Remote Sensing 1: GEOG 4/585

Lecture 2.1.

Electromagnetic energy

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Office hours: Monday 15:00-17:00
in 165 Condon Hall

Required reading:
Principles of Remote Sensing pp 53-80

Overview

- Forms of energy and transfer of energy
- Electromagnetic radiation
- Blackbody radiation
- Wave theory and particle theory

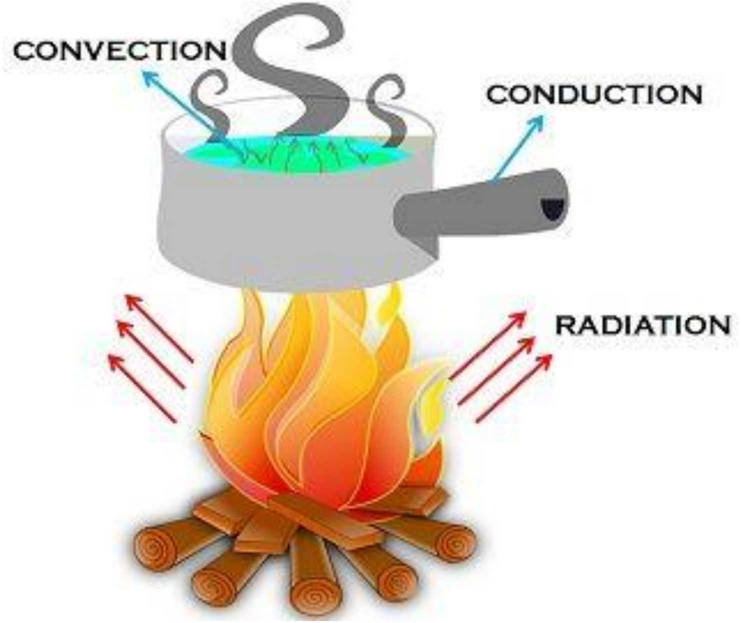
Energy

- Energy is the property that must be transferred to perform work on the body, or to heat it
- Several different forms of energy exist to explain all known natural phenomena
- These forms include…?

Energy

- Energy is the property that must be transferred to perform work on the body, or to heat it
- Several different forms of energy exist to explain all known natural phenomena
- These forms include kinetic, potential, thermal, gravitational, sound, light, elastic, and electromagnetic energy
- Any form of energy can be transformed into another form, but the total energy always remains the same (conservation of energy). Energy cannot be destroyed.
- The accepted unit of measurement for energy is the joule (J).

Transfer of energy



- Conduction - transfer of energy between objects in direct contact
- Convection - transfer of energy by physically moving objects
- Radiation - transfer of energy by waves or particles through space

Transfer of energy

- Work with a partner and provide an example of:

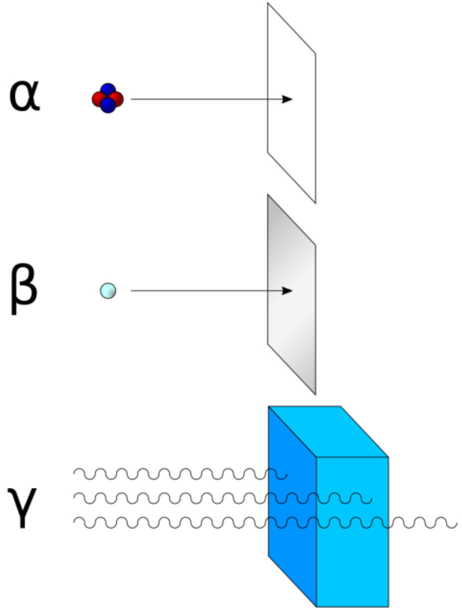
  a) Conduction - transfer of energy between objects in direct contact

  b) Convection - transfer of energy by physically moving objects

  c) Radiation - transfer of energy by waves or particles through space

Types of radiation

- <u>Electromagnetic radiation</u>, such as radio waves, microwaves, visible light, x-rays, and gamma radiation (γ)
- <u>Particle radiation</u>, such as alpha radiation (α), beta radiation (β), proton radiation and neutron radiation (mass + energy)
- <u>Acoustic radiation</u>, such as ultrasound, sound, and seismic waves (requires a physical transmission medium)
- <u>Gravitational radiation</u>, such as gravitational waves or ripples in the curvature of spacetime



