# Maxwell's Equations

$$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$$

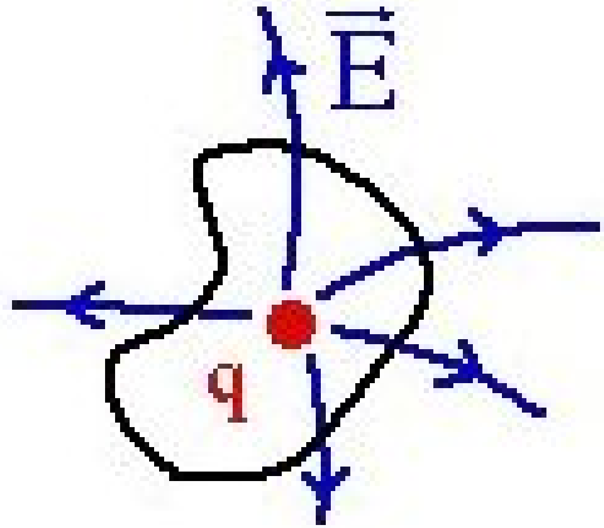
$$\oint \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I + \frac{1}{c^2}\frac{\partial}{\partial t}\int \vec{E} \cdot d\vec{A}$$

Maxwell's Equations

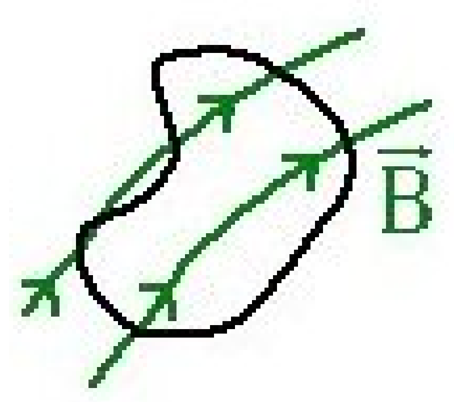
$$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$$




Number of field lines penetrating a closed surface is proportional to the amount of charge contained within the surface

Maxwell's Equations

$$\oint \vec{B} \cdot d\vec{A} = 0$$

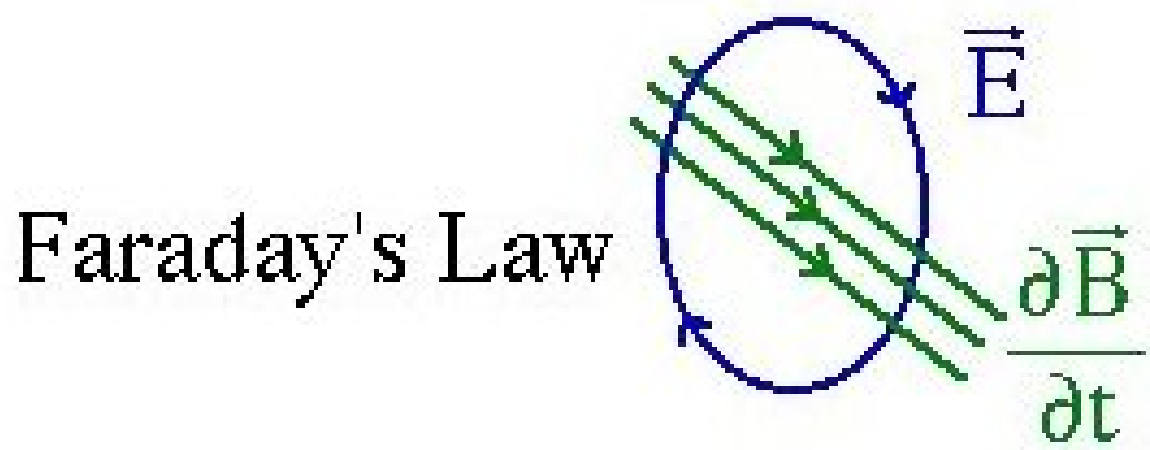



There are no magnetic monopoles…so you can't draw a closed surface that contains one.

# Maxwell's Equations

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

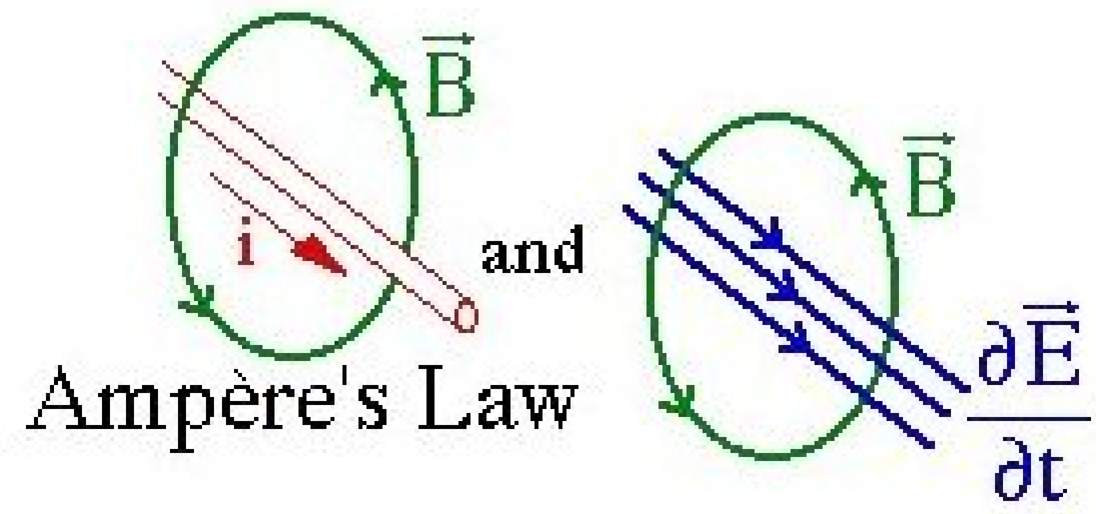
Magnetic Flux




A time-varying magnetic field produces an circulation in the electric field.

Maxwell's Equations

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I + \frac{1}{c^2} \frac{\partial}{\partial t} \int \vec{E} \cdot d\vec{A}$$




Current causes a magnetic field. And a time-varying electric field produces a magnetic field the same way that a time-varying magnetic field produces an electric field.

Maxwell's Equations

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I + \frac{1}{c^2} \frac{\partial}{\partial t} \int \vec{E} \cdot d\vec{A}$$

$$c = \frac{1}{\mu_0 \varepsilon_0}$$

Where 'c' is a constant that depends only on electrical permittivity and magnetic permeability.

# Quick Quiz 72a

A bullet is fired from a horizontal gun at a height ‘L’ above the ground. At the same time as the bullet leaves the muzzle of the gun, another bullet is dropped vertically from height ‘L’. Which bullet hits the ground first?

**A. The shot bullet**

**B. The dropped bullet**

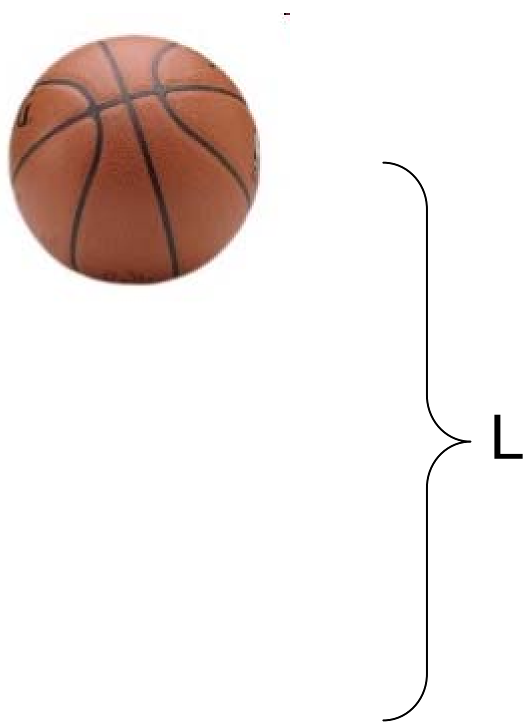
**C. Both hit at the same time**

# Quick Quiz 72b

A bullet is fired from a horizontal gun at a height 'L' above the ground. At the same time as the bullet leaves the muzzle of the gun, another bullet is dropped vertically from height 'L'. Which bullet has the larger velocity just before hitting the ground?

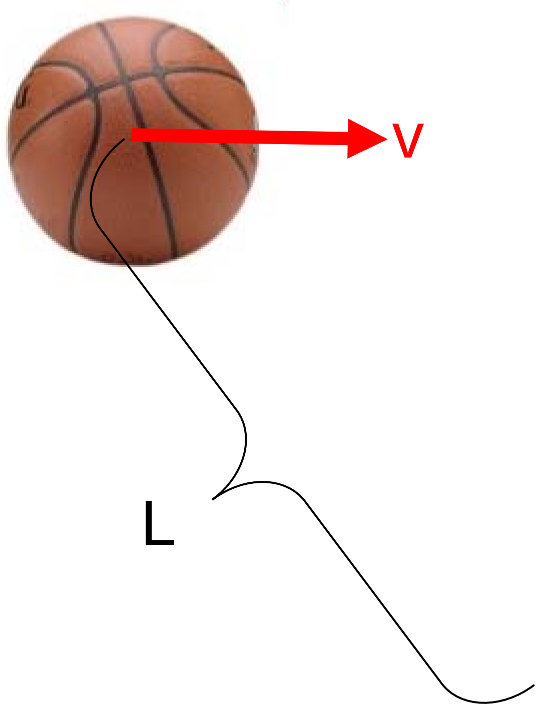
A. **The shot bullet**
B. **The dropped bullet**
C. **Both hit at the same time**

# Implications of a constant ‘c’



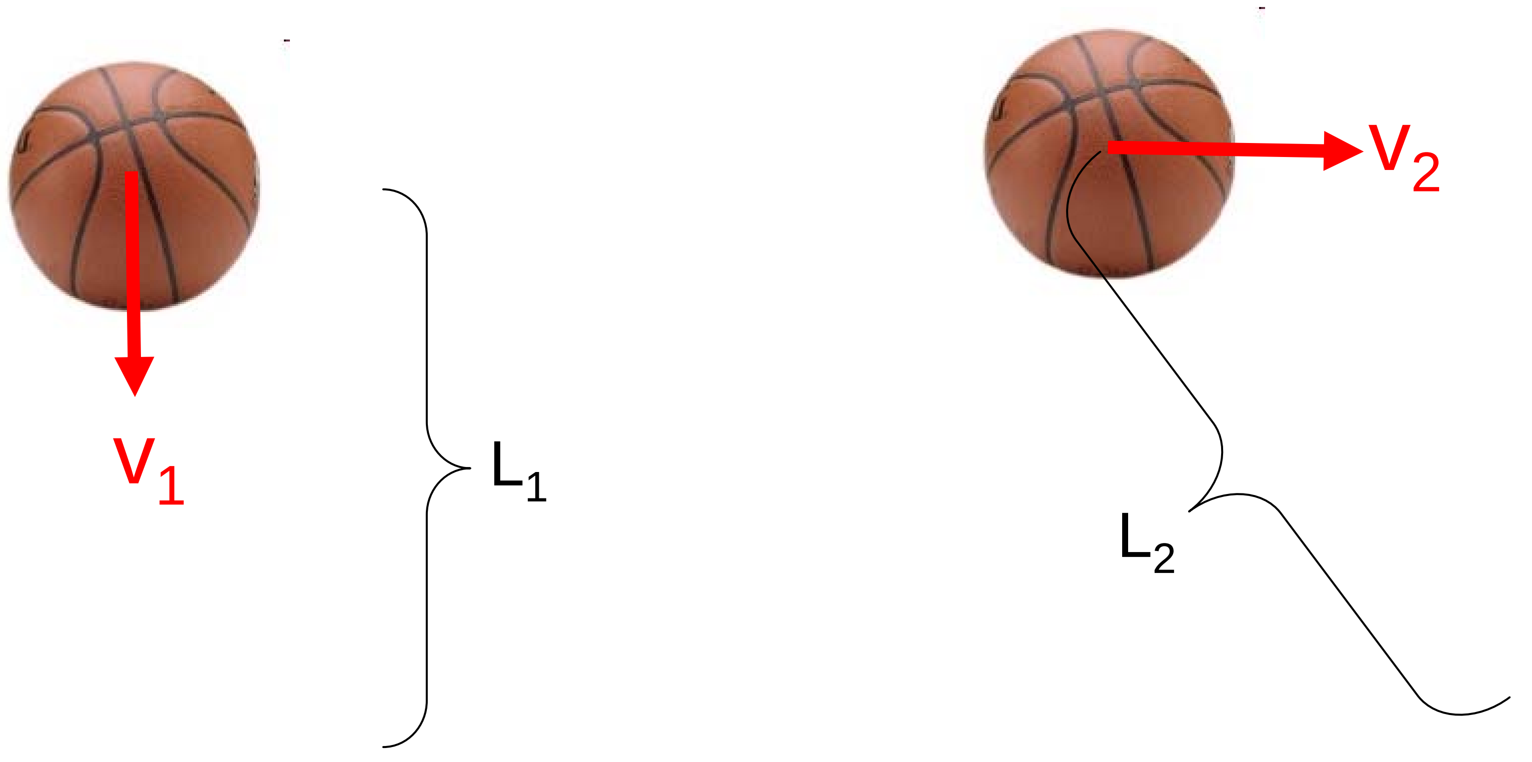

A ball falling at a constant speed ’v’ takes time t = L / v to fall a distance ‘L’.

