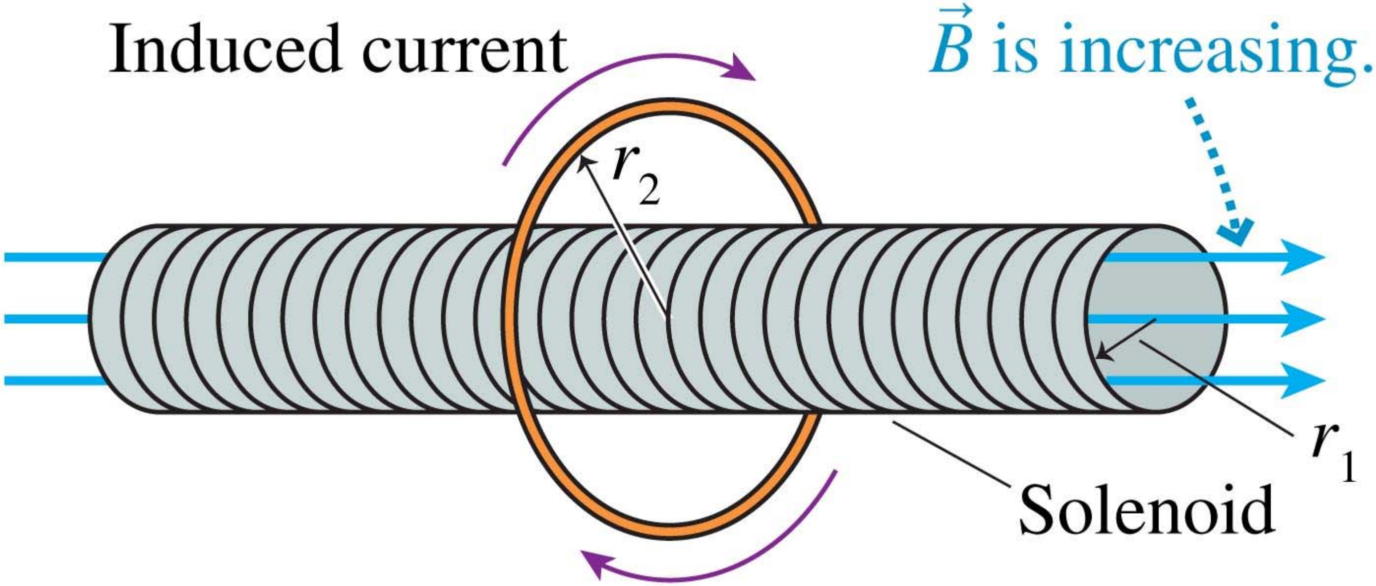
General Physics II

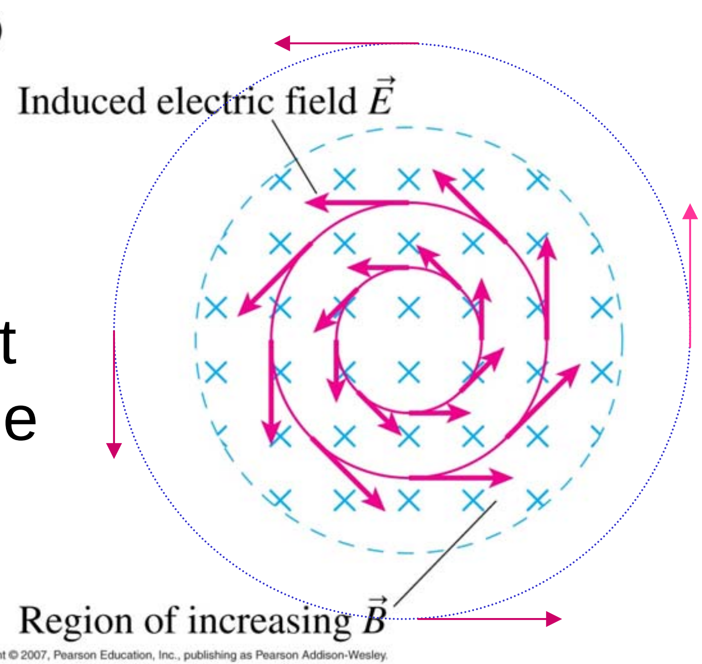
Electromagnetic Induction and
Electromagnetic Waves

Induced Electric Fields

- When a magnetic field changes through a *stationary* conducting loop, there is an induced current. What causes the emf that results in the motion of the charge carriers? It is *not* motional emf due to a magnetic force because the conductor is not moving.
- If not a magnetic force, then the force exerted on the charges must be an *electric force.* An electric field is induced when a magnetic field changes with time. This electric field exerts an electric force on the charges, which causes the induced current.
- Note that this is induced electric field is not like electric fields we have seen before, which were caused by positive and negative charges. Induced electric fields arise from changing magnetic fields and have nothing to do with charges.
- An electric field can therefore be induced even in the absence of any conducting loop, i.e., in empty space!

