Hypotheses concerning light and polarization

In Table 25.1 we found that polarization effects can only be observed with transverse waves and not longitudinal waves. We just found from the light polarization experiments in Table 25.2 that light seems to behave like a transverse wave with amplitude A and intensity $I \propto A^2$. However, since light can travel through a vacuum (for example, when it travels from the Sun to Earth), what is actually vibrating in a light wave?

To answer this question, we need to look carefully at how a transverse wave travels through a medium, such as a Slinky. When one coil is displaced, it pulls the next coil in a direction perpendicular to the direction of propagation of the wave. That coil then does the same to the coil next to it, and so on. The individual vibrating coils (analogous to the particles of the medium) exert elastic forces on each other. These elastic forces point perpendicular to the propagation direction of the wave and accelerate the displaced coils back toward equilibrium.

However, light can travel through a vacuum—a medium with no particles at all. How then can it be a transverse wave? Here are two hypotheses.

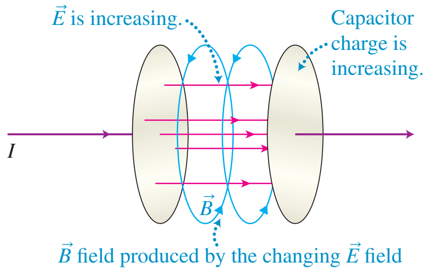
1. Light is actually a mechanical vibration that travels through an elastic medium. This medium is completely transparent and has exactly zero mass (just like the vacuum). This medium will be called *ether* (not related to the chemical compound of the same name).
2. A light wave is some new type of vibration that does not involve physical particles vibrating around equilibrium positions due to restoring forces being exerted on them.

The next section will show how studies of electricity and magnetism helped test the second hypothesis.

25.2 Discovery of electromagnetic waves

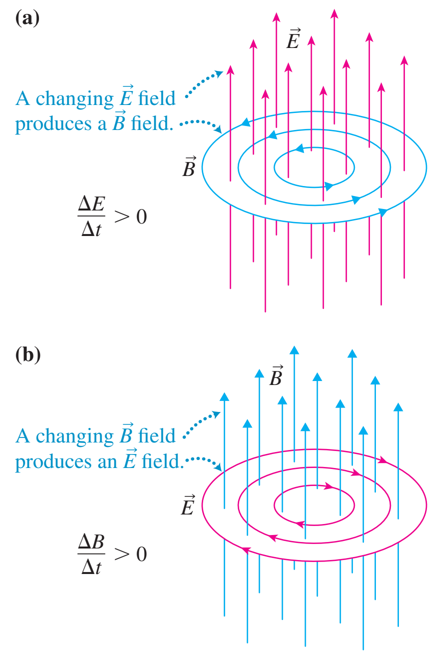
Before the second half of the 19th century, the investigations of light and electromagnetic phenomena proceeded independently. However, around 1860 the work of a British physicist, James Clerk Maxwell (1831–1879), led to the unification of those phenomena and helped finally answer the question of how a transverse wave can propagate in a vacuum. We know from our study of electromagnetic induction (Chapter 21) that Michael Faraday introduced the concept of a field and the relationship between electric and magnetic fields. According to Faraday, *a changing magnetic field can produce an electric field*. Subsequently, in 1865 Maxwell suggested a new field relationship: *a changing electric field can produce a magnetic field*. This idea was motivated by a thought experiment devised by Maxwell in which he imagined what would happen in the space between the plates of a charging or discharging capacitor. He suggested that the changing electric field between the capacitor plates could be viewed as a special nonphysical current, but one that would still produce a magnetic field (**Figure 25.3**). This magnetic field was first detected in 1929 but not measured precisely until 1985 due to its extremely tiny magnitude. Maxwell summarized this new idea and other electric and magnetic field ideas mathematically in a set of four equations, now known as Maxwell's equations. The equations are written using calculus, but we can summarize them conceptually:

FIGURE 25.3 A changing electric field produces a magnetic field.



1. Stationary electric charges produce a constant electric field. The $\vec{E}$ field lines representing this electric field start on positive changes and end on negative charges.
2. There are no individual magnetic charges (magnetic monopoles).
3. A magnetic field is produced either by electric currents or by a changing electric field (Figures 25.3 and **25.4a**). The $\vec{B}$ field lines that represent the magnetic field form closed loops and have no beginnings or ends.
4. A changing magnetic field produces an electric field. The $\vec{E}$ field lines representing this electric field are closed loops (Figure 25.4b).

FIGURE 25.4 Changing $\vec{E}$ and $\vec{B}$ fields produce $\vec{B}$ and $\vec{E}$ fields.



Producing an electromagnetic wave

Maxwell's equations had important consequences. First, the equations led to an understanding that a changing electric field can produce a changing magnetic field, which in turn can produce a changing electric field, and on and on in a sort of feedback loop (**Figure 25.5**). This feedback loop does not require the presence of any electric charges or currents. Maxwell investigated this idea mathematically using the four equations, and to his surprise he found they led to a wave equation similar to Eq. (11.4) in which the electric and magnetic fields themselves were vibrating. The speed of propagation of these waves in a vacuum turned out to be a combination of two familiar constants: $v = (1/\sqrt{\epsilon_0\mu_0})$, where the constants $\epsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2$ and $\mu_0 = 4\pi \times 10^{-7}\ \text{N}/\text{A}^2$ relate to the electric and magnetic interactions of electrically charged particles in a vacuum. The constant ϵ_0 is the **vacuum permittivity** and is related to Coulomb's constant k_C through the relationship

