

Answer to Essential Question 22.1 In the denominator under the square root in Equation 22.1, units of $(\text{T m/A}) \times \text{C}^2/(\text{N m}^2)$ become $\text{T C}^2/(\text{A N m})$, canceling a factor of meters. $1 \text{ A} = 1 \text{ C/s}$, so this leads to units of $\text{T C s}/(\text{N m})$. The fact that $E/B = v$ tells us that electric field units of N/C , divided by magnetic field units of T , can be replaced by m/s . This leads to units of s^2/m^2 . Bringing these up to the numerator, we invert the units to m^2/s^2 , and taking the square root gives the required units of the speed of light, m/s .

22-2 Electromagnetic Waves and the Electromagnetic Spectrum

Although we often focus on light, because we rely on light so much as we interact with the world around us, light is just one example of an electromagnetic wave. As shown in Figure 22.2, we classify electromagnetic waves into a variety of categories based on their frequency (or wavelength), as well as on how the waves are produced.

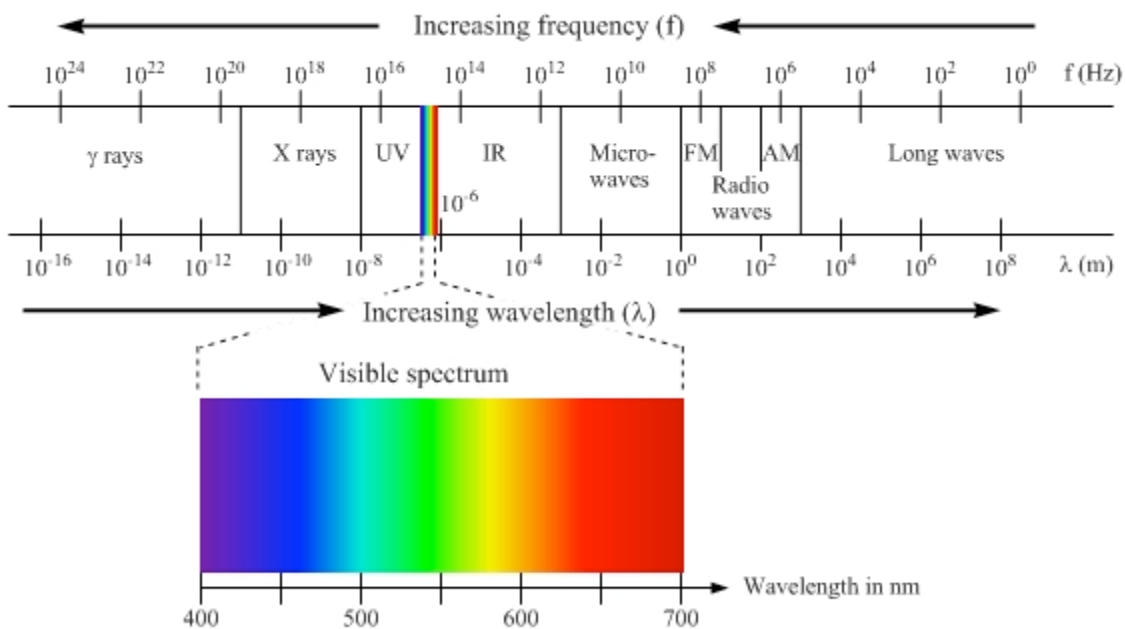


Figure 22.2: An overview of the electromagnetic spectrum. Note that the diagram covers 24 orders of magnitude in both frequency and wavelength.

Our eyes are sensitive to electromagnetic (EM) waves that have wavelengths in the visible spectrum, between 400 and 700 nm, but our bodies can be affected by EM waves in other ways, too. We have some sensors on the backs of our hands, in particular, that are sensitive to infrared radiation, which we can use to tell, without touching it, whether an object is hot. Ultraviolet radiation, in small doses, can produce tanning of the skin, but it is also associated with premature aging of the skin and cataracts. As you move to the left on the diagram in Figure 22.2, the energy associated with packets of EM radiation increases, and thus x-rays and gamma rays have enough energy to pass into and through our bodies. This makes them useful, because they can be used for diagnostic imaging (x-rays) or in cancer treatment (gamma rays), but they also have enough energy to be able to change DNA molecules, which is generally not a good thing. At the other end of the spectrum, we are generally insensitive to EM waves that have a longer wavelength than microwave radiation, such as radio waves.

