Chapter 25

Electromagnetic Waves

25.1 Polarization of waves

OALG 25.1.1 Observe and find a pattern

Watch the following video https://youtu.be/Fqt218pU410 and answer the following questions" Several experiments involving traveling waves on a Slinky are described below.

a. Construct a sketch for each experiment. The outcome is shown in the right column.

Experiment	**Sketch**	**The outcome**
A Slinky rests on its side on a table. One end is held away from the edge of the table. The Slinky end is shaken side to side, parallel to the table. Make a sketch of the process.		
The same as above except the Slinky is shaken up and down, perpendicular to the table.		
The same as above except the Slinky is shaken forward and backward, along the direction of the Slinky.		
The same as above except part of the Slinky on the table passes through a tube. The Slinky is shaken forward and backward, a longitudinal pulse.		

b. Devise a rule or rules that describe the pattern of conditions under which the pulse can continue across the table.

c. Read and interrogate Observational Experiment Table 25.1 and compare the patterns you found in part b to the patterns described in the table. What does the term "polarization of waves" mean? How are transverse and longitudinal waves different in terms of their ability to be polarized?

OALG 25.1.2 Test an idea

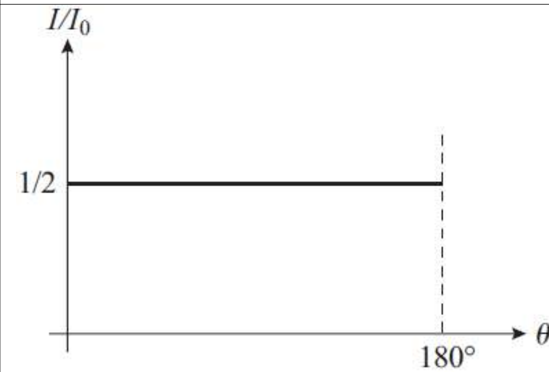
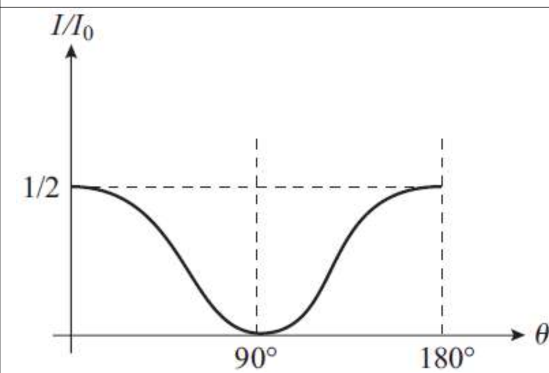
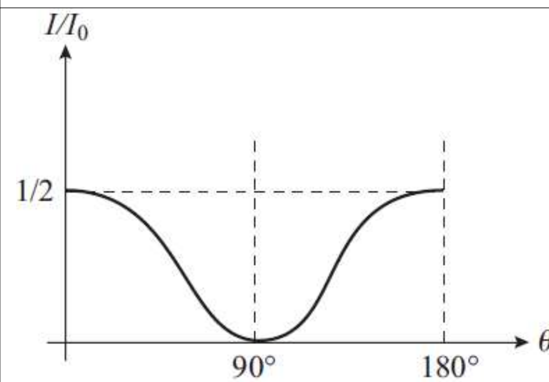
Light is either a transverse wave or a longitudinal wave. Watch the videos of several experiments https://youtu.be/suwX1pclDa4 that test these two hypotheses are described below. The experiments make use of a polarizer, a device made from material that prevents light waves from passing through if something in the wave is vibrating perpendicular to the axis of the polarizer.
a. Make predictions, based on each of the two hypotheses, about the brightness of the light once it has passed through the polarizer(s).

