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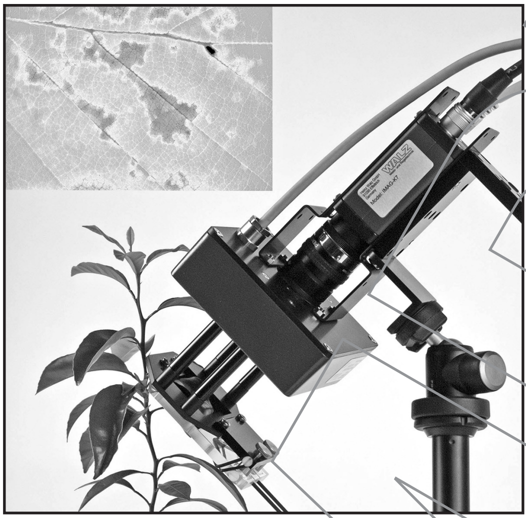
Lesson 7

Electromagnetic and Mechanical Waves

3.2.6-8.Q, R, S; 3.5.6-8.DD

Using light and sound waves, engineers have developed an instrument that creates internal images in much more detail than traditional methods. In these machines, light is transferred into a living thing, sound is emitted and measured, and an image is created from the data. This is an example of how wave energy can be harnessed to create innovative devices.



A photoacoustic imaging scope uses light and sound waves to produce images.

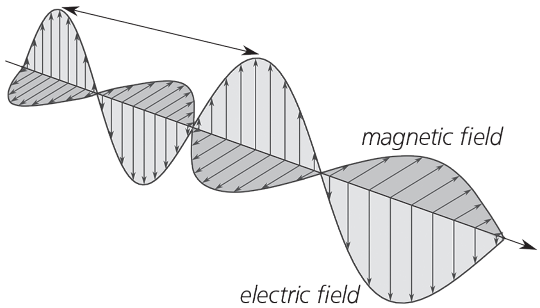
A wave is the transfer of energy from one point to another. Waves carry energy, not matter. In this lesson, you will learn about two types of waves: electromagnetic and mechanical waves. While both carry energy, there are differences between them. Let's first look at electromagnetic waves, also known as light waves.

Electromagnetic Waves

In the previous lesson, we explored how electric and magnetic forces act through fields, influencing objects without direct contact. Now, we'll take that understanding a step further by learning another way these two forces can work together. When an electric field changes, it creates a magnetic field. And the opposite is also true; when a magnetic field changes, it creates an electric field. This interaction forms **electromagnetic waves,** which carry energy across space without needing a **medium,** such as air or water. From sunlight to cellphone signals, these waves are all around us and play a major role in everyday life.

Unlike sound waves, electromagnetic waves travel faster in a vacuum than they do in any other medium, or vessel that waves can travel through. Mediums, such as glass and water, slow electromagnetic waves. This is why you see rainbows, which you will learn more about later in the lesson.

Waves that need a medium to transfer energy are called mechanical waves. You will learn more about these later in the lesson.



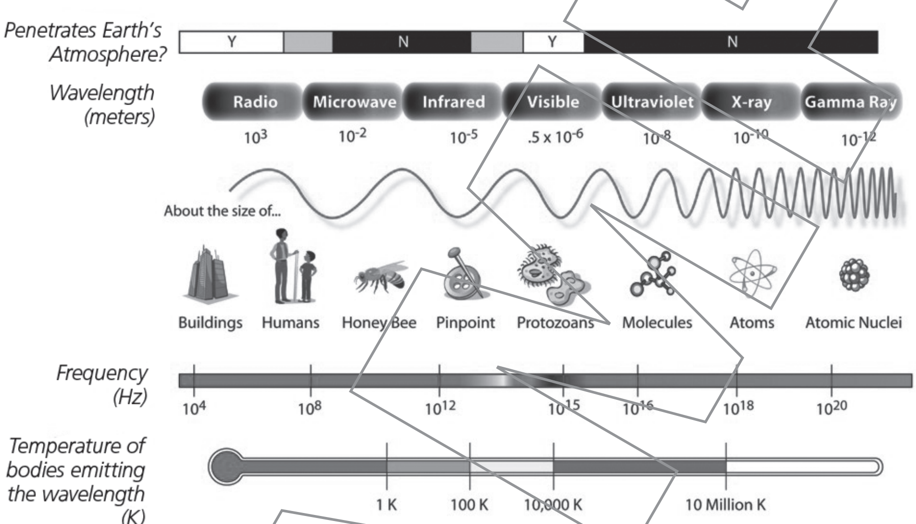
Electromagnetic waves travel in perpendicular magnetic and electric fields.

