electromagnetic waves

electromagnetic waves?

➜ Faraday's law told us that

"time-varying magnetic fields generate electric fields"

➜ James Clerk Maxwell found that

"time-varying electric fields generate magnetic fields"

➜ taken together then

electric field → magnetic field → electric field → …

➜ with this we can have disturbances in the electric and magnetic fields that propagate across space

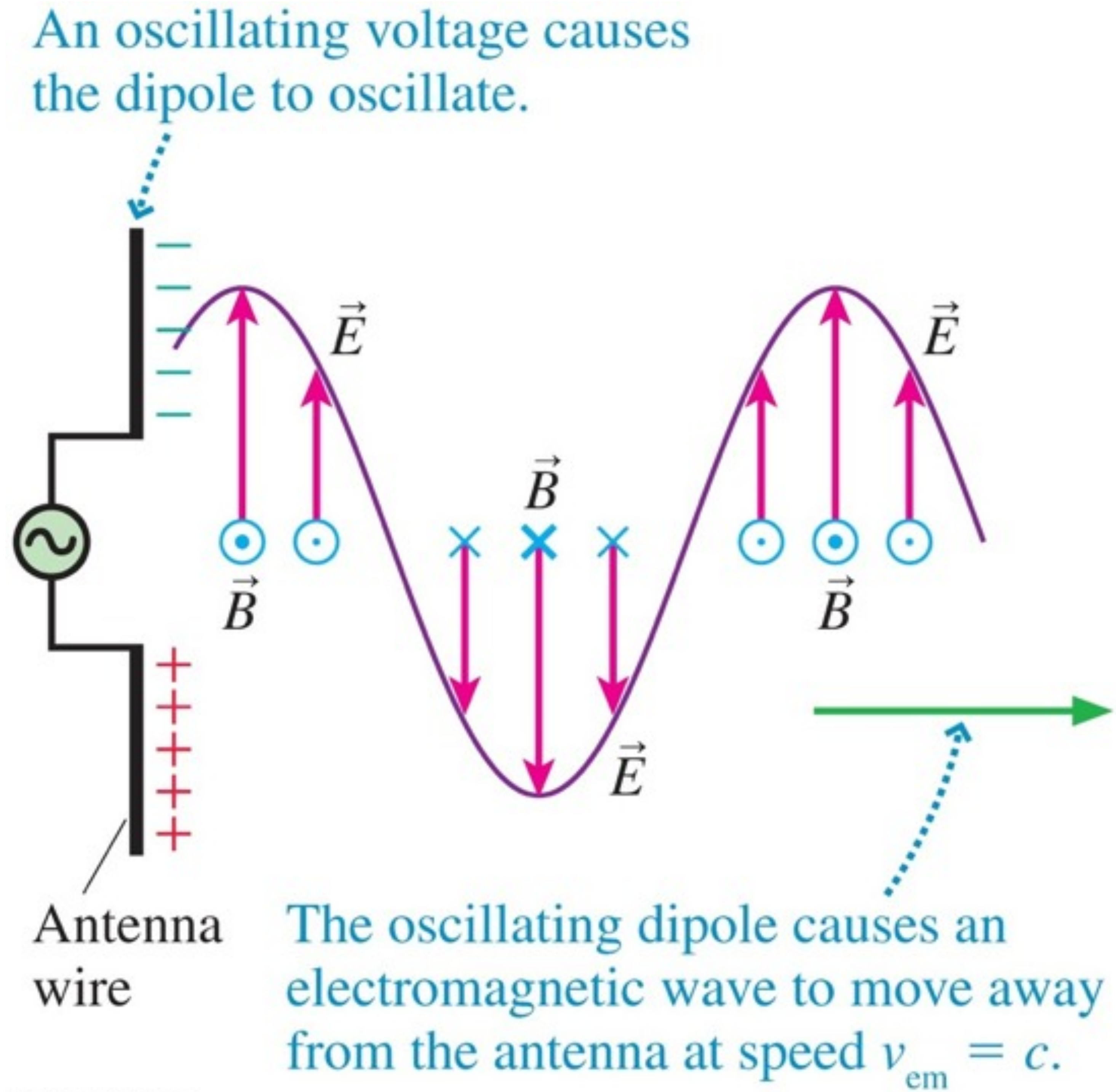
➜ *ELECTROMAGNETIC WAVES*

unlike the waves we met last semester, such as sound waves or waves on a string, no medium is required - it is not atoms moving around, but instead the electric and magnetic fields and these can exist even in a vacuum

electromagnetic waves?

➜ just need a source to get the thing started

e.g. ‘radio’ antenna



speed of electromagnetic waves

➜ a very simple em wave:
electric field in the y-direction
magnetic field in the z-direction
propagation in the x-direction,
with unknown speed, *c*

➜ turns out this satisfies the equations of electromagnetism (Faraday's law and some others I haven't shown you) but only if

$$E = cB$$

where

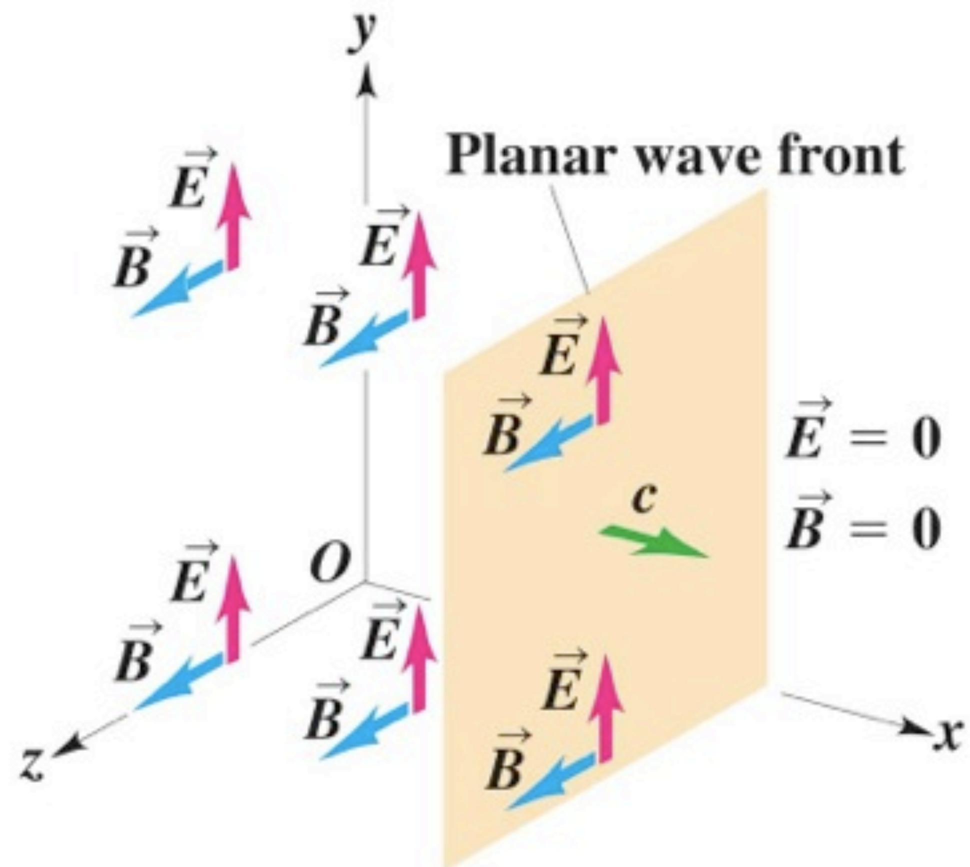
$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

$$c = 3.00 \times 10^8 \mathrm{m/s}$$

experiments with mirrors and long distances indicate
that the speed of light (in vacuum, strictly) also has this value

➜ **LIGHT IS AN ELECTROMAGNETIC WAVE**

A rudimentary electromagnetic wave. The electric and magnetic fields are uniform behind the advancing wave front and zero in front of it.



general properties of electromagnetic waves

➜ we considered a very simple em wave, there are many more possibilities, but they all have certain common properties:

➜ they are transverse : $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of motion

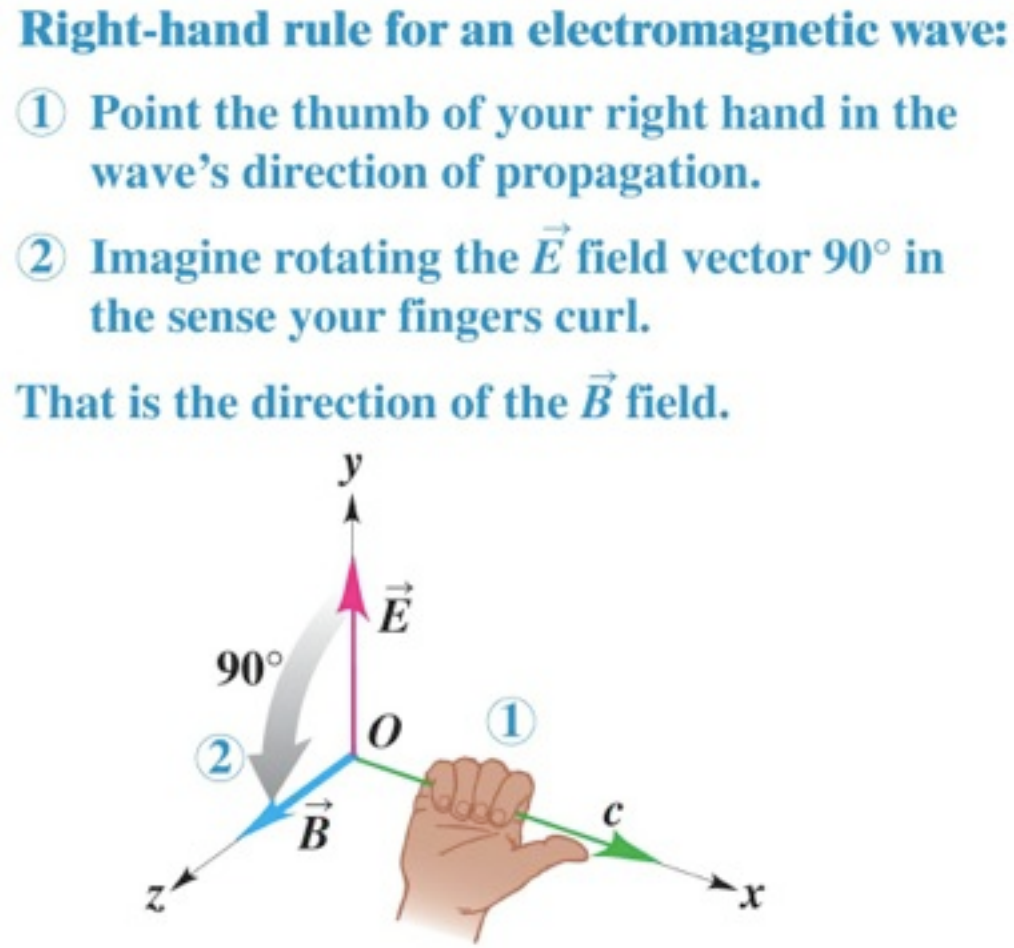
➜ the ratio of magnitudes of electric and magnetic fields is fixed

$$\frac{E}{B} = c$$

➜ travel with a fixed speed (in vacuum)

$$c = 3.00 \times 10^8 \mathrm{m/s}$$

➜ no medium is required for propagation



how fast is *c* ? $c = 3.00 \times 10^8 \mathrm{m/s}$

➜ looks like a big number

convert to familiar units, $c = 1.34 \times 10^8 \, \mathrm{mph}$

compare with sound, $\dfrac{c}{v_{\mathrm{sound}}} \sim 10^6$

once around the world takes light about a tenth of a second

to the moon takes about a second (Apollo 11 took about 4 days)