Electromagnetic radiation (EMR) models

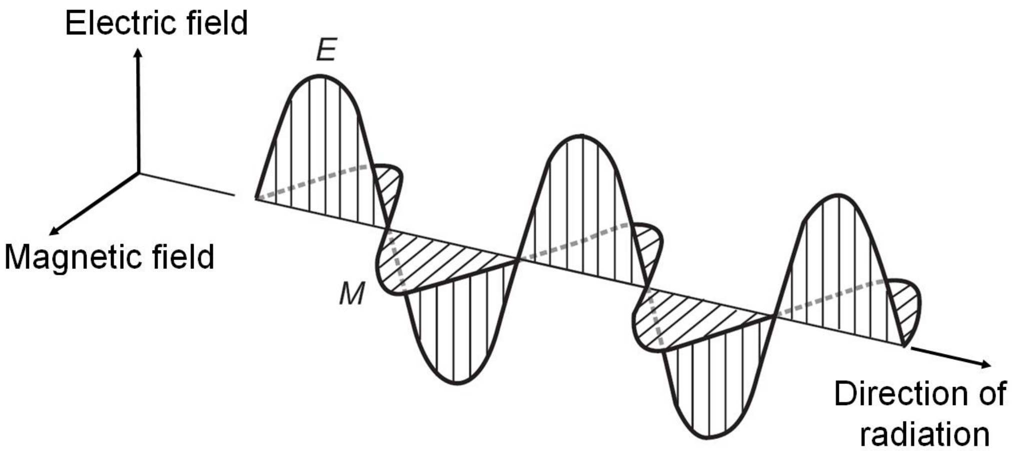
To understand how electromagnetic radiation is produced, how it propagates through space, and how it interacts with other matter, we will describe the processes using two different models:

- wave model, and
- particle model

EMR wave theory

All electromagnetic radiation has fundamental properties and behaves in predictable ways according to the basics of wave theory.

Electromagnetic waves consist of both an electric wave and a magnetic wave. The two waves oscillate at right angles to one another, and as the wave travels through space, energy gets swapped between the electric and magnetic waves.



EMR wave theory

All electromagnetic energy travels at the speed of light, which is…?

EMR wave theory

All electromagnetic energy travels at the speed of light, which is 300,000,000 m/s

Two characteristics of electromagnetic waves are:

- Wavelength (λ) is formally defined as the distance between maximums (or minimums) of a roughly periodic pattern and is normally measured in micrometers (µm) or nanometers (nm)

- Frequency (*f*) is the number of wavelengths that pass a point per unit time, measured in cycles per second or Hertz (Hz).

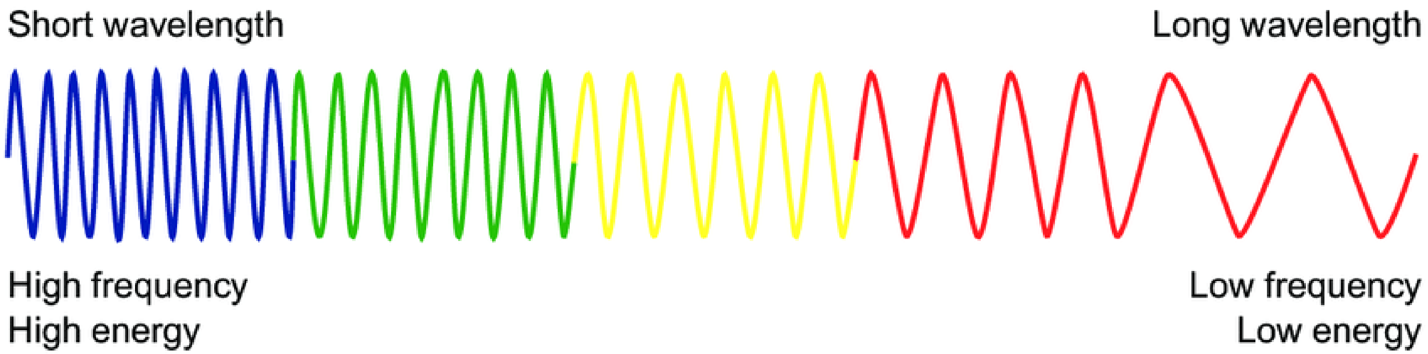
Note: Frequency is inversely proportional to wavelength

EMR wave theory

Since the speed of light is constant, the relationship between wavelength and frequency is:

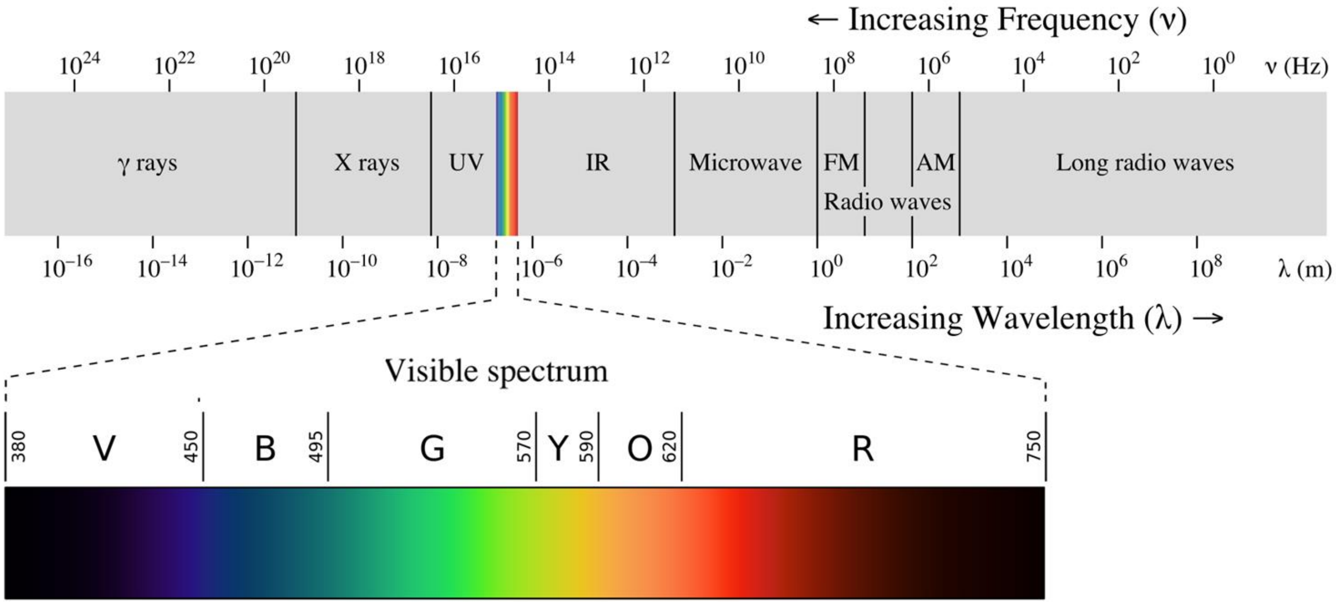
$$c = \lambda \times f$$

c = speed of light (300,000,000 m/s or 3 x 10^8 m/s)
f = frequency (cycles per second)
λ = wavelength



