PHYS11 CH:15 The Invisible Rainbow

From Radio Waves to Gamma Rays

Mr. Gullo

December 2025

Outline

The Mystery

What if everything you see
is only 0.0035% of what exists?

The Mystery

What if everything you see
is only 0.0035% of what exists?

Visible light is a narrow sliver of electromagnetic radiation.

The Mystery

What if everything you see
is only 0.0035% of what exists?

Visible light is a narrow sliver of electromagnetic radiation.

The universe broadcasts in frequencies we cannot see.

Seeing the Unseeable

Seeing the Unseeable

The Mental Model

Fish eyes detect visible light. Our instruments detect the rest.

Learning Objectives

By the end of this lesson, you will be able to:

- **15.1:** Define the electromagnetic spectrum in terms of frequencies and wavelengths

Learning Objectives

By the end of this lesson, you will be able to:

- **15.1:** Define the electromagnetic spectrum in terms of frequencies and wavelengths
- **15.1:** Describe the differences and similarities of each section of the EM spectrum

Learning Objectives

By the end of this lesson, you will be able to:

- **15.1:** Define the electromagnetic spectrum in terms of frequencies and wavelengths
- **15.1:** Describe the differences and similarities of each section of the EM spectrum
- **15.1:** Explain applications of radiation from each section

15.1 The Source: Oscillating Charge

Nature's Broadcasting System

Electromagnetic radiation is generated by a moving electric charge.

15.1 The Source: Oscillating Charge

Nature's Broadcasting System

Electromagnetic radiation is generated by a moving electric charge.

What makes an EM wave:

- Electric current creates electric field E

15.1 The Source: Oscillating Charge

Nature's Broadcasting System

Electromagnetic radiation is generated by a moving electric charge.

What makes an EM wave:

- Electric current creates electric field E
- Electric current creates magnetic field B

15.1 The Source: Oscillating Charge

Nature's Broadcasting System

Electromagnetic radiation is generated by a moving electric charge.

What makes an EM wave:

- Electric current creates electric field E
- Electric current creates magnetic field B
- E and B perpendicular to each other

15.1 The Source: Oscillating Charge

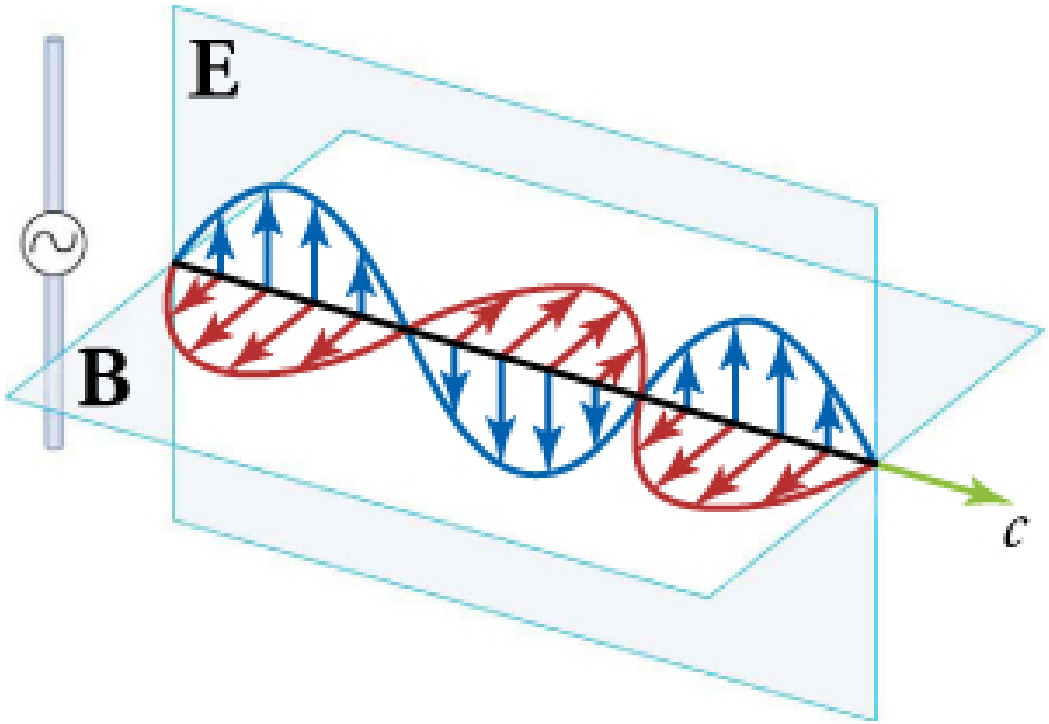
Nature's Broadcasting System

Electromagnetic radiation is generated by a moving electric charge.

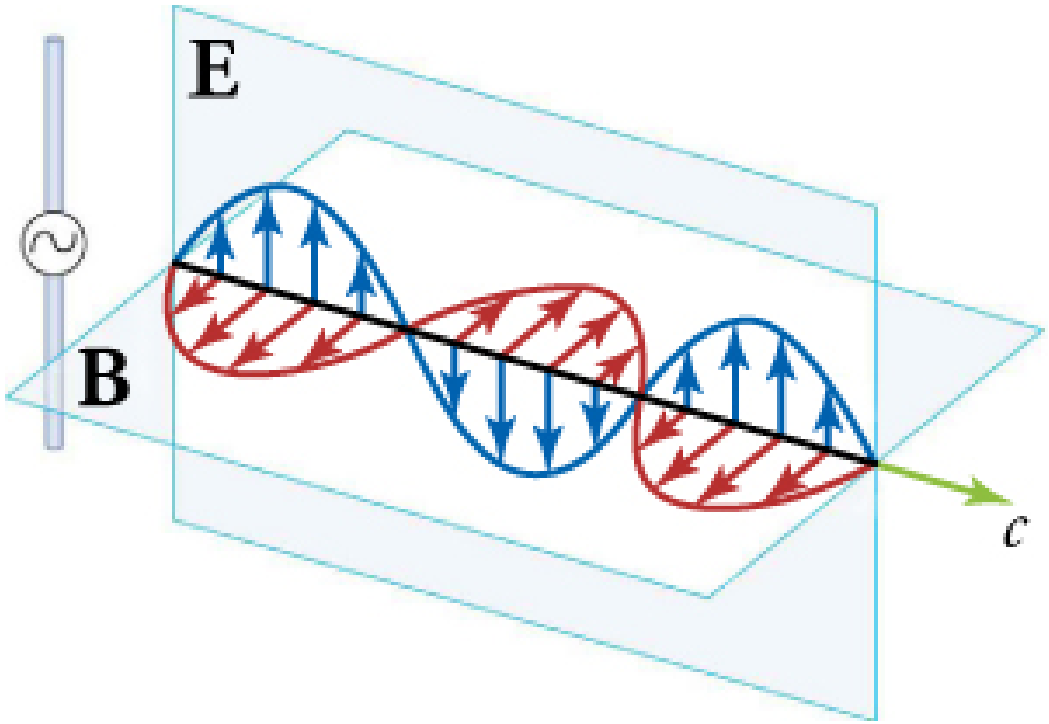
What makes an EM wave:

- Electric current creates electric field E
- Electric current creates magnetic field B
- E and B perpendicular to each other
- When charge oscillates, wave propagates

15.1 Anatomy of an EM Wave



15.1 Anatomy of an EM Wave



E and B fields oscillate in phase, perpendicular to each other and to direction of propagation.