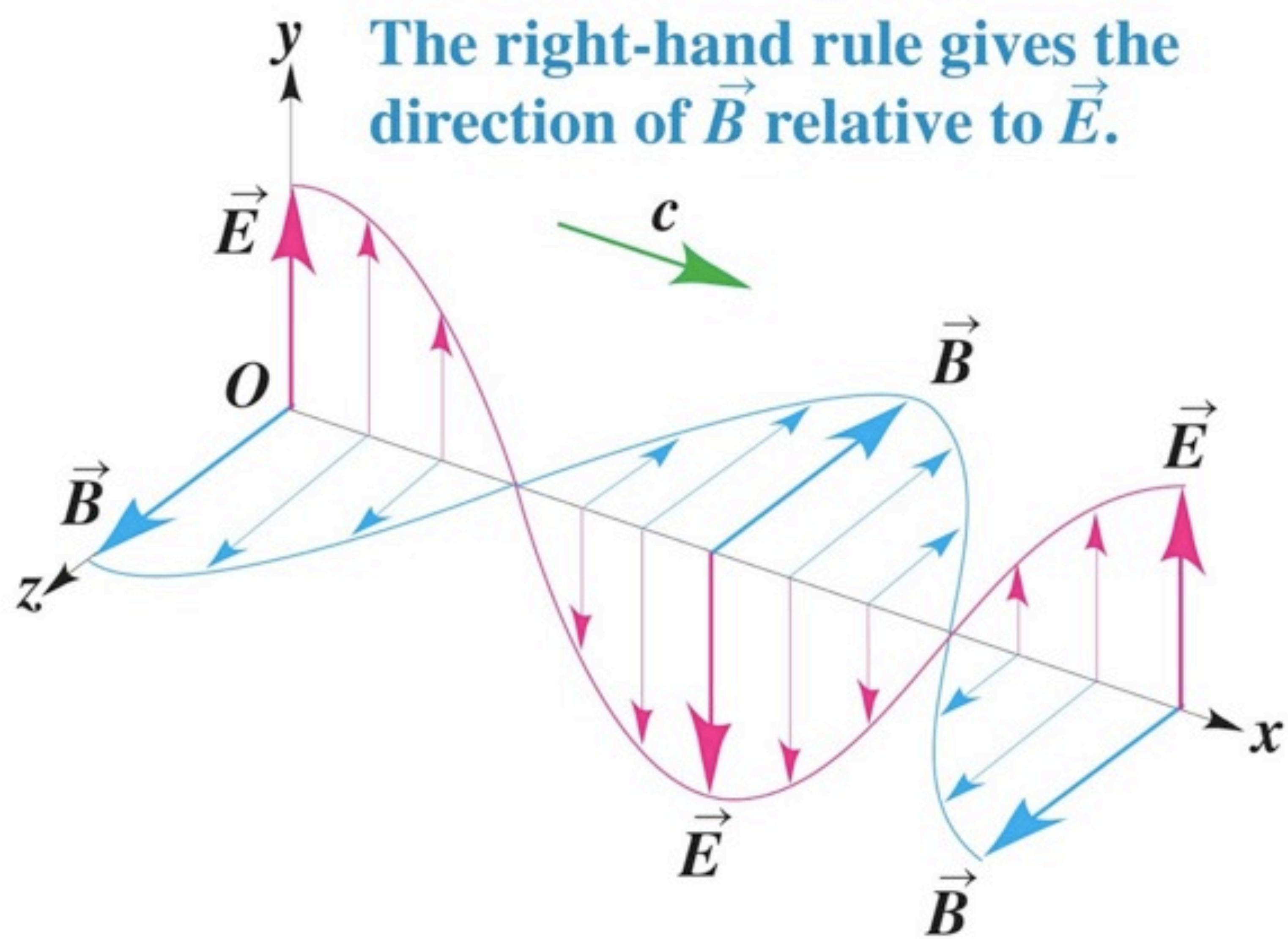
from the Sun takes 8 minutes

electromagnetic waves travel really fast
(later we'll learn that probably nothing travels faster)

sinusoidal waves

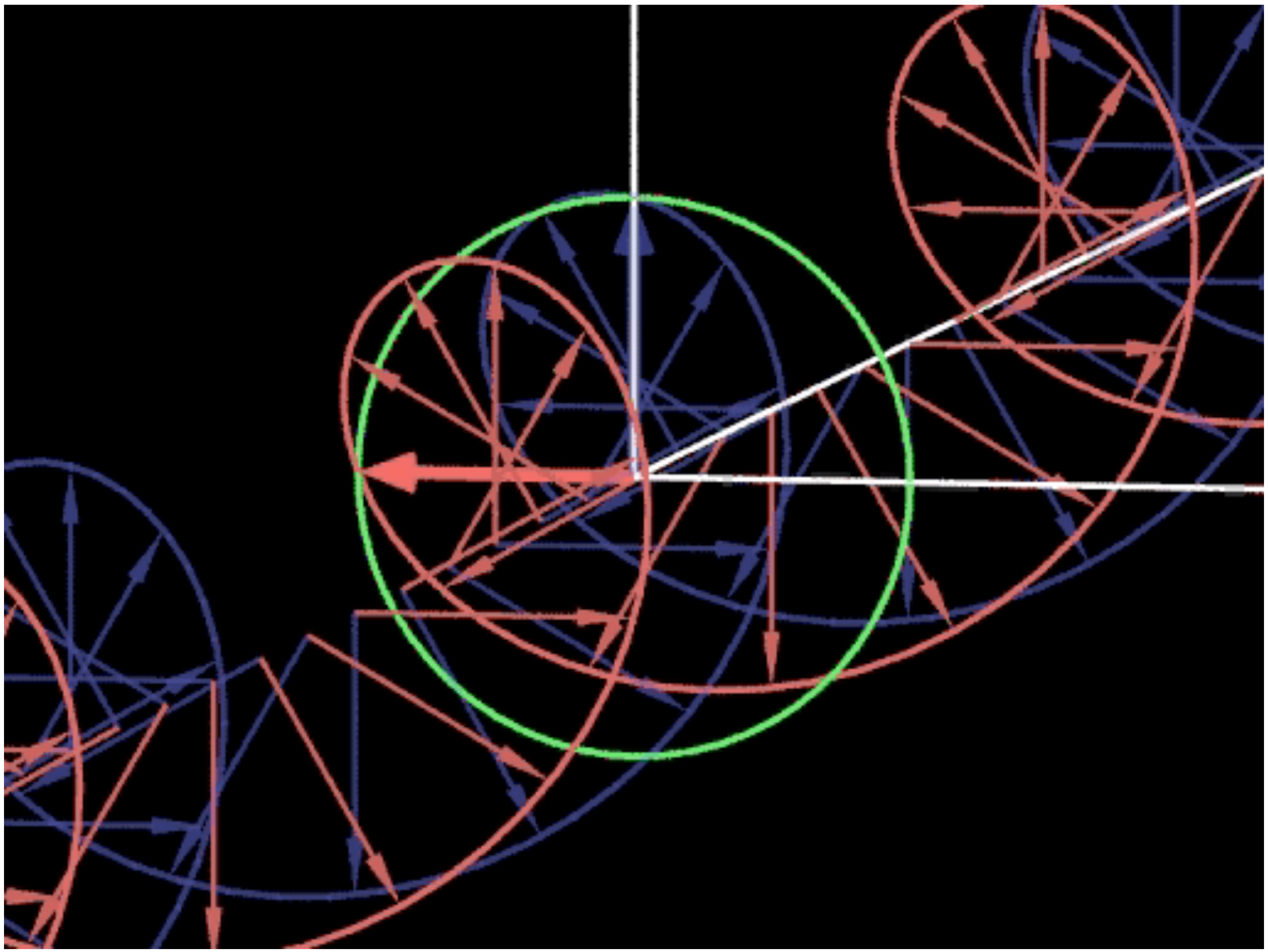
➜a very important type of wave is one whose time and space dependence is like that of the sine function

a snapshot of one of these waves might look like



a circularly polarized wave

➜a very important type of wave is one whose time and space dependence is like that of the sine function

