Phys 100: The Physical World
Chapters 26 & 27

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Maxwell's Prediction

In the 1860's, while the US was engaging in civil war, a far more significant event was taking place in Europe. James Clerk Maxwell was working to unify the laws of electricity and magnetism. Through a set of mathematical equations–now called Maxwell's equations–he made a surprising prediction: **light is an electromagnetic wave.**

Up to this point in history, fields were a convenient way to describe action at a distance. Electromagnetic waves consist of self-propagating electric and magnetic fields that vary with time, and according to Maxwell's theory, *they carry energy and momentum through space like ordinary matter!* We will learn the most important properties of EM waves and the various physical processes that create them.

The Speed of Light

Maxwell predicted the existence of electromagnetic waves that consist of oscillating electric and magnetic fields capable of traveling through empty space with a fixed speed denoted by the letter c and showed that

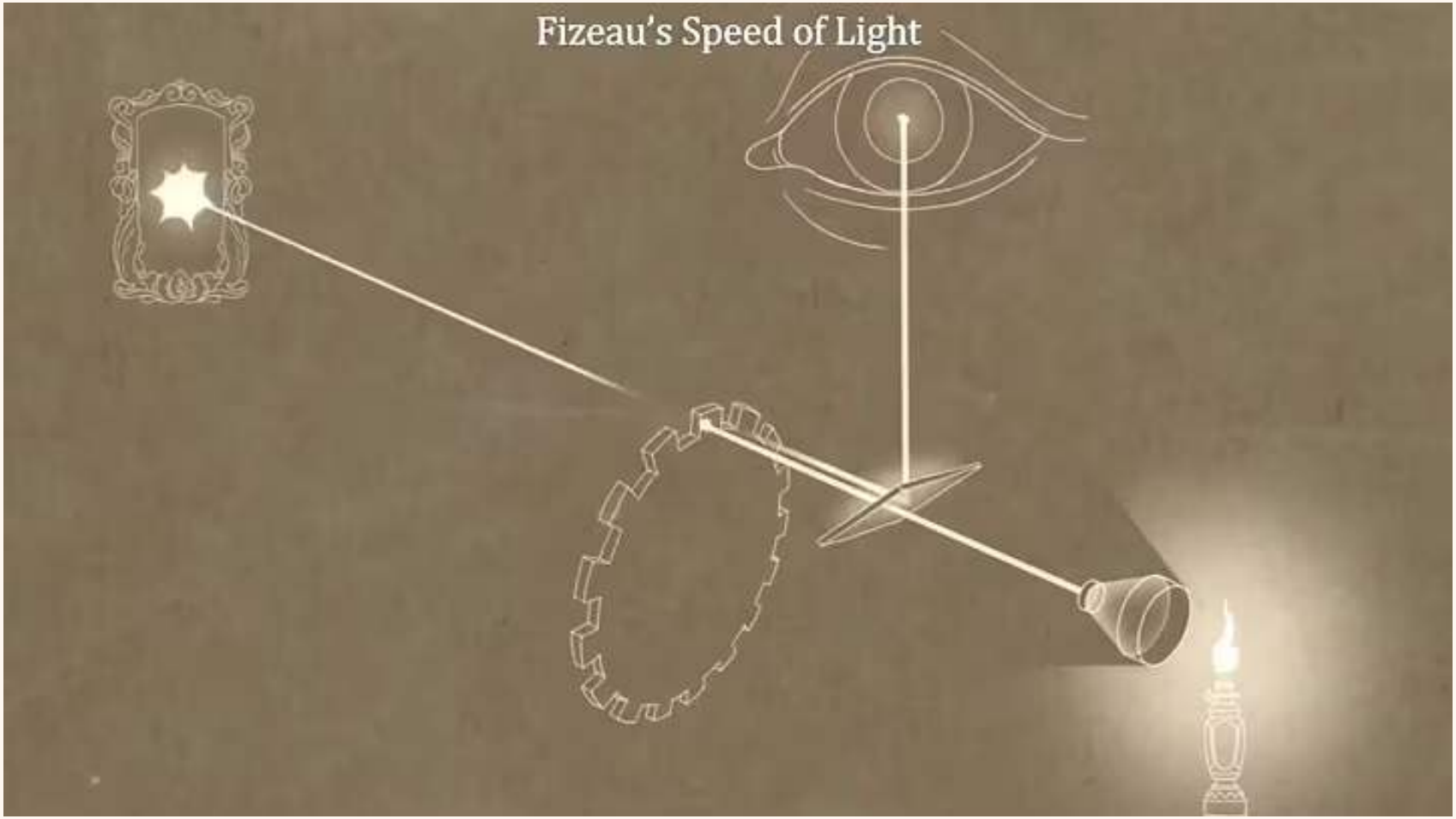
$$c = 299,792,458 \text{ m/s}$$

using only the magnetic constant (from Biot-Savart) and the electric constant (from Coulomb). This figure was in good agreement with measurements of the speed of light taken around that time. Today the figure is exact in the SI system of units–we use it to define the meter as the distance traveled by light in $1/c$ seconds.

Fizeau's Experiment

Light is incredibly fast–in just a single second, light would travel around the equator 7.5 times. In 1849, French physicist Fizeau, using clever techniques of experimental science, made the first terrestrial measurement of the speed of light. He passed light through a rotating toothed wheel, which then bounced off a distant mirror and came back. When the wheel was spinning fast enough, the returning light would be blocked by the next tooth. The speed of light was calculated from (i) the rotational speed of the wheel, (ii) the number of teeth, and (iii) the distance between the wheel and the mirror. You might wonder, why not just measure the speed by measuring the time it takes light to travel a one-way distance? There are subtle problems with measuring the "one-way speed of light" that we'll discuss later.

