Chapter 6 WAVES

1. Introduction

Waves are all around us. They are a fundamental concept in physics and play a crucial role in our understanding of the behavior of various phenomena in the natural world. Although we tend to be most familiar with ocean waves, waves are actually present in a wide range of systems including sound and light and exhibit unique characteristics and behaviors that govern their propagation. Because waves exist in so many of our natural systems, a good understanding of their properties and behavior is critical to our ability to engineer and build solid, safe structures.

A wave is best described as a disturbance that carries energy through space and time. By definition a **wave** ***is the transfer of energy from one point to another without the physical movement of particles***; more precisely, waves are moving energy. It is important to emphasize at this point that waves transport energy, they do not transport matter. This distinctive property of waves makes them different from other forms of energy transfer, such as the flow of fluids or the transfer of heat by conduction.

Waves fall into two major groups: mechanical waves and electromagnetic waves. The primary difference between the two types of waves is the manner in which they propagate. Mechanical waves require a medium, such as a solid or fluid, to propagate. Electromagnetic waves, on the other hand, do not require a physical medium to propagate and thus can travel through a vacuum. Examples of mechanical waves include ocean waves, sound waves and seismic waves, while light waves, radio waves, and X-rays are all examples of electromagnetic waves.

The study of waves has extensive applications and is fundamental to fields like acoustics, optics, seismology, and electromagnetism. Waves also have practical implications in numerous areas, including communication systems (such as radio, television and phones), in medical imaging (MRI, ultrasounds, CT, X-rays), weather prediction, and the exploration of outer space. By exploring the characteristics, behaviors, and interactions of waves, scientists have been able to unlock a deeper understanding of the natural world and develop technological advancements that have revolutionized society.

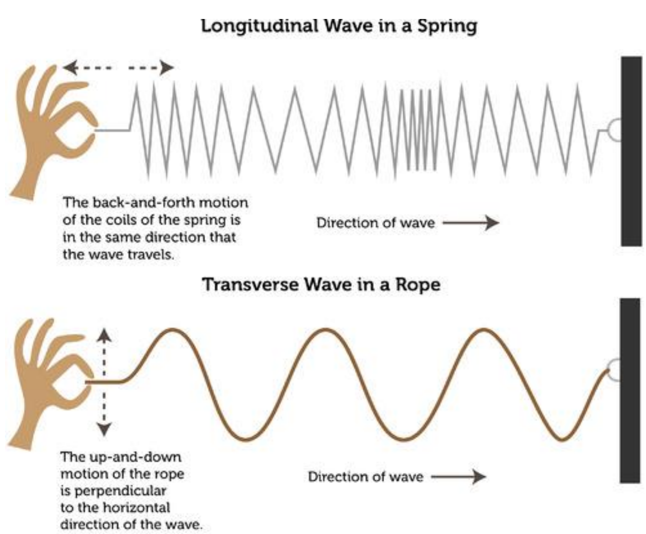
6.1 What is a wave?

When the particles in a substance are disturbed, they begin to oscillate which creates a pulse or ripple in the substance. This pulse is known as a **vibration**. As the substance vibrates, the pulse travels through the medium causing the particles in the medium to move which transfers the energy from one particle to another. Importantly, while the energy moves through the medium, the particles of the medium themselves do not travel with the wave. The **wave** *is the movement of the energy* through the **medium** and the medium is *just the substance or material through which waves* *propagate or move*. Of note, the waves move through the medium, but the medium does not create the wave nor is the medium the wave. As previously mentioned, based on their nature and how they propagate, waves can be classified as mechanical or electromagnetic. In this chapter, we will focus on mechanical waves.

