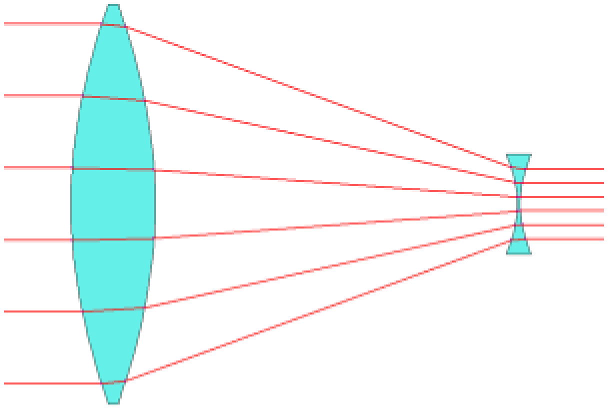
EP 324
Applied Optics

Topic 2

Reflection, Refraction and Prisms



Department of

Engineering of Physics

Gaziantep University

Oct 2015

Geometric Optics

The field of Geometric Optics involves the study of the propagation of light with the assumption that

the light travels in a fixed direction in a straight line called ray.

- Rays are defined to propagate in a rectilinear path as they travel in a homogeneous medium.
- Rays bend (and may split in two) at the interface between two dissimilar media.
- Rays may curve in a medium where the refractive index changes.
- Rays may be absorbed and reflected.

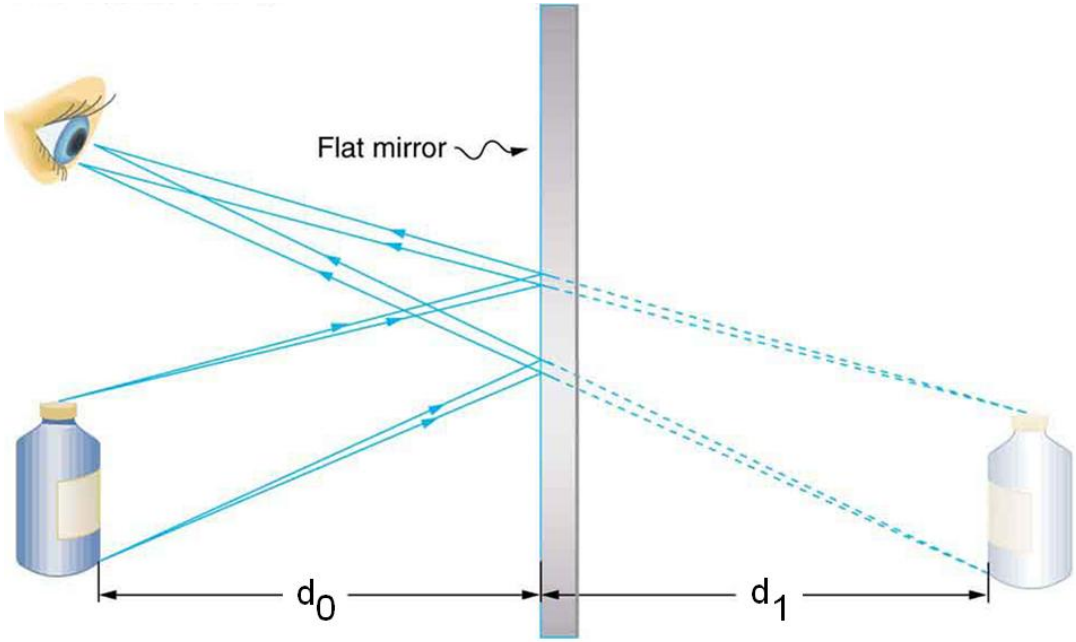
PART I

REFLECTION & REFRACTION

Reflection

Shining surfaces (e.g. mirrors) reflect the light in a simple way:

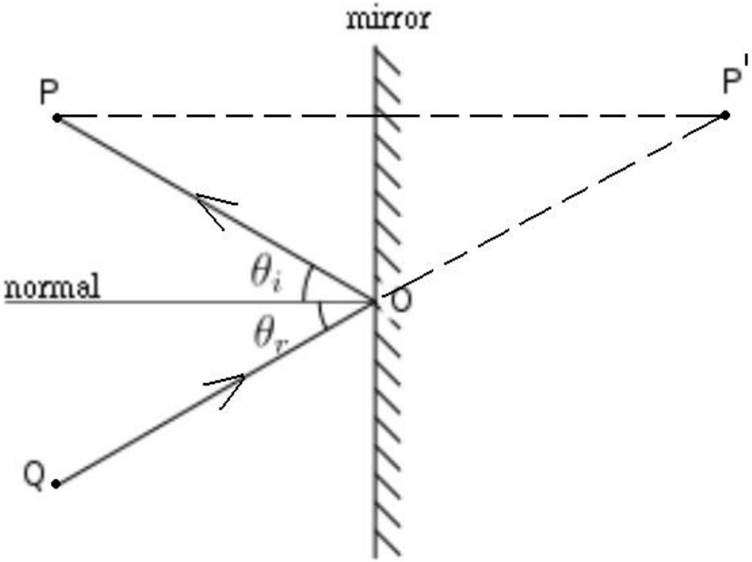
$$d_0 = d_1$$

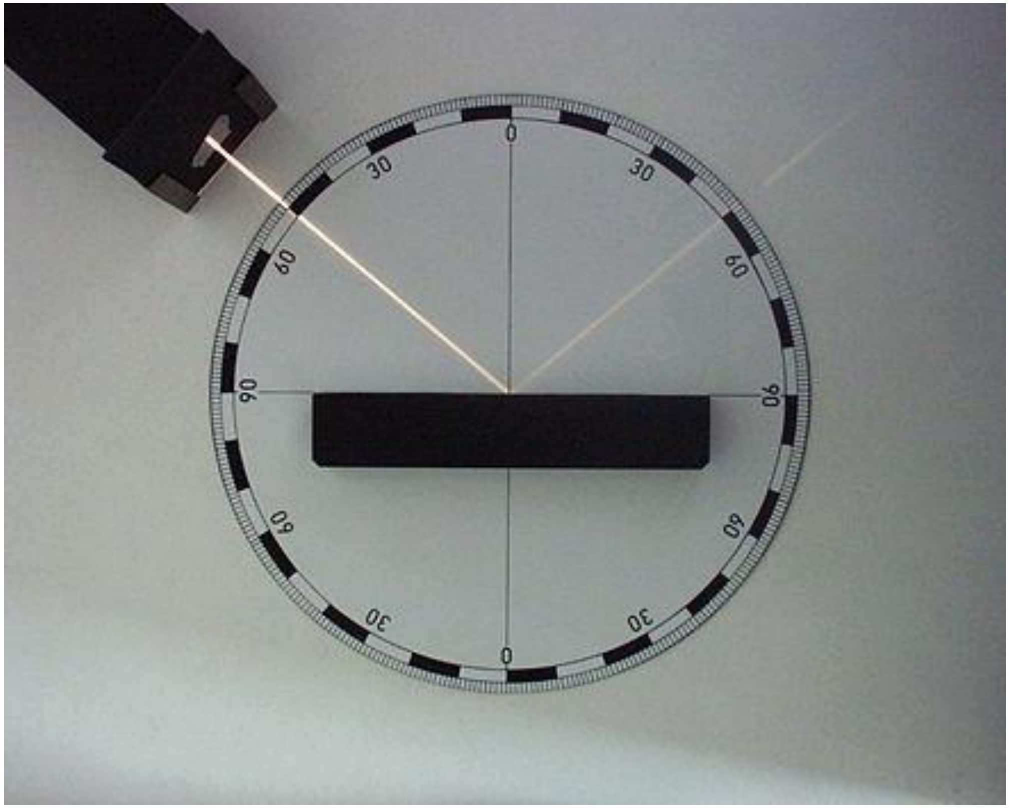


Reflection

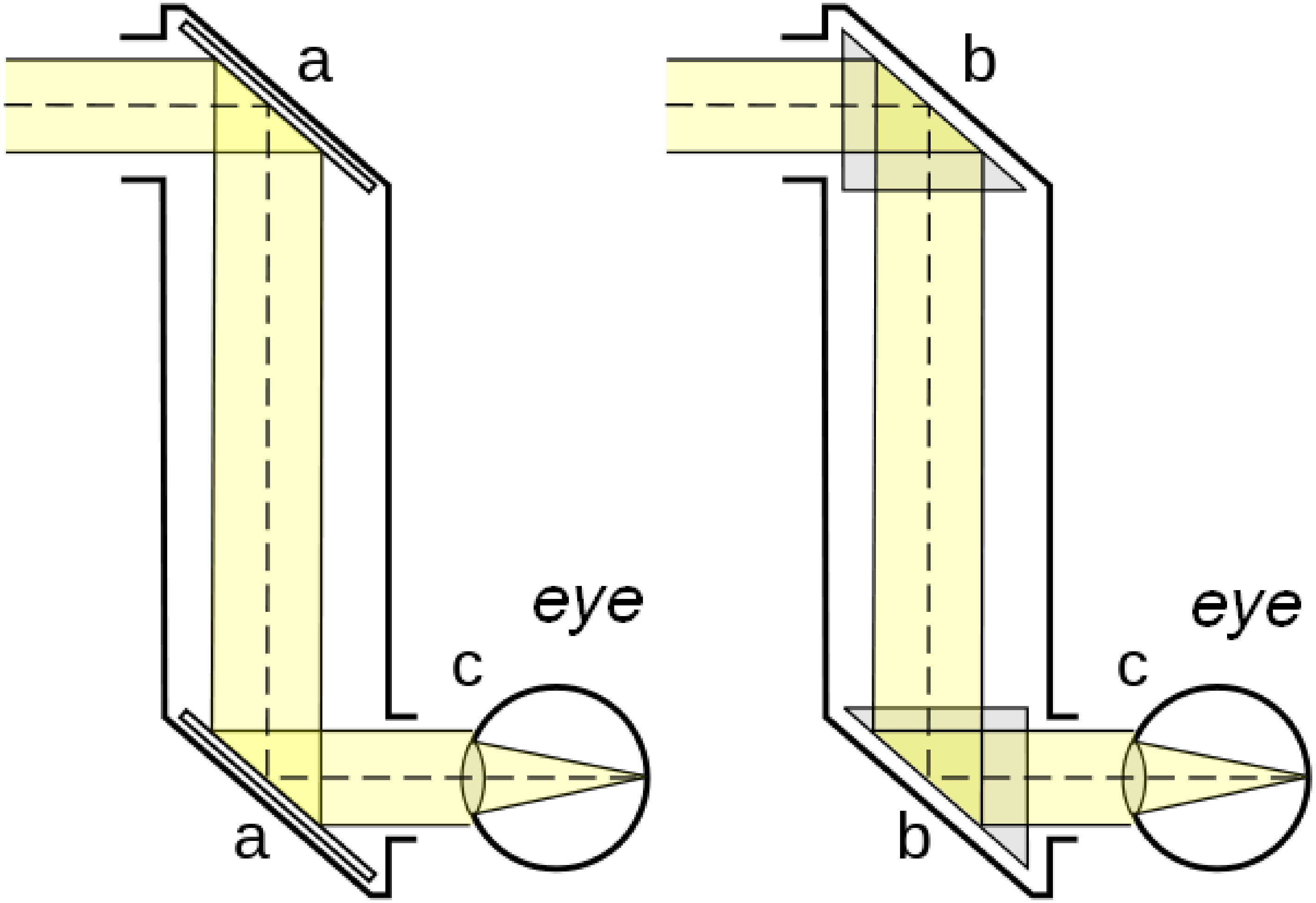
The law of reflection:

$$\theta_i = \theta_r$$

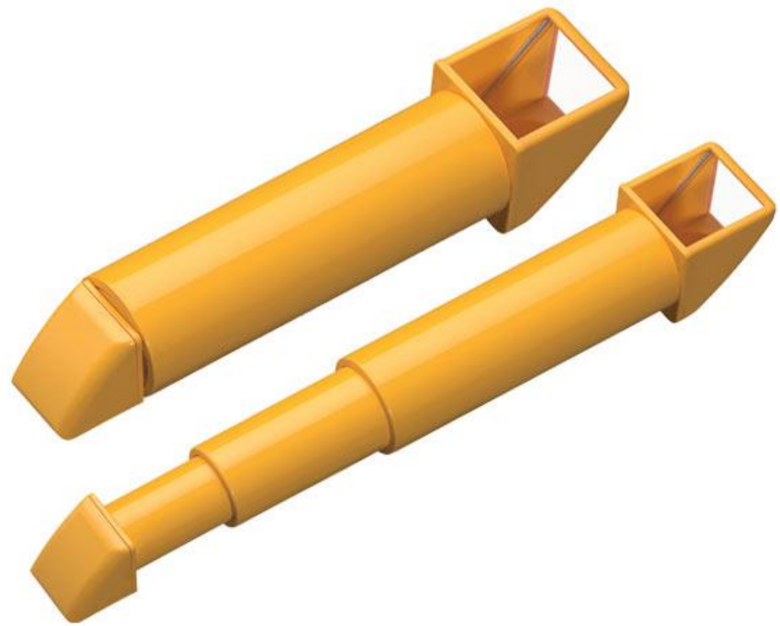




Periscope



Periscope

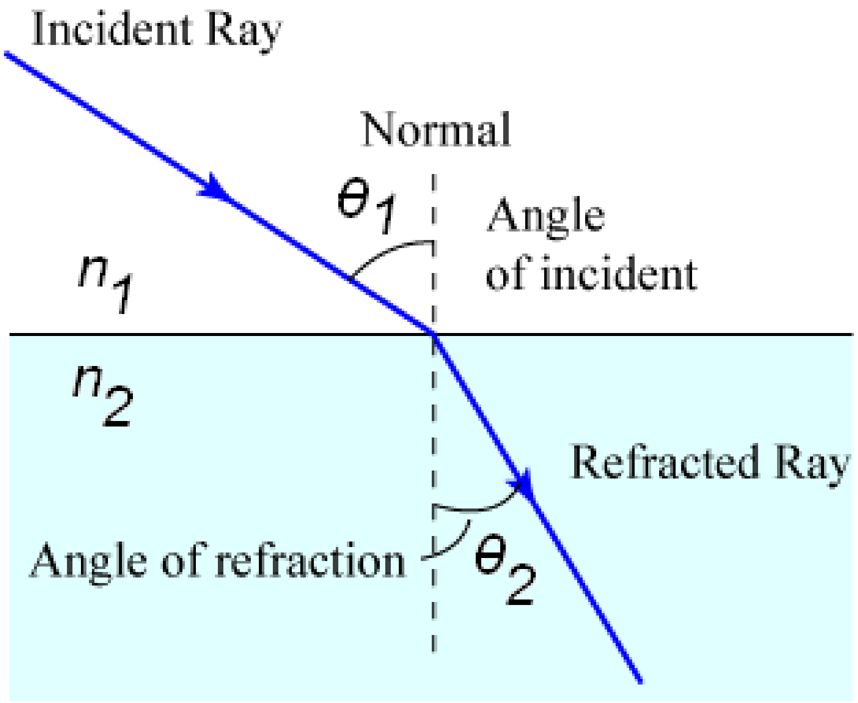


Refraction

Refraction is the change in direction of a ray due to a change in its transmission medium.

Snell's Law of refraction:

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

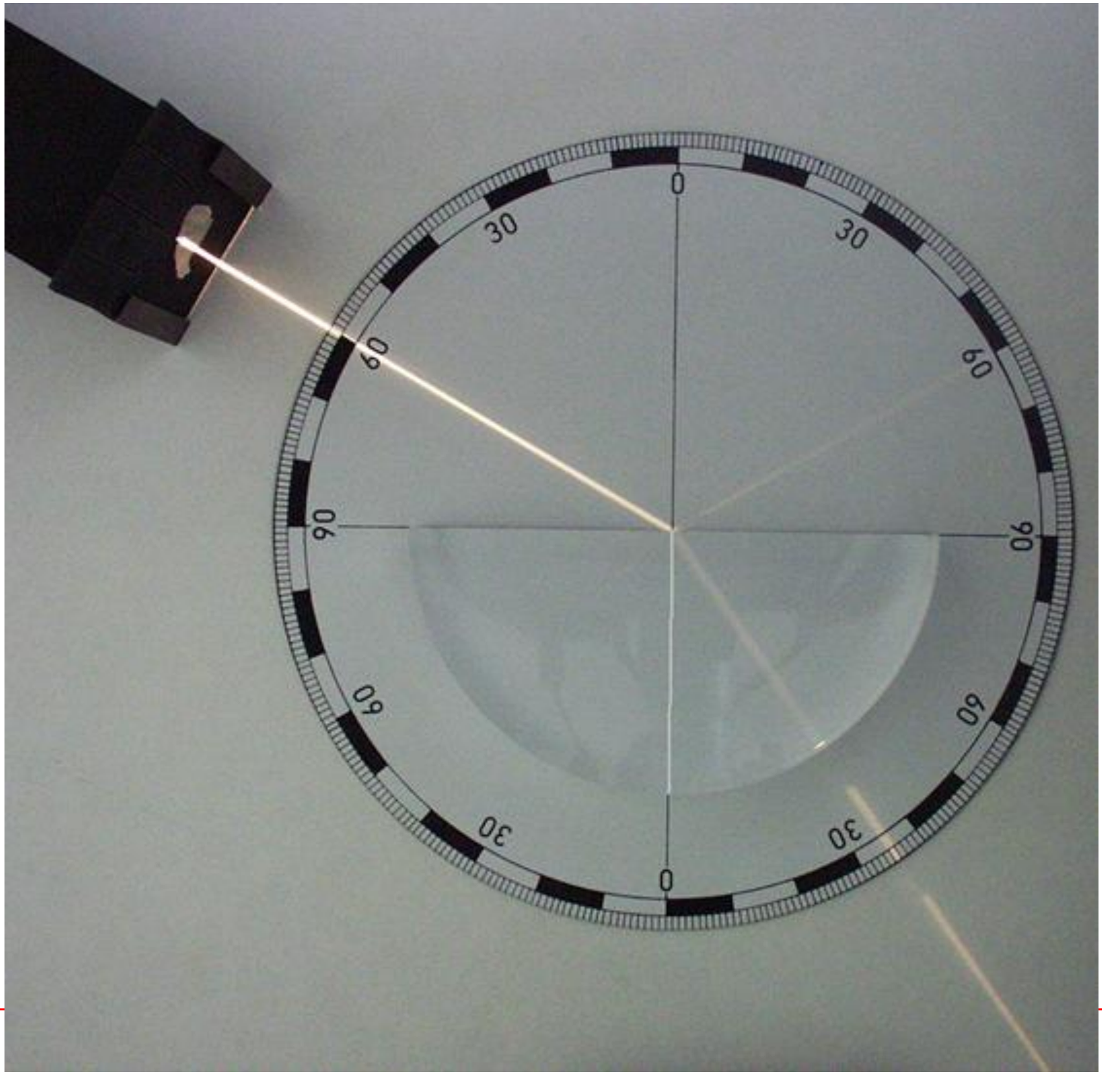


Example

Determine

(a) the index of refraction of the material and

(b) the speed of light in the matrial as shown in Figure.



Example

For commercial purposes,
perfume bottles are made from thick glasses.

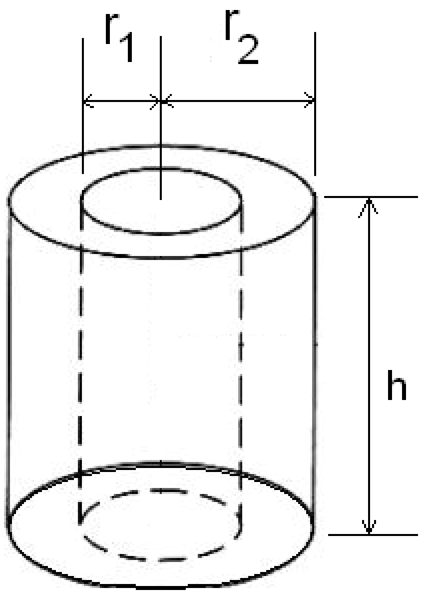
Consider a concertric cylindrical bottle:

Innder radius $r_1 = 1cm$

Outer radius $r_2 = 2$ cm

Refractive index $n = 1.33$

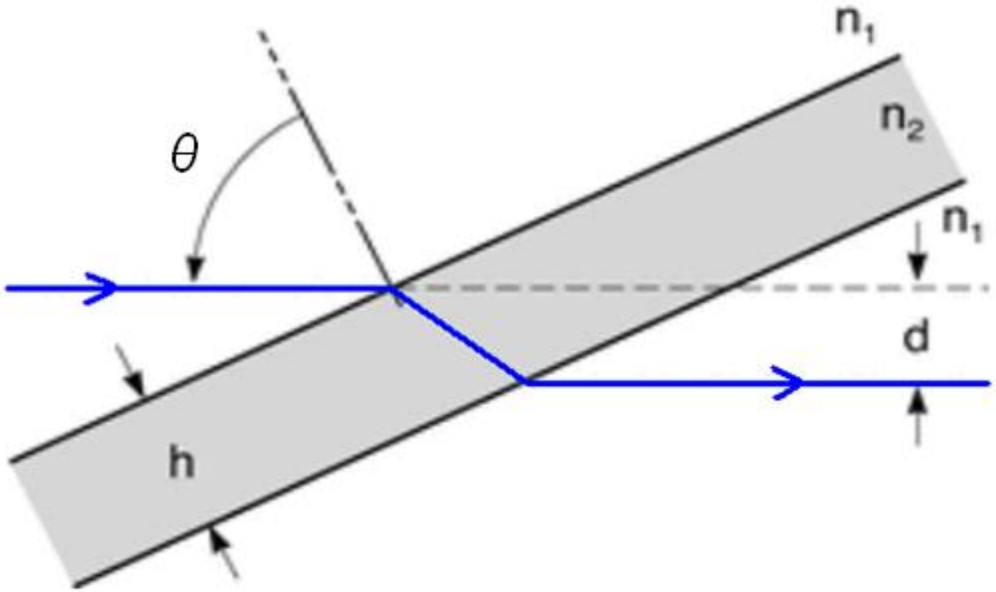
Height $h = 5$ cm



Compute the real volume and
seen volume of the liquid in the bottle.

