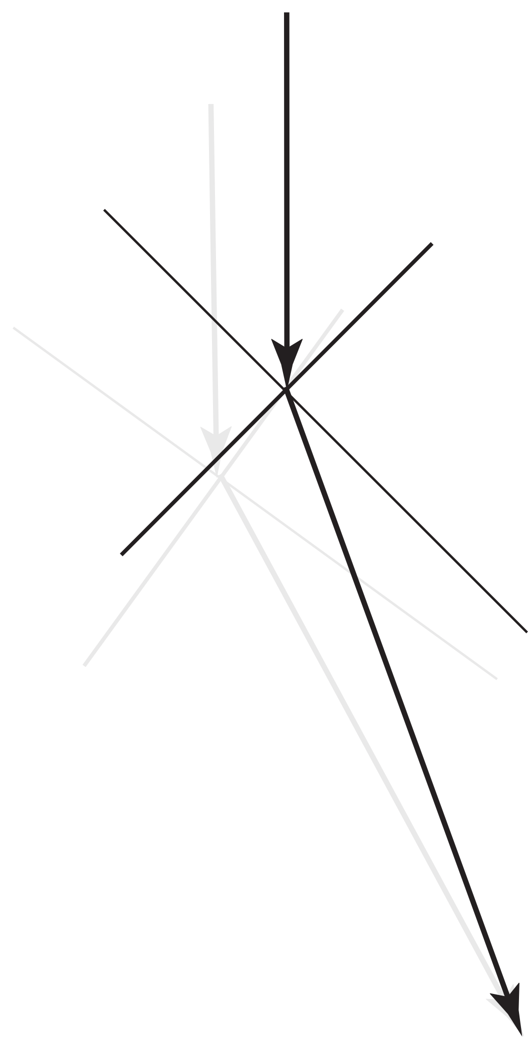
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



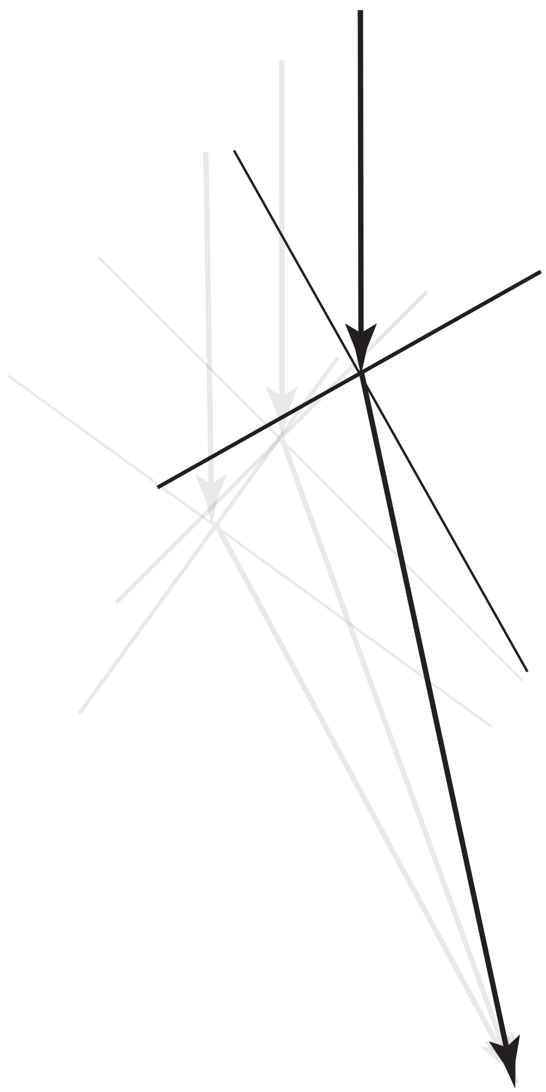
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



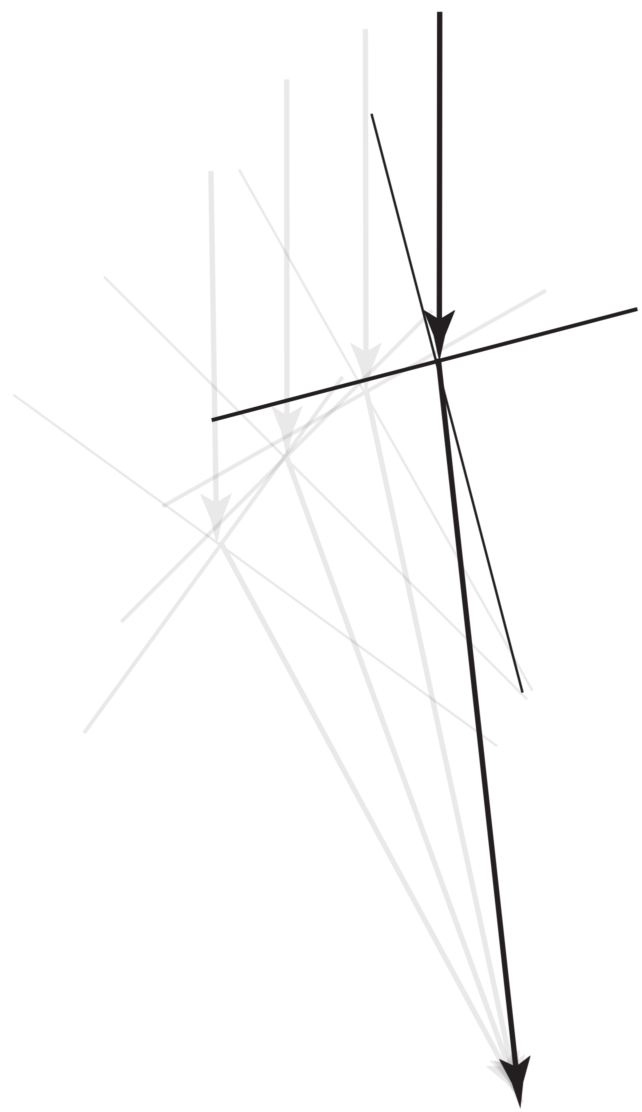
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



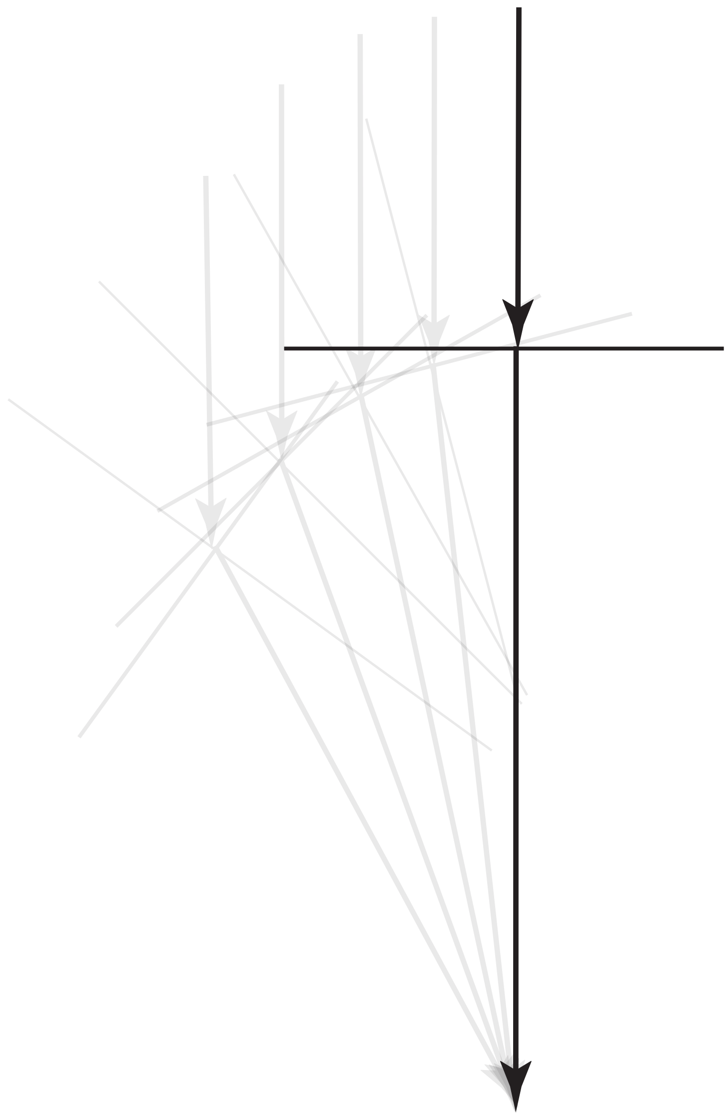
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



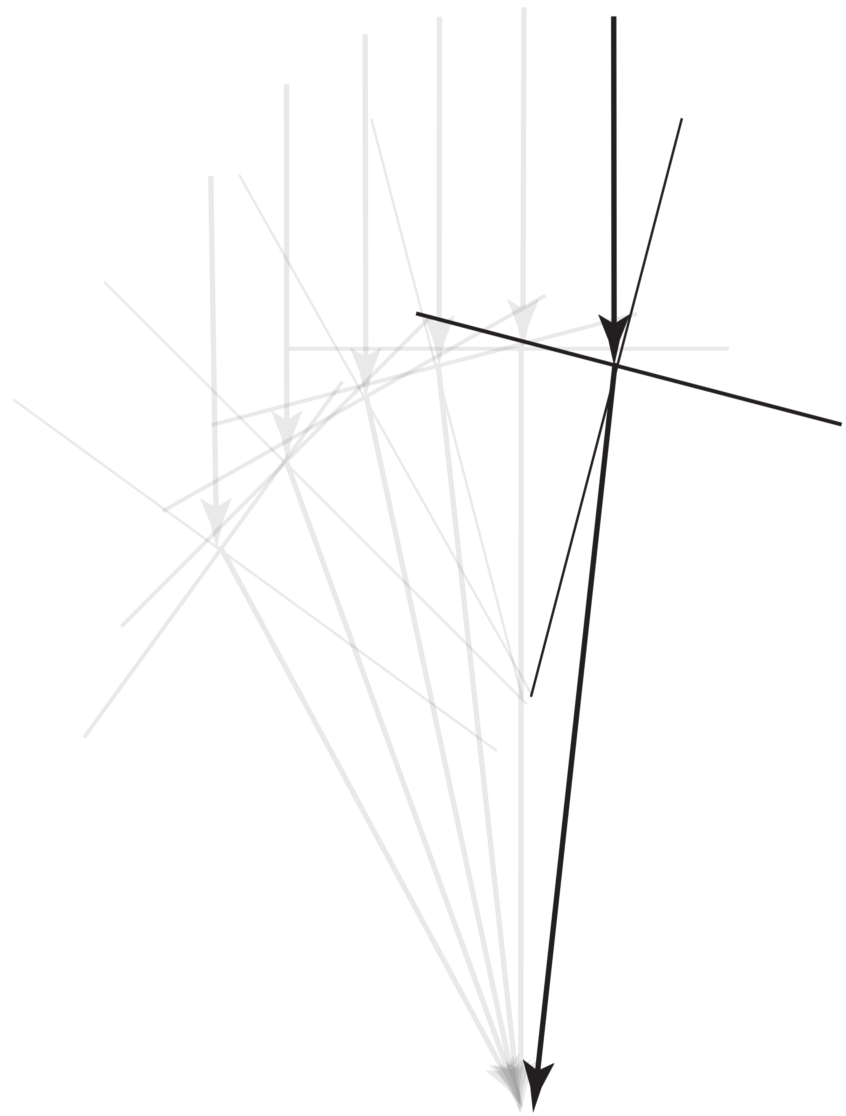
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



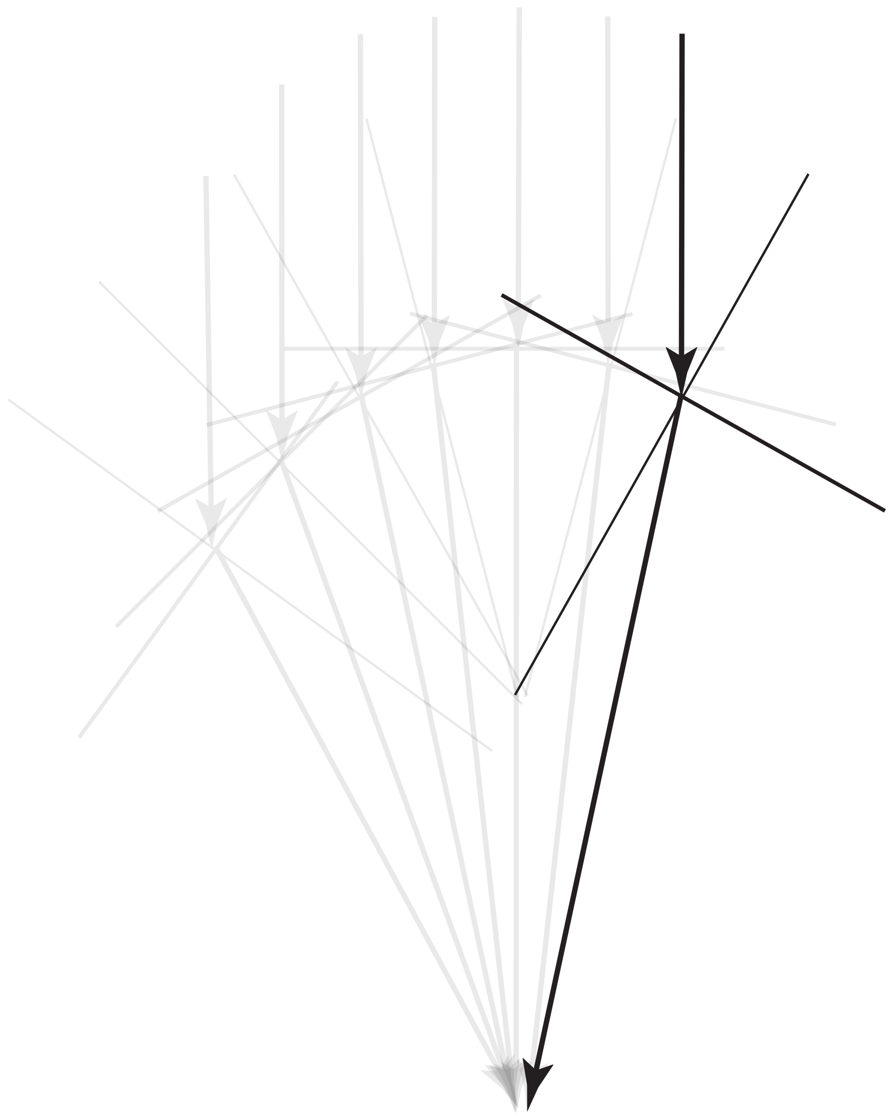
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



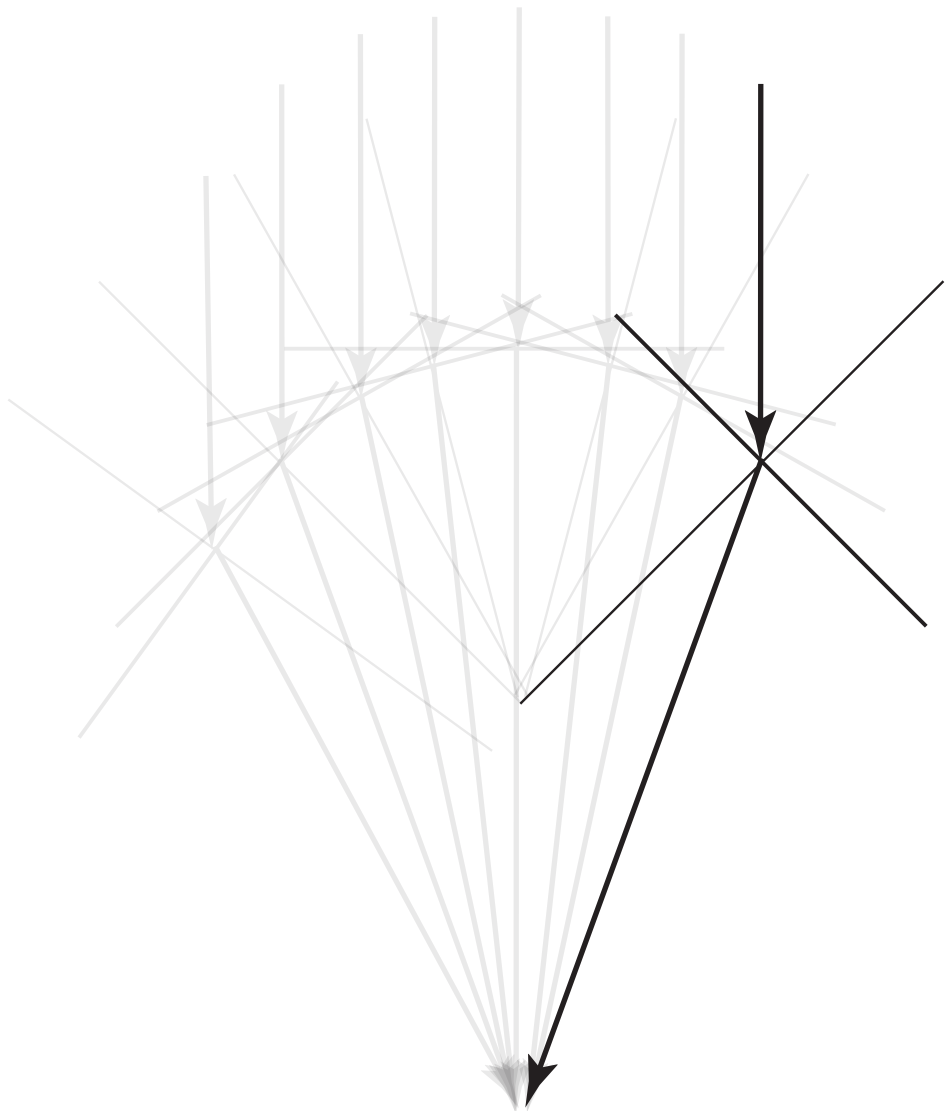
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