# Implications of a constant 'c'



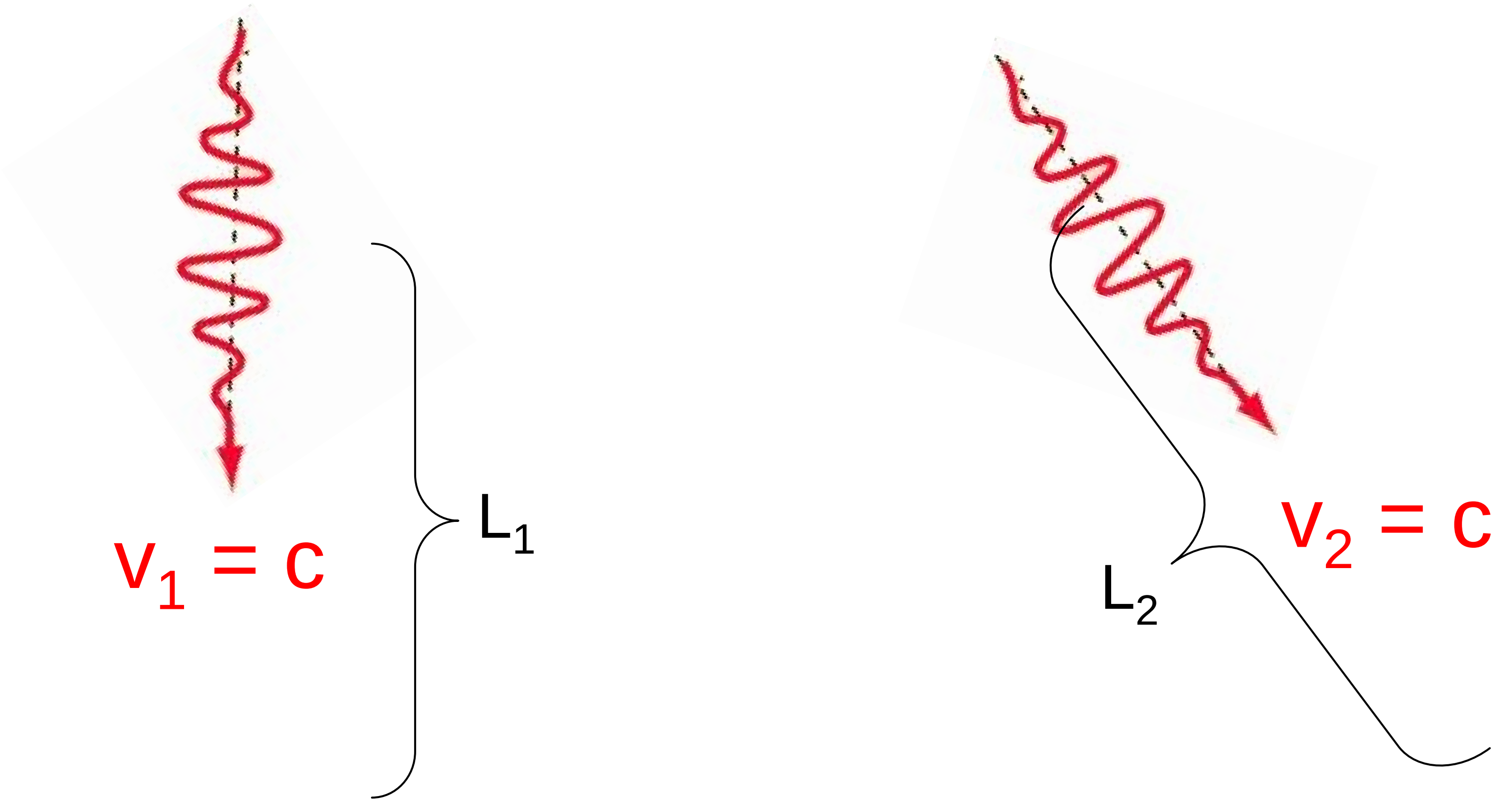

If the ball is falling at a constant speed while moving horizontally at a constant speed, it travels further at the same speed. But t = L / v still holds true…L is just bigger.

# Implications of a constant 'c'



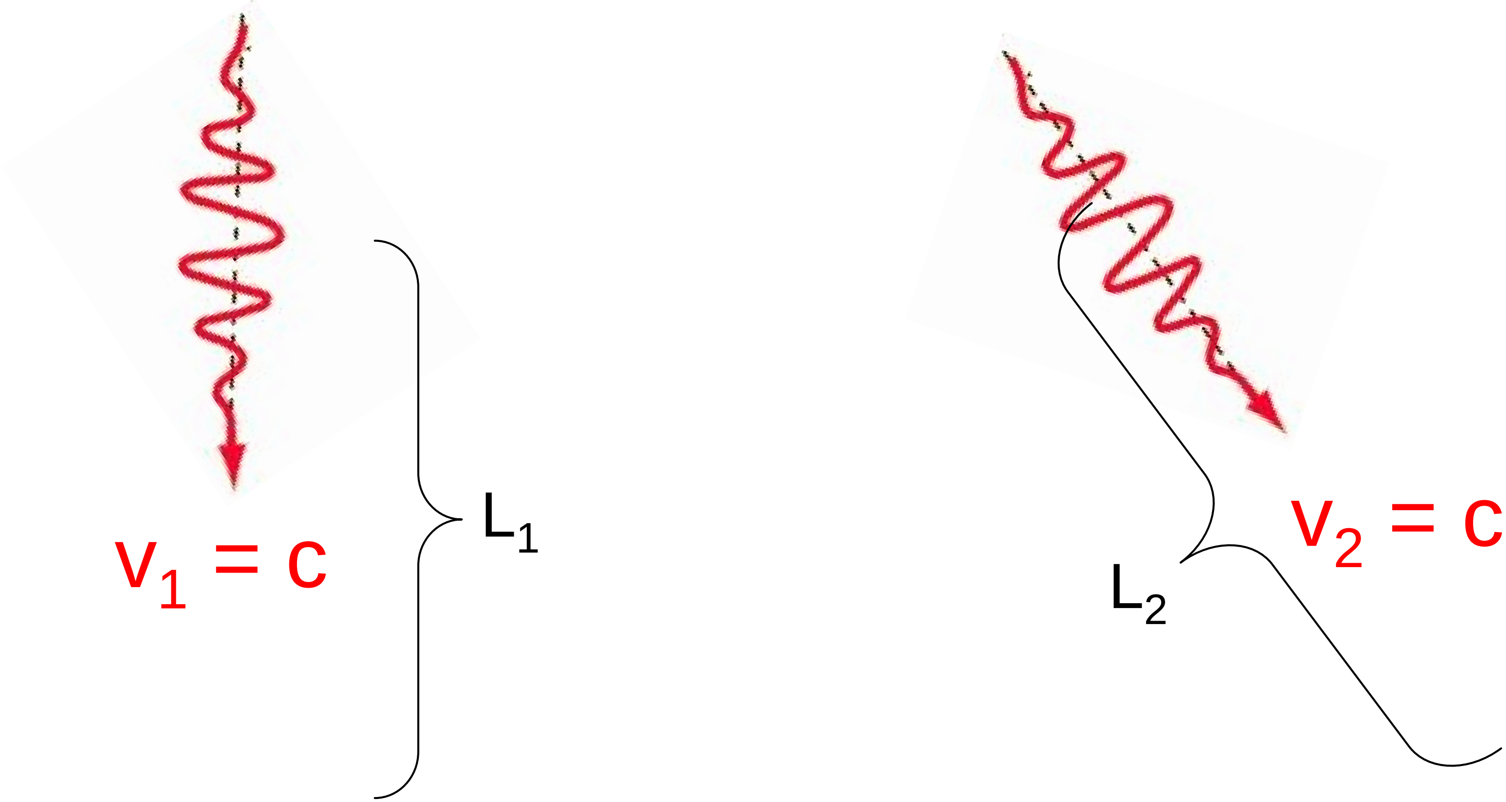

$t = L / v$ ⇨ $t_1 = t_2$ because $L_2 > L_1$ and $v_2 > v_1$

# Implications of a constant ‘c’




But the speed of light is the same in all reference frames.

# Implications of a constant 'c'




$t = L / v$ → So $t_2$ must be greater than $t_1$

# The Beginning of the End

- Prior to the late 19th century, we viewed the universe as:
  - divisible into particles (matter) and waves (light)
  - smooth on small scales (no structure on scales smaller than atoms)
  - deterministic, so that if you know the state of a system *now*, you can know its state at any time by using the laws of kinematics and dynamics

- We call this way of describing the universe “classical physics” or “Newtonian physics”
- In the 1800’s, physicists began to do experiments whose results simply could not be predicted or explained by classical physics
- It was the beginning of the end of the whole Newtonian worldview…

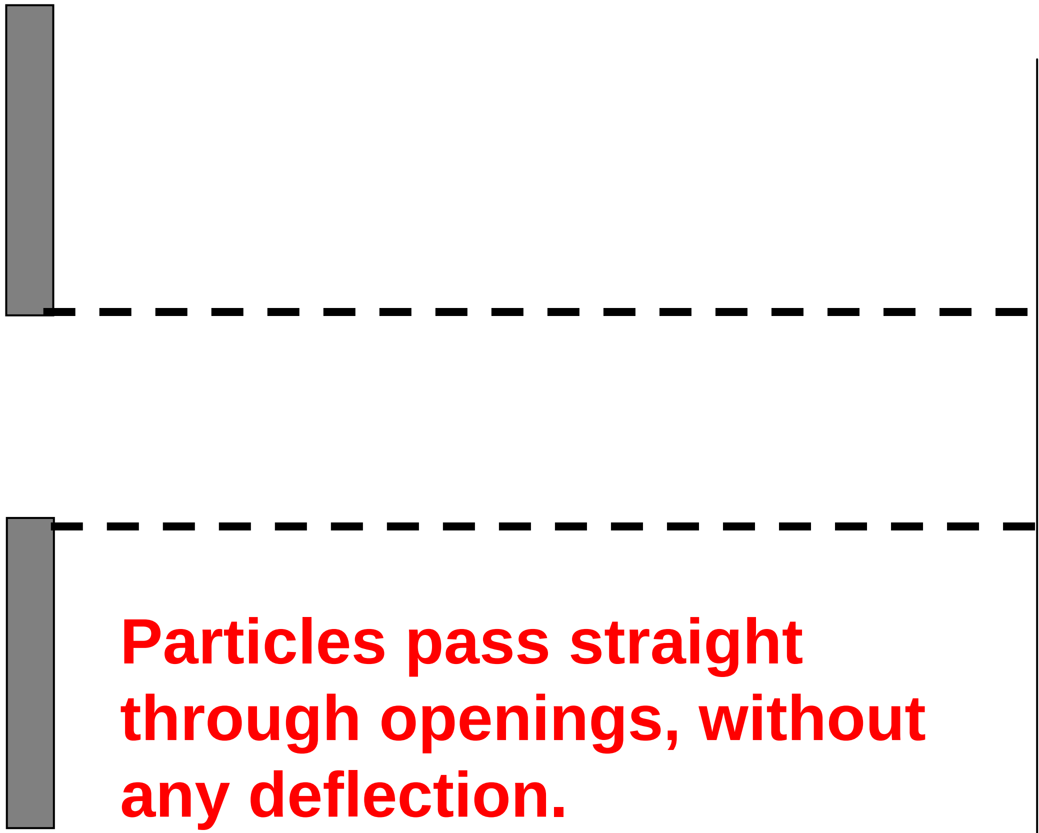
# But First, a Quick Refresher on Waves…

Consult Chapter 22 as needed to remind yourselves how interference and diffraction work, but don’t worry about their mathematical descriptions.