Induced Electric Fields





- Note that the electric field also exists *outside* the region where the field is confined. This is what causes the induced current in the conducting loop above.

The Origin of Electromagnetic Waves

- A changing magnetic field induces an electric field. J. C. Maxwell hypothesized that a changing electric field induces a magnetic field. He realized that under the right conditions, these fields could mutually induce each other in a self-sustaining way, in the absence of any charges. Maxwell found that these self-sustaining electric and magnetic fields constitute an *electromagnetic wave*, which travel in vacuum at a speed

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3.00 \times 10^8 \text{ m/s},$$

  i.e., the speed of light!
- Thus, Maxwell discovered that light is an electromagnetic wave!

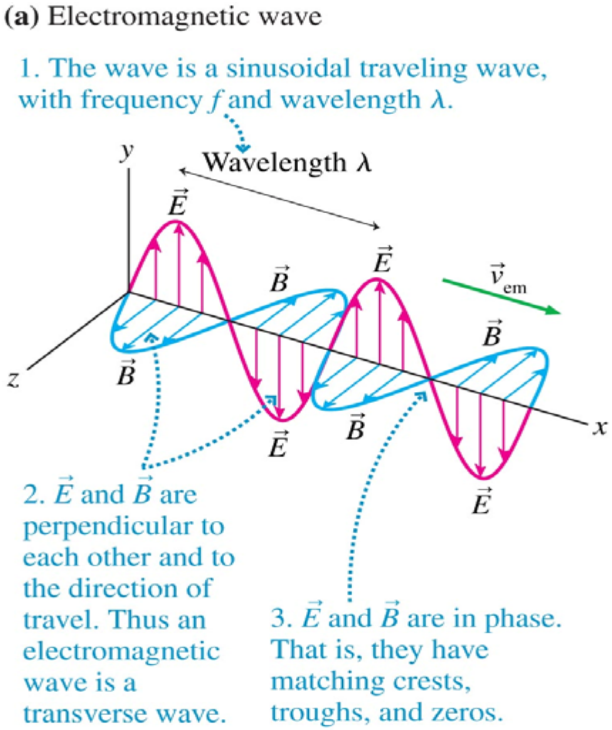
Electromagnetic Waves

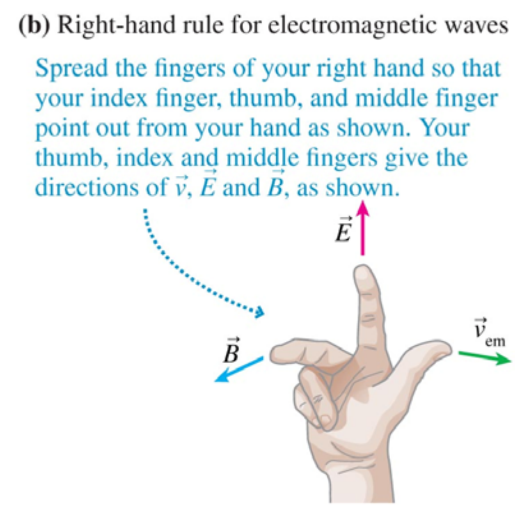
- Electromagnetic waves are *transverse* waves because the electric and magnetic fields oscillate in planes perpendicular to the direction of travel of the wave. At any point on the wave,

