TOPIC 3.2

How can models explain the properties of electromagnetic radiation?

Models are useful tools in many areas of science. Scientists use models to represent ideas and concepts, and to understand them better. Models also help scientists generate hypotheses and plan experiments. Models can be helpful in everyday life as well. For instance, the game plan shown here is a type of model. Coaches use game plans like this to explain strategies they want to use in a game.

Key Concepts

- Visible light can be used to model all types of electromagnetic radiation.
- The ray model of light explains that light travels in straight lines.
- The wave model of light explains that light has wave-like properties.
- The particle model of light explains that light has particle-like properties.

Curricular Competencies

- Demonstrate an understanding and appreciation of evidence
- Formulate "If… then…" hypotheses based on your questions
- Identify possible sources of error and suggest improvements to investigations
- Ensure that safety and ethical guidelines are followed in investigations

Starting Points

Choose one, some, or all of the following to start your exploration of this Topic.

1. **Identifying Preconceptions** Demonstrate your understanding of what a model is. Share your explanations, and see if your class can reach a consensus on a definition.
2. **Questioning** Think of another scientific model you have learned about this year or in previous studies. How is it helpful to scientists? How can it be used to make predictions?
3. **Applying** How might models help scientists understand the properties of visible light and other types of electromagnetic radiation?

Key Terms

There are six key terms that are highlighted in bold type in this Topic:

- ray model of light
- wave model of light
- amplitude
- particle model of light
- wavelength
- frequency

Flip through the pages of this Topic to find these terms. Add them to your class Word Wall along with their meaning. Add other terms that you think are important and want to remember.

CONCEPT 1

Visible light can be used to model all types of electromagnetic radiation.

Activity

What's In a Name?

In science, names often give you information about the things they describe. The term electromagnetic radiation combines three smaller words: electric, magnetic, and radiation.

1. Find definitions of these three words and record them.
2. Based on these definitions, describe three properties that you think electromagnetic radiation might have.

Figure 3.7 Visible light and other electromagnetic radiation from the Sun travels 150 million km to reach Earth. Much of its journey is through empty space. (The brighter object here is Earth. The smaller, paler speck is our Moon.)

Observations and experiments have helped scientists learn a lot about the properties of electromagnetic radiation. For instance, they know:

- It is invisible as it travels. (Visible light must interact with matter to become visible.)
- It involves the transfer of energy from one place to another.
- It can travel through empty space (**Figure 3.7**).
- It travels through empty space at the speed of light (3.00×10^8 m/s).
- It has both electrical and magnetic properties.

As you can see, the seven types of electromagnetic radiation have much in common. In fact, they are so alike that studying one type can tell you a lot about the others. Visible light is often used as a model to study other types of electromagnetic radiation. It is fairly easy and safe to study. It also becomes visible when it interacts with matter.

Before you leave this page . . .

1. Why is visible light used as a model for other types of electromagnetic radiation?
2. Explain one way that visible light is different from other types of electromagnetic radiation and one way it is similar to them.

CONCEPT 2

The ray model of light explains that light travels in straight lines.

Activity

Evidence That Light Travels in Straight Lines

The photo demonstrates that light travels in straight lines. Consider your own experiences with light. What evidence have you seen that light travels in straight lines? How could you demonstrate that it does?

Fernie-based band Shred Kelly in concert.

It has taken thousands of years for people all over the world to develop an understanding of light. For example, more than 2000 years ago, a Greek mathematician named Euclid suggested that light travels in straight lines. You can use this idea to understand how shadows like those in **Figure 3.8** form.

Connect to Investigation 3-C on page 216

Understanding the Ray Model of Light

Look at **Figure 3.8** again. In each photo, light from the light source cannot bend around the person's hands. The hands block the light and cast a sharp-edged shadow on the wall. This tells you that light must travel in straight lines. This idea is now referred to as the **ray model of light**. A *ray* is an arrow that is used to show the direction of the straight-line path of light.

ray model of light the idea that light travels in straight lines

Figure 3.8 Hand shadow games like this were used by many First Peoples, not only for play, but also to develop various kinds of skills of benefit to the community. **What kinds of skills could hand shadow games help someone develop?**