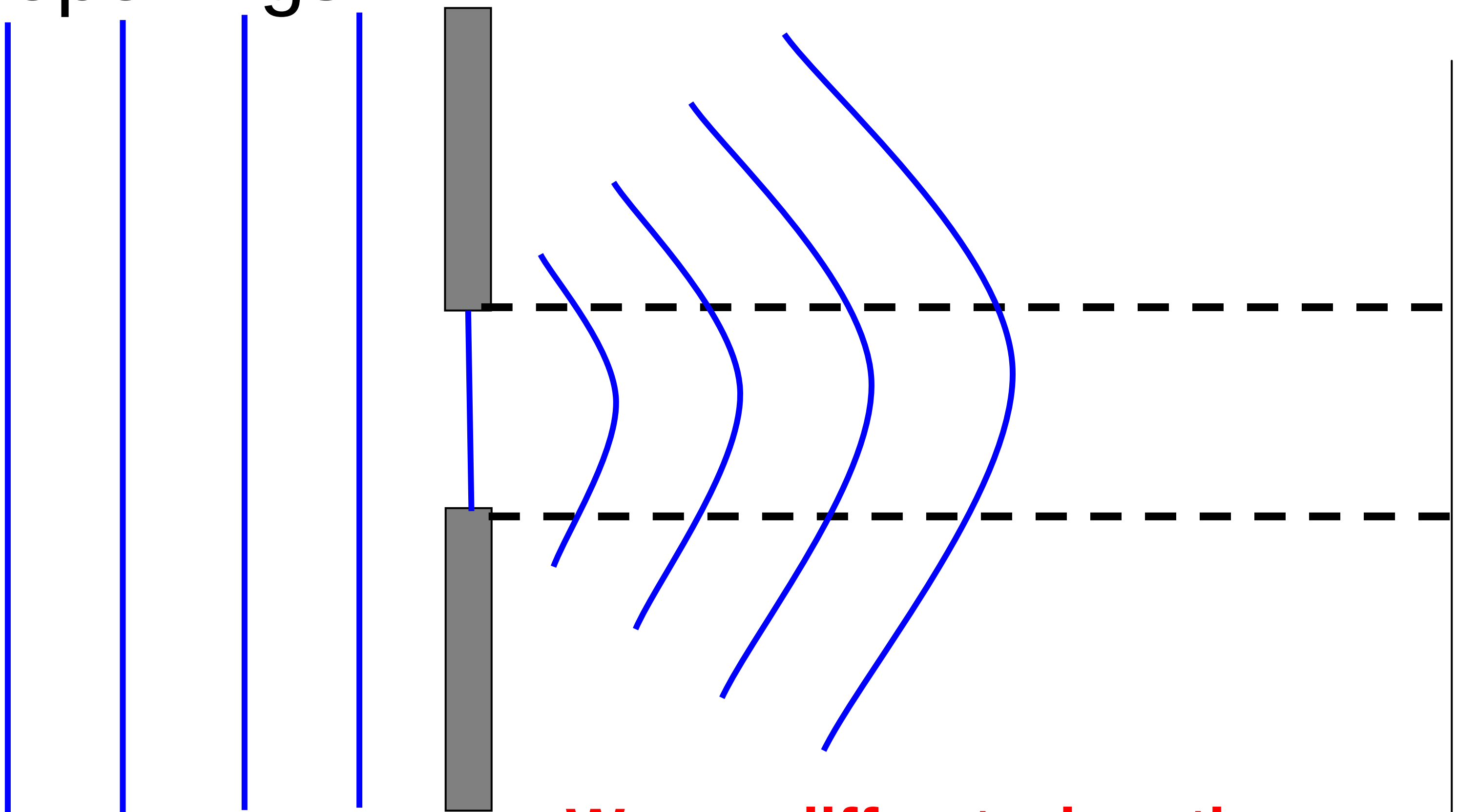
# What Is Light?

- You’ve already learned that most of the “components of stuff” are particles—protons, neutrons, electrons
- What about light?
- Originally, it wasn’t clear that light was anything separate from the sense of vision
- Newton was one of the first people to do experiments to determine the nature of light

- Simple thought experiment: what happens when particles pass through an opening?



- Waves, on the other hand, ***diffract*** (bend and spread) when they pass through openings

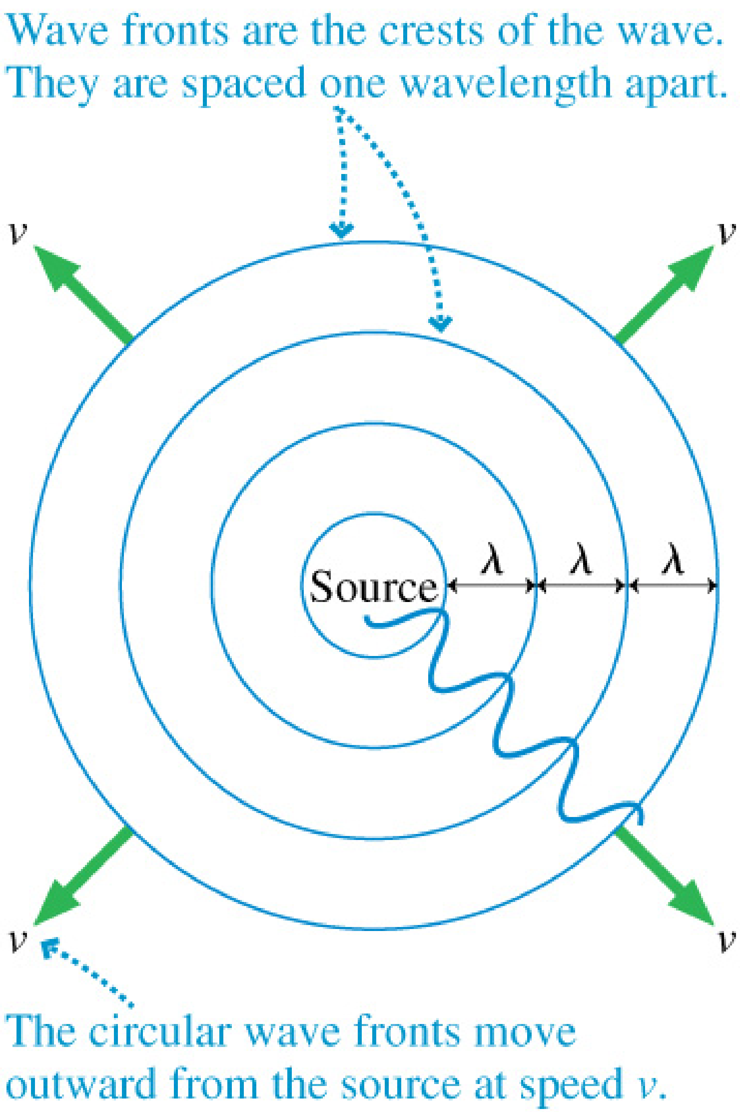


**Waves diffract when they pass through openings.**

- 1675: Newton argued that, since shadows have sharp edges, light must be some kind of particle
  - This particle must travel really, really fast

- In 1801, Thomas Young demonstrated ***interference*** of light using his now-famous ***double-slit experiment***
  - Light must be a wave