Experiment	Prediction if light is a transverse wave	Prediction if light is a longitudinal wave	Outcome
Light from a lightbulb shines on a polarizer and its brightness is detected on the other side.			The light reaching the other side of the polarizer is significantly dimmer.
The same as above except the polarizer is slowly rotated.			The light reaching the other side of the polarizer is significantly dimmer and does not change as the polarizer is rotated.
Light from a lightbulb shines on a polarizer. A second polarizer is positioned behind the first one. The second polarizer is slowly rotated relative to the first.			The light is dimmer overall but also fades in and out (depending on the angle) completely as the second polarizer is rotated.

b. Make a judgment about each of the two hypotheses. Which (if any) of them are disproved by these experiments?

OALG 25.1.3 Observe and find a pattern

Experiments involving light waves passing through one or more ideal polarizers are described in the table below. The light intensity I is measured at a fixed distance from the lightbulb using a device known as a photometer. I_0 is the intensity without a polarizer between the lightbulb and the photometer.

Experiment	**Outcome of the experiment**
a. A polarizer is placed between the lightbulb and the photometer. The polarizer is slowly rotated around the axis that connects the lightbulb and the photometer. The light intensity is measured at several angles θ of the polarizer.	
b. The set-up described in part **a.** is modified: a second polarizer, initially oriented in the same direction as the first polarize is positioned behind the first one. The second polarizer is slowly rotated relative to the first (by angle θ), and the light intensity is measured.	
c. The experiment in part **b**. is repeated, only this time the first polarizer is rotated and the second polarizer is held still. The light intensity on each side of the second polarizer is measured.	

For each of the above cases, devise a mathematical relationship between the light intensity I_0 before the polarizer(s) and the light intensity I after.

OALG 25.1.4 Read and interrogate

Read and interrogate Section 25.1 in the textbook and answer Review Question 25.1.

OALG 25.1.5 Equation Jeopardy

Come up with a problem that is consistent with the solution below.

$$\frac{I}{I_0} = \frac{1}{4} = \cos^2(\theta)$$

$$\frac{1}{2} = \cos(\theta)$$

$$\theta = \cos^{-1}\left(\frac{1}{2}\right) = 60^\circ$$

25.2 Discovery of electromagnetic waves

OALG 25.2.1 Summarize

You learned in Chapter 21 that a changing magnetic field produces an electric field. Describe experimental evidence for this.