15.1 Wave Properties Review

All waves share these features:

- **Wavelength** λ: Distance between two crests (meters)

15.1 Wave Properties Review

All waves share these features:

- **Wavelength** λ: Distance between two crests (meters)
- **Frequency** f: Number of crests passing per second (Hz)

15.1 Wave Properties Review

All waves share these features:

- **Wavelength** λ: Distance between two crests (meters)
- **Frequency** f: Number of crests passing per second (Hz)
- **Amplitude**: Height of crest above null point

15.1 Wave Properties Review

All waves share these features:

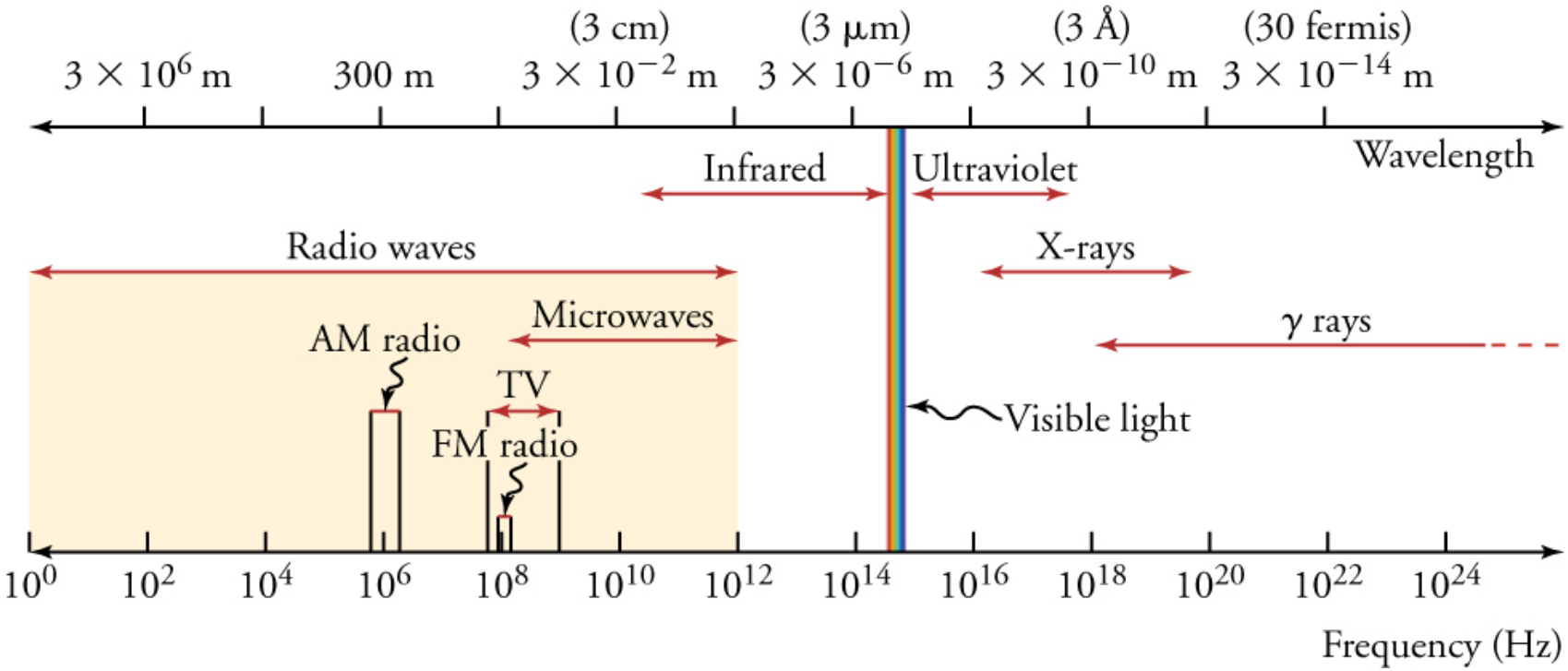
- **Wavelength** λ: Distance between two crests (meters)
- **Frequency** f: Number of crests passing per second (Hz)
- **Amplitude**: Height of crest above null point

Universal Law: The Speed of Light

$$\boxed{c = f\lambda}$$

Speed equals frequency times wavelength. $c = 3.00 \times 10^8$ m/s.

15.1 The Full Spectrum



15.1 Decoding the Spectrum

Low Frequency (IR):

- Radio waves
- Microwaves
- Infrared (heat)

15.1 Decoding the Spectrum

Low Frequency (IR):

- Radio waves
- Microwaves
- Infrared (heat)

High Frequency (UV):

- Ultraviolet
- X-rays
- Gamma rays

15.1 Decoding the Spectrum

Low Frequency (IR):

- Radio waves
- Microwaves
- Infrared (heat)

High Frequency (UV):

- Ultraviolet
- X-rays
- Gamma rays

The Mental Model

IR = below red. UV = beyond violet. Visible light in the middle.

15.1 The Intuition Trap

What Your Brain Gets Wrong

Misconception: Visible light is somehow different from other EM radiation.

Reality: All EM radiation is identical except for frequency and wavelength.

15.1 The Intuition Trap

What Your Brain Gets Wrong

Misconception: Visible light is somehow different from other EM radiation.

Reality: All EM radiation is identical except for frequency and wavelength.

Why we see visible light:

- Our eyes evolved to detect 400-700 nm wavelengths
- This is the frequency range that penetrates atmosphere
- Has nothing to do with the radiation itself

15.1 Radio Waves

Real-World: Broadcasting

- AM/FM radio, TV signals
- Cell phones, Wi-Fi
- Longest wavelengths, lowest frequencies

15.1 Radio Waves

Real-World: Broadcasting

- AM/FM radio, TV signals
- Cell phones, Wi-Fi
- Longest wavelengths, lowest frequencies

AM vs FM:

- AM: Amplitude Modulation (varies amplitude)
- FM: Frequency Modulation (varies frequency)

15.1 Microwaves

Real-World: Cooking and Radar

- Microwave ovens: frequency 2.45×10^9 Hz
- Cause polar molecules (water) to rotate
- Rotational energy becomes heat
- Radar: detect location and speed of objects

15.1 Microwaves

Real-World: Cooking and Radar

- Microwave ovens: frequency 2.45×10^9 Hz
- Cause polar molecules (water) to rotate
- Rotational energy becomes heat
- Radar: detect location and speed of objects

Doppler radar: Measures speed using frequency shift of reflected waves.

15.1 Infrared Radiation

Real-World: Heat

- What we feel as radiant heat
- Night-vision goggles detect body heat
- Remote controls use IR signals

15.1 Infrared Radiation

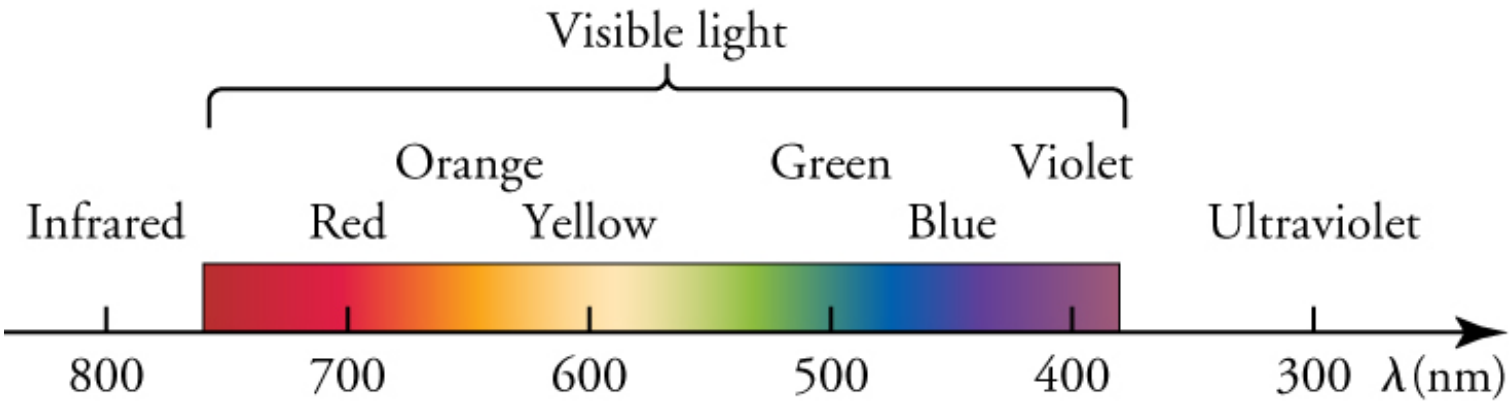
Real-World: Heat

- What we feel as radiant heat
- Night-vision goggles detect body heat
- Remote controls use IR signals

