SECTION 6

Electromagnetic Spectrum: Maxwell's Great Synthesis

Section Overview

Students consider how patterns help scientists form and test concepts in science. They practice finding different patterns in data sets and review an incomplete data table about electricity and magnetism. They look for patterns and complete the table using the ideas presented in this chapter. Students are then introduced to the speed of light and the history behind measuring its speed. They review and complete a data table about electric and magnetic fields. A discussion of the electromagnetic spectrum, electromagnetic waves, and the speed of light follows in the *Physics Talk*. Students apply what they know to solve various problems involving electromagnetic waves.

Background Information

Electromagnetic waves are created by the vibration and acceleration of a charged particle. An electromagnetic wave does not need a medium to travel in, and, unlike mechanical waves, their energy is related to their frequency rather than amplitude. The higher the frequency of the wave, the more energy it carries. The speed of a wave is equal to its wavelength multiplied by its frequency. Electromagnetic waves carry energy and momentum that they can transfer to particles of matter.

Electromagnetic waves travel with speeds less than the speed of light in a vacuum $\left(3\times10^{8}\text{ m/s}\right)$ when they are in a medium. When an electromagnetic wave enters a medium from a vacuum, it slows down and its wavelength decreases. Its frequency does not change. All objects emit and absorb electromagnetic radiation. An object may emit or absorb frequencies of radiation that are characteristic of the substance(s) the object is composed of. For example, the Sun tends to emit or absorb frequencies of radiation that are characteristic of hydrogen, helium, carbon, oxygen, iron, and other elements it is composed of. However, most objects emit radiation related to the temperature of the object. This is called the blackbody spectrum because it is radiation that the object emits rather than reflects. The higher the temperature of the object, the higher the frequency of radiation emitted. For example, a sample brought to 450 pK (the nearest measurement to 0 K to date) emits most strongly around 50 Hz (with a wavelength of 6400 km). In this situation, the constituents of the atoms composing the substance are nearly motionless. Everyday objects near room temperature (≈ 293 K) emit radiation in the infrared spectrum. The Sun's core at 16 MK emits X-rays. Objects at temperatures produced by processes ranging from exploding stars (350 MK) to collisions produced in CERN (European organization for nuclear research) between protons and nuclei (10 TK) result in the emission of emit gamma rays (frequencies between 3.5×10^{10} and 1×10^{15} Hz). All these emissions are caused by allowed states of motion (vibrational, rotational, spin, and so on) of the molecules and atoms constituting that object.

Crucial Physics

- Scientists use patterns to construct classification schemes.
- Patterns in electric and magnetic fields led to the understanding of the electromagnetic spectrum and the prediction of the speed of light.
- The electromagnetic spectrum consists of many different types of light, including gamma rays, X-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves. These waves will have different frequencies and wavelengths, but all electromagnetic waves travel at the speed of light in a vacuum.
- The speed of light in a vacuum is 3×10^8 m/s. Nothing can travel faster than this speed.

Learning Outcomes	Location in the Section	Evidence of Understanding
Practice discovering patterns to classify and make predictions.	***Investigate*** Part A, Steps 1-2 Part B, Step 1.b) ***Physics Talk***	Students practice picking out patterns. By picking out patterns of properties for electricity and magnetism, students predict what might be missing in data for electricity and magnetism. Similarly, students consider data that James Clerk Maxwell had on electric and magnetic fields and discuss patterns he found.
Identify the symmetry pattern between changing electric and magnetic fields that led to the discovery of electromagnetic waves.	***Investigate*** Part B, Step 1.b) ***Physics Talk***	Students review information about electric and magnetic fields and look for patterns. They read and discuss the patterns that James Clerk Maxwell found.
Calculate the distance traveled by electromagnetic waves during a time interval.	***Investigate*** Part C Step 2.b) and 3.a) ***Physics Talk*** ***Physics to Go*** Questions 1 and 7	Students read about the historical experiments designed to measure the speed of light. Students read and discuss the speed of light and calculate distances light travels, given the time interval or the time it takes light to travel a given distance.

Section 6 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Toothpicks, pkg 100		2 per class

Time Requirements

- Allow one and one-half class periods or 65 minutes to complete all parts of the *Investigate* portion of this section.

Teacher Preparation

- Assemble the required material. A commercial package of toothpicks should be more than sufficient for the entire class. Collect all the toothpicks after students have finished playing "Nim." They can be reused for other classes.
- Prepare transparencies of the "paynes," "howes," "chiavs," and "stengels" to discuss grouping with students. Also, prepare a transparency of the electricity and magnetism table in the *Investigate* for discussion.

Safety Requirements

- There are no particular safety concerns with this *Investigate* other than general lab concerns.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Toothpicks, pkg 100		2 per class

Time Requirements

- Allow two class periods or 90 minutes to complete all parts of the section including the *Physics Talk*.

Teacher Preparation

- Assemble the required material. A commercial package of toothpicks should be more than sufficient for the entire class. Collect all the toothpicks after students have finished playing "Nim." They can be reused for other classes.
- Prepare transparencies of the "paynes," "howes," "chiavs," and "stengels" to discuss grouping with students. Also, prepare a transparency of the electricity and magnetism table in the *Investigate* for discussion.

Safety Requirements

- There are no particular safety concerns with this *Investigate* other than general lab concerns.

NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Recognizing patterns	***Investigate*** Parts A and B ***Physics to Go*** Questions 4 and 5	**Augmentation** • Students with learning disabilities often struggle to recognize patterns, and this makes many academic tasks, including reading and math, more challenging. Students may recognize the visual patterns of the alien life-forms but struggle to find the number pattern in Nim or vice versa. For *Part A*, provide ample time for students to look for patterns. Then ask them to brainstorm in small groups or as a whole group to talk about the process of finding patterns. Ask students why patterns are useful and what strategies they use to identify a pattern. Keep this list posted for students to refer to if they get stuck when trying to find a pattern. • For *Part B*, students need to remember the individual concepts before they will be able to recognize the pattern. If students are struggling to remember the concept, refer them back to pages in the book that review the concept. **Accommodation** • Provide a completed table and ask students to identify the pattern or provide the pattern and complete the chart.
Using scientific notation for calculations	***Investigate*** Part C: Steps 2 and 3 ***Active Physics Plus*** ***Physics to Go*** Questions 1, 6, 7, 11, and Preparing for the Chapter Challenge	**Augmentation** • Review the rules for scientific notation, including what the coefficient, base number, and exponent represent and how to multiply and divide using scientific notation. Provide students opportunities to practice using scientific notation. • Ask students to express their answers for their speed of light calculations with numbers and decimals and in scientific notation. Then ask them to compare their answers and look for a pattern. • Students may need references of common items for comparing very small numbers (nano- and micro-) with much larger numbers (kilo-). Do an Internet search for a printable poster using key words such as "electromagnetic spectrum, scale of things" to show the nanometer measurement of many different objects.
Understanding the meaning of vacuum	***Physics Talk***	**Augmentation** • When asked what a vacuum is, many students respond with an answer that describes a vacuum cleaner. Understanding that a vacuum is "a space entirely devoid of matter" helps students understand why it is so important that scientists discovered that electromagnetic waves could travel in a vacuum as opposed to sound waves that require a medium.
Memorizing the electromagnetic spectrum	***Physics Talk***	**Augmentation** • Memorizing the order of the seven sections of the electromagnetic spectrum will help students apply the patterns of the spectrum to new questions. Help students develop a song or mnemonic device to memorize the spectrum using the first letters of each word (RMIVUXG) or the entire word for each region. • Ask students what patterns they see on the electromagnetic spectrum diagram in *Physics Talk*. From radio waves to gamma rays, frequency increases, wavelength decreases, energy increases, and speed remains constant. **Accommodation** • Provide a paper copy of the electromagnetic spectrum for students who struggle with memorization. With more time, some of these students may be able to memorize the electromagnetic spectrum but others will continue to need this visual aid.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Vocabulary comprehension Understanding concepts	***Investigate*** Introductory paragraph	Of course, students are familiar with countless patterns. But have they really stopped to look at and think about patterns? Bring in examples of patterns for students to look at (such as fabrics with checks or stripes, or the stitching on a soccer ball). Include some examples from nature, such as a honeycomb or leopard skin. Also show some designs without a pattern. Ask: Is there a pattern in all designs? [no.] What makes a design a pattern? [repetition.] Point out that repetition is what makes a pattern predictable, and it is the predictable nature of patterns that makes them particularly useful. (For the wow factor, you may wish to include images of fractals when you show patterns. But be careful: There is some randomness at work in nature's creation of fractals. Mathematical fractals, however, are truly repetitive and predictable.) To fully understand electromagnetic fields, students must also understand the concept of symmetry. As with patterns, there are many examples of symmetry in nature. Bring in some pictures showing symmetry. A leaf, a butterfly, and a snowflake are only a few possibilities. Have students think up or bring in examples of their own.
Comprehension	***Investigate*** Part C, introductory paragraph	Be sure students recall and can state in words the equation for calculating speed: $v = d/t$ (velocity equals distance divided by time). This is the equation used to determine the speed of light. It is remarkable that one of the simplest physics equations is used to find, perhaps, the most important fundamental physical constant.
Vocabulary comprehension	***Physics Words***	The term "oscillating" is used in the definition of electromagnetic waves. Challenge students to recall that back in *Chapter 5*, *Section 2* they learned that an oscillation is a back-and-forth motion. In that same definition is the term "perpendicular." If necessary, use two pencils or rulers to reinforce the meaning of "perpendicular." You may wish to contrast with the term "parallel."
Vocabulary comprehension	***Active Physics Plus***	You may wish to review other terms students encountered in *Chapter 5*: wavelength, frequency, wave speed, crest, and constructive interference. These terms can also be stumbling blocks for students. In particular, make sure students can clearly differentiate between frequency and wave speed. All electromagnetic waves move at the same speed in a vacuum, but their frequencies vary in inverse proportion to their wavelength.
Vocabulary comprehension	***Physics to Go*** Question 3	Before they can answer the question, ELL students, and possibly other students, may need help in order to understand the term "radiation." In addition, they may not be aware of radiation's many applications: in nuclear weapons; in nuclear power; and in medical imaging, diagnosis, and treatment.