6.2 Mechanical Waves

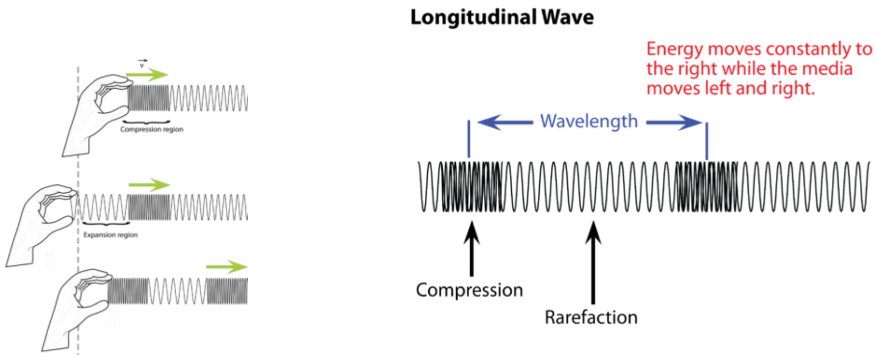
As mentioned above, mechanical waves require a medium to propagate and cannot exist in a vacuum. A **medium** is a substance or material through which a wave moves and can be a solid or fluid (i.e. liquid or gas). Mechanical waves fall into two major categories based on the direction in which the particles of the substance oscillate as the wave propagates through the medium. The two types of mechanical waves are ***longitudinal*** and ***transverse***. Understanding the differences between transverse and longitudinal waves is crucial for comprehending various wave phenomena and their applications in different fields.

When the particles in a medium vibrate, the direction in which the particles oscillate determines the type of wave produced. For example, when a string of a guitar is plucked, the string vibrates or moves back and forth in a rhythmic pattern. Though the string moves back and forth, the wave moves from side to side. When the oscillation or movement of the particles in a medium is perpendicular to the travel of the energy or the direction of the wave, it creates a transverse wave.



Longitudinal and Transverse Waves (*Credit:* Bacic, S. (2013) CK-12 Foundation)

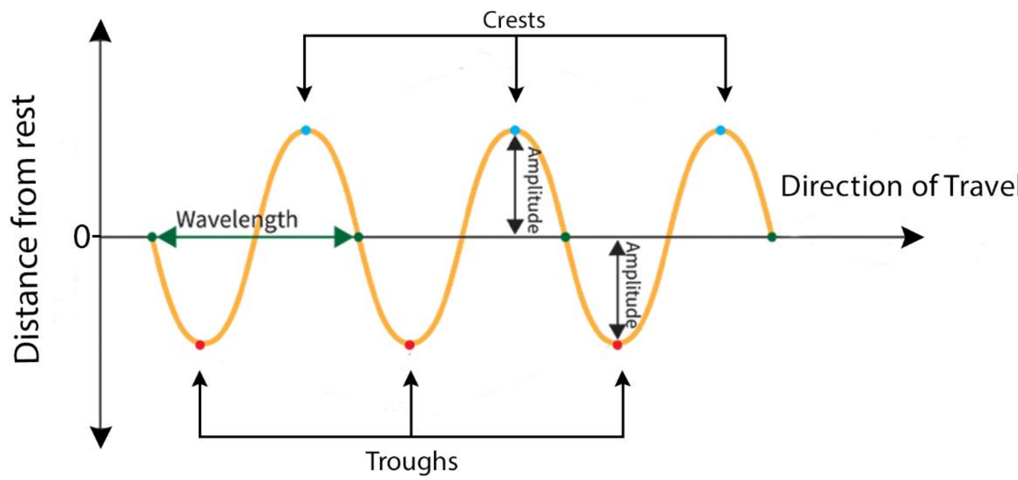
On the other hand, in longitudinal waves, the particles in the medium oscillate parallel to or in the same direction as the wave travels. In a longitudinal wave, as the particles vibrate back and forth, the molecules in the particles tend to move closer together (bunch up) and away from each other (spread out) rhythmically. The bunching up and spreading out of the molecules creates a series of **compressions** and **rarefactions** along the same axis as the wave motion, so the particles vibrate in the same direction that the wave moves. Sound waves are the most common example of longitudinal waves.



