Electromagnetic Waves Worksheet

An ***electromagnetic wave*** is a particular arrangement of electric and magnetic fields that is produced when charged particles are ***accelerated.*** (Recall that when charged particles are moving at constant velocity, as in a steady electric current where *I* does not vary, only magnetic fields are produced.) The key properties of the electromagnetic wave are the following:

1) The electric field is perpendicular to the magnetic field

2) The wave travels through space, and its direction of motion is perpendicular to ***both*** the direction of the electric field ***and*** the direction of the magnetic field. (That is, the direction of motion of the wave – called its direction of "propagation" – is perpendicular to the plane containing the electric and magnetic field vectors.)

3) When traveling through a vacuum, the speed of propagation of the e-m wave always has the same value: 3×10^8 m/s. This is the "speed of light," symbolized by the letter *c*. (The speed of propagation is lower when traveling through matter.)

4) When observed from one fixed ***location***, the magnitude ***and*** the direction of ***both*** the electric field and the magnetic field ***vary in time***. (The propagation speed of the wave is equal to the distance traveled each second by any one particular peak in the electric field pattern.)

5) When observed at one moment in ***time,*** the magnitude ***and*** the direction of ***both*** the electric field and the magnetic field ***vary in space***, i.e. they have different magnitudes and directions at different locations.

6) At a particular point in space, the maximum magnitude of the electric field occurs at the same moment as the maximum magnitude of the magnetic field, and the magnitudes of the two fields are always proportional to each other with the same constant of proportionality.

7) The most general form of electromagnetic wave has a specific, regular "*frequency*." The frequency [symbol: *f*] is the number of times per second that the electric field returns to a maximum value in one particular direction. *(For instance: suppose the electric field vector – which varies with time – returns to a maximum magnitude of 3 N/C, pointing along the positive x direction, 1000 times per second. Then the frequency of that wave is said to be 1000 Hz. [1 Hz is 1 sec^{-1}; 5 Hz is 5 "per second"].)*

8) An electromagnetic wave can travel through space indefinitely – essentially forever, unless it is blocked or absorbed by matter – even though it may be separated from the charges that produced it by many trillions of miles.

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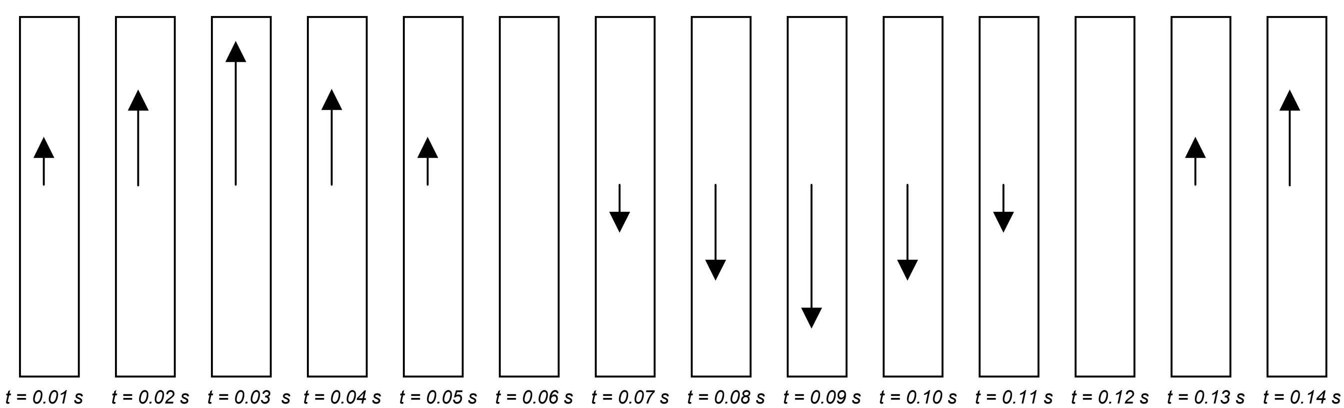
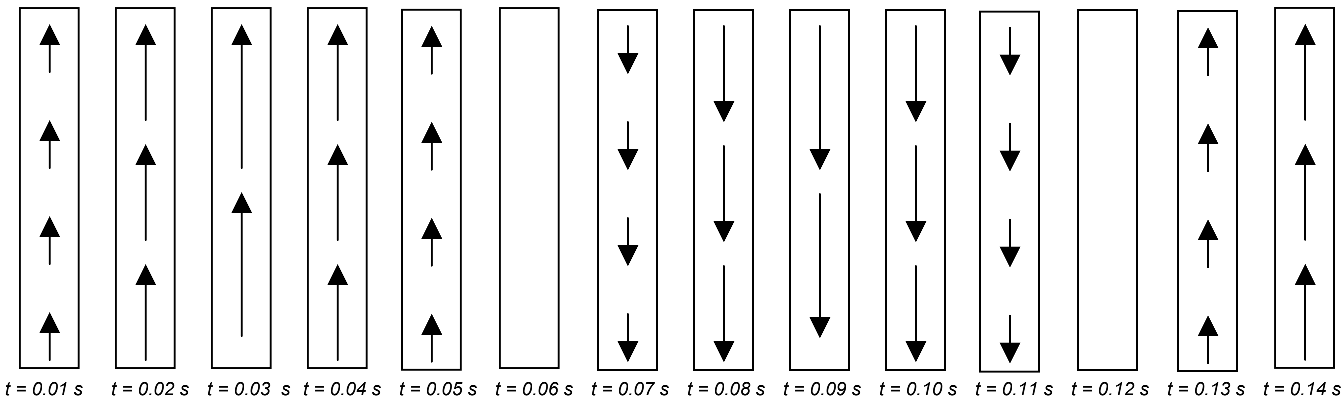
1. An electromagnetic wave is traveling through a vacuum from left to right. You are observing it through a narrow opening in a fence (represented by the rectangular box below). You are able to measure the magnitude and direction of both the electric and magnetic fields in the space viewed through that opening. The sequence below (note the different observation times) shows your observations of the ***electric*** field at the center point of the opening. (The field is zero at t = 0.06 s and t = 0.12 s.)