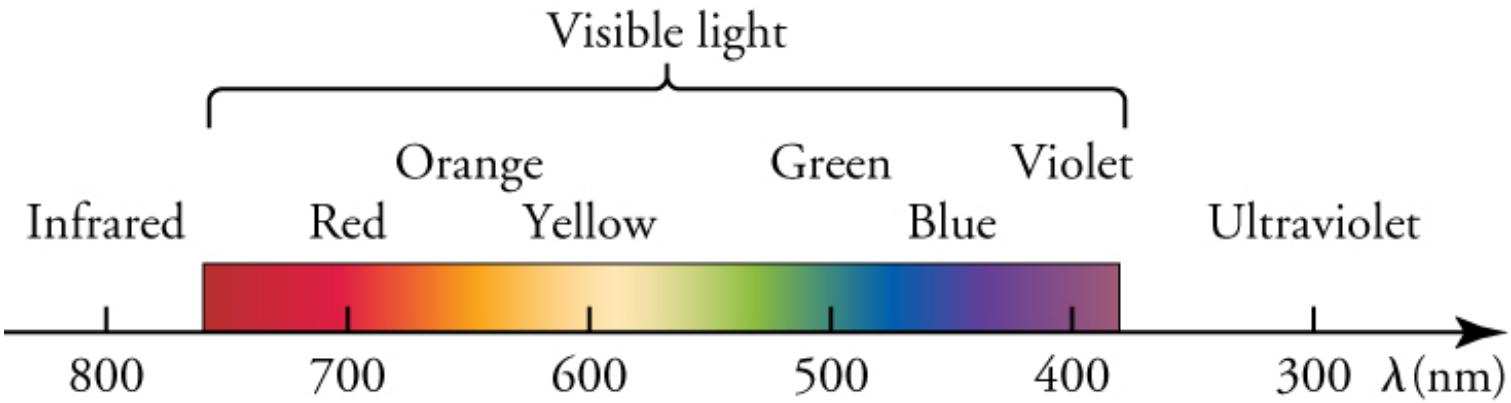
Misconception Alert

Heat waves are no different from other EM waves. We feel them as heat because their frequency interacts with our bodies to create thermal energy.