SECTION 6

Teaching Suggestions and Sample Answers

What Do You See?

The bright colors offset by the audiences' dull colored background is likely to draw students' attention to the dress patterns being displayed by the models on the ramp.

Initiate a class discussion on the electromagnetic spectrum; elicit students' ideas of the illustration and how it connects to the title of the section. Consider using the overhead of the illustration as a focal point for discussion and ask students what patterns they see in the illustration. Students should describe the rainbow of colors that each person on the platform is wearing.

What Do You Think?

Have students quietly think about the questions. Have them record and discuss their ideas with their group members. Ask students to come up with a pattern they have seen in nature and how it might be used to make a prediction. Students should reflect on the concepts they have studied so far and relate their previous *Investigates* to how light travels through space. You might want to discuss the analogy of a fashion industry's predictions based on patterns of consumer taste with a scientific discovery based on observations. Emphasize the similarity between a designer who uses his creativity to predict the outcome and a scientist who also uses his creative intellect to aid his discovery of a scientific truth.

What Do You Think?

A Physicist's Response

Scientists use patterns to make predictions of concepts that may not yet be discovered. This provides scientists with educated reasoning to predict and investigate relationships between physical quantities. Science is based on repeatable and measurable observations. Many discoveries in science were based on observed patterns before supporting measurements were made.

Electric and magnetic field patterns are essential to light and how light travels. Light is an electromagnetic wave created by oscillating perpendicular electric and magnetic fields. This is what Maxwell discovered while looking for patterns in the information between electricity and magnetism. He found mathematical proof that a changing electric field induces a magnetic field and that a changing magnetic field induces an electric field. These fields travel at the speed of light. Maxwell also found that these electromagnetic waves were not confined to the frequencies of visible light but defined the electromagnetic spectrum!

Students' Prior Conceptions

This section truly is a synthesis in that it affords teachers the opportunity to revisit, examine, and call attention to prior conceptions that were evident in other *Active Physics* chapters. This will be obvious as students discuss how waves travel and relate wavelength, speed, and frequency to one another. The crux of this chapter is to encourage students to seek the overarching pattern, to identify the symmetry between changing electric and magnetic fields, and to read about the discovery of electromagnetic waves.

1. **The spectrum of electromagnetic radiation consists of only visible light.** The primary misconception for you to address in this section is to alter student belief that light waves only consist of those waves that are visible to humans. The existence of invisible field lines and Maxwell's mathematical description of fields point out that light is an electromagnetic wave. The spectrum of this light encompasses all wavelengths from gamma rays to radio waves.

CHAPTER 7

Section 6 Electromagnetic Spectrum: Maxwell's Great Synthesis

Section 6 Electromagnetic Spectrum: Maxwell's Great Synthesis

What Do You See?

Learning Outcomes

In this section, you will

- **Practice** discovering patterns to classify and make predictions.
- **Identify** the symmetry pattern between changing electric and magnetic fields that led to the discovery of electromagnetic waves.
- **Calculate** the distance traveled by electromagnetic waves during a time interval.

What Do You Think?

The fashion industry depends on creative designers producing patterns that can be used for this year's new clothing lines. When these patterns correctly predict the consumer's tastes, this is a billion-dollar industry. Scientists are also creative individuals who search for patterns in nature and in mathematics.

- **How do patterns in nature allow scientists to predict the existence of things not yet discovered?**
- **What do electric and magnetic field patterns have to do with how light travels through space?**

Write your answers in your *Active Physics* log. Be prepared to discuss your ideas with your small group and other members of your class.

Investigate

In this *Investigate*, you will first see how patterns in science and nature determine the decisions scientists make, and how they use patterns to make discoveries. Then, you will investigate the symmetry pattern of electric and magnetic fields.

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Investigate

Part A: Patterns

1.a)

Students should come up with a classification system similar to the examples. For example, "chiavs" are things that have clear circles for heads, or rectangles for feet.

1.b)

Students repeat the process for "howes."

1.c)

Students repeat the process for "stengels."

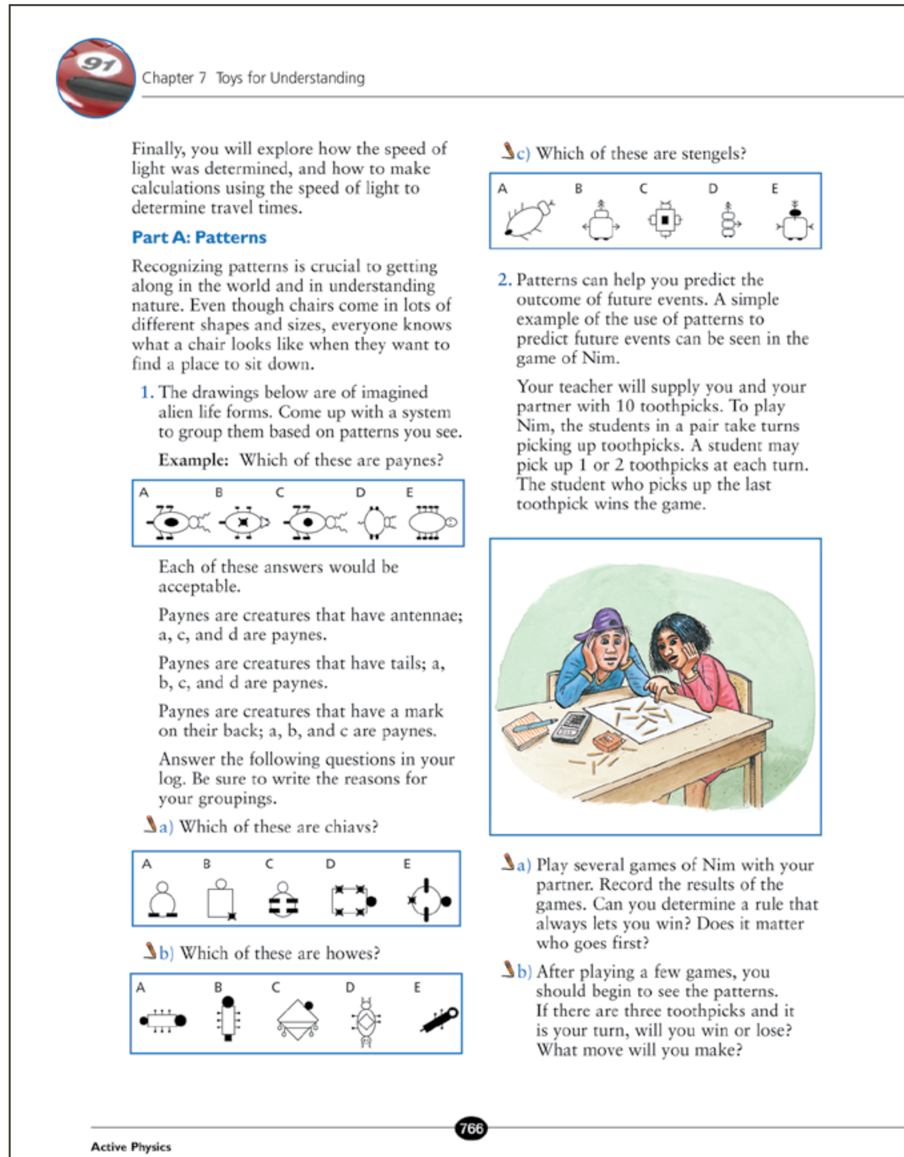
2.a)

Students will discover the rule that allows them to win after a few games. Others will take longer to see the pattern. Going first determines who can win.

2.b)

You will lose; If you take either one or two, you will leave either one or two, which can then be picked up by your partner.

7-6a **Blackline Master**


Chapter 7 Toys for Understanding

Finally, you will explore how the speed of light was determined, and how to make calculations using the speed of light to determine travel times.

Part A: Patterns

Recognizing patterns is crucial to getting along in the world and in understanding nature. Even though chairs come in lots of different shapes and sizes, everyone knows what a chair looks like when they want to find a place to sit down.

1. The drawings below are of imagined alien life forms. Come up with a system to group them based on patterns you see.

Example: Which of these are paynes?

A B C D E

Each of these answers would be acceptable.

Paynes are creatures that have antennae; a, c, and d are paynes.

Paynes are creatures that have tails; a, b, c, and d are paynes.

Paynes are creatures that have a mark on their back; a, b, and c are paynes.

Answer the following questions in your log. Be sure to write the reasons for your groupings.

a) Which of these are chiavs?

A B C D E

b) Which of these are howes?

A B C D E

c) Which of these are stengels?