Fizeau's Speed of Light



Click here to watch video (2:30)

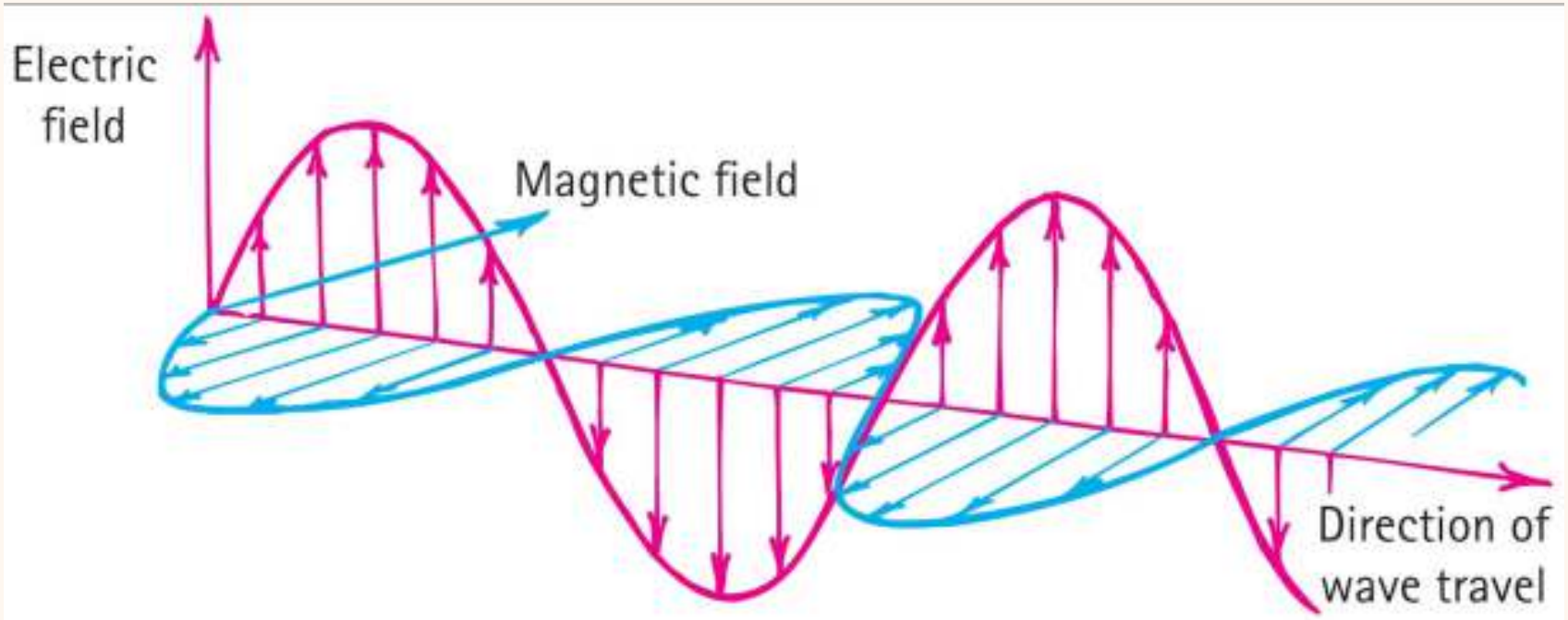
Hertz's Experiments

Heinrich Hertz experimentally verified Maxwell's predictions about electromagnetic waves in 1887-1888 by generating them using a spark-gap transmitter and detecting them with a wire loop resonator. He demonstrated that these waves exhibited properties like reflection, refraction, interference, diffraction, and polarization, confirming their similarity to light waves. By measuring their wavelength and speed, he showed they traveled at the speed of light, precisely as Maxwell predicted. Hertz provided the first direct evidence of electromagnetic waves before tragically passing away at the age of 36. Today we honor him with the unit of frequency, $1\ \mathrm{Hz} = 1\ \mathrm{s}^{-1}$.

Click here to watch a video on Hertz's experiments.

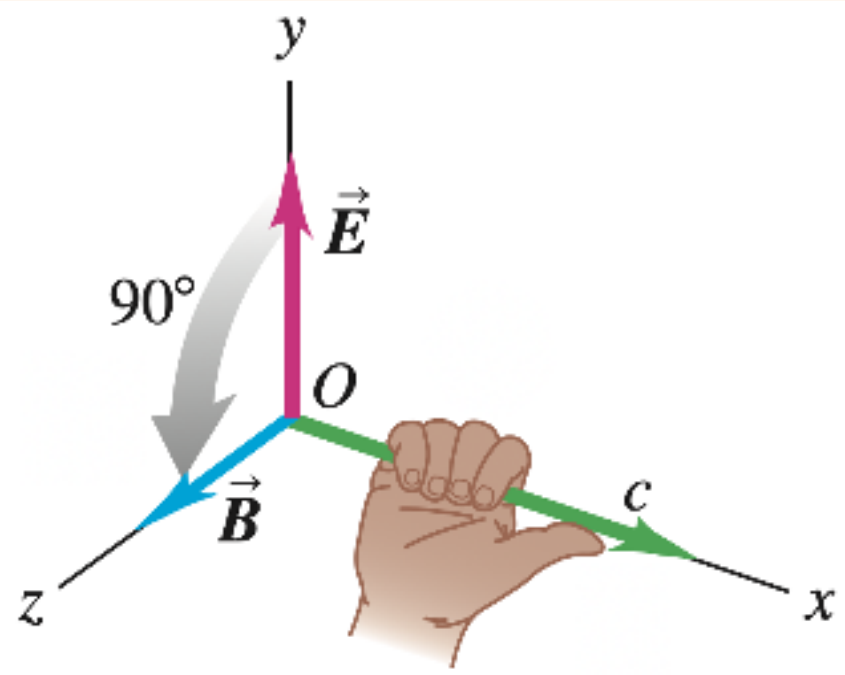
Electromagnetic Waves

Any time a charged object accelerates, it produces ripples in the electromagnetic field that we call electromagnetic waves. An oscillating charge creates an oscillating wave with the same frequency, and the speed of the wave is constant in vacuum.



Properties of EM Waves

1. EM waves travel in vacuum with a definite and unchanging speed c. They require no medium unlike mechanical waves.
2. EM waves are **transverse**; both $\mathbf{E}$ and $\mathbf{B}$ vectors are perpendicular to each other and to the direction of propagation.
3. There is a definite ratio between the magnitudes: $E = cB$



Wave Speed Equation

We simplify our discussion of EM waves by focusing on waves that have definite frequency and wavelength. They are called "sinusoidal waves" because they create a pattern in space that resembles the sine function from trigonometry. If the wavelength of a wave is the distance between two crests and the period of a wave is how long it takes to complete one oscillation, then the wave speed is

$$\text{wave speed} = \frac{\text{wavelength}}{\text{period}} = \text{wavelength} \times \text{frequency}$$

The frequency is the number of oscillations per unit of time while the period is the time per oscillation. **The wave speed is fixed while the frequency depends on the source.** The wavelength is like a "dependent variable."