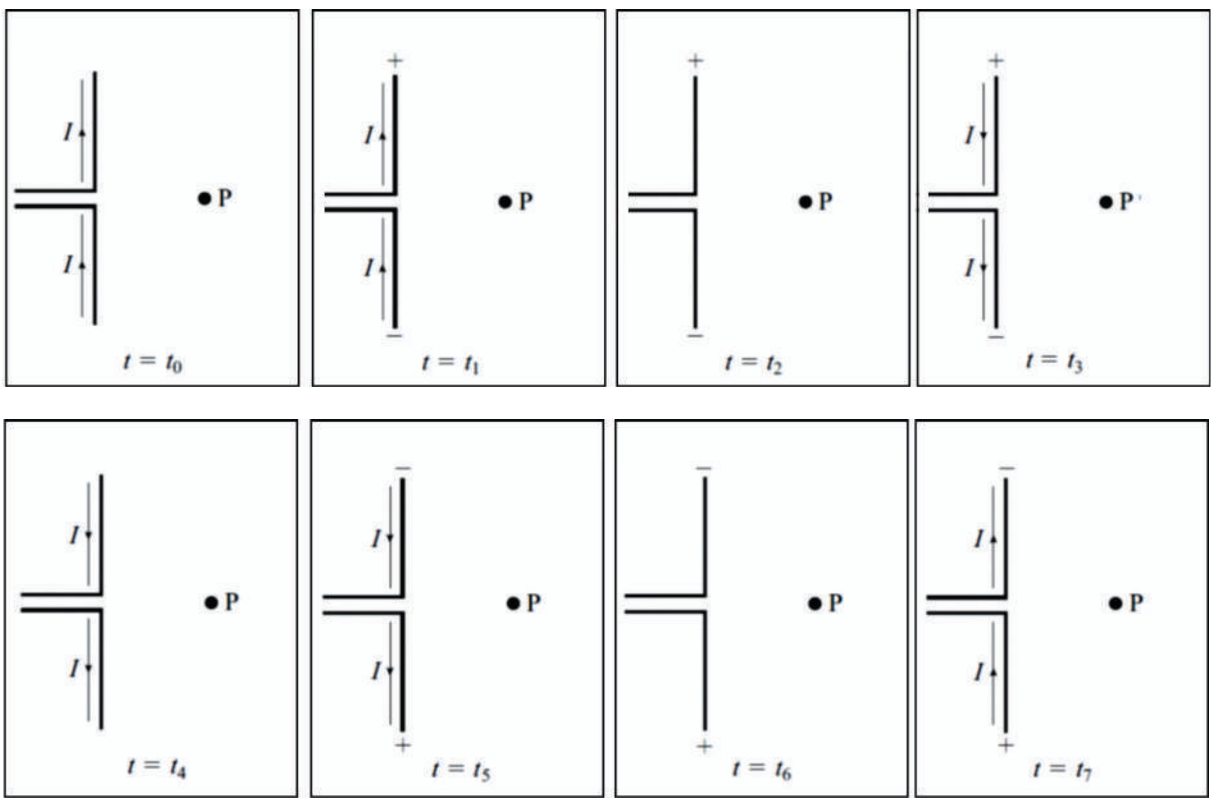
OALG 25.2.2 Read and interrogate

Read and interrogate Section 25.2 in the textbook and answer Review Question 25.2.

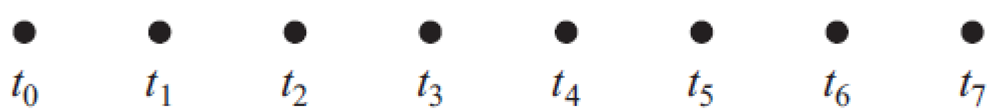
OALG 25.2.3 Represent and reason

Antennas are used to produce electromagnetic (EM) waves. This is accomplished by connecting the antenna to a source of an alternating emf. In this activity you will represent the production of an EM wave by using field line diagrams. The figures below show the current and charge separation in the antenna at various clock readings.

a. Add appropriate electric and magnetic field lines to these figures. Be sure to include an electric and magnetic field line that passes through the indicated point P.



b. For each clock reading t_0 through t_7 draw a vector representing the $\vec{E}$ field at the point P.



c. For each clock reading t_0 through t_7 draw a vector representing the $\vec{B}$ field at the point P.

d. Describe the patterns of the $\vec{E}$ field and $\vec{B}$ field at the point P.

25.3 Applications of electromagnetic waves

OALG 25.3.1 Read and interrogate

Read and interrogate Section 25.3 in the textbook and answer Review Question 25.3.

OALG 25.3.2 Analyze

A secret mission needs to be flown by the military aircraft into a neighboring country. There are two radar stations that the aircraft must fly between. They are 60 km apart. The radio waves emitted by station 1 have a period of 2.0×10^{-4} s and a pulse width of 12.0 μs. The waves emitted by station 2 have a period of 2.7×10^{-4} s and a pulse width of 10.0 μs. Is it possible for the aircraft to fly undetected into the neighboring country? Justify your answer quantitatively.

OALG 25.3.3 Observe and explain

Equipment: a big plain chocolate var, plate, a ruler, and a microwave oven.

a. Place a chocolate bar withiest flat side up in a microwave oven and turn it on for 15 seconds.

b. Take out the chocolate and carefully examine it. Describe what you see.

c. Use your observations (and a ruler) and a hypothesis that microwaves are a type of electromagnetic waves to determine the frequency of microwaves in your microwave oven.

d. What assumptions do you need to make about the types of microwaves that warmed the chocolate bar to do the calculation? *Hint*: EM waves reflect from the metal walls inside the oven.

e. Compare your calculated value to the one written on back of the microwave oven.

OALG 25.3.4 Observe and explain

Equipment: microwave oven (that uses a rotating tray), two identical glass beakers, water and mineral oil (about 100 ml of each), digital thermometers.