A B C D E

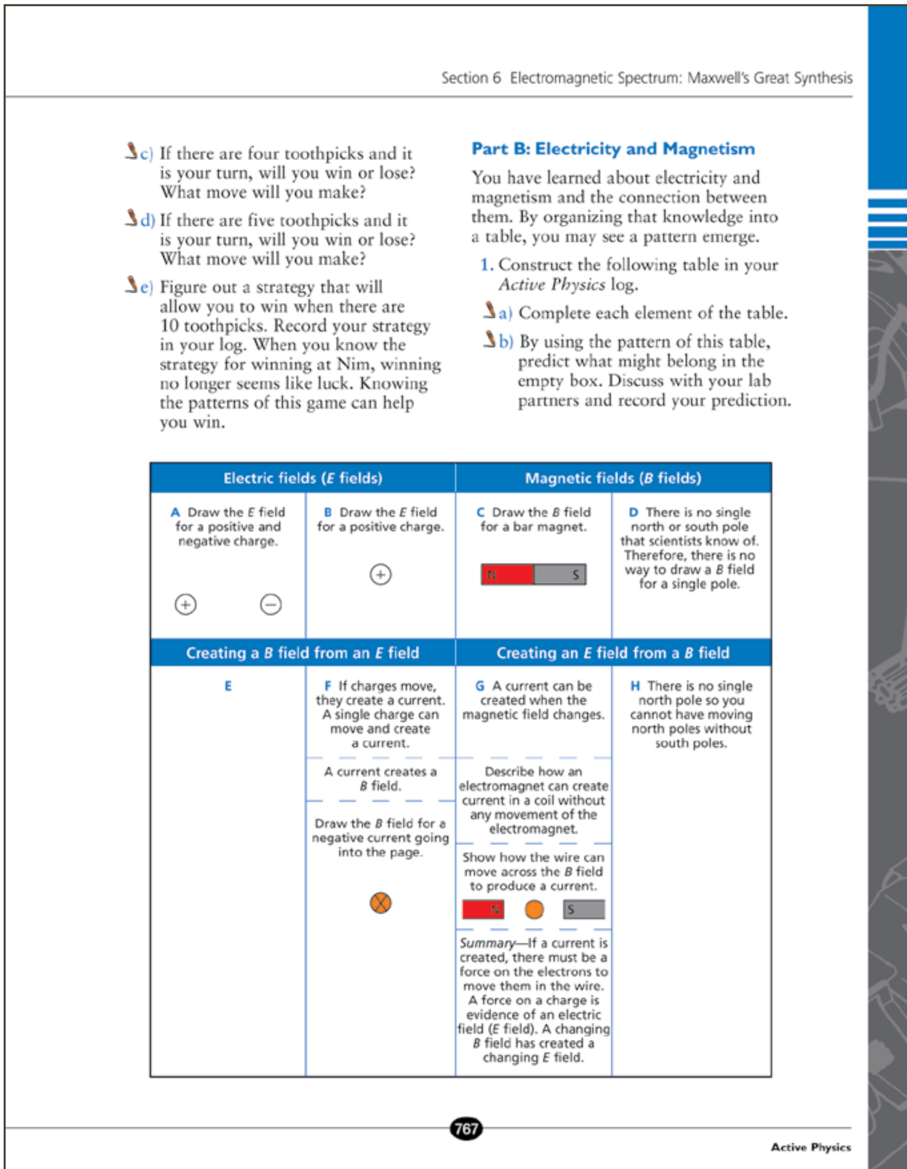
2. Patterns can help you predict the outcome of future events. A simple example of the use of patterns to predict future events can be seen in the game of Nim.

Your teacher will supply you and your partner with 10 toothpicks. To play Nim, the students in a pair take turns picking up toothpicks. A student may pick up 1 or 2 toothpicks at each turn. The student who picks up the last toothpick wins the game.

a) Play several games of Nim with your partner. Record the results of the games. Can you determine a rule that always lets you win? Does it matter who goes first?

b) After playing a few games, you should begin to see the patterns. If there are three toothpicks and it is your turn, will you win or lose? What move will you make?

Active Physics 766



c) If there are four toothpicks and it is your turn, will you win or lose? What move will you make?

d) If there are five toothpicks and it is your turn, will you win or lose? What move will you make?

e) Figure out a strategy that will allow you to win when there are 10 toothpicks. Record your strategy in your log. When you know the strategy for winning at Nim, winning no longer seems like luck. Knowing the patterns of this game can help you win.

Part B: Electricity and Magnetism

You have learned about electricity and magnetism and the connection between them. By organizing that knowledge into a table, you may see a pattern emerge.

1. Construct the following table in your *Active Physics* log.

a) Complete each element of the table.

b) By using the pattern of this table, predict what might belong in the empty box. Discuss with your lab partners and record your prediction.

Electric fields (*E* fields)		Magnetic fields (*B* fields)	
A Draw the *E* field for a positive and negative charge.	B Draw the *E* field for a positive charge.	C Draw the *B* field for a bar magnet. N S	D There is no single north or south pole that scientists know of. Therefore, there is no way to draw a *B* field for a single pole.
Creating a *B* field from an *E* field		**Creating an *E* field from a *B* field**	
E	F If charges move, they create a current. A single charge can move and create a current. A current creates a *B* field. Draw the *B* field for a negative current going into the page.	G A current can be created when the magnetic field changes. Describe how an electromagnet can create current in a coil without any movement of the electromagnet. Show how the wire can move across the *B* field to produce a current. N S *Summary*—If a current is created, there must be a force on the electrons to move them in the wire. A force on a charge is evidence of an electric field (*E* field). A changing *B* field has created a changing *E* field.	H There is no single north pole so you cannot have moving north poles without south poles.

2.c)

You will win if you take only one toothpick, leaving three. You will lose if you take two toothpicks.

2.d)

To win, take two toothpicks, leaving three. If you take only one toothpick, you could lose.

2.e)

The key is to leave a multiple of three toothpicks at the end of a turn. The strategies that enable you to do so will vary with your partner's strategy.

Part B: Electricity and Magnetism

1.a)

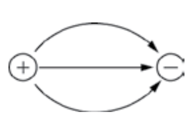
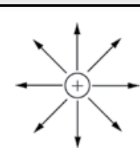
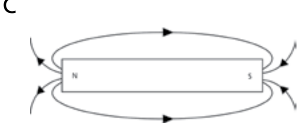
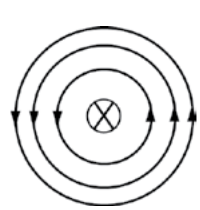
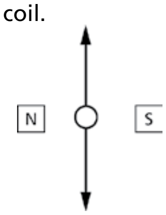
Students copy the table in their log.

1.b)

Students' entries for A through H should appear like the ones below.

CHAPTER 7

7-6b Blackline Master

A	B	C	D
			Blank
E	**F**	**G**	**H**
If the *E* field is changing, it will induce a changing *B* field, just as a changing *B* field induces an *E* field. The interaction of these two changing fields produces an electromagnetic wave. Many simulations of electromagnetic waves are available on the Internet.		If an electromagnet has an expanding or contracting field, it can induce a current in the coil.  Move the wire either up or down.	Blank

Part C: The Speed of Light

1.a)

Human reaction time is much too slow for this experiment to work. The quickest human reaction time is around 0.2 s. If the hilltops were 5 km apart, the time for the light to travel between the hilltops would be

$$\frac{5 \text{ km}}{300{,}000 \text{ km/s}} = 0.000017 \text{ s}.$$

2.a)

Roemer increased the distance, *d*, the measured light traveled, and thus the time, *t*, required to travel that distance also increased.

2.b)

Given:
$d = 3 \times 10^{11} \text{m}$ or $d = 1.86 \times 10^{8} \text{mi}$
$t = 22$ min

Using $v = d/t$, yields

$$v = \frac{3 \times 10^{11} \text{m}}{(22 \text{ min})(60 \text{ s/min})} =$$
2.3×10^{8} m/s,
or
$$v = \frac{1.86 \times 10^{8} \text{mi}}{(22 \text{ min})(60 \text{ s/min})} =$$
1.4×10^{5} mi/s.

2.c)

Given:
$d = 3 \times 10^{11} \text{m}$ or $d = 1.86 \times 10^{8} \text{mi}$
$t = 16$ min

Using $v = d/t$ gives

$$v = \frac{3 \times 10^{11} \text{m}}{(16 \text{ min})(60 \text{ s/min})} =$$
3.1×10^{8} m/s,
or
$$v = \frac{1.86 \times 10^{8} \text{mi}}{(16 \text{ min})(60 \text{ s/min})} =$$
1.9×10^{5} mi/s.

Part C: The Speed of Light

The speed of light can be calculated by using the equation $v = d/t$. To make this calculation, you need a measurement of the time for light to travel a specific distance.

1. About 400 years ago, Italian scientist Galileo Galilei tried to measure the speed of light. He had no sophisticated instruments, not even a clock. Galileo stood on a hilltop in Italy, uncovered a lantern and began counting. When his assistant on a distant hilltop saw the light from Galileo's lantern, the assistant uncovered his lantern. When Galileo saw the assistant's lantern, he stopped counting. Galileo realized immediately that the speed of light was too fast to measure in this way.

   a) How does human reaction time affect Galileo's experiment?

2. Although Galileo's experiment was not successful, he recognized that light takes time to move from one place to another. This meant light has a speed. Galileo inspired others to try measuring the speed of light. Danish astronomer Ole Roemer succeeded about 70 years later by viewing Jupiter's moons. Roemer observed the moons at two different positions in Earth's orbit. This let him increase the total time the light traveled and allowed him to measure this longer time accurately. He then calculated a value for the speed of light. Because the distance of Jupiter to the two positions of Earth was so large, the time was long enough to be measured.

   a) In the motion equation $v = d/t$, which quantities did Roemer change to provide a more precise measurement of the speed of light?

   b) Roemer had measured the distance to be the diameter of Earth's orbit (3×10^{11} m or 186,000,000 mi) and the time difference for light to travel this distance was 22 min. Calculate the speed of light in meters per second and in miles per second.

   c) A better value for the time difference for light to travel that distance is 16 min. Calculate the speed of light in meters per second and in miles per second using this value for the time.