$$E = cB.$$

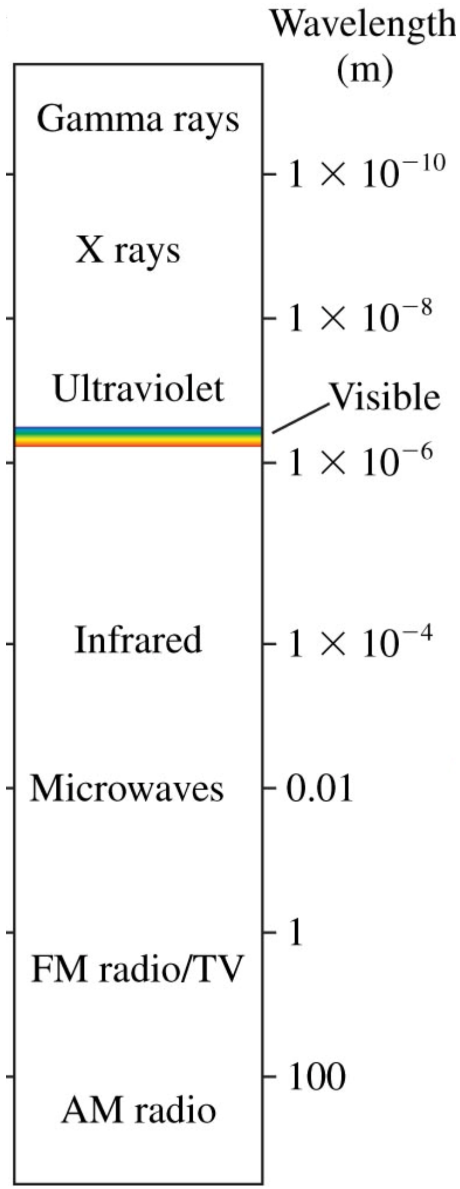
- The electric field, magnetic field, and direction of travel of the wave have directions given by a right hand rule, as shown.
- Electromagnetic waves can have any frequency. This infinite range of frequencies constitutes the *electromagnetic spectrum.*
- Frequency *(f)*, wavelength (λ), and speed (*c*) are related by