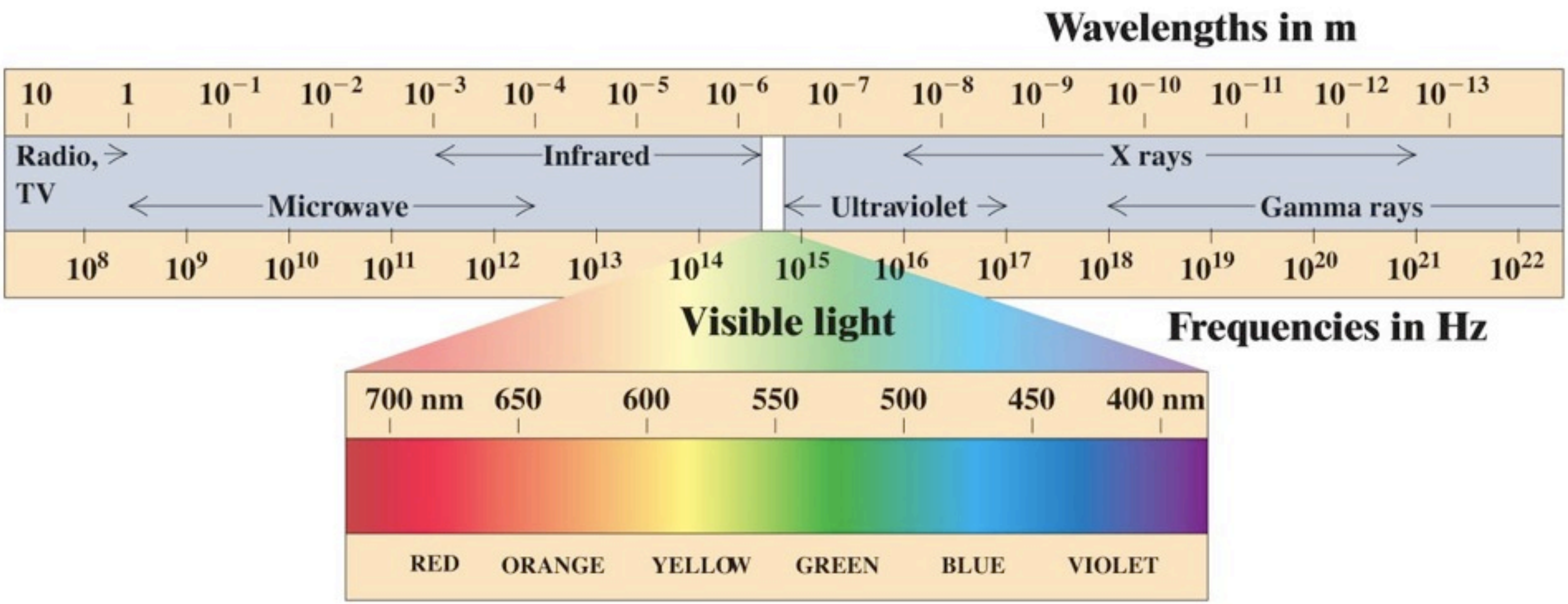


the electromagnetic spectrum

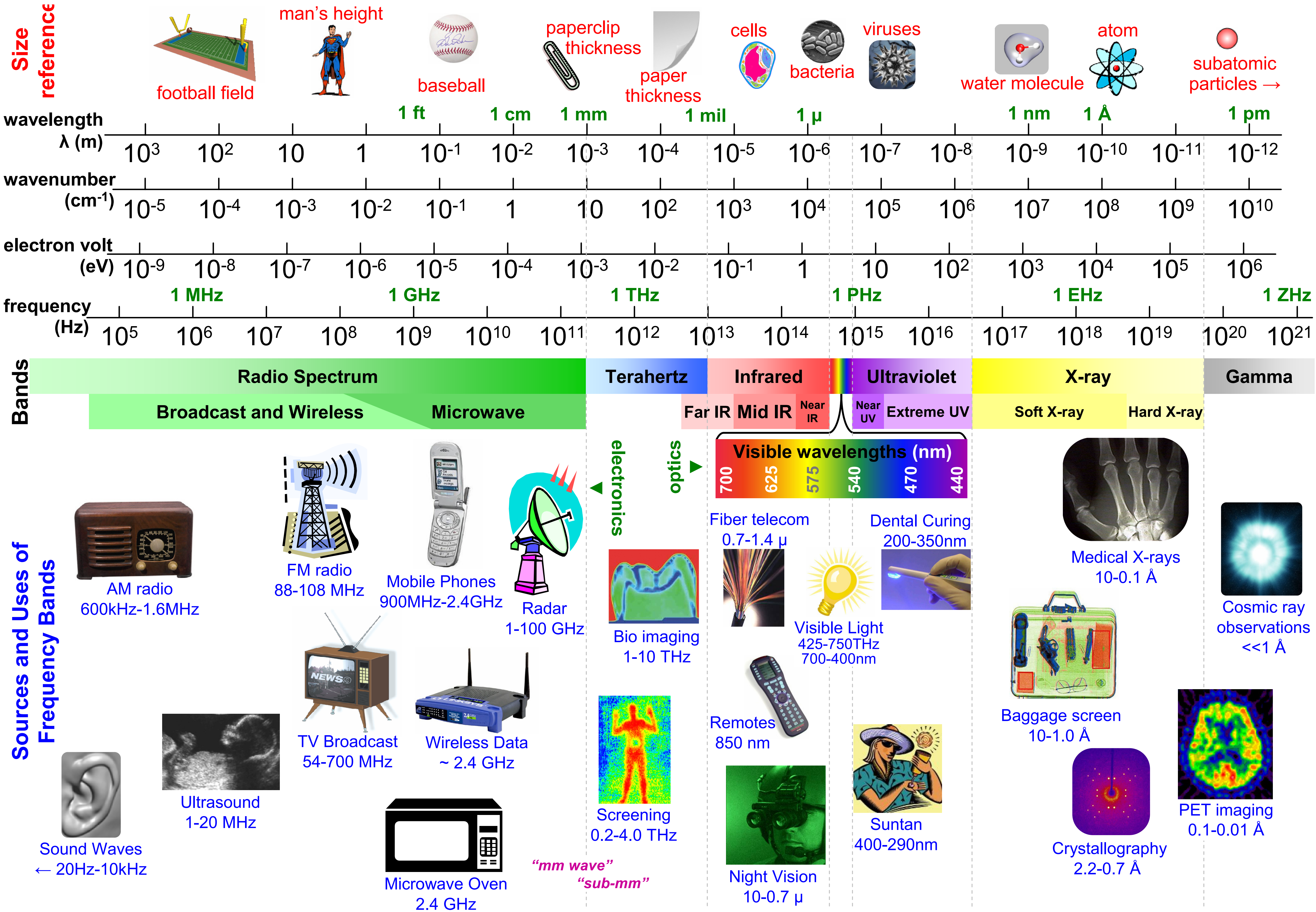
➜ remember that sinusoidal waves are described by a wavelength, λ, and a frequency, *f*

➜ they are related by $c = f\lambda$

➜ e/m waves of different wavelengths have different names



the electromagnetic spectrum

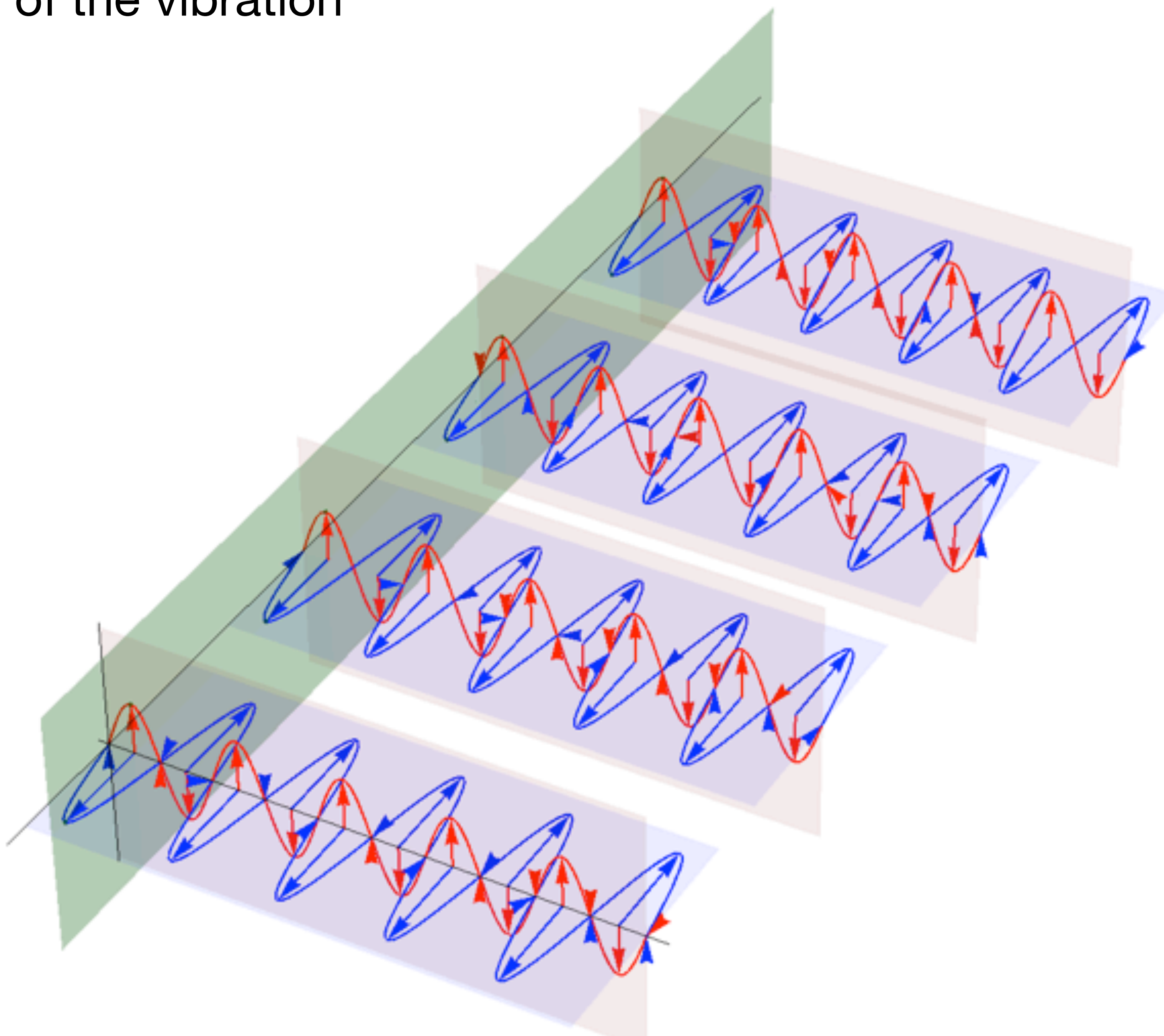


wave fronts

➜ a wave-front is a handy concept in understanding waves

➜ defined as the surface on which the phase of a wave is the same, i.e. where the wave is at the same bit of the vibration

➜ e.g. a plane-wave

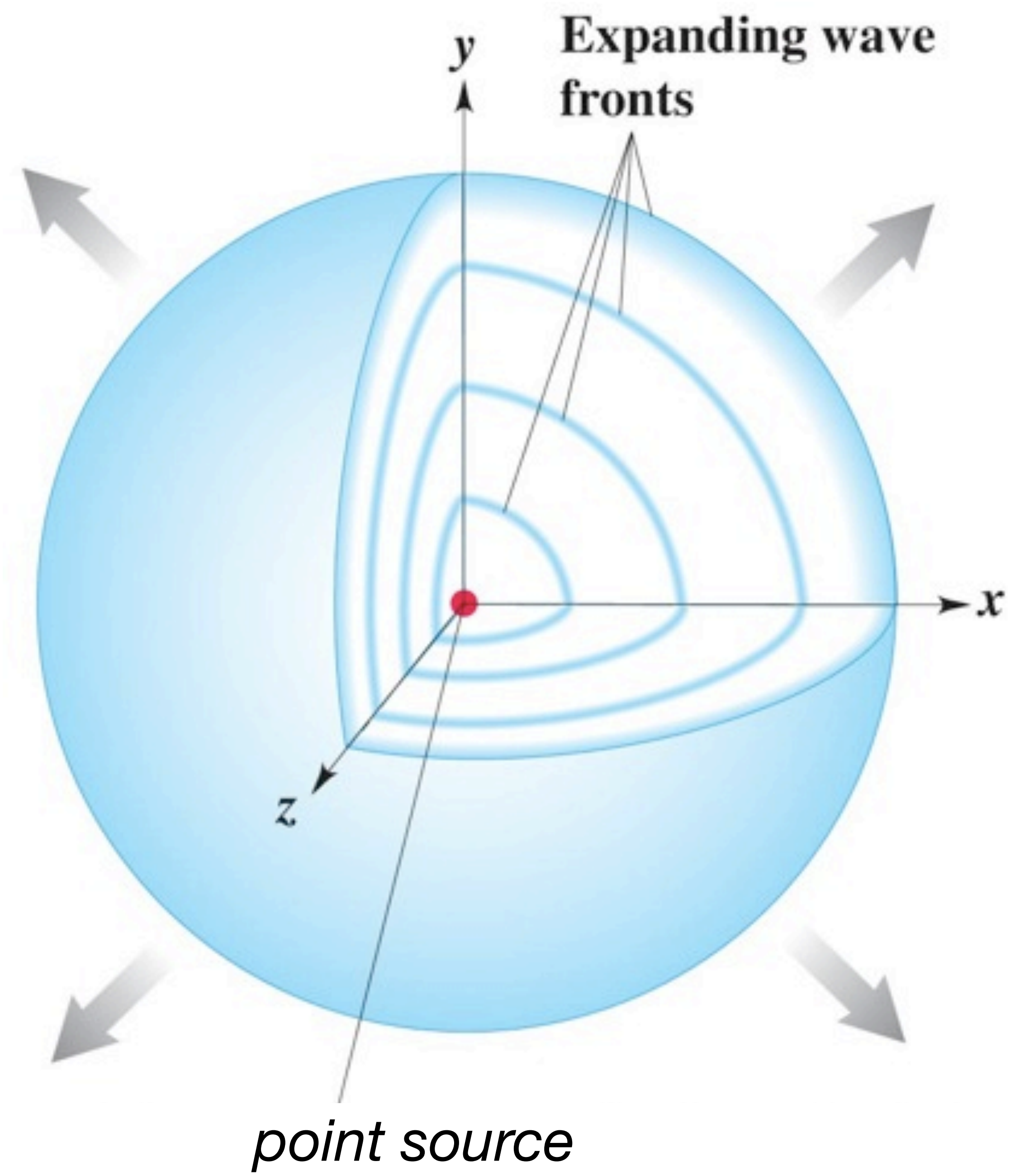


wave fronts

➜ a wave-front is a handy concept in understanding waves

➜ defined as the surface on which the phase of a wave is the same, i.e. where the wave is at the same bit of the vibration