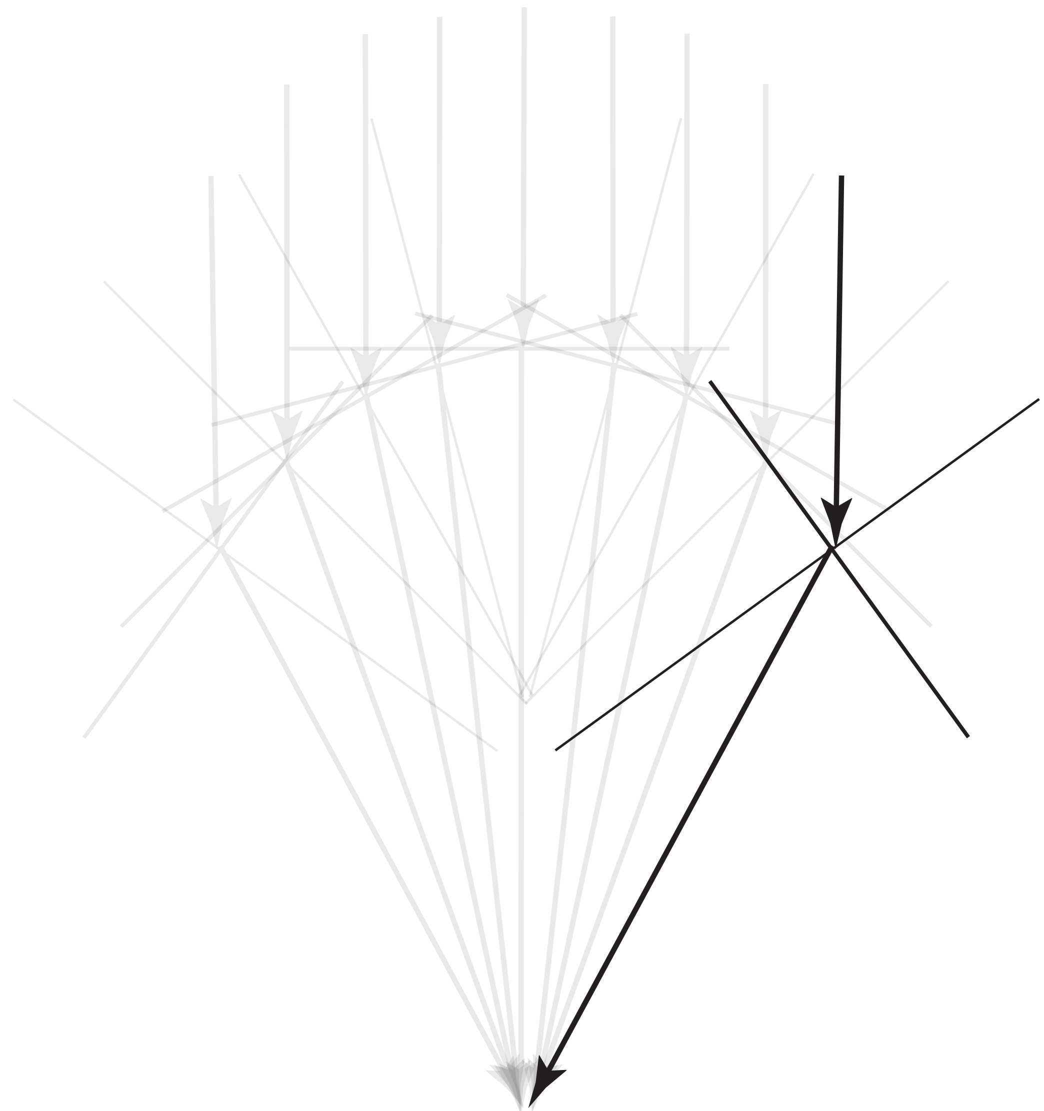
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



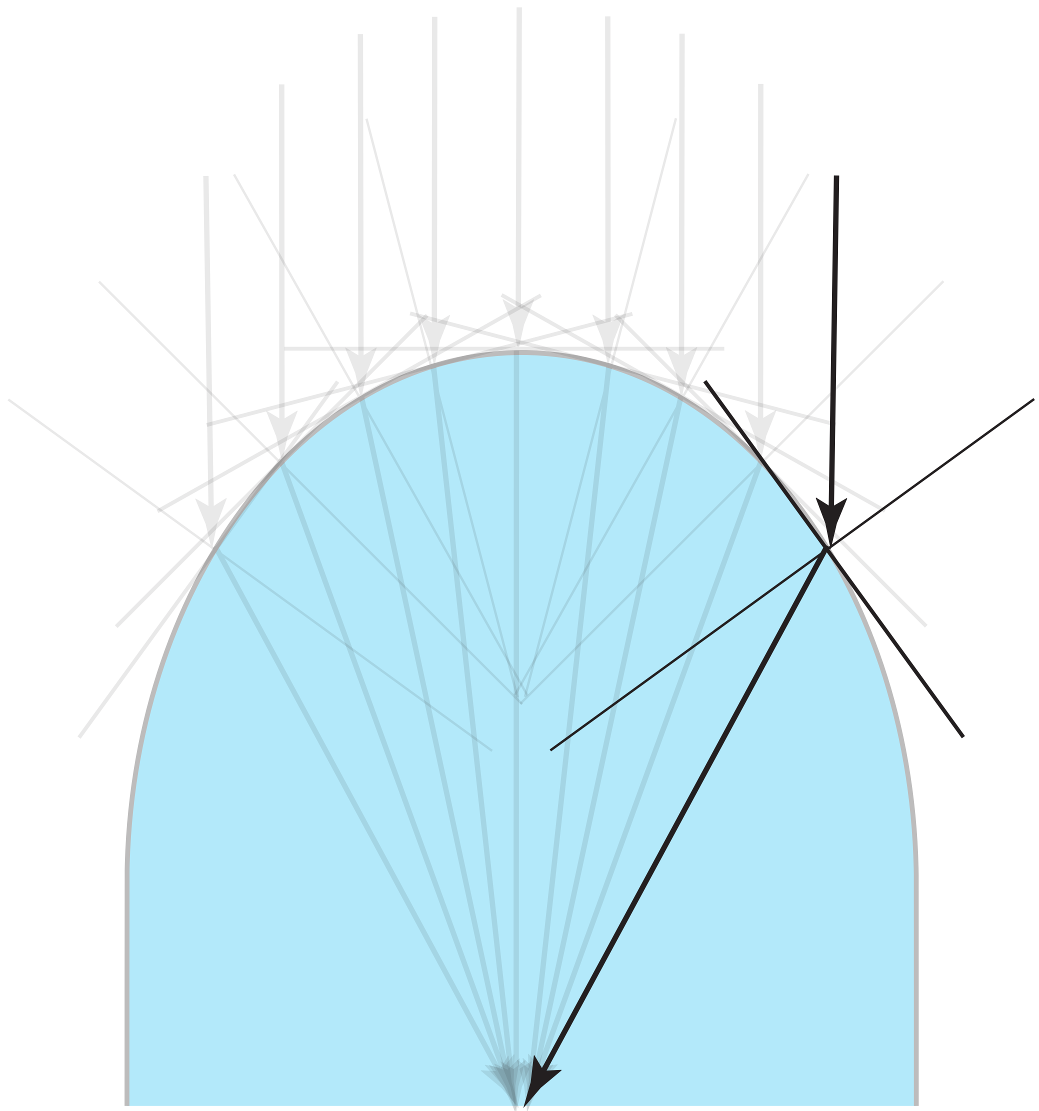
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



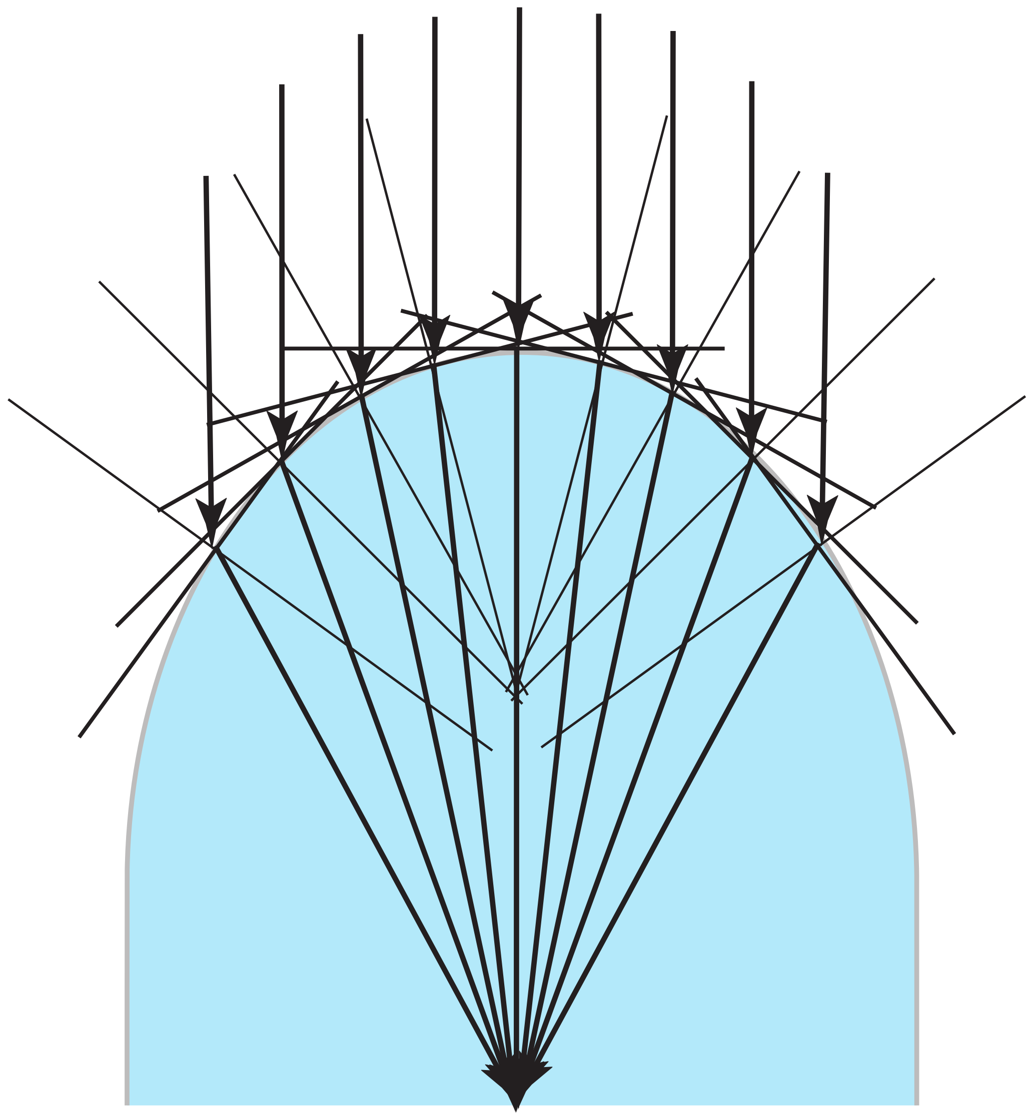
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



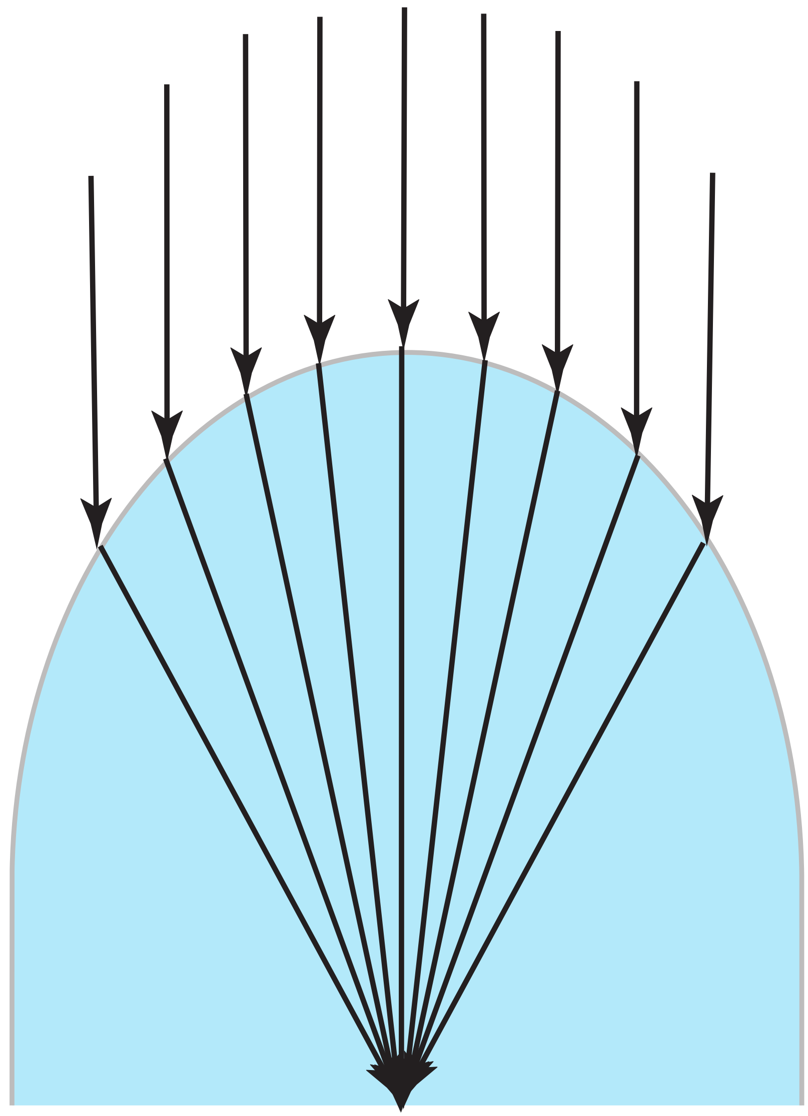
Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



Refraction at a Curved Surface

Apply Snell's Law in piece-wise linear fashion



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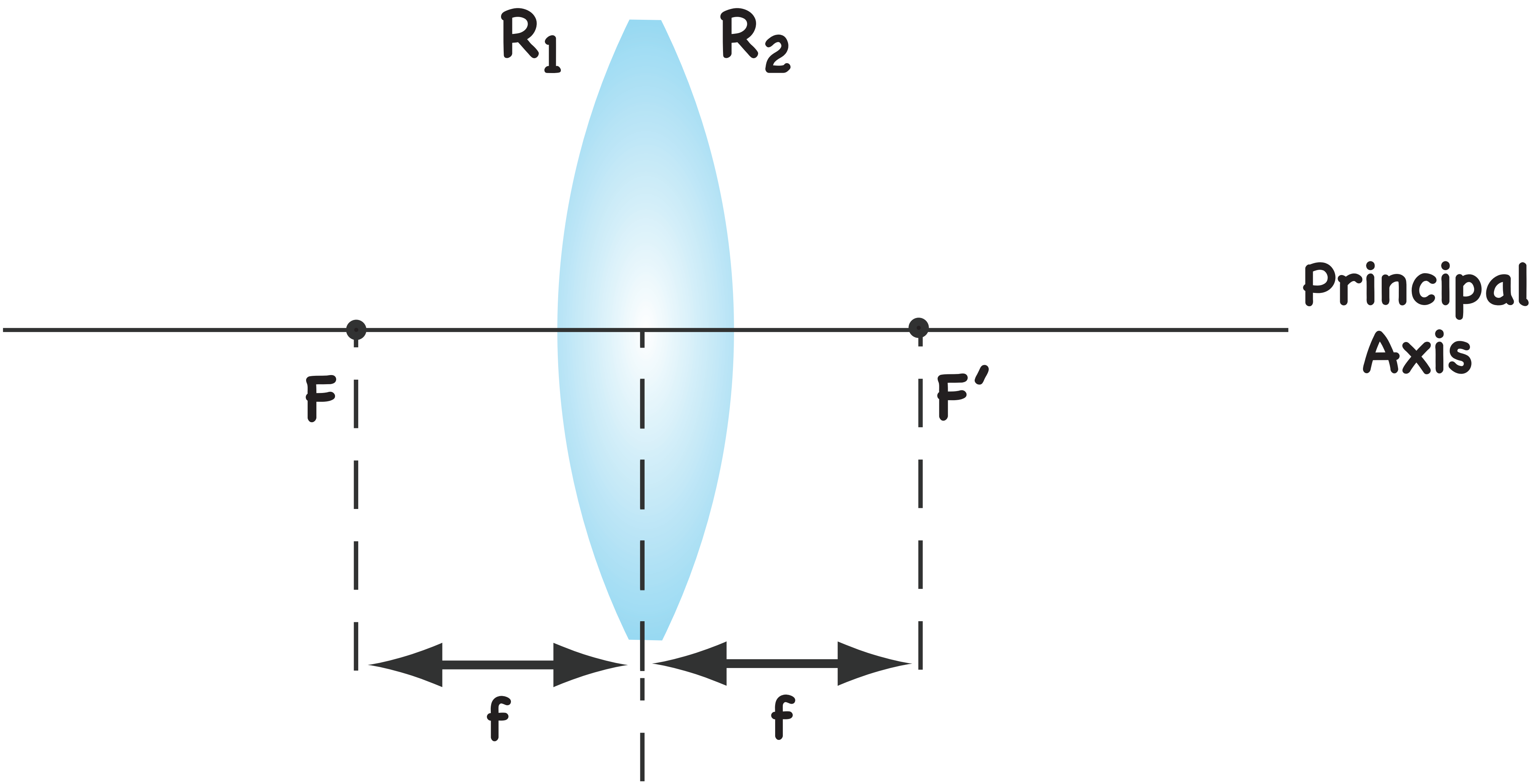
Approximations