Conceptual Question 1

If an electron vibrates up and down 1000 times each second, it generates an electromagnetic wave with a

(a) period of 1000 s

(b) speed of 1000 m/s

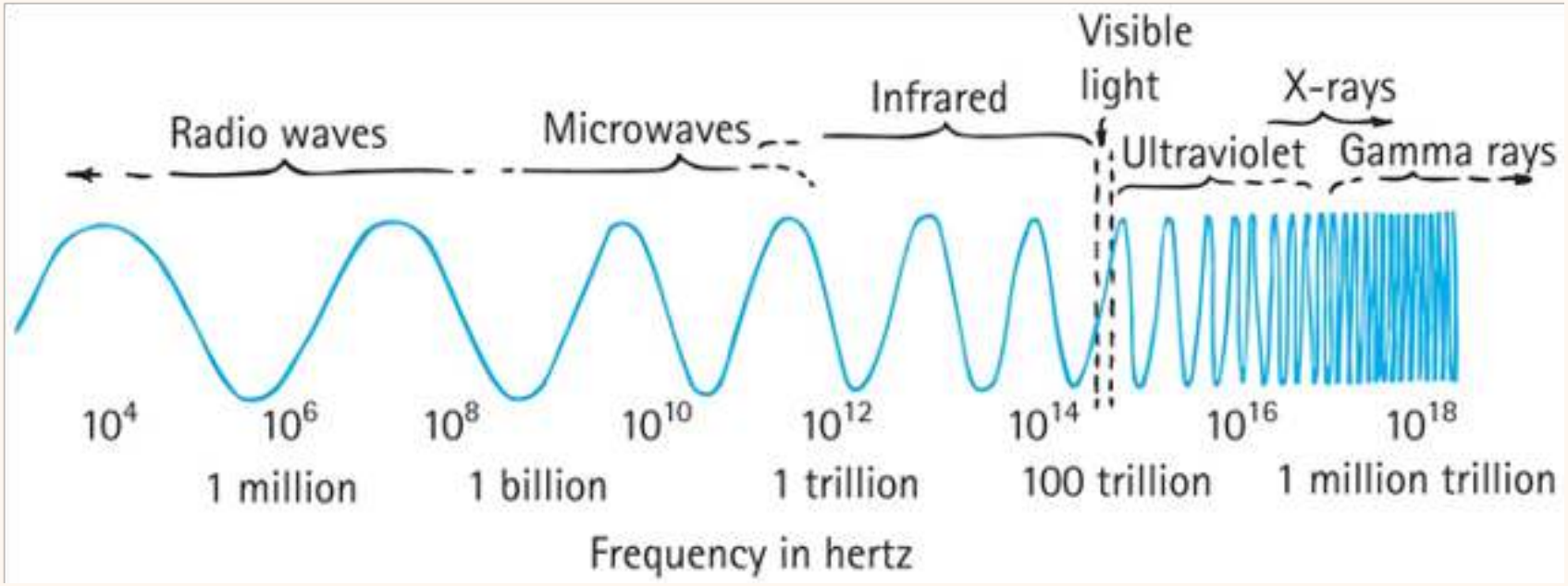
(c) wavelength of 1000 m

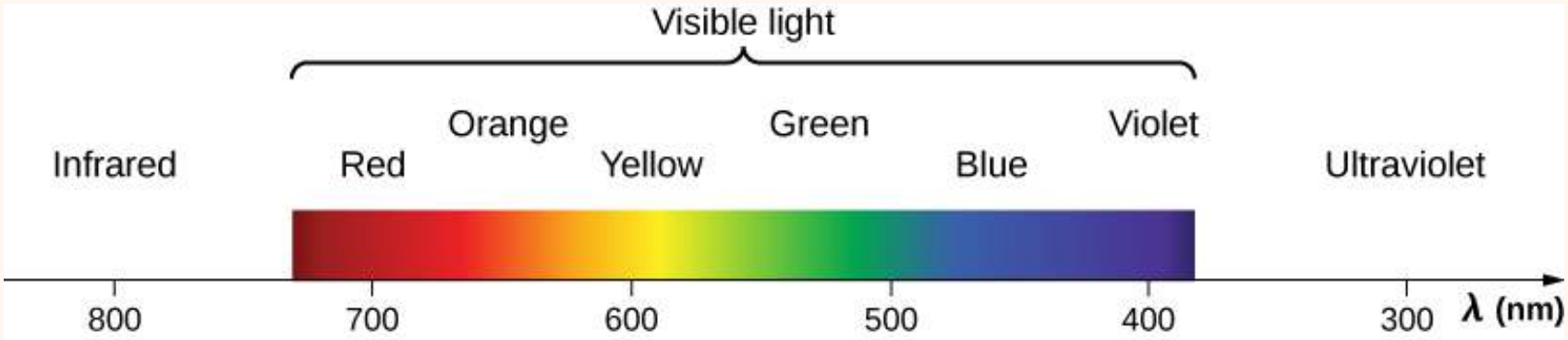
(d) none of the above is correct

Electromagnetic Spectrum

The **electromagnetic spectrum** is the range of all possible electromagnetic waves, classified by wavelength or frequency. It consists of radio waves (longest wavelength, from stars and artificial transmitters, used in communication), microwaves (produced by oscillating currents, used in radar and cooking), infrared (IR) radiation (emitted by warm objects, used in thermal imaging and remote controls), visible light (from the Sun, detected by the human eye), ultraviolet (UV) radiation (also from the Sun and high-energy processes, can cause ionization and DNA damage), X-rays (from high-energy atomic transitions, used in medical imaging), and gamma rays (from nuclear reactions and cosmic events, highly penetrating and dangerous). Each region originates from different physical processes, from electron oscillations in antennas to nuclear transitions.

Electromagnetic Spectrum





Conceptual Question 2

The electromagnetic spectrum spans waves ranging from lower to higher frequencies. The narrowest named portion of the electromagnetic spectrum is that of

(a) radio waves

(b) microwaves

(c) visible light

(d) gamma rays

Conceptual Question 3

Which of these is fundamentally different from the others?

(a) sound waves

(b) light waves

(c) radio waves

(d) x-rays

Conceptual Question 4

The speed at which visible light travels is a constant no matter what.

