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.

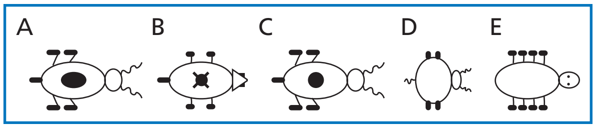
Finally, you will explore how the speed of light was determined, and how to make calculations using the speed of light to determine travel times.

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?



   Each of these answers would be acceptable.

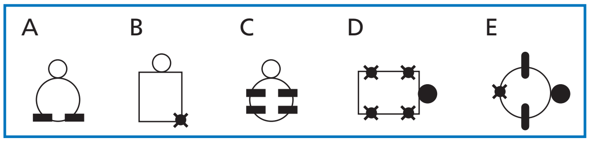
   Paynes are creatures that have antennae; a, c, and d are paynes.

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

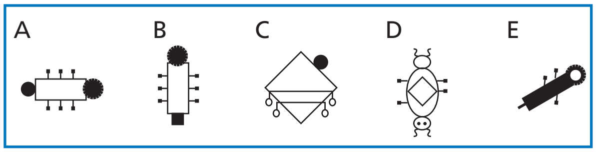
   Paynes are creatures that have a mark on their back; a, b, and c are paynes.

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

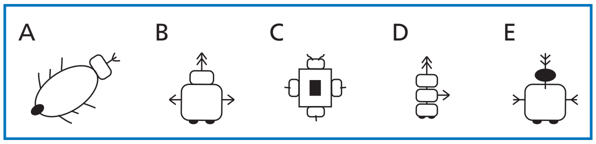
   a) Which of these are chiavs?



   b) Which of these are howes?



   c) Which of these are stengels?



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?

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)	
I Draw the *E* field for a positive and negative charge. ⊕ ⊖	**II** Draw the *E* field for a positive charge. ⊕	**III** Draw the *B* field for a bar magnet. N S	**IV** 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**	
V	**VI** If charges move, they create a current. A single charge can move and create a current.	**VII** A current can be created when the magnetic field changes.	**VIII** There is no single north pole so you cannot have moving north poles without south poles.
	A current creates a *B* field.	Describe how an electromagnet can create current in a coil without any movement of the electromagnet.	
	Draw the *B* field for a negative current going into the page. ⊗	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.	

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.

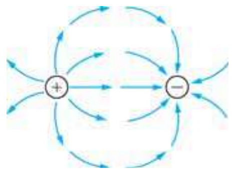
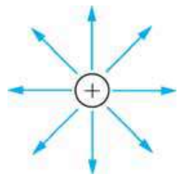
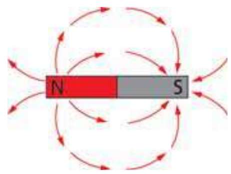
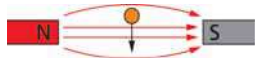
   a) Michelson had measured the distance to be 0.7576 mi (1219 m), and the precise time he was able to measure for the light to travel that far was 4.065×10^{-6} s (0.000004065 s). Calculate the speed of light in meters per second and in miles per second using this value for the time.

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.

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)**	
I The *E* field for a positive and negative charge.  *Coulomb showed that there is a force between two charges.* $F = k\frac{q_1q_2}{d^2}$ *Faraday showed that this force could be explained with the introduction of the concept of electric fields*	**II** The *E* field for a positive charge.  *Gauss derived an equation that could mathematically relate the electric field to the charge.*	**III** The *B* field for a bar magnet.  *Gilbert investigated the properties of magnets and found that like poles repel and unlike poles attract.*	**IV** 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 from an *E* field		**Creating an *E* field from a *B* field**	
V	**VI** 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.*	**VII** 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.*	**VIII** There is no single north pole so you cannot have moving north poles without south poles.

James Clerk Maxwell saw that there was a pattern in the mathematical equations that described these phenomena. In the table, I relates to II, III to IV and I relates to III, II to IV. Also, II relates to VI, III to VII, and IV to VIII. The missing element in the pattern begged the question: If a changing magnetic field can create a changing electric field (that produces a current, VII), can a changing electric field produce a changing magnetic field, V? If so, this would make the pattern of the mathematical equations much more symmetric and beautiful. (V would relate to VII.)

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, V, then that *changing* magnetic field would in turn create a *changing* electric field, VII 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.