15.1 Visible Light



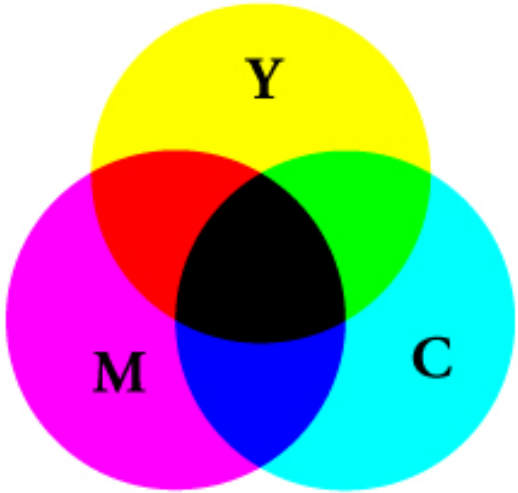
15.1 Visible Light



Wavelengths: 400-700 nm
Frequencies: 4.0×10^{14} to 7.9×10^{14} Hz

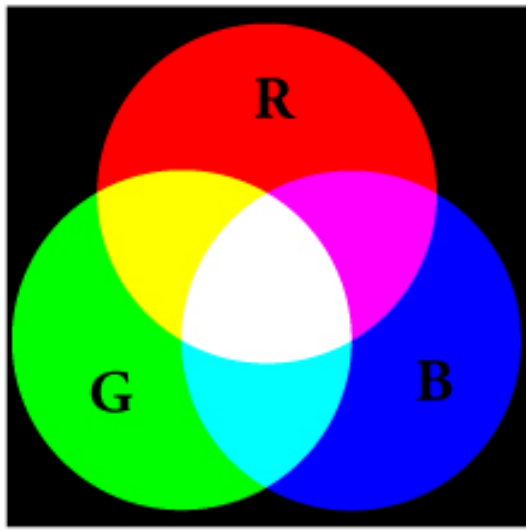
15.1 The Color Wheels

Pigment



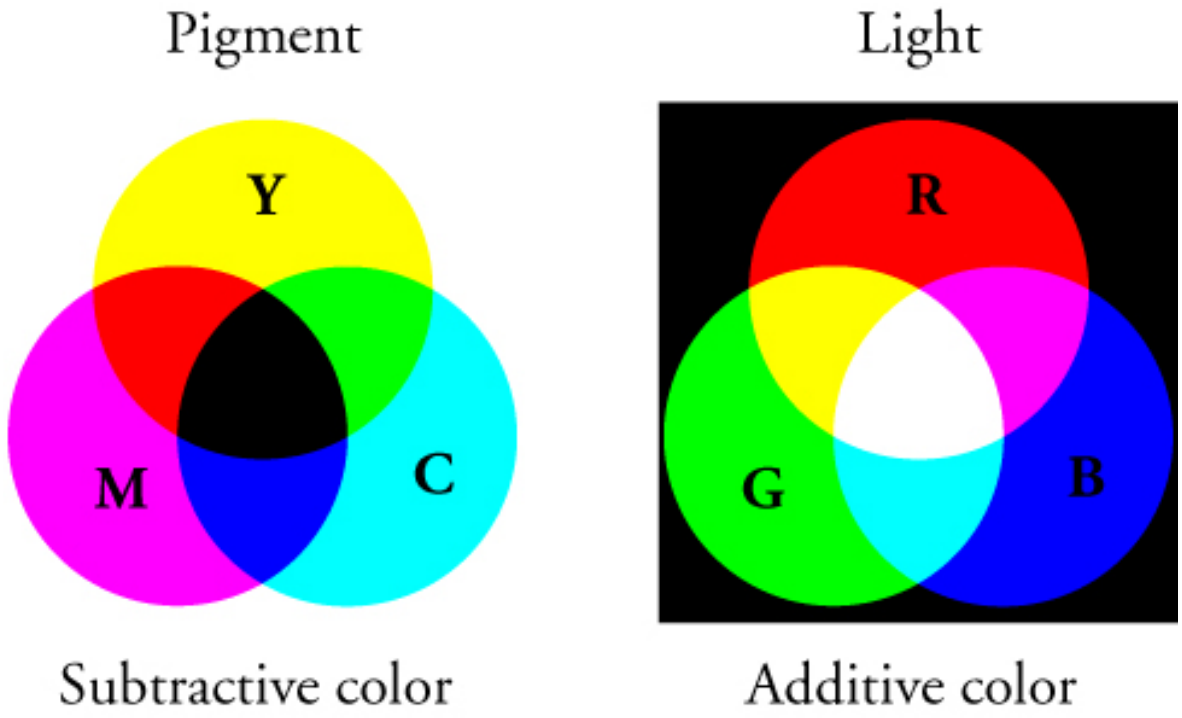
Subtractive color

Light



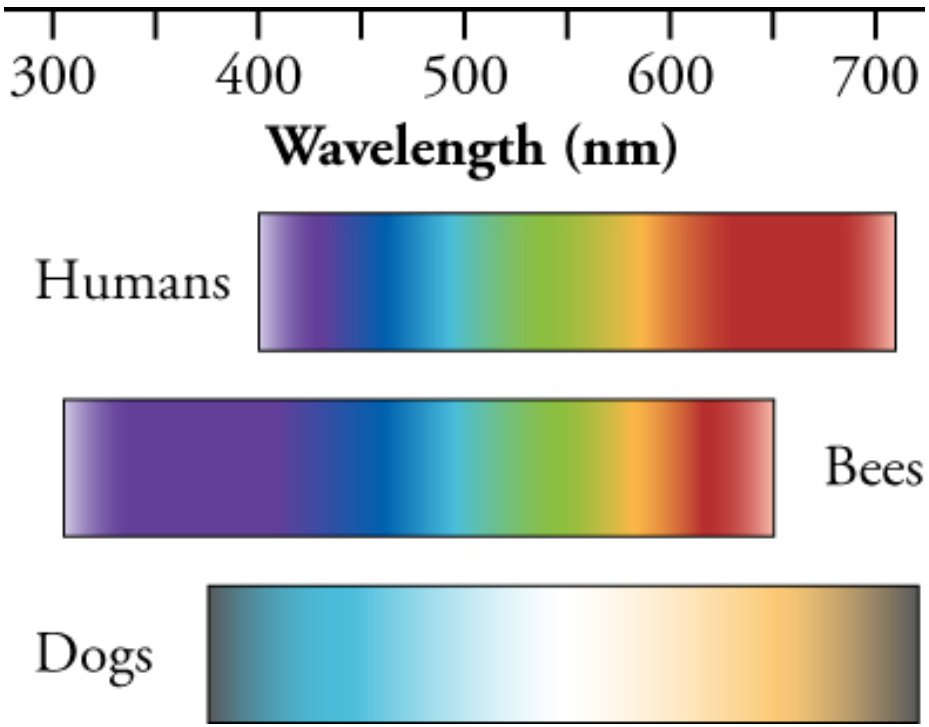
Additive color

15.1 The Color Wheels

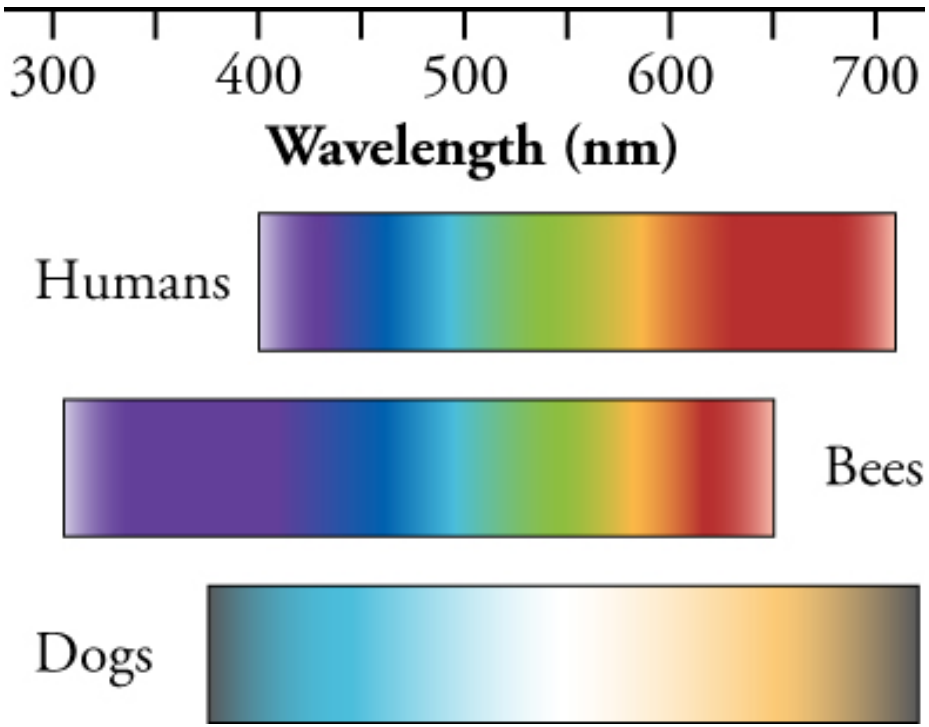


Subtractive (pigments): Cyan, Magenta, Yellow primaries $\rightarrow$ Black
Additive (light): Red, Green, Blue primaries $\rightarrow$ White

15.1 Animal Color Perception

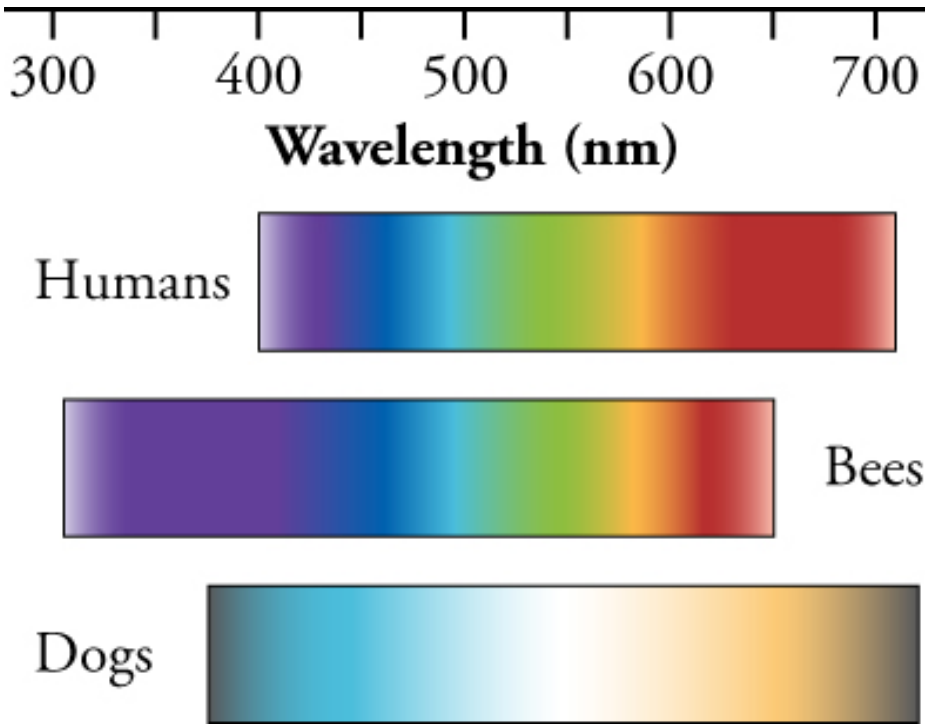


15.1 Animal Color Perception



Human vision: Three cones (red, green, blue)

15.1 Animal Color Perception

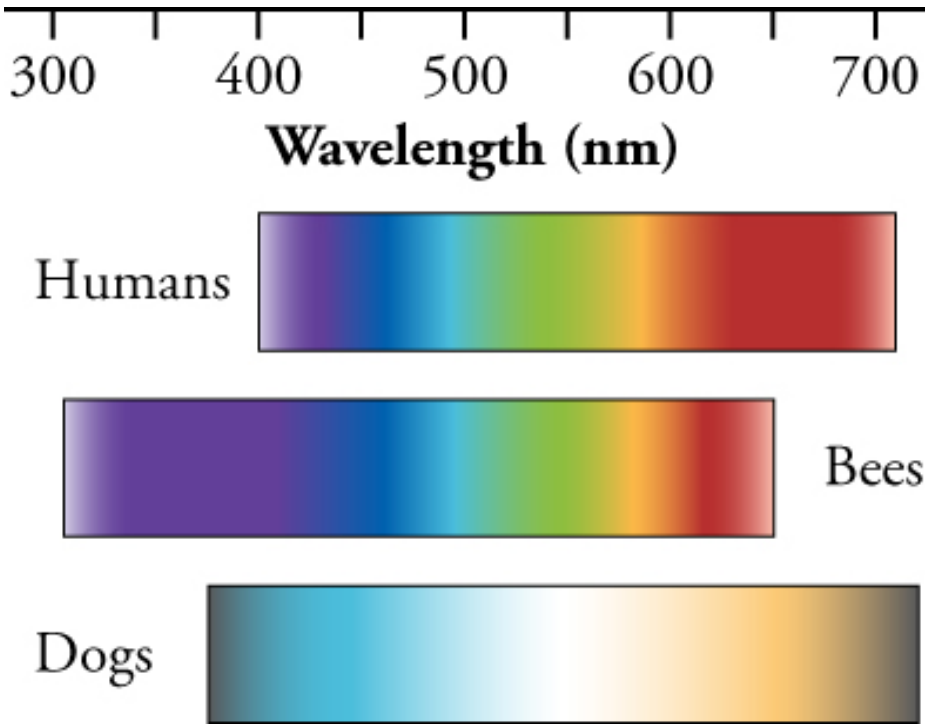


Human vision: Three cones (red, green, blue)