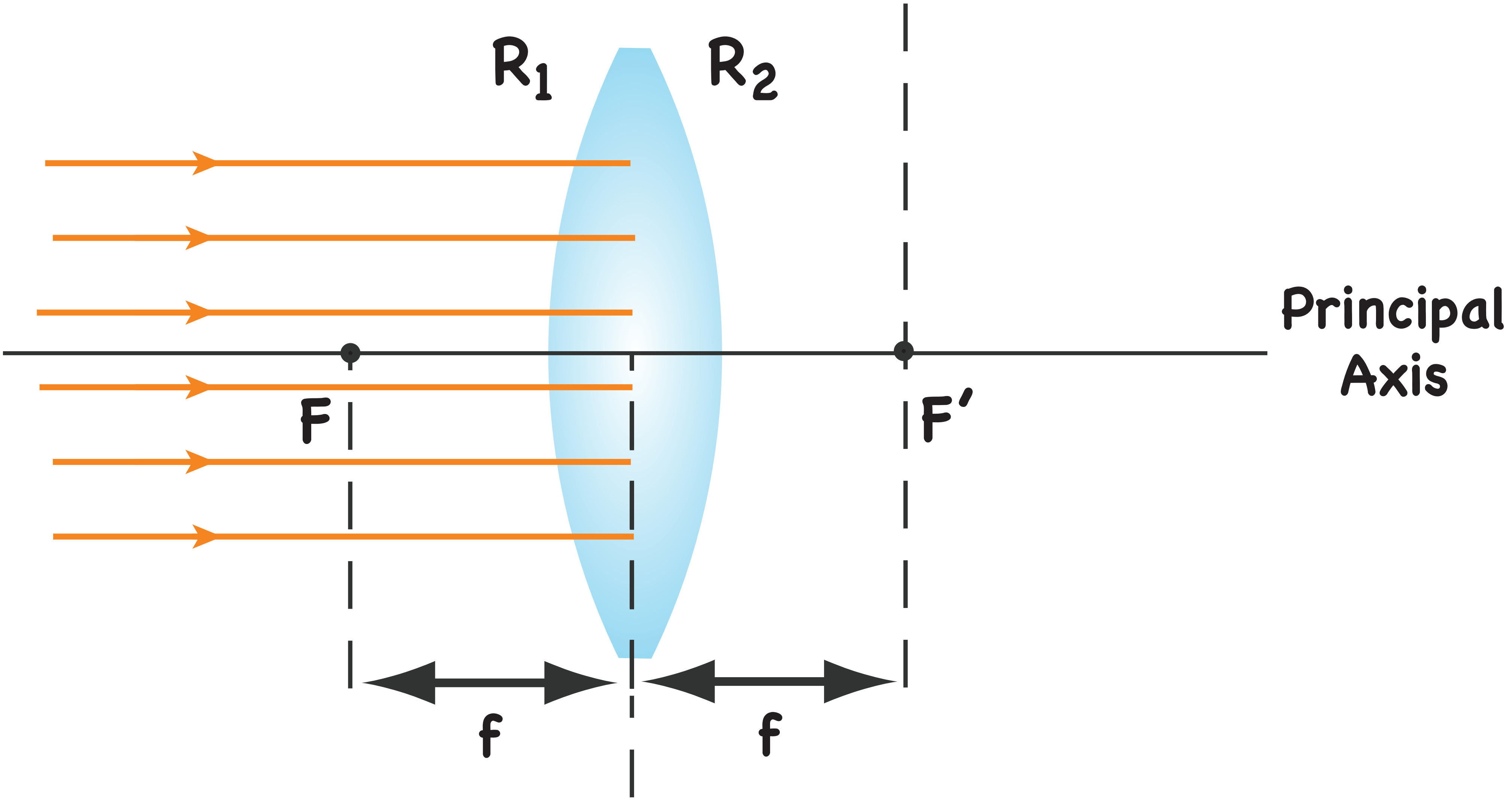
Brutalizing optics into 4 limiting regimes

- Ray (Geometric Optics) : $\lambda \rightarrow 0$
- Paraxial Approximation : $\theta \ll \pi/2$
- Thin Lens Approximation : lens thickness $\rightarrow 0$
- Lossless Approximation : scatter, absorption $\rightarrow 0$