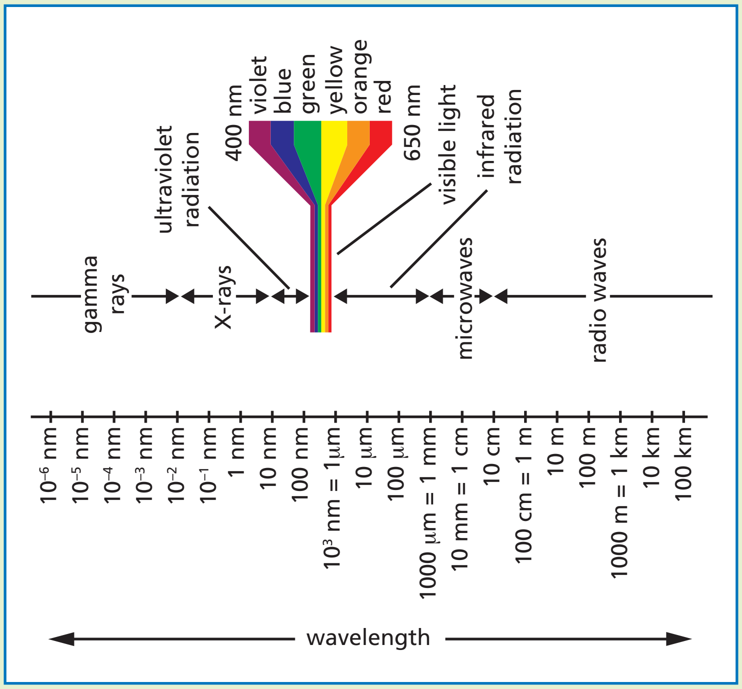
Maxwell's four equations are powerful stuff. But the story does not end there. Light has a very specific band of wavelengths. Blue light has a wavelength of 450 nm (nanometers) 450×10^{-9} m and red light has a wavelength of 700 nm. Maxwell tried to find out why light was restricted to this range of 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.

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.

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.



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?

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
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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: λ = 650 nm = 650×10^{-9} m

   Yellow: λ = 570 nm = 570×10^{-9} m

   Blue: λ = 475 nm = 475×10^{-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.

Example:

An FM radio antenna on a car is approximately 1 m long. Since the lengths of the antennas are comparable to the wavelengths they radiate or receive, assume that FM radio waves have a wavelength of about 2 m. You can find the approximate frequency for FM radio from

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

$$f = \frac{3 \times 10^8 \text{m/s}}{2\text{m}}$$

$$f = 1.5 \times 10^8 \text{/s} = 1.5 \times 10^8 \text{ Hz} = 150 \text{ MHz}$$

Recall that 1 Hz = 1 oscillation/s. MHz means megahertz, which is the same as 10^6 oscillations per second. The actual FM broadcast band is from 88 to 108 MHz.

3. Look at the list below of electromagnetic waves and their frequencies:

Type of wave	Typical frequency
AM radio	1 MHz (10^6 Hz)
FM radio / commercial TV	100 MHz
radar	1 GHz (10^9 Hz)
microwave	10 GHz
infrared radiation	6×10^{12} Hz
light	10^{14} Hz
ultraviolet radiation	10^{16} Hz
X-rays	10^{18} Hz
gamma rays	10^{21} Hz

a) Calculate the wavelength of each type of wave.

b) Describe an object that is about the same size of each of those wavelengths. For the higher frequencies (shorter wavelengths), the objects will be small, perhaps bacteria, atoms, or nuclei.

4. Explore the wavelength of microwaves. You can measure the wavelength of microwaves in a microwave oven by placing a rectangular glass dish filled with marshmallows in the oven. Be sure that the dish will not rotate when you turn on the microwave. (You may have to remove the rotating glass dish from the microwave, but you want to make sure that the rectangular glass dish sits evenly on the bottom. Use waxed paper or pads of plastic wrap to make an even foundation for the glass dish.) Put the marshmallow dish in the microwave oven, and then turn on the microwaves for about 30 s. Take a look at the marshmallows. If you don't see any brown spots on the tops of the marshmallows, return the dish to the microwave oven in the same spot and turn on the microwave for another 30 s. As soon as the brown spots appear, carefully remove the glass dish and measure the distance between the brown spots on the marshmallows. This distance is about half the wavelength of the microwaves.

The pattern is due to wave interference within the microwave enclosure. The brown spots occur where the microwaves reinforce each other in what is called constructive interference. This creates areas where the microwaves are more intense, as shown by where the marshmallows were heated first.

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?

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.

7. The table shows some astronomical distances in meters.

   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:

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}

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

   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.

Inquiring Further

Speed of light

1. 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.
2. 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?