Other species:

- Most primates: 3 cones (like humans)

15.1 Animal Color Perception

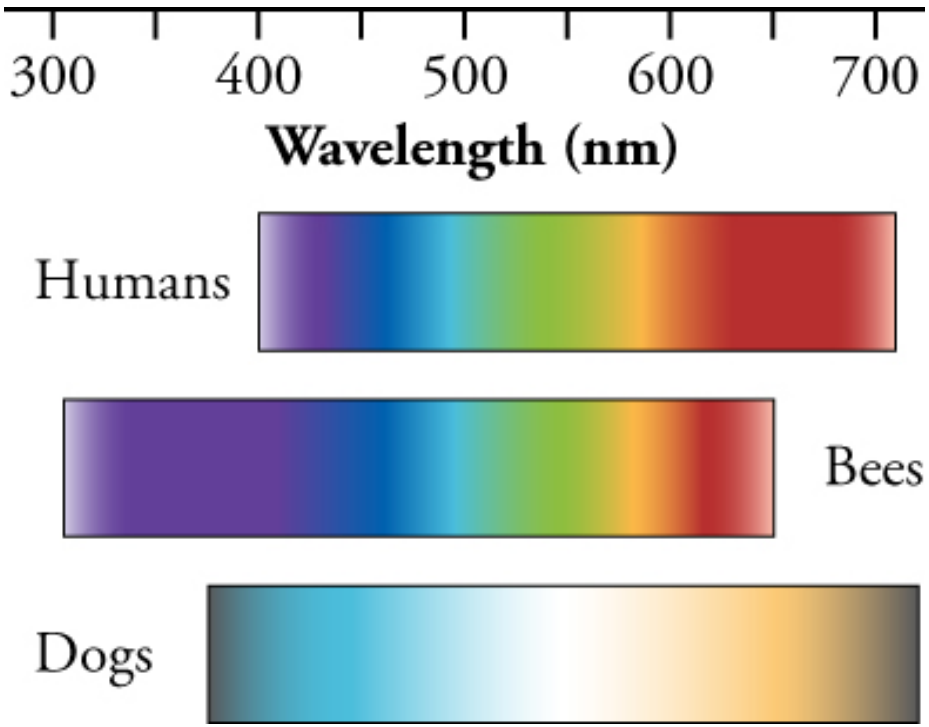


Human vision: Three cones (red, green, blue)

Other species:

- Most primates: 3 cones (like humans)
- Dogs: 2 cones (blue and yellow, colorblind to red/green)

15.1 Animal Color Perception

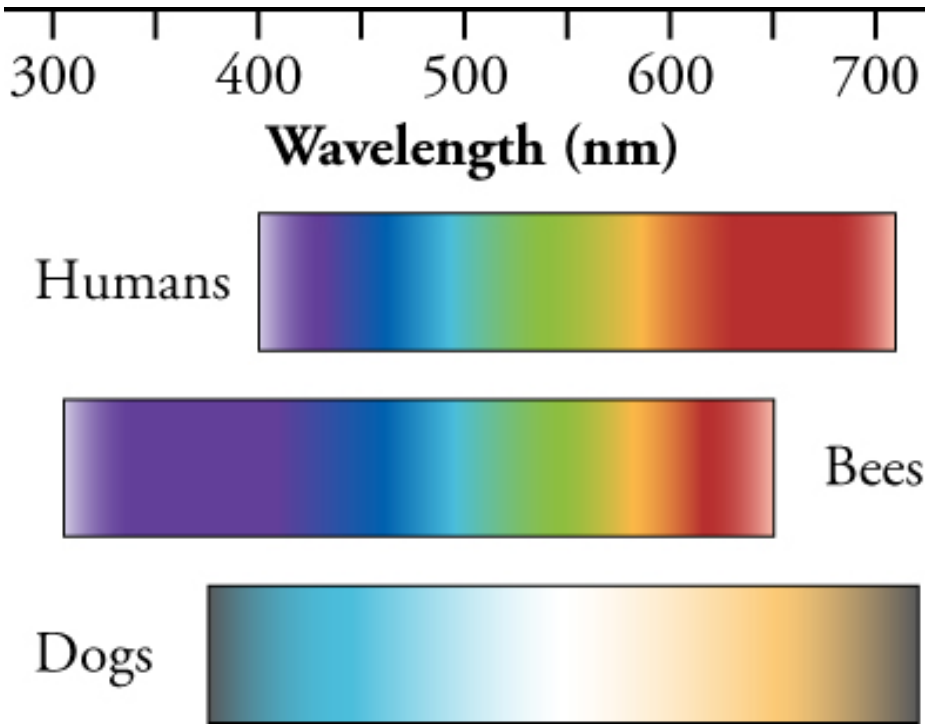


Human vision: Three cones (red, green, blue)

Other species:

- Most primates: 3 cones (like humans)
- Dogs: 2 cones (blue and yellow, colorblind to red/green)
- Birds, reptiles, insects: 4-5 cones (more hues)

15.1 Animal Color Perception

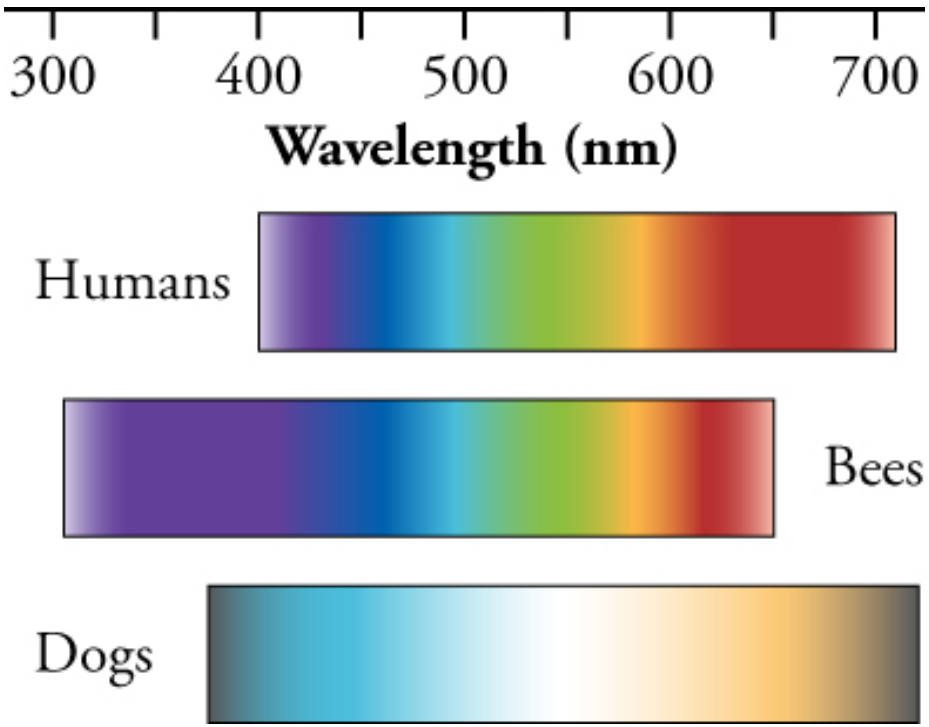


Human vision: Three cones (red, green, blue)

Other species:

- Most primates: 3 cones (like humans)
- Dogs: 2 cones (blue and yellow, colorblind to red/green)
- Birds, reptiles, insects: 4-5 cones (more hues)
- Bees: See UV; rattlesnakes: See IR

15.1 Animal Color Perception



Human vision: Three cones (red, green, blue)

Other species:

- Most primates: 3 cones (like humans)
- Dogs: 2 cones (blue and yellow, colorblind to red/green)
- Birds, reptiles, insects: 4-5 cones (more hues)
- Bees: See UV; rattlesnakes: See IR

15.1 Ultraviolet Radiation

Real-World: Sun and Sterilization

- Sunlight contains UV (causes sunburn)
- Kills bacteria (UV sterilization)
- Black lights, counterfeit detection