*[Note: If you were also able to measure the electric field at **other** points within the opening (besides the center point), you would observe a pattern something like this:*



In order to simplify our diagrams, we will continue to show only the field at the center point of the opening.]

a) Consider the peak value in the pattern that you observe at t = 0.03 s. As time goes on, that peak value (with direction pointing *upward*) will reappear again at *what* value of t?

b) The *period* of an e-m wave [symbol: *T*] is the elapsed time between two consecutive maxima in the magnitude of the electric field that point in the ***same direction***. What is the period of this wave?

c) We will need to find the relationship between the period *T* and the frequency *f*. This is a relationship that holds for ***all*** "periodic phenomena" [phenomena that continuously recur at regular intervals]. If a system goes through a series of changes ***but keeps returning to the same arrangement after a fixed interval of time,*** then the time it takes for ***one*** complete repetition is called one ***period.*** (For instance, the time required for ***one*** back-and-forth swing of a pendulum.)

   i) Suppose that you are running around a track at a steady rate of one lap per minute. We can say that the *period* of "running a lap" is one minute, because you complete one full lap (and are ready to start the next one) every time one minute has elapsed. In units of "laps per minute," what is the *frequency* of this phenomenon (i.e., how many times does it repeat in one minute)?

   ii) Now suppose you change to a pace of *two* laps per minute. What is the new period, and the new frequency, of "running a lap"? (Specify your units.)

   iii) If the frequency of a wave is 10 Hz (ten complete oscillations per second), what is the period of the wave (the time for ***one*** complete oscillation)?

   iv) Write down a mathematical relationship between *T* and *f*.

d) What is the frequency of the wave described on page 1?

e) When you observe the reappearance of that peak in the pattern (at the time found in [a]), how far will the wave have traveled in the time elapsed ***since*** t = 0.03 s?

f) What is the distance between two consecutive maximum values (same magnitude ***and*** direction) of the electric field? (This value is called the *wavelength* [symbol: λ] of the wave.) *(Hint: Imagine other observers looking at the wave through their own narrow openings in the fence, and recall the propagation speed of this wave.[P.S. this is a* ***very long*** *fence!] Now suppose you could break down the fence and observe the wave over a long distance at the same moment.)*

g)