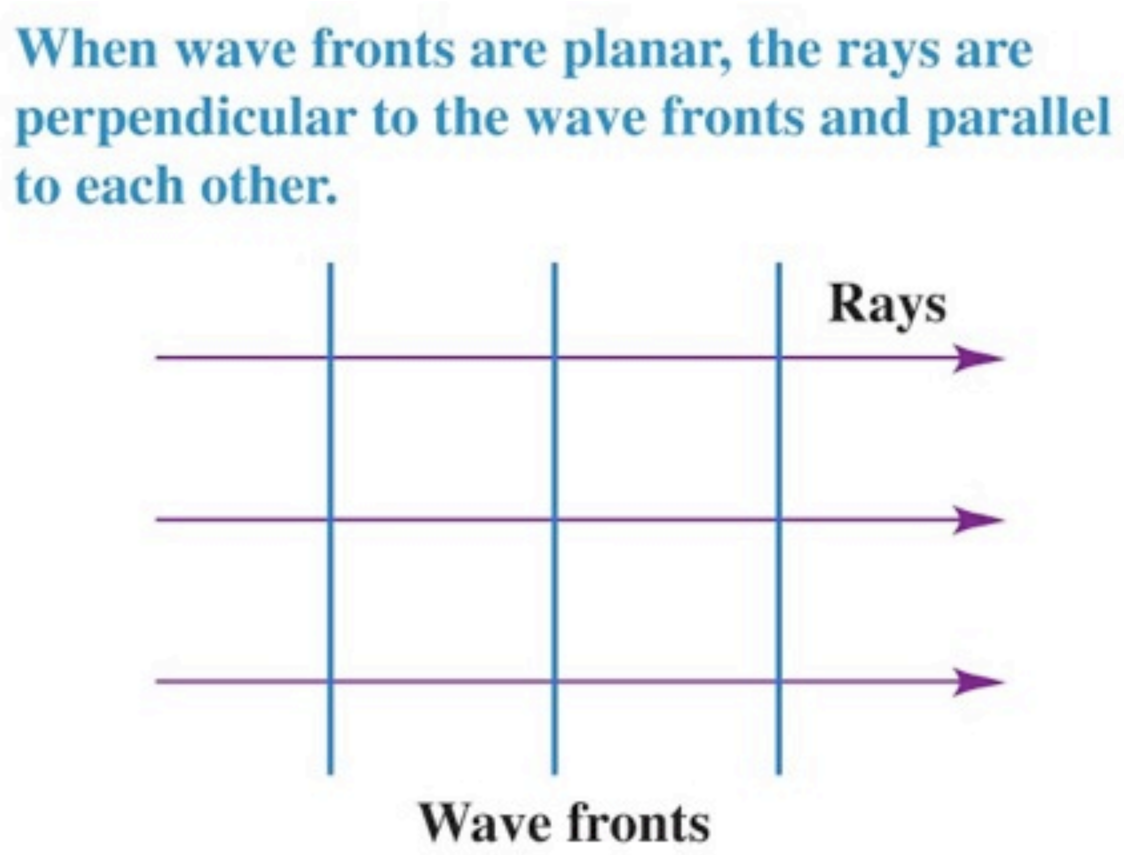
➜ e.g. spherical wave

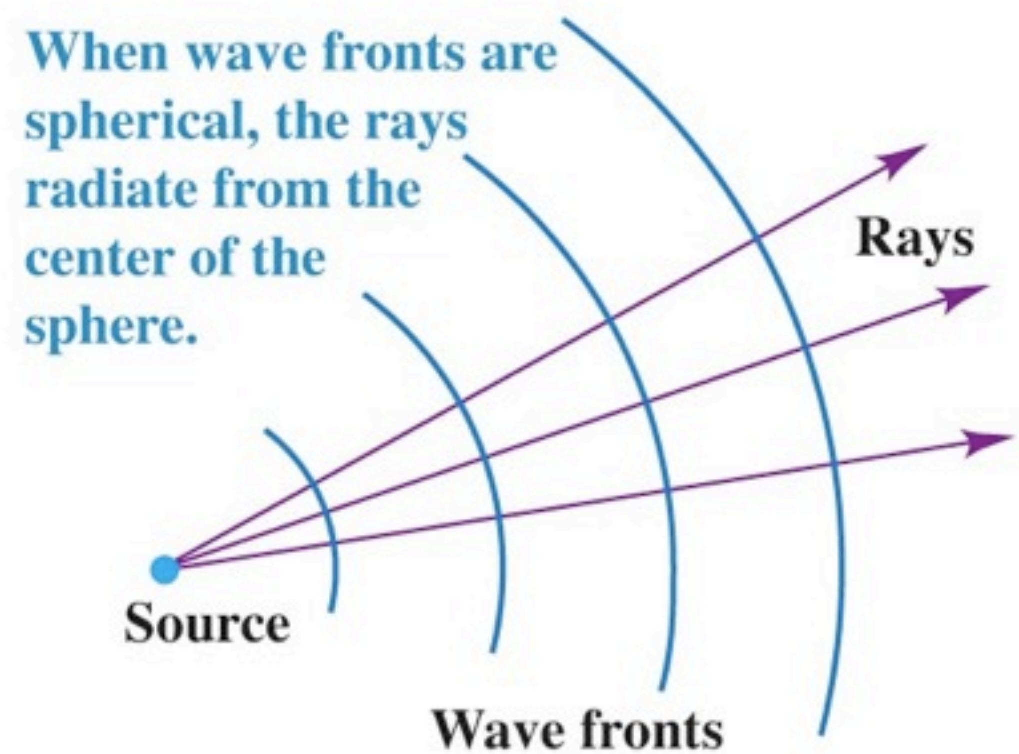


rays and wave fronts

➜ can also define rays which are imaginary lines at right angles to the wavefronts

➜ rays are very handy for describing geometric optics

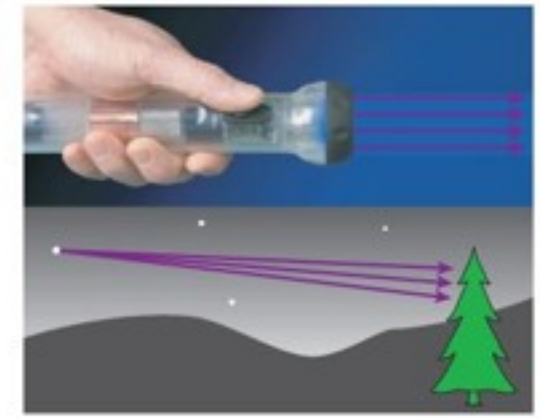




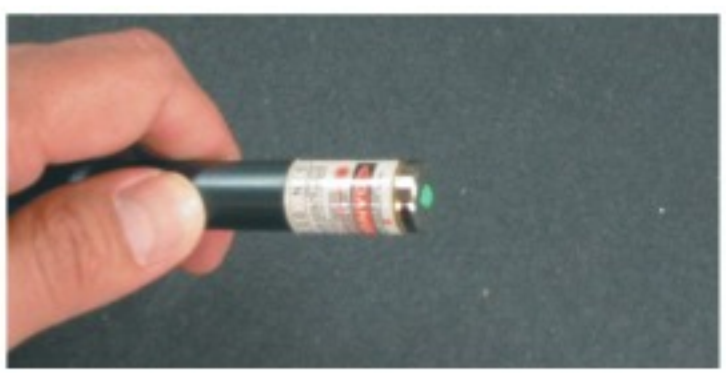
describing light using rays

➜ self-luminous object emit light rays

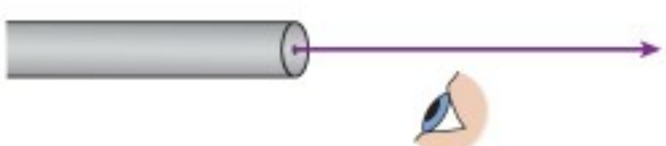


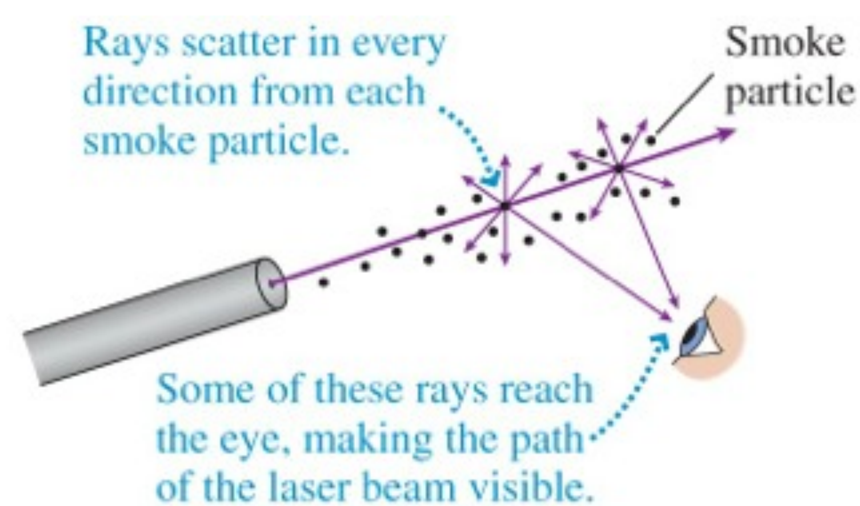



➜ rays are not themselves directly visible



You can't see a laser beam crossing the room because no light ray enters your eye.