Optical Slab

$$d = h \sin\theta \left[1 - \frac{\cos\theta}{\sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2\theta}} \right]$$



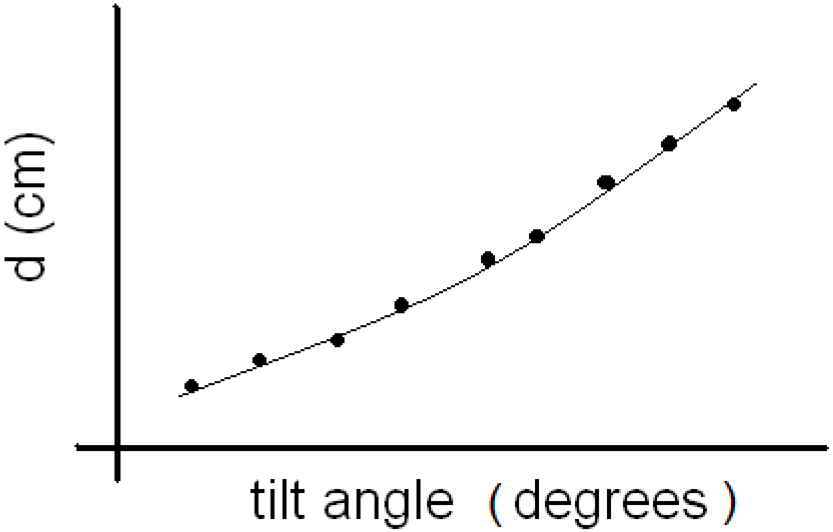
HW

On a millimeter paper, plot the tilt angle (from 0 to 90 degrees with step 10 degrees) vs d for

h = 1.0 cm

$n_1 = 1.0$

$n_2 = 1.5$



Fermat's Principle of Least Time

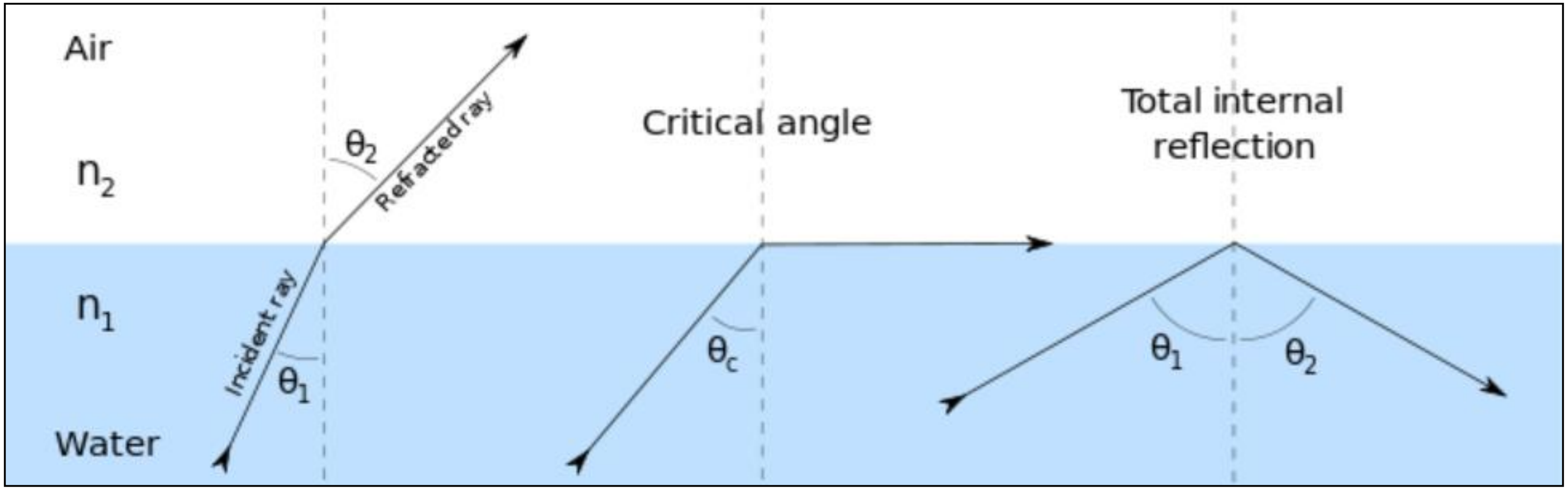
Light takes the path which requires the shortest time.

Derivations for
the law of reflection and the law of refraction
will be given in the lecture.

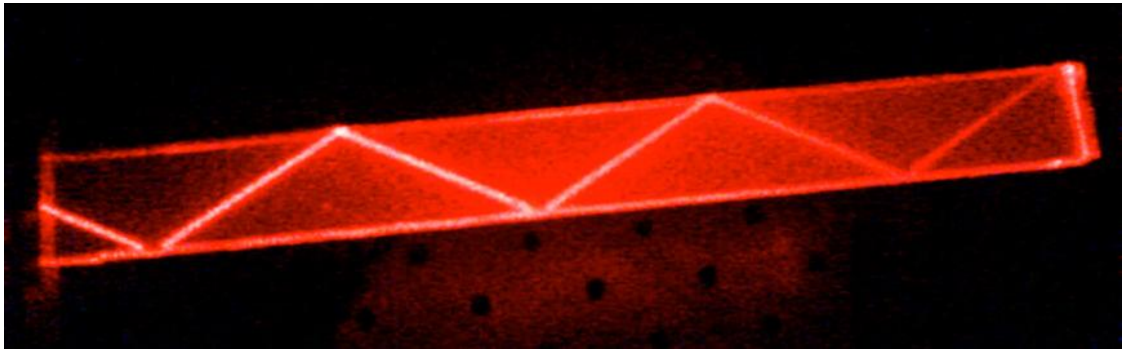
Total Internal Reflection (TIR)

TIR happens when a ray strikes a medium boundary at an angle larger than a particular critical angle given by:

$$\sin\theta_c = n_2 / n_1$$

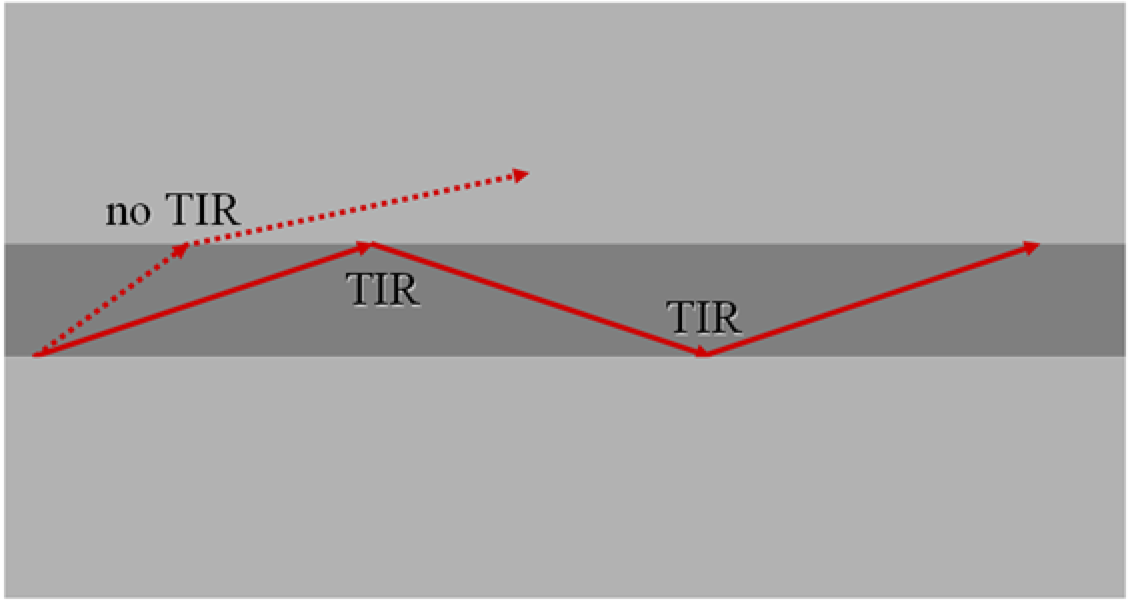


TIRs in a block of acrylic ==>



Total Internal Reflection (TIR)

Optical waveguides



"planar" waveguide: high-index dielectric material sandwiched between lower-index dielectrics

MIT 2.71/2.710
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Applications of TIR

Optical Fibers

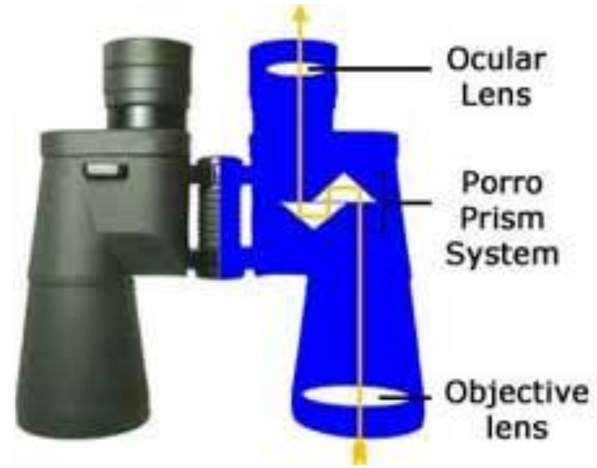
- flexible, transparent fiber made of extruded glass or plastic, slightly thicker than a human hair.
- used in fiber-optic communications

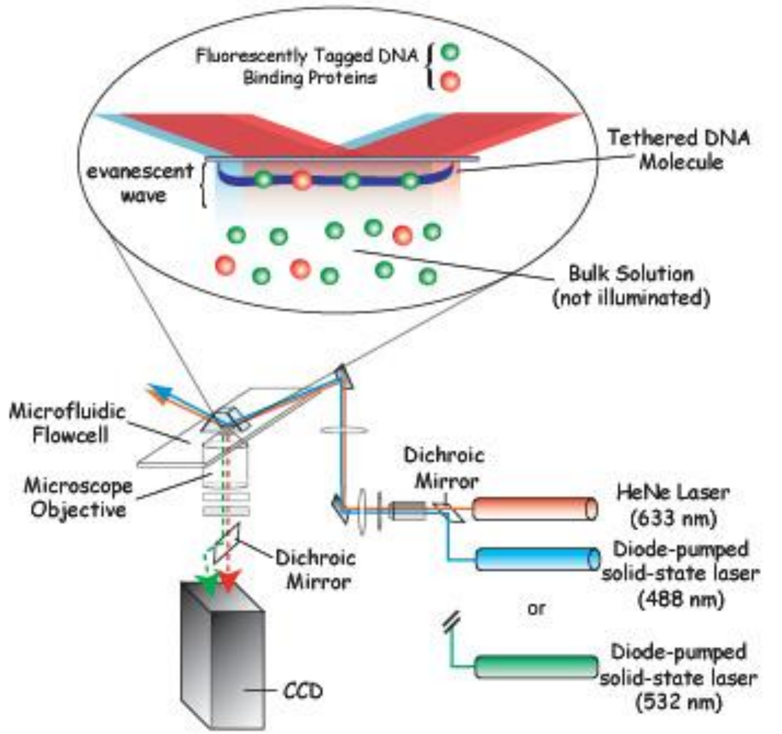
Endoscope

An instrument used to examine the interior of a hollow organ or cavity of the body.

Applications of TIR

Prisms in binoculars





Total Internal Reflection Fluorescence Microscopy.

Total internal reflection fluorescence microscope (TIRFM)

PART II

PRISMS

Transparent medium between two planes is called a prism

Prism

Deflecting Prisms

Wedge prism

Anamorphic Prism Pairs

Reflective prisms

Dove prism

Porro prism

Porro–Abbe prism

Amici roof prism

Pentaprism

Abbe–Koenig prism

Schmidt–Pechan prism

Bauernfeind prism

Retroreflector prism

Polarizing Prisms

Nicol prism

Wollaston prism

Nomarski prism

Rochon prism

Senarmont prism

Glan–Foucault prism

Glan–Taylor prism

Glan–Thompson prism

Dispersive Prisms

Triangular prism

Abbe prism

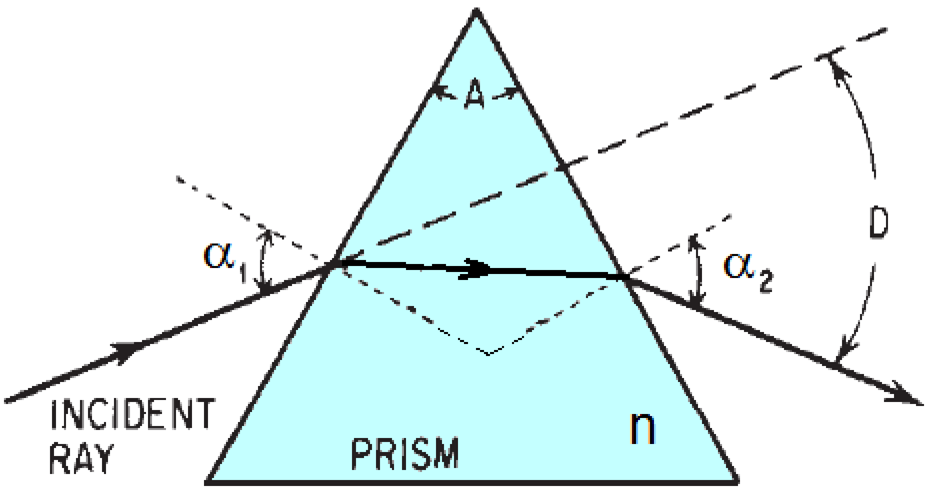
Pellin–Broca prism

Roof prism

Compound prism

Prisms

In a typical dispersing prism:



α1= angle of incidence

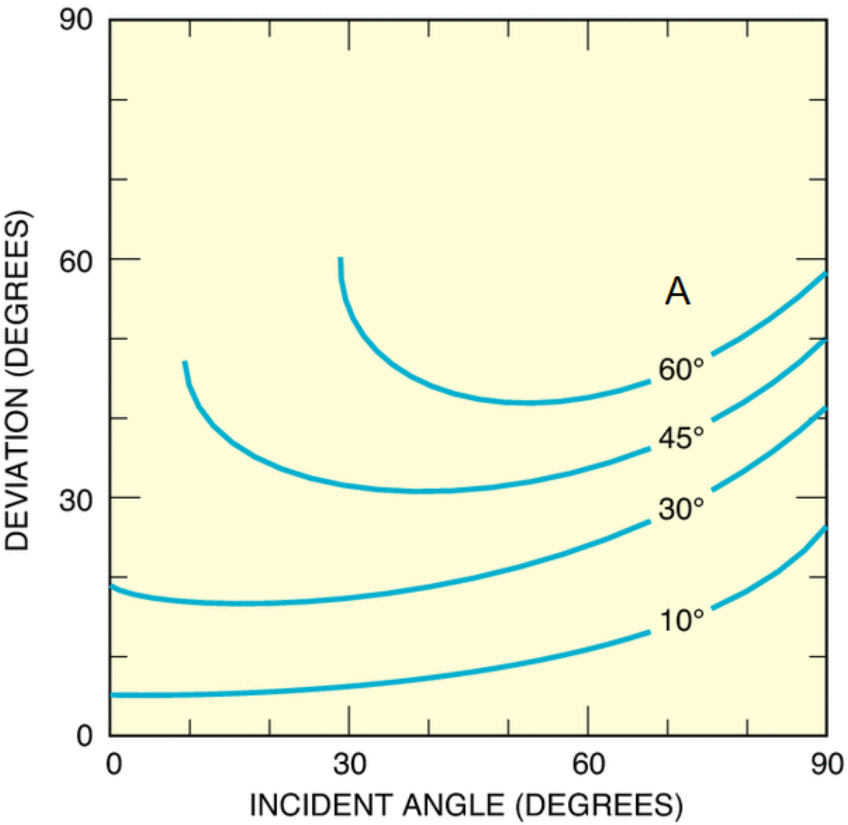
α2 = outgoing angle

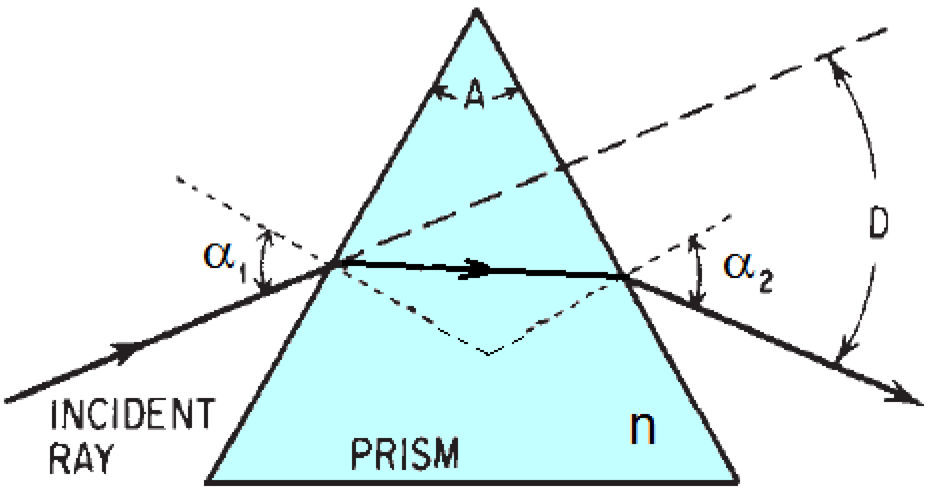
A = apex angle

D = angle of deviation

$$D = \alpha_1 + \alpha_2 - A$$

Prisms





$$D = \alpha_1 + \alpha_2 - A$$

HW

(a) Show that the deviation angle D is given by:

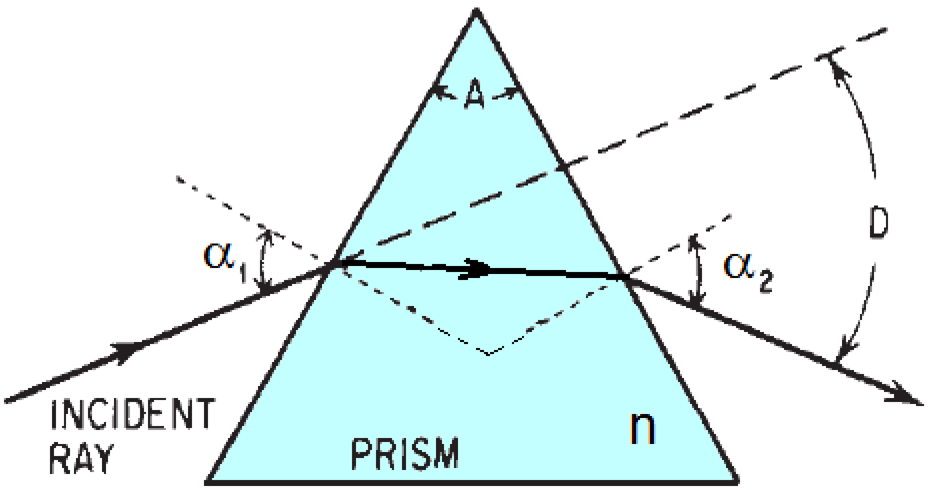
$$D = \alpha_1 + \sin^{-1}[(n^2 - \sin^2 \alpha_1)^{1/2} \sin A - \cos A \sin \alpha_1] - A$$

(b) By using calculus, show that minimum deviation occurs when $\alpha 1 = \alpha 2$.

(c) On a millimeter paper, plot the incident angle α1 (from 0 to 90 degrees with step 10 degrees) vs deviation angle for n = 1.5, A = 45 degrees.

Minimum Deviation

Minimum deviation occurs when α1 = α2.



$$D_{\min} = 2\alpha_1 - A$$

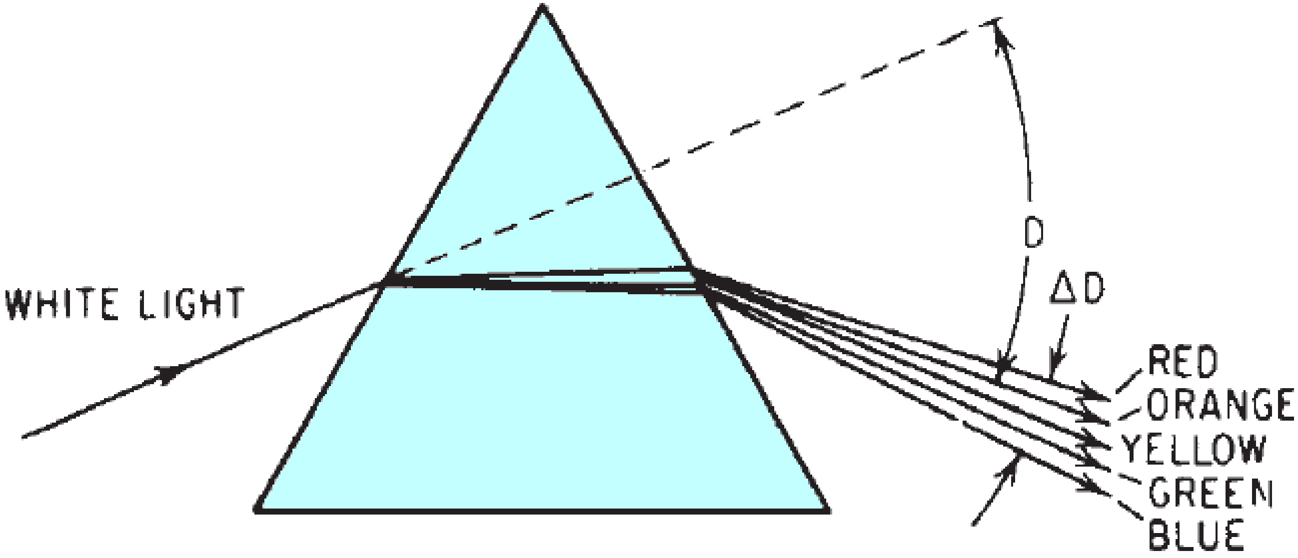
$$n = \frac{\sin[(A + D_{\min})/2]}{\sin[A/2]}$$

Note that for a thin prsim (A is small)

$$D \approx (n-1)A$$

Dispersion

Refractive index is function of the wavelength



The dispersion of white light into its component wavelengths by a refracting prism (highly exaggerated).

dispersion = *dn/dλ*

For a thin prism:

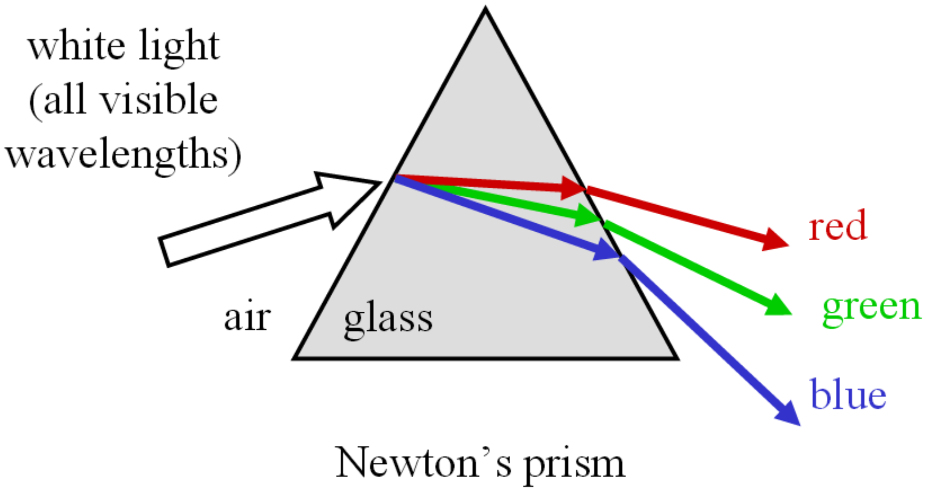
$$D = A(n-1)$$

==>

$$dD = A\,dn = D\frac{dn}{n-1} = \frac{D}{V}$$

where V is the Abbe number.

Dispersion Measure



Reference color lines:

C (H- λ=656.3nm, red),

D (Na-λ=589.2nm, yellow),

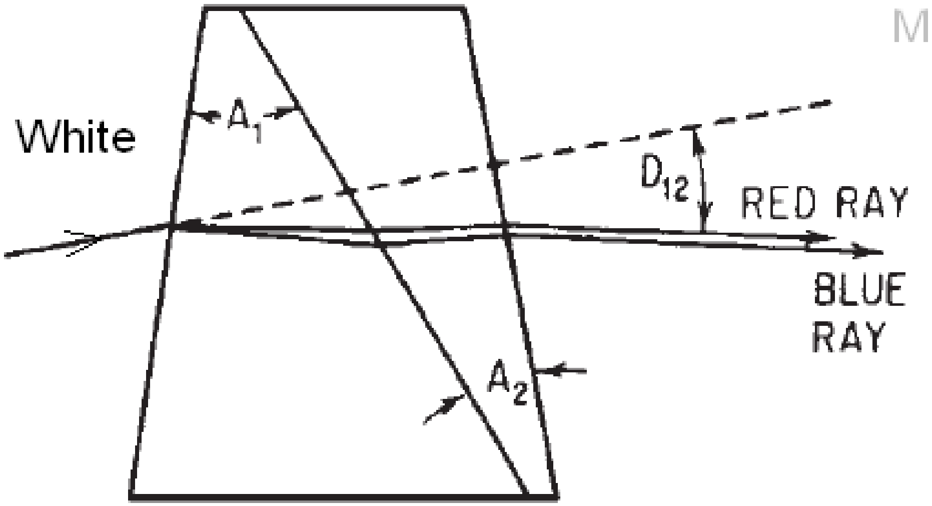
F (H - λ=486.1nm, blue)

$$\text{Abbe value} = V = \frac{n_D - 1}{n_F - n_C}$$

For a crown glass:

$$V_{crown} = \frac{1.5233 - 1.0000}{1.5290 - 1.5204} = 60.8$$

Types of Prisms: Acromatic Prism



Modern Optical Engineering, W.J.Smith

Figure 4.3 An achromatic prism. The red and blue rays emerge parallel to each other; no chromatic dispersion is introduced by the deviation.