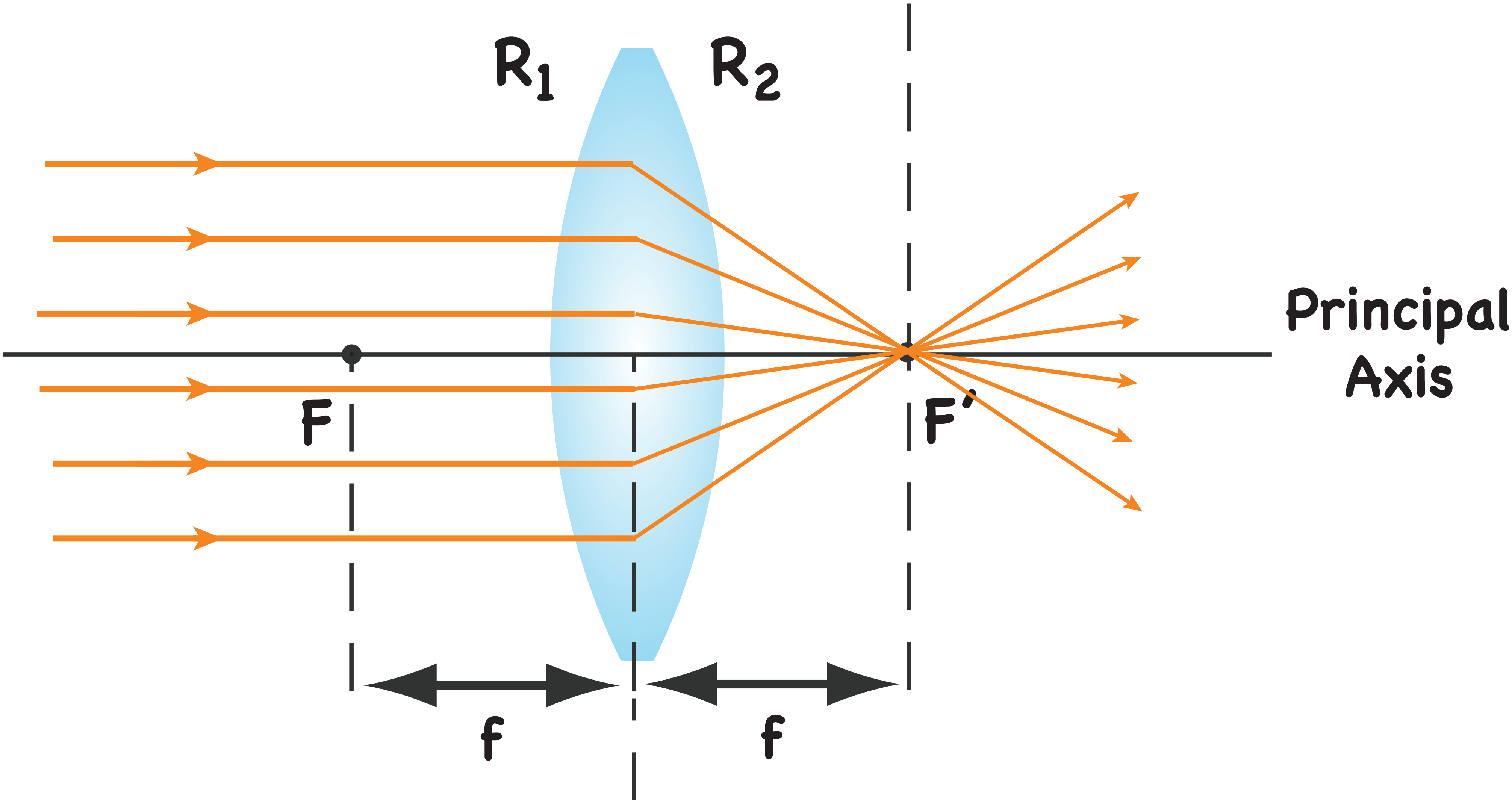
Focal Point , Focal Length, Focal Plane



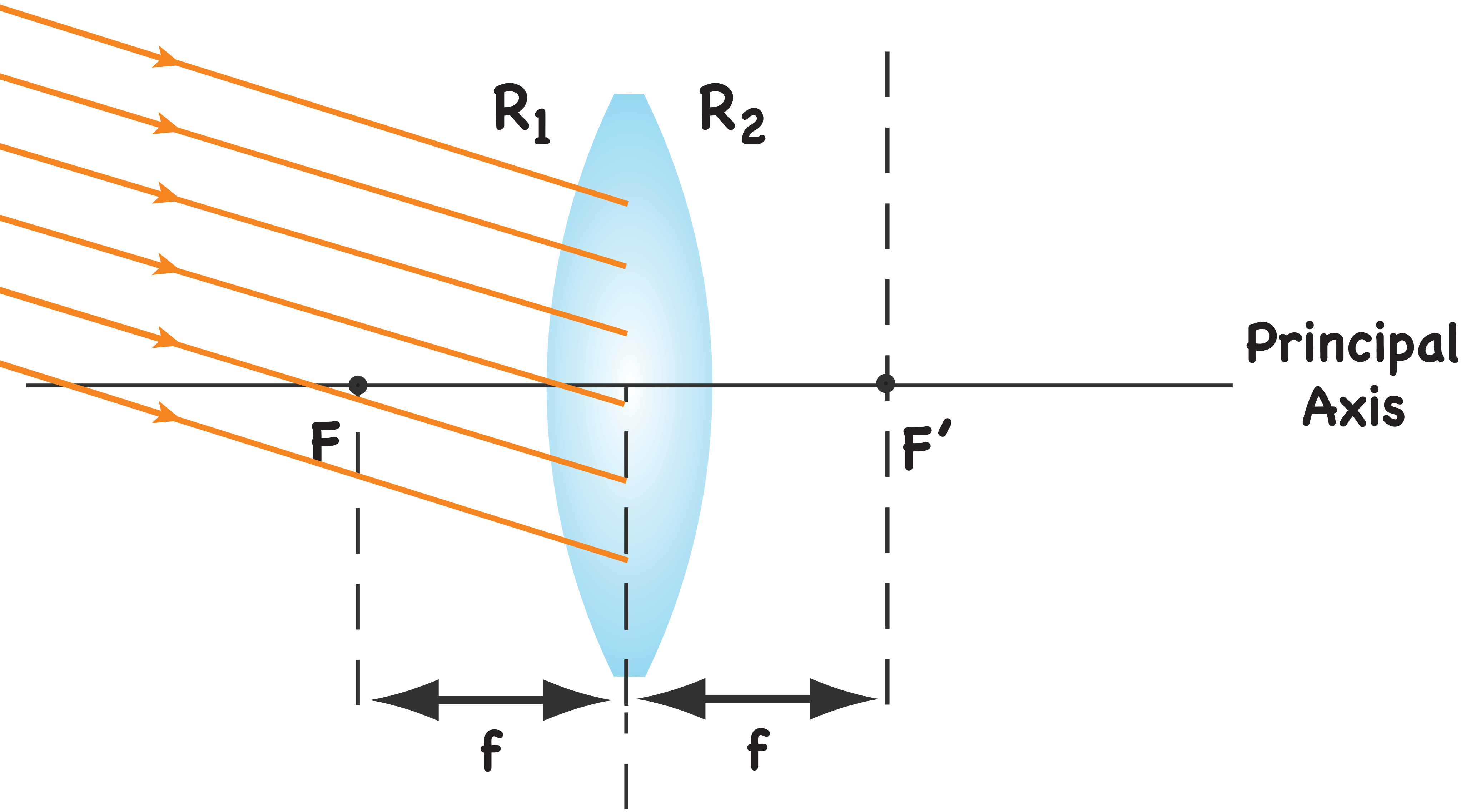
Focal Point , Focal Length, Focal Plane



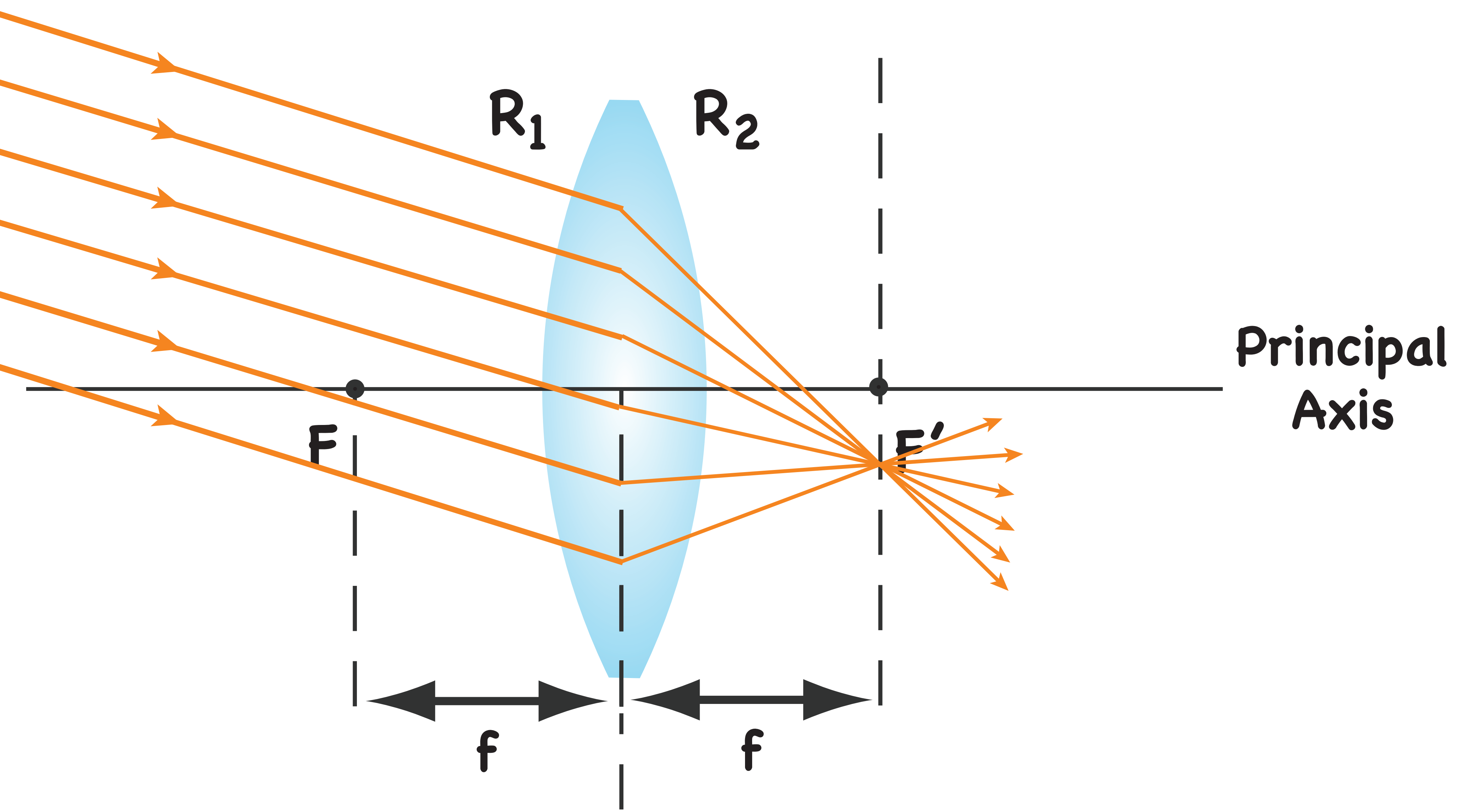
Focal Point , Focal Length, Focal Plane



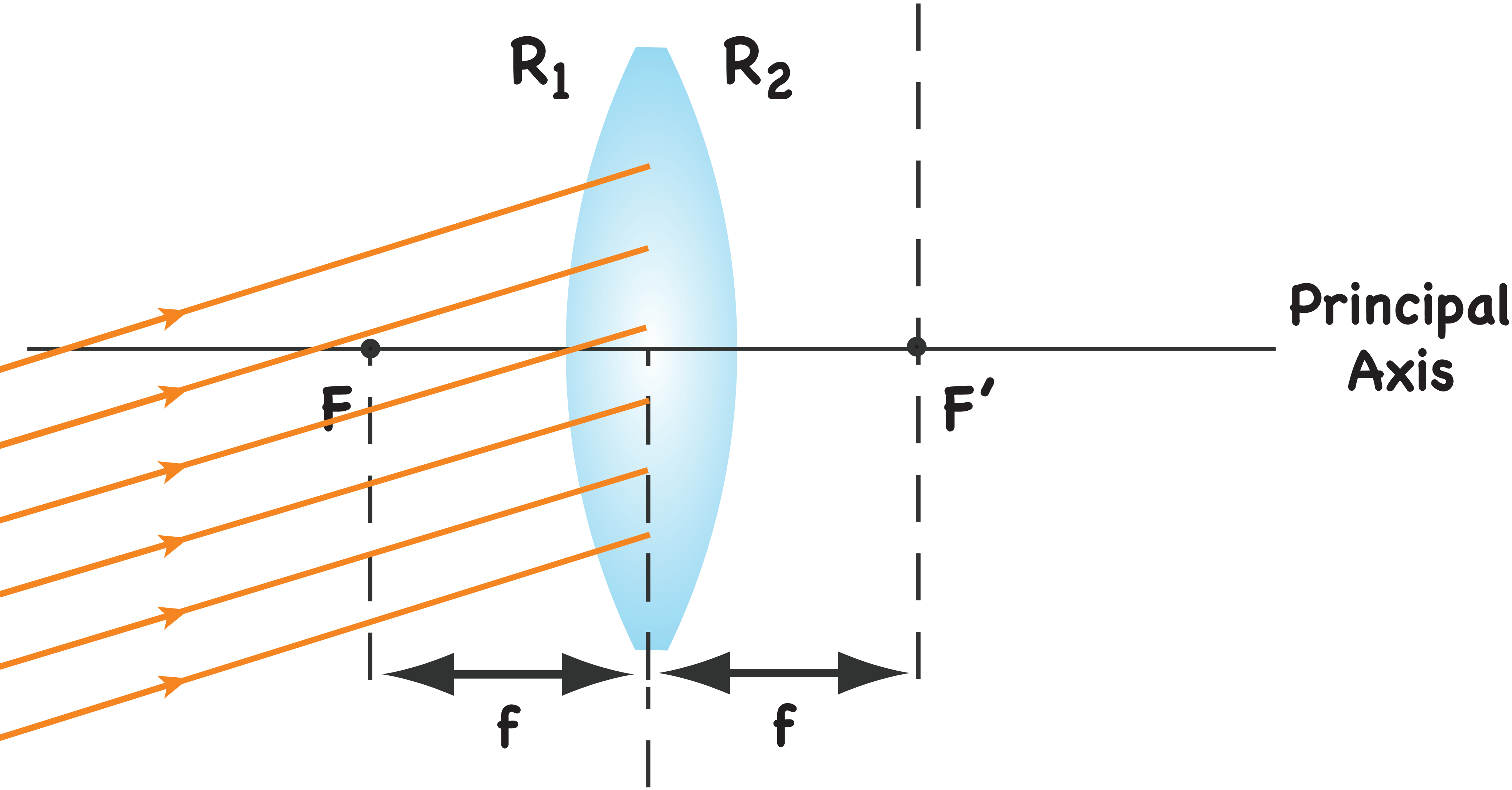
Focal Point , Focal Length, Focal Plane



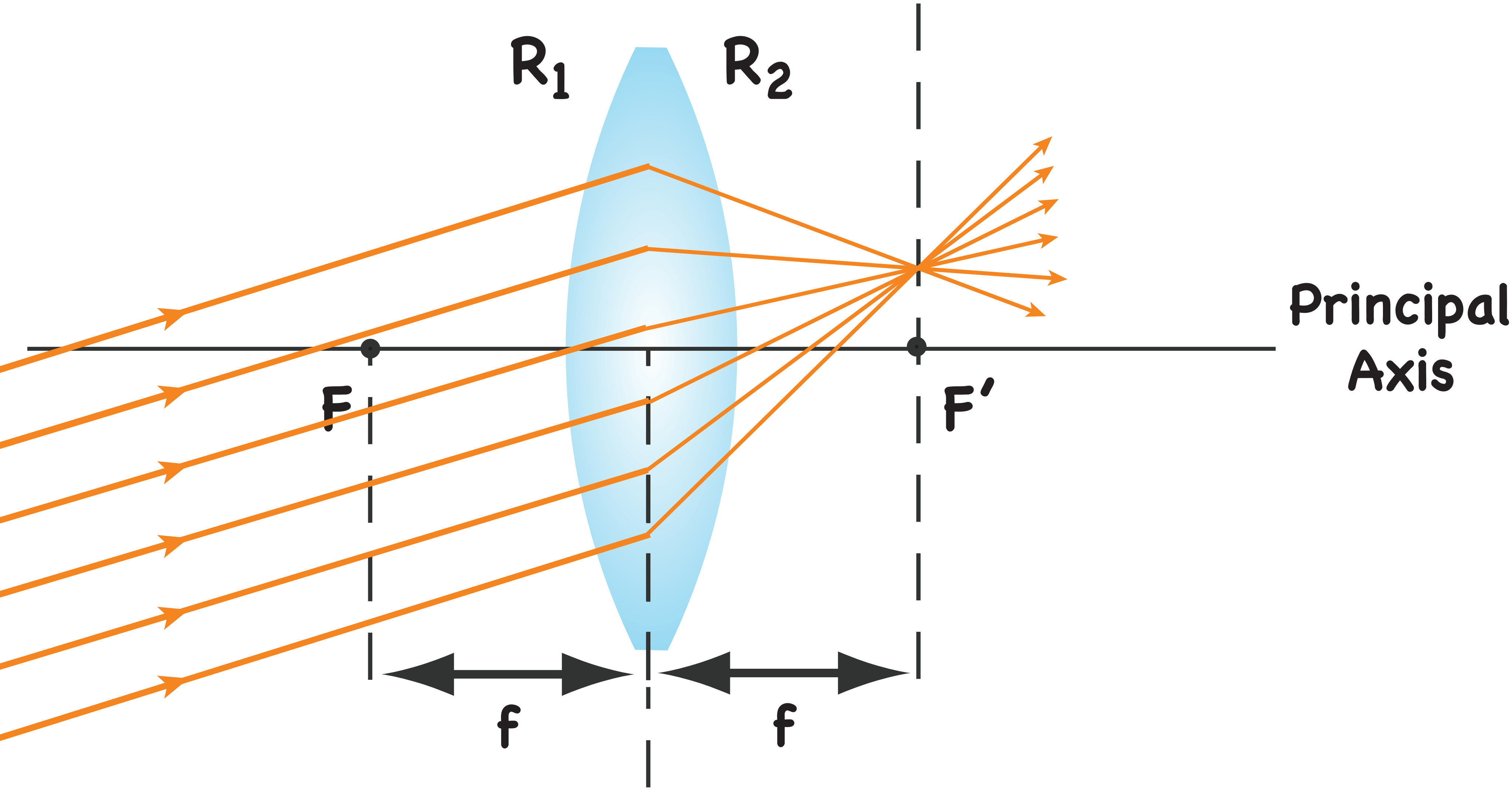
Focal Point , Focal Length, Focal Plane



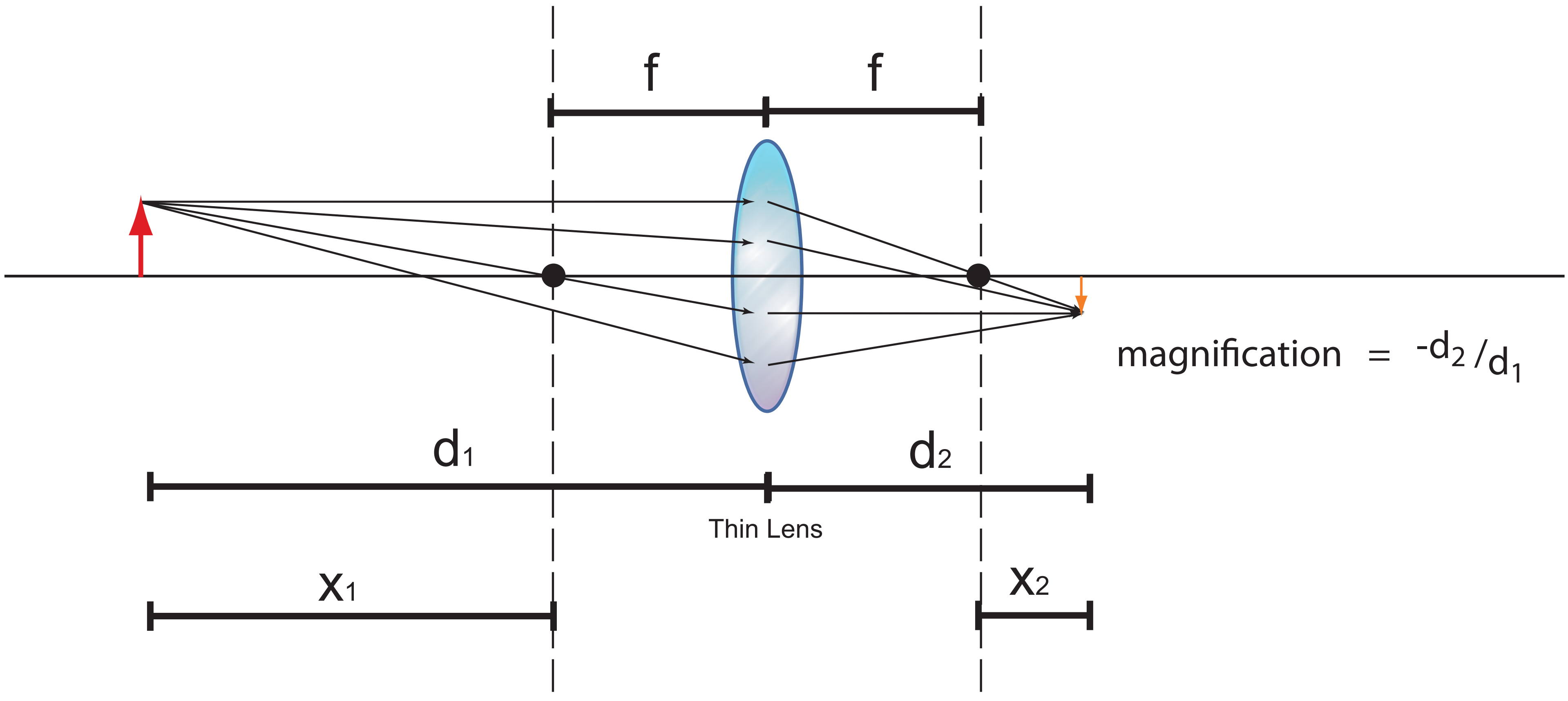
Focal Point , Focal Length, Focal Plane



Focal Point , Focal Length, Focal Plane



Lens Equation

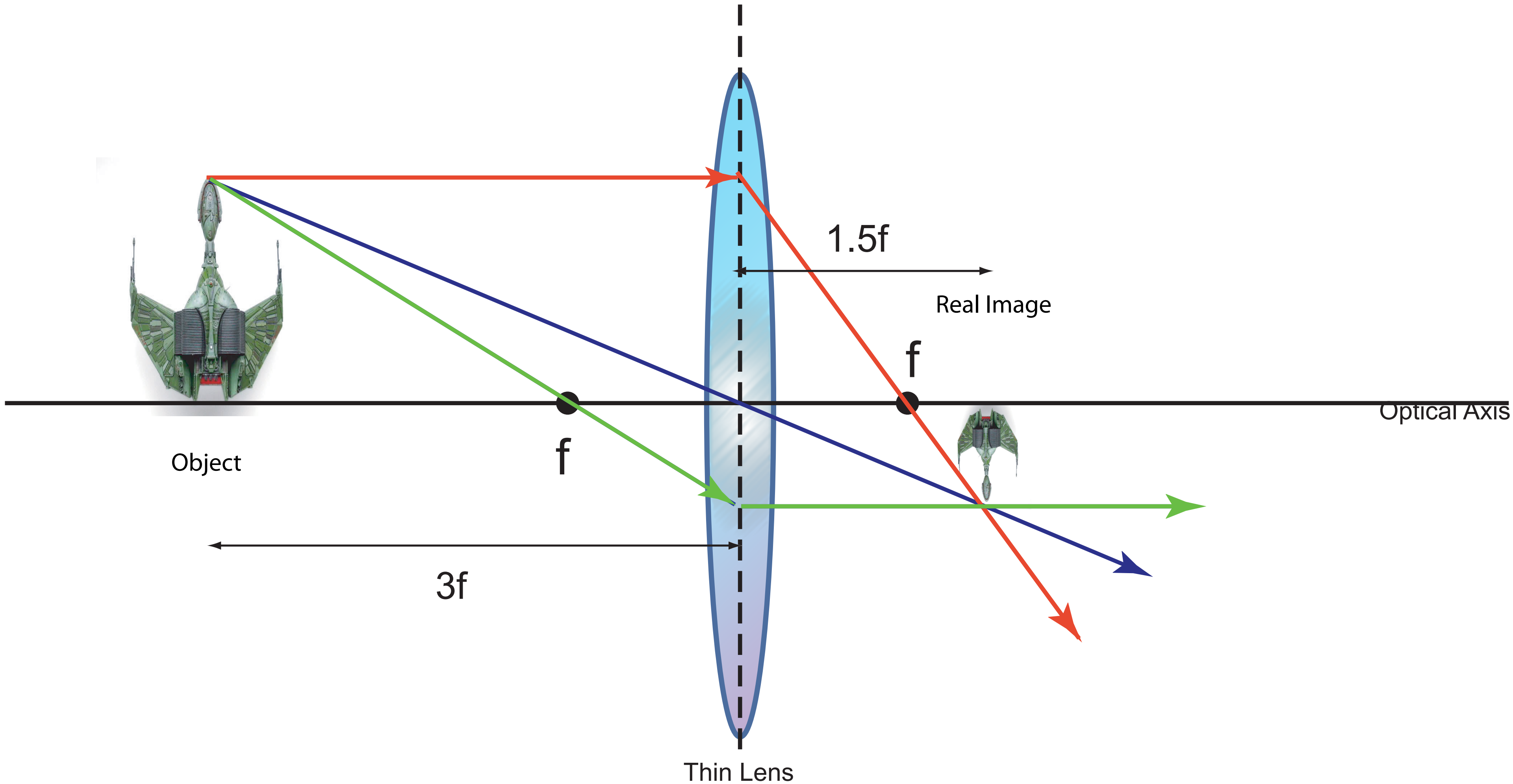


Gaussian Formulation : $1/f = (1/d_1) + (1/d_2)$

Newtonian Formulation : $f^2 = x_1 * x_2$

Ray Tracing Rules : Real Images

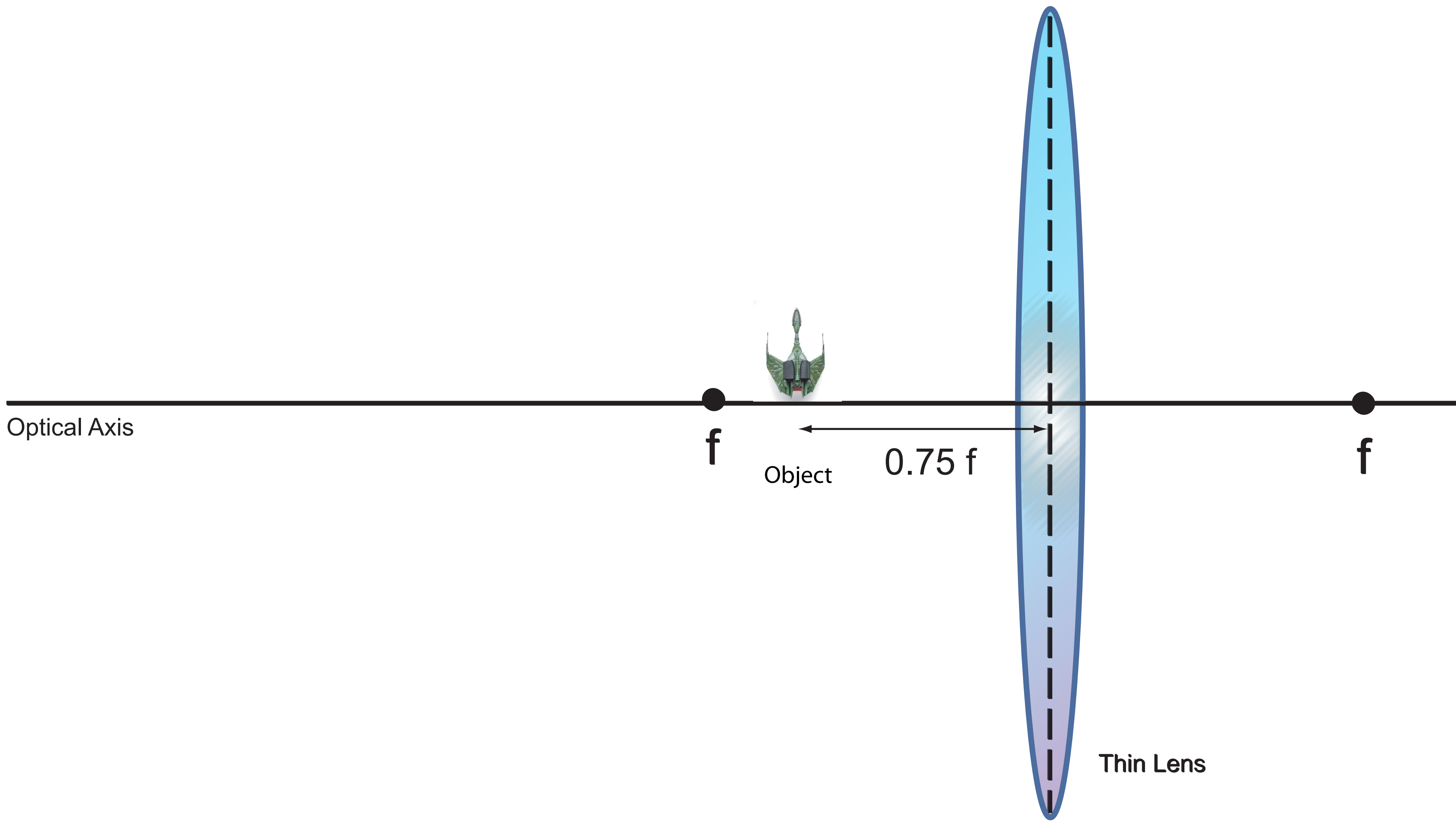
Positive lens, Object outside the focal point



In: Parallel to optical axis — Out: Through back focal point
In: Through front focal point — Out: Parallel to optical axis
In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