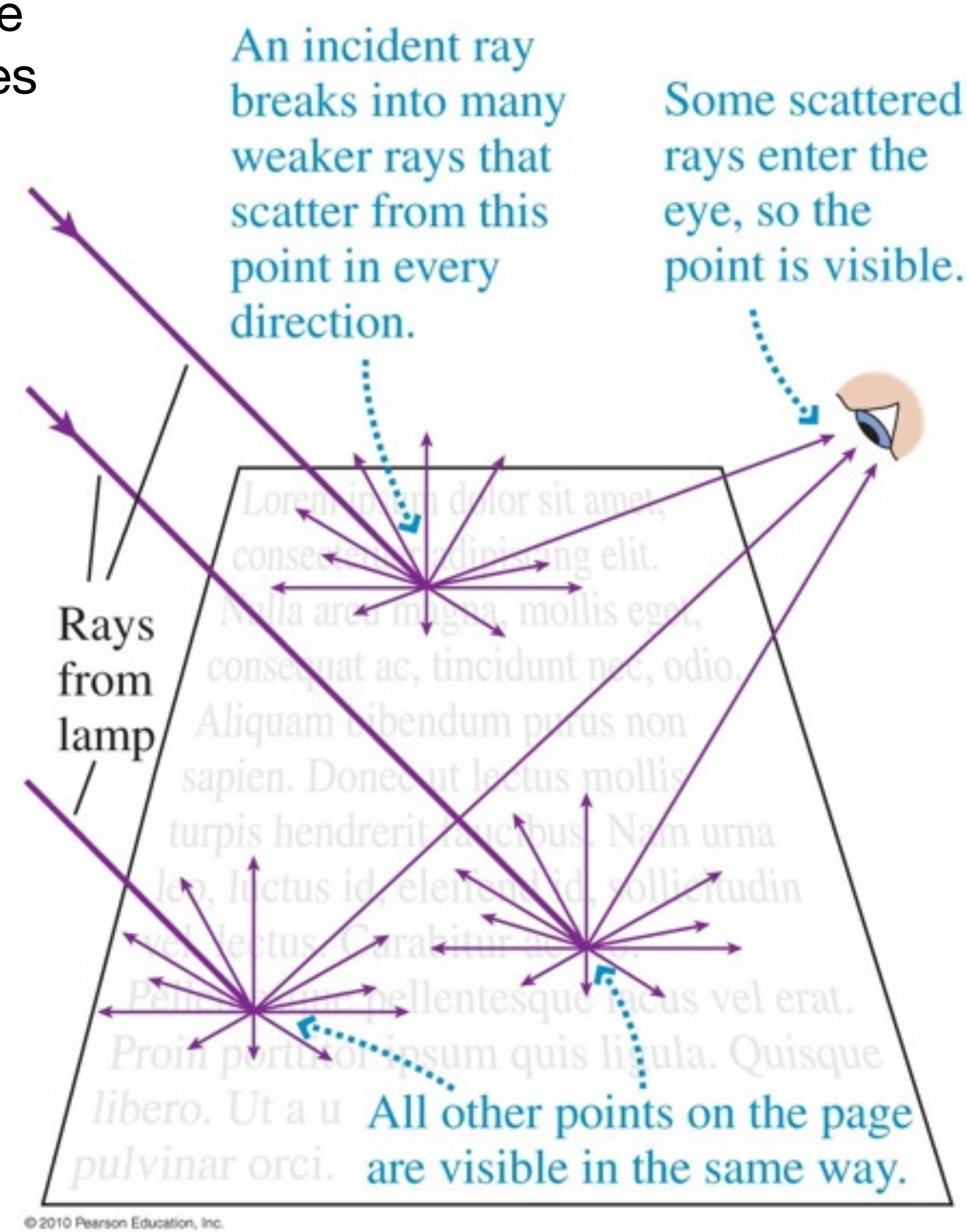




describing light by rays

➜ objects which are not self-luminous can be seen using light 'scattered' from their surfaces

e.g. reading a page:



➜ 'scattering' occurs at 'rough' surfaces

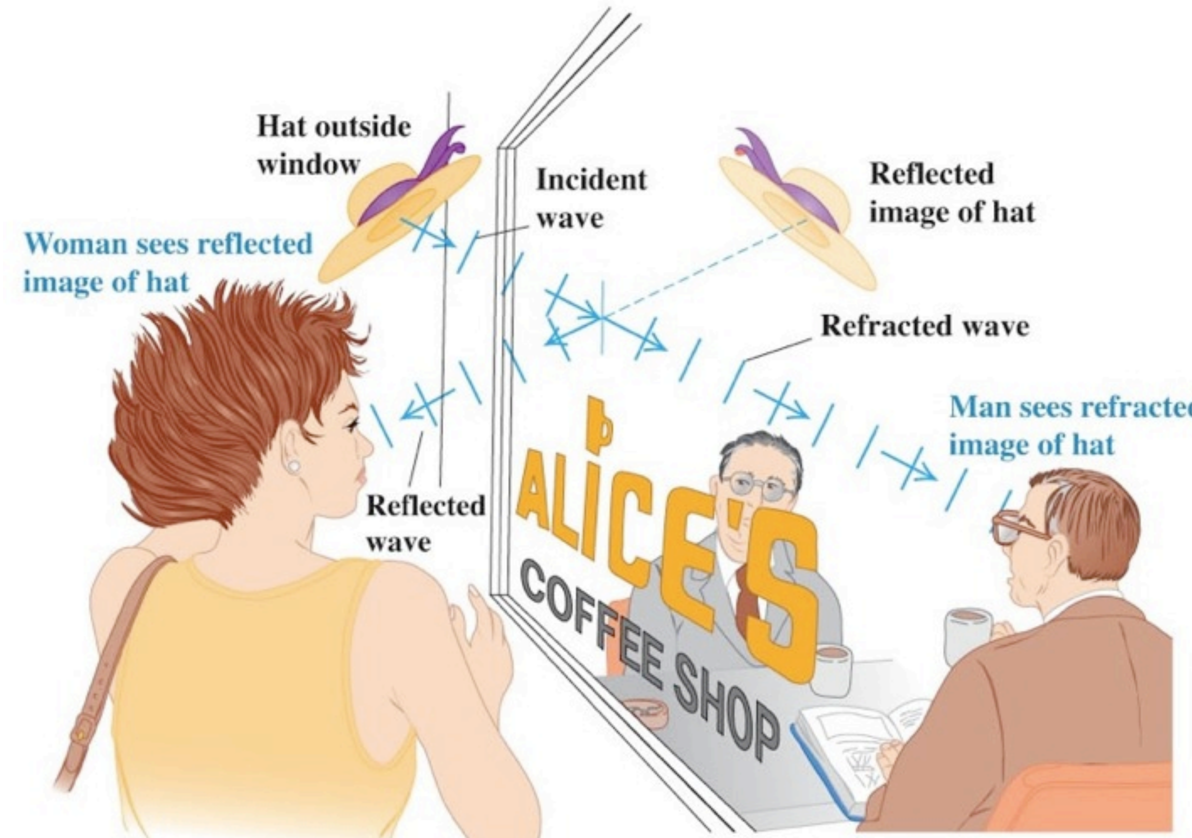
➜ what about smooth surfaces?

describing light by rays

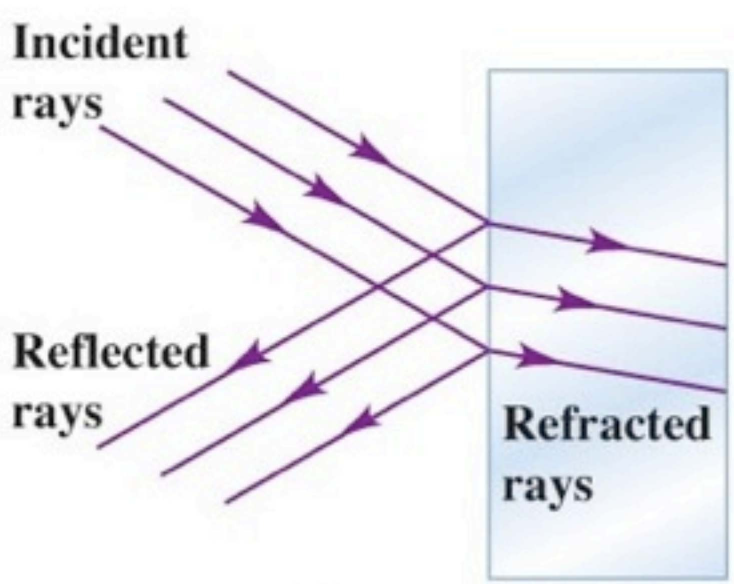
➜ when light moves from one medium to another (say from air to glass) two things can happen

➜ some light can be **reflected**, continuing to propagate in the air, but in a new direction

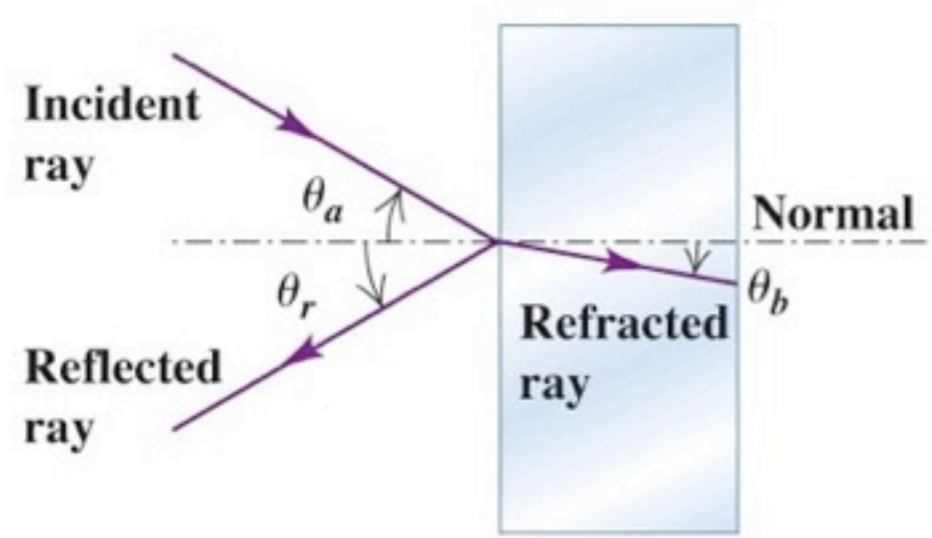
➜ some light can be **refracted**, propagating then through the glass, usually in a different direction



(a) Plane waves reflected and refracted from a window.



(b) The waves in the outside air and glass represented by rays.