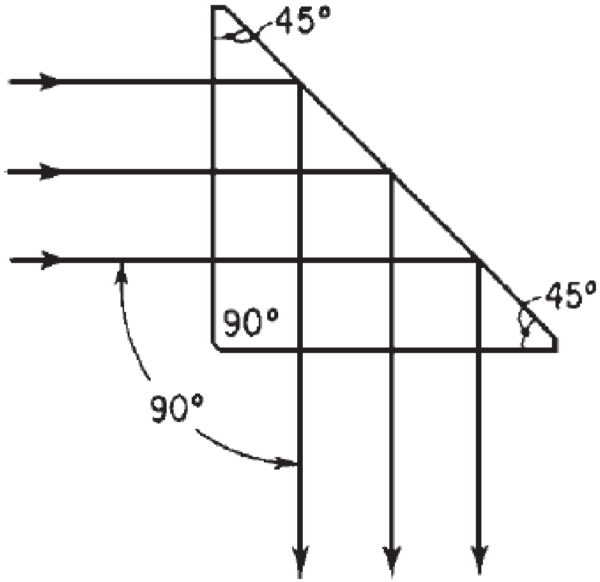
The aim:

Angular deviation of a light beam without introducing any chromatic dispersion. For thin prisms, we have two equations:

$$D_1 + D_2 = D_{12}$$

$$dD_1 + dD_2 = 0$$

Right-Angle Prism



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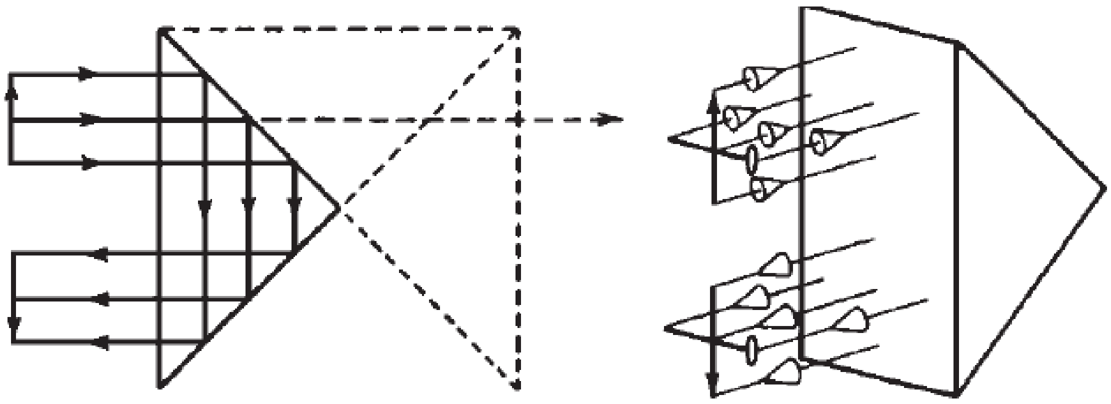
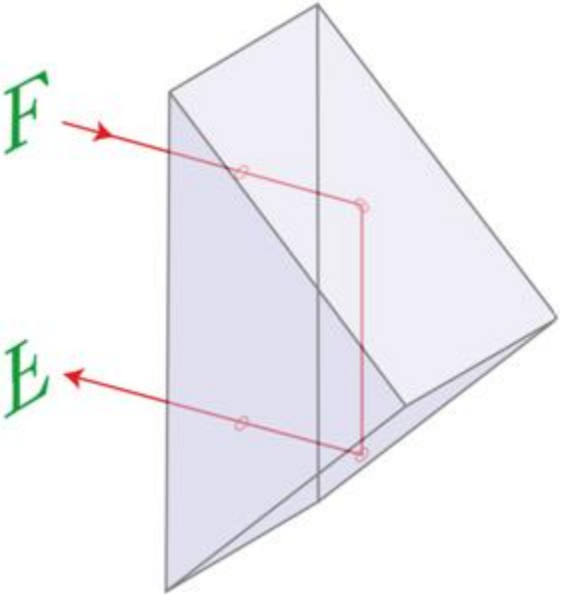
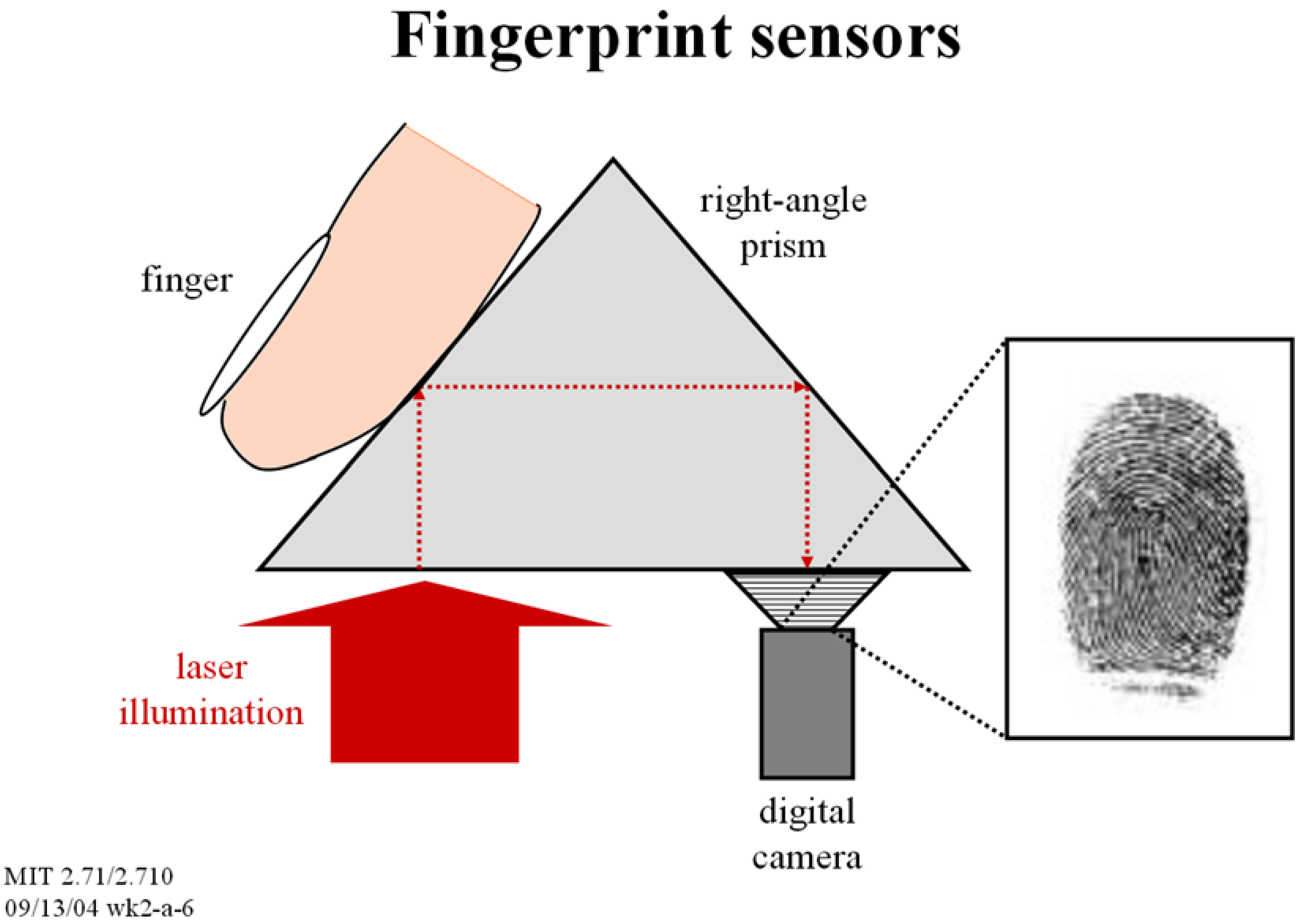




Right-Angle Prism



Fabrication Errors

Due to manufacturing tolerances, the prism angles can be produced with certain errors.

Assume that the upper angle is 45 + ε degrees.

Final outgoing ray will deviate at angle 3ε w.r.t normal.