3. In the late 1800s, Albert Michelson, an American physicist, made a more accurate measurement of the speed of light with rotating mirrors. Instead of having humans on hills adjust the lanterns, Michelson used mirrors and a very precise timing mechanism. For his work, Michelson won the 1907 Nobel Prize, the first ever awarded to an American scientist.

   a) Michelson had measured the distance to be 0.7576 mi (1219 m), and the precise time he was able to measure for the light to travel that far was 4.065×10^{-6} s (0.000004065 s). Calculate the speed of light in meters per second and in miles per second using this value for the time.

Physics Talk

ELECTROMAGNETIC SPECTRUM

Isaac Newton said, "If I have seen further than others, it is because I have stood on the shoulders of giants." The same could have been said by James Clerk Maxwell, a Scottish physicist. Maxwell was able to take the contributions of Coulomb, Oersted, Ampere, and Faraday and create a pattern that mathematically predicted one of the greatest achievements in the understanding of the world. It also changed the world in ways that nobody imagined.

3.a)

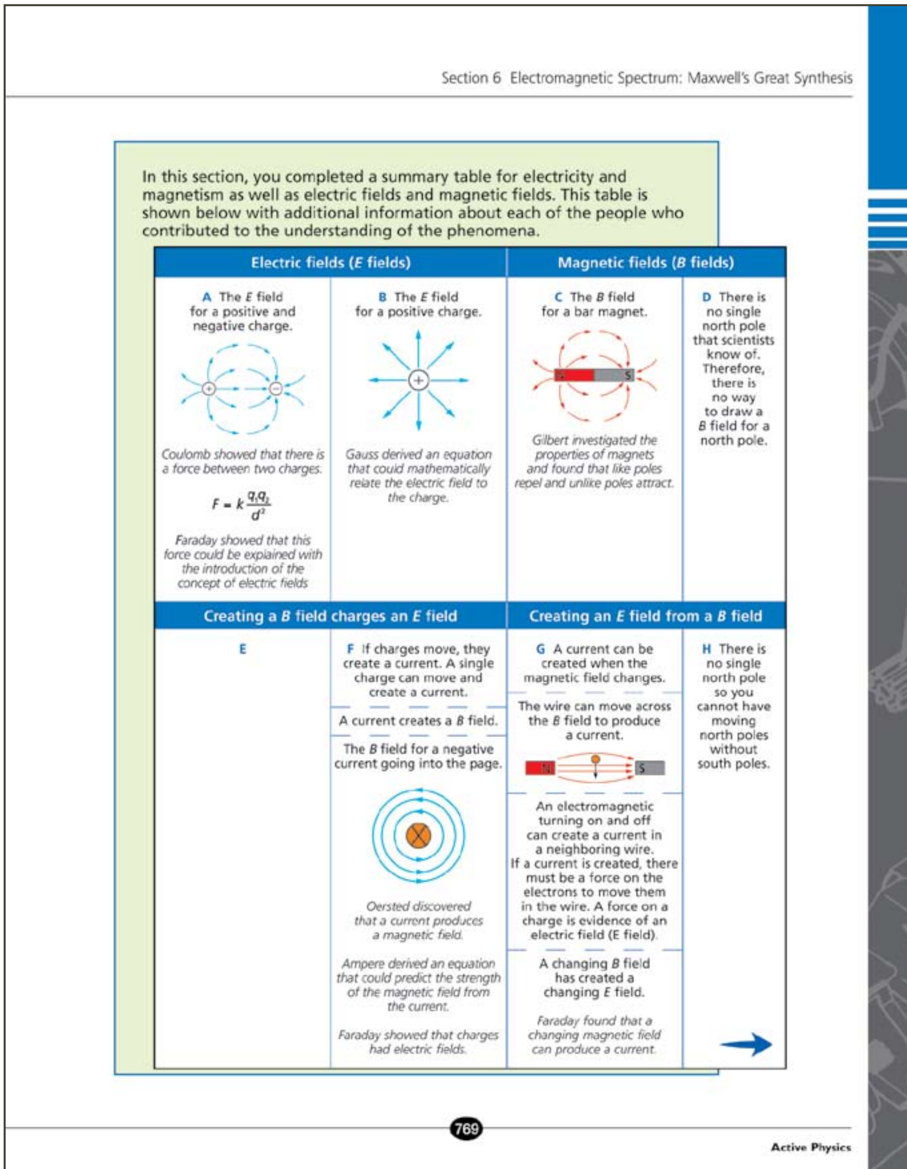
Given:
$d = 0.7576$ mi or $d = 1219$ m
$t = 4.065 \times 10^{-6}$ s

Using $v = d/t$, gives

$$v = \frac{0.7576 \text{ mi}}{4.065 \times 10^{-6} \text{s}} =$$
1.864×10^{5} mi/s,
or
$$v = \frac{1219 \text{ m}}{4.065 \times 10^{-6} \text{s}} =$$
2.9988×10^{8} m/s.

Physics Talk

This *Physics Talk* presents how scientists build on each other's ideas. It emphasizes the importance of patterns in making scientific discoveries. Students read how Maxwell's equations predicted the existence of electromagnetic waves of different wavelengths, such as gamma rays, X-rays, microwaves, radio waves, ultraviolet and infrared radiation, and the properties shared by



Section 6 Electromagnetic Spectrum: Maxwell's Great Synthesis

In this section, you completed a summary table for electricity and magnetism as well as electric fields and magnetic fields. This table is shown below with additional information about each of the people who contributed to the understanding of the phenomena.

Electric fields (*E* fields)		Magnetic fields (*B* fields)	
A The *E* field for a positive and negative charge. *Coulomb showed that there is a force between two charges.* $F = k\frac{q_1 q_2}{d^2}$ *Faraday showed that this force could be explained with the introduction of the concept of electric fields*	**B** The *E* field for a positive charge. *Gauss derived an equation that could mathematically relate the electric field to the charge.*	**C** The *B* field for a bar magnet. *Gilbert investigated the properties of magnets and found that like poles repel and unlike poles attract.*	**D** There is no single north pole that scientists know of. Therefore, there is no way to draw a *B* field for a north pole.
Creating a *B* field charges an *E* field		**Creating an *E* field from a *B* field**	
E	**F** If charges move, they create a current. A single charge can move and create a current. A current creates a *B* field. The *B* field for a negative current going into the page. *Oersted discovered that a current produces a magnetic field.* *Ampere derived an equation that could predict the strength of the magnetic field from the current.* *Faraday showed that charges had electric fields.*	**G** A current can be created when the magnetic field changes. The wire can move across the *B* field to produce a current. An electromagnetic turning on and off can create a current in a neighboring wire. If a current is created, there must be a force on the electrons to move them in the wire. A force on a charge is evidence of an electric field (E field). A changing *B* field has created a changing *E* field. *Faraday found that a changing magnetic field can produce a current.*	**H** There is no single north pole so you cannot have moving north poles without south poles.

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and led to the concepts of electromagnetic waves and the electromagnetic spectrum. Define electromagnetic waves.

Describe the electromagnetic spectrum and how increasing frequency corresponds to increasing energy. Provide examples, such as gamma rays that carry more energy than microwaves. Discuss the properties of electromagnetic waves listed in the student text. Let students know that all electromagnetic waves (all light) travels at the speed of light when it is in a vacuum, and that the speed with which it travels in air is close to this speed. When light travels in some other medium, such as water, it travels more slowly and its speed depends on how the medium interacts with the light.

these waves, which are used in communications, health, and other useful technologies that have increased the efficiency of machines.

7-6c **Blackline Master**

Make connections to the *Investigate* during class discussions. Discuss how Maxwell observed a pattern between electric and magnetic fields and believed that since a changing magnetic field produced a changing electric field, a changing electric field should produce a changing magnetic field. Describe how Maxwell used mathematics to describe and model the situation and obtained supporting evidence that electromagnetic fields could travel, as waves, at the speed of light. Emphasize that this was later proven experimentally

CHAPTER 7

Chapter 7 Toys for Understanding

James Clerk Maxwell saw that there was a pattern in the mathematical equations that described these phenomena. In the table, A relates to B, C to D and A relates to C, B to D. Also, B relates to F, C to G, and D to H. The missing element in the pattern begged the question: If a changing magnetic field can create a changing electric field (that produces a current, *G*), can a changing electric field produce a changing magnetic field, *E*? If so, this would make the pattern of the mathematical equations much more symmetric and beautiful. (*E* would relate to *G*.)

Maxwell was not able to do any experiments to check his insight. He was, however, able to use mathematics to describe what Faraday had been talking about with his concept of "fields." When Maxwell developed the mathematics, he found that if a changing electric field produced a *changing* magnetic field, *E*, then that *changing* magnetic field would in turn create a *changing* electric field, *G* and so on. He also found that these electric and magnetic fields would move across the room. Maxwell used his equations to determine the speed at which the "electromagnetic fields" would move. The value he found was

$$3 \times 10^8 \text{ m/s} = 186{,}000 \text{ mi/s}$$

Maxwell recognized that this was the speed of light. Maxwell had discovered the essence of light. Light is an electromagnetic field. With Maxwell's four equations, physicists can now explain everything you know about electric charges, electric fields, electricity, magnetism, as well as everything that was known about light.