The **electromagnetic spectrum** is the full range of energy waves that travel through space, including the ones we can see and many we cannot. **Electromagnetic radiation** is the energy carried by electromagnetic waves. The spectrum includes radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays. Only a small part of the spectrum is visible to our eyes, which we see as light and colors. The rest of the spectrum is *invisible* but still very important in our everyday lives.

The electromagnetic spectrum is the full range of electromagnetic waves.

Electromagnetic radiation is the energy carried by electromagnetic waves. All electromagnetic radiation is light, although humans can only see light in the visible spectrum.

THE ELECTROMAGNETIC SPECTRUM

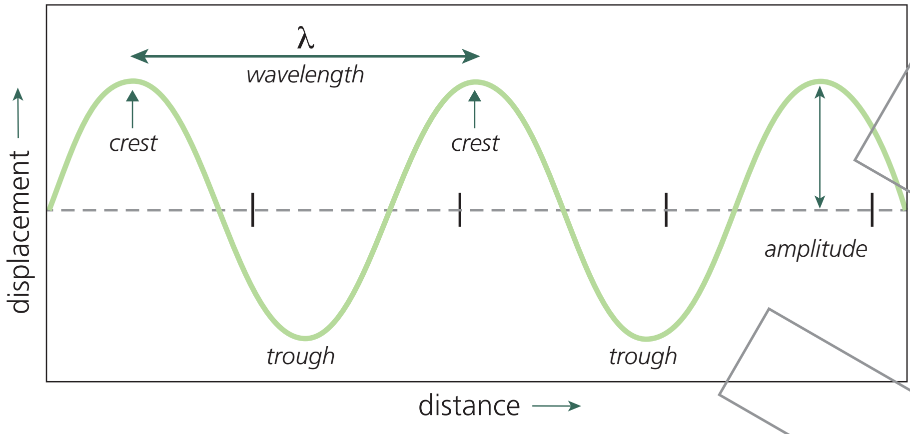


The electromagnetic spectrum is the full range of electromagnetic radiation.

All electromagnetic waves move at the speed of light but have different amounts of energy. They also have different wavelengths. A **wavelength** is the distance between the *crests* or *troughs* of a wave. The **amplitude** of a wave is the maximum displacement; in other words, it is the height of a wave. The **frequency** of a wave is the number of waves that pass through a given point in one second. In the chart above, notice the differences in the wavelengths as you move from left to right in the electromagnetic spectrum. The wavelengths decrease while the frequencies increase. Gamma rays have the highest energy of all electromagnetic

The wavelength is the distance between two crests or two troughs of a wave. The amplitude is the height of a wave. The frequency is the number of waves that pass through a given point in one second.

radiation, with the smallest wavelength and highest frequency. These can be extremely dangerous to the cells of living things and are used in medicine to treat cancer.



The wave diagram shows the parts of a wave. The frequency is the number of waves that move through a specific point in one second.

You might wonder how differences in wavelength, frequency, and amplitude affect the amount of energy a wave carries. First, let's take a look at mechanical waves, and then we can compare the factors that determine wave energy.

Mechanical Waves

Have you ever dropped a rock into a lake and watched the water ripple? Or, have you listened to the change in sound as a fire engine speeds by? These are both examples of mechanical waves. **Mechanical waves** require a medium to travel through, such as air or water. Energy is carried through the vibrations of particles. As one particle vibrates, it transfers energy to the particle next to it. There are three types of mechanical waves based on the direction of particle vibration.