# Recall: Properties of Waves

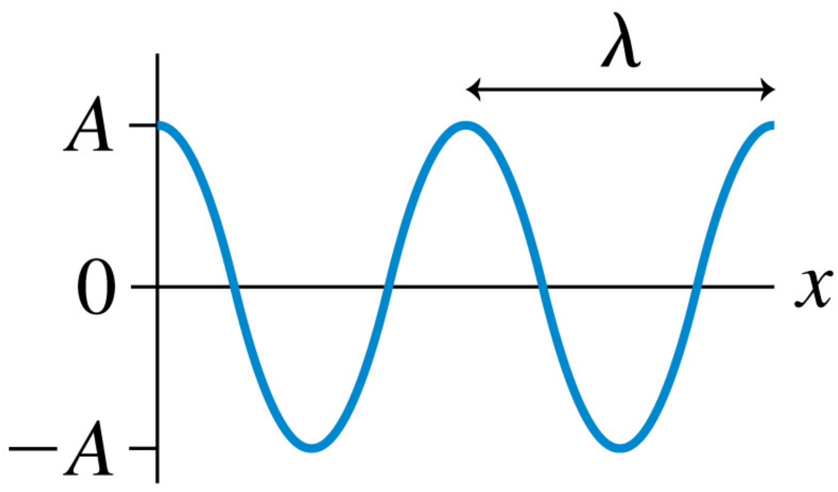



**λ = wavelength of the wave**

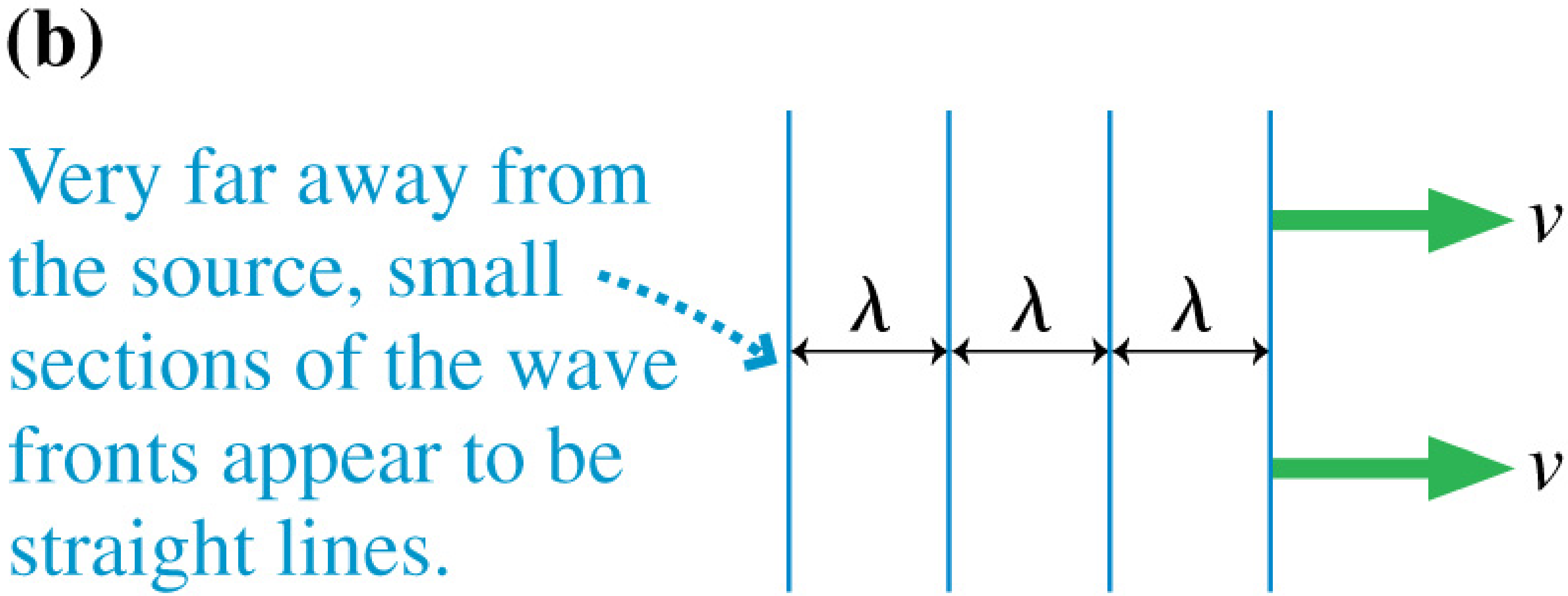
**v = speed of the wave**

**A = amplitude of the wave**

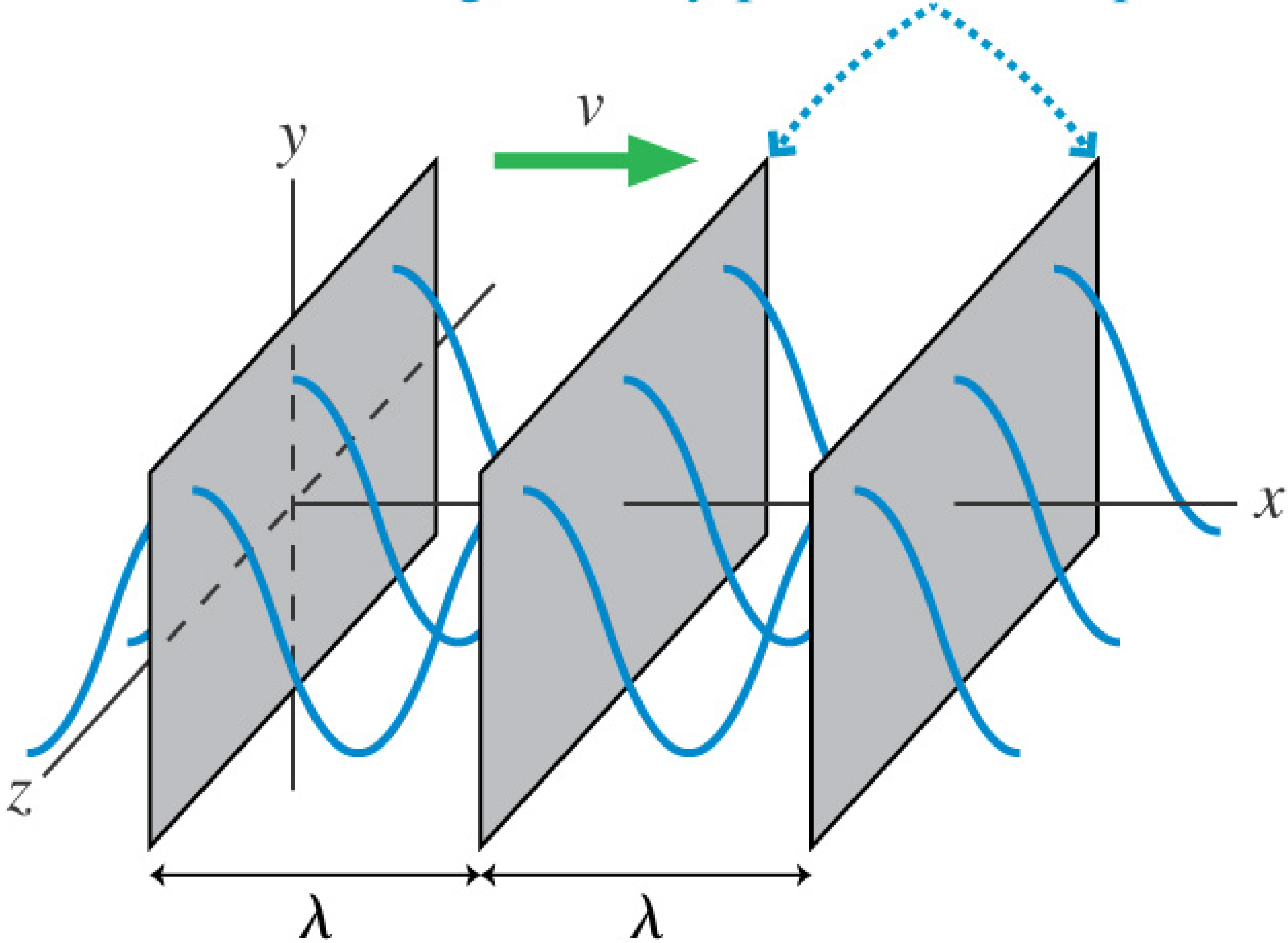
**υ = frequency of the wave**
**= v/λ**



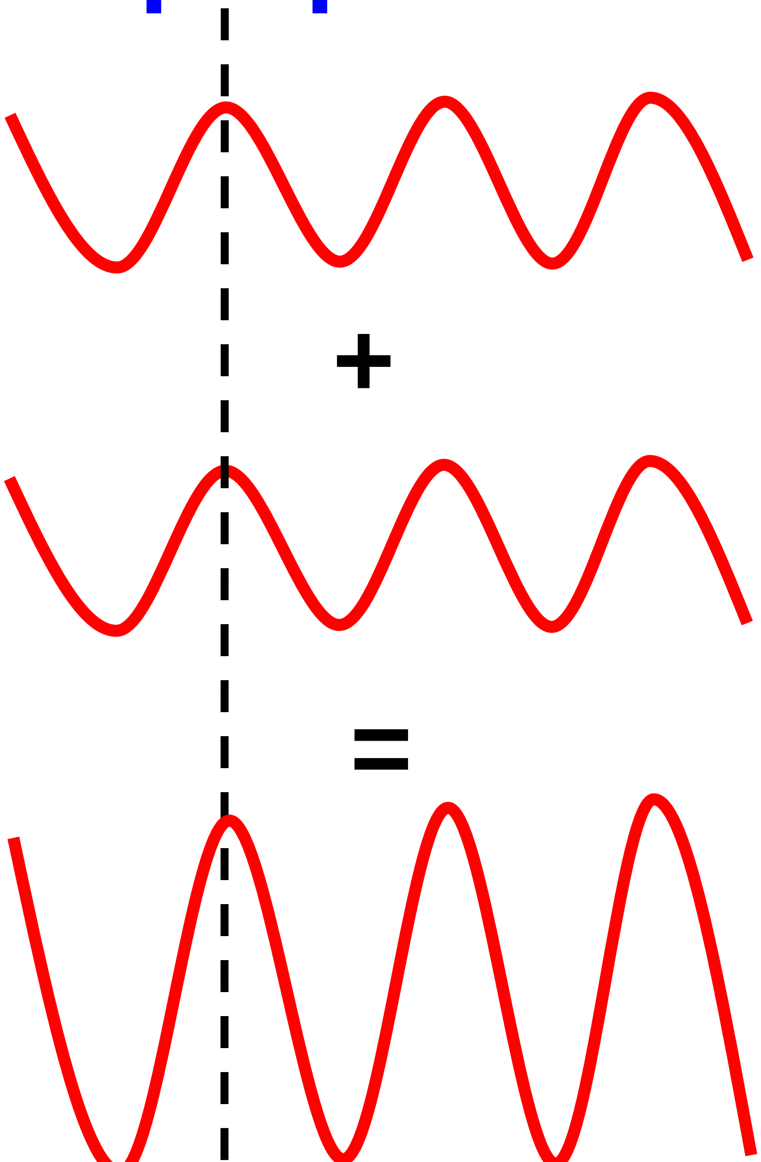
# Recall: Plane Waves



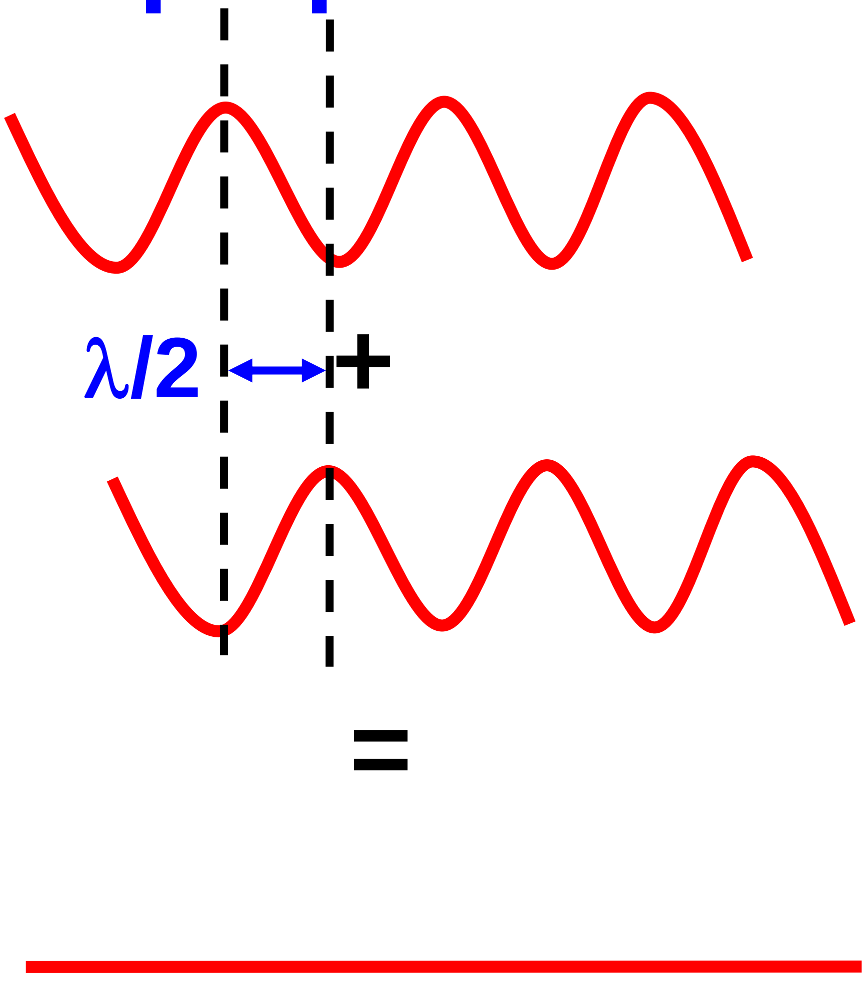
Very far from the source, small segments of spherical wave fronts appear to be planes. The wave is cresting at every point in these planes.