$$c = \lambda f.$$





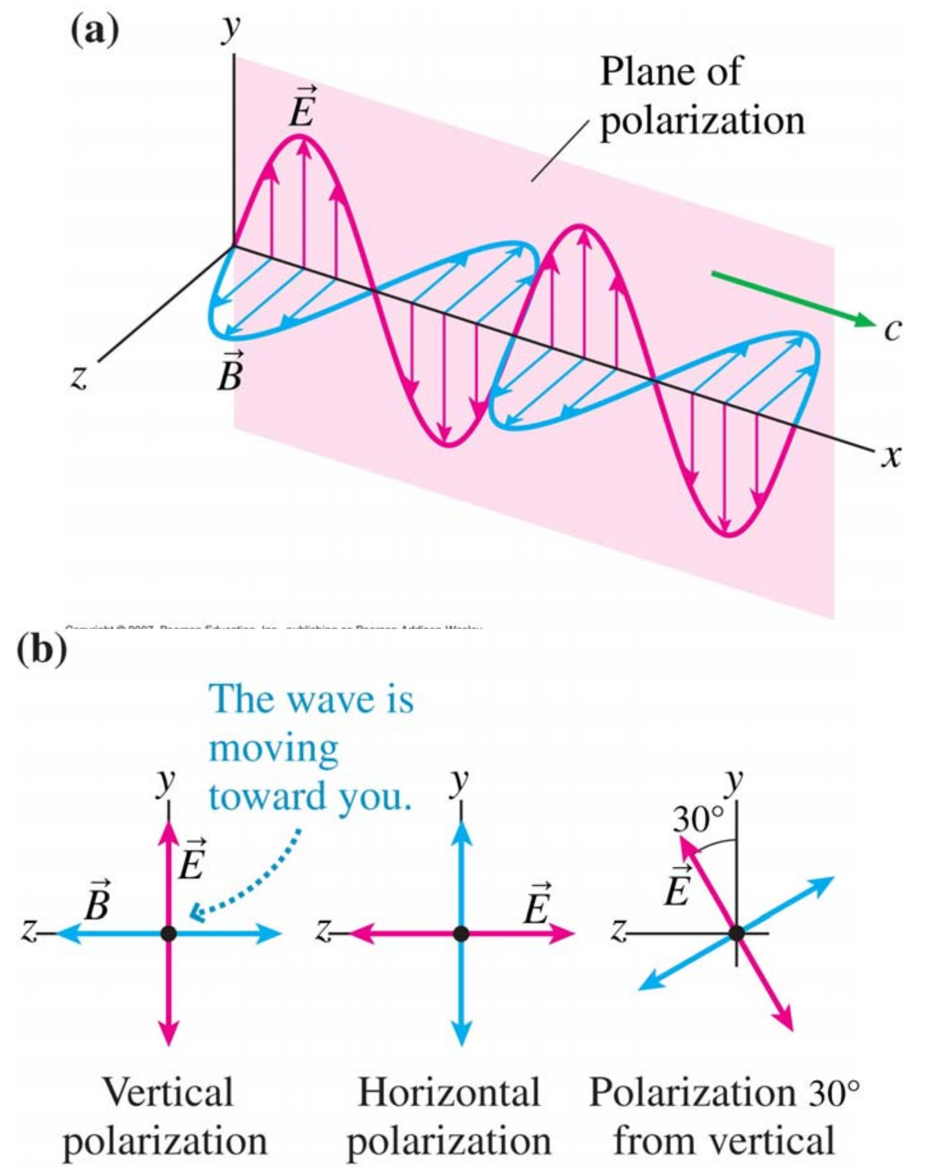
Electromagnetic Spectrum



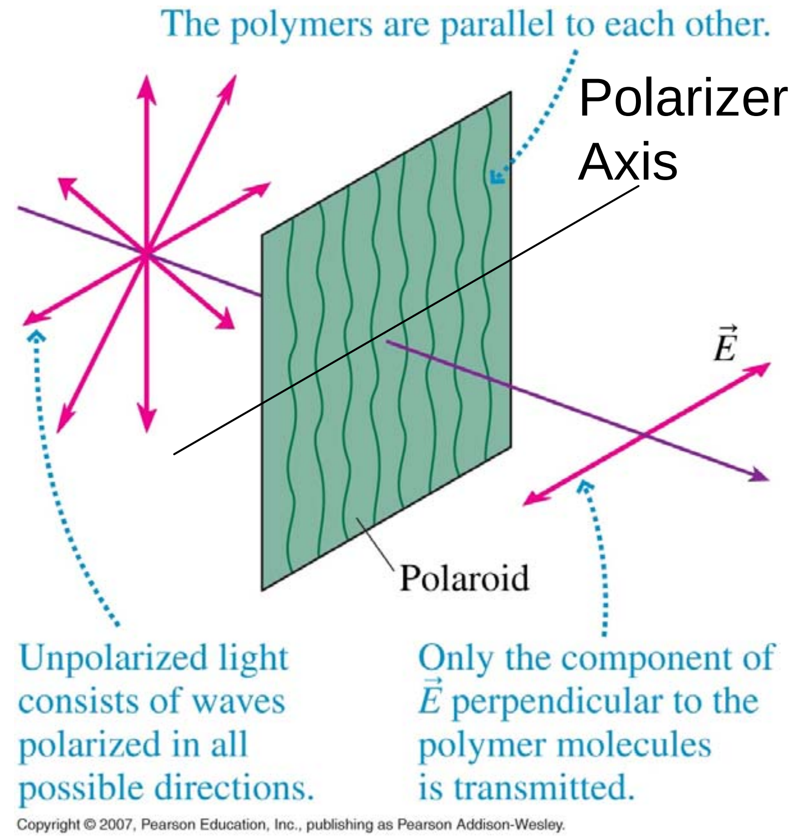
Workbook: Chapter 25, Question 13, 15

Polarization

- The polarization of an electromagnetic wave is the plane in which the electric field vectors lie. For example, the wave shown to the right is vertically polarized, with the electric field vectors oscillating along the *y*-axis.
- The plane of polarization can be any plane, as shown in the lower figure.