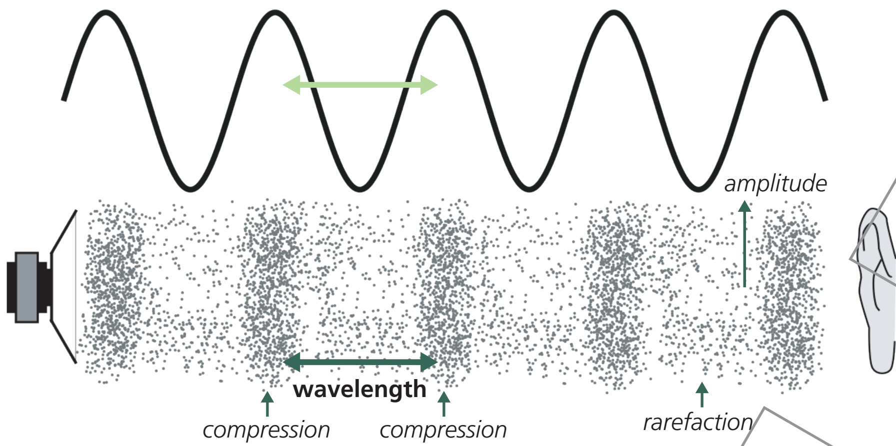
Remember, mechanical waves are vibrations that transfer energy through a medium.

TYPES OF MECHANICAL WAVES

Wave Type	Particle Motion	Example
Transverse ↕	Perpendicular to the wave direction	Rope wave
Longitudinal ↔	Parallel to the wave direction	Sound wave
Surface	Circular motion (combination)	Water wave

Notice that some mechanical waves, such as a wave produced when you move a rope, are transverse. Remember that all electromagnetic waves are transverse.

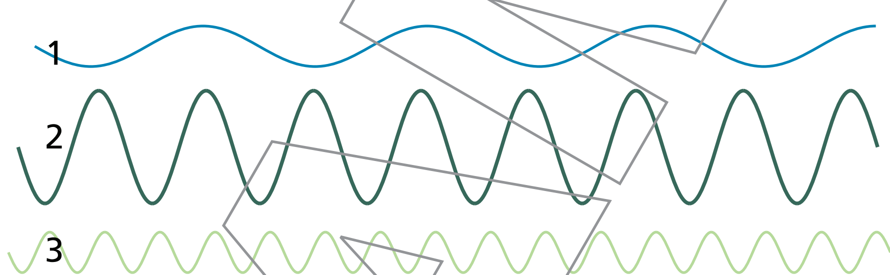
Longitudinal Wave Design



The dark, compressed areas of a longitudinal wave are the points of greatest energy, similar to the crests of a transverse wave, where the amplitude is the point of greatest energy.

In a longitudinal wave, such as sound, the dark areas are called *compressions* as the particles are pressed together. The less dense areas are called *rarefactions.* The *wavelength* is the distance between the centers of two adjacent compressions. The *amplitude* is measured the same as in a transverse wave; it is the height or maximum displacement from the center line, or equilibrium position.

This is important in the transmission of sound. As the areas of compression become closer together, the wavelength decreases and the frequency increases. What you hear is a higher pitch. If the distance between compressions decreases, the frequency decreases, resulting in a lower-pitched sound. So, how does amplitude affect sound? The higher the amplitude, the louder the sound.



How would you describe each of the sound waves in the image?

The first wave (1) is a low-amplitude, low-frequency sound wave with a quiet, low pitch. The second wave (2) is a high-amplitude, medium-frequency sound wave with a loud, medium pitch. The third wave (3) is a low-amplitude, high-frequency wave with a quiet, high pitch.

Wave Properties

Let's look at the properties of both mechanical and electromagnetic waves to see how each property affects wave energy. There are mathematical formulas to calculate energy and other variables, such as wavelengths. What is most important is understanding how one property affects another and which properties are completely independent of one another.