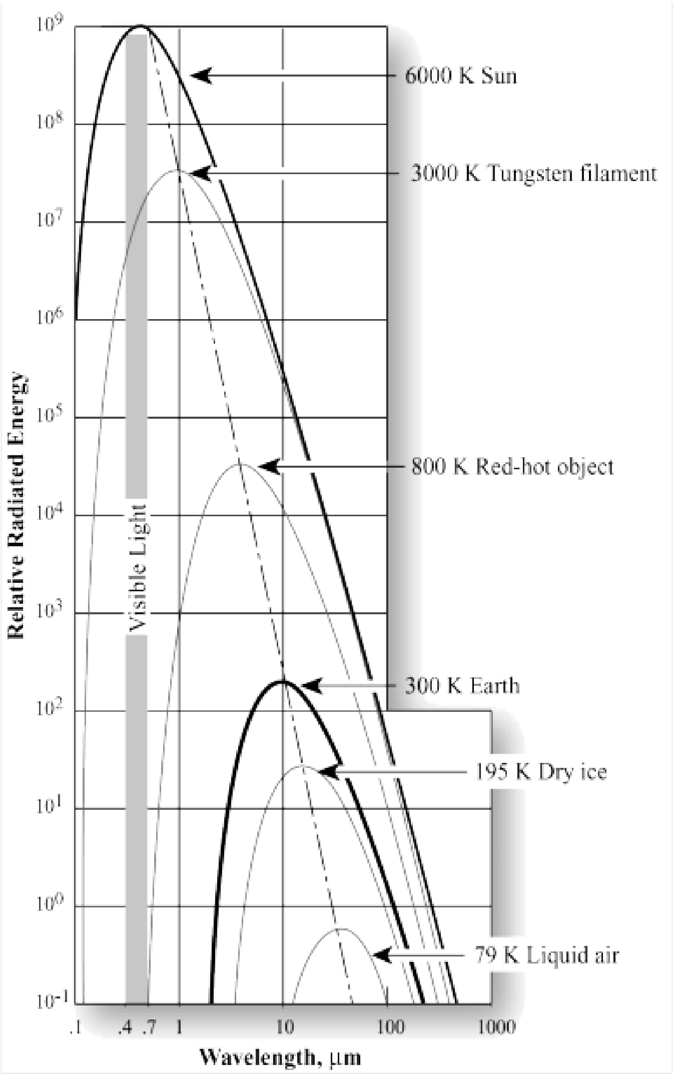
EMR wave theory

Electromagnetic radiation outside the range 0.38 to 0.76 µm is not visible to the human eye.



EMR wave theory: Blackbody concept

- All materials with temperature above absolute zero emit radiation
- Blackbody: A theoretical object which radiates electromagnetic energy of all wavelengths with perfect efficiency
- The total amount of radiation energy emitted by an object such as the Sun or the Earth is a function of its temperature.



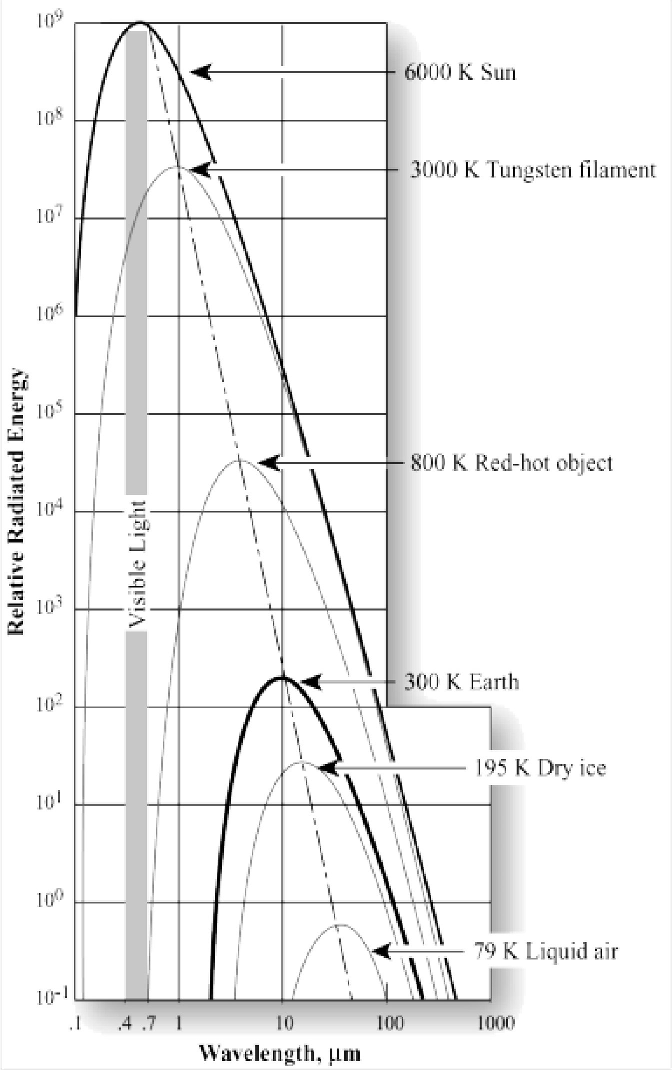
EMR wave theory: Stefan-Boltzmann law

The total emitted radiation from a blackbody per unit surface area (i.e. area under curve) is proportional to the fourth power of its absolute temperature (degrees Kelvin). This is known as the Stefan-Boltzmann law (measured in W m^{-2}):

$$M_\lambda = \sigma T^4$$

(σ is the Stefan-Boltzmann constant:

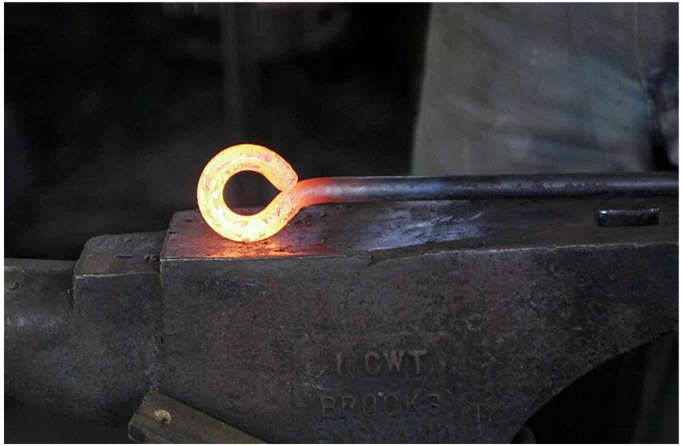
5.6697×10^{-8} W $m^{-2}K^{-4}$)

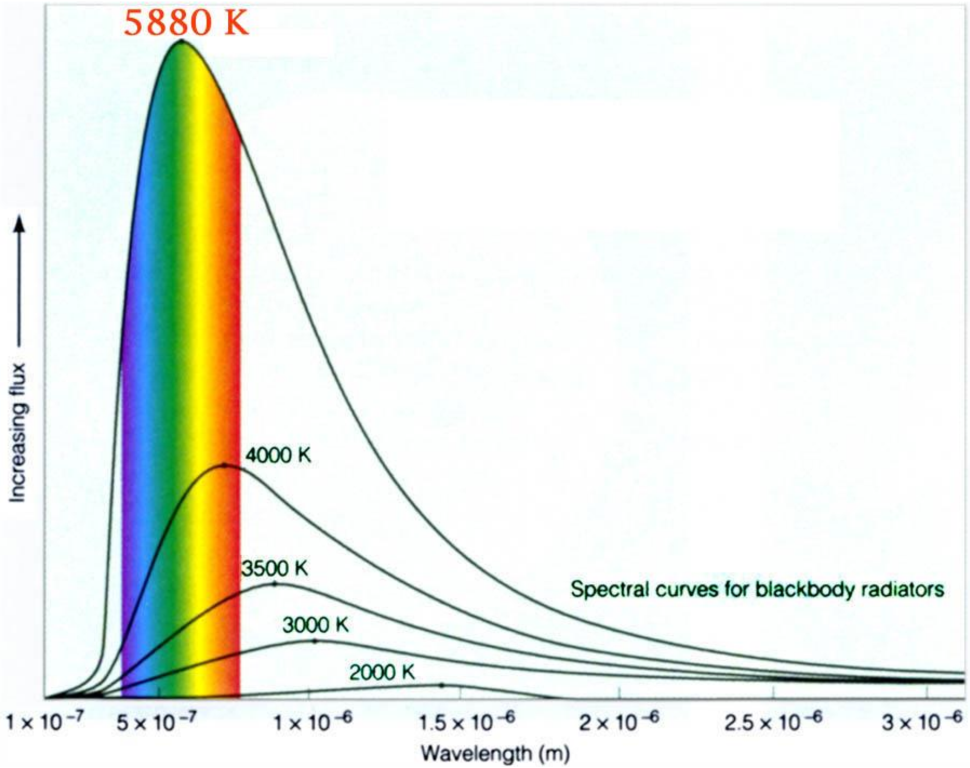


EMR wave theory: Plank's law

The black body emits a temperature-dependent spectrum of light

i.e. as the temperature of the object increases, the dominant wavelength gets shorter.





EMR wave theory: Emissivity

However, relatively few objects on Earth are blackbodies. We must know an object's emissivity (ε): ability of an object to radiate energy, on a scale of 0 to 1; a blackbody's emissivity is 1.0.

Therefore, a more accurate Stefan-Boltzmann law is written as:

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How much energy are we radiating (assume skin has emissivity of 0.98)?