Longitudinal Waves (*Credit:* Bacic, S. (2015) CK-12 Foundation)

6.3 Structure of a Wave

All waves share certain basic characteristics or features. These include an amplitude, a frequency and a wavelength. In order to fully understand waves, the following key parameters must be considered. Waves are essentially vibrations or periodic oscillations which are rhythmic motions that repeat in a regular cycle around their original rest point of **equilibrium** position. As a wave passes through a medium, the particles are disturbed from their original rest or equilibrium position to a high and a low point. The high and low points as the **crest** and **trough** of the wave. The intensity or maximum displacement of the particles in the medium, more specifically, the distance from the equilibrium position to the crest or trough of the wave is known as the **amplitude** of the wave.



Structure of a Wave (*credit:* WGBH Educational Foundation 2020©)

6.4 Properties of Waves

The length of a wave or its **wavelength** is the distance between two consecutive crests or troughs which is the distance between adjacent identical parts of the wave. The wavelength is measured in meters and is denoted by the Greek letter **lambda** (**λ**). The **frequency** of a wave represents the *number of complete wave cycles passing through a given point in one second*. Frequency is measured in **hertz (Hz)**. The **period** of a wave *is the time it takes for one complete cycle to pass a fixed point.* Based on this, frequency and period are related as follows:

$$\boldsymbol{f = \frac{1}{T}}$$

$$\boldsymbol{T = \frac{1}{f}}$$

Exercise:

If a wave has a period of 0.02 seconds, determine its frequency.

T = 0.02 s
f = ?

$$f = \frac{1}{T} = \frac{1}{0.02\ s} = 50 \text{ Hz}$$

The rate at which the wave travels through a medium or speed of a wave is known as the wave **velocity.** The wave velocity is determined by the properties of the medium itself such as its density and elasticity. For example, in dry air at room temperature, sound travels at a rate of 343 m/s but the speed of sound varies depending on the medium and will travel faster in solids than in liquids or gases. Recall, velocity is calculated as the ratio of the distance travelled to the time taken. In relation to wave velocity, how quickly a wave travels or its velocity is related to the length of the wave (wavelength, **λ**), and the number of waves than pass a given point in a second (frequency, ***f***). As such, the velocity of a wave can be calculated as follows:

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

where ***v*** is the velocity of the wave, **λ** is the wavelength and ***f*** is the frequency**.**

Because the *period* of a wave or many seconds it takes to complete a cycle is the reciprocal of its *frequency* or how many cycles in a second, the relationship above can also be expressed as:

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

where ***v*** is the velocity of the wave, **λ** is the wavelength and ***T*** is the period**.**

Exercise:

A wave with a frequency of 500 Hz has a wavelength of 0.6 meters. Calculate the speed of the wave.

λ = 0.6 m
f = 500 Hz

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

$$\boldsymbol{v} = 0.6 \text{ m} \times 500 \text{ Hz} \;=\; 0.6 \text{ m x } 500\,\frac{\mathbf{1}}{\boldsymbol{s}} \;=\; \mathbf{300}\,\frac{\mathbf{m}}{\boldsymbol{s}}$$

6.5 Reflection, Refraction, Diffraction and Absorption of Waves

When a wave encounters a medium or passes from one medium to another with different properties, such as density or speed; their resulting behavior depends on the type of matter with which they interact. All waves behave similarly when they encounter a different medium such as a hard surface, soft surface, different material, or even a change in density or temperature within the same medium. For example, whenever a sound wave encounters a boundary or obstacle, it can be either reflected, refracted, diffracted or absorbed.

When a wave encounters a hard surface, such as a wall, it bounces back off the surface or is reflected. The ***reflection*** of a sound wave is known as an **echo**. An echo can best be described as a single reflection of a sound wave. Echoes are distinctly differentiable from the original sound and are typically heard no sooner that 1/10 of a second after the original sound wave interacts with the hard surface. When multiple sound waves encounter a hard surface, the waves tend to bounce back and forth off the surface. The resulting reflected waves or echoes occur within a relatively short time period, i.e. less than that 1/10 of a second after the original sound, and result in a **reverberation**. Reverberations build up with each echo or reflection of the soundwave and persist for a relatively long time after the original sound source has stopped, for example when you pluck a guitar string. They slowly die off as they become gradually absorbed by their surroundings.