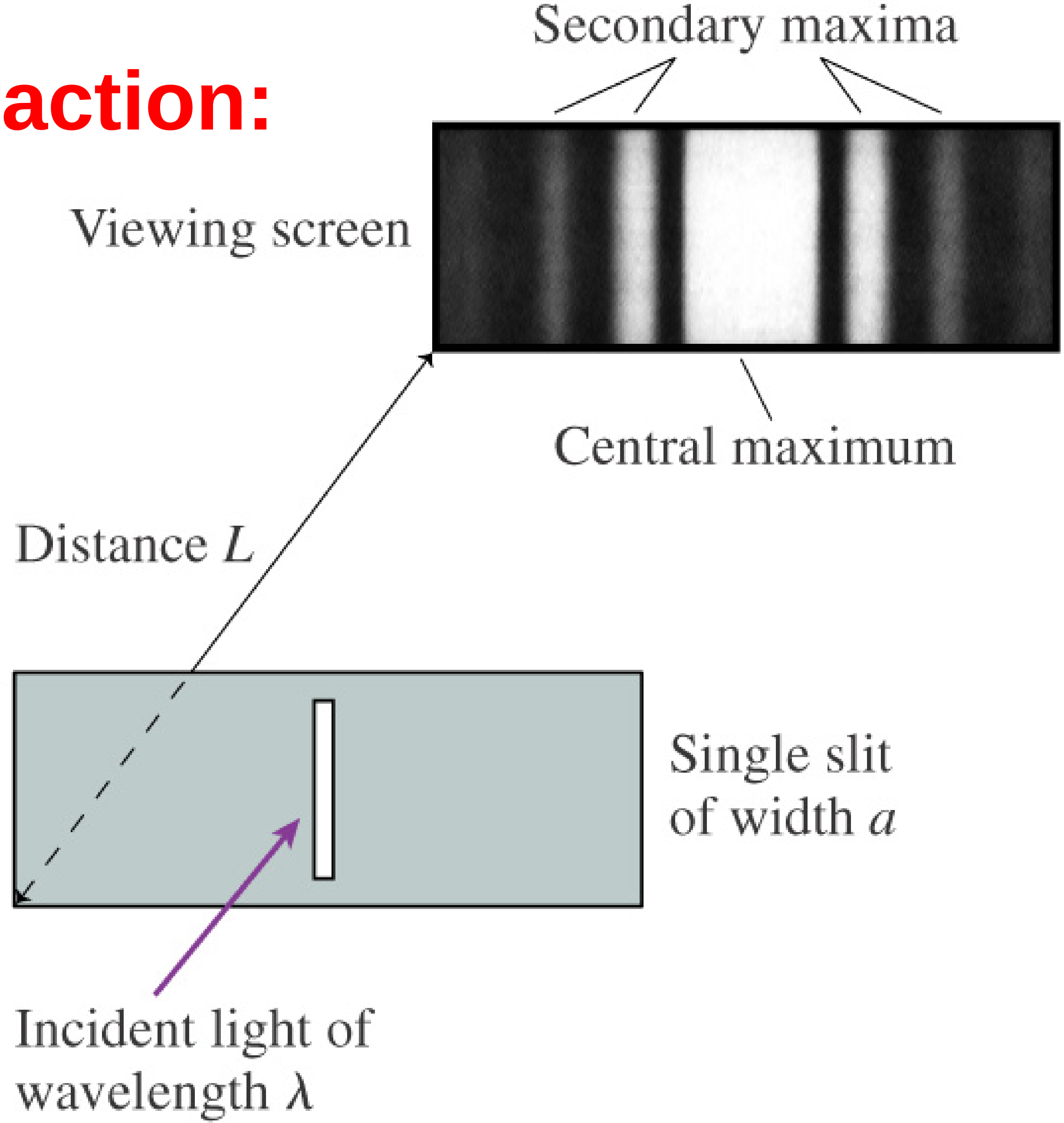
# Recall: Superposition of Waves



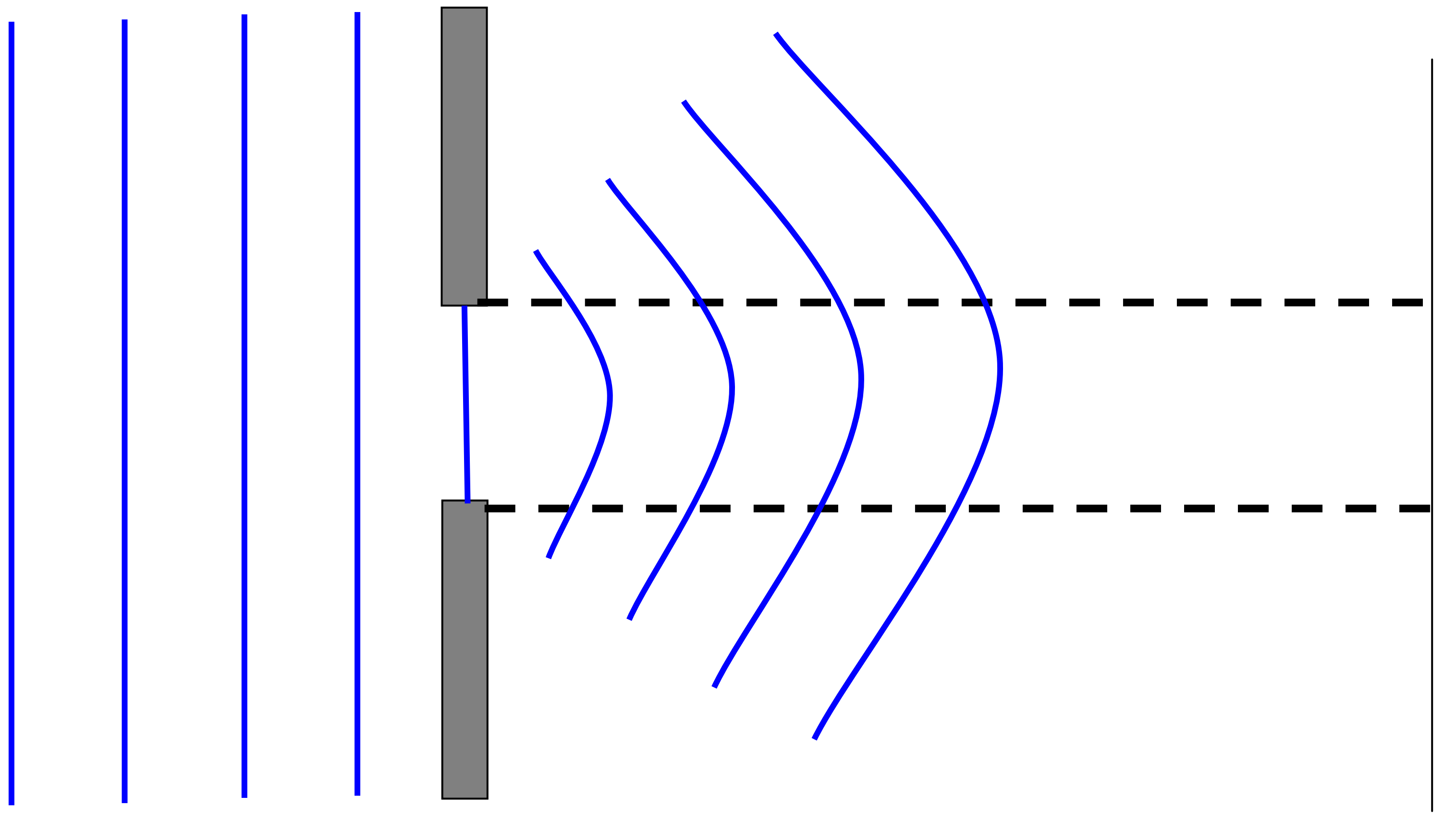
# Recall: Superposition of Waves



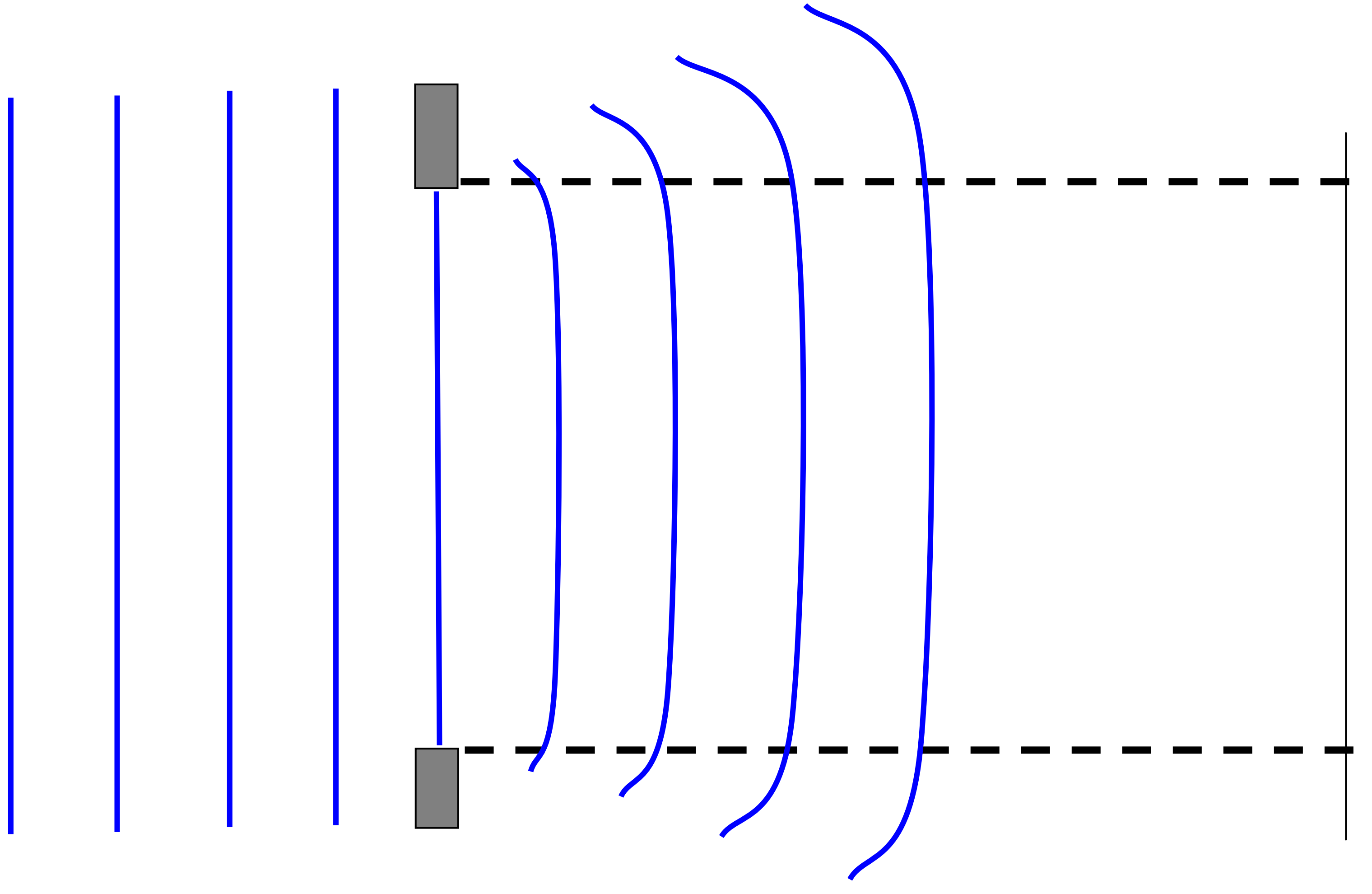
# Diffraction:



- For there to be significant diffraction of a wave through an opening, the size of the opening must be close to the wavelength of the wave
- Young proved that light was a wave by using a very, very small opening in his experiment
- For large openings, like doorways, there is little diffraction of light waves, so shadows on these scales are sharp.

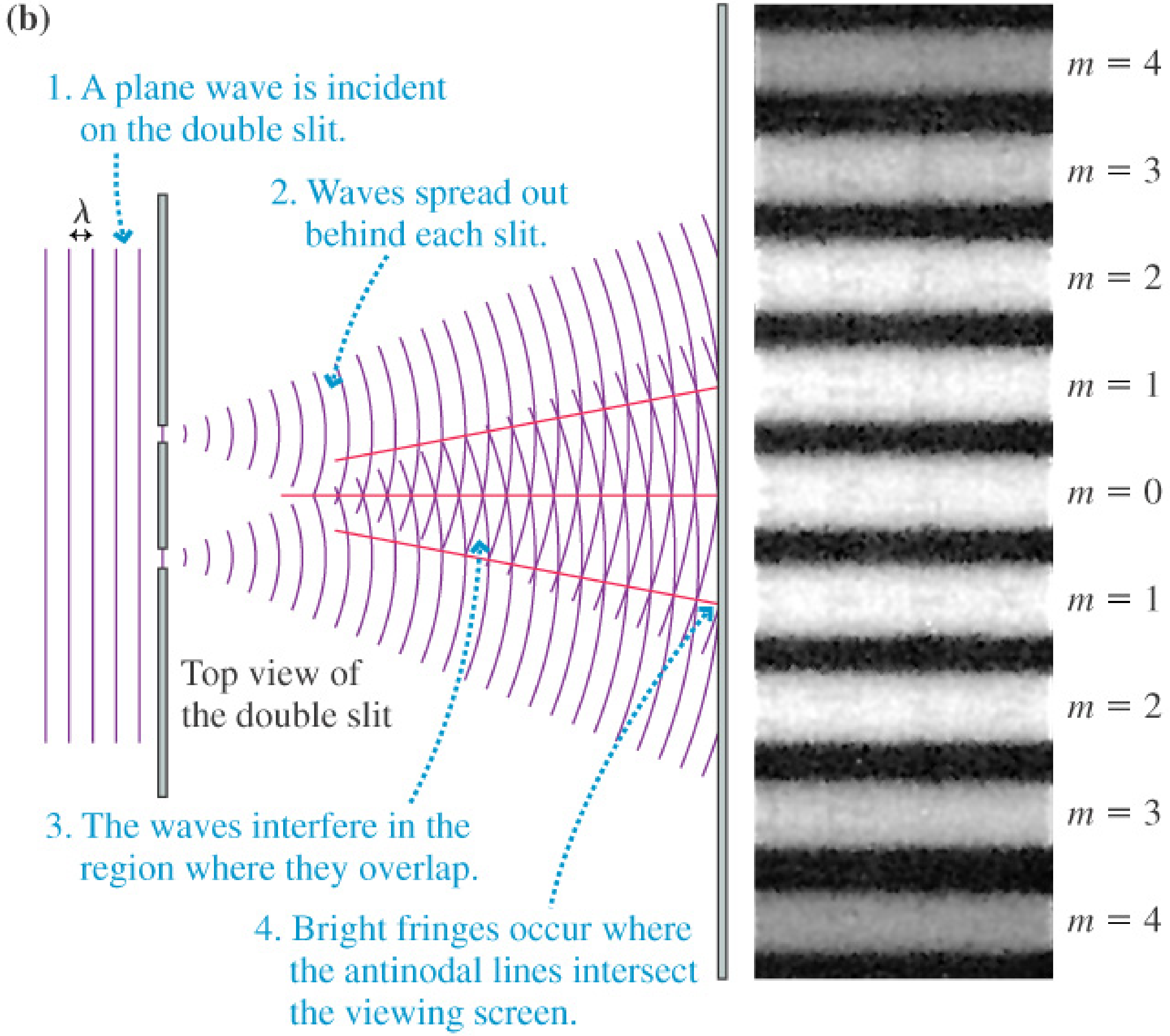


**λ ~ slit size ➔ more diffraction**



**λ << slit size ➔ less diffraction**

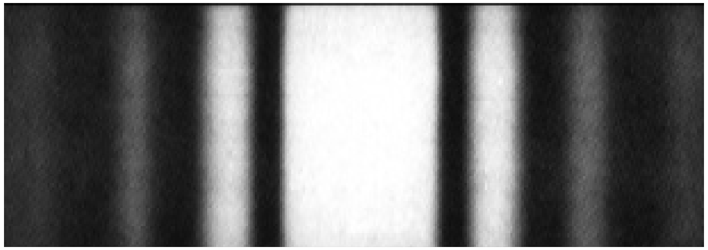
# Interference:



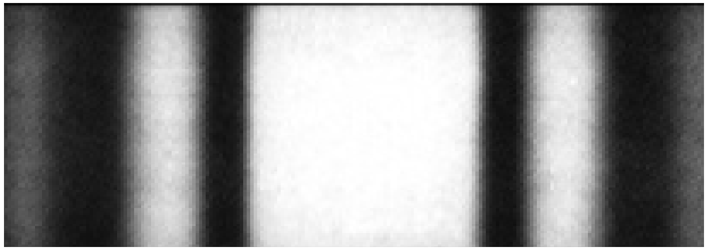
# Quick Quiz 72

The light diffraction patterns shown below were both made using the same slit. Which of the following statements could be true?