$$M_\lambda = 5.6697 \times 10^{-8} * (310^4) * 0.98 = 513 \text{ W m}^{-2}$$

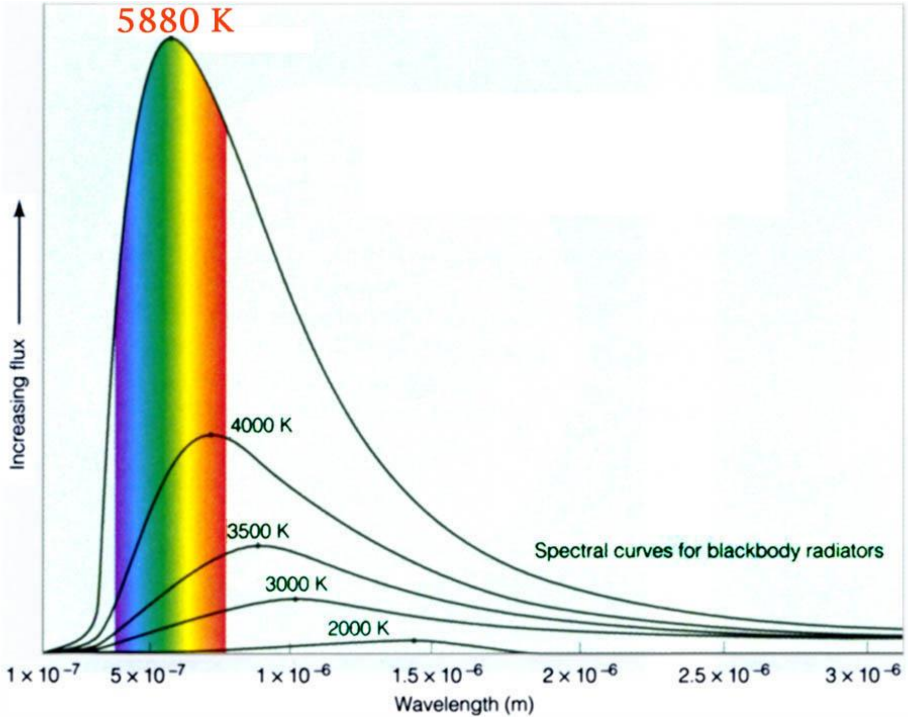
EMR wave theory: Wien's Displacement Law

- A formula used to calculate the dominant wavelength of a blackbody.

$$\lambda_{max} = k / T$$

k is a constant: 2898 µm K

THE POINT: As the temperature of an object increases, its dominant wavelength shifts towards shorter wavelengths



EMR wave theory: Questions

1a) Calculate the total energy emitted by the Sun (5880 K)

1b) Calculate the total energy emitted by the Earth (288 K)

2a) Calculate the dominant wavelength emitted by the Sun (5880 K)

2b) Which supergiant star is hotter? Rigel (blue) or Betelgeuse (red)?

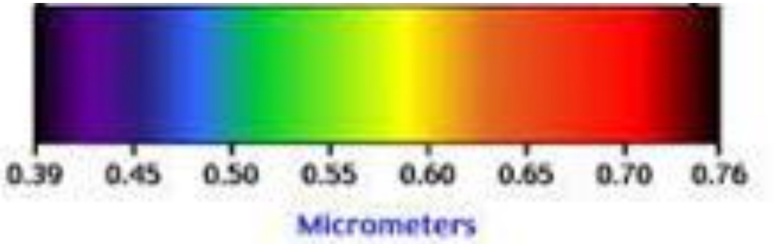
2c) What is the optimal wavelength for remote sensing of mammals (310 K)?

$$M_\lambda = \sigma T^4$$

$$\lambda_{max} = k / T$$

$$\sigma = 5.6697 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4}$$

$$k = 2898 \text{ µm K}$$



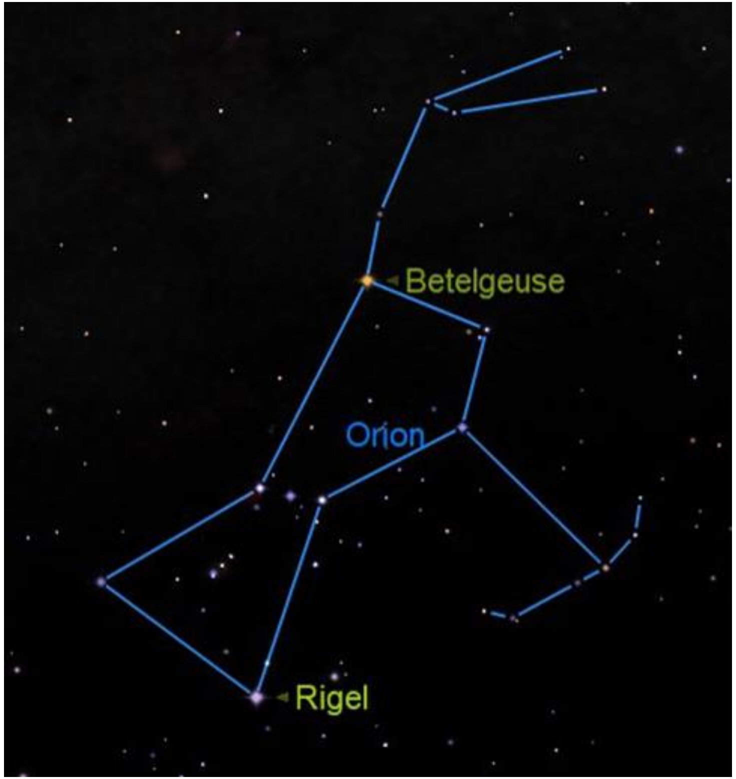
Why is this useful?