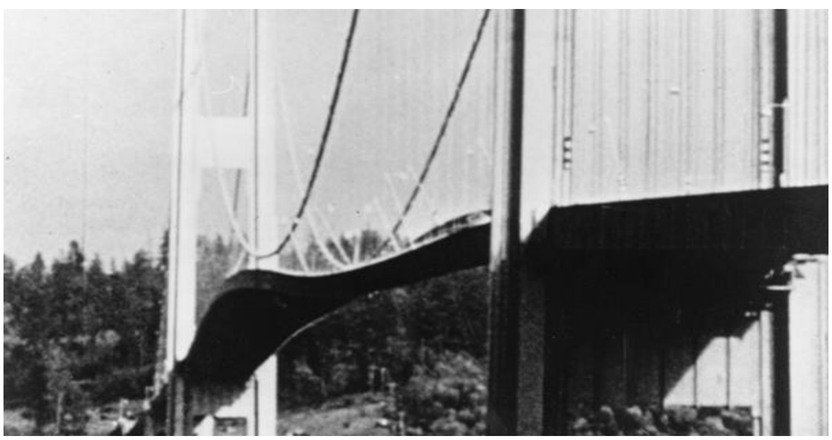
Whenever a wave encounters another medium with different properties, the speed of the wave changes as it passes from one medium to the other which causes the waves to bend and/or change direction. This change in direction is known as ***refraction***. The angle at which a wave bends or refracts or its angle of refraction is directly related to how much the speed of the waves increases or decreases as it passes through the new medium.

Diffraction *is the bending or spreading out of waves when they encounter an obstacle or pass through small openings*. This occurs when waves encounter an obstruction comparable in size to their wavelength which causes the waves to diffract around the edges of an obstacle or through narrow openings and spreading out of the wave pattern. For example, sound waves can diffract around objects and reach areas that are not directly visible enabling us to hear sounds around corners.

Whenever a sound wave loses most of its energy to the medium it encounters, instead of being reflected, refracted or diffracted, the wave can be absorbed by the medium. ***Absorption*** occurs whenever the amount of energy transferred to the medium during the interaction with the medium lowers the original energy of the wave which lowers its amplitude. An example of this would be the interaction between a sound wave and a foam pad. As the waves travels through the pad, the amplitude is lowered to the level where most, if not all, of the wave energy is absorbed by the pad. Since the sound is not reflected, it does not result in an echo or reverberation – a principle exploited by engineers in the design and building of music studios and soundproof rooms.

6.6 Resonance

All objects vibrate at different frequencies and if the frequency of an external force matches the natural frequency of an object or a system, the vibrations are amplified and the object is said to *resonate*. **Resonance** plays a crucial role in various phenomena, including designing musical instruments and sound amplification systems, and engineering structures. Failure to consider resonance in structural engineering can lead to building failure such as the collapse of the Tacoma Narrows Bridge in Washington State. On a windy morning in early November 1940, the frequency of the swaying bridge matched the frequency of the 47-mph winds amplifying the vibrations and increasing the amplitude of the wobbling bridge leading to failure of its main span and the bridge collapsing into the Puget Sound four months after it opened to the public.



Tacoma Narrows Bridge Collapse, November 7th 1940.
Courtesy Keystone/ Getty Images©

Resonance is also what gives a singer the ability to shatter a glass with their voice. Glass has a low natural frequency and depending on it size and shape can begin vibrating at frequencies as low as 100 Hz. So, if a large sound wave vibrates at a frequency that matches the natural frequency of the glass, due to constructive interference and the principle of superposition, the ensuing energy increases the size and intensity of the vibration. The resulting vibration can cause the glass to vibrate so violently that it shatters.

https://futurism.com/science-sound-breaking-glass-panes-car-speakers

This property was demonstrated by legendary jazz singer Ella Fitzgerald the 1976 commercial produced by Memorex© to advertise its audio cassettes.

Scientists and engineers manipulate and utilize the structure and properties sound waves, such as wave interference and superposition in acoustics and structural systems in engineering. These properties are very important in the design and development of technologies such as communication systems; sound recording, reproduction and noise cancellation; signal processing and medical imaging techniques including ultrasound and magnetic resonance imaging (MRI).