1



2



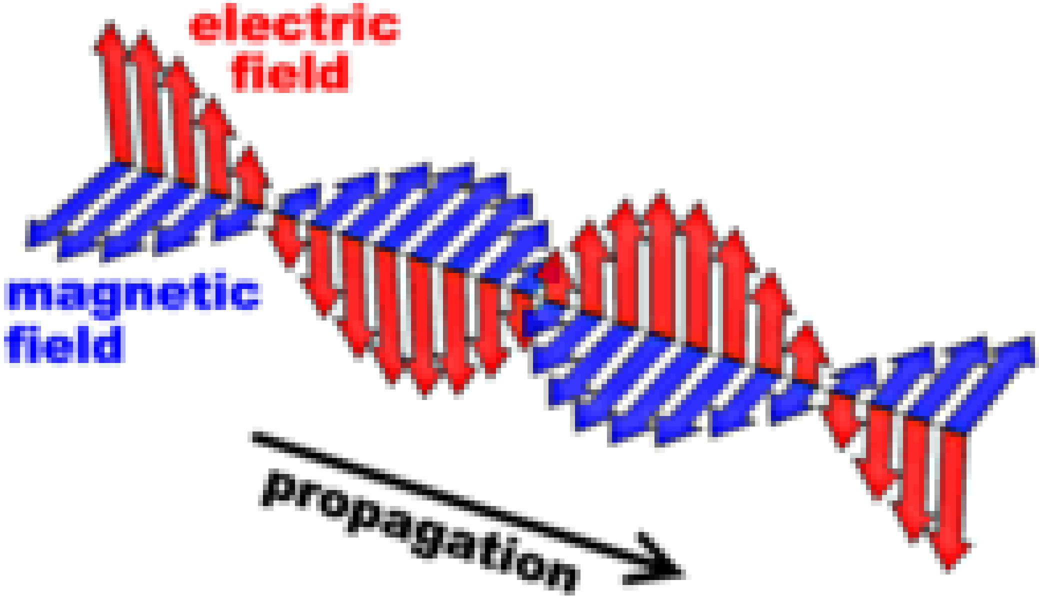
A. $\lambda_1 > \lambda_2$

B. $\lambda_2 > \lambda_1$

C. $\lambda_1 = \lambda_2$

D. none of the above

- If light is a wave, what is it a wave ***<u>in</u>***?
- Very important point: light is not a wave ***in*** anything; it is a wave ***of*** something
- Light is an ***electromagnetic wave***
- An electromagnetic wave is a combination of oscillating electric and magnetic fields

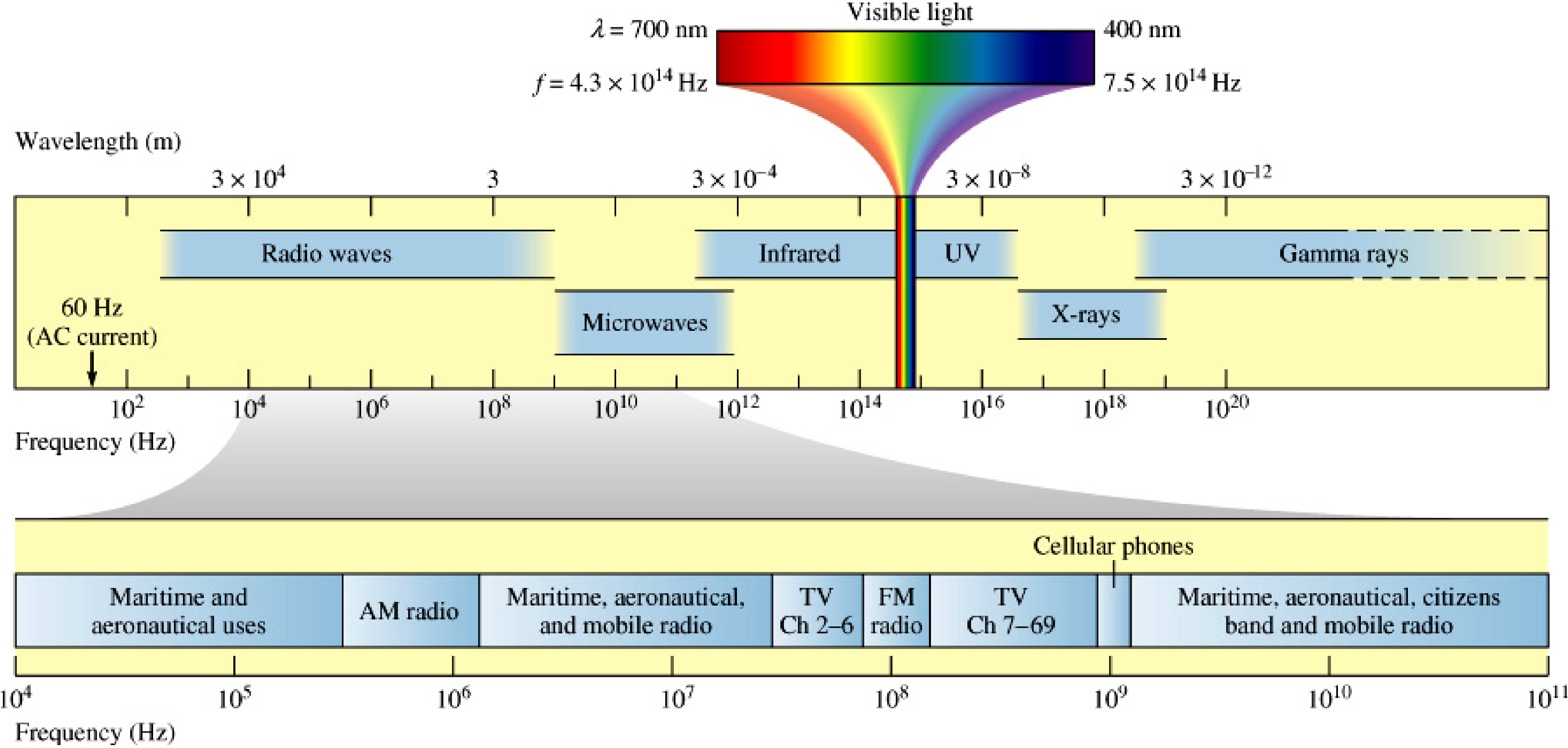


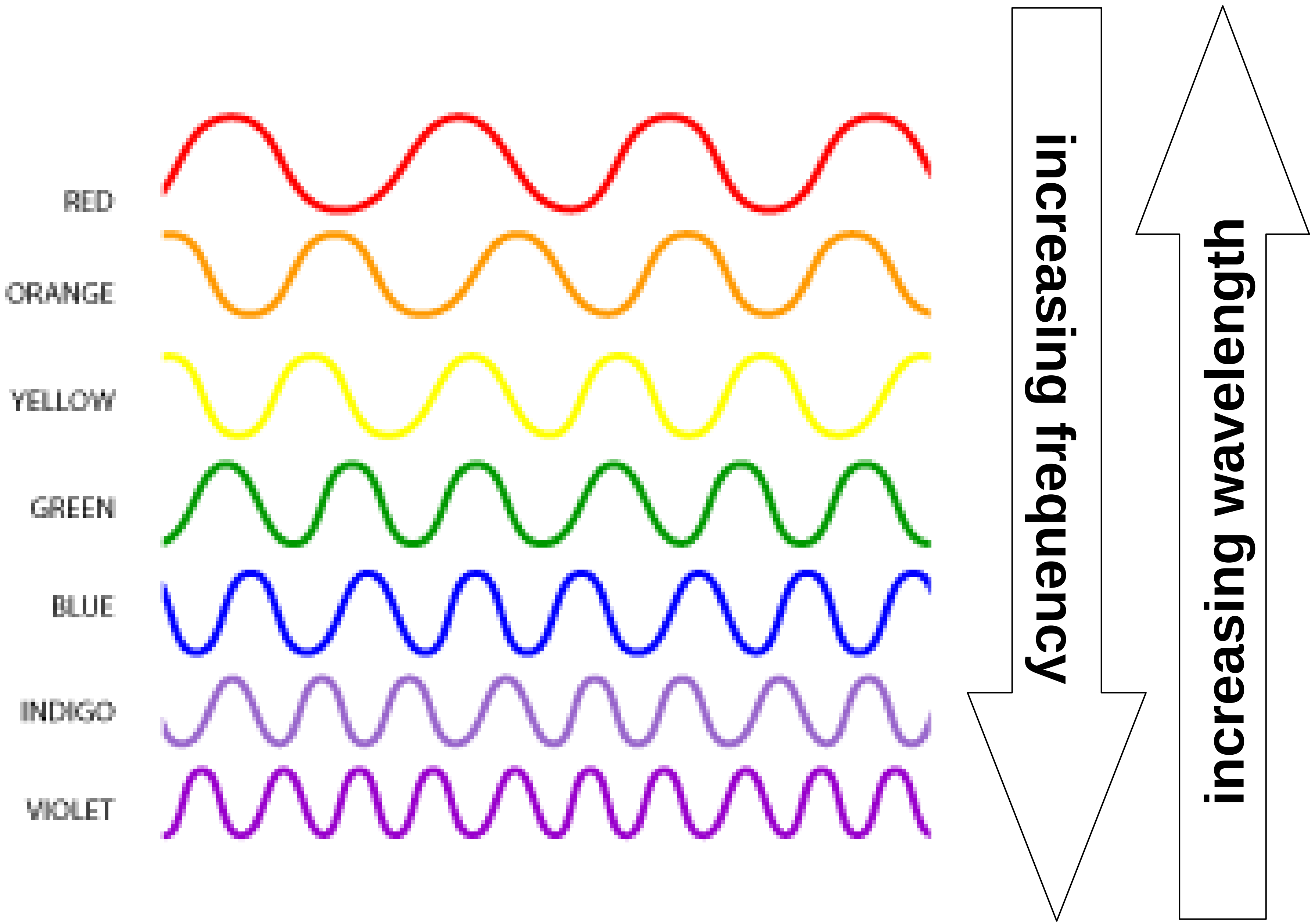
# The Electromagnetic Spectrum

- Light waves can have an infinite range of frequencies (or wavelengths)
- Some frequencies (wavelengths) are visible to the unaided human eye, which interprets different frequencies as different colours
- Most of the frequencies are not visible to the human eye

# The Electromagnetic Spectrum






RED
ORANGE
YELLOW
GREEN
BLUE
INDIGO
VIOLET
increasing frequency
increasing wavelength

- All light waves travel at the same speed, the ***speed of light:***

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

- The relationship between the speed, c, wavelength, λ, and frequency, υ,of a light wave:

$$c = \lambda \upsilon$$

"nu" not "vee"

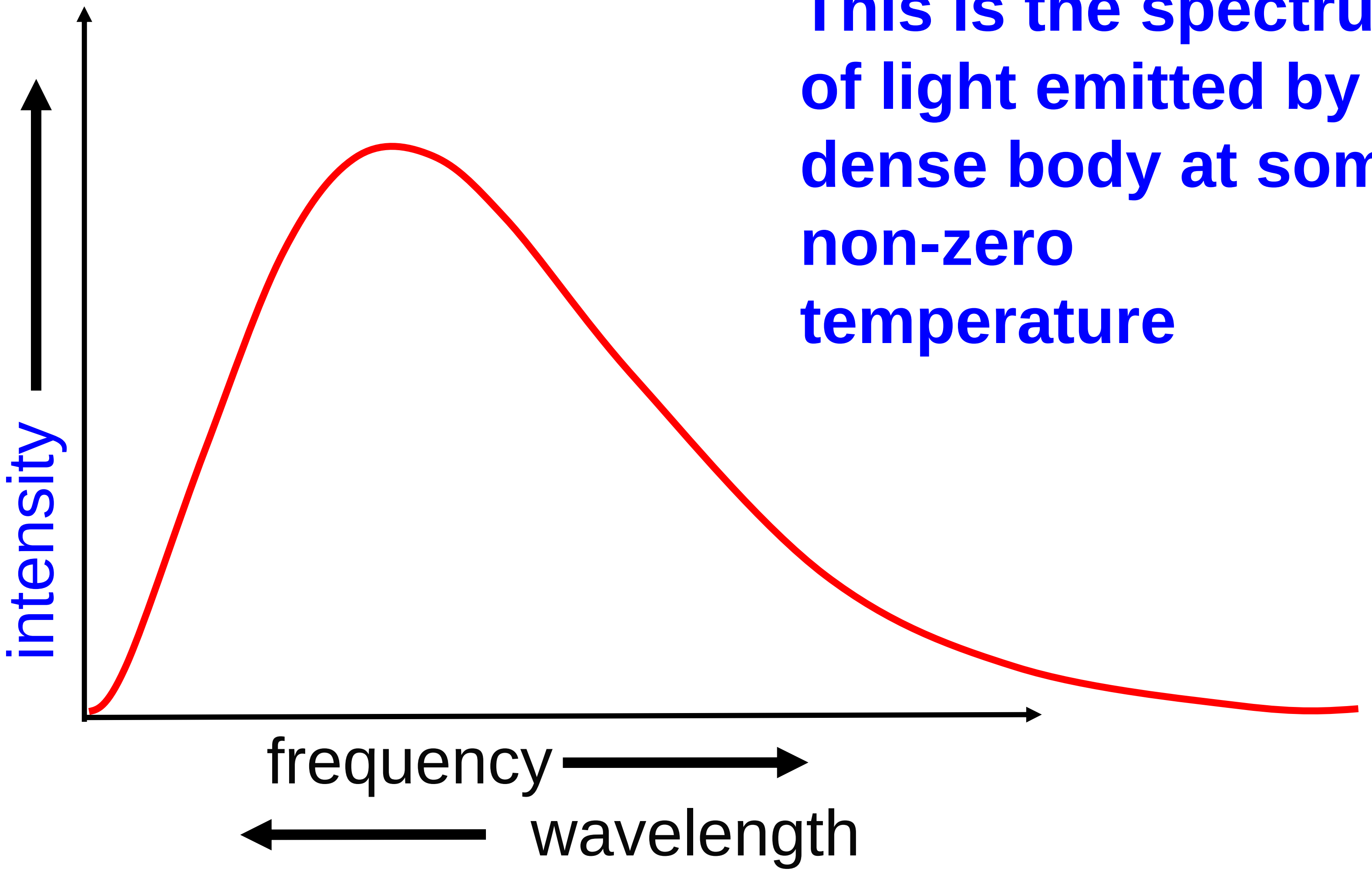
# Quick Quiz 73

A light wave with a high frequency…

A. …has a small wavelength
B. …travels at a high speed
C. …has a long wavelength
D. …travels at a low speed

# Blackbody Radiation

- In 1792, Thomas Wedgewood, a maker of fine china, noticed that all dense materials he put in his ovens glowed the same colour if they were heated to the same temperature
- The colour didn’t depend on what the material was made of
  - hot china glowed the same colour as the hot iron walls of the stoves
- Later experiments showed that all dense bodies emitted essentially the same spectrum of light if they were at the same temperature