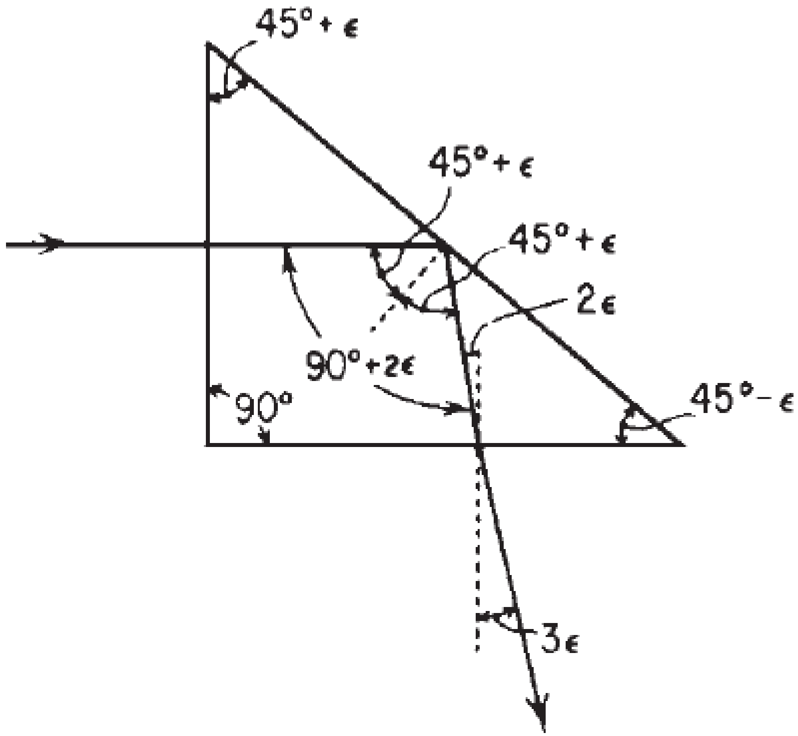


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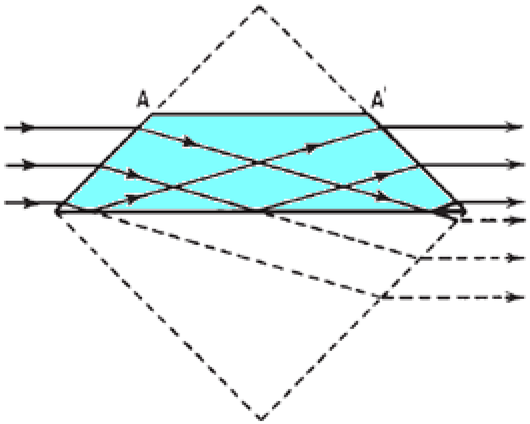
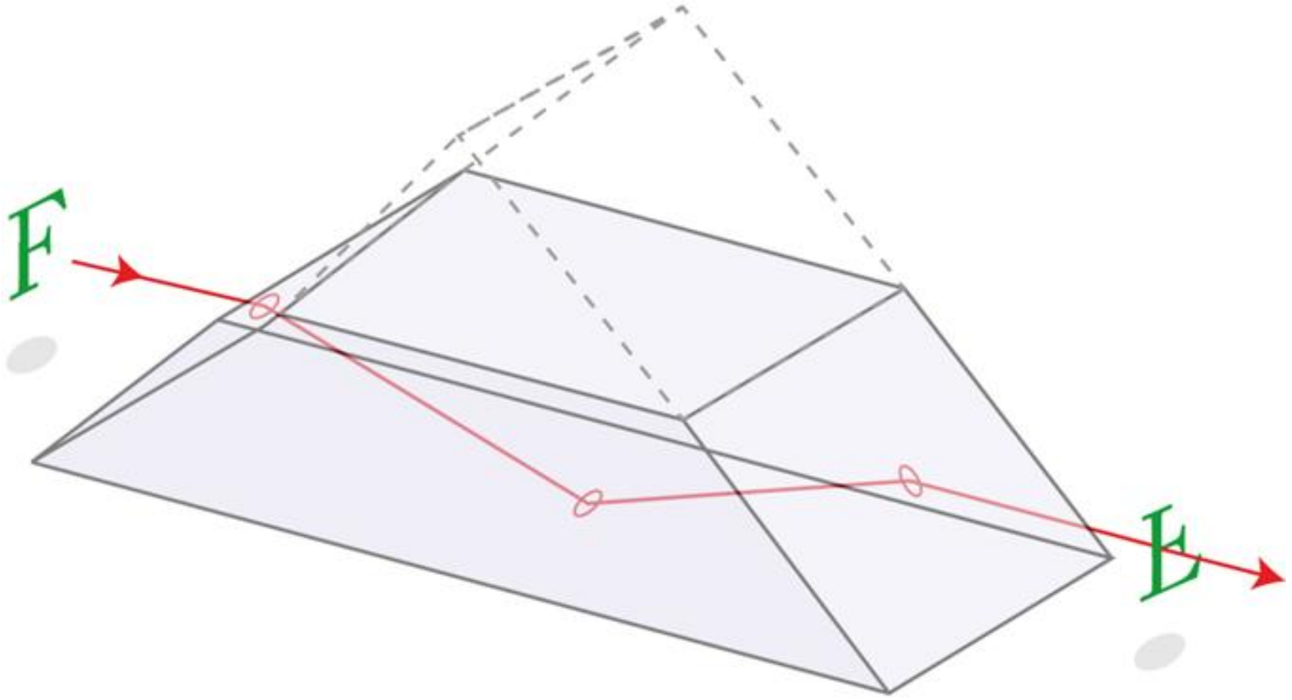
Figure 4.40 The passage of a ray through a right-angle prism whose hypotenuse face is tilted from its proper position by a small angle ϵ. After reflection, the ray is deviated by 2ϵ; this is increased to 3ϵ (or $2n\epsilon$) by refraction at the exit face.

Dove Prism

Dove prism is used to invert an image.

Dove prisms are shaped from a truncated right-angle prism.





Dove Prism as Beam Rotator

- *When a Dove Prism is rotated along its longitudinal axis, the transmitted image rotates at twice the rate of the prism.*
- *This property is used in astronomy and pattern recognition.*

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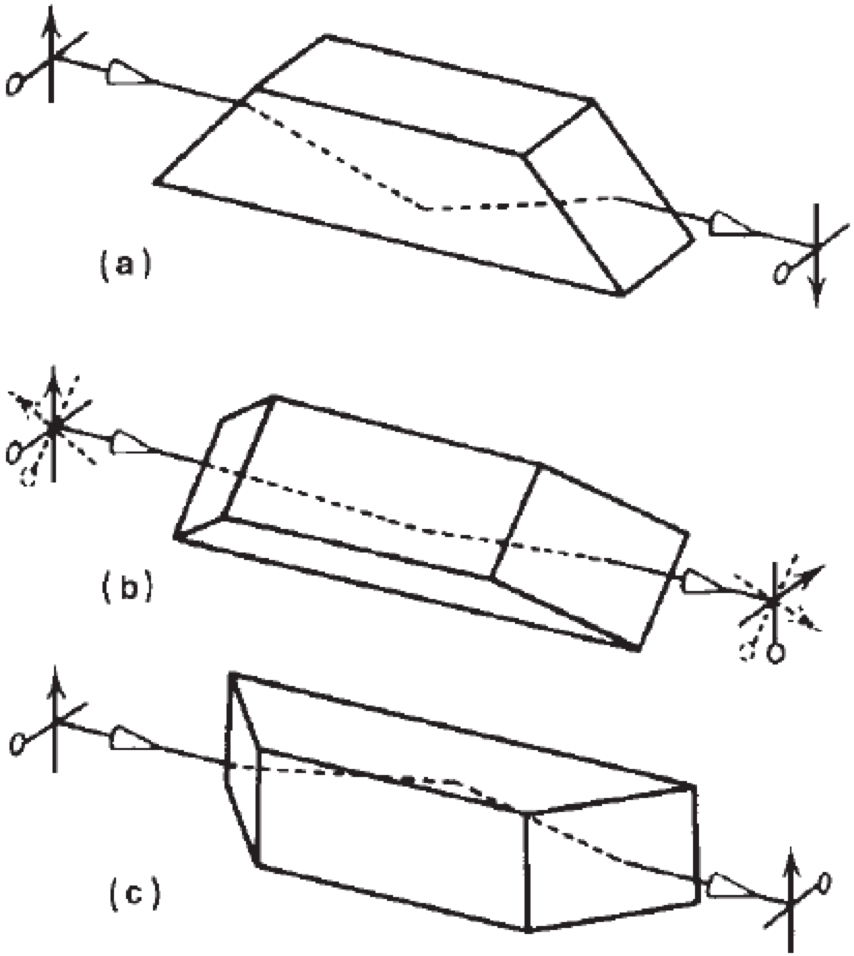
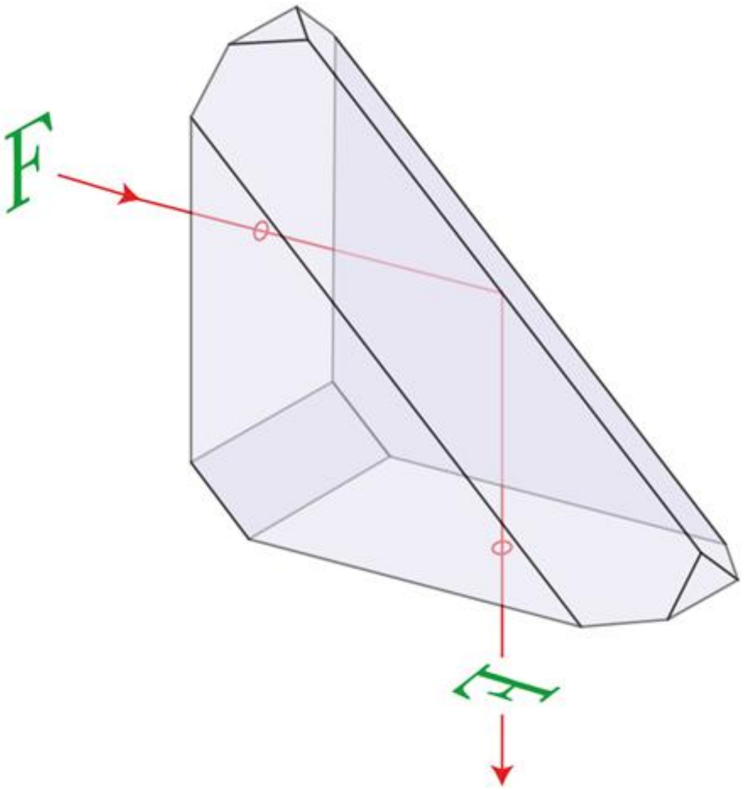


Figure 4.20 The orientation of an image by a Dove prism. (a) Original position. (b) Prism rotated 45°; image is rotated 90° (c) Prism rotated 90°; image is rotated 180°. Note that the dotted arrow and crossbar in (b) is oriented so that the dotted arrow is in the plane of incidence to simplify the analysis of the image orientation.

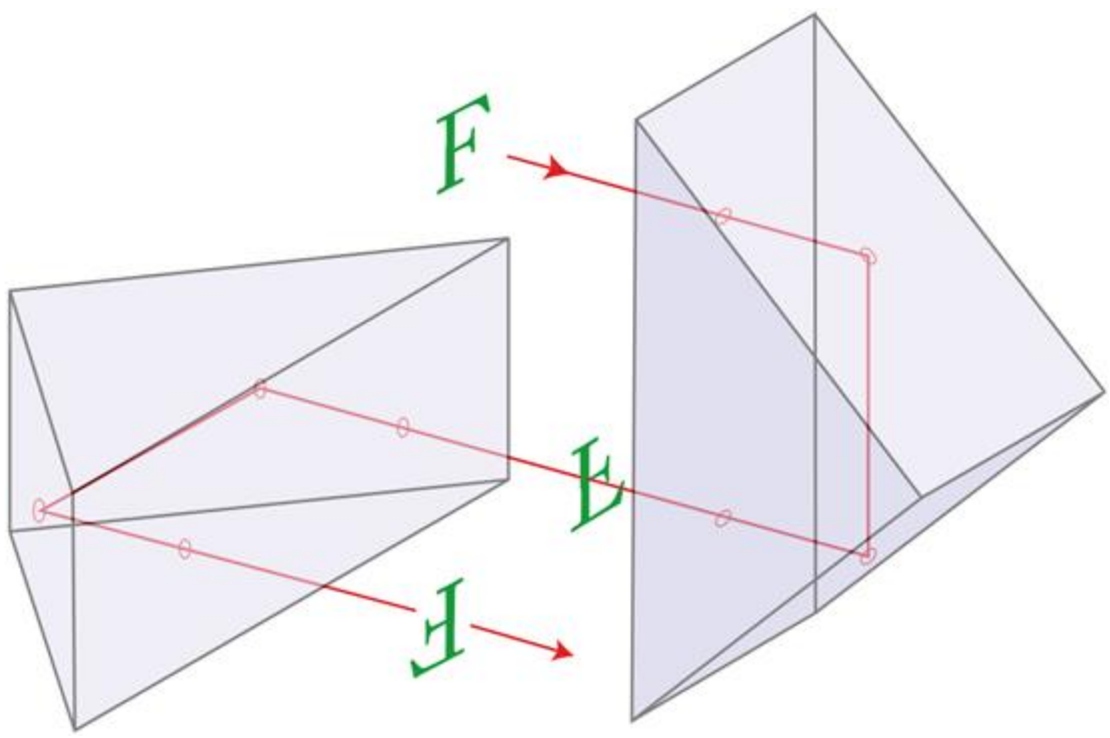
Roof Prisim

- A roof prism is a reflective optical prism containing a section where two faces meet at a 90º angle.
- If there is an error in the roof angle (90º), the beam is split into two beams which diverge at an angle which is six times the error.



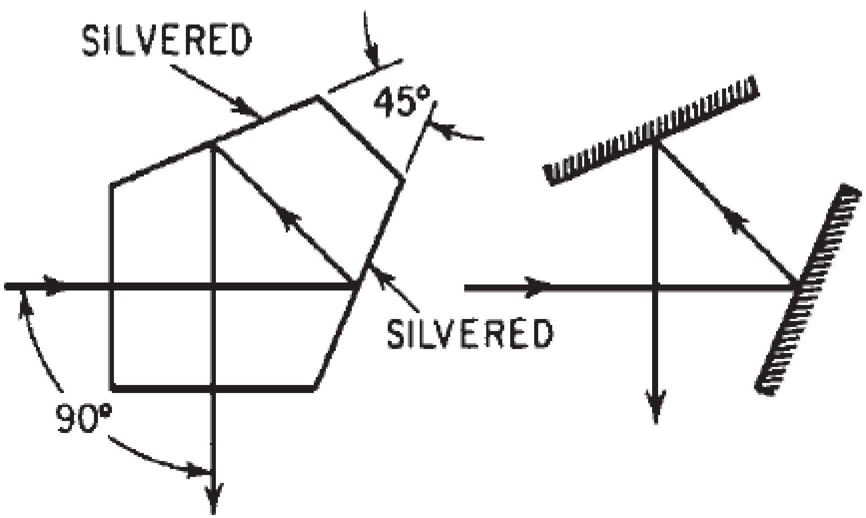
Porro Prism

- Porro prism is used to alter the orientation of an image.
- Porro prism systems are used in small optical telescopes to re-orient an inverted.