6.7 Wave Interference and Superposition

Another important concept in the study of waves is **wave interference** or how waves behave when two or more waves meet or overlap with each other. Wave interference leads to superposition or the combined effect of their individual displacement of each wave and results in either constructive or destructive interference of the waves.

Constructive interference occurs when two waves meet **in phase**, which occurs when the crests and troughs of two waves align with one another. As a result, the individual wave displacements add together, leading to an increase in the overall amplitude or intensity of the resulting wave.

Constructive interference creates regions of reinforcement, where the waves amplify each other, resulting in a stronger and more pronounced wave. This phenomenon is observed in musical instruments, where multiple sound waves combine to produce a louder and richer sound.

When two waves meet **out of phase**, meaning that the crests of one wave aligns with the troughs of the other wave **destructive interference** occurs. In this case, the individual wave displacements subtract from each other, leading to a decrease in the overall amplitude or intensity of the resulting wave. Destructive interference creates regions of cancellation, where the waves partially or completely nullify each other, resulting in a weaker or even no wave at all. This phenomenon is utilized in noise-canceling technologies, where sound waves with inverted phases are used to cancel out unwanted noise.

When two or more waves meet, their displacements add algebraically. In other words, the resulting displacement of a wave at any given point is the sum of the displacements of the individual waves at that point. This is known as the **principle of superposition**. This principle allows us to be able to analyze and understand the complex wave patterns that arise from the interaction of multiple waves. Superposition applies to both interference phenomena and the addition of individual wave amplitudes.

6.8 Standing Waves

When a wave reflects back and forth between two fixed points, the incoming and reflected waves interfere with each other and create a distinct interference pattern. Since both waves have the same frequency and amplitude and are traveling in opposite directions, the waves interfere with each other leading to regions of constructive and destructive interference. Due on the principle of superposition of the incoming and reflected waves, a unique pattern is created where certain points along the wave experience maximum displacement while other points experience minimum displacement and appear stationary or to *stand still*. This pattern is known as a **standing wave.** Standing waves have distinct regions of constructive and destructive interference which resulting in creation of **nodes** and **antinodes.**

In a standing wave, a **node** *is the point of minimum displacement, where the interfering waves cancel each other ou*t. An **antinode**, on the other hand, *is the point of maximum displacement, where the waves experience maximum energy of its greatest amplitude*. The distance between two adjacent nodes (or two adjacent antinodes) is half the wavelength of the standing wave and antinodes occur midway between adjacent nodes. This fluctuation in energy between the nodes and antinodes is what is responsible for the creation of beats in music.

Standing waves are fundamental to the production of sound in musical instruments. Wind, string and percussion instruments are designed with specific modes at which instruments vibrate for the example, strings, air columns in wind instruments, and the membranes in drums. These modes of vibration correspond to the natural frequencies of the standing waves produces and determine the pitches produced by the instrument.

6.9 Conclusion

In conclusion, the study of waves and their various applications provides a deeper understanding of the fundamental principles that govern our world. Waves are ubiquitous and can be found in different forms, from electromagnetic waves to mechanical waves like sound. They exhibit unique behaviors and interactions, such as interference and superposition, which allow us to comprehend complex wave patterns and phenomena.

Problems:

1. What is a wave?
2. A small boat creates a wake in a river. The resultant waves pass by the buoy at a rate of 5 waves per second. If the waves are 3.5 com long, what is the period of the waves?
3. How does an echo differ from a reverberation?
4. What is resonance and why is it an important consideration in structural engineering?
5. How fast does a series of 2.5 m long waves travel, if they have a frequency of 10.5 Hz?
6. How do transverse waves differ from longitudinal waves?
7. Are there any similarities between a longitudinal wave and a transverse wave?
8. What is the meaning of constructive and destructive interference?
9. What is the frequency of a wave with a period of 0.05 seconds?
10. A wave with a frequency of 750 Hz has a wavelength of 0.50 meters. Calculate the speed of the wave.