**This is the spectrum of light emitted by a dense body at some non-zero temperature**

# Rayleigh-Jeans Law

- Classical physics predicts that the intensity of light emitted by a dense body is described by the ***Rayleigh–Jeans law***:

frequency of light, υ (“nu”)

temperature of the emitting object, T

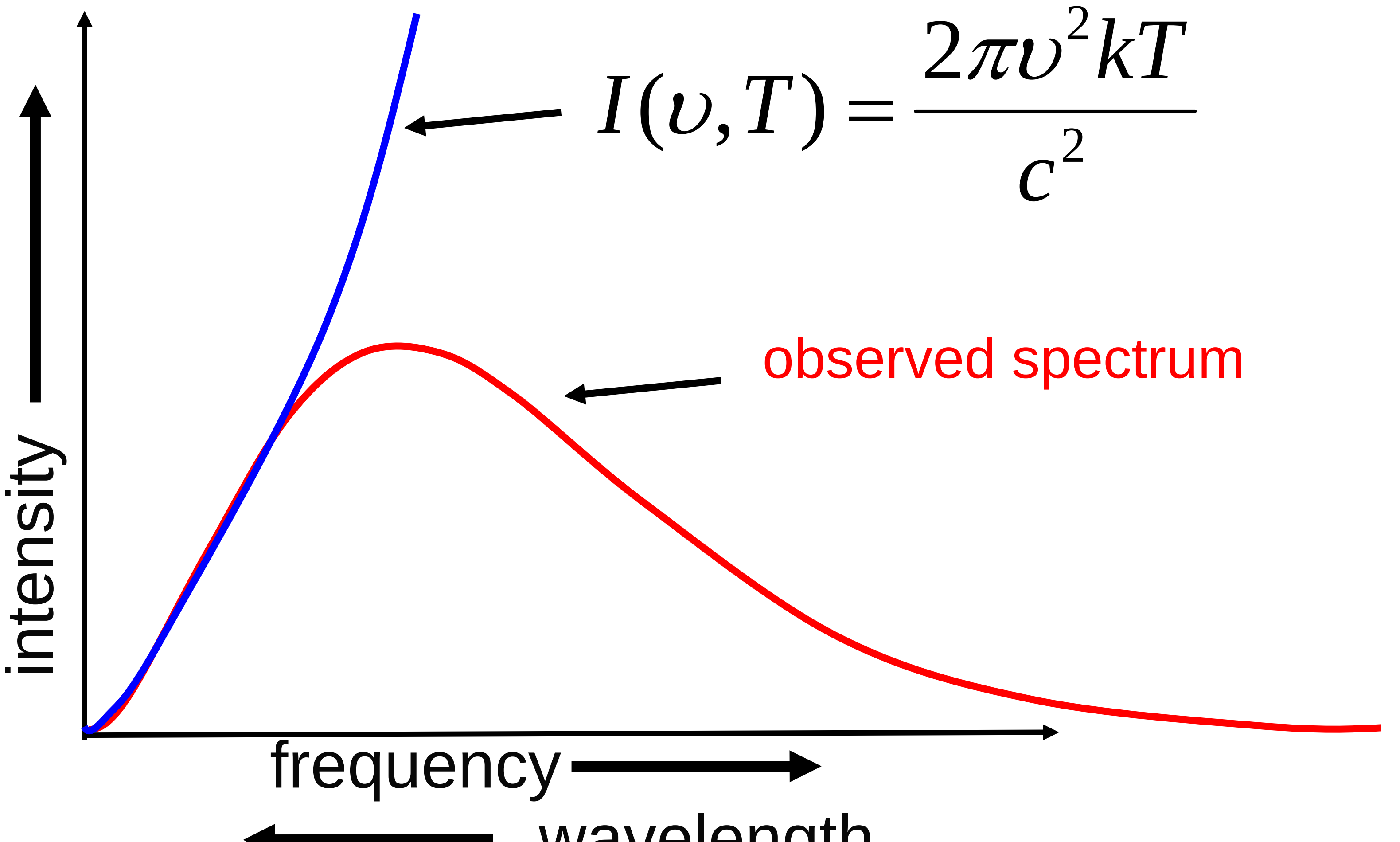
$$I(\upsilon, T) = \frac{2\pi\upsilon^2 kT}{c^2}$$

intensity of light, I

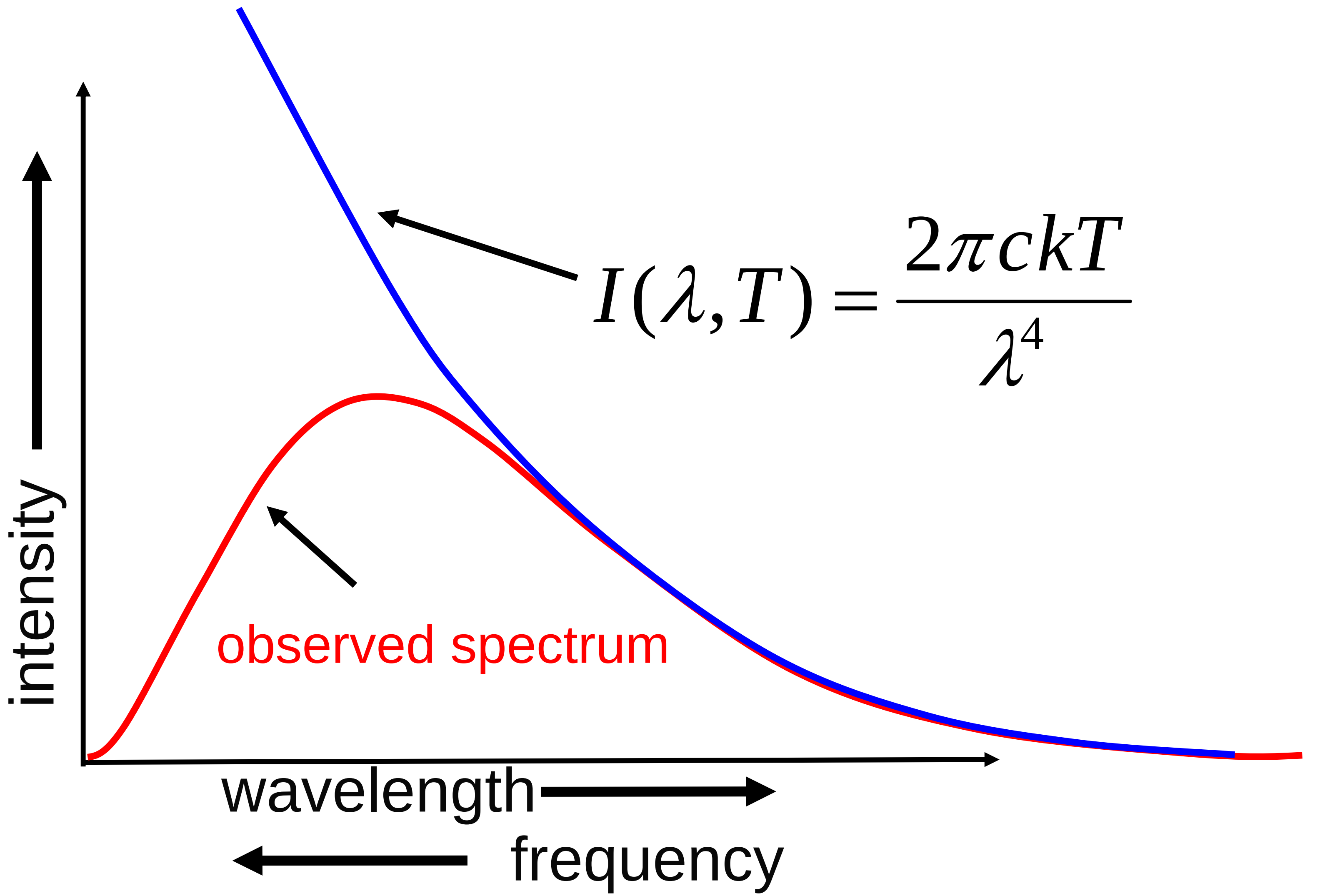
speed of light, c

Boltzmann’s constant, k

# Ultraviolet Catastrophe



# Ultraviolet Catastrophe



- Integrate up the area under the curve
  - classical physics ➔ infinite energy
  - observed curve ➔ finite energy

- Clearly classical physics fails here—a chunk of hot iron does not contain an infinite amount of energy!

# Quick Quiz 74

The “ultraviolet catastrophe” refers to:

A. The dangerous amount of ultraviolet light emitted by hot ovens
B. The prediction by classical physics that objects should store less energy at high frequencies than they actually do
C. The divergence between the Rayleigh-Jeans spectrum and the real spectrum of light for objects at very high temperature
D. The prediction by classical physics that objects should store more energy at short wavelengths than they actually do

- In 1900, Max Planck found that he could solve the ultraviolet catastrophe by assuming that waves of light can only take on discrete multiples of energy

- Instead of the energy of the light wave being proportional to the amplitude, it must only be proportional to the frequency.

$$E \propto \upsilon$$

$$E = h\upsilon$$

- ***Planck's constant:*** $h = 6.63 \times 10^{-34}\ Js$

- All light of a given frequency (i.e. blue) has exactly the same energy.

- If something is very bright in a particular colour of blue, it is because it emits many of these packets of blue energy.
  - NOT because the blue wave has a larger amplitude

- Planck showed that, if you said each wave carried energy $h\upsilon$, you could exactly reproduce the spectra of warm bodies!
- We call the spectrum the ***Planck spectrum***

frequency of light, $\upsilon$ (“nu”)