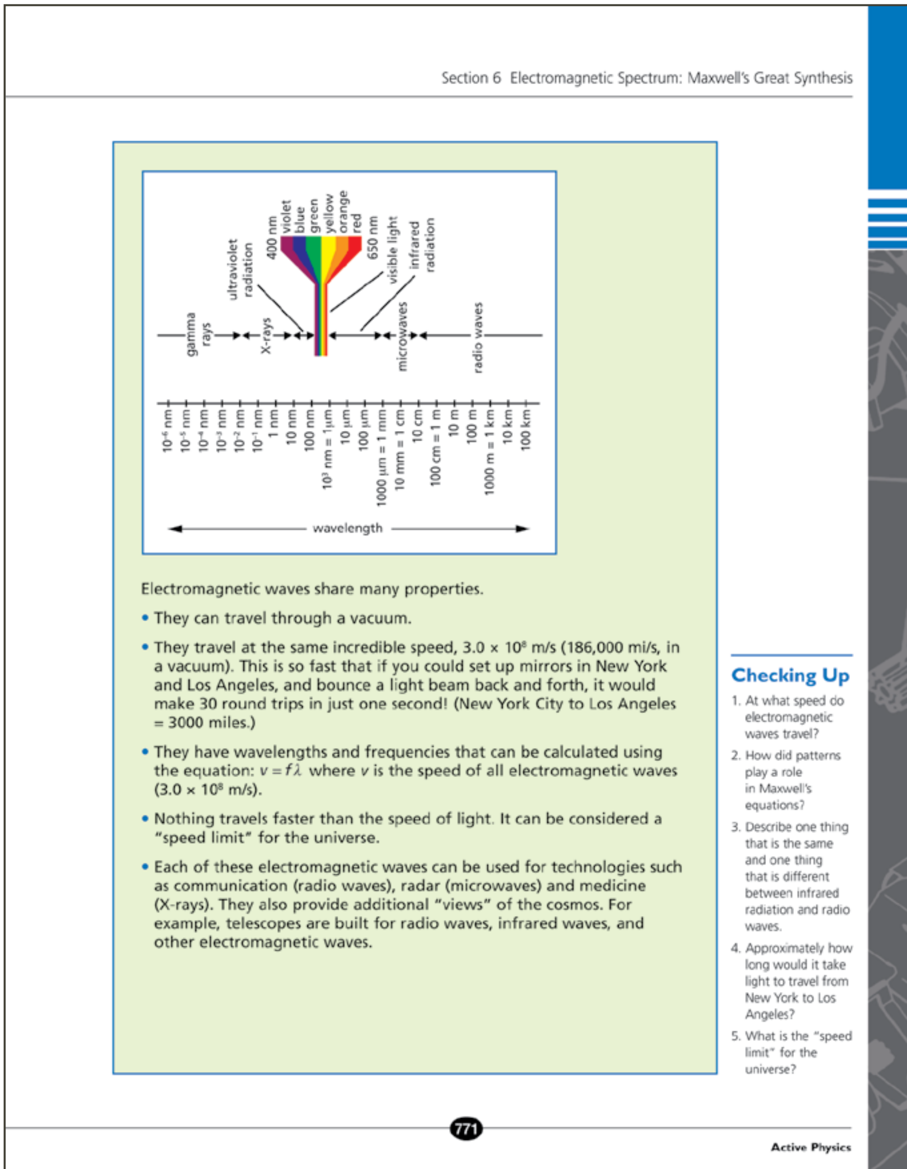
Maxwell's four equations are powerful stuff. But the story does not end there. Light has a very specific band of wavelengths. Blue light has a wavelength of 450 nm (nanometers) 450 x 10^{-9} m and red light has a wavelength of 700 nm. Maxwell tried to find out why light was restricted to this range of wavelengths and could not find a mathematical reason. That being the case, it was hypothesized that there were other **electromagnetic waves** of different wavelengths that had not yet been discovered and that the human eye could not see.

Physics Words

electromagnetic waves: transverse waves that are composed of oscillating perpendicular electric and magnetic fields that travel at 3×10^8 m/s in a vacuum; examples of electromagnetic waves listed in order of increasing wavelength are gamma rays, X-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves.

Maxwell's equations predicted the existence of gamma rays, X-rays, ultraviolet radiation, infrared radiation, microwaves, television waves, and radio waves. The first of these to be discovered were radio waves by the German physicist Heinrich Hertz a few years after Maxwell died. Each of these has since been discovered. In fact, people have invented all sorts of technologies that rely on this electromagnetic spectrum.

Most people delight in seeing a rainbow — a band of colors in the sky including red, orange, yellow, green, blue, and violet. The electromagnetic spectrum is Maxwell's rainbow. It shows a beauty and pattern in the world that nobody before Maxwell imagined.


Section 6 Electromagnetic Spectrum: Maxwell's Great Synthesis

Electromagnetic waves share many properties.

- They can travel through a vacuum.
- They travel at the same incredible speed, 3.0×10^8 m/s (186,000 mi/s, in a vacuum). This is so fast that if you could set up mirrors in New York and Los Angeles, and bounce a light beam back and forth, it would make 30 round trips in just one second! (New York City to Los Angeles = 3000 miles.)
- They have wavelengths and frequencies that can be calculated using the equation: $v = f\lambda$ where v is the speed of all electromagnetic waves (3.0×10^8 m/s).
- Nothing travels faster than the speed of light. It can be considered a "speed limit" for the universe.
- Each of these electromagnetic waves can be used for technologies such as communication (radio waves), radar (microwaves) and medicine (X-rays). They also provide additional "views" of the cosmos. For example, telescopes are built for radio waves, infrared waves, and other electromagnetic waves.

Checking Up

1. At what speed do electromagnetic waves travel?
2. How did patterns play a role in Maxwell's equations?
3. Describe one thing that is the same and one thing that is different between infrared radiation and radio waves.
4. Approximately how long would it take light to travel from New York to Los Angeles?
5. What is the "speed limit" for the universe?

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Active Physics

Checking Up

1.

All electromagnetic waves travel at the speed of light if they are in a vacuum. That speed is approximately 3.0×10^8 m/s. Light travels at approximately this speed in air as well. Light travels more slowly in different mediums and that speed depends on what the medium is made of and how it interacts with the light.

2.

Maxwell observed an incomplete pattern between electric fields and magnetic fields and predicted that to complete the pattern, a changing electric field should produce a magnetic field. As he explored this idea using mathematics, he predicted electromagnetic waves that traveled at the speed of light in a vacuum could be of any frequency.

3.

Both infrared radiation and radio waves are electromagnetic waves, and both travel at the speed of light in a vacuum. Infrared radiation has a higher frequency and shorter wavelength than radio waves.

4.

Since New York and Los Angeles are about 3000 miles apart, it would take approximately

$$t = d/v = \frac{3000 \text{ mi}}{186{,}000 \text{ mi/s}} = 0.016 \text{ s}.$$

5.

The speed limit for the universe is the speed of light in a vacuum, or approximately 3.0×10^8 m/s.

CHAPTER 7

Active Physics Plus

This *Active Physics Plus* provides an opportunity for students to increase the depth of their understanding, exploration, and apply mathematics to describe the physics concepts involved.

1.

Red: $f = \dfrac{v}{\lambda} = \dfrac{3.0 \times 10^8 \text{ m/s}}{650 \text{ nm}} = 4.6 \times 10^{14} \text{ Hz}$

Yellow: $f = \dfrac{v}{\lambda} = \dfrac{3.0 \times 10^8 \text{ m/s}}{570 \text{ nm}} = 5.3 \times 10^{14} \text{ Hz}$

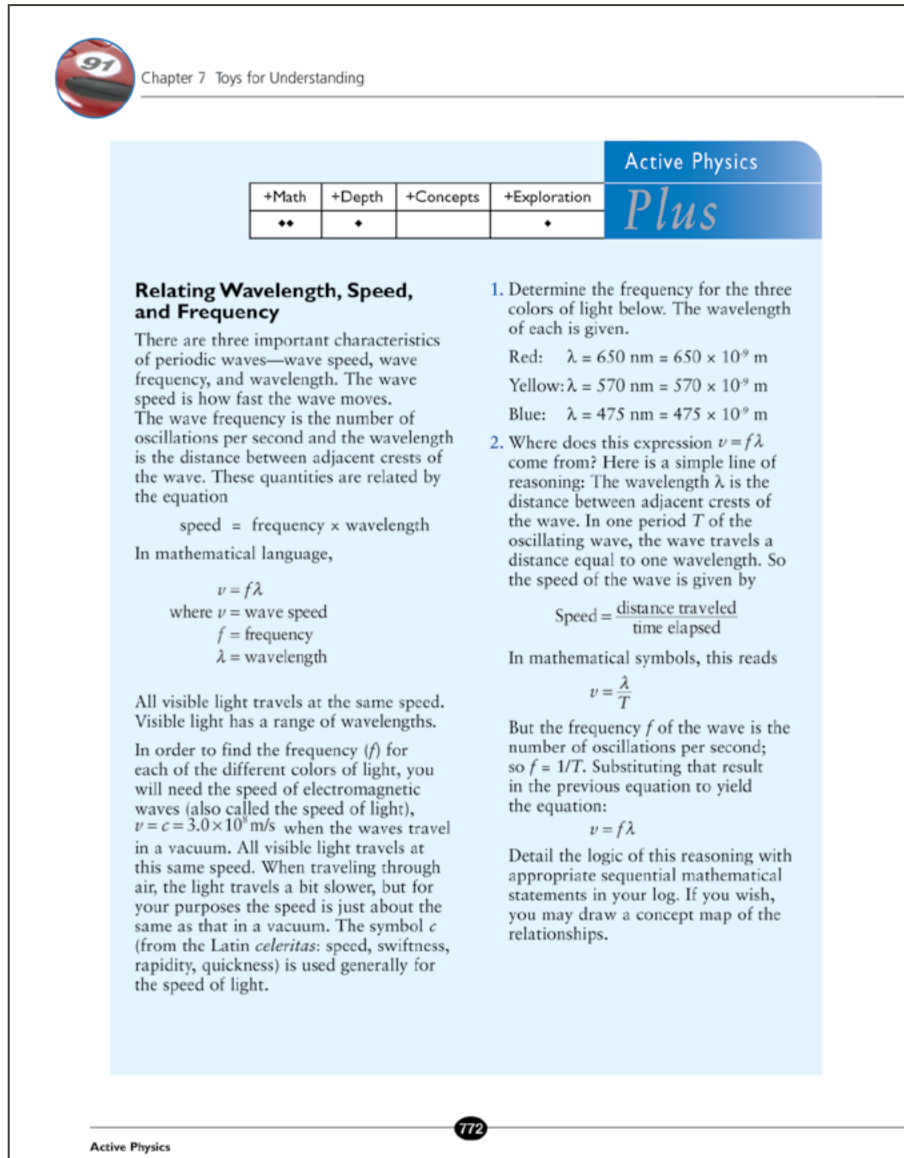
Blue: $f = \dfrac{v}{\lambda} = \dfrac{3.0 \times 10^8 \text{m/s}}{475 \text{ nm}} = 6.3 \times 10^{14} \text{ Hz}$

2.