WAVE PROPERTIES

Property	Electromagnetic Waves	Mechanical Waves (e.g., Sound)
Amplitude	It is directly proportional to light intensity. (As amplitude increases, intensity increases.)	The higher the amplitude, the louder the sound. (Higher amplitude creates stronger vibrations.)
Frequency	It determines the energy and type of radiation. Higher frequencies = higher energy.	It determines the pitch; low frequencies have a low pitch.
Wavelength	The shorter the wavelength, the higher the frequency and energy.	The shorter the wavelength, the higher the pitch (higher frequency).
Energy	It increases with higher frequencies. It has a proportional relationship with the square of the amplitude.	It has a proportional relationship with the square of the amplitude.

When we summarize the key points of properties for all waves, we see that amplitude and frequency are independent of each other. One property does not affect the other. But, wave energy is directly proportional to the squared amplitude or energy amplitude squared. This means that if you double the amplitude, you increase the energy by a factor of four (2^2). If you triple the amplitude, you increase the energy by a factor of nine (3^2).

Frequency and amplitude determine the energy of electromagnetic waves. For mechanical waves, amplitude is the key variable. Why is this? The energy of waves depends on frequency and amplitude. For light waves, both are important. Light carries energy in tiny packets called **photons.** When the frequency is higher, each photon has more energy. For sound waves, energy depends on how big the vibrations are—that's called amplitude. The bigger the vibrations, the more energy the sound has.

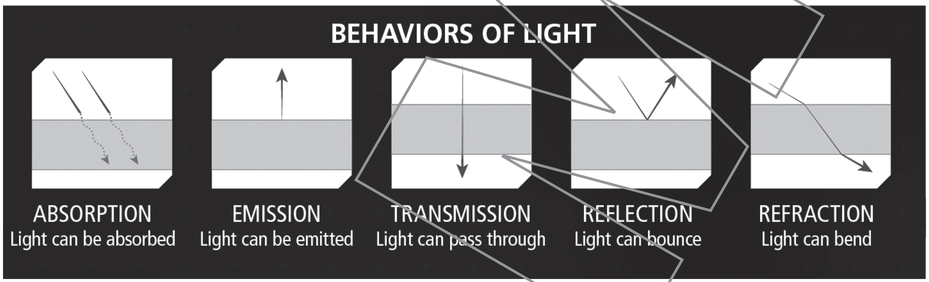
A photon is a tiny particle of light—the smallest possible unit of electromagnetic energy. Even though it behaves like a particle, it also acts like a wave, which is why we say light has a wave-particle duality.

A lab group is comparing two sound waves. Wave 1 has an amplitude of 10 dB (decibels), and wave 2 has an amplitude of 20 dB. One of the students says that the energy of wave 2 is twice that of wave 1. Why is he incorrect?

The energy of a wave is proportional to the square of the amplitude. For wave 1, the energy is a factor of 100 (10^2). The energy for wave 2 is a factor of 400 (20^2). So, wave 2 has four times the energy of wave 1.

Wave Behaviors

Light and sound waves share similar behaviors as they interact with different materials. **Reflection** occurs when waves bounce off surfaces like a mirror or a wall. **Transmission** happens when waves travel through materials such as glass for light or a thin wall for sound. **Absorption** occurs when materials take in wave energy. Dark colors absorb more light, as soft materials, like foam, absorb sound. **Emission** is when a source gives off energy, such as a glowing bulb or a vibrating speaker. Lastly, **refraction** happens when waves bend as they pass through different media. For example, a straw appears to bend in water due to light, or a sound wave changes direction when moving from air to water. Even though light is an electromagnetic wave and sound is a mechanical wave, their behaviors in various materials can be strikingly similar.



You have likely seen a rainbow after a storm. A rainbow forms when sunlight passes through tiny raindrops in the atmosphere. The light bends, or refracts, as it enters the raindrop, then reflects off the inside of the drop, and bends again as it exits. This bending causes the white light to separate into its different colors because each color (or wavelength) bends a little differently.