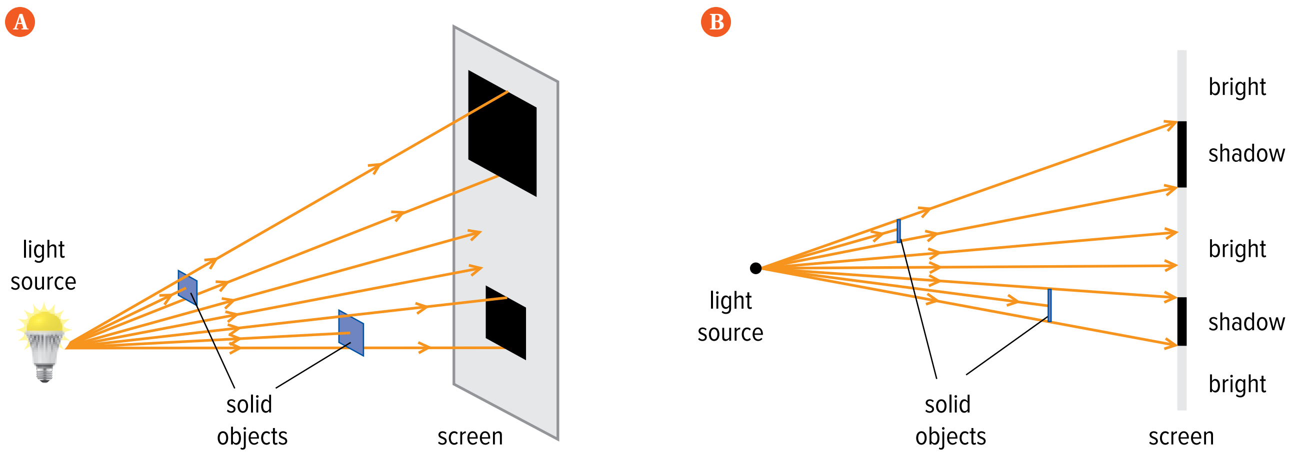


Figure 3.9 Ⓐ You can use ray diagrams to predict the location, size, and shape of shadows. Notice that the distance between an object and the light source affects the size of its shadow. Ⓑ Ray diagrams are easier to draw if you view the object from the side. The light source can also be represented as a dot.

Using Ray Diagrams to Model Visible Light

Diagrams that involve rays are called *ray diagrams*. Ray diagrams are used to study and predict how light behaves. **Figure 3.9** shows how rays can be used to predict the location, size, and shape of shadows. The source of light is a small light bulb. It sends out rays in every direction. However, with a ray diagram, only a few of the rays travelling toward the objects need to be drawn.

Did you notice that the rays spread out in **Figure 3.9**? Light rays spread out as they travel from a light source. Because the rays spread out, light also gets dimmer as it travels. This effect is shown in **Figure 3.10**.

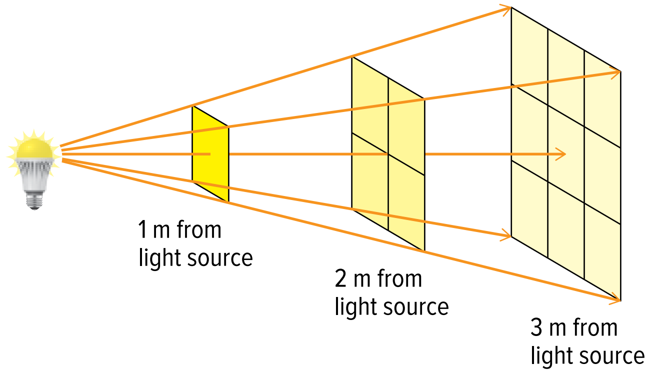


Figure 3.10 Light rays spread out from a source and dim with distance. At 2 m from the light source, the light is $\frac{1}{4}$ as bright as it was at 1 m from the source. At 3 m, it is $\frac{1}{9}$ as bright.

Before you leave this page . . .

1. Like visible light, microwaves spread out from a source. How might this affect cell phone use?
2. In **Figure 3.9**, why does the smaller object cast the bigger shadow?

CONCEPT 3

The wave model of light explains that light has wave-like properties.

Activity

Can Waves Carry Energy?

You can observe that water waves carry energy when you see a photo like this. But how can you demonstrate that waves actually do carry energy? And does this apply to more than water waves? To start to investigate these questions, you will need a pan of water and a rope.

1. With a partner or in small groups, decide what is necessary to produce a wave using
   a) water **b)** rope
2. Is energy always needed to produce a wave? Explain your thinking.
3. How does a wave move energy from one place to another?
4. How can you change the size of the wave?
5. How can you change the speed of the wave?

Observations of shadows enabled scientists to infer that light travels in a straight line. But there was still much about the properties of light to understand. Many scientists thought that light was made of streams of particles. The idea that light has particle-like properties is known as the **particle model of light**. A scientist named Isaac Newton was one of the first people to propose that light has these properties. However, he could not demonstrate this in an experiment.

As other scientists continued to study light, they realized that some properties could not be possible if light was simply a stream of particles. Some scientists argued that light has wave-like properties. In the early 1800s, a scientist named Thomas Young designed an experiment to test the hypothesis that light has the properties of a wave. His experiment supported the idea of a **wave model of light**. Young's experiment is explained in Figure 3.11 on the next page.