Speed is the distance traversed over the time it takes to travel that distance. $v = d/t$.

If the wavelength is the amount of distance traveled in one cycle of the wave (λ = distance/cycle), and the period is the amount of time to complete one cycle (T = time/cycle), then the speed is given by the wavelength divided by the period, or

$$v = \lambda/T = \frac{\text{distance/cycle}}{\text{time/cycle}} = \frac{\text{distance}}{\text{cycle}} \times \frac{\text{cycle}}{\text{time}} = \lambda f.$$



Chapter 7 Toys for Understanding

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
••	•		•

Relating Wavelength, Speed, and Frequency

There are three important characteristics of periodic waves—wave speed, wave frequency, and wavelength. The wave speed is how fast the wave moves. The wave frequency is the number of oscillations per second and the wavelength is the distance between adjacent crests of the wave. These quantities are related by the equation

speed = frequency × wavelength

In mathematical language,

$v = f\lambda$

where v = wave speed
f = frequency
λ = wavelength

All visible light travels at the same speed. Visible light has a range of wavelengths.

In order to find the frequency (f) for each of the different colors of light, you will need the speed of electromagnetic waves (also called the speed of light), $v = c = 3.0 \times 10^8$ m/s when the waves travel in a vacuum. All visible light travels at this same speed. When traveling through air, the light travels a bit slower, but for your purposes the speed is just about the same as that in a vacuum. The symbol c (from the Latin *celeritas*: speed, swiftness, rapidity, quickness) is used generally for the speed of light.

1. Determine the frequency for the three colors of light below. The wavelength of each is given.

   Red: $\lambda = 650 \text{ nm} = 650 \times 10^{-9}$ m

   Yellow: $\lambda = 570 \text{ nm} = 570 \times 10^{-9}$ m

   Blue: $\lambda = 475 \text{ nm} = 475 \times 10^{-9}$ m

2. Where does this expression $v = f\lambda$ come from? Here is a simple line of reasoning: The wavelength λ is the distance between adjacent crests of the wave. In one period T of the oscillating wave, the wave travels a distance equal to one wavelength. So the speed of the wave is given by

   $$\text{Speed} = \frac{\text{distance traveled}}{\text{time elapsed}}$$

   In mathematical symbols, this reads

   $$v = \frac{\lambda}{T}$$

   But the frequency f of the wave is the number of oscillations per second; so $f = 1/T$. Substituting that result in the previous equation to yield the equation:

   $$v = f\lambda$$

   Detail the logic of this reasoning with appropriate sequential mathematical statements in your log. If you wish, you may draw a concept map of the relationships.

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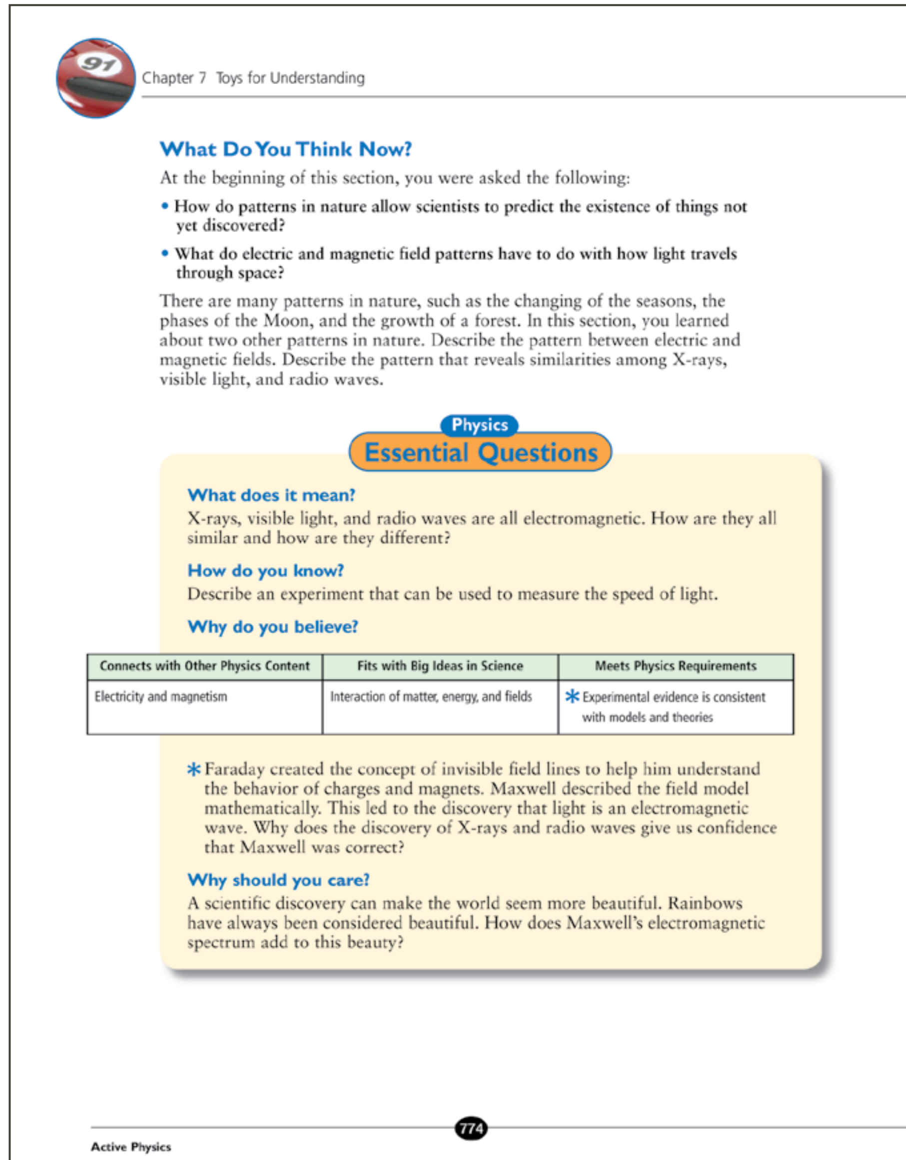
What Do You Think Now?

Ask students to review their previous answers and survey the class for how many students changed their ideas. Consider discussing the information in *A Physicist's Response*. Point out that scientists often change their ideas or build on previous knowledge as they gather more information. One of science's ultimate goals is to discover as many patterns in nature as possible. Have students describe the patterns between electric and magnetic fields. Their descriptions should include the electromagnetic nature of all wavelengths, both visible and invisible, and that these waves move at the speed of light.



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What Do You Think Now?

At the beginning of this section, you were asked the following:

- How do patterns in nature allow scientists to predict the existence of things not yet discovered?
- What do electric and magnetic field patterns have to do with how light travels through space?

There are many patterns in nature, such as the changing of the seasons, the phases of the Moon, and the growth of a forest. In this section, you learned about two other patterns in nature. Describe the pattern between electric and magnetic fields. Describe the pattern that reveals similarities among X-rays, visible light, and radio waves.

Physics **Essential Questions**

What does it mean?

X-rays, visible light, and radio waves are all electromagnetic. How are they all similar and how are they different?

How do you know?

Describe an experiment that can be used to measure the speed of light.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	Interaction of matter, energy, and fields	* Experimental evidence is consistent with models and theories

* Faraday created the concept of invisible field lines to help him understand the behavior of charges and magnets. Maxwell described the field model mathematically. This led to the discovery that light is an electromagnetic wave. Why does the discovery of X-rays and radio waves give us confidence that Maxwell was correct?

Why should you care?

A scientific discovery can make the world seem more beautiful. Rainbows have always been considered beautiful. How does Maxwell's electromagnetic spectrum add to this beauty?

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Physics Essential Questions

What does it mean?

All of these are electromagnetic waves. They all travel at the same speed in a vacuum, which is 3×10^8 m/s. They vary in wavelength and frequency.

How do you know?