(a) true

(b) false

Speed of Light in Different Materials

Some materials are transparent, meaning they allow light to pass through them, and some materials are opaque, meaning light is completely blocked by them. The speed of light in a transparent material depends on its chemical composition. Light interacts with matter, and the interactions tend to slow light down.

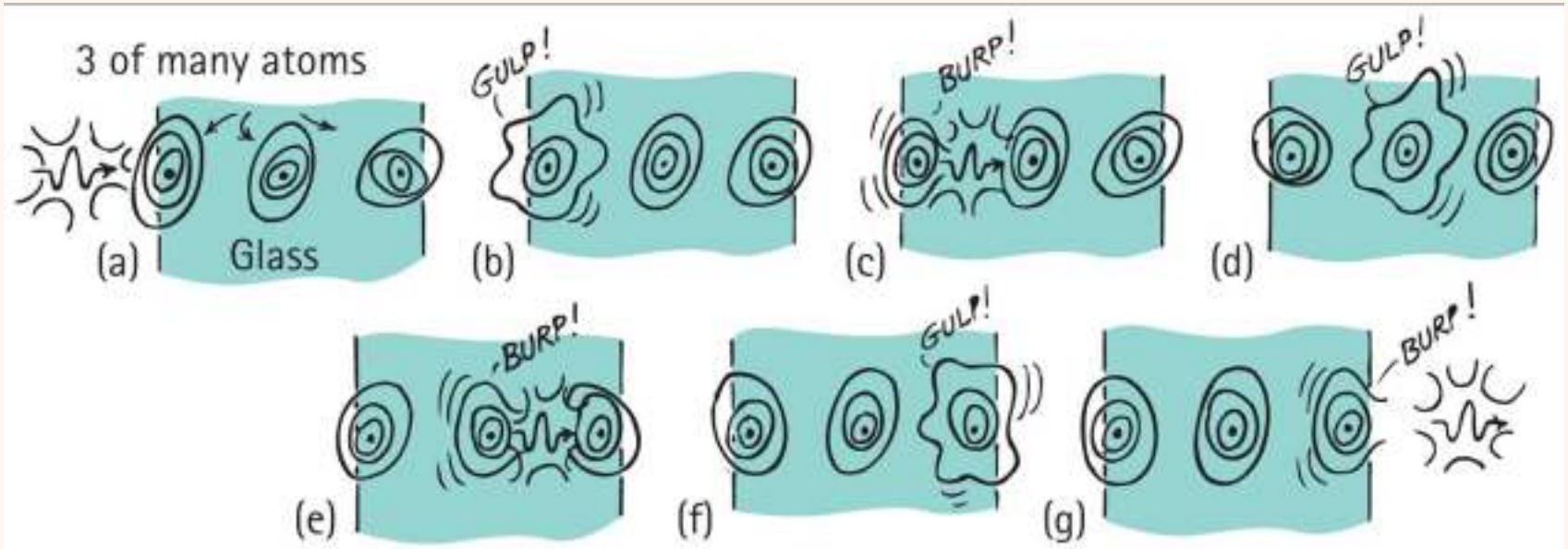
Average speed of light through different materials

- vacuum, $c \approx 300,000,000$ m/s
- atmosphere, $0.9997c$ (very slightly less than c)
- water, $0.75c$
- glass, $0.67c$, depending on material
- diamond, $0.41c$

From Transparent to Opaque

Click here to watch video (3:37)

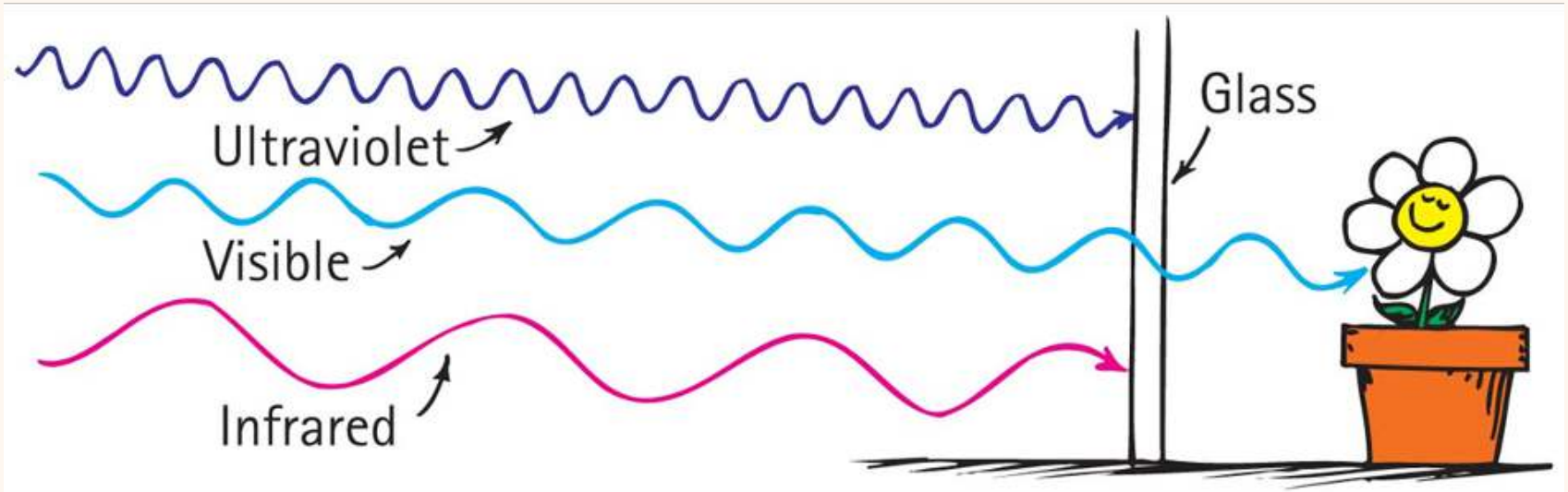
The "Gulp-Burp" Model



Electrons or molecules in the glass are forced into vibration. Energy is momentarily absorbed and vibrates the electrons in the glass. This vibrating electron either emits a photon (a packet of light) or transfers the energy as heat.

Resonance Phenomena

Resonance is the amplification of an oscillation that occurs when the frequency of a driving force matches the natural frequency of the system. We say things "vibe" when little effort is required to produce a response. The transparency of a material depends on the frequency of incident light because some frequencies vibe with the material and other do not.