If you have the equipment, conduct the experiments described below. If you do not have the equipment, watch the following video https://youtu.be/7w0n1o8K1HU. It helps us devise an explanation of how microwaves cook food. We use water and mineral oil because water molecules are polar (they can be treated as dipoles) and mineral oil molecules are non-polar.
a. We placed identical volumes of water and mineral oil in identical containers. We measured the initial temperatures of both fluids (in degrees C). Then, we placed the containers on a rotating tray in a microwave oven, turned the oven on and heat both fluids for about 20 seconds. We measured the final temperatures.

b. Use your observations to propose an explanation concerning how microwave ovens cook food.

25.5 Mathematical description of EM waves and EM wave energy

OALG 25.5.1 Derive

The constant k_C (Coulomb's constant) and the constant μ_0 (vacuum permeability) have appeared in your study of electric and magnetic phenomenon.

a. By analyzing the units of these two constants, devise a mathematical expression involving these two constants that has units of speed, m/s, and determine its value.

b. What is the significance of this value?

OALG 25.5.2 Represent and reason

An electromagnetic wave traveling in the positive x-direction can be represented by the following wave equations for the $\vec{E}$ field and $\vec{B}$ field.

$$E_y = E_{\max}\cos\left[2\pi\left(\frac{t}{T}-\frac{x}{\lambda}\right)\right] \quad B_z = B_{\max}\cos\left[2\pi\left(\frac{t}{T}-\frac{x}{\lambda}\right)\right]$$

To see if these equations are reasonable, draw graphs of E_y as a function of x at the clock readings below. Assume the wave is a signal from a 2100 MHz 3G cell phone tower.

Graph E_y as a function of x at the given clock readings

a. $t = 0$

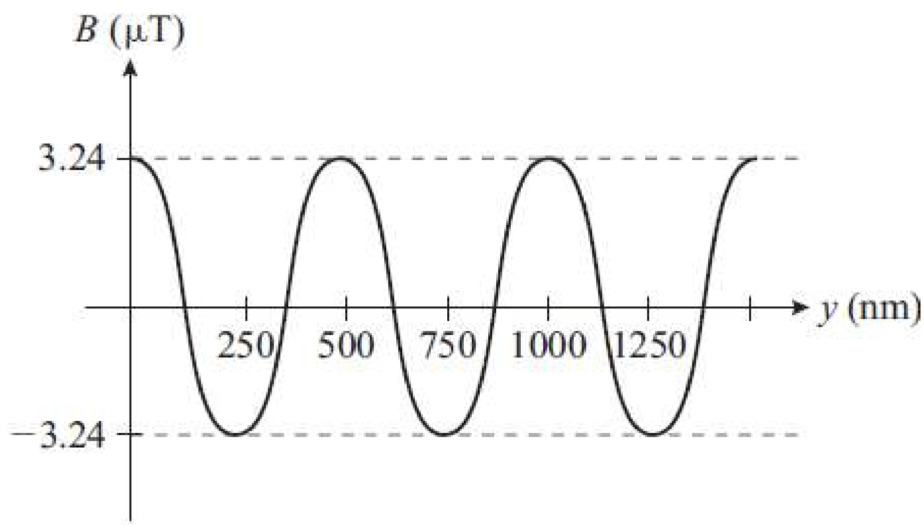
b. $t = \frac{T}{4}$

c. $t = \dfrac{T}{2}$

d. $t = \dfrac{3T}{4}$

OALG 25.5.3 Determine everything you can

Below is the graph of the $\vec{B}$-field z-component of an electromagnetic wave. Write down everything that you can about this wave.



OALG 25.5.4 Evaluate

The expressions for the electric and magnetic field energy densities are

$$u_E = \frac{1}{2}\varepsilon_0 E^2 \text{ and } u_B = \frac{1}{2\mu_0}B^2$$

Check that the units of these expressions are consistent. Recall that $k_C = \dfrac{1}{4\pi\varepsilon_0}$.