(c) The representation simplified to show just one set of rays.

describing light by rays

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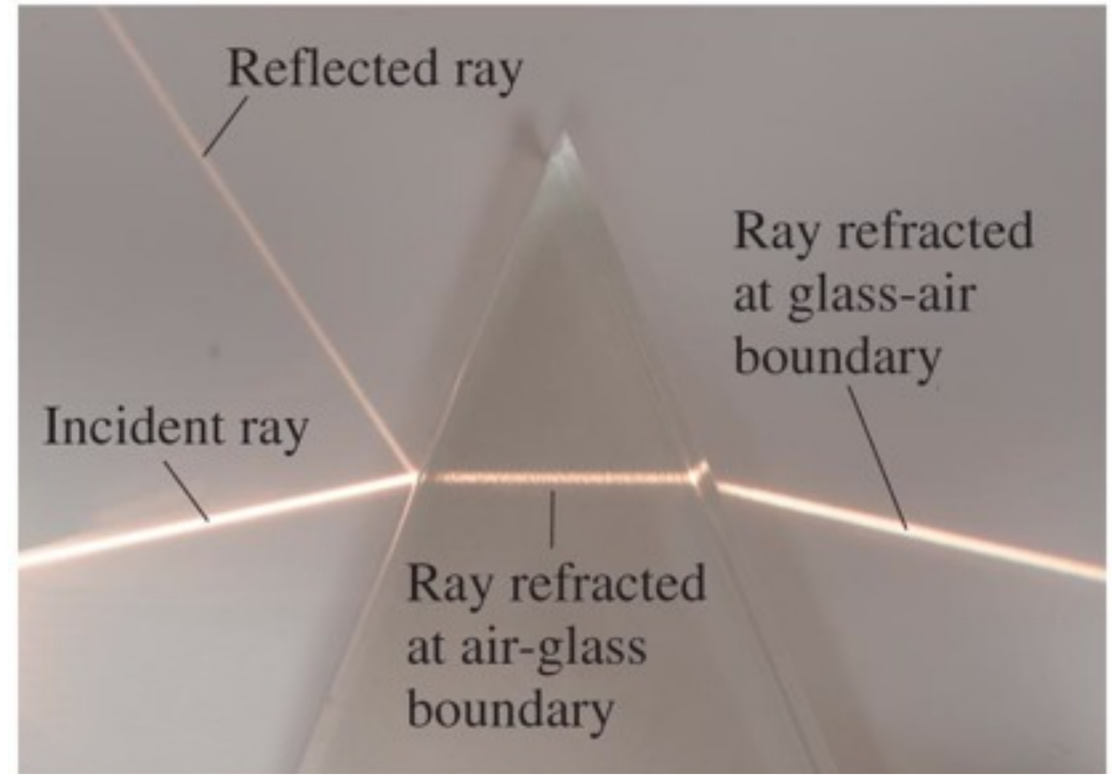
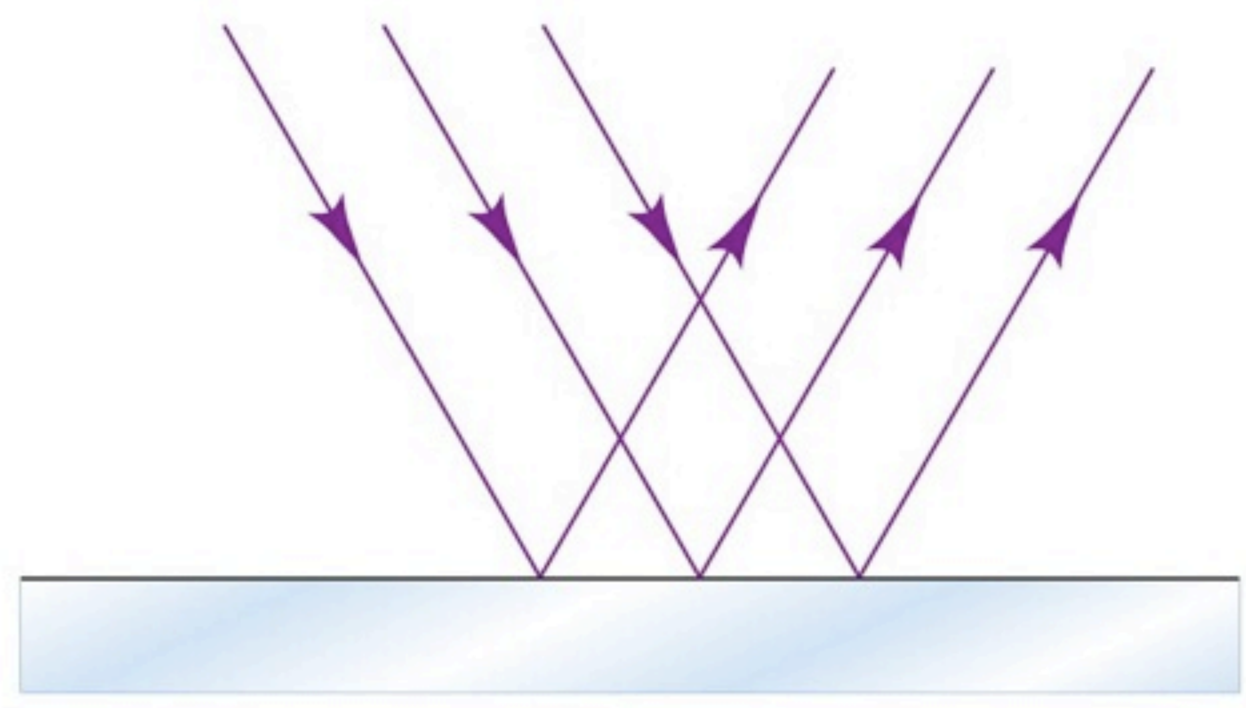


reflection of light

➜ when light moves from one medium to another (say from air to glass) two things can happen

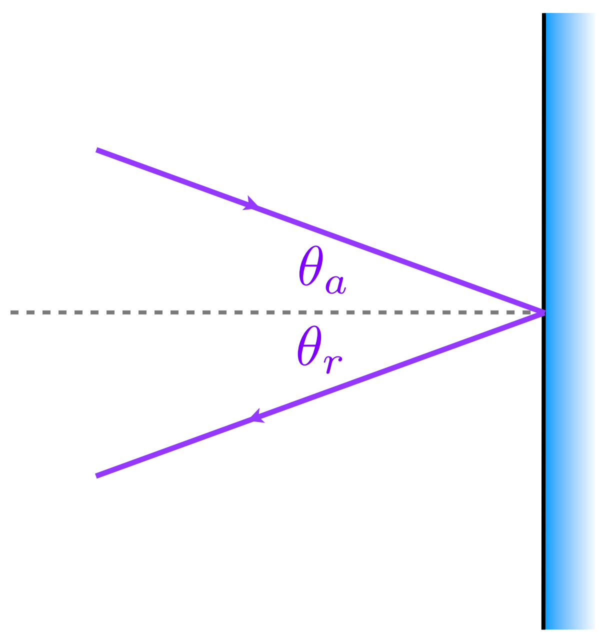


➜ some light can be **reflected**, continuing to propagate in the air, but in a new direction

➜ the following rule is found to describe reflection

angle of incidence = angle of reflection

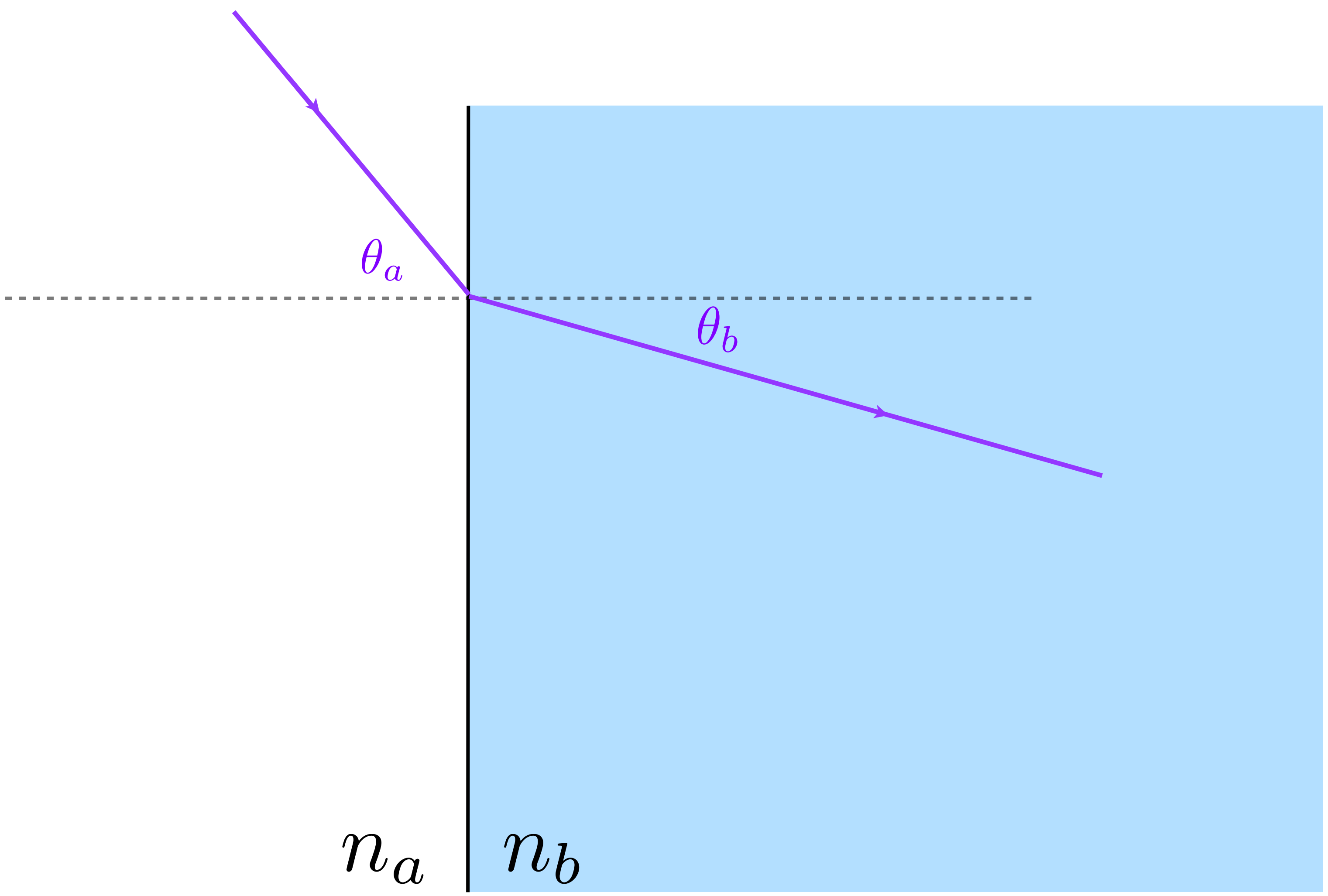
$$\theta_a = \theta_r$$



refraction of light

➜ the amount the light bends is determined by optical properties of the two materials

➜ expressed by a quantity called **refractive index**, *n*



refractive index

➜ in a material, light always travels somewhat slower than it does in vacuum

➜ basically this is due to interactions between the light and the electric charges in atoms

➜ we can define a quantity, the **index of refraction**, that is the ratio of the speed of light in a vacuum to the speed in a material

$$n = \frac{c}{v} \qquad n \geq 1$$

➜ this is the number that determines the optical properties of a material

TABLE 23.1 Index of refraction for yellow sodium light ($\lambda_0 = 589$ nm)