Conceptual Question 5

Strictly speaking, the photons of light incident on glass are

(a) also the ones that travel through and exit the other side.

(b) not the ones that travel through and exit the other side.

(c) absorbed and transformed to thermal energy.

(d) diffracted.

Conceptual Question 6

Compared with the frequency of illuminating light on a sheet of transparent plastic, the frequency of light that is transmitted

(a) is slightly less

(b) is the same

(c) is slightly higher

(d) depends on the type of plastic

Coceptual Question 7

Light passes through a pane of glass in a window. The speed of the light is least in

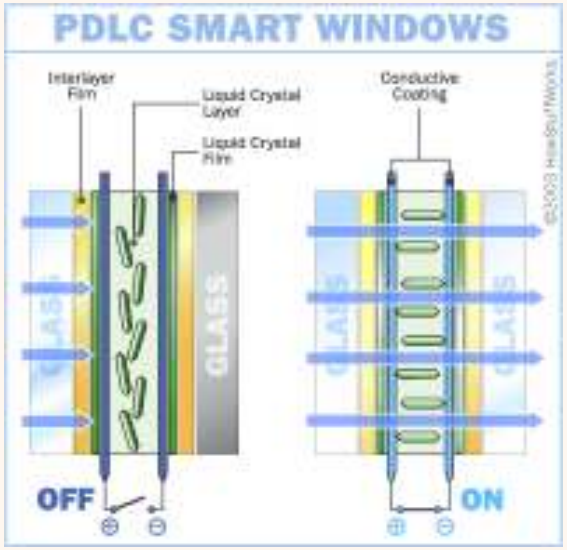
(a) the air before entering glass

(b) the glass

(c) the air after emerging from glass

(d) none of the above is correct

Translucent Materials



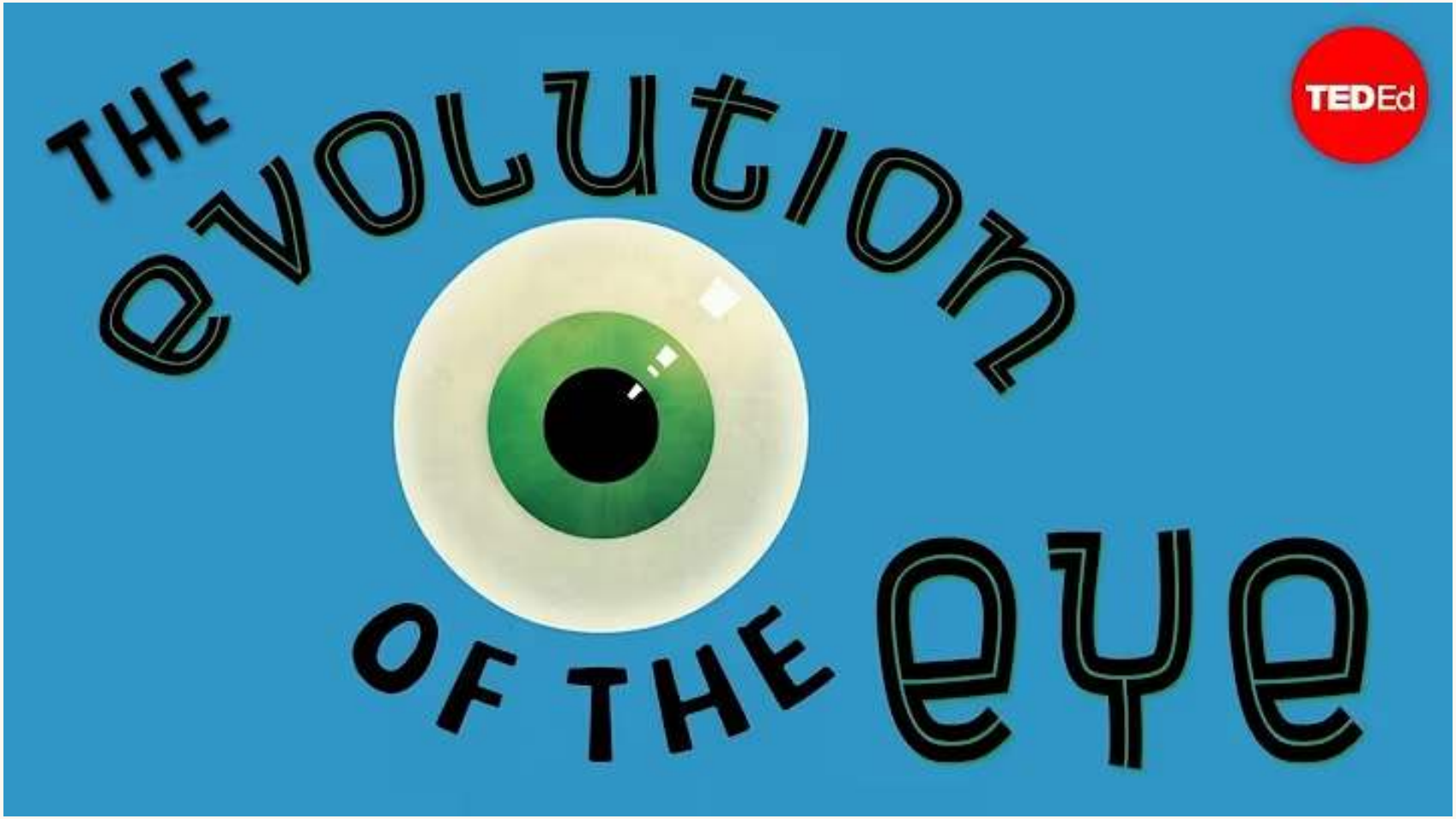
Opaque Materials

Most things around us are opaque—they absorb light without re-emitting it. Books, desks, chairs, and people are opaque. Vibrations given by light to their atoms and molecules are turned into random kinetic energy–into internal energy or thermal energy. These materials become slightly warmer.

Light shining on metal forces free electrons in the metal into vibrations that emit their own light as reflection. Light incident on dry surfaces bounces directly to your eye. Light incident on wet surfaces bounces inside the transparent wet region, absorbing energy with each bounce, and reaches your eye darker than from a dry surface.

Using the "ray picture of light," we understand that opaque objects will stop the light rays that hit them and cast a shadow.