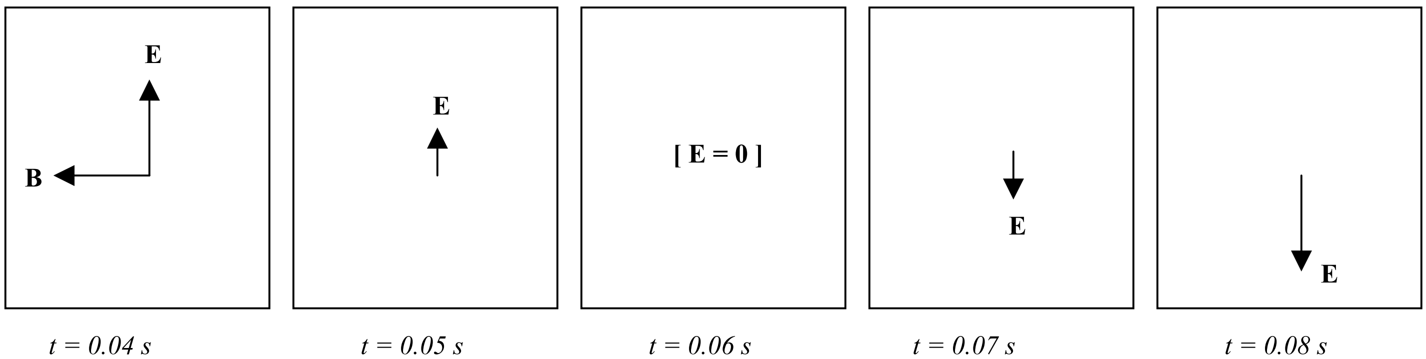
i) How many periods does it take for a peak in the wave to travel a distance equal to λ?

ii) Find a mathematical relationship among period *T*, wavelength λ, and propagation speed *c*. *(Hint: What is the relationship between speed, distance, and time?)*

iii) What is the relationship among frequency *f*, wavelength λ, and propagation speed *c*? Write a mathematical equation, and explain how you obtained it.

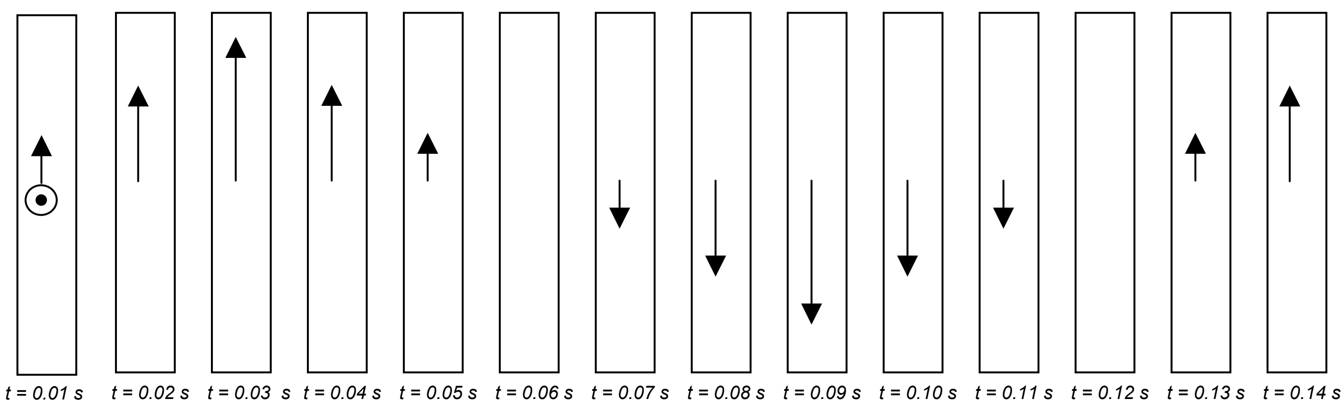
2.

a) In these views, we switch to the perspective of an observer directly in the path of the oncoming e-m wave, who sees it coming "head-on." The electric field vector is shown for several of the observation times. The magnetic field vector is shown only for the *first* observation time.



Draw in the magnetic field vectors at the other four observation times. (Refer to #6 of the introductory notes.) ***Note:*** *The magnetic field will reverse direction at the same moment as does the electric field.*

b) This is the same set of observations as shown before. At the center point of the opening, indicate the direction of the magnetic field at each of the 14 observation times. The direction at t = 0.01 seconds is shown. (Use arrows or dot and cross symbols.) *(Hint: Refer to #1, 2 and 6 of the introductory notes.)*



3. Answer these questions about the magnetic field:

a) At which time[s] is the magnitude of the magnetic field zero?