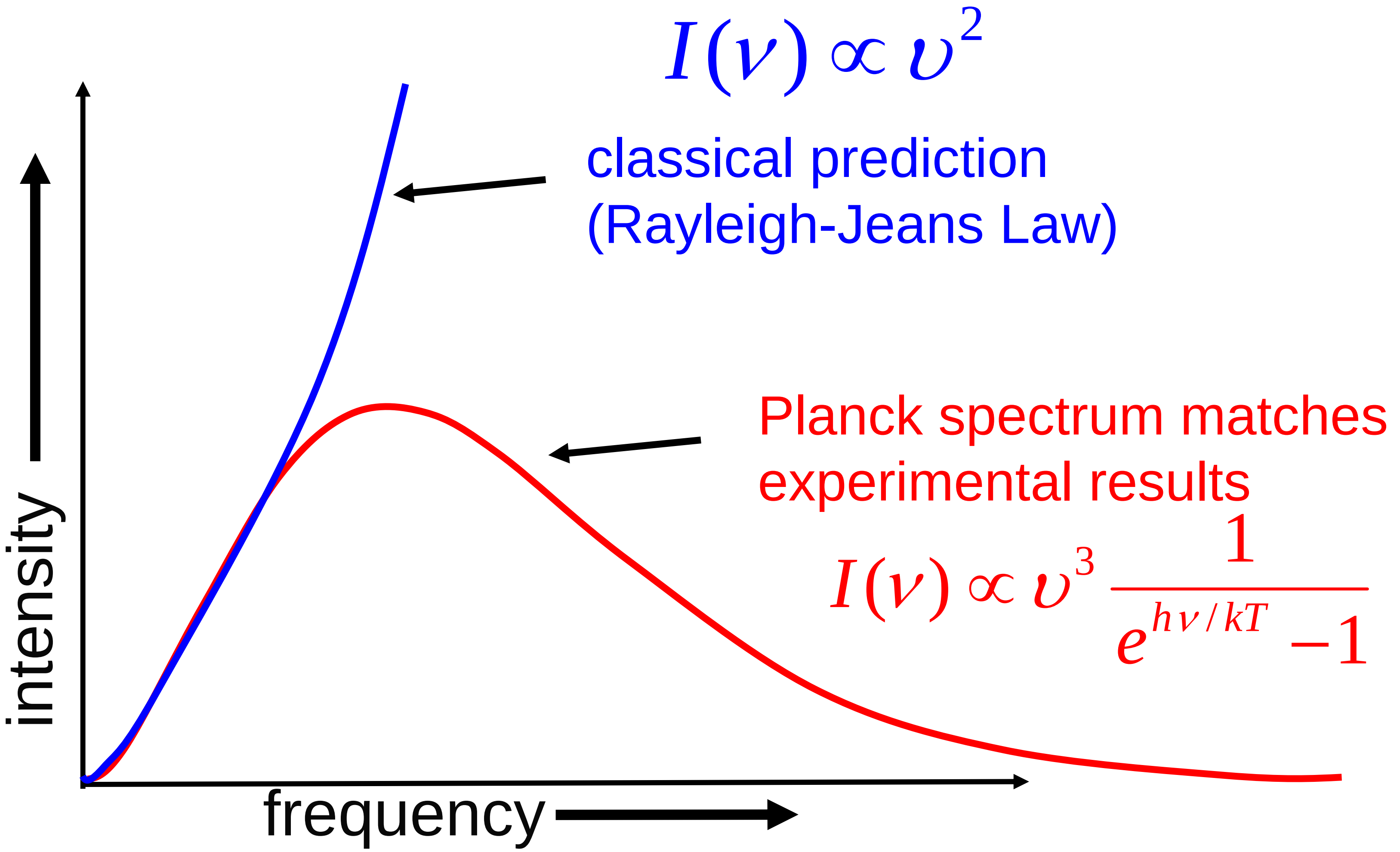
Boltzmann’s constant, k

$$I(\nu,T)=\frac{2h\nu^{3}}{c^{2}}\frac{1}{e^{h\nu/kT}-1}$$

intensity of light, I

speed of light, c
Planck’s constant, h

temperature of blackbody, T

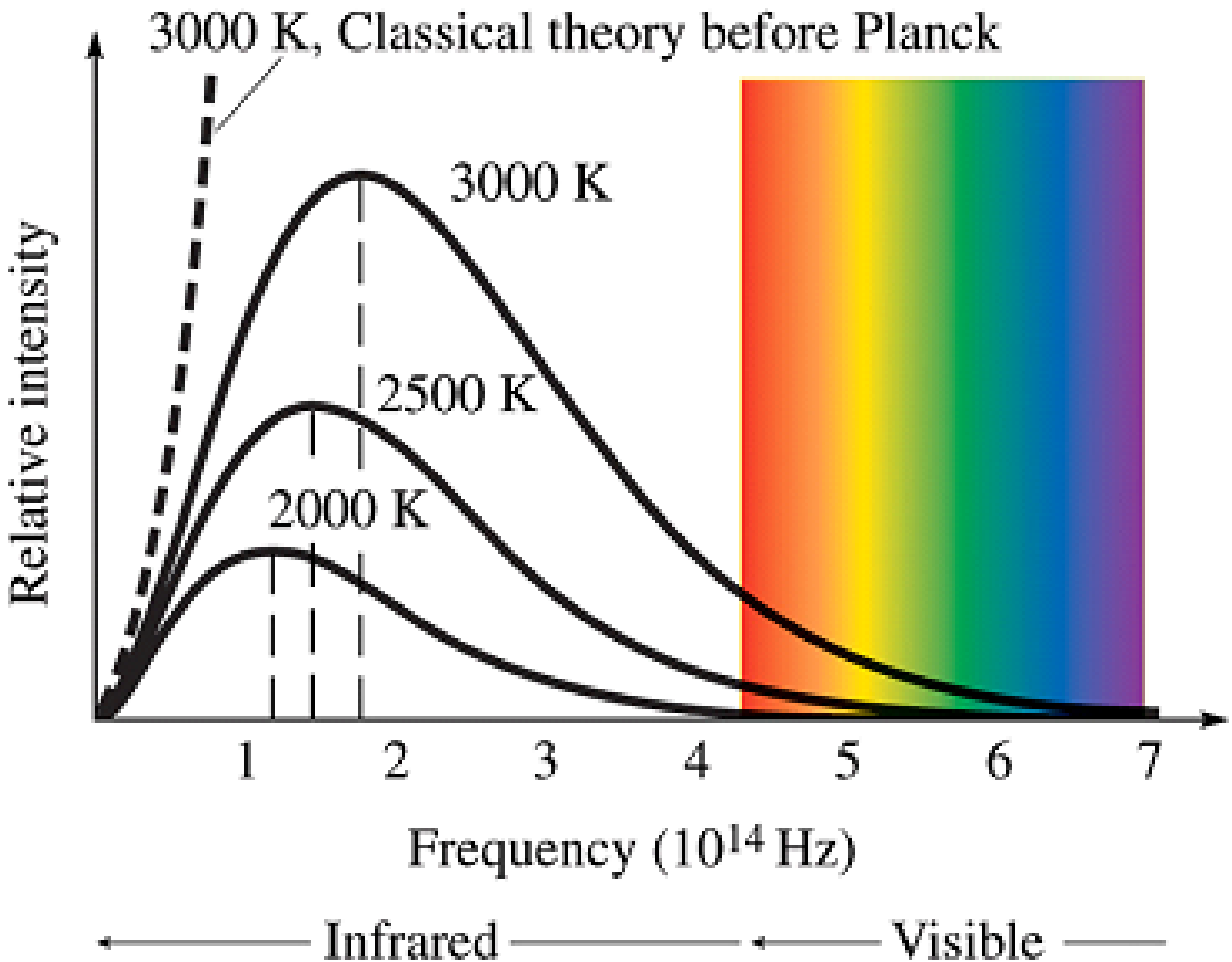


$I(\nu) \propto \upsilon^2$
classical prediction
(Rayleigh-Jeans Law)
Planck spectrum matches
experimental results
$I(\nu) \propto \upsilon^3 \frac{1}{e^{h\nu/kT} - 1}$
intensity
frequency

# Blackbody Radiation

- We now call the spectrum we have been talking about the ***blackbody spectrum*** or the ***Planck spectrum***
- The bodies that emit it are called ***blackbodies***
- ***A blackbody is a substance which absorbs all light incident upon it and re-radiates it with the frequency distribution given by the Planck spectrum***
- Because it absorbs all of the radiation incident upon it, a black body is perfectly black when it is cold (hence the name)

- The ***form*** of the Planck spectrum depends on the temperature of the emitting blackbody, but not on any other property of that body
- As the temperature of a blackbody increases, two things happen:
  - the total energy emitted (i.e. the area under the curve) increases → ***Stefan's law***
  - the peak of the curve shifts to shorter wavelengths (larger frequencies) → ***Wien's Law***

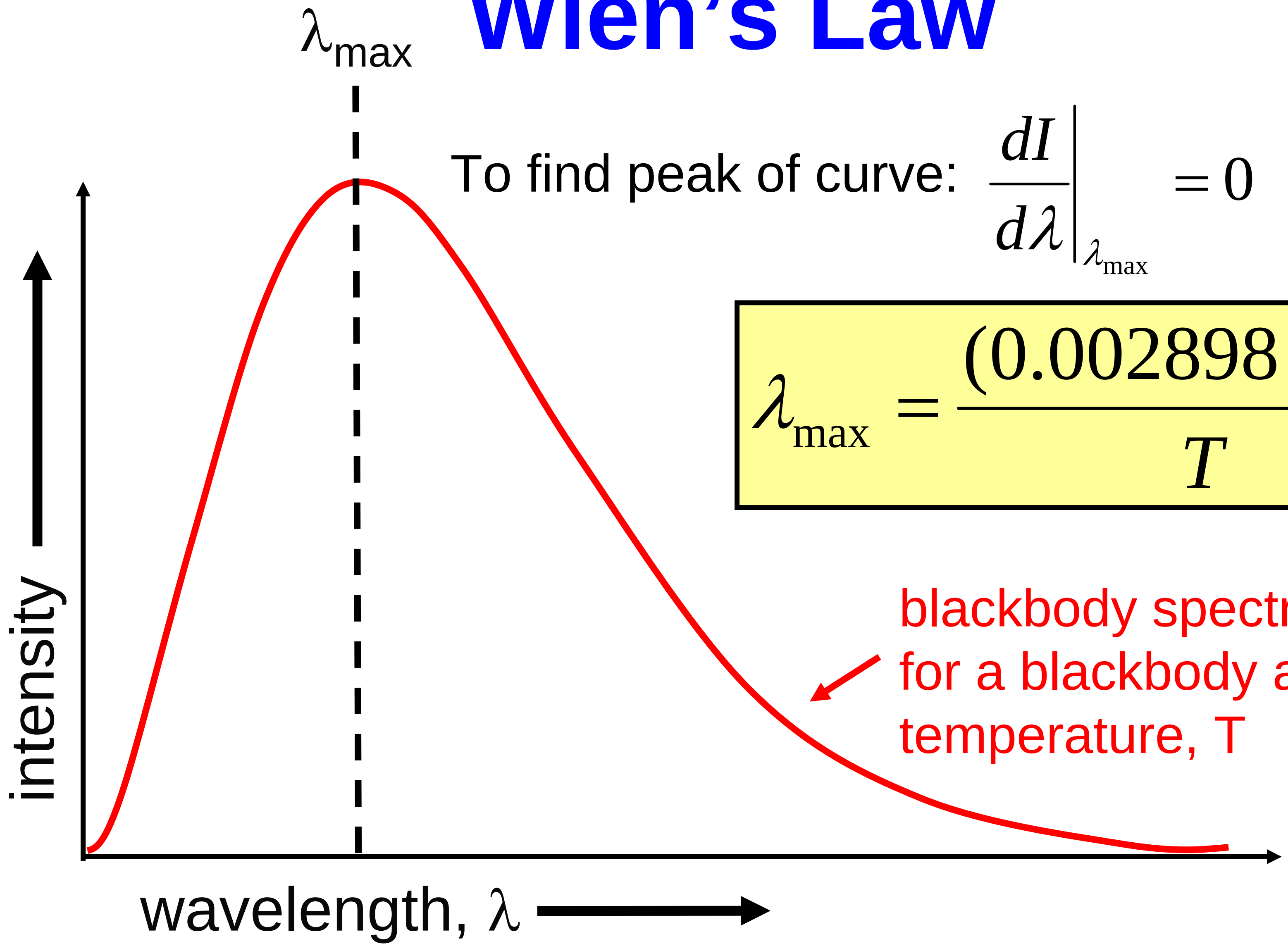


3000 K, Classical theory before Planck
3000 K
2500 K
2000 K
Relative intensity
1
2
3
4
5
6
7
Frequency (10^14 Hz)
Infrared
Visible

# Wien's Law

To find peak of curve: $$\left.\frac{dI}{d\lambda}\right|_{\lambda_{\max}} = 0$$

$$\lambda_{\max} = \frac{(0.002898\,\mathrm{m\,K})}{T}$$



# Quick Quiz 75

At what wavelength would the human body emit the most light? You may assume that the human body is approximately a blackbody.

A. $10^{-3}$ m
B. $10^{-4}$ m
C. $10^{-5}$ m
D. $10^{-6}$ m

# Stefan's Law

- The total power (energy per unit time) a blackbody emits is:

$$P = \sigma A e T^4$$

where $P$ = power of radiation

$\sigma$ = Stefan's constant

$= 5.669 \times 10^{-8}\ \mathrm{W/m^2K^4}$

$T$ = absolute temperature of the object (in K)

$A$ = total surface area of the object.

$e$ = emissivity of the body,

# Emissivity

- Ideal blackbodies absorb all of the radiation incident upon them and re-emit 100% of it, so they have e=1
- An ideal mirror reflects all of the radiation incident upon it and therefore neither absorbs nor emits energy, so it would have e=0
- For real objects, $0 \le e \le 1$

- The emissivity of an object is a property of the object (specifically, of its surface)
- The emissivity can also vary with frequency, so that a body absorbs some frequencies of radiation and reflects others

| **surface** | **emissivity** |
|---|---|
| polished aluminum | 0.05 |
| black carbon | 0.95 |
| human skin | 0.97 (in the infrared) |

# Absorption

- We can also use Stefan's law to express the power ***absorbed*** by an object via electromagnetic radiation from its environment:

$$P_{abs} = \sigma A e T_{env}^{4}$$

where $T_{env}$ is the temperature of the environment

# Intensity

- Sometimes we speak of the ***intensity*** of light emitted by an object, which is the amount of energy emitted per unit time per unit of a body's surface area (i.e. power/area):

$$I = P/A = \sigma e T^4$$

# Example

- We know that human bodies are warmer than room temperature, so they must radiate more energy than they take in, $P_{out} > P_{abs}$. The temperature of human skin is about 34 C, while room temperature is about 22 C. A human body has a total surface area of about 2 $m^2$. What is the net energy output of the human body?

- Step 1: What we know:
  - $T_{env}$ = 22 C = 295.15 K
  - $T_{skin}$ = 34 C = 307.15 K
  - $e_{skin}$ ~ 0.97
  - A = 2 $m^2$
- Step 2: What are we looking for?
  - $P_{net} = P_{out} – P_{in}$
- Step 3: Find $P_{out}$

- Step 3: Find $P_{out}$

$$P_{out} = \sigma A e_{skin} T_{skin}{}^{4}$$

$$P_{out} = (5.669 \times 10^{-8}\,\mathrm{Wm^{-2}K^{-4}})(2\mathrm{m}^2)(0.97)(307.15\mathrm{K})^4$$

$$P_{out} = 979\,\mathrm{W}$$

- Step 4: Find $P_{in}$:

$$P_{in} = \sigma A e_{skin} T_{env}{}^{4}$$

$$P_{out} = (5.669\times10^{-8}\,\mathrm{Wm^{-2}K^{-4}})(2\mathrm{m}^2)(0.97)(295.15\mathrm{K})^4$$

$$P_{out} = 834\,\mathrm{W}$$

- Step 5: Find $P_{net}$:

$$P_{net} = P_{out} - P_{in} = 979\ \mathrm{W} - 834\ \mathrm{W} = 144\ \mathrm{W}$$

So the net power output of the human body is about **144 W**