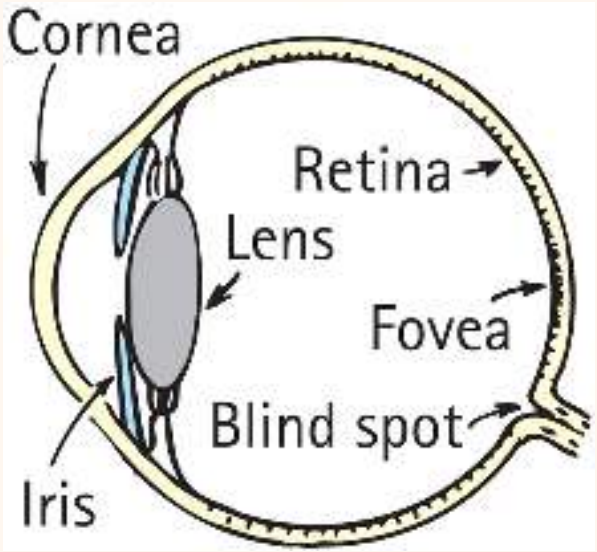
Evolution of the Eye



Click here to watch video (4:43)

Seeing Light–The Eye

As light enters the eye, it moves through the transparent cover called the cornea, which does about 70% of the necessary bending of the light before it passes through an opening in the iris (colored part of the eye). The opening is called the pupil.



The light then reaches the crystalline lens, which fine-tunes the focusing of light that passes through a gelatinous fluid called vitreous humor. Light then passes to the retina, which covers the back two-thirds of the eye and is responsible for the wide field of vision that we experience.

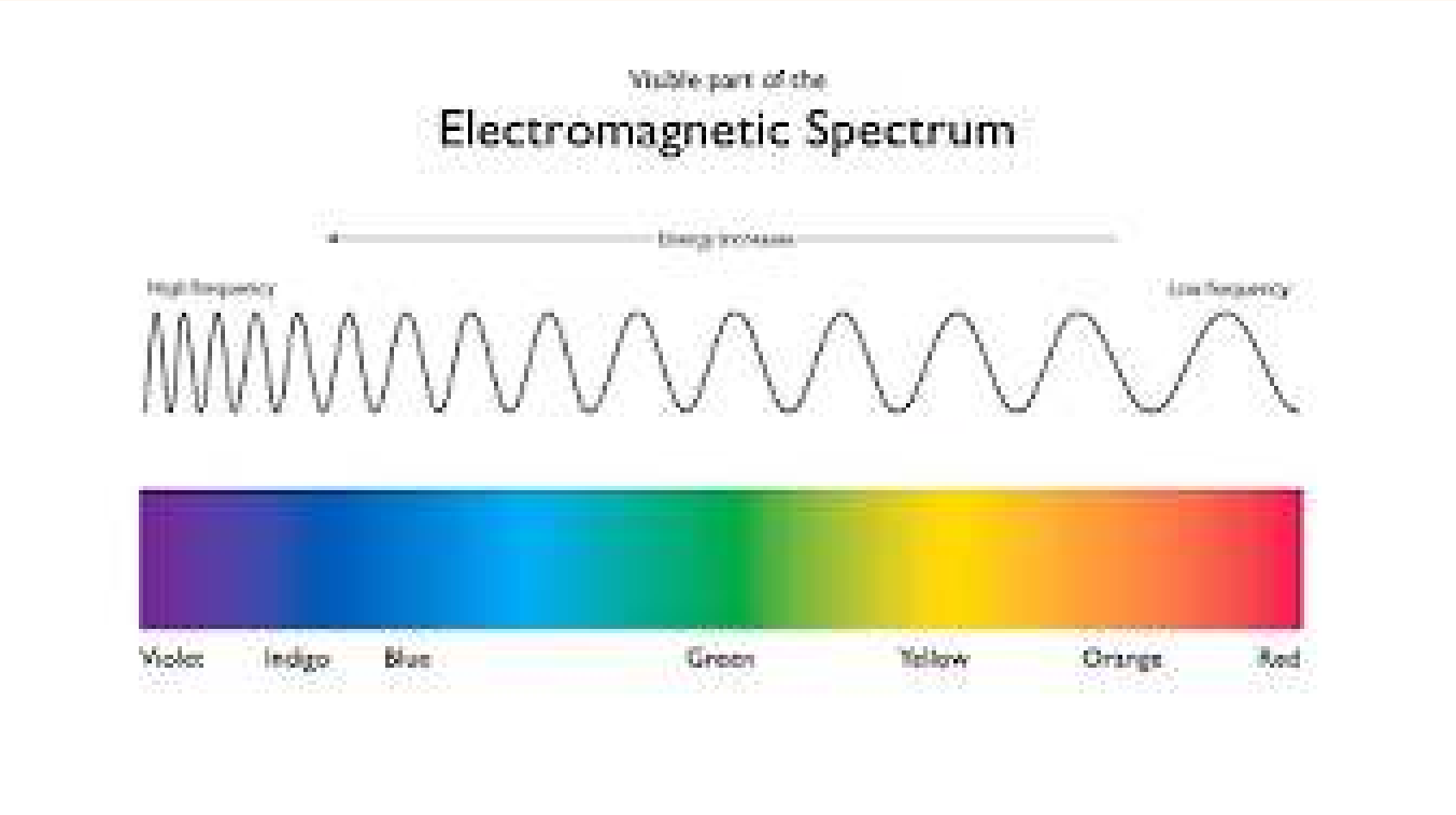
The Retina

The retina is composed of tiny antennae that resonate to the incoming light.

Rods handle vision in low light and sit near the periphery of the retina.

Cones handle color vision and detail. They are denser toward the fovea. There are three types, stimulated by low, intermediate, and high frequencies of light.

Color in Our World



Click here to watch video (2:20)

Conceptual Question 8

Which of the following is invisible to the human eye?