2a) Peak emission wavelength of the Sun is about 500 nm which is in the green portion of the spectrum near the peak sensitivity of the human eye.

2b) Rigel is a young, hot star (~12100 K) while Betelgeuse is an old, cool star (~3300 K).

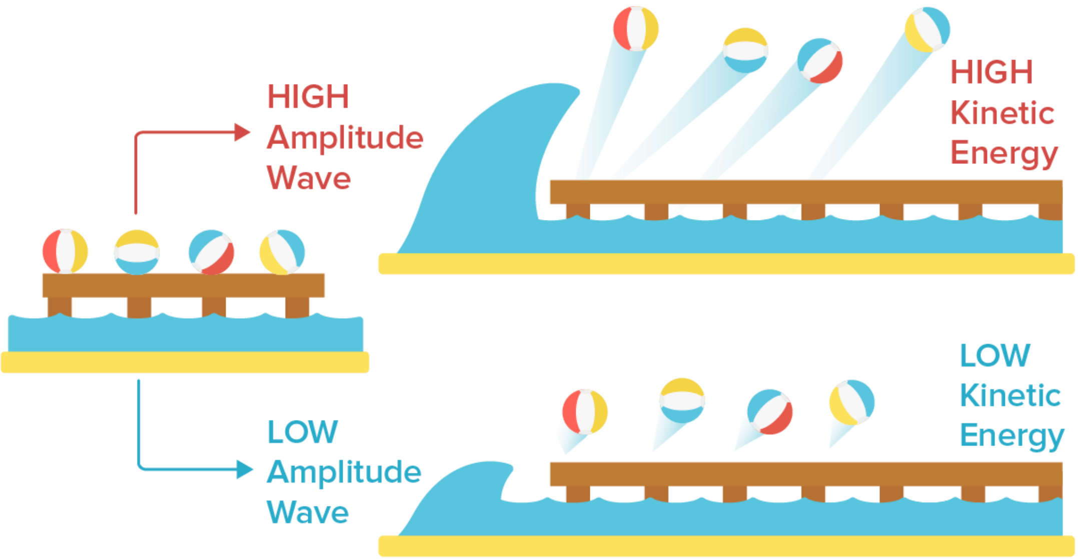
2c) Mammals with a skin temperature of about 300 K emit peak radiation in the far infrared which is what pit viper snakes sense.

THE POINT: Wave theory of electromagnetic radiation is a useful model



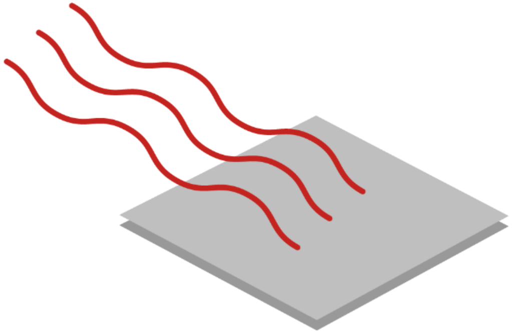
Problems with wave theory: interactions with matter

- Based on the wave theory of light, 19th-century physicists theorized that the oscillating electric field of a light wave heated electrons, causing them to vibrate, eventually freeing them from the metal surface



Photoelectric effect experiments

- But no matter the intensity of red light, they could not eject an electron from certain types of metal
- A result at odds with the predictions based on the classical description of light as a wave