Positive lens, Object inisde the focal point



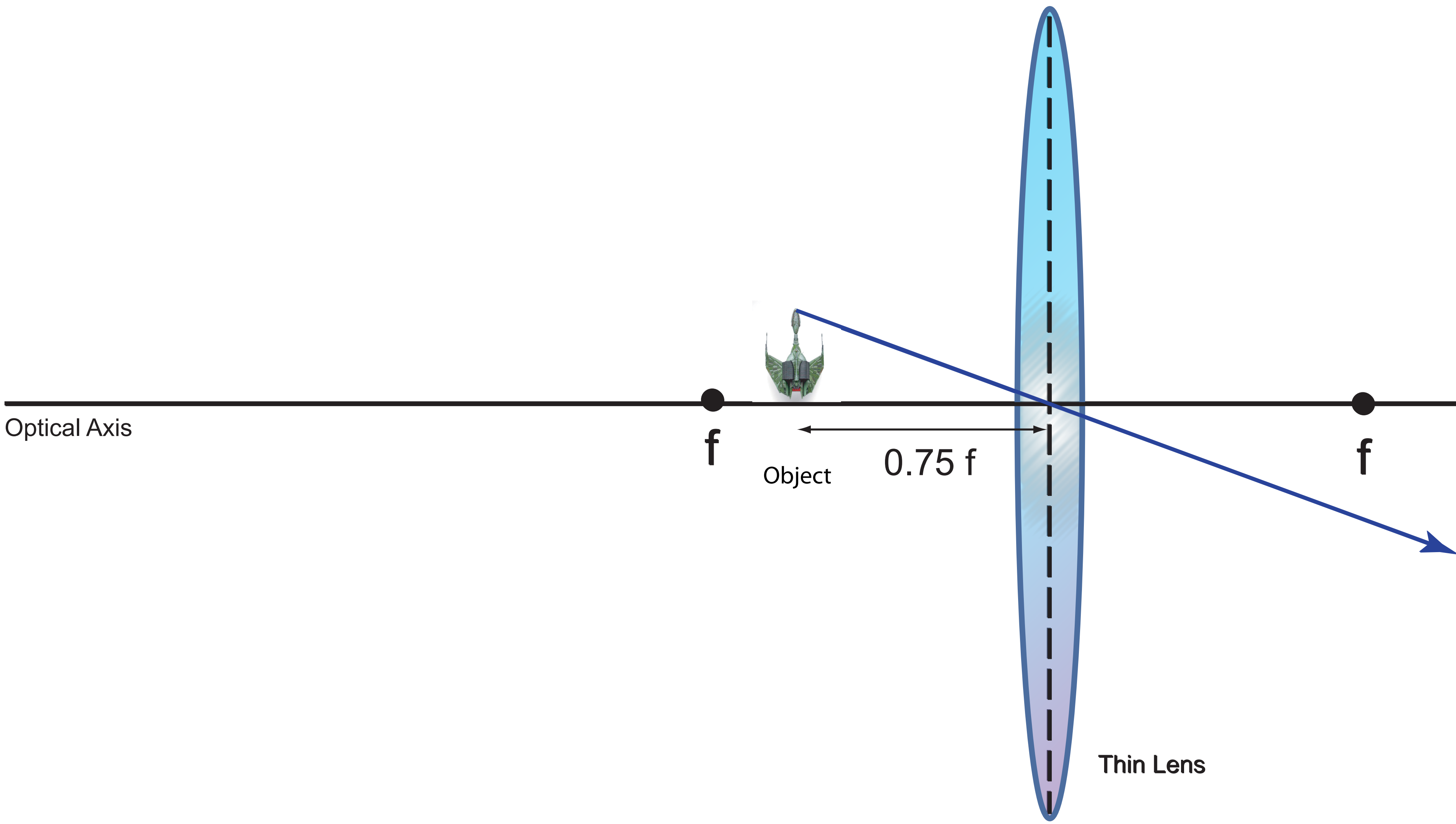
In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

Positive lens, Object inisde the focal point



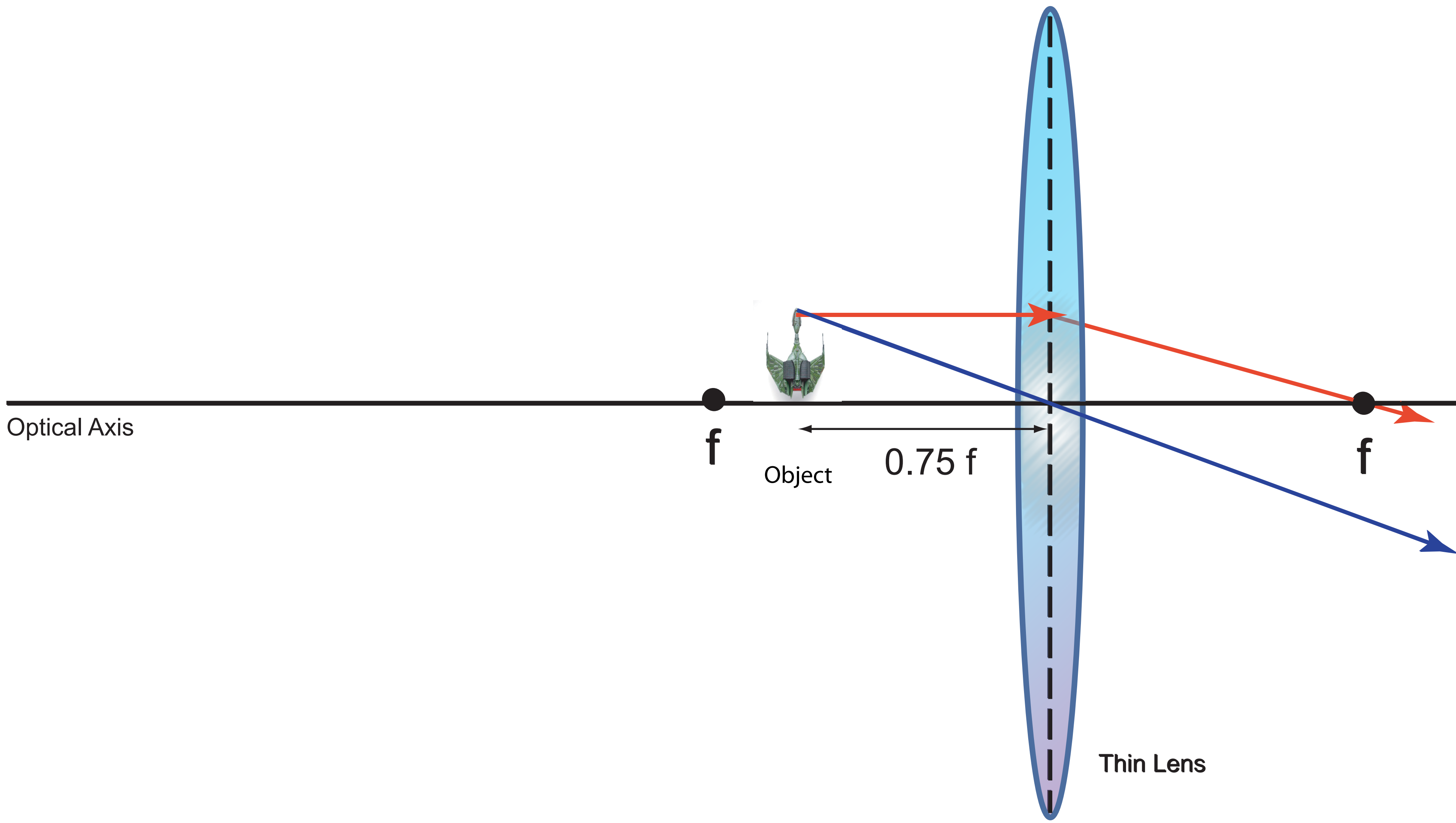
In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

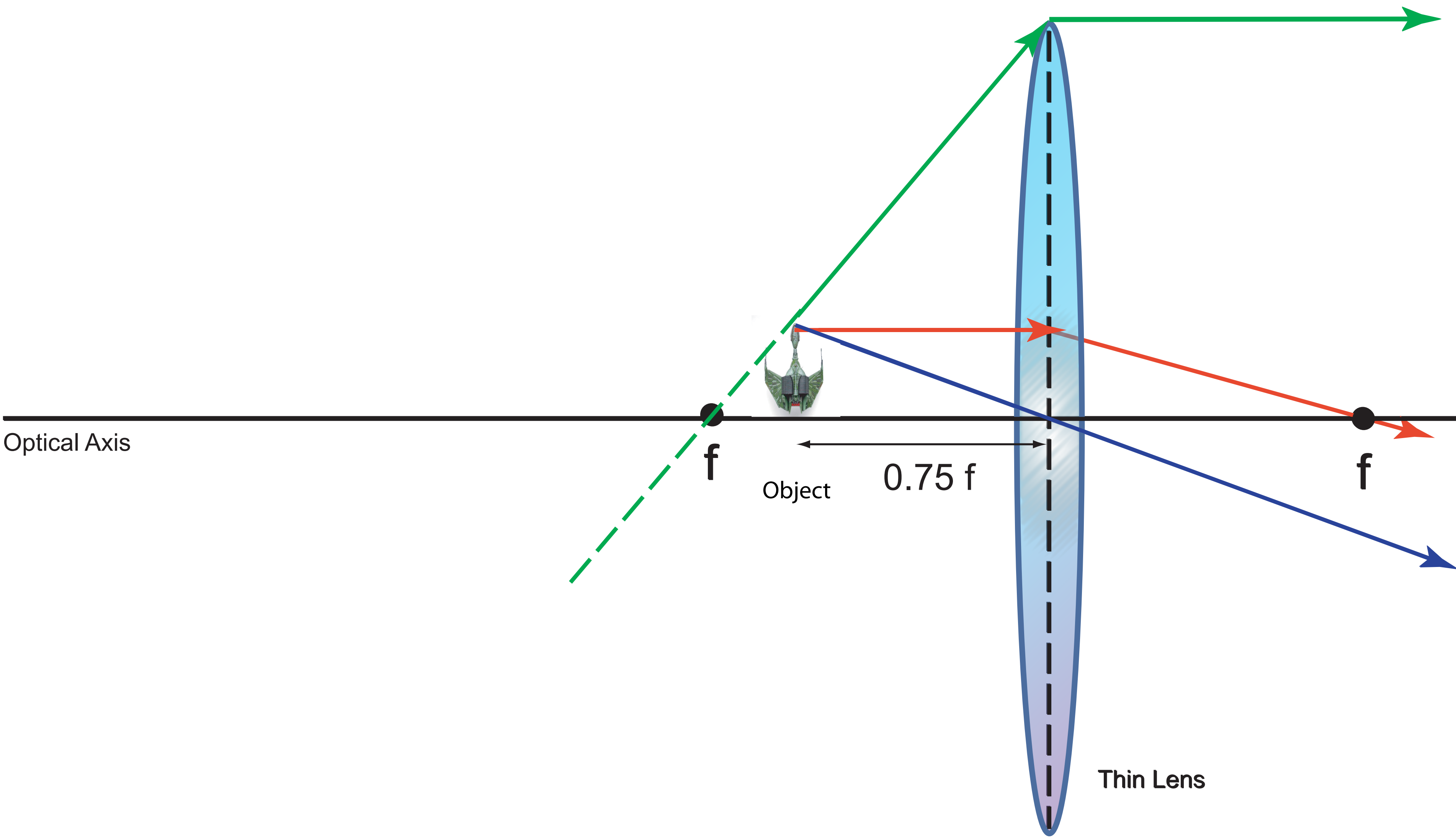
Positive lens, Object inisde the focal point



In: Parallel to optical axis — Out: Through back focal point
In: Through front focal point — Out: Parallel to optical axis
In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

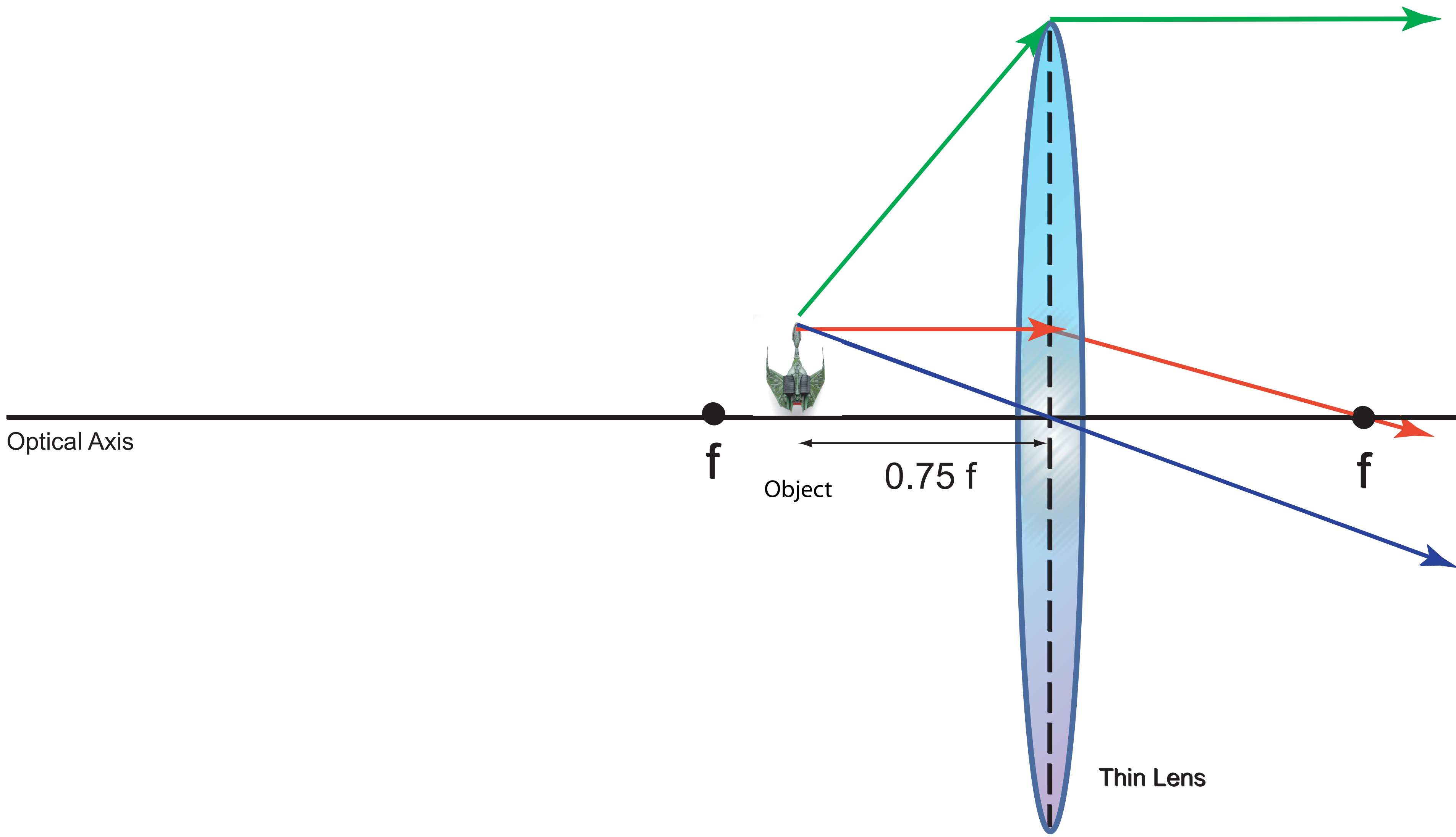
Positive lens, Object inisde the focal point



In: Parallel to optical axis — Out: Through back focal point
In: Through front focal point — Out: Parallel to optical axis
In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

Positive lens, Object inisde the focal point



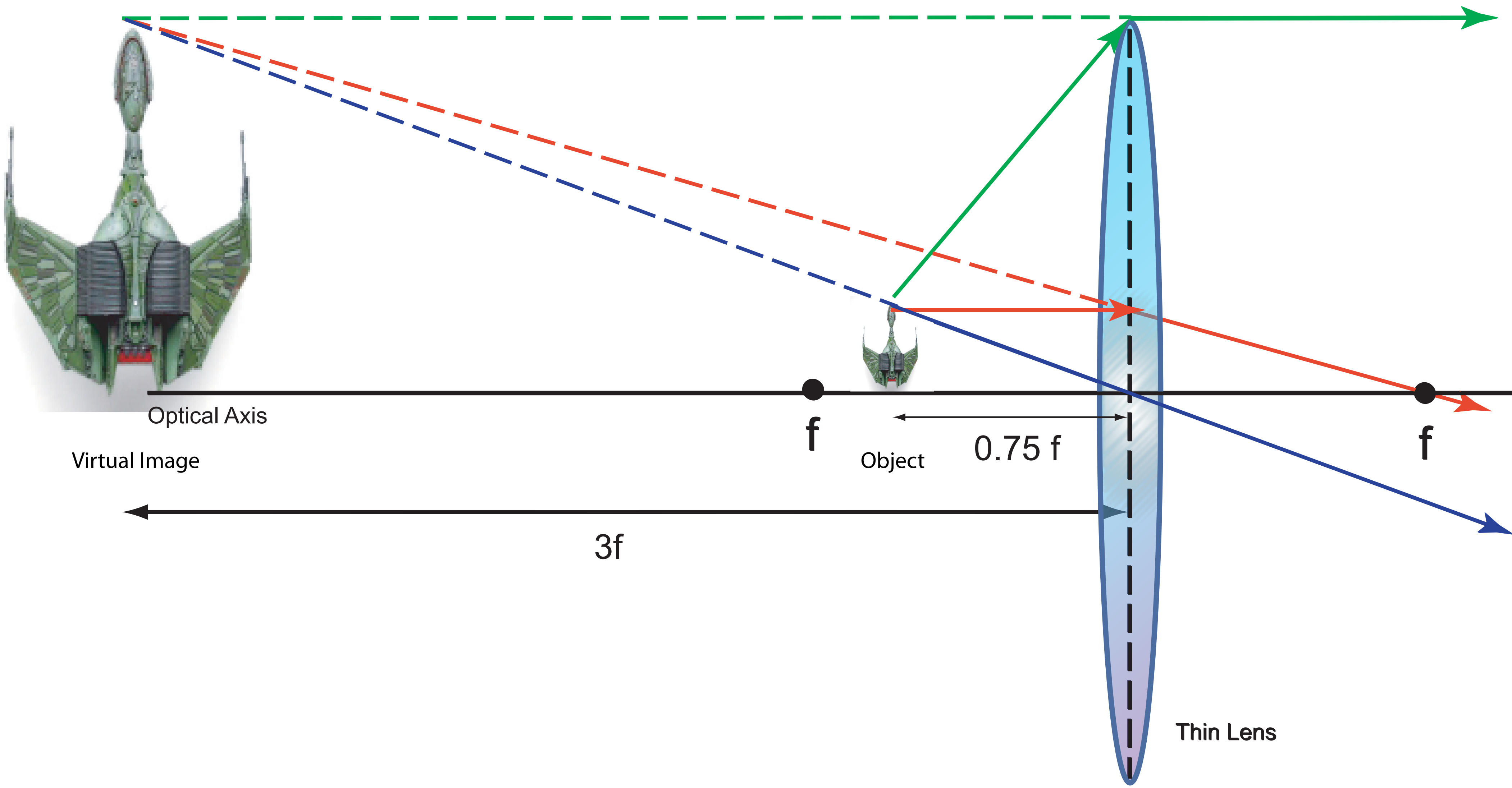
In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