Unpolarized and Polarized Waves



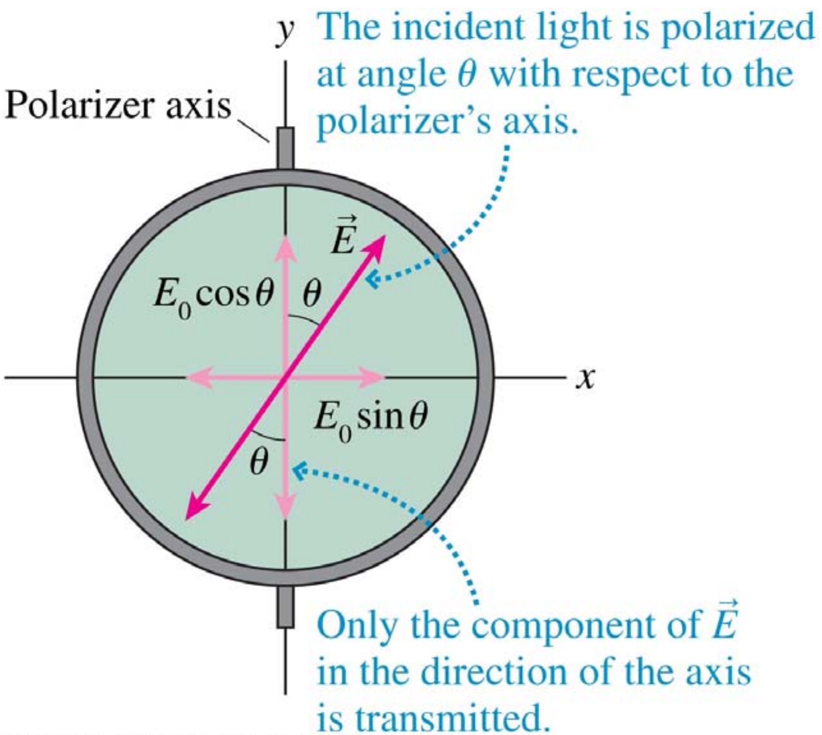
- Light from most sources, e.g., light bulbs, is said to be *unpolarized.* This means that the light is a combination of waves with planes of polarization in all possible directions.
- If light waves pass through a *polarizing filter*, the emerging waves will be polarized in a plane parallel to the *axis* of the polarizer.
- Only the electric field component parallel to the polarizer axis is transmitted. The perpendicular component is absorbed. Since all possible polarization directions are represented in unpolarized light, 50% of ***unpolarized*** light is transmitted by a polarizing filter and 50% is absorbed.

Malus's Law

- If *polarized light* is incident on a polarizing filter, only the component of the incident electric field parallel to the polarizer axis will be transmitted. Thus,

  $$E_{transmitted} = E_{incident} \cos\theta,$$

  where θ is the angle between the polarization direction of the incident light and the axis of the polarizer and *E* is the magnitude of the electric field.



- Intensity is proportional to the square of the electric field magnitude, so

  $$I_{transmitted} = I_{incident} \cos^2\theta.$$

  (Malus's law)

Applying Malus's Law

- If the intensity of the incident *unpolarized* light is I_0, then $I_0/2$ is transmitted through the first polarizer. Thus, $I_0/2$ will be incident on the second polarizer.
- From Malus's law,

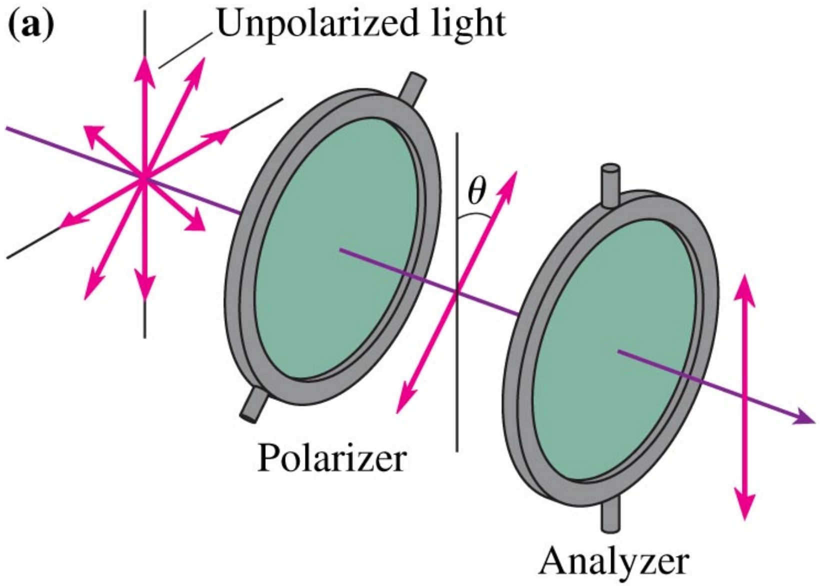
  $$I_{transmitted} = I_{incident} \cos^2\theta.$$

  The intensity transmitted through the second polarizer is then

  $I_{final} = (I_0/2)\cos^2\theta.$

  Note that if $\theta = 90°$, $I_{final} = 0$.