OALG 25.5.5 Evaluate the solution

Determine the magnitude of the $\vec{B}$ field between the plates of a parallel plate capacitor. The capacitor is connected to a 12-V source of emf, which keeps the plates at a constant potential difference of 12 V. The plates of the capacitor are separated by 1.0 cm. State any assumptions that you make.

Solution:

$$E = \frac{\Delta V}{d} = \frac{12 \text{ V}}{1.0 \text{ cm}} = 12 \text{ N/C}$$

$$B = \frac{E}{c} = \frac{12 \text{ N/C}}{3.0 \times 10^{8} \text{ m/s}} = 4.0 \times 10^{-8} \text{ T}$$

This assumes the current in the circuit is constant.

a. Identify any errors in the solution.

b. If there are errors, provide a correct solution

OALG 25.5.6 Determine everything you can

A satellite broadcasting a satellite television signal orbits at an altitude of 22,300 miles above Earth's surface. It broadcasts radio waves with a total power output of 200 W per channel. Receivers designed to tune in to this signal are dish-like in shape and have a radius of about 40 cm. Determine as many physical quantities relevant to this situation as you can.

OALG 25.5.7 Read and interrogate

Read and interrogate Section 25.5 in the textbook and answer Review Question 25.5.

25.6 Polarization and light reflection

OALG 25.6.1 Observe and find a pattern

You are working late at night. The light from a rising full Moon hits a small pool left outside. Some of the light hitting the water reflects off and reaches your eyes. You decide to watch the reflected light through your polarizing sunglasses. As you do this you notice that the reflected moonlight passing through the sunglasses varies in brightness as you rotate your sunglasses. You investigate this and record your observations shown in the table that follows.

Experiment	**Outcome of experiment**	
As the Moon rises (decreasing the angle of incidence) you observe the light passing through the rotating sunglasses	$\theta_i,\ \theta_{refl}(°),\ \theta_i = \theta_{refl}$	Brightness variation
	35	Moderate
	45	Large
	53	Maximal (brightness goes to zero for some orientations)
	65	Large

a. You decide to investigate the pattern by analyzing not only the angle of reflection but also the angle of refraction. Complete the table below.

θ_{refr} (°), **from Snell's law**	**Ray diagram in which both the reflected ray and refracted ray are present (use a protractor for angle accuracy)**

b. Devise a rule or rules that describe the conditions under which the reflected light is completely polarized in the plane that is parallel to the reflecting surface. *Hint:* Look at each ray diagram and the corresponding values of the angles of reflection and refraction.

OALG 25.6.2 Derive

The pattern discovered in the preceding activity can be expressed more conveniently as an equation for the so-called polarization angle θ_p, the angle of incidence at which the reflected light is completely polarized in the plane of the reflecting surface. Follow these steps to derive this relationship:

a. Begin with Snell's law.

b. Use the third ray diagram above under Activity 25.6.1 part **a**. to come up with an equation involving angles in the diagram that relates θ_2 and θ_p.

c. Use this equation to substitute for θ_2 in Snell's law.

d. Finally, use the trigonometric identity $\cos\theta = \sin(90° - \theta)$ and simplify the result as much as possible to arrive at what is known as Brewster's law (check textbook Section 25.6).

OALG 25.6.3 Test an idea

Review the preceding two activities. The next day you are again working late. You see that a piece of Plexiglass® sheet has been placed over the pool. This is an opportunity to test the idea developed in the preceding activities.

Analyze the following experiment:

The light from a rising full Moon reflects off the Plexiglass® sheet and reaches your eyes. The index of refraction of Plexiglass® is 1.50.

a. Using the equation from Activity 25.6.2 Make a prediction of the reflection angle for completely polarized reflected moonlight off the Plexiglass® sheet.

b. Outcome of experiment: $54° \pm 3°$. Make a judgment about the idea being tested. Has it been disproved by this experiment?

25.6.4 Read and interrogate

Read and interrogate Section 25.6 in the textbook and answer Review Question 25.6.