15.1 Ultraviolet Radiation

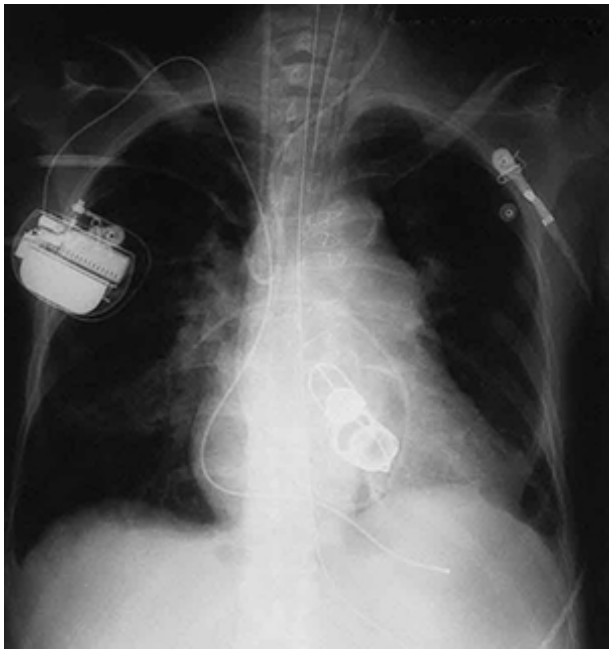
Real-World: Sun and Sterilization

- Sunlight contains UV (causes sunburn)
- Kills bacteria (UV sterilization)
- Black lights, counterfeit detection

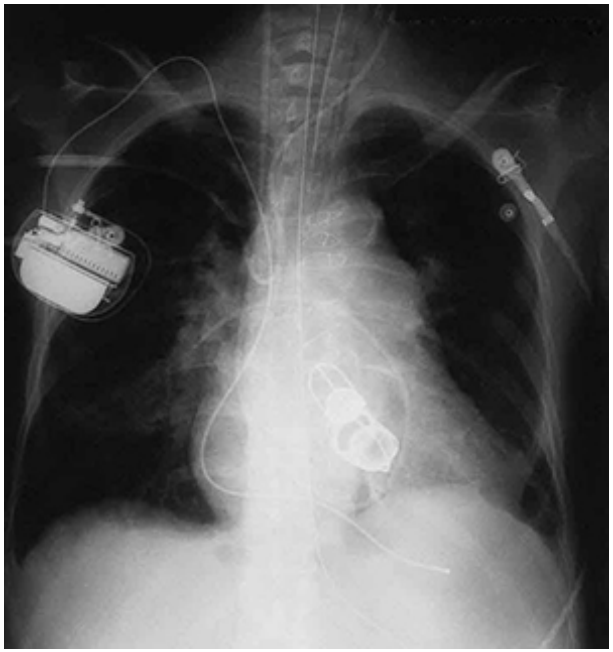
Health Hazard

UV radiation damages cells. Higher energy than visible light. Always use sunscreen!

15.1 X-Rays



15.1 X-Rays



Very high energy, very penetrating
Applications:

- Medical imaging (see bones)
- Airport security scanners

15.1 Gamma Rays

Highest energy, most penetrating EM radiation

15.1 Gamma Rays

Highest energy, most penetrating EM radiation

Sources:

- Radioactive decay
- Nuclear reactions
- Cosmic rays from space

15.1 Gamma Rays

Highest energy, most penetrating EM radiation

Sources:

- Radioactive decay
- Nuclear reactions
- Cosmic rays from space

Applications:

- Cancer treatment (radiation therapy)
- Sterilization of medical equipment

15.1 Gamma Rays

Highest energy, most penetrating EM radiation

Sources:

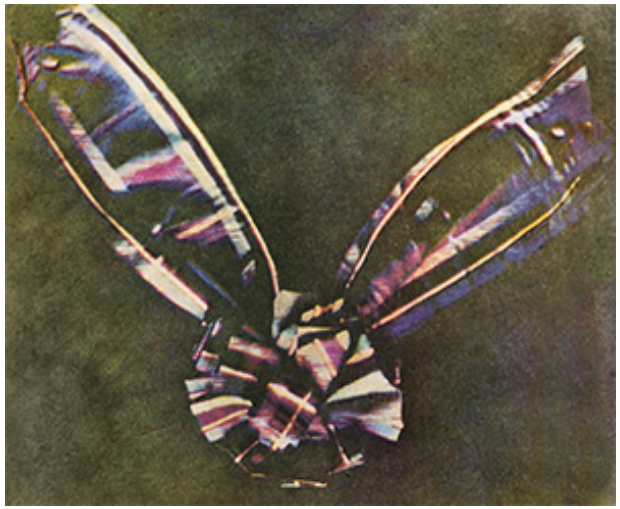
- Radioactive decay
- Nuclear reactions
- Cosmic rays from space

Applications:

- Cancer treatment (radiation therapy)
- Sterilization of medical equipment

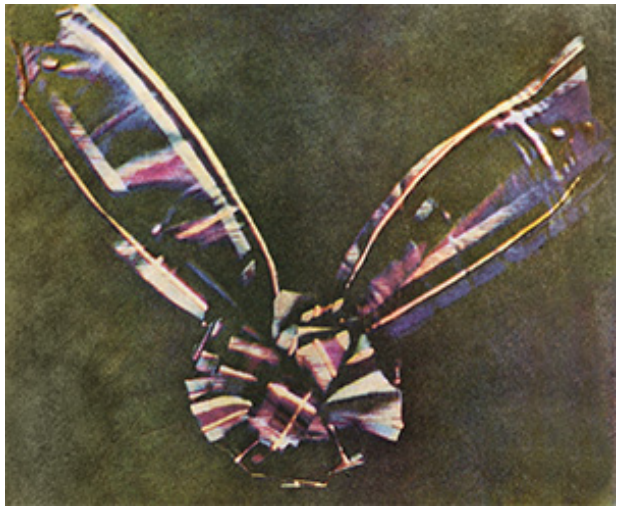
Extremely dangerous - ionizing radiation damages DNA

15.1 Maxwell's Unification



James Clerk Maxwell (1831-1879)

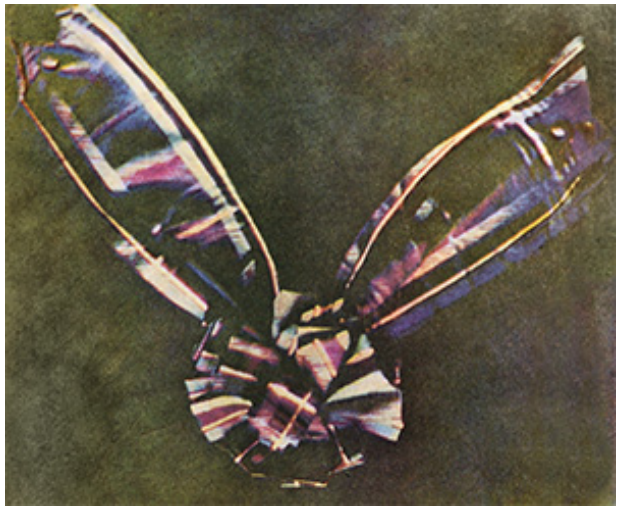
15.1 Maxwell's Unification



James Clerk Maxwell (1831-1879)

Achievement: Unified electricity and magnetism into electromagnetism

15.1 Maxwell's Unification



James Clerk Maxwell (1831-1879)

Achievement: Unified electricity and magnetism into electromagnetism

Electric and magnetic forces are two manifestations of the same thing - the electromagnetic force

Learning Objectives

By the end of this section, you will be able to:

- **15.2:** Describe the behavior of electromagnetic radiation

Learning Objectives

By the end of this section, you will be able to:

- **15.2:** Describe the behavior of electromagnetic radiation
- **15.2:** Solve quantitative problems involving EM radiation

15.2 The Universal Speed Limit

Nature's Law: Speed of Light

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

All EM radiation travels at this speed in a vacuum. 671 million mph. Constant everywhere in the universe.

15.2 The Universal Speed Limit

Nature's Law: Speed of Light

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

All EM radiation travels at this speed in a vacuum. 671 million mph. Constant everywhere in the universe.