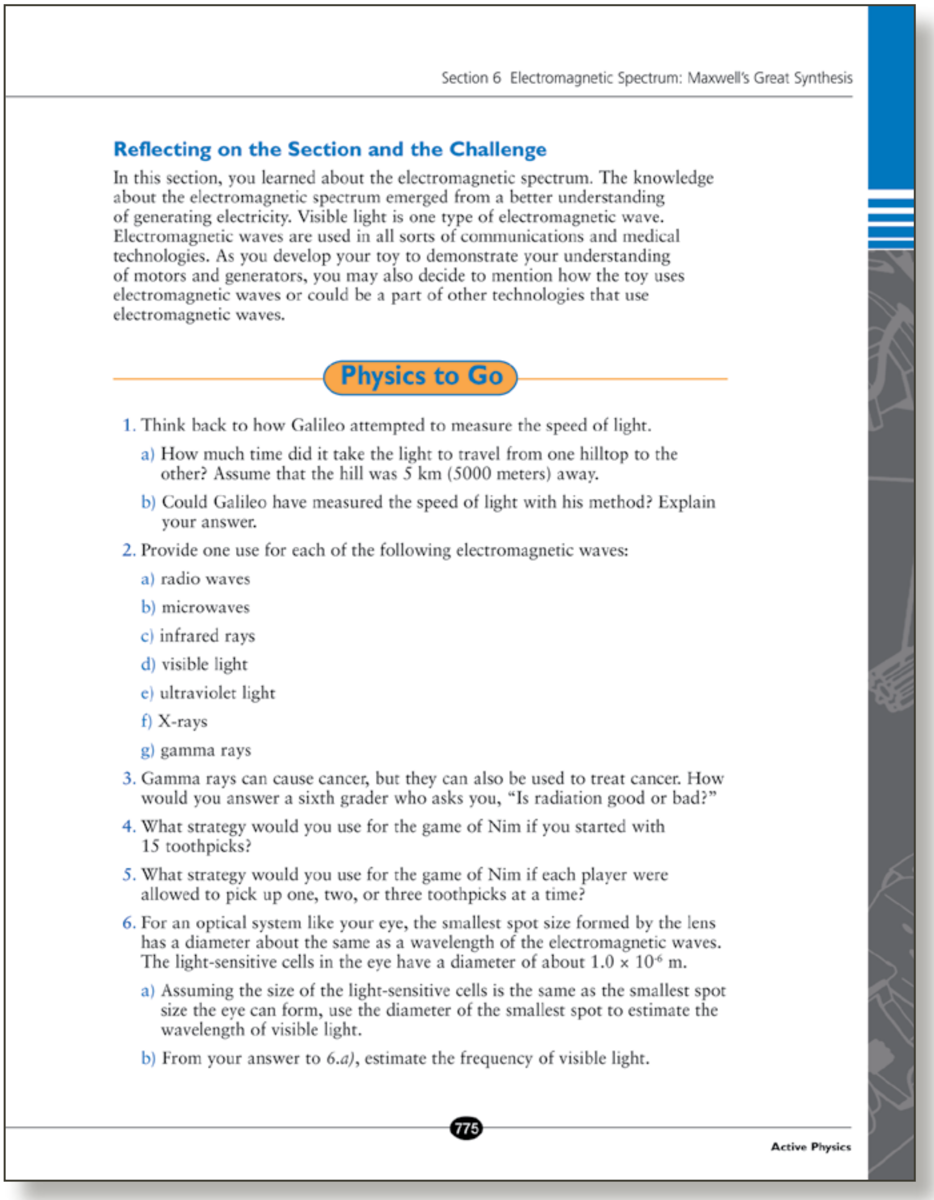
A beam of light travels a specific distance. A timing device is able to accurately measure the time of travel. The speed is equal to the distance traveled divided by the time. Michelson used a rotating mirror to assist him in measuring a very short time. Roemer used the moons of Jupiter to have a very large distance.

Why do you believe?

Nobody knew about the existence of X-rays or radio waves. Maxwell's equations predicted them. When they were discovered, they behaved as Maxwell had predicted.

Why should you care?

Maxwell's electromagnetic spectrum reveals that our eyes are only detecting a small part of the electromagnetic spectrum. It's as if you could only hear one note and then someone introduced you to a symphony.


Section 6 Electromagnetic Spectrum: Maxwell's Great Synthesis

Reflecting on the Section and the Challenge

In this section, you learned about the electromagnetic spectrum. The knowledge about the electromagnetic spectrum emerged from a better understanding of generating electricity. Visible light is one type of electromagnetic wave. Electromagnetic waves are used in all sorts of communications and medical technologies. As you develop your toy to demonstrate your understanding of motors and generators, you may also decide to mention how the toy uses electromagnetic waves or could be a part of other technologies that use electromagnetic waves.

Physics to Go

1. Think back to how Galileo attempted to measure the speed of light.
   a) How much time did it take the light to travel from one hilltop to the other? Assume that the hill was 5 km (5000 meters) away.
   b) Could Galileo have measured the speed of light with his method? Explain your answer.
2. Provide one use for each of the following electromagnetic waves:
   a) radio waves
   b) microwaves
   c) infrared rays
   d) visible light
   e) ultraviolet light
   f) X-rays
   g) gamma rays
3. Gamma rays can cause cancer, but they can also be used to treat cancer. How would you answer a sixth grader who asks you, "Is radiation good or bad?"
4. What strategy would you use for the game of Nim if you started with 15 toothpicks?
5. What strategy would you use for the game of Nim if each player were allowed to pick up one, two, or three toothpicks at a time?
6. For an optical system like your eye, the smallest spot size formed by the lens has a diameter about the same as a wavelength of the electromagnetic waves. The light-sensitive cells in the eye have a diameter of about 1.0×10^{-6} m.
   a) Assuming the size of the light-sensitive cells is the same as the smallest spot size the eye can form, use the diameter of the smallest spot to estimate the wavelength of visible light.
   b) From your answer to *6.a)*, estimate the frequency of visible light.

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Reflecting on the Section and the Challenge

Consider asking students how their knowledge of electricity would help them explain how their toy generates electromagnetic waves similar to the noise heard on the radio when there is lightning. Review how the discovery of electromagnetic waves helped in advancing medical and communications technology. Discuss what students have learned in this section about electromagnetic waves and the electromagnetic spectrum. Point out that their toy should include their demonstration of motors and generators. Have them reflect on the instructions they want to include for their toy and how their toy could be a part of other technologies.

Physics to Go

1.a)

$$t = d/v = \frac{5000 \text{ m}}{3 \times 10^8 \text{ m/s}} = 0.000017 \text{ s}$$

1.b)

Galileo could not measure the speed of light with his method because the average human reaction time is 0.2 s, which is 1000 times greater than the time it takes light to travel a distance of 5 km.

2.a)

Radio waves are used to transmit signals through the atmosphere as AM and FM waves.

2.b)

Microwaves can be used to heat food. The energy carried by microwaves is readily absorbed by water molecules and causes rapid temperature increases of water molecules.

2.c)

Infrared rays often are used to warm food and warm homes. Often times, other electromagnetic waves are absorbed and infrared rays are emitted, such as in the greenhouse effect of cars or global warming.

2.d)

Visible light is used to assist human vision. To see anything, light from the object must enter the eye.

2.e)

Ultraviolet light can be used as an energy source for phosphorescent materials that absorb ultraviolet light and emit visible light. This is done with black lights. Ultraviolet radiation is also what tans or burns us.

CHAPTER 7

2.f)

X-rays are used to image bones and determine crystalline structures.

2.g)

Gamma rays are given off during nuclear reactions and can be used as a radiation treatment to kill cancer cells. They are also capable of killing healthy cells and causing cancer.

3.

Students should describe how gamma rays can be good when they destroy bad cells such as cancer cells, but also can be bad because they can kill healthy cells and cause cancer.

4.

The key would be to leave a multiple of three toothpicks at the end of a turn. The strategies that enable you to do so will vary with how your partner plays the game.

5.

The key would be to leave multiples of four toothpicks at the end of a turn.

6.a)

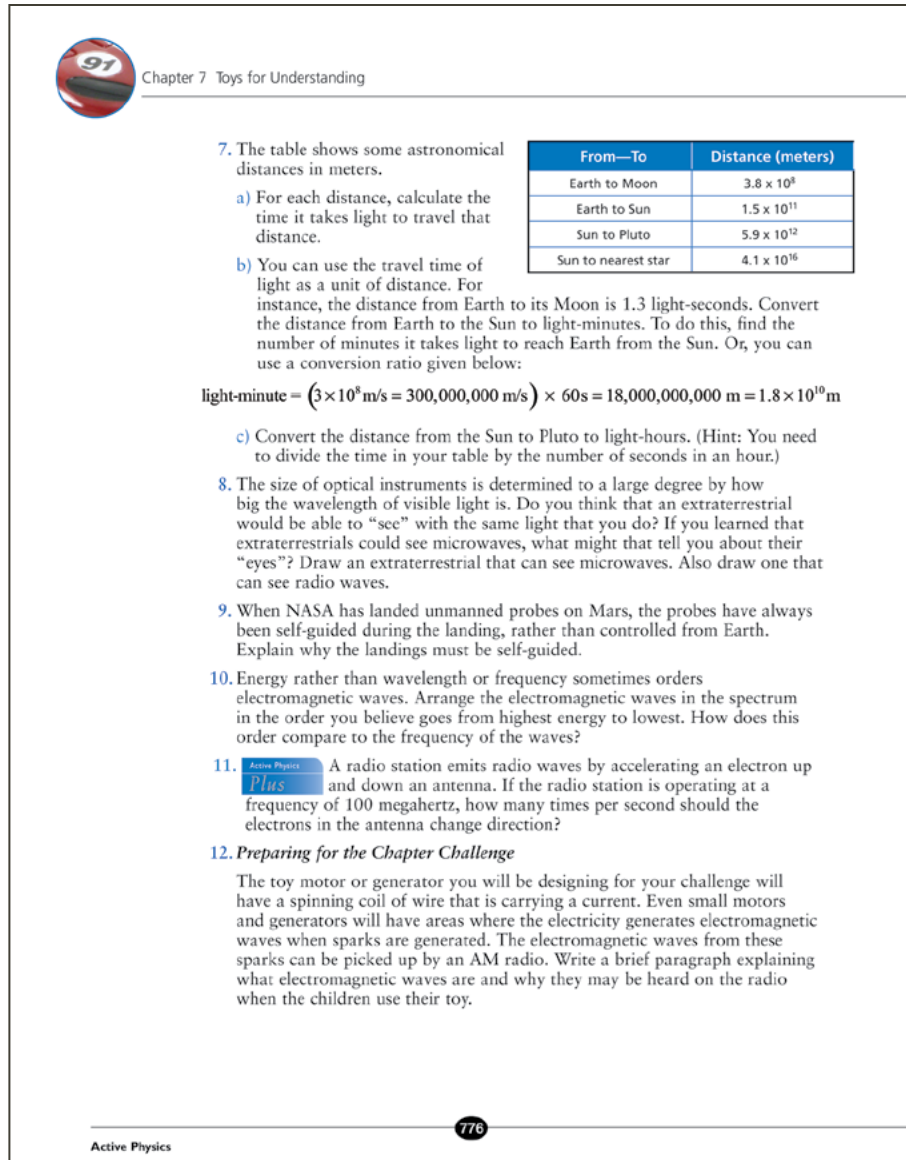
1.0×10^{-6} m

6.b)