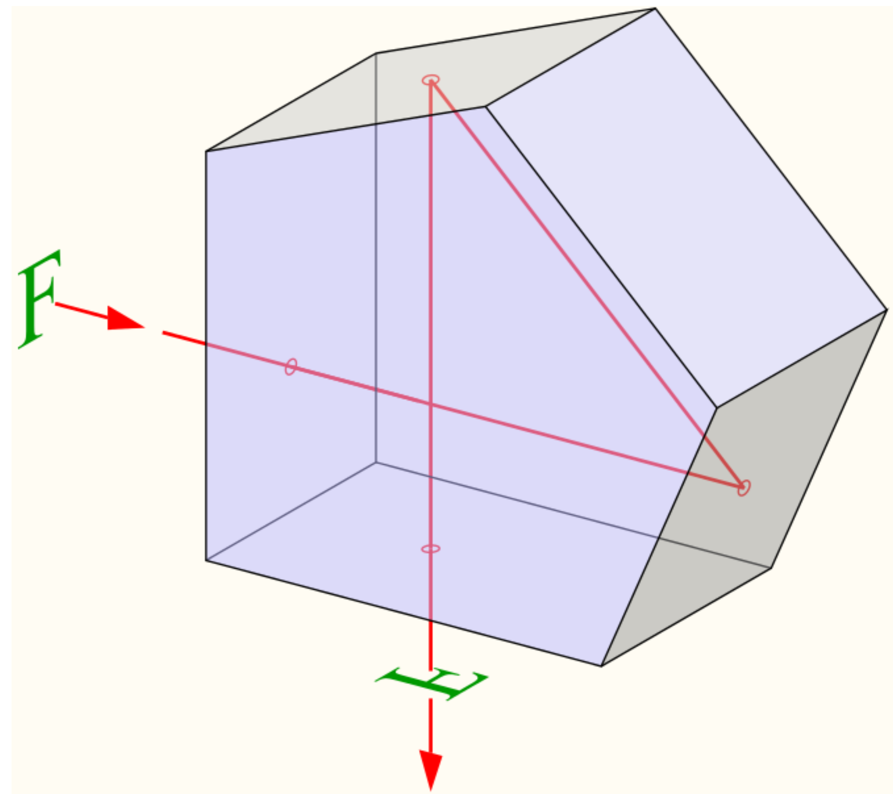


Penta Prism

- Neither invert nor reverse the image.
- The function is to deviate the line of sight by 90º.
- Commonly used in the viewfinder of single-lens reflex cameras.

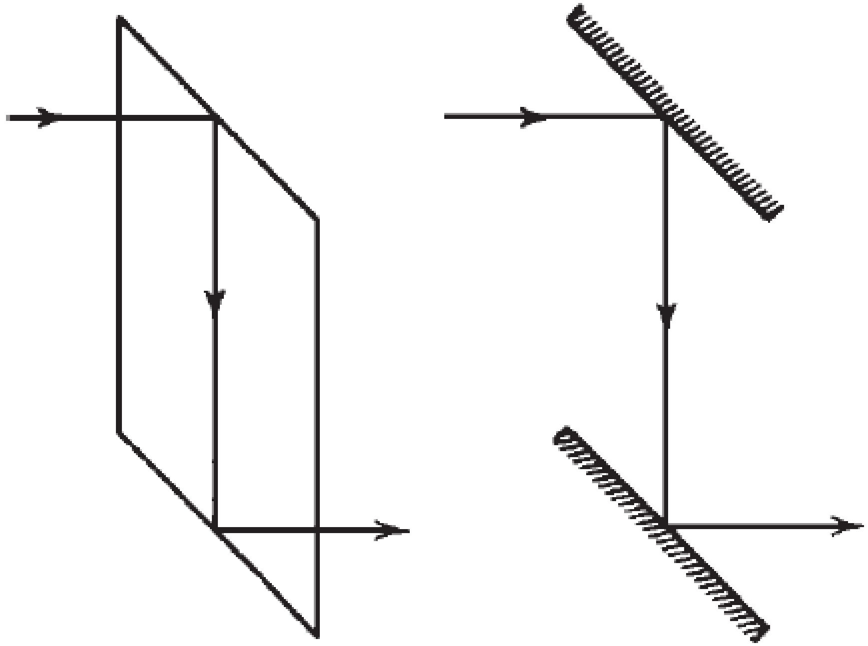


Penta prism and its mirror equivalent



Rhomboid Prism

The rhomboid prism displaces the ray without affecting the orientation of the image or deviating the line of sight.

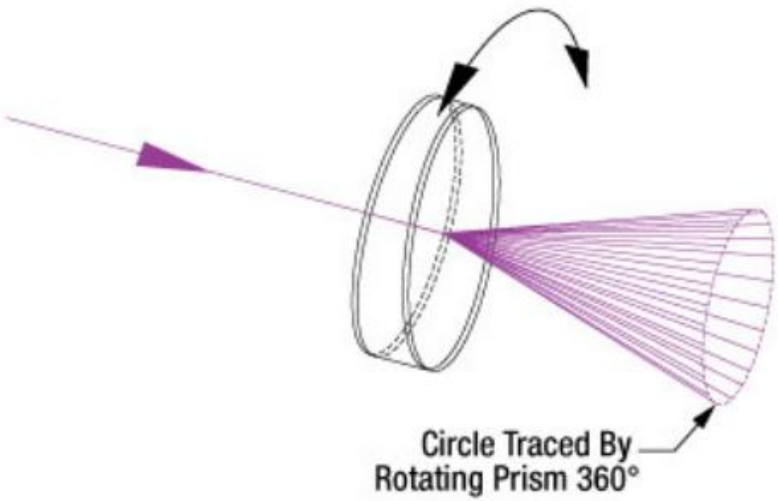


Rhomboid prism and its mirror equivalent

Wedge Prisms

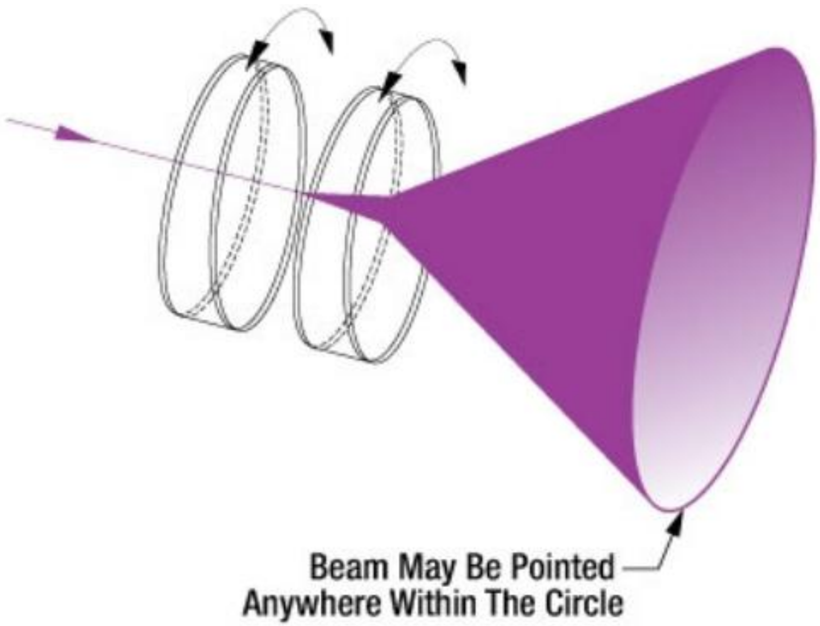
- Wedge Prisms are ideal for laser beam steering applications.
- Deflect a beam normal to the prism's perpendicular surface through an angular deviation ranging from 2o to 10o.

www.thorlabs.com



Click to Enlarge

The drawing above depicts a single wedge prism and an incident beam of light. The incident light is refracted at the specified deviation angle. As the wedge is rotated, the deviated beam traces out a circle defined by an angle equal to two times the specified deviation angle.



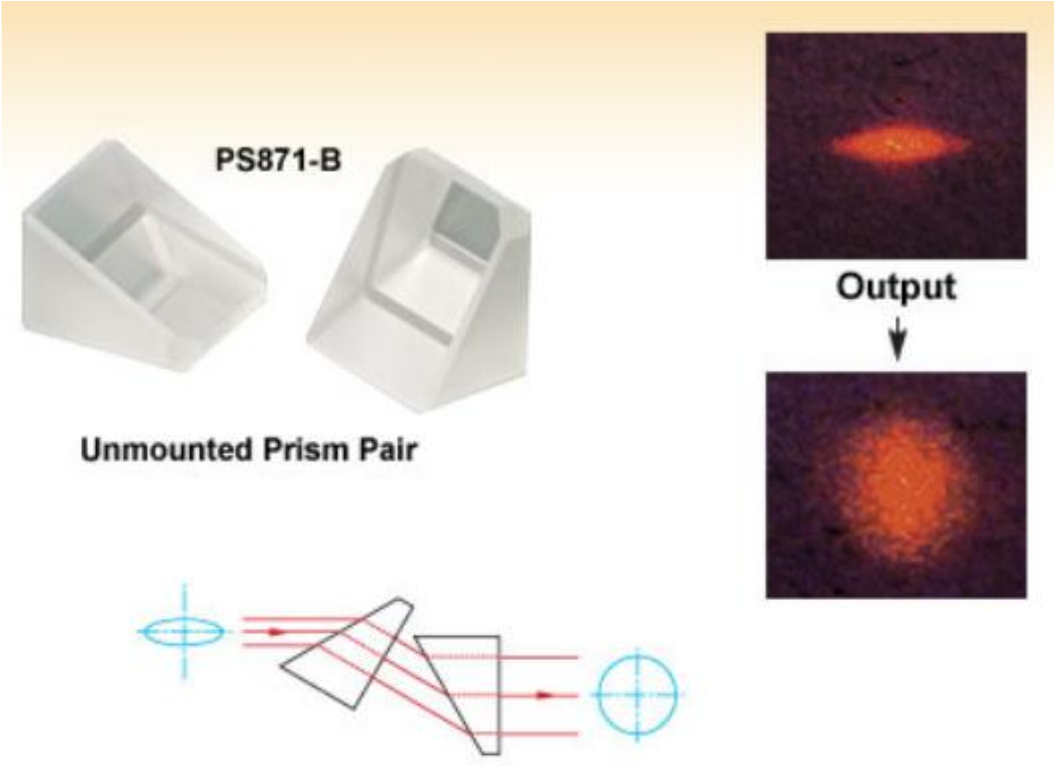
Click to Enlarge

The drawing above depicts two wedge prisms and an incident beam of light. Since each individual prism can trace out a circle of two times the deviation angle, the total deviation by two prisms will be four times the deviation angle. By controlling the angle of each prism independently, the beam can be positioned at any point within the circle.