particle model of light the idea that light has particle-like properties

wave model of light the idea that light has wave-like properties

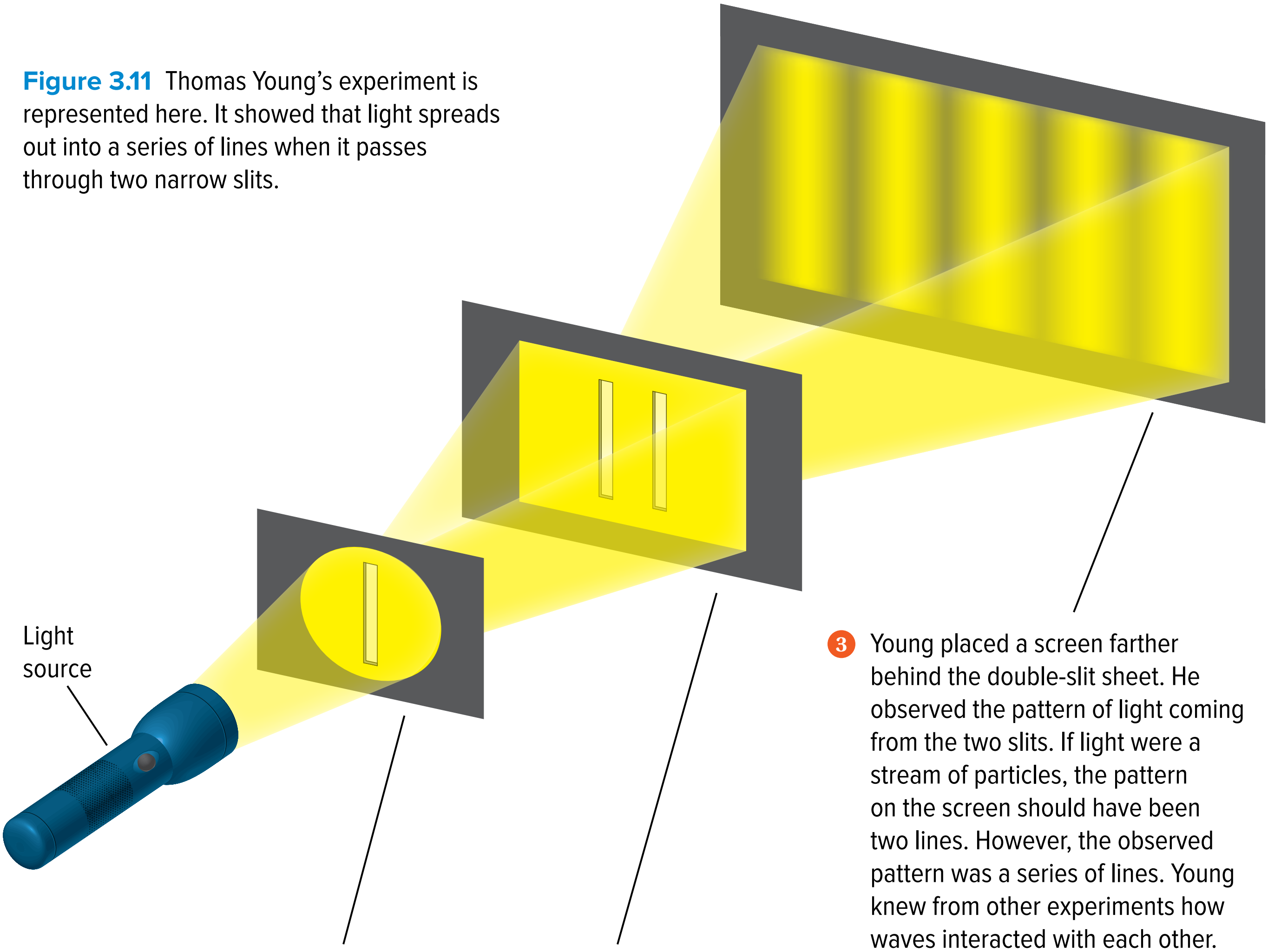


Figure 3.11 Thomas Young's experiment is represented here. It showed that light spreads out into a series of lines when it passes through two narrow slits.

1. Young shone light through a single slit in a solid sheet.
2. He then directed this light to two slits in another solid sheet.
3. Young placed a screen farther behind the double-slit sheet. He observed the pattern of light coming from the two slits. If light were a stream of particles, the pattern on the screen should have been two lines. However, the observed pattern was a series of lines. Young knew from other experiments how waves interacted with each other. The pattern of lines he observed could only be explained if light had wave-like properties.

Extending the Connections

How Do Waves Interact?

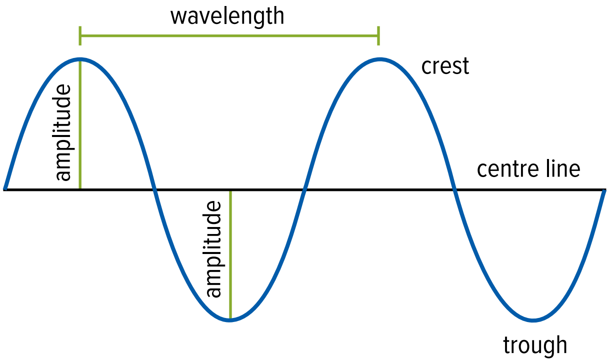
What do you think Thomas Young knew about waves that helped him interpret his experimental results? Investigate your own questions and ideas about waves. Find out what Young knew, and compare your own ideas to his.

Properties of Light Waves

Light waves have some things in common with water waves. Both types of waves move energy from one place to another. In water waves, the energy causes water molecules to vibrate up and down. This motion produces the shape shown in Figure 3.12. Scientists use the shape of a water wave to model light waves. Like a water wave, light waves have a wavelength. They also have amplitude and frequency. These terms are explained in Figure 3.12 and 3.13.