$$f = v/\lambda = \frac{3 \times 10^{8}\ \text{m/s}}{1.0 \times 10^{-6}\ \text{m}} = 3 \times 10^{14}\ \text{Hz}$$

NOTES

NOTES



Chapter 7 Toys for Understanding

7. The table shows some astronomical distances in meters.

From—To	Distance (meters)
Earth to Moon	3.8×10^8
Earth to Sun	1.5×10^{11}
Sun to Pluto	5.9×10^{12}
Sun to nearest star	4.1×10^{16}

a) For each distance, calculate the time it takes light to travel that distance.

b) You can use the travel time of light as a unit of distance. For instance, the distance from Earth to its Moon is 1.3 light-seconds. Convert the distance from Earth to the Sun to light-minutes. To do this, find the number of minutes it takes light to reach Earth from the Sun. Or, you can use a conversion ratio given below:

$$\text{light-minute} = \left(3 \times 10^8 \text{ m/s} = 300{,}000{,}000 \text{ m/s}\right) \times 60\text{s} = 18{,}000{,}000{,}000 \text{ m} = 1.8 \times 10^{10}\text{m}$$

c) Convert the distance from the Sun to Pluto to light-hours. (Hint: You need to divide the time in your table by the number of seconds in an hour.)

8. The size of optical instruments is determined to a large degree by how big the wavelength of visible light is. Do you think that an extraterrestrial would be able to "see" with the same light that you do? If you learned that extraterrestrials could see microwaves, what might that tell you about their "eyes"? Draw an extraterrestrial that can see microwaves. Also draw one that can see radio waves.

9. When NASA has landed unmanned probes on Mars, the probes have always been self-guided during the landing, rather than controlled from Earth. Explain why the landings must be self-guided.

10. Energy rather than wavelength or frequency sometimes orders electromagnetic waves. Arrange the electromagnetic waves in the spectrum in the order you believe goes from highest energy to lowest. How does this order compare to the frequency of the waves?

11. Active Physics Plus A radio station emits radio waves by accelerating an electron up and down an antenna. If the radio station is operating at a frequency of 100 megahertz, how many times per second should the electrons in the antenna change direction?

12. *Preparing for the Chapter Challenge*

The toy motor or generator you will be designing for your challenge will have a spinning coil of wire that is carrying a current. Even small motors and generators will have areas where the electricity generates electromagnetic waves when sparks are generated. The electromagnetic waves from these sparks can be picked up by an AM radio. Write a brief paragraph explaining what electromagnetic waves are and why they may be heard on the radio when the children use their toy.

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7.a)-c)

For all distance calculations, the following formula is used: $t = d/v$

- Earth to Moon: 1.3 s.
- Earth to Sun: 500 s, 8.3 light-minutes.
- Sun to Pluto: 19,667 s, 5.5 light-hours ($1 \text{ light-hour} = 1.08 \times 10^{12}$ m).
- Sun to nearest star: 1.4×10^8 m.

8.

As described in *Question* 6, the light-sensitive cells in the eye have a diameter of about the wavelength of light they are sensitive to. For microwaves, this would be between 10 mm and 10 cm, or a factor of 10,000 to 100,000 times larger than human eyes, hence, a reasonable prediction is that these aliens would have very large eyes. For an alien with eyes sensitive to radio waves, (10 cm to 100 km) you could predict the extraterrestrial's eyes may between 100,000 to 100,000,000,000 times larger than human eyes. Students should draw an extraterrestrial that can see microwaves, and one that can see radio waves.

9.

The landings must be self-guided because sending commands from Earth would take too long for the unmanned probes to adjust themselves quickly enough while landing on Mars.

10.

Responses will vary. The energy is directly proportional to the frequency—as the frequency increases so does the energy.

11. Active Physics Plus

If the station is operating at 100 MHz it means the electrons go through one 100,000,000 cycles per second and change direction twice each cycle or 200,000,000 times per second.

12.

Preparing for the Chapter Challenge

Students' paragraphs should include an explanation that electromagnetic waves are oscillating electric and magnetic fields that travel as a wave, and that these electromagnetic waves can have different frequencies and energies, including radio waves. Students should discuss


Section 6 Electromagnetic Spectrum: Maxwell's Great Synthesis

Inquiring Further

Speed of light

The speed of light is known to such accuracy that its value has been used to calculate the distance to Earth's Moon. A laser beam was sent to the Moon and it reflected off a mirror placed there and returned to Earth. By measuring the time of flight, and using the accepted value of the speed of light, the distance to the Moon was calculated.

a) Find a reference to this experiment and check the results.

b) Conduct a similar experiment of your own by listening to a tape recording of a conversation with an astronaut on the Moon. The time delay between a question asked at Mission Control and hearing the response is approximately equal to the time for the radio wave to travel to the Moon and back. Determine this value and use the speed of light (and radio waves) to calculate the distance to the Moon.

The speed of light is known to such accuracy that it is used to determine other constants. Find a reference that allows you to answer the following questions.

a) How is a meter defined?

b) How is a second defined?

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Active Physics

how a generator may produce an occasional electromagnetic wave that can be picked up by a radio.

Inquiring Further

Speed of light

a)

Students should find a reference on the Internet to the experiments that were done in 1969 and after that measure the distance between Earth and the Moon using a laser. The experiment was made possible by a retroreflector array installed on the Moon on July 21, 1969, during the Apollo 11 mission. Two more retroreflectors were placed on the Moon during the Apollo 14 and 15 missions. The difficulties of the experiment include hitting the retroreflector and detecting the weak signal that returns to Earth.

b)

Tape recordings of the astronaut's conversations with NASA while on the Moon may be found on the Internet at the NASA and JPL (Jet Propulsion Labs of Cal Tech) Web sites. Students should listen for the length of time required for the astronauts to respond to a question from NASA, and time this with a stopwatch. After deducting a reasonable time (about 0.5 seconds) as a response time, students should come up with a time of approximately 1.3 seconds for the time delay.

Using the equation $d = vt$ and substituting in the values for the speed of light and the time, students should calculate a distance to the Moon of

d = (300,000,000 m/s)(1.3 s) = 450,000,000 m, or 240,000 miles.

a)

As our knowledge base increases and technology improves, so do the measuring tools. Because of this, the meter has been redefined a number of times. The last time the meter was redefined was in 1983 by the International Bureau of Weights and Measures (BIPM) as the distance traveled by light in free space in 1/299,792,458 of a second. BIPM does not distinguish between quantum vacuum and free space.

b)

The second is the time duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two-hyperfine levels of the ground state of the cesium 133 atom.

SECTION 6 QUIZ

7-6d **Blackline Master**

1. An astronaut on the Moon wishes to talk to another astronaut who is on a space station 1.5×10^9 meters away. How long does it take the radio signal from the astronaut on the Moon to reach the space station?

   a) 0.5 seconds.
   b) 2 seconds.
   c) 3 seconds.
   d) 5 seconds.

2. Which of the following waves are not electromagnetic waves?

   a) Radio waves.
   b) Sound waves.
   c) Light waves.
   d) X-rays.

3. In a vacuum, all electromagnetic waves have the same

   a) amplitude.
   b) frequency.
   c) speed.
   d) wavelength.

4. A changing electric field can produce

   a) a changing magnetic field.
   b) a steady magnetic field.
   c) another steady electric field.
   d) a random series of electromagnetic pulses.

5. An electromagnetic wave traveling in a vacuum has a frequency of 6×10^{15} Hertz. What is the wavelength of this electromagnetic wave?

   a) 3×10^8 m
   b) 6×10^7 m
   c) 1.8×10^{-23} m
   d) 5×10^{-8} m

SECTION 6 QUIZ ANSWERS

1. d) 5 seconds. $t = \frac{d}{v} = \frac{1.5 \times 10^9 \text{ m}}{3 \times 10^8 \text{ m/s}} = 5$ s.

2. b) Sound waves. Sound waves require a medium to travel through—electromagnetic waves do not.

3. c) speed. Electromagnetic waves may have different frequencies, wavelengths, energies, and amplitudes but they travel at the same speed, 3×10^8 m/s, in a vacuum.

4. a) a changing magnetic field.

5. d) 5×10^{-8} m. $\lambda = \frac{v}{f} = \frac{3 \times 10^8 \text{ m/s}}{6 \times 10^{15} \text{ Hz}} = 5 \times 10^{-8}$ m.