Cosmic distances:

- Sun to Earth: 8.3 minutes
- Nearest star: 4.2 years
- Nearest galaxy: 25,000 years

15.2 Light in Different Media

In vacuum: $c = 3.00 \times 10^8$ m/s

15.2 Light in Different Media

In vacuum: $c = 3.00 \times 10^8$ m/s

In other materials (slower):

- Air: 99.97% of c
- Water: 75% of c
- Diamond: 41% of c

15.2 Light in Different Media

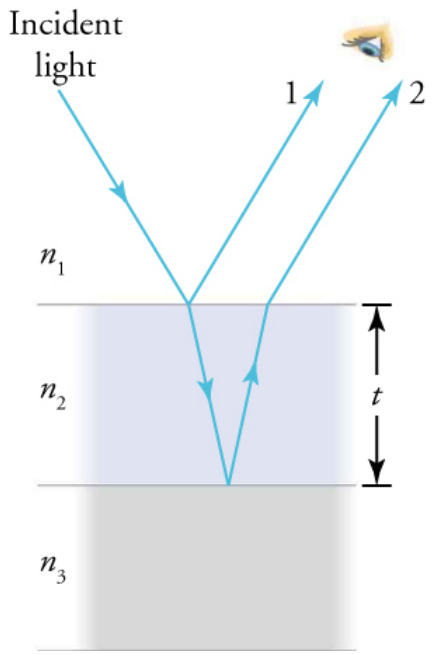
In vacuum: $c = 3.00 \times 10^8$ m/s

In other materials (slower):

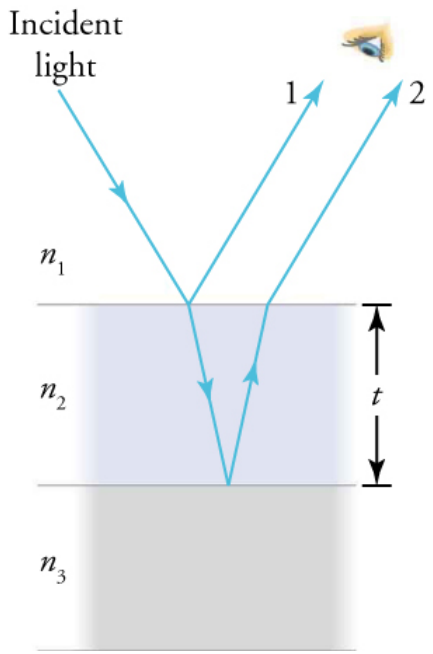
- Air: 99.97% of c
- Water: 75% of c
- Diamond: 41% of c

When light changes speed at boundary, it changes direction. This is called **refraction**.

15.2 Thin-Film Interference



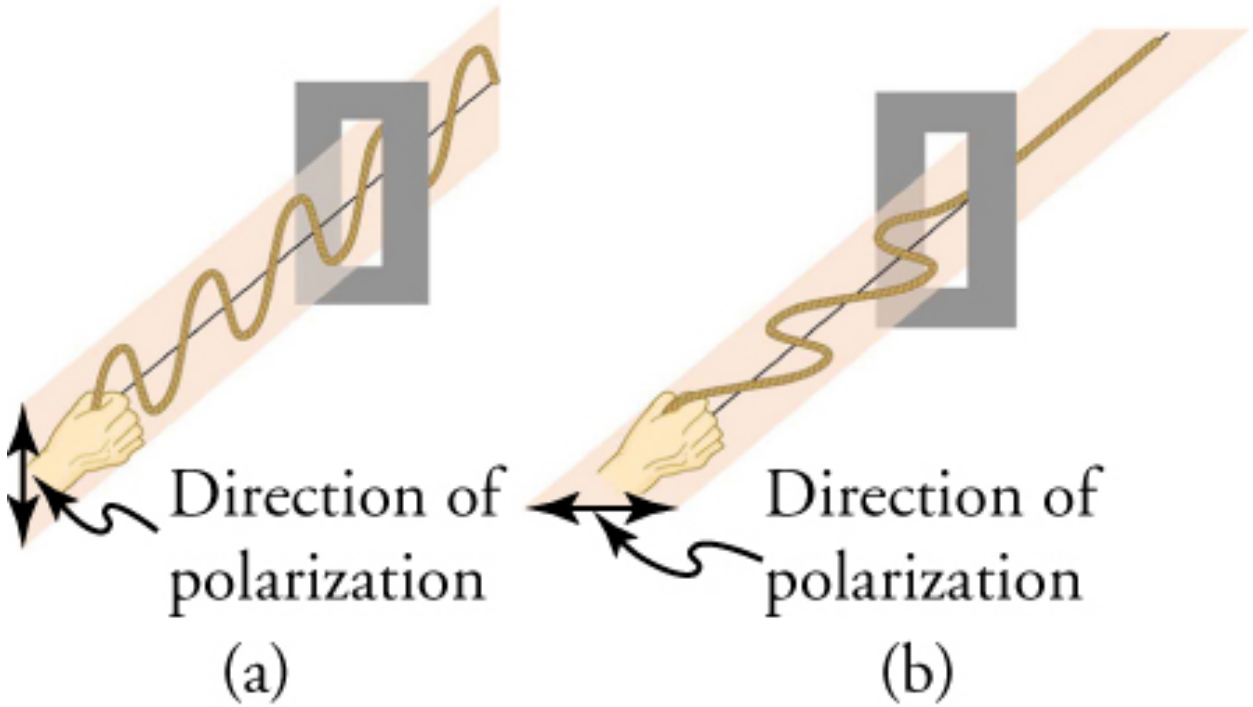
15.2 Thin-Film Interference



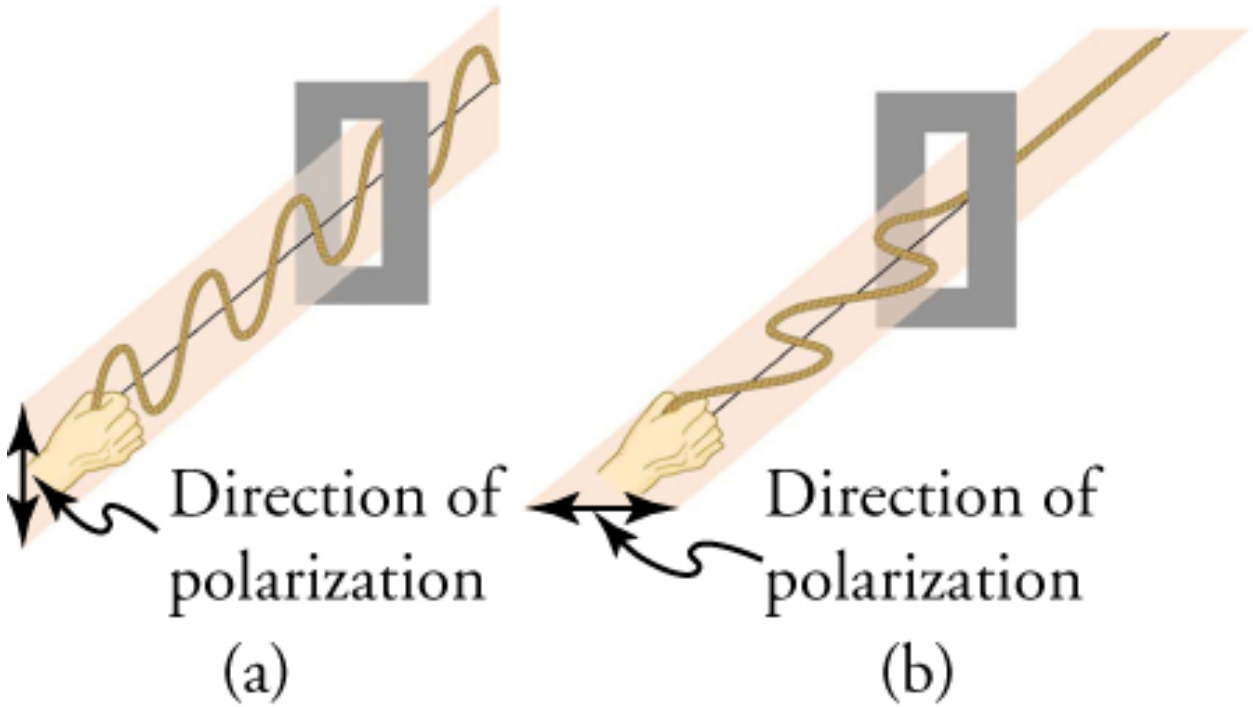
Rainbow colors from: Soap bubbles, oil slicks, CDs

Cause: Light reflects from top and bottom of thin film, waves interfere

15.2 Polarization



15.2 Polarization



Polarized light: Electric field vibrates in only one direction
Polarizing filter: Transmits one direction, blocks others

15.2 Polarized Sunglasses

(a) (b)

15.2 Polarized Sunglasses

(a) (b)

How they work: Block horizontally polarized light (glare from water/glass)
Result: Reduced glare, clearer vision

Attempt: Decoding Yellow Light

The Challenge (3 min, silent)

Yellow light has a wavelength of $\lambda = 6.00 \times 10^{-7}$ m.