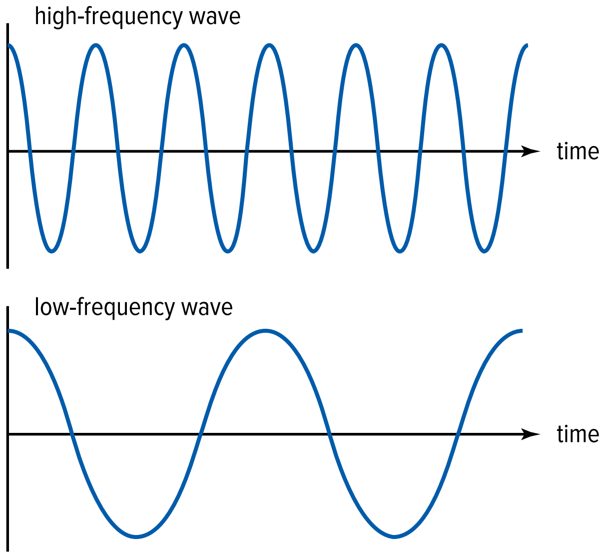
Connect to Investigation 3-D on page 217

Figure 3.12 This wave illustrates wavelength and amplitude.



The crest of a wave is the highest point, and the trough of a wave is the lowest point. The distance from the centre line to the crest is the same as from the centre line to the trough. **Wavelength** refers to the distance from one crest (or trough) of a wave to the next crest (or trough). **Amplitude** is the distance from the centre line to the crest or trough of the wave.

Figure 3.13 This wave illustrates frequency.



This diagram shows two waves with different frequencies. **Frequency** refers to the number of complete wavelengths that pass a point in one second as the wave goes by. As the wavelength decreases, the frequency increases. And as the wavelength increases, the frequency decreases.

Extending the Connections

Light Waves Are More Complicated Than Water Waves

Even though scientists use a water wave as a model for a light wave, light waves are more complicated. This is because light waves have electrical and magnetic properties. Find out how electromagnetic waves are different from the simpler model used for water waves.

wavelength the distance from one crest (or trough) of a wave to the next crest (or trough)

amplitude the distance from the centre line to the crest or trough of a wave

frequency the number of complete wavelengths that pass a point in one second as the wave goes by

Light, Wavelength, and Colour

In the 1600s, Isaac Newton used a prism to separate visible light into the colours of the rainbow (**Figure 3.14**). He hypothesized that if light were a mixture of colours, the colours would recombine to form white light if they passed through another prism. He set up an experiment to test this idea and observed that they did. In this way, Newton was the first scientist to show that sunlight was actually a mixture of light of different colours.

Connect to Investigation 3-E on page 218

The colours of light are actually different wavelengths of visible light. Together, they are referred to as the *visible light spectrum*. The colour red has the longest wavelength of visible light. Violet has the shortest.

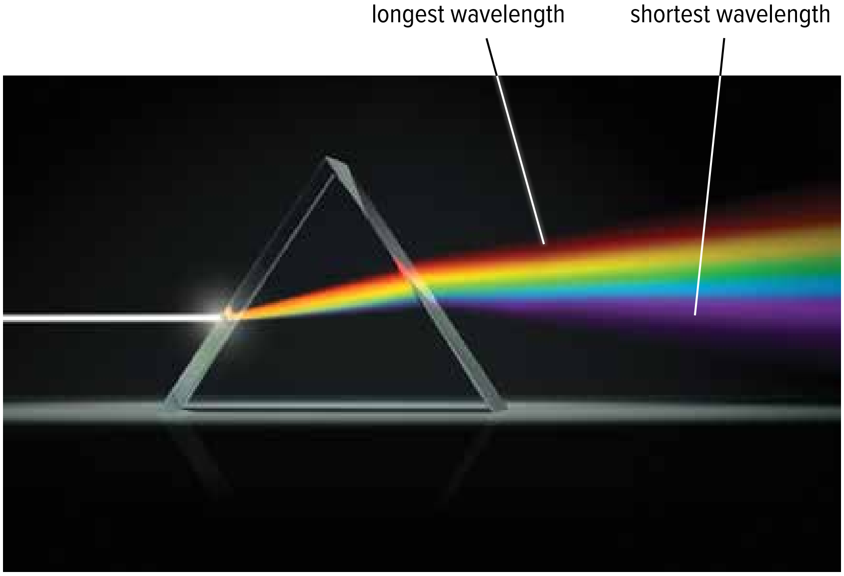


Figure 3.14 Newton separated visible light into colours. At the time, he did not know that the colours are actually different wavelengths of light. **The colours of the spectrum fall in a certain order. You can remember the colours and their order using the mnemonic ROY G BIV. Use this figure to determine what each letter in the mnemonic stands for.**

Before you leave this page . . .

1. Describe one way that a light wave is like a water wave. Describe one way that it is different.
2. One wave has a higher frequency than another wave. Which wave would have the longer wavelength? Explain your reasoning.

CONCEPT 4

The particle model of light explains that light has particle-like properties.

Activity

Thought Experiment

A thought experiment is an experiment that is carried out in your head.