$$\epsilon_0 = \frac{1}{4\pi k_C}$$

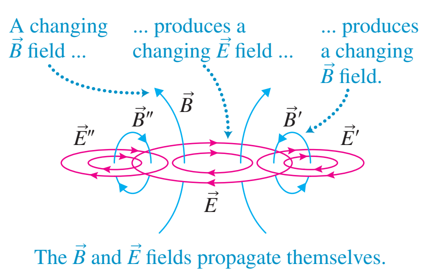
(See Chapter 17 for more on vacuum permittivity.) The constant μ_0 is the **vacuum permeability**. We discussed vacuum permeability in the chapter on magnetism (Chapter 20). When Maxwell inserted the values of the constants into the expression for the speed of electromagnetic waves, he obtained

$$v = \frac{1}{\sqrt{\epsilon_0\mu_0}} = \frac{1}{\sqrt{(8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2)(4\pi \times 10^{-7}\ \text{N}/\text{A}^2)}}$$

$$= \sqrt{9.00 \times 10^{16}\,\frac{\text{N}\cdot\text{m}^2\cdot\text{A}^2}{\text{C}^2\cdot\text{N}}} = \sqrt{9.00 \times 10^{16}\,\frac{\text{m}^2\cdot\text{A}^2}{\text{A}^2\cdot\text{s}^2}} = 3.00 \times 10^8\ \text{m/s}$$

At the time Maxwell did this calculation, the speed of light in air had already been measured and was consistent with this value. Could it be that light is an electromagnetic wave? This was the second testable consequence of Maxwell's model. *If* the relationship between the changing electric and magnetic fields suggested by the model is correct, *then* a change in either of these fields could generate an electromagnetic wave that would propagate at the speed of light. This prediction, if consistent with the experiment, would support the hypothesis that light is an electromagnetic wave composed of vibrating electric and magnetic fields!

FIGURE 25.5 The changing $\vec{B}$ and $\vec{E}$ fields can spread without any charges or currents.

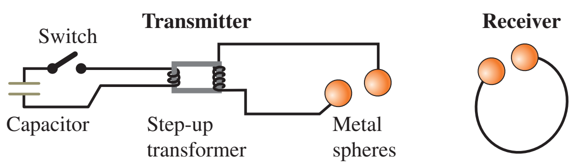


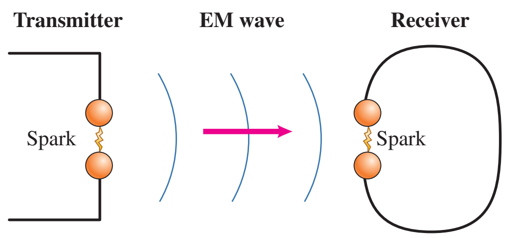
Testing the hypothesis that light can be modeled as an electromagnetic wave

The German physicist Heinrich Hertz (1857–1894) was the first to test the hypothesis. In 1888 Hertz built a device called a **spark gap transmitter** and used it in his experiments. His work is summarized in Testing Experiment **Table 25.3**.

TESTING EXPERIMENT TABLE 25.3 Hertz's experiments

Testing experiment	Prediction	Outcome
Hertz used a switch to connect a transmitter with a charged capacitor to the primary coil of a transformer. He connected the secondary coil of the transformer to two metal spheres. When he discharged the capacitor, the changing current through the primary coil induced a huge emf across the secondary coil, which in turn charged the spheres, causing them to spark. A receiver that consisted of two small metal spheres separated by a small gap and connected to a loop of wire was placed some distance from the metal transmitter spheres.	A spark between the transmitter spheres would indicate a large changing electric field between the spheres of the transmitter. If Maxwell's hypothesis was correct, then this changing electric field would produce an electromagnetic wave. When the wave reached the receiver loop, it would induce a current in the loop and cause a weak spark between the spheres of the receiver.	After hours in a dark room watching for a spark, Hertz eventually saw a spark between the receiver spheres.





Conclusion
That Hertz could see a spark between the spheres of the receiver in response to the spark between the spheres of the transmitter meant that something had traveled from the transmitter to the receiver.

Hertz's experiment was the first supporting evidence for the idea that electromagnetic waves existed. He performed many additional experiments to determine if the electromagnetic waves generated in his experiment had the same properties as light waves. The only difference he found was in their frequency—Hertz's waves had a much smaller frequency than visible light waves. Hertz used metal sheets of different shapes to observe reflection. He let the waves pass through different media and observed refraction. He performed an analog of a double-slit experiment and observed interference. He even observed polarization of the waves using a metal fence. Finally, he performed experiments to measure the speed of the propagation of the waves, which turned out to be $3.00 \times 10^8\ \text{m/s}$. These experiments supported the idea that light could be modeled as a transverse wave of vibrating electric and magnetic fields.

Maxwell's model of light as an electromagnetic wave seems to resolve the problem of what is vibrating in the light wave: the $\vec{E}$ field and the $\vec{B}$ field. Each field is vibrating perpendicular to the direction of travel of the wave. Thus we have a new model of light as a *transverse electromagnetic wave* that travels in a vacuum and in other media. In a vacuum, the speed of light is $3.00 \times 10^8\ \text{m/s}$.

The waves predicted by Maxwell and experimentally discovered by Hertz soon found a practical application. In 1892 Nikola Tesla used an improved version of Hertz's transmitter to conduct the first transmission of information via radio waves, one form of electromagnetic waves. By 1899 there was successful radio wave-based communication across the English Channel.

You might be curious about what happened to the idea of ether. Although it was no longer needed to explain the nature of light, it still remained in physics until 1905. We will return to the fate of ether in Chapter 26.