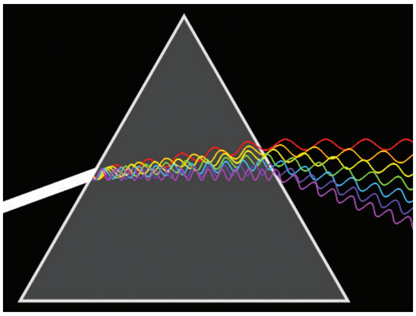
Reflection is the bouncing back of a wave when it hits a surface it cannot pass through. This is why you can see yourself in a mirror—light reflects off the mirror, transferring the image into your eyes.

Transmission is the movement of a wave through a medium. Sound travels slower in air than light. This is why you see lightning before you hear thunder.

Absorption is a wave's energy taken in by a material, often converting it into heat. Darker surfaces absorb more light waves than white surfaces, which reflect the light.

Emission is a material releasing energy in the form of light or sound waves, such as lightning or steam coming out of a kettle.

Refraction is the bending of light or sound as it passes through something like a wall for sound or a window for light.



This is an artist's conceptual drawing to show how white light interacts with a prism, similar to a rainbow formation. Notice the different wavelengths of light as each exits the prism. We can't see the individual wavelengths, like those in the drawing, but we do see the individual colors of each different wavelength of visible light.

Finn is explaining the concept of wave absorption to his friend. What would be a good descriptive model that Finn could use?

Finn could explain that the heat inside a car easily describes wave absorption on a sunny day. Darker-colored cars absorb light, and the energy is converted into heat. This is why darker cars are hotter on a sunny day. Light color cars reflect light, so less wave energy is absorbed and converted into heat.

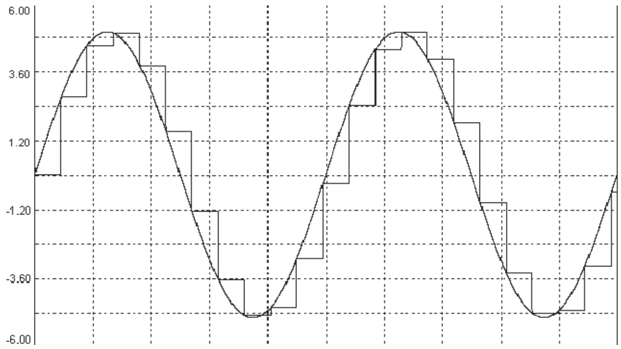
Waves and Communication

You have learned about different types of waves and their properties. Waves are an important part of our everyday lives. The things we see and hear are all due to wave energy. Think about all the things you use each day that require waves. If your digital devices come to mind, then you are right on track. Waves also play a vital role in modern communication.

Historically, information like sound was recorded and transmitted using **analog** signals. These are continuous waveforms that represent data, such as music or voice. Devices like radios, cassette tapes, and early telephones relied on analog technology. As technology advanced, there was a shift toward **digital** signals. These convert wave energy into a series of 1s and 0s (binary code). Digital signals are less affected by noise, allowing for clearer, faster, and more reliable communication.

Analog signals are representations of data in a continuous line.

Digital signals are separate representations of data in a step-like pattern.



Analog signals are smooth, continuous lines, while digital signals are step-like waveforms. Since digital signals are separate values, information can be copied, edited, and stored without loss.

Waves are used in many forms of communication today. One crucial technology is fiber optic cables, made of thin strands of glass or plastic. Quick pulses of light waves send data through the cables. Because light travels extremely fast and is not easily distorted, fiber optics can carry large amounts of information over long distances while maintaining signal quality. This makes them better than older copper wire systems, which use electric signals that could slow down or become noisy over long distances.

Fiber optic cables transmit light pulses over long distances, making them ideal for carrying internet, telephone, and cable television data.

Another way waves are used is through radio waves, which send information wirelessly. Devices like smartphones, Wi-Fi routers, and Bluetooth speakers use radio wave pulses to connect and share data. Information is stored in digital binary code inside a computer or phone. These patterns can be quickly converted into sound (like music or voices), images, or text that appears on a screen. This works because wave signals, whether light or radio, can carry huge amounts of information and allow us to communicate almost instantly worldwide.