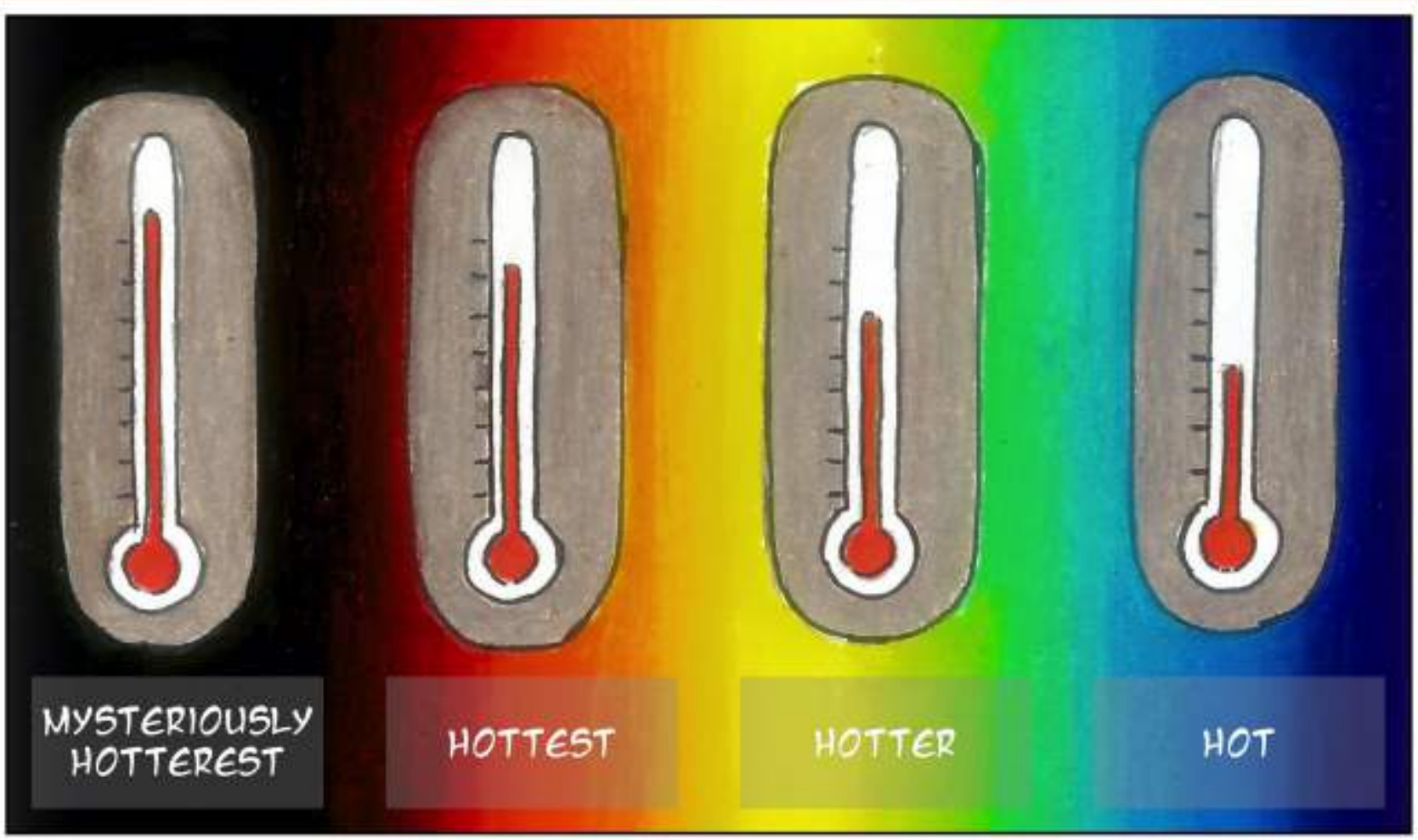
(a) Infrared radiation

(b) Ultraviolet radiation

(c) Both A and B are correct

(d) Neither A nor B is correct

Infrared Light



Selective Reflection

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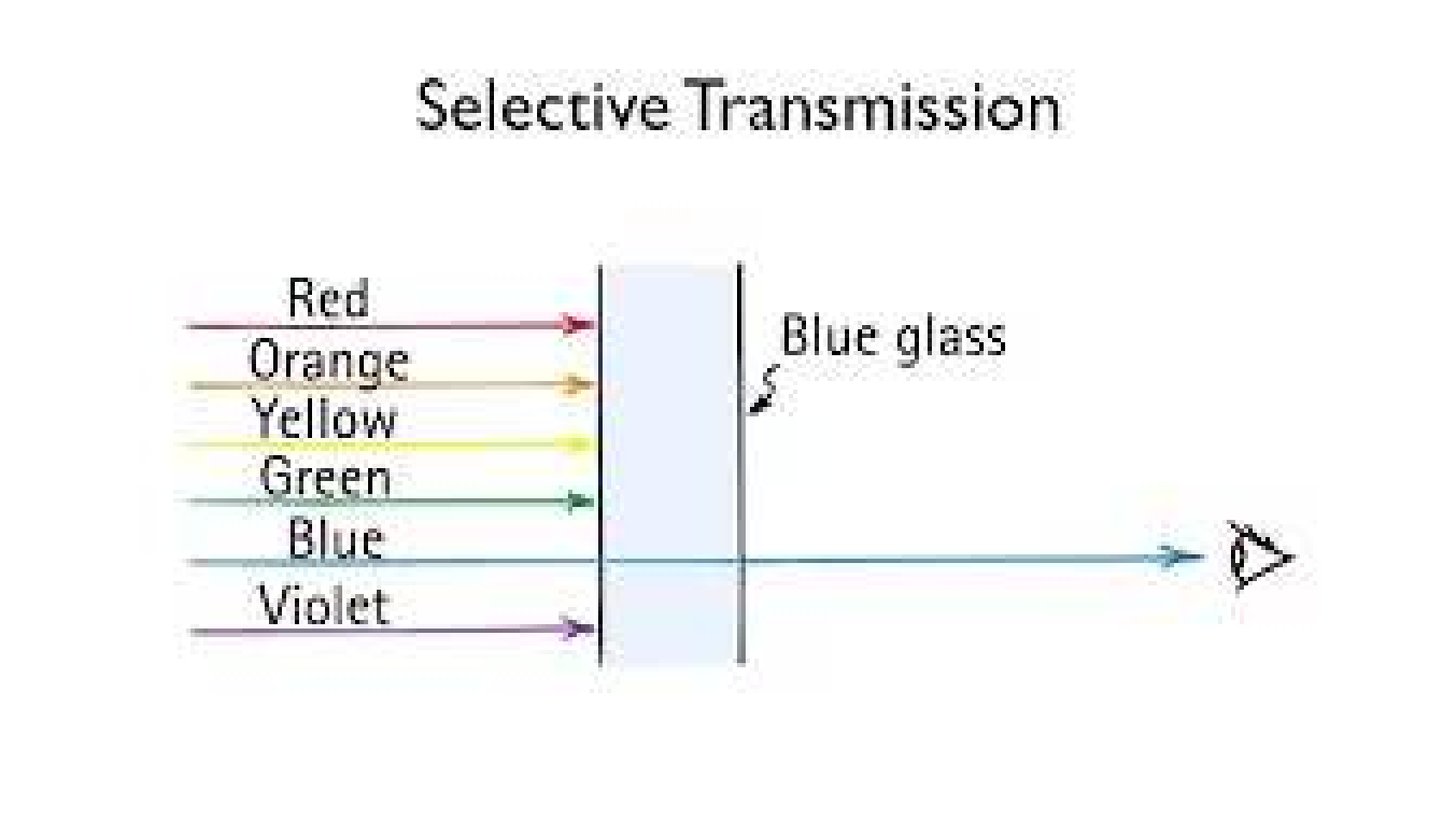
Selective Transmission