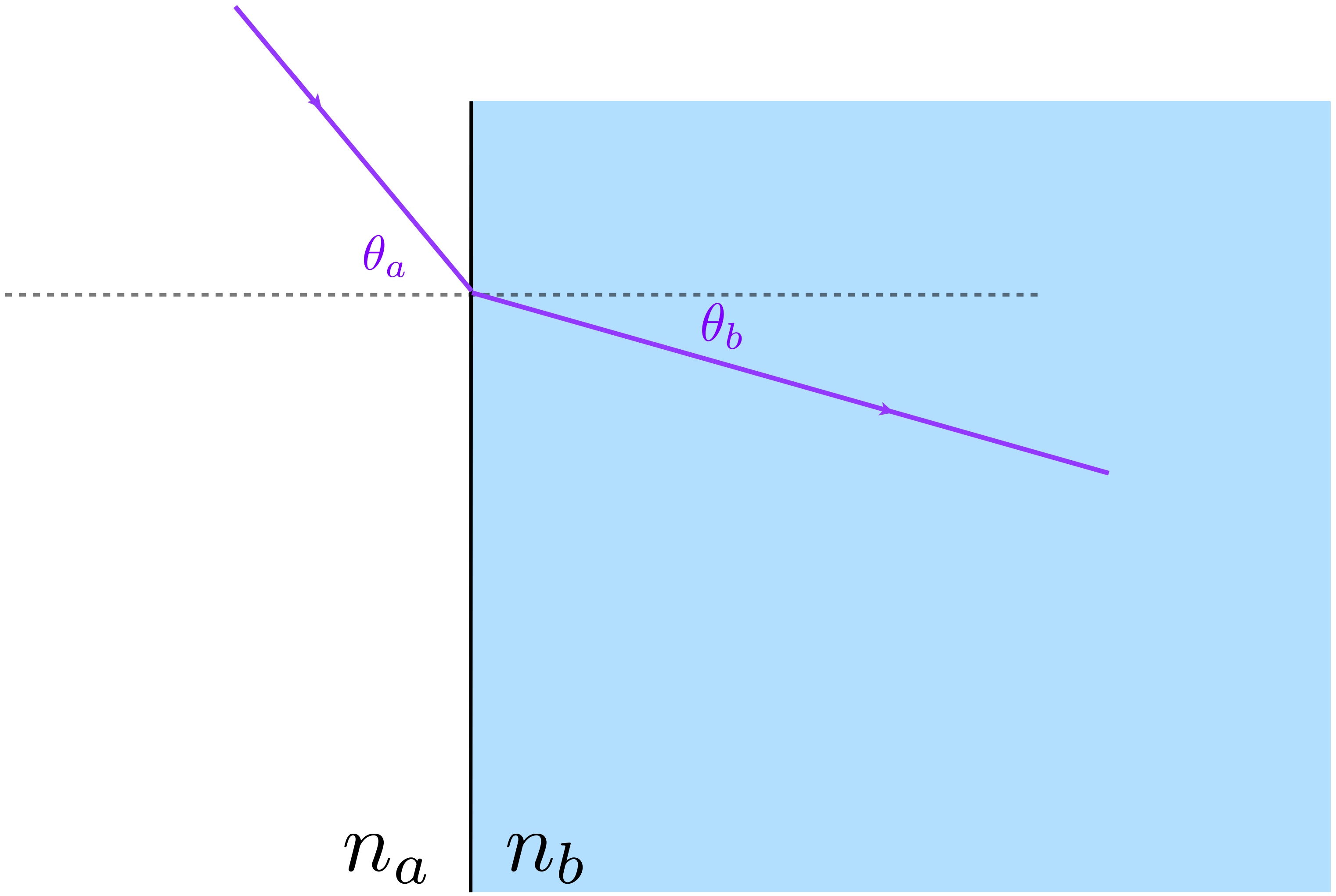
Substance	Index of refraction, n	Substance	Index of refraction, n
Solids		Medium flint	1.62
Ice (H_2O)	1.309	Dense flint	1.66
Fluorite (CaF_2)	1.434	Lanthanum flint	1.80
Polystyrene	1.49	*Liquids at 20°C*	
Rock salt (NaCl)	1.544	Methanol (CH_3OH)	1.329
Quartz (SiO_2)	1.544	Water (H_2O)	1.333
Zircon ($ZrO_2 \cdot SiO_2$)	1.923	Ethanol (C_2H_5OH)	1.36
Fabulite ($SrTiO_3$)	2.409	Carbon tetrachloride (CCl_4)	1.460
Diamond (C)	2.417	Turpentine	1.472
Rutile (TiO_2)	2.62	Glycerine	1.473
Glasses (typical values)		Benzene	1.501
Crown	1.52	Carbon disulfide (CS_2)	1.628
Light flint	1.58		

refraction of light

➜ the amount the light bends is determined by optical properties of the two materials

➜ the angle of refraction is determined using **Snell's law**

$$n_a \sin\theta_a = n_b \sin\theta_b$$



refraction of light

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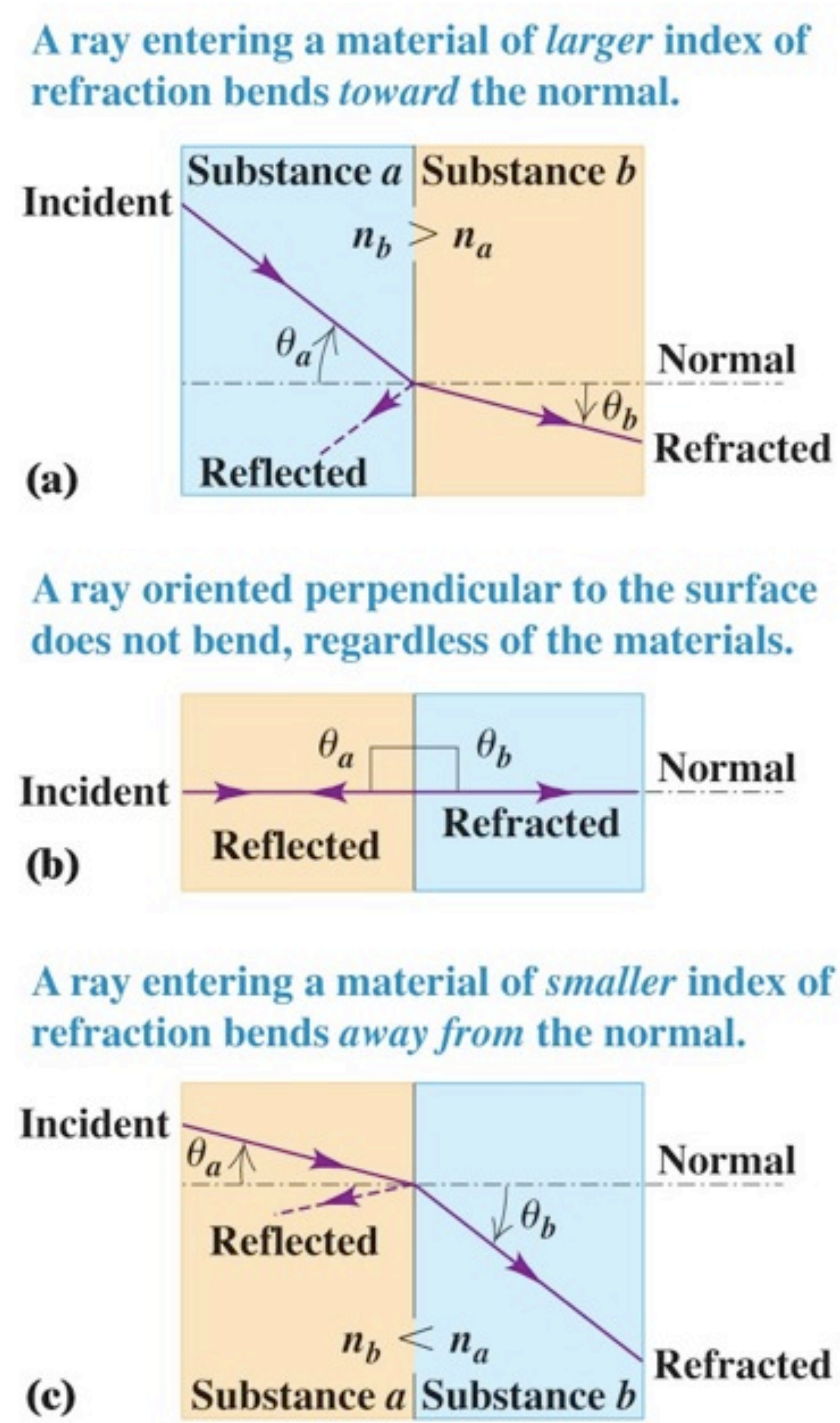
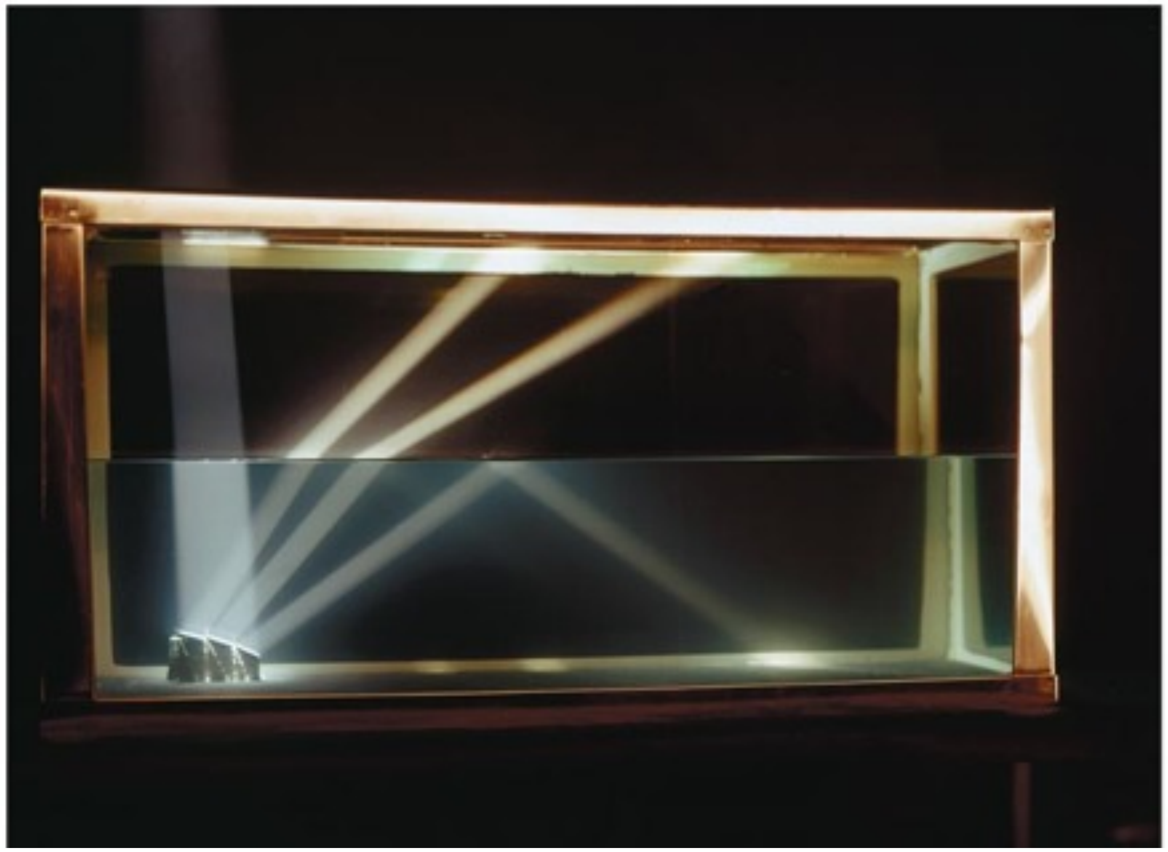
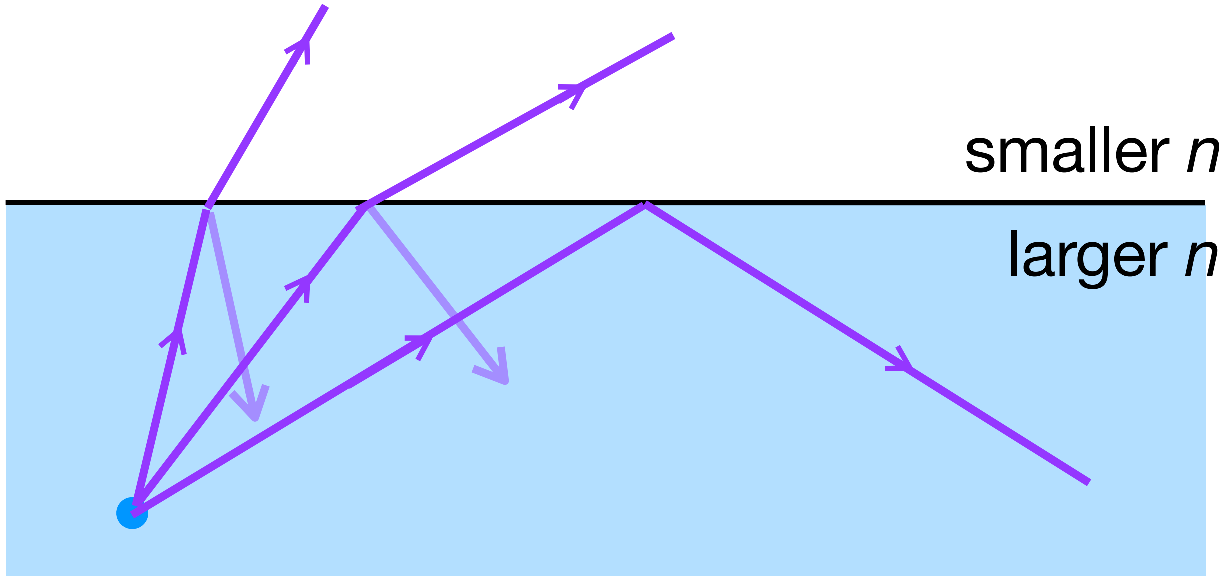