Electromagnetic waves are produced by accelerating charged particles. Visible light, for instance, can be produced by electrons changing energy levels inside atoms, or by vibrating atoms. X-rays are produced by firing electrons at a metal target, with the x-rays being given off when the electrons are slowed abruptly by the metal atoms. Radio waves are produced by connecting a source of oscillating voltage to one or more metal rods (antennas), causing electrons to oscillate back and forth along the rod. The charge separation is associated with the production of electric fields, while the current associated with the moving electrons generates the magnetic fields.

Properties of electromagnetic waves

Figure 22.3 shows a snapshot of a particular kind of electromagnetic wave, known as a plane (or linearly) polarized wave. The vectors parallel to the y - z plane represent the electric field vectors in the wave at the particular instant shown, while the vectors parallel to the x - y plane represent the magnetic field vectors at the same instant. Note that all the electric field vectors are in one plane, while all the magnetic field vectors are aligned in a plane that is perpendicular to the plane defined by the electric field vectors.

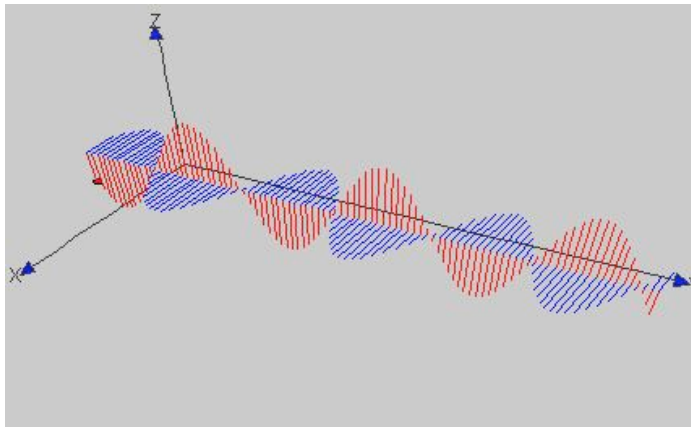


Figure 22.3: A linearly-polarized electromagnetic wave. The lines parallel to the y - z plane represent the electric field vectors, while the lines parallel to the x - y plane represent the magnetic field vectors. The wave is shown at a particular instant in time. As time goes by, the wave propagates to the right at the speed of light.

Some general features of electromagnetic waves include:

- the energy carried by an electromagnetic wave is divided equally between the electric fields and the magnetic fields.
- the electric and magnetic fields are in phase with one another.
- both the electric field vectors and the magnetic field vectors are perpendicular to the direction of propagation of the wave. Thus, an EM wave is classified as a transverse wave.
- the direction of propagation can be determined by applying a right-hand rule. Start with the fingers on your right hand pointing in the direction of the electric field at a particular point on the wave. If you align your hand so that you can curl your fingers from the electric field direction to the magnetic field direction, your thumb, when it is stuck out, will point in the propagation direction of the wave.
- at all points on the wave, the ratio of the electric field to the magnetic field is given by

$$c = \frac{E}{B}. \quad (\text{Eq. 22.2: Ratio of electric and magnetic fields in an EM wave})$$

Related End-of-Chapter Exercises: 15 – 17.

Essential Question 22.2: (a) What is the wavelength of an x-ray beam if its frequency is 1×10^{18} Hz? How does it compare to the wavelength of the radio wave emitted by the FM radio station WBUR, which broadcasts at a frequency of 90.9 MHz? Assume both waves travel through the air. (b) If the electric field vectors in a linearly-polarized laser beam oscillate with an amplitude of 75 millivolts / meter, what is the amplitude at which the magnetic field vectors in the beam oscillate?