Given:

- $\lambda = 6.00 \times 10^{-7}$ m
- $c = 3.00 \times 10^{8}$ m/s

Find: Frequency f in Hz

Can you calculate the frequency? Work silently.

Compare: Wave Equation

Turn and talk (2 min):

1. What equation relates c, f, and λ?
2. How did you rearrange to solve for f?
3. Did you divide or multiply?

Compare: Wave Equation

Turn and talk (2 min):

1. What equation relates c, f, and λ?
2. How did you rearrange to solve for f?
3. Did you divide or multiply?

Name wheel: One pair share your approach (not your answer).

Reveal: Frequency of Yellow Light

Self-correct in a different color:

Equation: $c = f\lambda$

Reveal: Frequency of Yellow Light

Self-correct in a different color:

Equation: $c = f\lambda$

Rearrange: $f = \frac{c}{\lambda}$

Reveal: Frequency of Yellow Light

Self-correct in a different color:

Equation: $c = f\lambda$

Rearrange: $f = \frac{c}{\lambda}$

Substitute: $f = \frac{3.00\times10^{8}\ \text{m/s}}{6.00\times10^{-7}\ \text{m}}$

Reveal: Frequency of Yellow Light

Self-correct in a different color:

Equation: $c = f\lambda$

Rearrange: $f = \frac{c}{\lambda}$

Substitute: $f = \frac{3.00\times10^{8}\ \text{m/s}}{6.00\times10^{-7}\ \text{m}}$

$$\boxed{f = 5.00 \times 10^{14}\ \text{Hz}}$$

Reveal: Frequency of Yellow Light

Self-correct in a different color:

Equation: $c = f\lambda$

Rearrange: $f = \frac{c}{\lambda}$

Substitute: $f = \frac{3.00\times10^{8}\ \text{m/s}}{6.00\times10^{-7}\ \text{m}}$

$$\boxed{f = 5.00 \times 10^{14}\ \text{Hz}}$$

Check: 10^{14} Hz is in visible range. Reasonable!

15.2 Illuminance: Light Intensity

Luminous flux P: Rate light radiates from source (lumens, lm)

15.2 Illuminance: Light Intensity

Luminous flux P: Rate light radiates from source (lumens, lm)

Illuminance: Lumens per square meter (lux, lx)

15.2 Illuminance: Light Intensity

Luminous flux P: Rate light radiates from source (lumens, lm)

Illuminance: Lumens per square meter (lux, lx)

Universal Law: Inverse Square Law

$$\text{Illuminance} = \frac{P}{4\pi r^2}$$

Light intensity decreases with square of distance.

Attempt: Reading Light

The Challenge (3 min, silent)

A floor lamp has luminous flux of 2000 lm. You hold a book 2.00 m from the bulb.

Given:

- $P = 2000$ lm
- $r = 2.00$ m
- $\pi = 3.14$

Find: Illuminance in lux

Can you calculate the illuminance? Work silently.

Compare: Inverse Square Law

Turn and talk (2 min):

1. What equation did you use?
2. What goes in the denominator?
3. Did you square the radius?

Compare: Inverse Square Law

Turn and talk (2 min):

1. What equation did you use?
2. What goes in the denominator?
3. Did you square the radius?

Name wheel: One pair share your approach (not your answer).

Reveal: Illuminance Calculation

Self-correct in a different color:

Equation: Illuminance $= \frac{P}{4\pi r^2}$

Reveal: Illuminance Calculation

Self-correct in a different color:

Equation: $\text{Illuminance} = \frac{P}{4\pi r^2}$

Substitute: $\text{Illuminance} = \frac{2000\ \text{lm}}{4(3.14)(2.00)^2\ \text{m}^2}$

Reveal: Illuminance Calculation

Self-correct in a different color:

Equation: $\text{Illuminance} = \frac{P}{4\pi r^2}$

Substitute: $\text{Illuminance} = \frac{2000 \text{ lm}}{4(3.14)(2.00)^2 \text{ m}^2}$

Calculate: $\text{Illuminance} = \frac{2000}{50.24}$

Reveal: Illuminance Calculation

Self-correct in a different color:

Equation: $\text{Illuminance} = \frac{P}{4\pi r^2}$

Substitute: $\text{Illuminance} = \frac{2000 \text{ lm}}{4(3.14)(2.00)^2 \text{ m}^2}$

Calculate: $\text{Illuminance} = \frac{2000}{50.24}$

$$\boxed{\text{Illuminance} = 39.8 \text{ lx}}$$

Reveal: Illuminance Calculation

Self-correct in a different color:

Equation: $\text{Illuminance} = \frac{P}{4\pi r^2}$

Substitute: $\text{Illuminance} = \frac{2000 \text{ lm}}{4(3.14)(2.00)^2 \text{ m}^2}$

Calculate: $\text{Illuminance} = \frac{2000}{50.24}$

$$\boxed{\text{Illuminance} = 39.8 \text{ lx}}$$

Check: At 3 m, illuminance drops to 17.7 lx. Light fades rapidly!

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)
2. Visible light = tiny sliver of what exists

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)
2. Visible light = tiny sliver of what exists
3. E and B fields oscillate perpendicular to propagation

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)
2. Visible light = tiny sliver of what exists
3. E and B fields oscillate perpendicular to propagation
4. $c = 3.00 \times 10^8$ m/s in vacuum (constant)

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)
2. Visible light = tiny sliver of what exists
3. E and B fields oscillate perpendicular to propagation
4. $c = 3.00 \times 10^8$ m/s in vacuum (constant)
5. Higher frequency = higher energy = more penetrating

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)
2. Visible light = tiny sliver of what exists
3. E and B fields oscillate perpendicular to propagation
4. $c = 3.00 \times 10^8$ m/s in vacuum (constant)
5. Higher frequency = higher energy = more penetrating
6. Polarization = E field vibrates in one direction

What You Now Know

The Revelations

1. EM spectrum = radio to gamma rays (same physics)
2. Visible light = tiny sliver of what exists
3. E and B fields oscillate perpendicular to propagation
4. $c = 3.00 \times 10^8$ m/s in vacuum (constant)
5. Higher frequency = higher energy = more penetrating
6. Polarization = E field vibrates in one direction
7. Illuminance decreases with inverse square of distance

Key Equations

$$c = f\lambda \tag{1}$$

$$c = 3.00 \times 10^8 \text{ m/s} \tag{2}$$

$$f = \frac{c}{\lambda} \tag{3}$$

$$\lambda = \frac{c}{f} \tag{4}$$

$$\text{Illuminance} = \frac{P}{4\pi r^2} \tag{5}$$

Homework

Complete the assigned problems

posted on the LMS

Temporary page!

LaTeX was unable to guess the total number of pages correctly. A
was some unprocessed data that should have been added to the
this extra page has been added to receive it.
If you rerun the document (without altering it) this surplus page
away, because LaTeX now knows how many pages to expect for t
document.