  The polarizers are then said to be *crossed*.



Workbook: Chapter 25, Question 18

Textbook: Chapter 25, Probs. 29, 31

Photon Model of Electromagnetic Waves

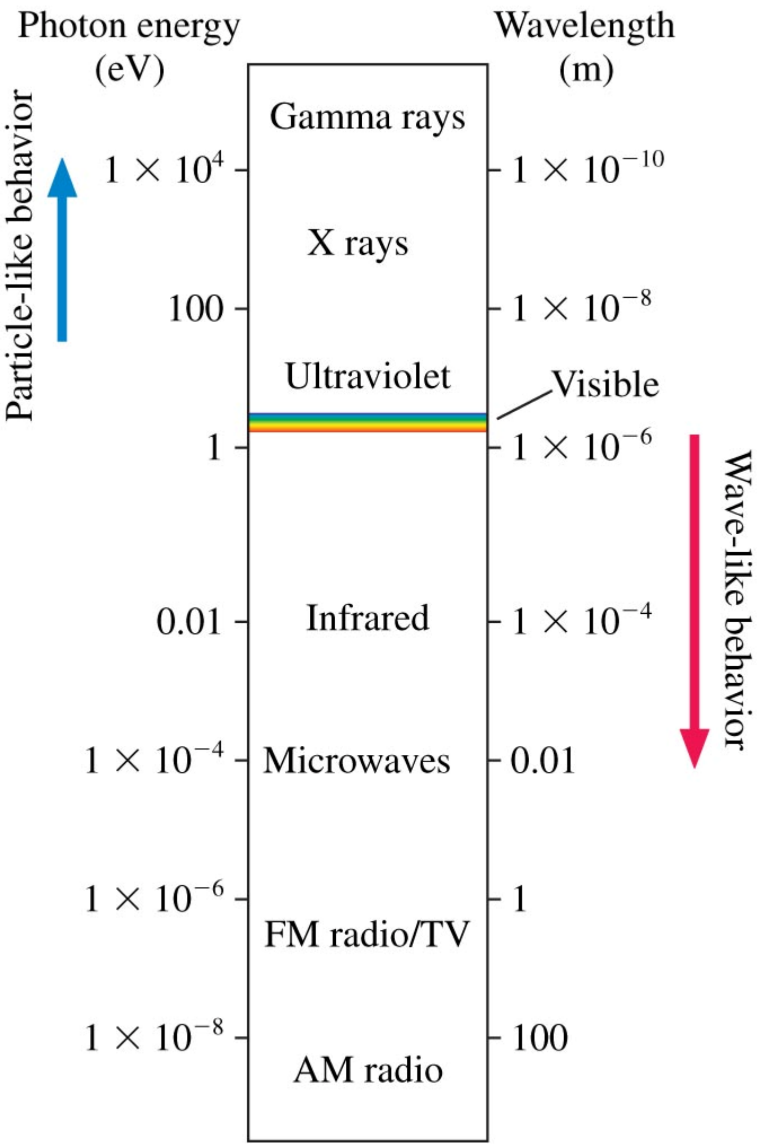
- In many cases, when electromagnetic waves interact with single electrons in metals or individual atoms, they exhibit particle-like characteristics.
- The waves behave as if they are made up of *discrete units with no mass and a fixed energy* that is independent of the amplitude (maximum magnitude) of the electric (or magnetic) field.
- These discrete units are called ***photons.*** The energy of a photon is given by

$$E_{photon} = hf,$$

where f is the frequency and $h = 6.63\times10^{-34}$ J·s is Planck's constant.
- We shall employ the photon model when we study quantum physics.

Electromagnetic Spectrum

- As said previously, the electromagnetic spectrum encompasses all the frequencies of electromagnetic waves.
- The spectrum is divided into several smaller ranges of frequencies and each of these ranges is given a name, e.g., *microwaves*.
- The higher the frequency (or, smaller the wavelength), the more likely photon behavior will be exhibited.



Thermal Radiation

- Electromagnetic waves spanning the entire spectrum are emitted by *all objects at temperatures above absolute zero*. The higher the temperature, the greater the relative amount of higher frequencies (smaller wavelengths) emitted.
- The wavelength of maximum intensity shifts to smaller values as the temperature increases.