➜ increasing *n* - bend toward the normal
➜ decreasing *n* - bend away from the normal

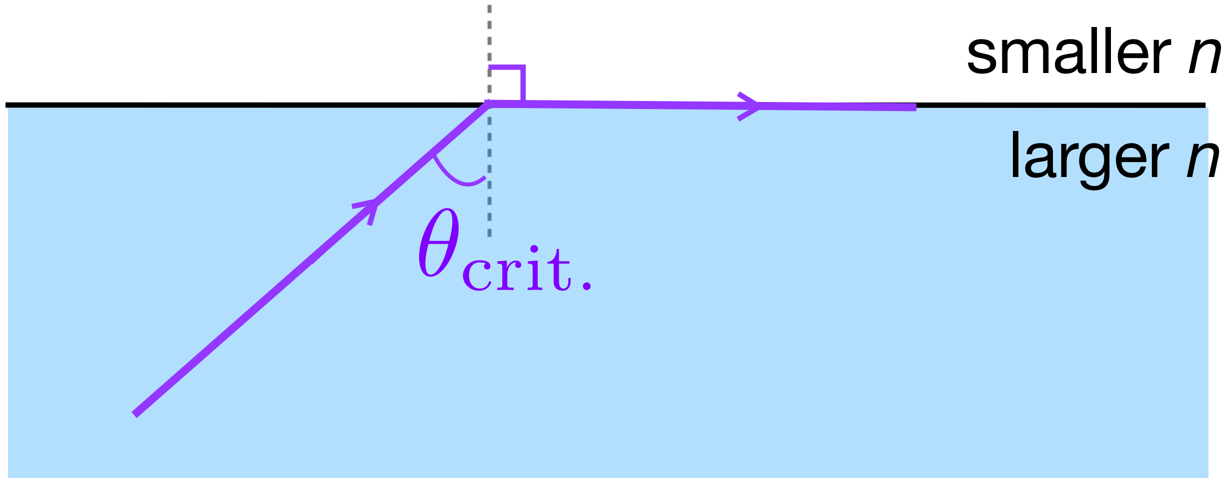
total internal reflection





➜ when $\theta_a = \theta_{\text{crit.}}$

$\theta_b = 90^\circ$ i.e. refracted ray doesn't leave



$$n_a \sin\theta_{\text{crit.}} = n_b \sin 90^\circ$$

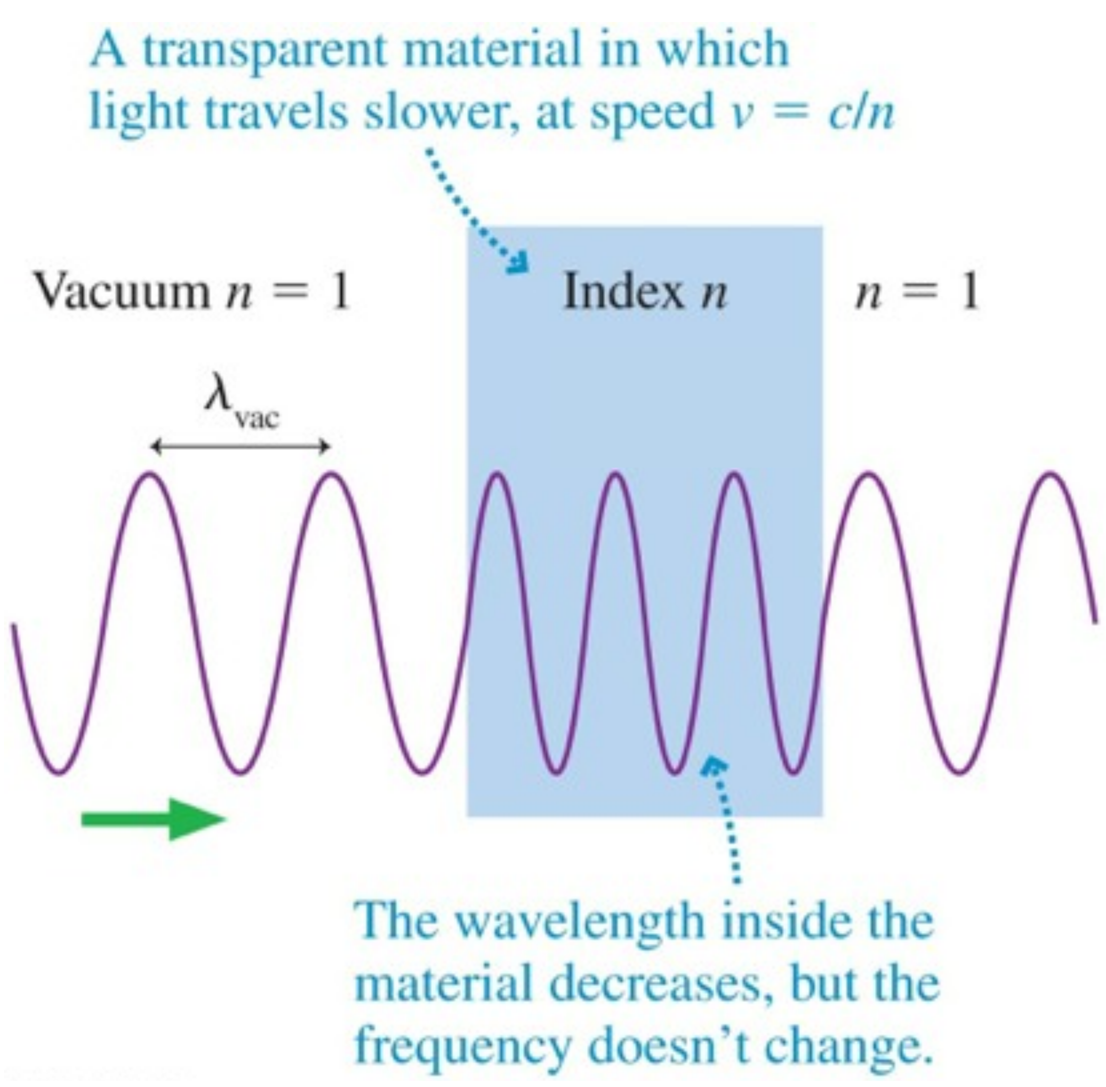
$$\theta_{\text{crit.}} = \sin^{-1}\frac{n_b}{n_a}$$

refractive index

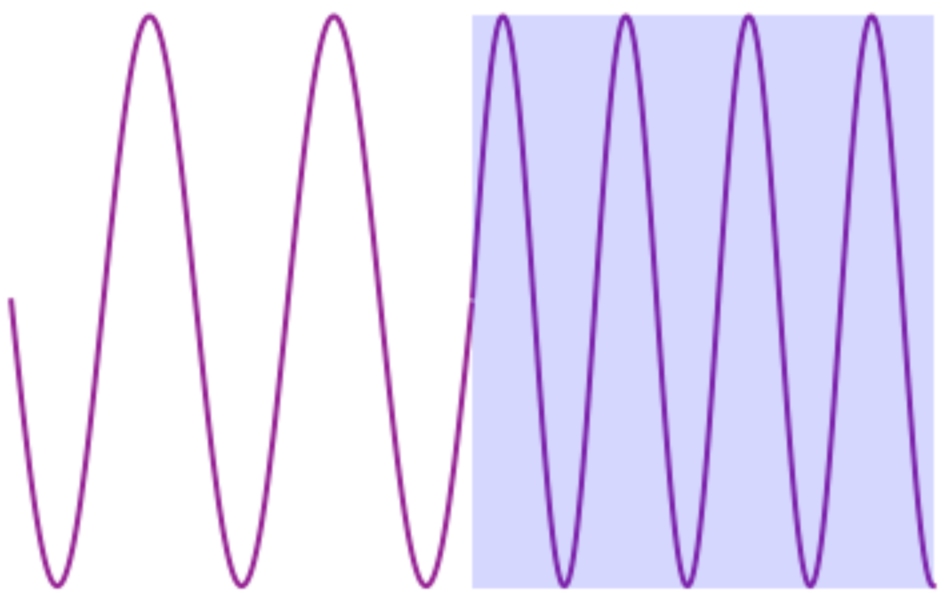
➜ light travels slower in materials, according to the refractive index $n = \frac{c}{v}$

➜ and we recall that wave speed, frequency and wavelength are related $v = f\lambda$

➜ if the wave speed decreases, which of *f*, λ changes ?



➜ it has to be the wavelength



dispersion

➜ the refractive index of a material actually depends somewhat on the frequency of the light

➜ so different colors of light are 'bent' by different amount when they pass from air into a material

➜ since white light is a superposition of waves covering the whole visible spectrum, we see dispersion of white light into a spectrum