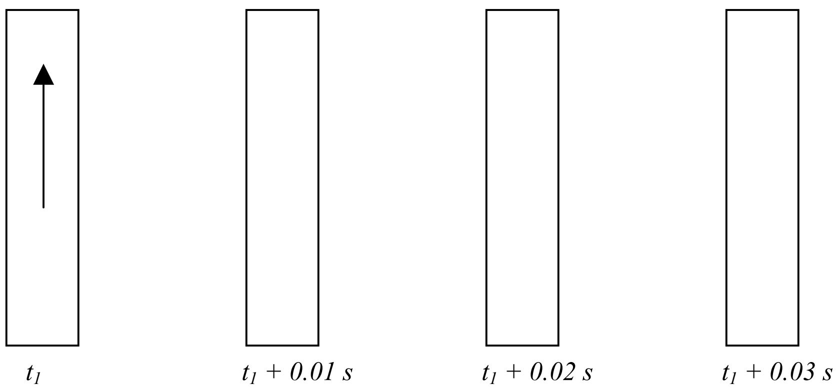
b) At which time[s] is the magnitude of the magnetic field a maximum (regardless of direction)?

4. Consider an e-m wave that had a frequency *six times* the frequency of this wave.

a) What would be the period of this new wave?

b) What would be the wavelength of this new wave?

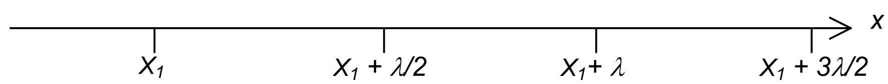
c) Describe how the set of observations through the narrow opening would be different as you observe the new wave. Sketch the electric field vectors at four consecutive time intervals separated by 0.01 s. The first observation is shown; assume that the electric field has its ***maximum magnitude*** at t_1.



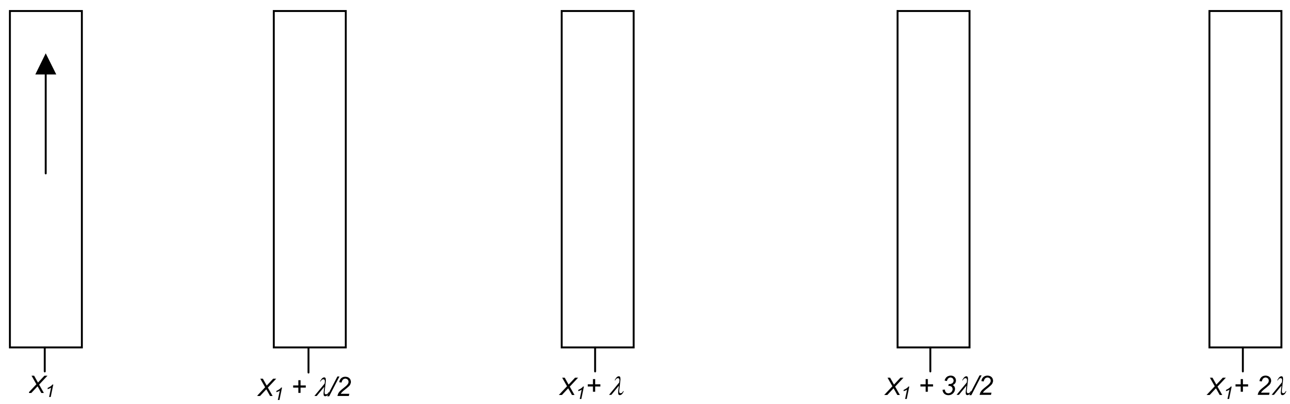
5. What type of e-m radiation would this wave represent? (i.e., gamma rays, x-rays, ultraviolet, visible, infrared, microwave, radio, etc.)

Interference of E-M Waves from Two Sources ("Double-Slit" interference)

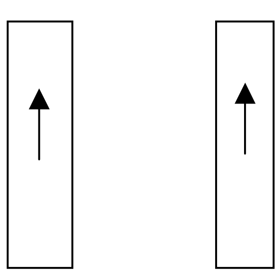
1. At one moment in time, we will observe an e-m wave at several different locations along the x axis. In each case, however, we will only consider the electric field at the point with y coordinate equal to 0. (The first few locations are indicated on the axes below.)



The electric field vector that we find at coordinate x_1 is shown in the first box on the left below. Assume that this is the ***maximum magnitude*** of the electric field for this wave. In the other boxes, sketch the electric field vector that you would observe at the other specified locations.