1. Complete the thought experiment below before you read Concept 4.

Your friend challenges you to try to make a bowling ball start rolling by rolling other balls toward it. What would happen in the following situations?

a) You roll table-tennis balls toward the bowling ball. You can use as many table-tennis balls as you want. Can you make the bowling ball roll?

b) Repeat the thought experiment with tennis balls. What will happen?

c) You can choose any other type of ball you want. What type of ball would you choose to roll at the bowling ball to make it start rolling? Explain why you made the choice that you made.

2. Read Concept 4. Compare the results of your thought experiment with Figure 3.16. What part of your thought experiment is similar to the red light? What part of your thought experiment is similar to the blue light?

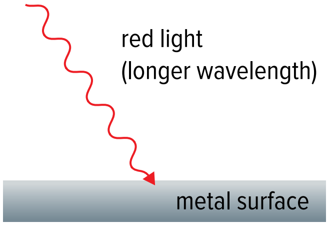
You might think Young's experiment convinced scientists that light (and every type of electromagnetic radiation) has the properties of a wave. But there was a property of light that the wave model could not explain: the photoelectric effect. Figure 3.15 describes this effect. Figure 3.16 on the next page gives Albert Einstein's explanation of why the effect occurs and why light has both wave-like and particle-like properties.

Figure 3.15 The Photoelectric Effect

This effect was first discovered by a scientist named Philipp Lenard. He shone different colours of light onto the surface of a certain metal and observed the following results:

Red Light: Electrons are *never* given off when energy from red light hits the metal.

- Electrons are not given off no matter how bright the red light is.
- Electrons are not given off no matter how long the red light shines on the metal.



Blue Light: Electrons are *always* given off when energy from blue light hits the metal.

- Electrons are always given off no matter how dim the blue light is.
- Electrons are always given off no matter how briefly the blue light shines on the metal.

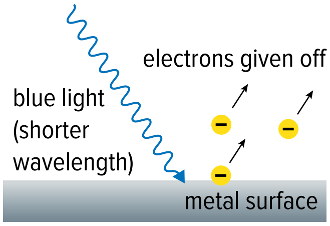


Figure 3.16 Einstein's Thought Experiment

Einstein realized that the wave model of light could not explain the photoelectric effect. If light interacts with the metal like a wave, waves of red light should eventually "pile up" enough energy to give off electrons. But this doesn't happen. So some other difference between red and blue light must cause the effect. Here is how Einstein reasoned.

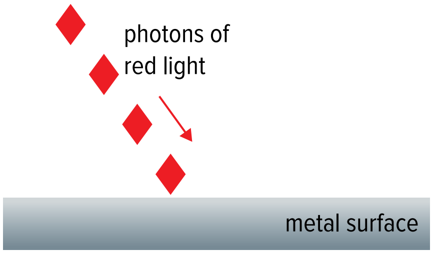
1. The photoelectric effect can only be explained if light acts like a particle when it interacts with matter.

Light does not interact with matter as a flowing stream, like water from a faucet.

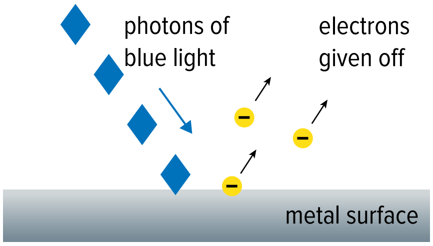
Light interacts with matter as packets or distinct particles, like water in ice cubes.

2. Einstein called the packets or particles of energy *photons*. Each photon must carry an exact amount of energy that is enough to make the metal give off electrons. Otherwise, nothing will happen when the photons strike the metal.

Red Light: Photons of red light *do not* carry enough energy to make the metal give off electrons.



Blue Light: Photons of blue light *do* carry enough energy to make the metal give off electrons.



3. Photons must carry more energy as the frequency of electromagnetic radiation increases and wavelength decreases.

Red Light: Red light has a lower frequency and a longer wavelength. Photons of red light carry less energy.

Blue Light: Blue light has a higher frequency and a shorter wavelength. Photons of blue light carry more energy.

In summary: Einstein realized that the best explanation for the photoelectric effect was that light acts like a particle when its energy is absorbed by an object. This particle, called a photon, acts a lot like a particle of matter.

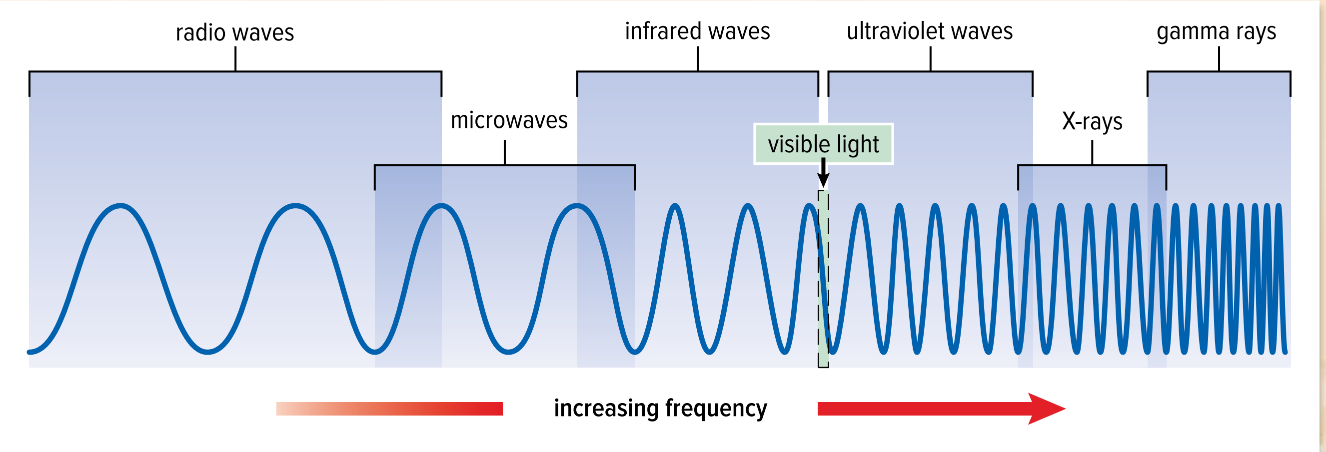
Before you leave this page . . .