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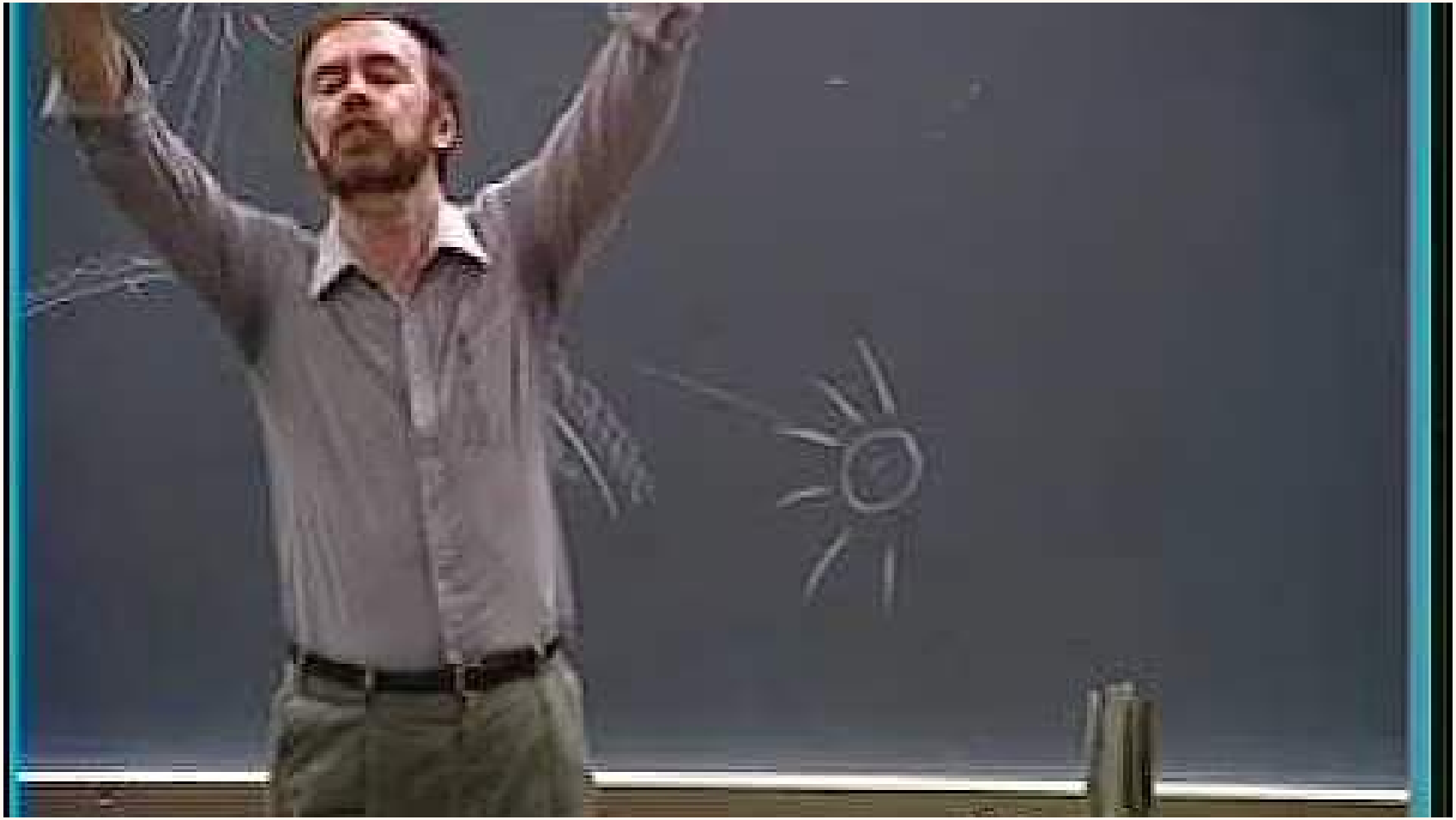
Why is the Sky Blue?



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Conceptual Question 9

Red, green, and blue light overlap to form

(a) red light

(b) green light

(c) blue light

(d) white light

Conceptual Question 10

When the color yellow is seen on your TV screen, the phosphors being activated on the screen are

(a) mainly yellow

(b) blue and red

(c) green and yellow

(d) red and green

Conceptual Question 11

A blue object will appear black when illuminated with

(a) blue light

(b) cyan light

(c) yellow light

(d) magenta light

Conceptual Question 12

A blue object will appear black when illuminated with

(a) blue light

(b) cyan light

(c) yellow light

(d) magenta light

Conceptual Question 13

A red rose will not appear red when illuminated only with

(a) red light

(b) orange light

(c) white light

(d) cyan light

Conceptual Question 14

A white sky is evidence that the atmosphere contains

(a) predominantly small particles

(b) predominantly large particles

(c) a mixture of particle sizes

(d) pollutants

Conceptual Question 15

A white sky is evidence that the atmosphere contains

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(c) a mixture of particle sizes

(d) pollutants

Conceptual Question 16

A variety of sunset colors is evidence for a variety of

(a) elements in the Sun

(b) apparent atmosphere thickness

(c) atmospheric particles

(d) primary colors

Conceptual Question 17

A variety of sunset colors is evidence for a variety of

(a) elements in the Sun

(b) apparent atmosphere thickness

(c) atmospheric particles

(d) primary colors

Conceptual Question 18

If molecules in the sky scattered orange light instead of blue light, sunsets would be

(a) orange

(b) yellow

(c) green

(d) blue