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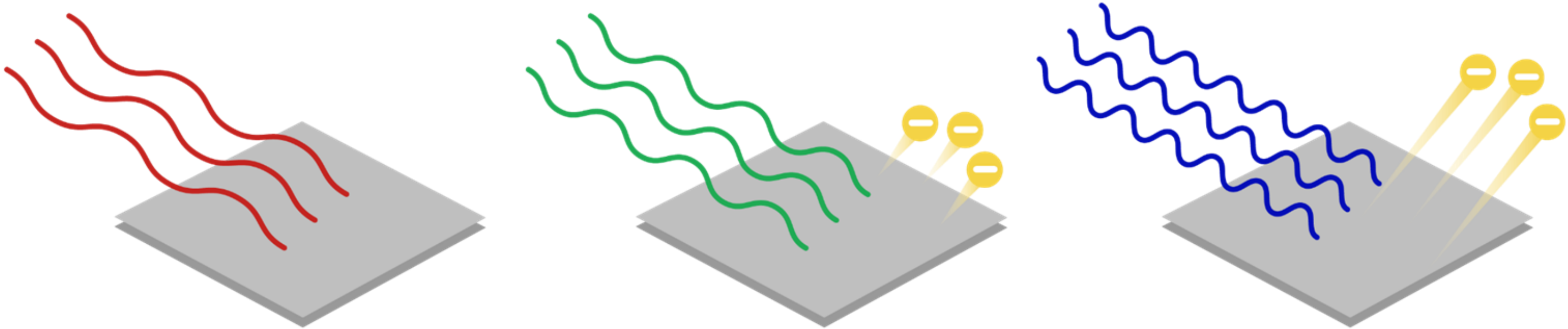


Particle model theory of electromagnetic energy

Quantum theory of electromagnetic radiation:

- Energy is transferred in discrete packets called quanta or photons.

- The relationship between the frequency of radiation (*f*) expressed by wave theory and energy of a quantum (*Q*, measured in joules) is:

$$Q = h * f$$

(h is the Planck constant: 6.626×10^{-34} J s^{-1})

All remote sensing instruments, including conventional cameras, measure the energy of photons, not waves.

Particle model theory of electromagnetic energy

We can combine the wave theory equation with the particle theory equation because they both call for frequency:

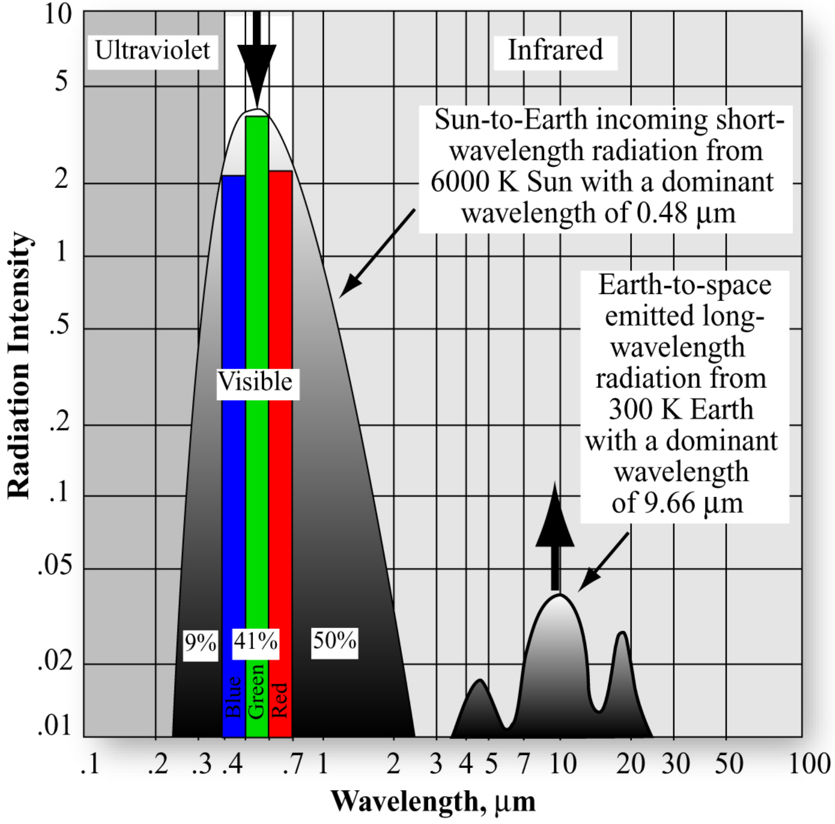
$$c = \lambda * f \qquad\qquad Q = h * f$$

Thus, we can express the wavelength associated with a quantum of energy as:

$$Q = (h * c) / \lambda$$

THE POINT: The energy of a photon is inversely proportional to its wavelength, i.e. the longer the wavelength, the lower its energy content.

Particle model theory of electromagnetic energy



THE POINT: Long wavelength EMR (IR) is harder to detect than short wavelength EMR (visible, UV)

We have to accept that EMR obeys <u>wave-particle duality</u>