The development of digital signals and the resulting supportive technologies, such as Wi-Fi and smartphones, are examples of the drive for innovative designs. Engineers recognized the need for improvement in communication systems. Analog signals proved to be inconsistent with distortion, static, and fuzziness. The solution to the problem was developing a design that provided clearer signals, faster transmission, and better storage capabilities. Engineers also recognized that new designs must meet limitations such as cost, compatibility, and available technologies.

Harper wants to simulate the design process for a class project. She decides to research the history of analog and digital signals in communication. What should she include in her project to show how engineers solve problems by creating innovative designs?

For her project, Harper should focus on describing the development of digital signals as an innovative solution to the problems with analog signals. She could create a timeline showing the use of analog signals along with the technologies that use them and the development of digital signals and the resulting technologies. She should describe how engineers developed digital signals as a solution to the problems with analog signals. This should also include the criteria: the design should produce clearer signals, have faster transmission, and include better storage capabilities. The constraint should include cost, available technologies, and compatibility with the present designs.

It's Your Turn

Please read each question carefully. For each multiple-choice question, circle the letter of the correct response. For an open-ended question, write your answer on the lines.

1 Which of these designs **best** describes the use of reflective behaviors of sound waves?

A A recording studio is designed with thick carpets and curtains to absorb echoes and background noise.

B A home theatre is designed with foam padding in the walls to minimize sound bouncing and improve sound quality.

C A new speaker is designed to enhance sound by converting electrical signals into sound waves, which are directed toward the center of the room.

D A concert hall is designed with curved wall surfaces to direct sound waves toward the center of the room, allowing the audience to hear the sounds clearly.

Use the information below to answer question 2.

COMPARISON OF SOUND WAVES

Sound Wave	Amplitude (dB)	Frequency (Hz)	Energy (units)
A	2	500	4
B	3	500	9
C	4	500	16
D	5	500	25

2 Which of these **best** describes the relationship between variables in sound waves?

A The energy increases by the magnitude of the squared amplitude.

B The amplitude decreases as the energy of a sound wave increases.

C The frequency remains constant in all sound waves, independent of the energy.

D The wavelength varies as the amplitude and energy of a sound wave change over time.

Use the information below to answer question 3.

Digital vs. Analog Signals

Digital signals are a more reliable way to encode and transmit information than analog signals because they use separate values—typically 0s and 1s—to represent data. Unlike analog signals, which vary continuously and are easily affected by noise or interference, digital signals maintain clarity over long distances and can be corrected with error-detection methods. In addition, digital data is easier to copy, edit, and store without losing quality, which makes it ideal for use in computers, communication networks, and media technologies. This efficiency and reliability are key reasons digital systems have replaced analog in most modern applications.

3 Which of these **best** describes how digital signals compare to analog signals?

A Digital signals use continuous waves, making them better for recording natural sound.

B Digital signals rely on magnetic fields, while analog signals use electrical currents for transmission.

C Digital signals vary smoothly, which makes them more sensitive to small changes in the environment.

D Digital signals use a binary code, which helps reduce signal loss and makes them easier to copy and store.

Engineering Feats Using Electromagnetic Waves

An innovative design that incorporates the use of light waves is the James Webb Space Telescope. This advanced telescope was engineered to detect infrared light from distant stars and galaxies, allowing scientists to see objects that are billions of light-years away. Its design includes a sun shield to block heat and light from the sun, which helps it detect faint light signals from the early universe. Earlier space telescopes primarily used visible light. However, infrared light has longer wavelengths, allowing it to penetrate dust clouds and reveal cooler or hidden objects, like stars, distant galaxies, and even exoplanets. This new space telescope was specifically designed to detect infrared radiation, making it better suited to see deeper into space and further back in time.

4 Innovations and inventions are the result of systematic testing and evaluation.

A Explain the design problem that engineers solved.

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B Describe at least one criterion and constraint of the design.

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C Why is it important to evaluate or critique designs?

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