1. Does light have the properties of a wave, a particle, or both? Explain your reasoning.
2. Scientists build on the work of other scientists. Explain how this is true of Einstein's explanation of the photoelectric effect.

AT ISSUE How can you model the electromagnetic spectrum?

What's the Issue?

Visible light is just one type of electromagnetic radiation, and all types of electromagnetic radiation have similar properties. This means that properties such as wavelength, frequency, and amplitude are properties of all types of electromagnetic radiation. The *electromagnetic spectrum* is a model that shows the range, or spectrum, of electromagnetic radiation in terms of wavelength. The spectrum begins with the radiation that has the longest wavelengths: radio waves. It ends with the shortest wavelengths: gamma rays.



Dig Deeper

Collaborate with your classmates to explore one or more of these questions—or generate your own questions of interest to explore.

1. Use the diagram of the electromagnetic spectrum on this page as a starting point. How can you bring more meaning and understanding to it? For example:
   - **a)** How could you compare the sizes of wavelengths to familiar objects?
   - **b)** How could you add numerical or mathematical information?
   - **c)** How and where could you use colour to enhance your understanding of the electromagnetic spectrum?
   - **d)** How could you add examples of applications of electromagnetic radiation, such as modern communications technology?
2. Find out how different parts of the spectrum were discovered. (For instance, the discovery of infrared built on the work of Isaac Newton. The discovery of ultraviolet built on work that led to infrared. But how?)