Anamorphic Prism Pairs

Transform Elliptical Laser Diode Beams into Nearly Circular Beams

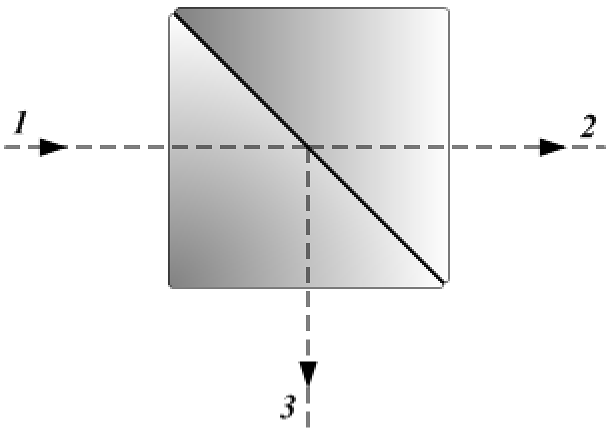
www.thorlabs.com/Anamorphic_Prisms



Beam-Spliters

A beamsplitter cube

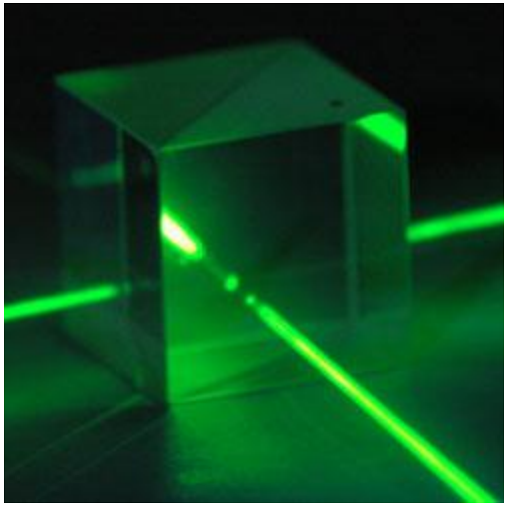
- is composed of two right-angle prisms cemented together (The hypotenuse of one prism is coated with a semi-reflecting coating before cementing)
- is used for combining two beams (or images) into one
- is used for separating one beam into two
- is the crucial part of most interferometers

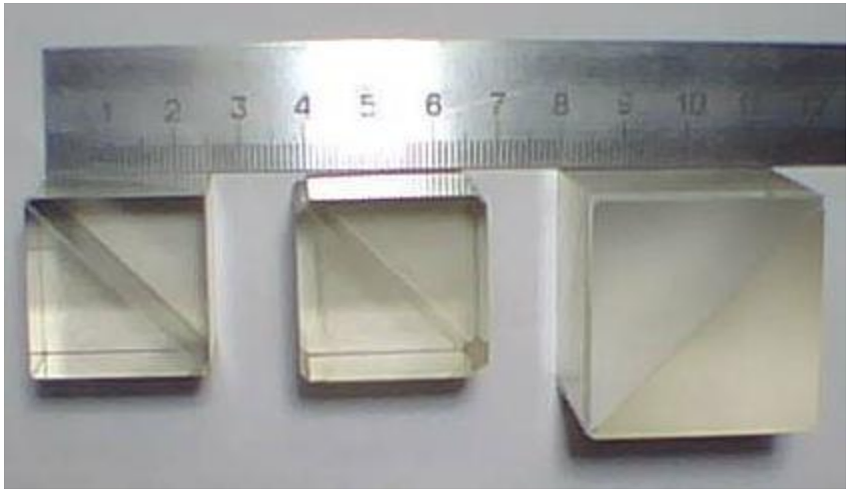


Beam splitter cube:

1 - Incident light
2 - 50% Transmitted light
3 - 50% Reflected light

Beam-Spliters



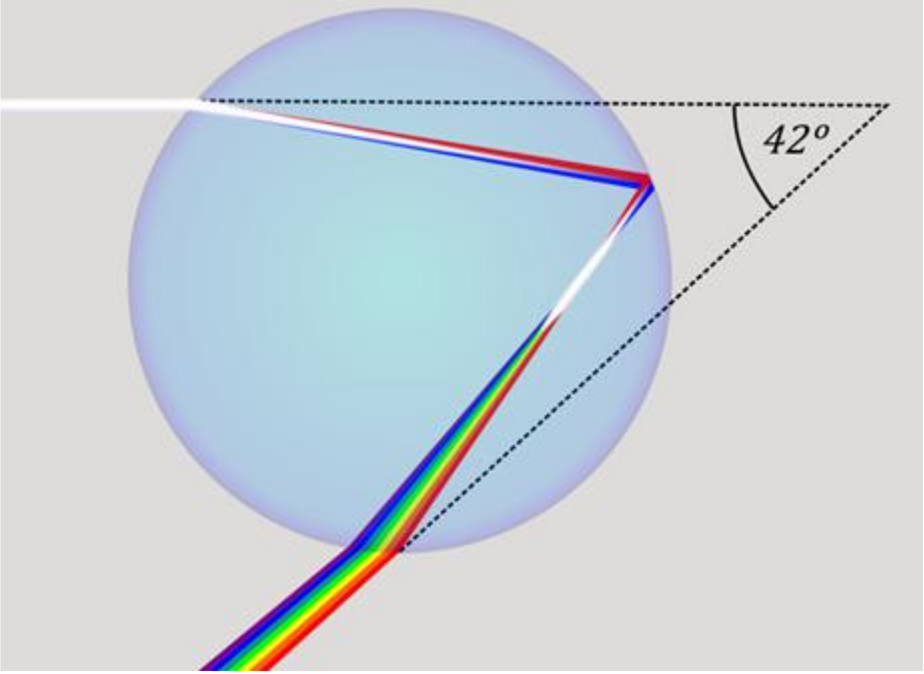


PART III

OPTICAL PHENOMENA

Rainbow

A rainbow is an optical phenomenon that is caused by both reflection and refraction of light in water droplets resulting in a spectrum of light appearing in the sky.



See also the course web page.

Atmosphere Effect

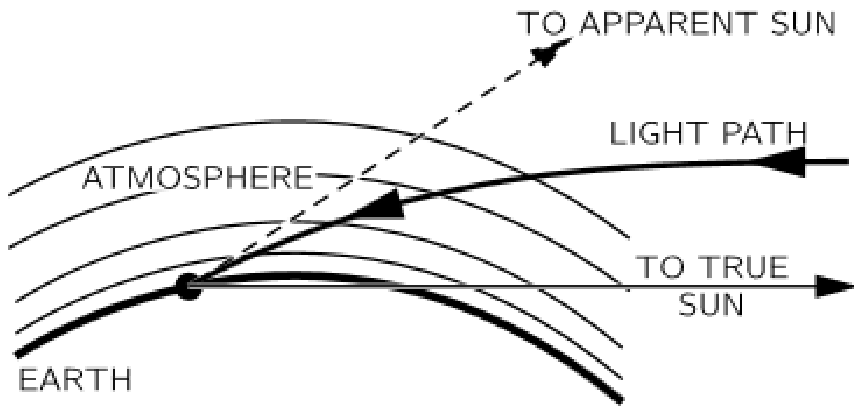


Fig. 26–7. Near the horizon, the apparent sun is higher than the true sun by about $1/2$ degree.

The Feynman Lectures on Physics, Volume I

When we see the sun setting, it is already below the horizon!

The earth's atmosphere is thin at the top and dense at the bottom. Light t ravels more slowly in air than it does in a vacuum, and so the light of the sun can get to point S beyond the horizon more quickly if, instead of just going in a straight line, it avoids the dense regions where it goes slowly by getting through them at a steeper tilt. When it appears to go below the horizon, it is actually already well below the horizon.

Mirage

A mirage is optical phenomenon in which light rays are bent to produce a displaced image of distant objects or the sky.

Mirage

One sees “water” on the hot road, but when he gets there, it is as dry as the desert!.

Fig. 26–8. A mirage.

The Feynman Lectures on Physics, Volume I

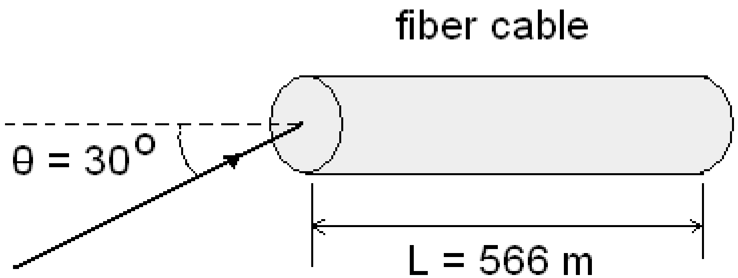
What we are really seeing is the sky light “reflected” on the road: light from the sky, heading for the road, can end up in the eye, The air is very hot just above the road but it is cooler up higher. Hotter air is more expanded than cooler air and is thinner, and this decreases the speed of light less. That is to say, light goes faster in the hot region than in the cool region. Therefore, instead of the light deciding to come in the straightforward way, it also has a least-time path by which it goes into the region where it goes faster for awhile, in order to save time. So, it can go in a curve.

Exercises

1. You might have noticed that emergency vehicles such as ambulances are often labeled on the front hood with reversed lettering (e.g., in Turkish SNALUBMA). Explain why this is so.

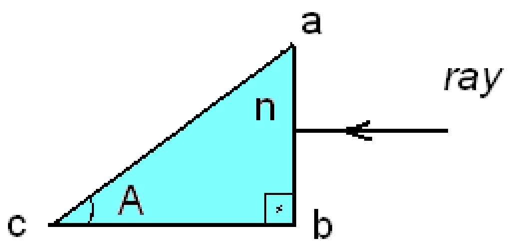
2. You run towards a plane mirror at a rate of 25 cm/s. What is the speed of your image w.r.t. mirror and w.r.t. you?

3. A light ray enter from left to a fiber cable whose diameter is 2 mm and length is 566 m as shown. Determine
(a) the number of TIRs that the ray can make in the cable.
(b) the time required for the light ray to pass through the cable.



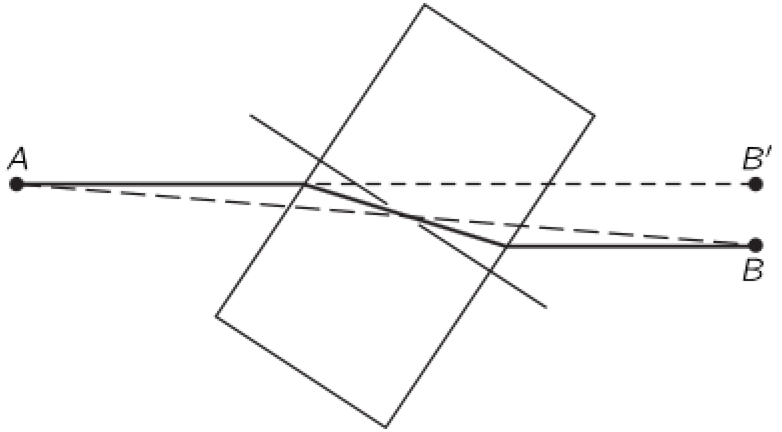
Exercises

4. A light ray is incident normally on a face ab of a glass prism (n=1.52) as shown.
 (a) Assume that the prism is immersed in air, find the largest value of the angle A so that the ray is totally reflected at face ac.
 (b) Find the angle A if the prism is immersed in water.



5. The atmosphere is a layer of gas whose index of refraction is n = 1.0003 and width is D = 100 km. The radius of Earth is approximately given by R = 6400 km. Calculate the time difference in seconds for the sun rise at the sea level on the equator if the index of refraction was n = 1.0000?

6. Using Fermat's Principle, analyze the path of the light passing through a block glass as shown.



Exercises

7. The distance of a lightbulb from a large plane mirror is twice the distance of a person from the plane mirror. Light from the lightbulb reaches the person by two paths. It travels to the mirror at an angle of incidence A and reflects from the mirror to the person. It also travels directly to the person without reflecting off the mirror. The total distance traveled by the light in the first case is twice the distance traveled by the light in the second case. Find the value of the angle A.

8. A glass fiber (n = 1.50) is submerged in water (n = 1.33). What is the critical angle for light to stay inside the optical fiber?

9. A narrow beam of light is incident from air onto the surface of glass with index of refraction 1.50. Find the angle of incidence for which the corresponding angle of refraction is half the angle of incidence.

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