Positive lens, Object inisde the focal point

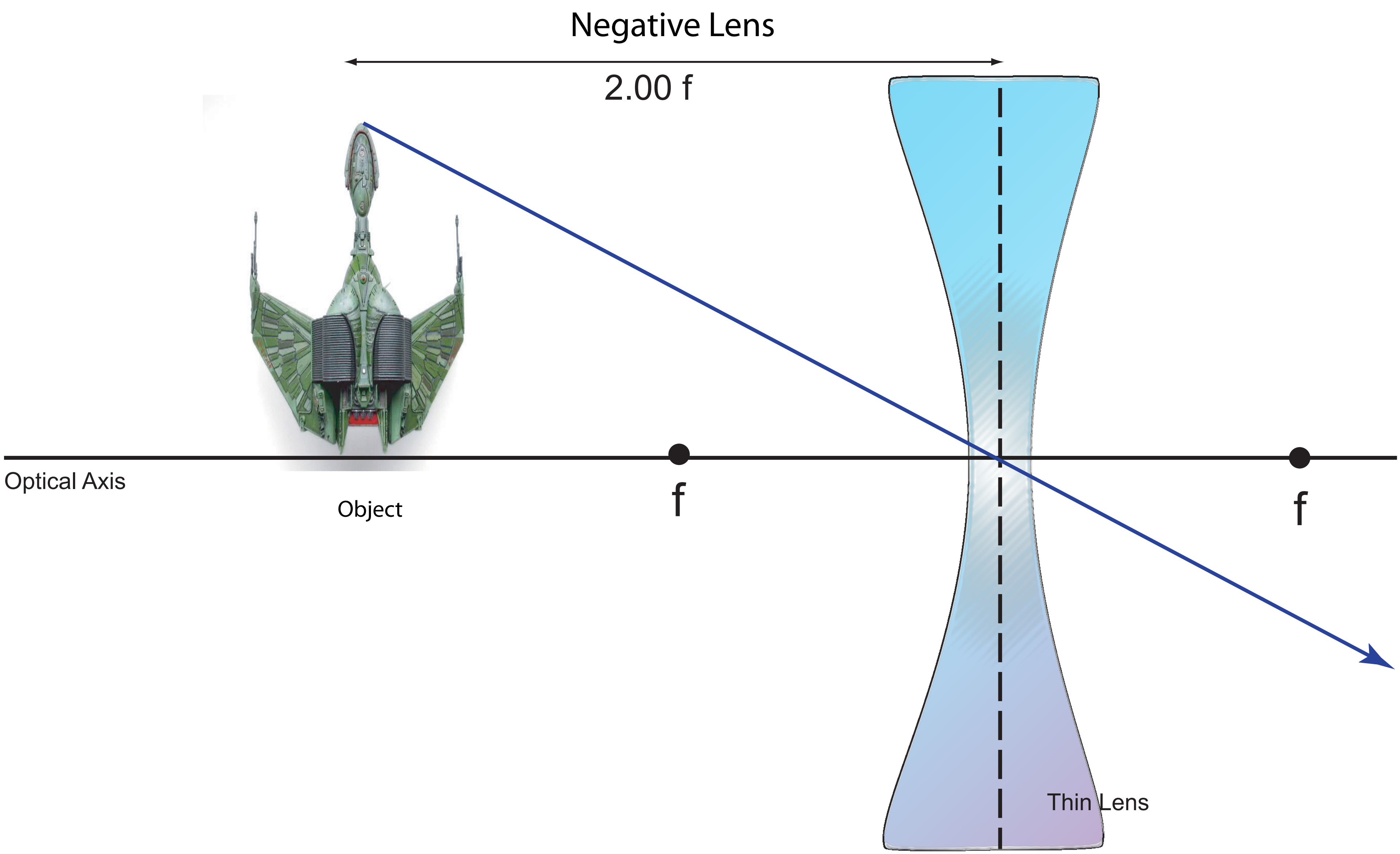


In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

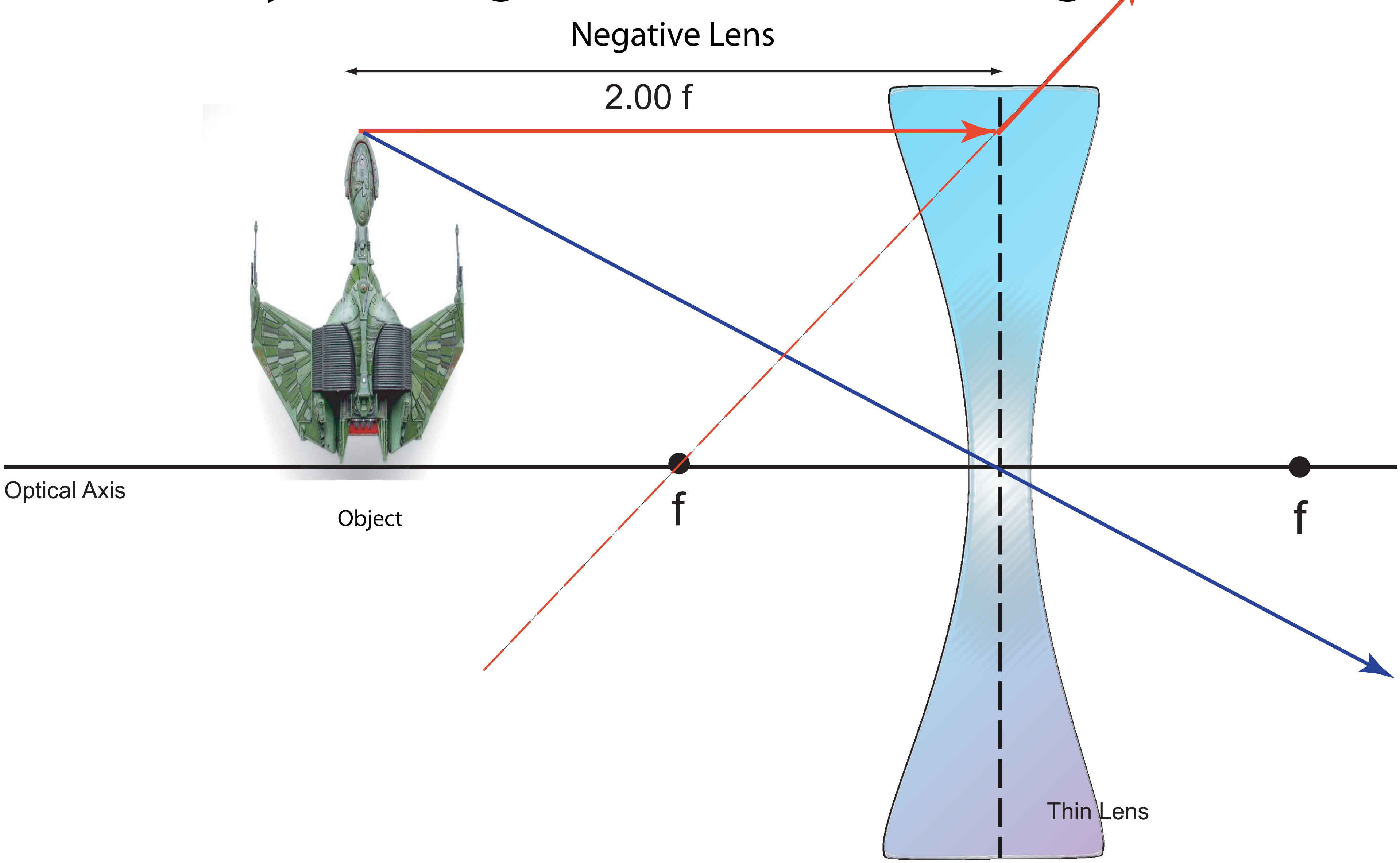


In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

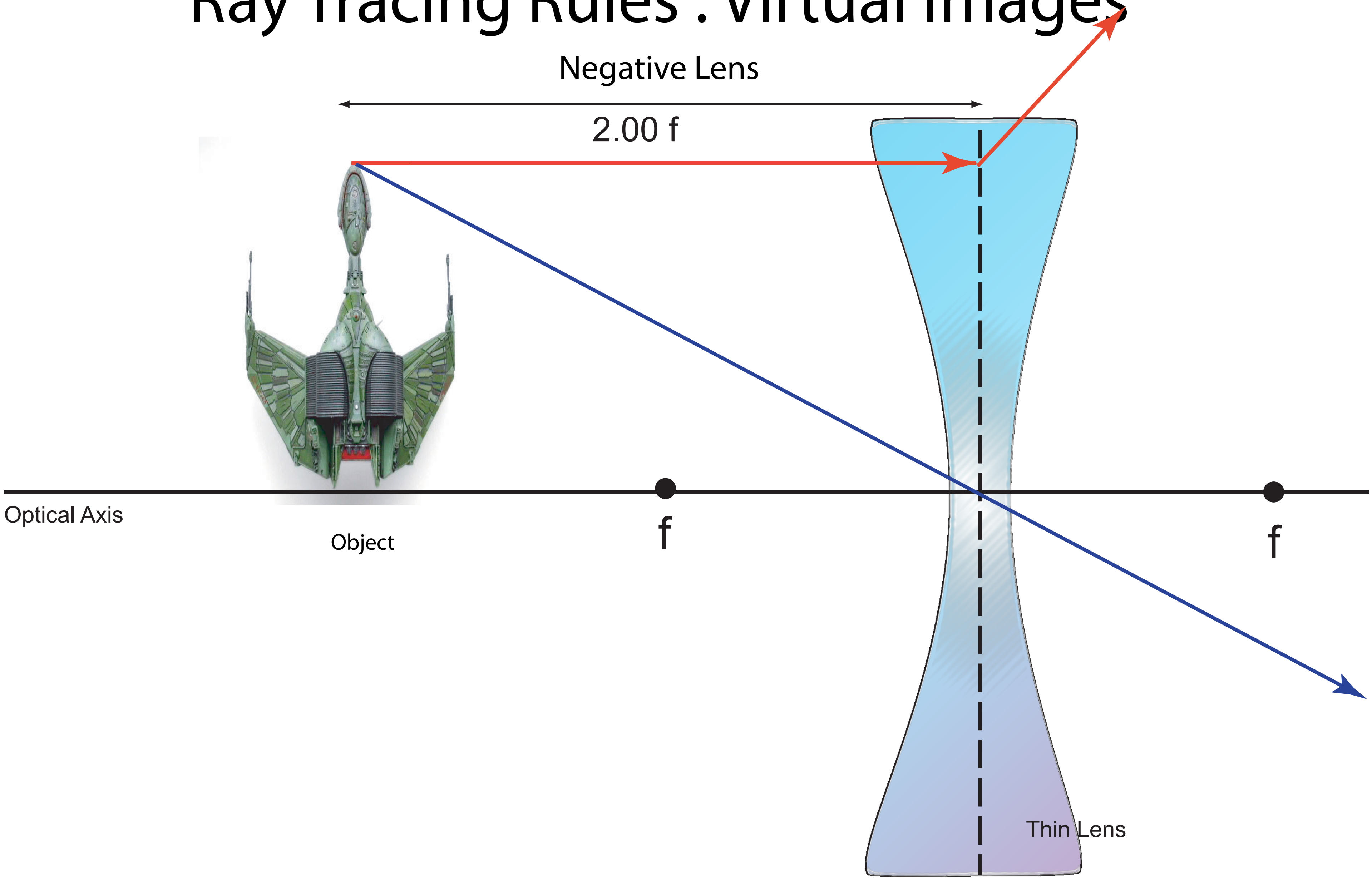


In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images

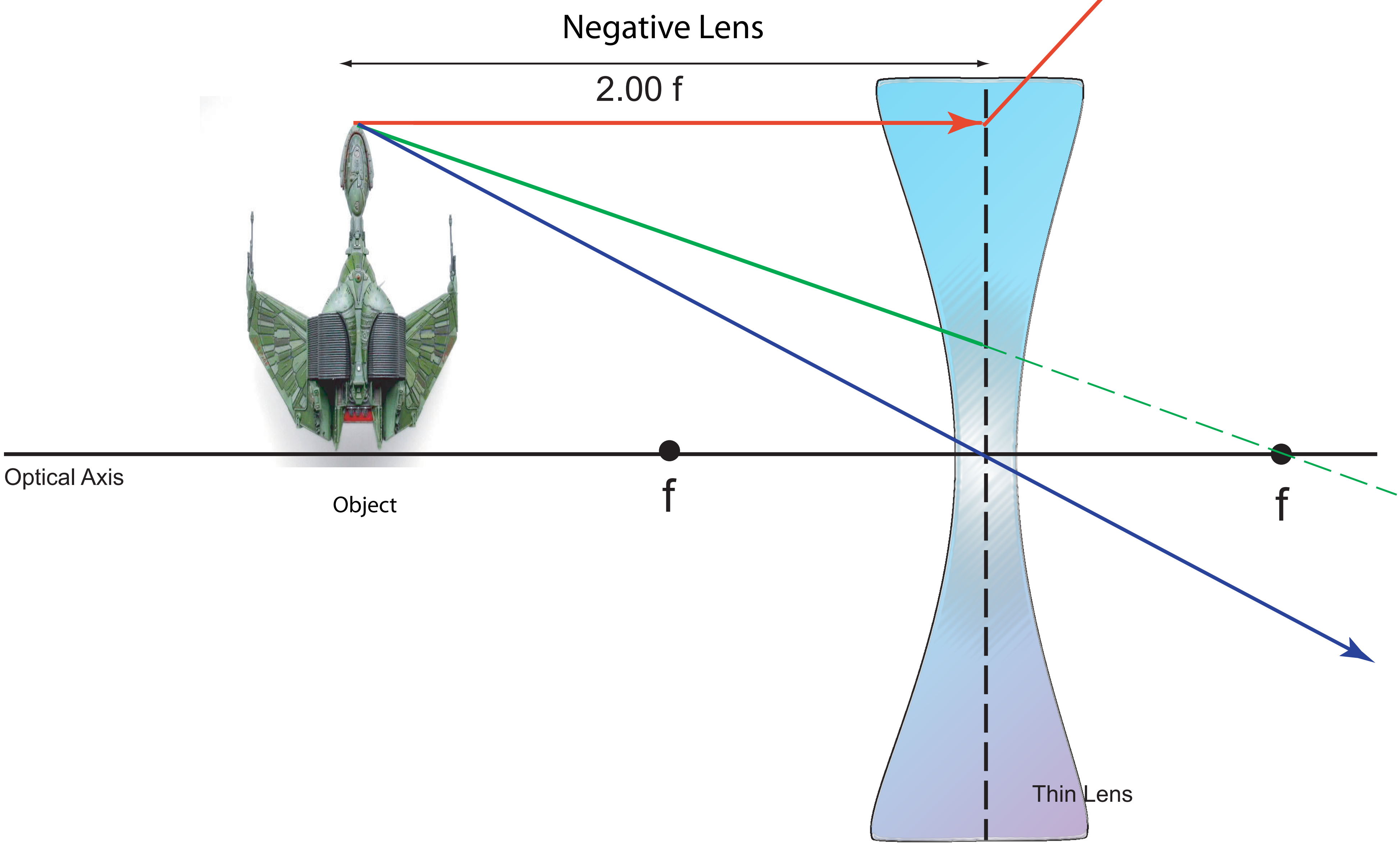


In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

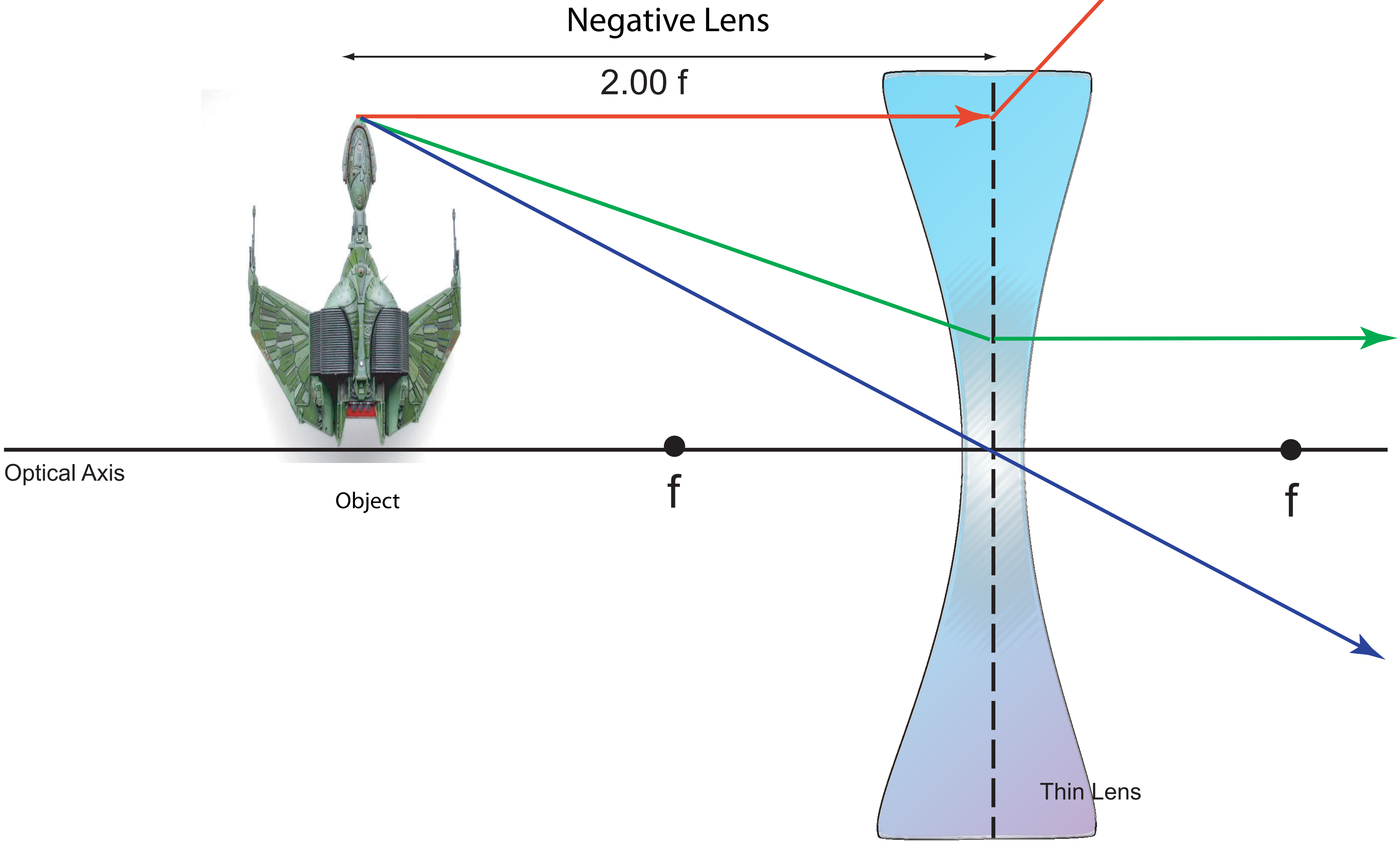
Ray Tracing Rules : Virtual Images



In: Parallel to optical axis
In: Through front focal point
In: Through center of lens