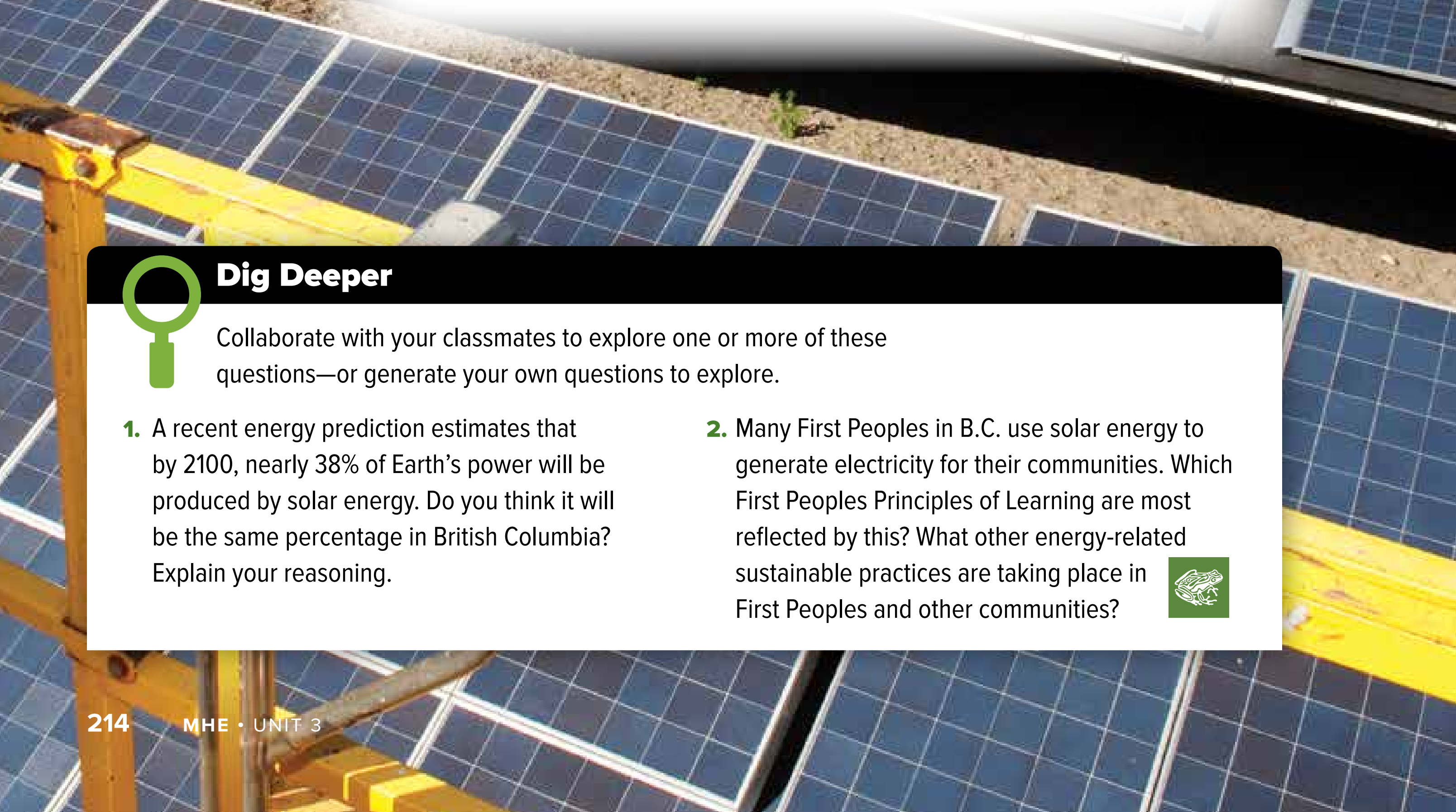
AT ISSUE

How Can Solar Power Projects Conserve Energy?

What's the Issue?

Chief Gordon Planes may just be one of the most innovative thinkers in B.C. He worked with the T'Sou-ke First Nation, located 45 minutes southwest of Victoria, to build what at the time was the largest photovoltaic project in B.C. Overall, the T'Sou-ke First Nation reduced its energy use by 75%. Planes's vision continues to lead the community toward energy conservation and self-sufficiency.

The photoelectric effect helps you understand how photovoltaic cells work. Electrons in the cells are trapped and need a certain amount of energy to escape to form an electric current. Photons in visible light from the Sun have just the right amount of energy. When the photons collide with the electrons, the energy frees the electrons and allows them to form a current. The current carries the energy to where it can be used. New materials are being developed that can also use photons of infrared and ultraviolet radiation to produce a current.



Dig Deeper

Collaborate with your classmates to explore one or more of these questions—or generate your own questions to explore.

1. A recent energy prediction estimates that by 2100, nearly 38% of Earth's power will be produced by solar energy. Do you think it will be the same percentage in British Columbia? Explain your reasoning.
2. Many First Peoples in B.C. use solar energy to generate electricity for their communities. Which First Peoples Principles of Learning are most reflected by this? What other energy-related sustainable practices are taking place in First Peoples and other communities?

Check Your Understanding of **Topic 3.2**

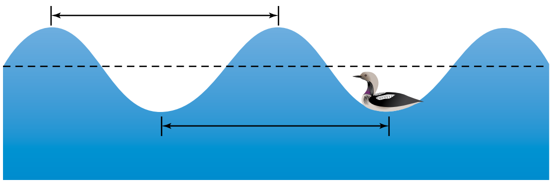
QP Questioning and Predicting **PC** Planning and Conducting **PA** Processing and Analyzing **E** Evaluating
AI Applying and Innovating **C** Communicating

Understanding Key Ideas

1. Why is it more useful or helpful to use visible light as a model for electromagnetic radiation, rather than X-rays or any other type? PA E

2. At 2 m from a light source, light is $\frac{1}{4}$ as bright as it was at 1 m from the source. Explain why this is the case. PA C

3. The diagram below shows a Pacific loon resting on water. Add labels to show your understanding of the following terms: wavelength, crest, trough. PA E AI C



4. Visible light travels through empty space at the speed of light (3.00×10^8 m/s). Would an astronaut in orbit around Earth see visible light from the Sun as it travels through outer space? Explain your reasoning. PA AI

5. Use a diagram to show how each model below explains at least one property of electromagnetic radiation. PA C

a) the ray model of light

b) the wave model of light

c) the particle model of light

6. Predict what a shadow would look like if light did not travel in a straight line. Justify your prediction. QP PA

Connecting Ideas

7. Einstein used a thought experiment to explain the photoelectric effect. In what ways is a thought experiment similar to and different from a hands-on experiment? What are the advantages and disadvantages of using thought experiments? E AI C

8. Create a comic strip showing a conversation that Young and Einstein might have had about the nature of light. PA C

9. **Figure 3.14** showed what happens when a beam of visible light passes through a prism. However, this photo does not provide conclusive evidence that visible light is made up of different colours.

a) Explain why this is the case.

b) Describe how Newton demonstrated that visible light is made up of colours.

PC E AI

Making New Connections

10. Sound is a different form of energy from electromagnetic radiation, but sound also has wave-like properties. QP PC AI

a) Predict how changes in wavelength, frequency, and amplitude affect sound. For example, imagine that you press a key on a piano keyboard. How would a change in frequency, wavelength, and amplitude change the sound?

b) Describe a plan for an investigation that you could conduct to test your prediction.

INVESTIGATION

3-C

STRUCTURED INQUIRY

Shadow City

Create a city skyline and explore the ray model of light by changing the size and shape of its shadow.

Question

How can you use shadows to demonstrate how light travels?