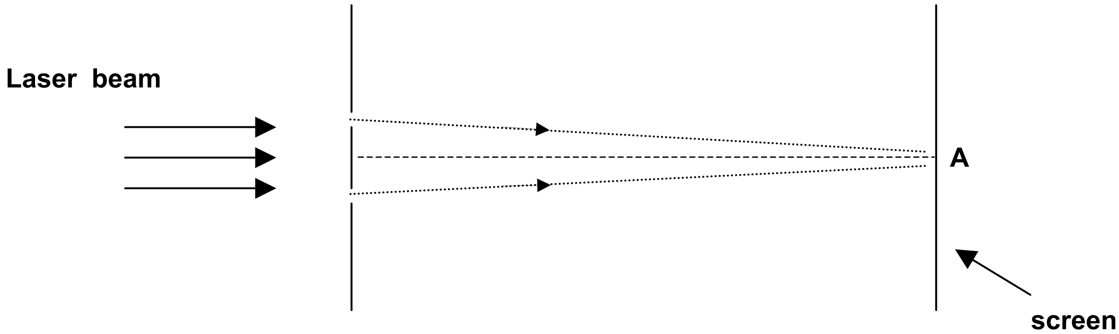
2. In the set-up diagrammed here, a beam of laser light is directed at two narrow slits spaced close together. This results in an electric field vector at the two slits that is "in phase," which means that when the field has a particular magnitude and direction in one slit at some moment in time, it has exactly the same magnitude and direction in the *other* slit at the same moment. This is represented in the boxes below the diagram.



Electric field at center of top slit

Electric field at center of bottom slit

2. *(continued)* After passing through the slits, the light spreads out from each slit and eventually strikes the screen shown on the right. The paths taken by the light that strikes point A on the screen are shown for both the upper and the lower slits.



a) For the light that strikes point A: is the distance traveled by the light from the upper slit *greater than, less than,* or *equal to* the distance traveled by the light from the lower slit?

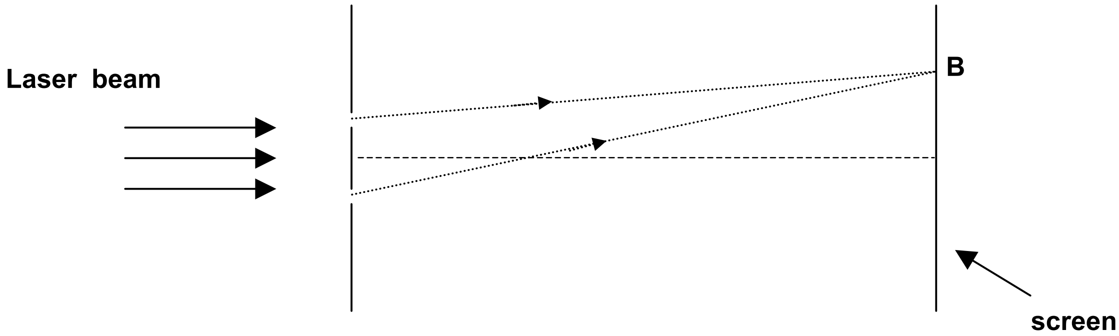
b) Assume that the distance traveled by the light from the upper slit is $n\lambda$, where n is some integer (e.g., 1, 2, 3, . . . etc.). Sketch the electric field vectors at point A of the light from both the upper slit and the lower slit, as well as the ***net*** electric field vector at point A. Refer to the diagram on page 6 that shows the electric field vectors ***in*** the slits themselves.

Electric field (at point A) of light from upper slit

Electric field (at point A) of light from lower slit

Net *electric field at point A*

3. In this diagram, the paths taken by light striking point B on the screen are shown.



a) Is the distance traveled by light from the upper and lower slits the same in this case? Which path is longer?

b) Suppose that the upper path distance is $m\lambda$, where m is some integer. Assume that the lower path distance is longer than the upper path by an amount exactly equal to $\lambda/2$. In the boxes below, sketch the electric field vectors at point B of the light from both upper and lower slits, as well as the ***net*** electric field vector at point B. Explain your sketches.

Electric field (at point B) of light from upper slit

Electric field (at point B) of light from lower slit

*<u>**Net**</u> electric field at point B*

c) What can you say about the net ***magnetic*** field at point B? Explain.

d) Based on your answers to [b] and [c], what do you expect to see on the screen at point B? Compare this with what you would see at point A.

e) What would you expect to see on the screen at a point ***between*** points A and B? Explain in terms of the net electric field vector at those points.

f) Suppose you looked at a point C on the screen ***below*** point A, but as far away from A as is point B. What would you expect to see there? Explain.

g) Describe the pattern you would expect to see on the screen at other points, further removed from A. Explain.