Out: Through back focal point
Out: Parallel to optical axis
Out: Undeviated

Ray Tracing Rules : Virtual Images



In: Parallel to optical axis — Out: Through back focal point

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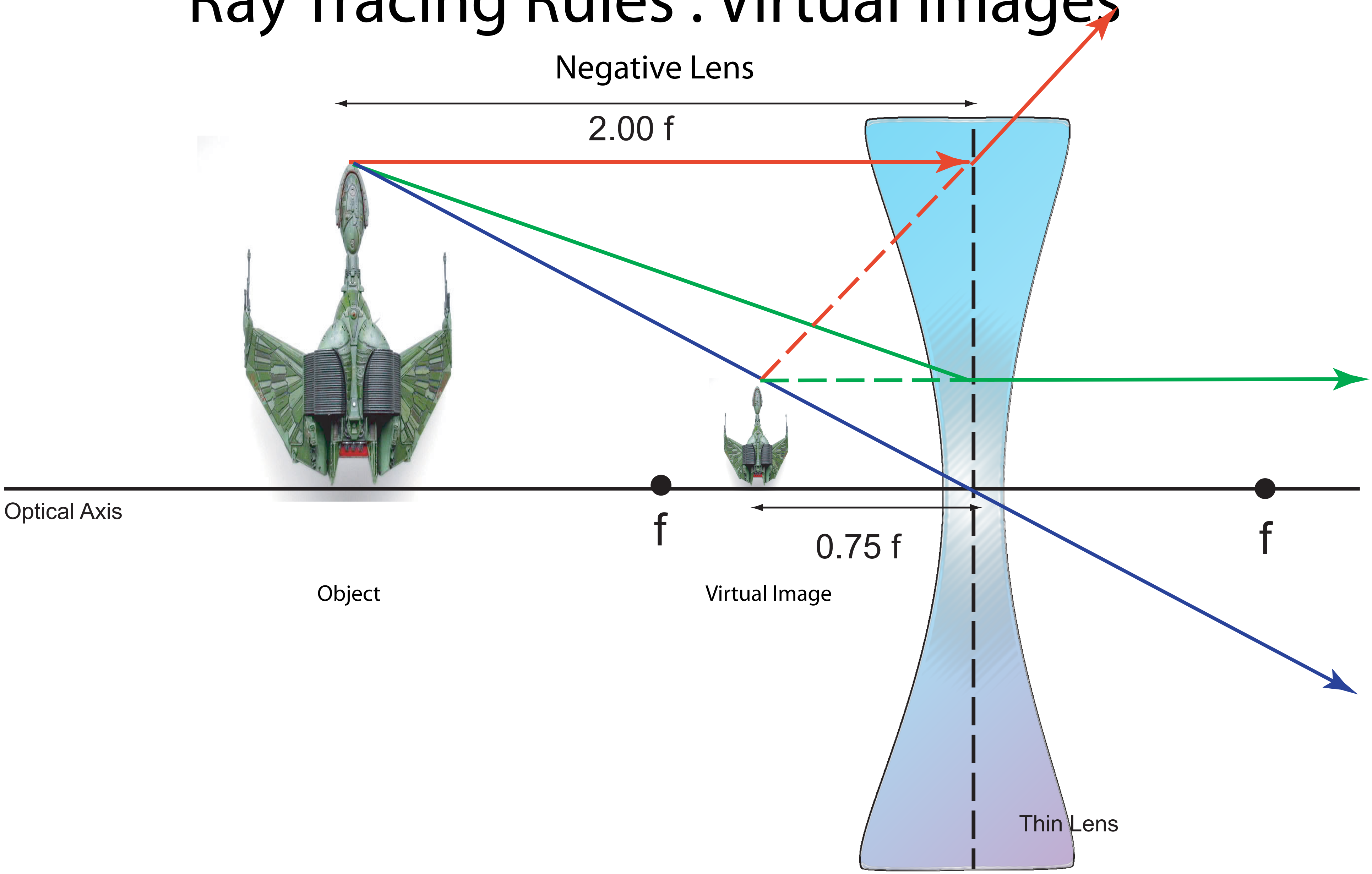
In: Through center of lens — Out: Undeviated

Ray Tracing Rules : Virtual Images



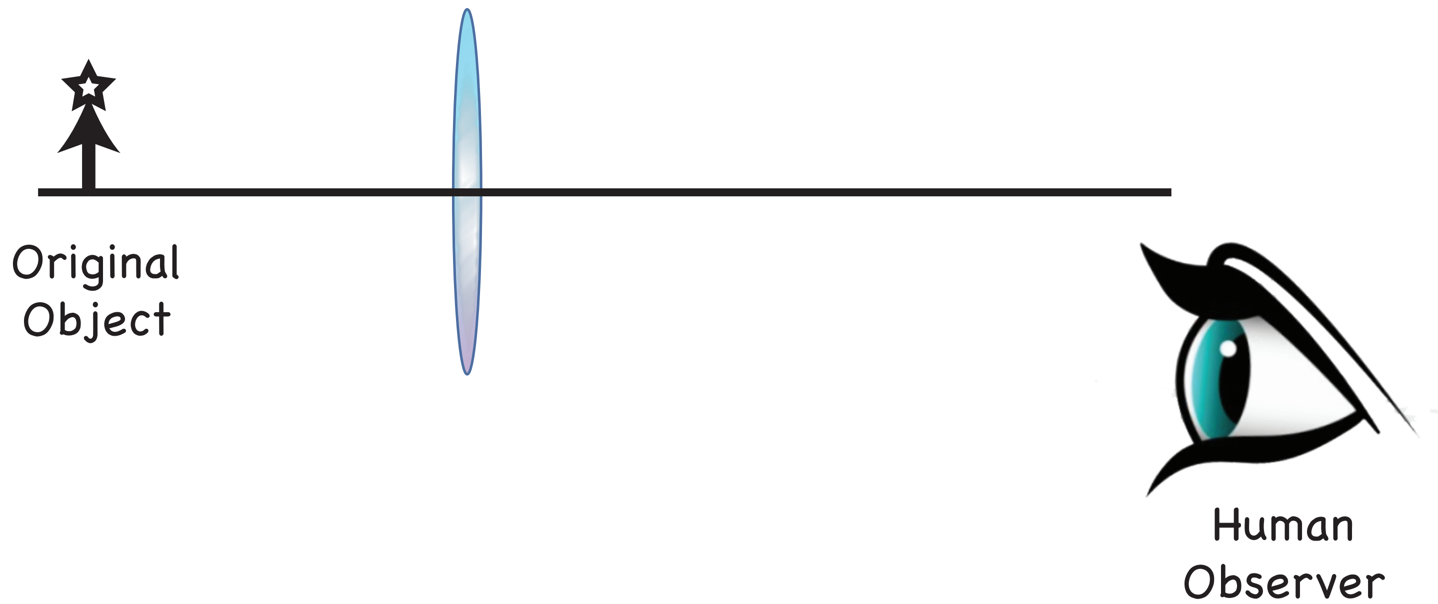
In: Parallel to optical axis — Out: Through back focal point