Procedure

1. In a small group, use books and boxes to create a city skyline. Place a light source about 50 cm in front of the skyline. Place a screen about 50 cm behind the skyline.
2. Measure the distance from the light source to the skyline, the distance from the skyline to the screen, and the height of the tallest “building” in the skyline. Record your measurements.
3. Draw a ray diagram showing your skyline, the light source, and the screen. Use **Figure 3.9** as a guide. Because you are viewing your skyline from the side, you can draw it as a simple box that is as tall as your tallest building. The diagram should be to scale. For example, 1 mm on your drawing could represent 1 cm on your skyline.
4. Draw several more ray diagrams. Try to make your shadows taller, shorter, larger, or smaller.
5. Your teacher will turn off the overhead light. Turn on your light source. Take turns changing the height and size of the shadow.

Process and Analyze

1. **a)** Did your observations support your ray diagrams?

   b) If not, try to account for any differences.

Skills and Strategies

- Questioning and Predicting
- Planning and Conducting
- Processing and Analyzing
- Evaluating
- Communicating

Safety

- Never shine a light directly into someone’s eyes.
- Do not touch the bulb of the light source. It may be extremely hot.

What You Need

- light source
- books and boxes
- ruler
- pencil
- paper

INVESTIGATION

3-D

STRUCTURED INQUIRY

Skills and Strategies

- Planning and Conducting
- Processing and Analyzing
- Applying and Innovating

Safety

- Do not release the spring when it is fully stretched or moving.
- The ends of the spring may be sharp.
- Keep the spring on the floor when making waves.

What You Need

- a coiled metal spring or skipping rope

Modelling Wavelength, Frequency, and Amplitude

Question

How can you model wavelength, frequency, and amplitude?

Procedure

1. Draw and label a diagram for each of the following:
   - **a)** a high-amplitude wave and a low-amplitude wave
   - **b)** a high-frequency wave and a low-frequency wave
   - **c)** a short-wavelength wave and long-wavelength wave
2. Plan how you can use a rope or spring to model the six waves in step 1.
3. Carry out your plan.
4. See if you can make the following:
   - **a)** a low-frequency, long-wavelength wave
   - **b)** a low-frequency, low-amplitude wave
   - **c)** a high-amplitude, short-wavelength wave
   - **d)** a high-frequency, long-wavelength wave
5. Draw a diagram of each wave that you made in step 4.

Process and Analyze

1. What relationships did you discover among wavelength, frequency, and amplitude? For example, if frequency decreases, what happens to wavelength?

Apply and Innovate

2. What other materials could you use to produce waves? Design an investigation in which you use these waves to model frequency, wavelength, and amplitude.

INVESTIGATION 3-E

STRUCTURED INQUIRY

Skills and Strategies

- Questioning and Predicting
- Processing and Analyzing
- Applying and Innovating

Safety

- Never look directly at the Sun. You may damage your eyes.
- Do not touch the bulb of any light source. It may be extremely hot.

What You Need

- spectroscope
- ruler
- coloured pencils

Seeing Through a Spectroscope

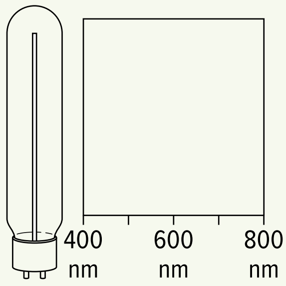
In this Investigation, you will observe different sources of light through a spectroscope.

Question

What property of a wave of visible light determines its colour?

Procedure

1. Make a hypothesis about what property of a wave of visible light determines its colour.
2. Your teacher will set up different light sources. Observe each one through the spectroscope. Draw your observations. If a pattern repeats, just draw one repetition.
3. Your teacher will give you several copies of the diagram on the right or ask you to copy it for each light source. Place the colours you saw through the spectroscope on the diagrams.



1 nm = 0.000 000 001 m

4. Use your answers to question 3 to estimate the wavelength for each colour of the visible light spectrum.

Process and Analyze

1. Did your observations in this experiment support your hypothesis? Why or why not?
2. How did light behave like a wave in this Investigation?
3. What sources of error might have occurred in this Investigation?

Apply and Innovate

4. Astronomers also use spectroscopes. Find out what a spectroscope can reveal about the stars.

INVESTIGATION

3-F

GUIDED INQUIRY

Skills and Strategies

- Questioning and Predicting
- Planning and Conducting
- Processing and Analyzing
- Evaluating
- Communicating

Safety

- You will write your own safety guidelines.

What You Need

- ultraviolet-sensitive beads
- other materials depending on your experimental design

Exploring Ultraviolet Radiation

Ultraviolet-sensitive beads change colour when exposed to ultraviolet radiation. The colours become more intense when the beads are exposed to more UV radiation.

Question

See step 1 below to choose a question to investigate.

Procedure

1. Choose one of these questions to investigate with your group, or come up with your own.
   a) How effective are different materials at blocking ultraviolet radiation?
   b) How effective are different sunscreens at blocking ultraviolet radiation?
   c) How can you demonstrate the existence of ultraviolet radiation just beyond violet light in the visible light spectrum?
2. Write a hypothesis that answers your question.
3. Design an experiment to test your hypothesis. Identify the variables in your experiment. Include safety guidelines and a materials list.
4. Share your hypothesis and design in a feedback session with your teacher and classmates.
5. Carry out your experiment.

Process, Analyze, and Communicate

1. Write a report based on your experiment. Identify possible sources of error and suggest improvements to your experimental design.
2. Did your results support your hypothesis? Explain.