In: Through front focal point — Out: Parallel to optical axis

In: Through center of lens — Out: Undeviated

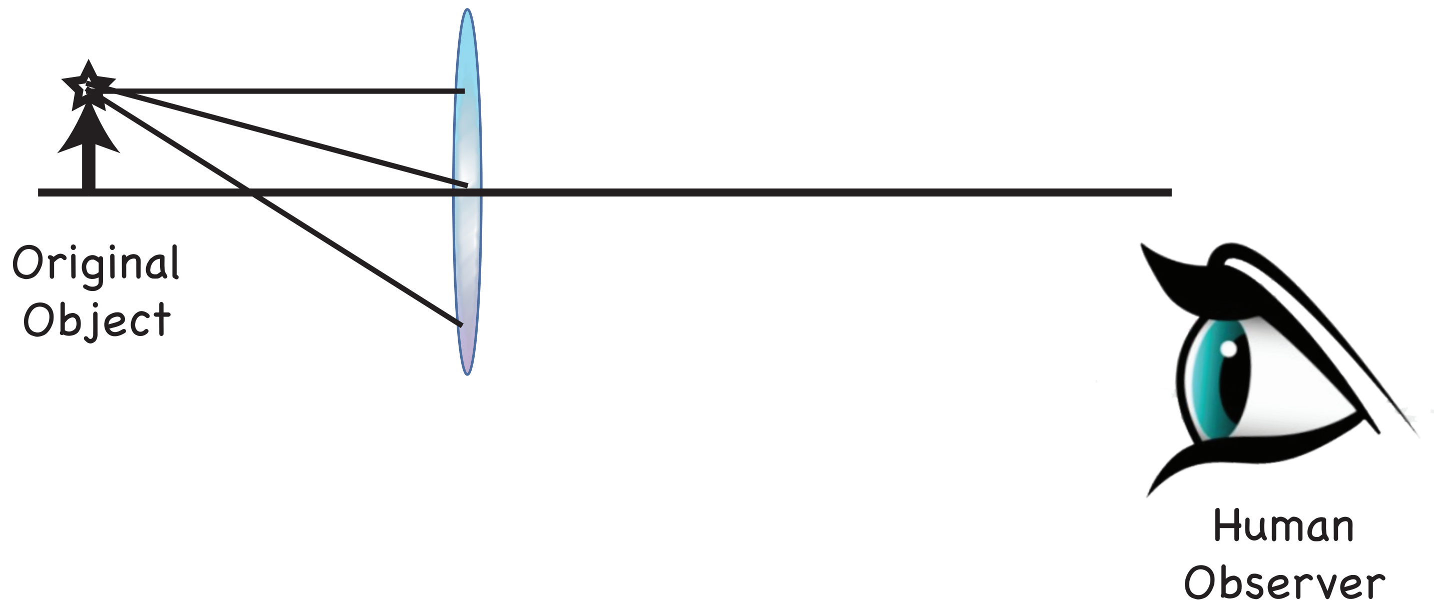
Real & Virtual Images

OBJECT FAR
AWAY FROM LENS



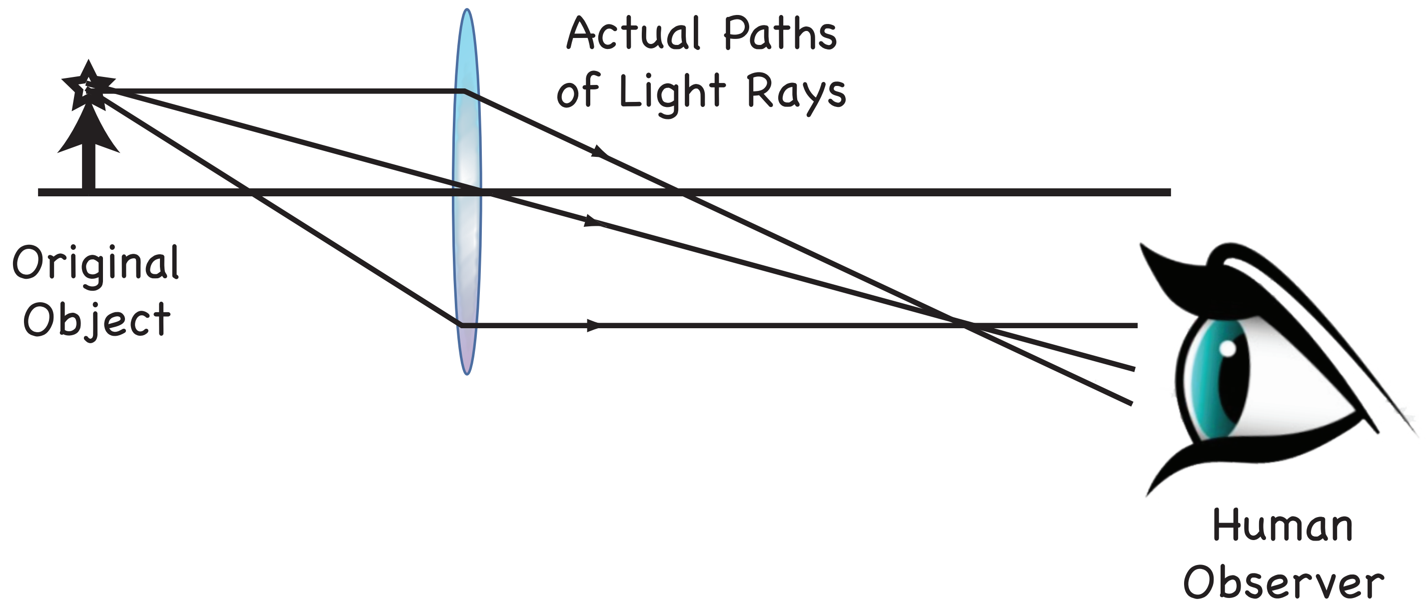
Real & Virtual Images

OBJECT FAR
AWAY FROM LENS



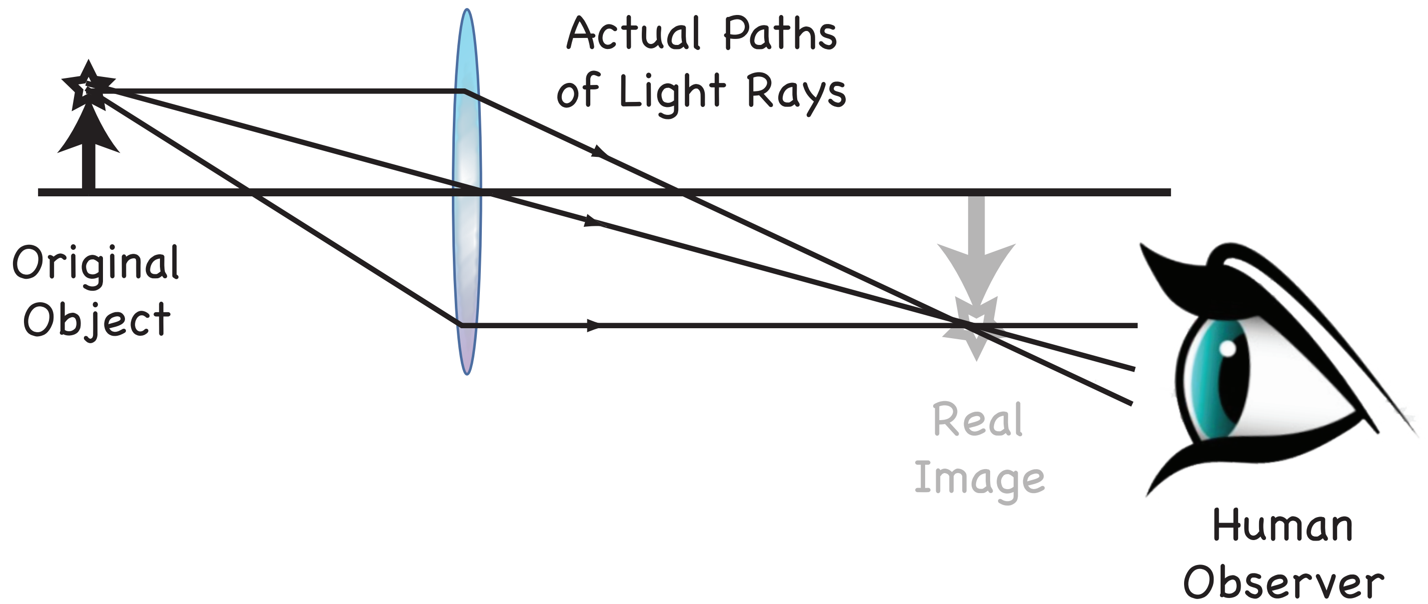
Real & Virtual Images

OBJECT FAR
AWAY FROM LENS

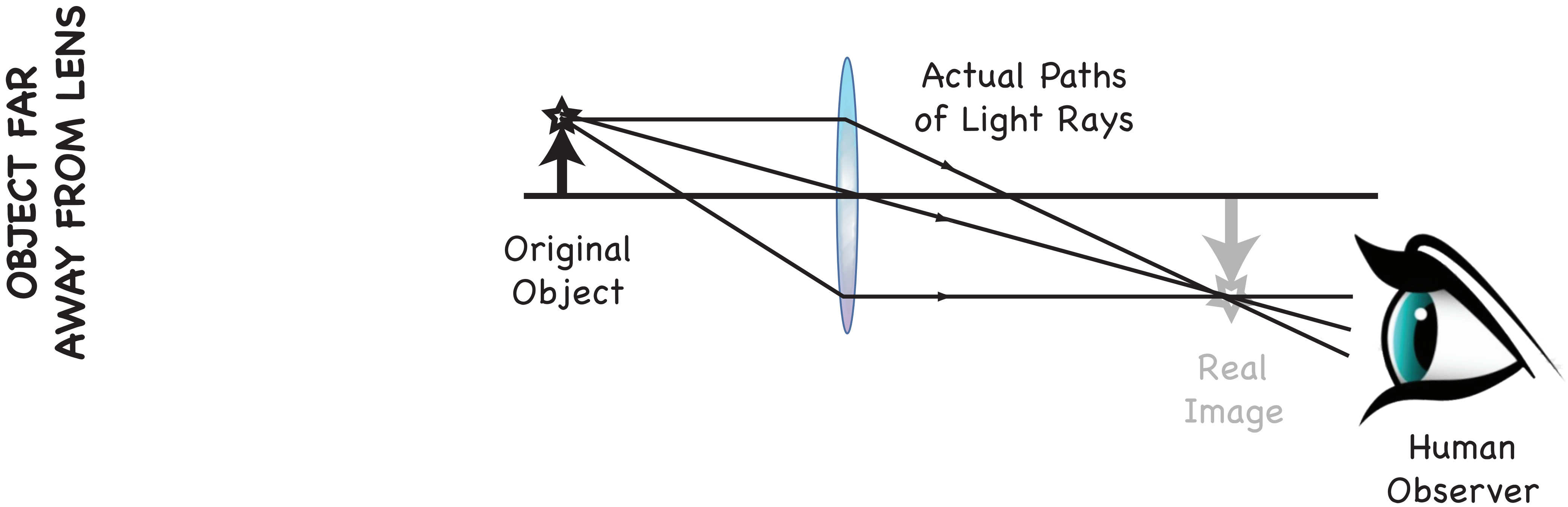


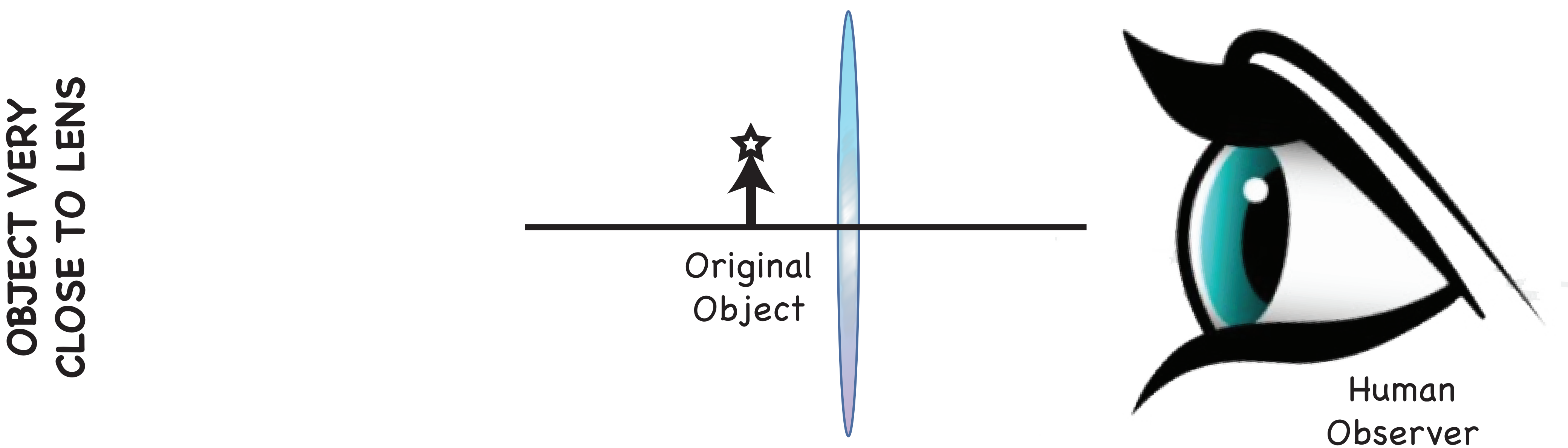
Real & Virtual Images

OBJECT FAR
AWAY FROM LENS



Real & Virtual Images





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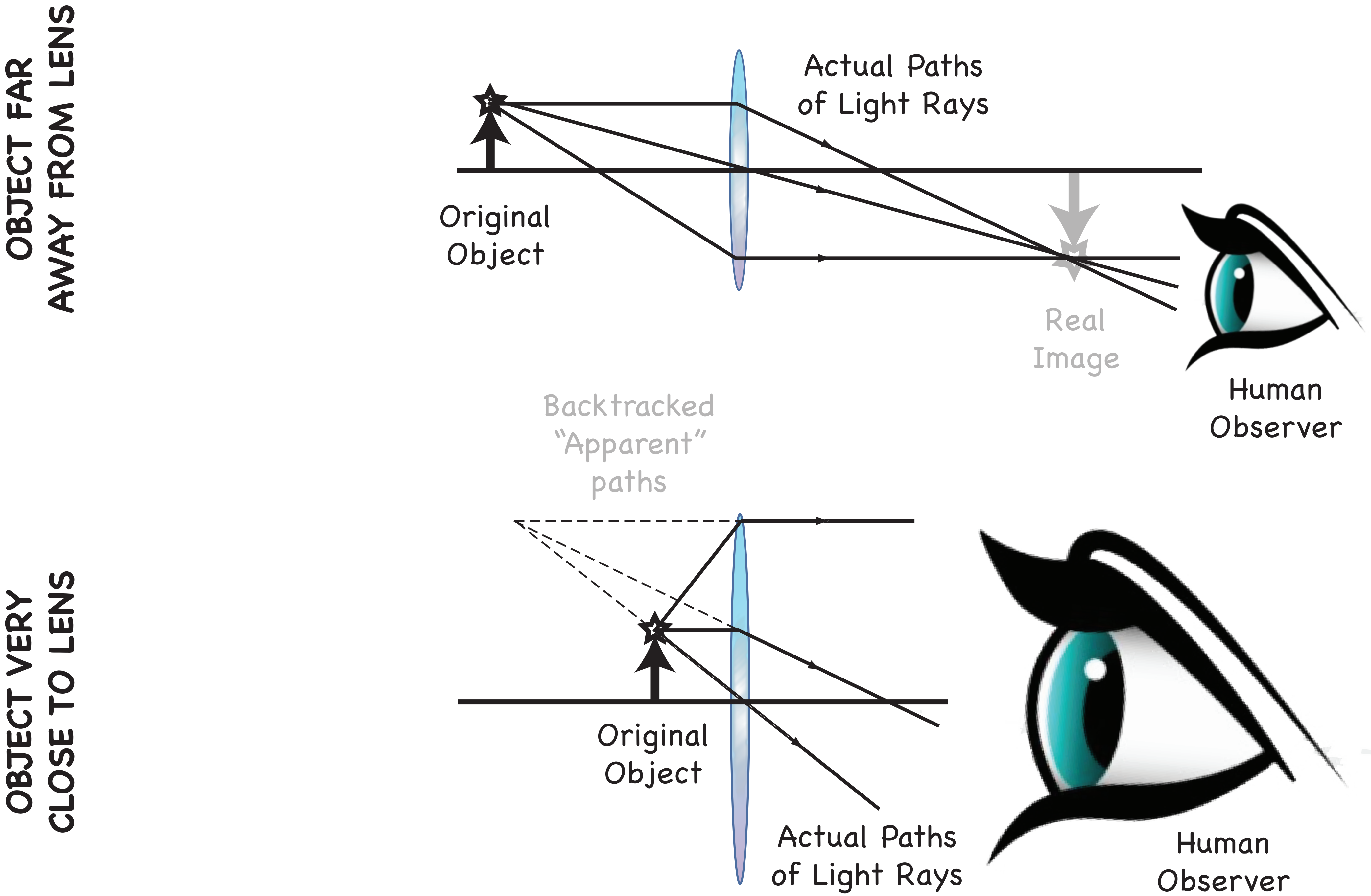

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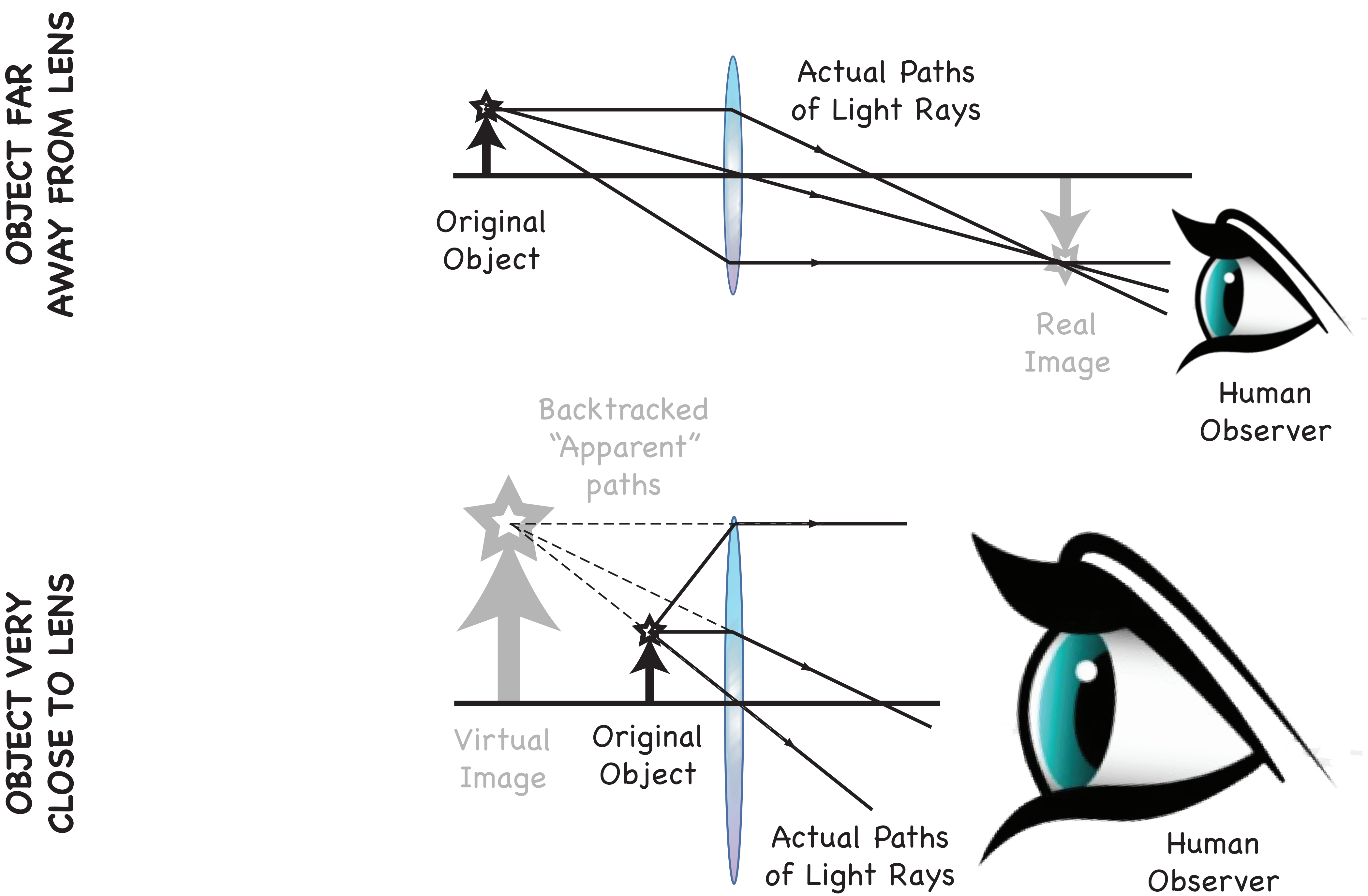
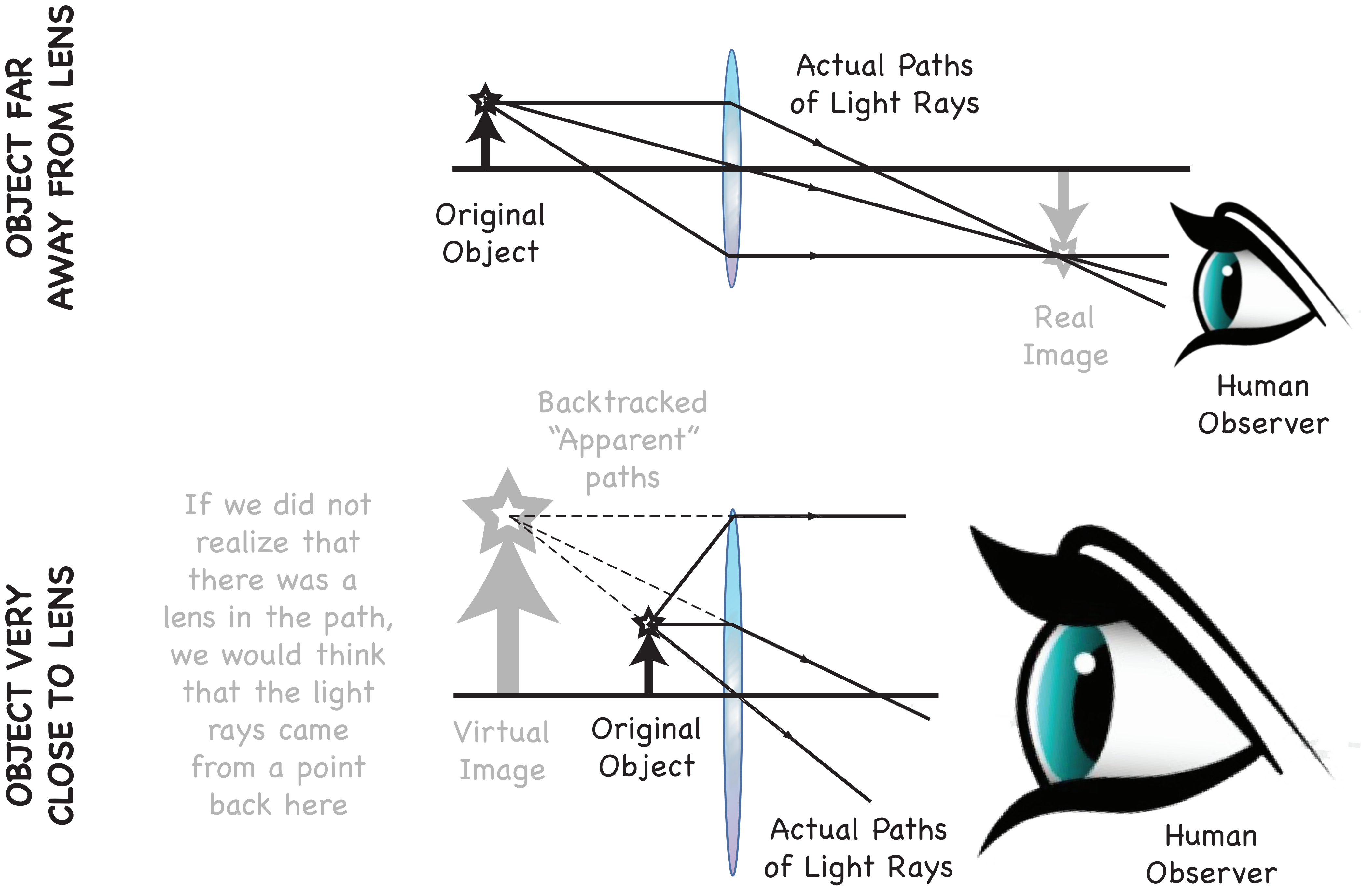
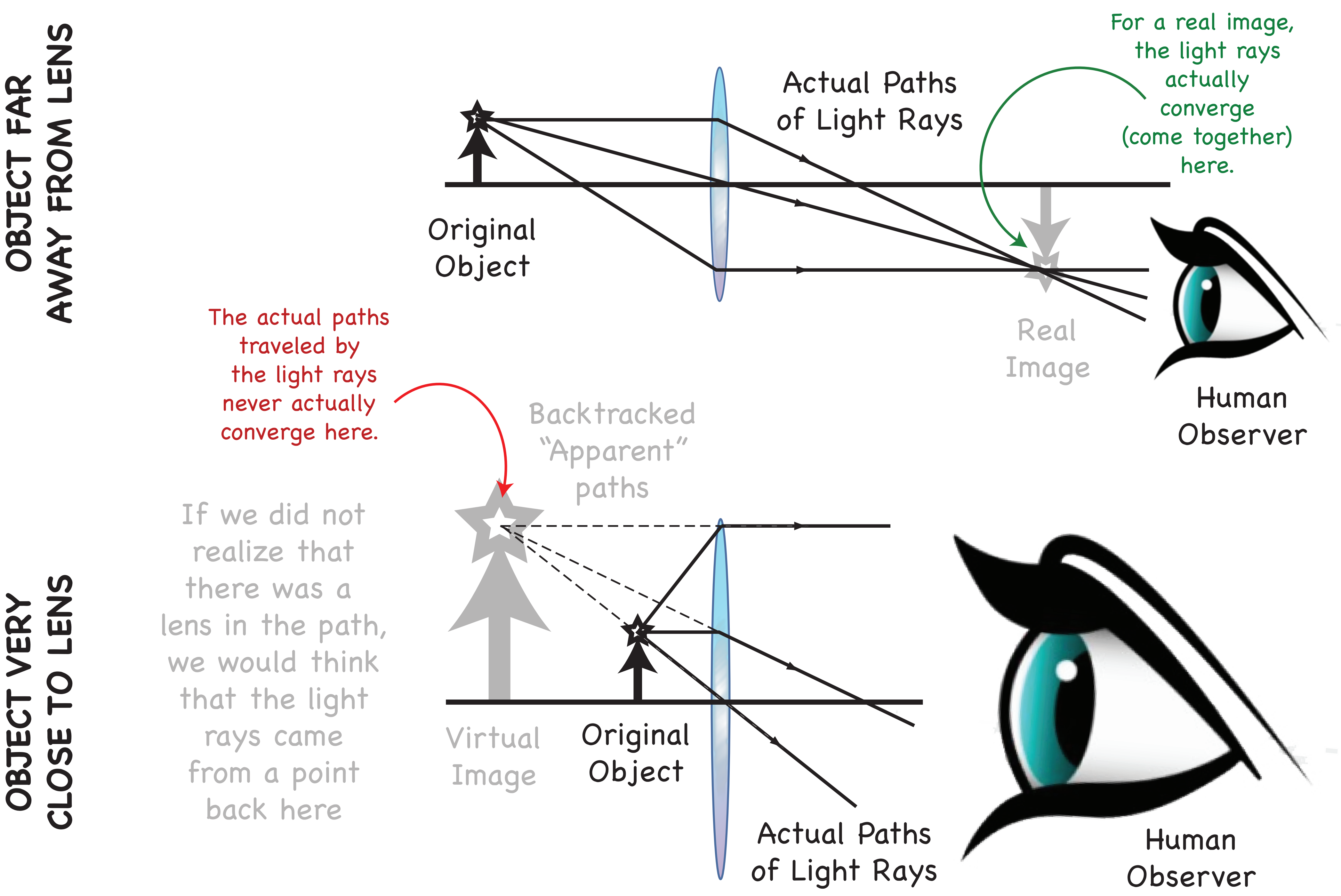


Real & Virtual Images



Real & Virtual Images



Imaging Conditions : d_2 vs d_1