2. Wave Properties and Characteristics

Material waves provide a mechanism for transferring energy over considerable distances, without the transport of the material medium itself.

In most material waves we typically encounter, the "shape" of the disturbance stays the same over short travel distances. In our example of a rock thrown into a pond, the ripples look similar as they expand away from the initial disturbance. Over greater distances, however, we notice changes. The ripples seem to die out as the radius of the circle they make increases. This is because as the wave spreads out, its energy disperses. In some waves, the shape may remain constant over very long distances, for example low frequency sound waves at large depths of the ocean.

Pulse Wave

A pulse is a disturbance with a finite length. For example, if you shook the end of a rope once you would produce a pulse wave as shown below.

The location of the rope before and after the pulse passes is the equilibrium position. The maximum magnitude of the displacement of the pulse from equilibrium is the **amplitude**, designated here by the letter \(A\). Note that as we've defined it, \(\Delta(A)\) is always positive.
Another example of a pulse-type wave is the example of a rock thrown into a pond. In this example the rock produces many ripples, but they are a pulse wave because there are a finite amount of ripples with a well-defined beginning and end.

A Repetitive (Periodic) Wave

Repetitive waves can have many different shapes. One of the simplest to deal with looks like a sine or cosine function. Such waves are called harmonic or sinusoidal waves, and are generated by oscillators moving in simple harmonic motion. For example, if you hold one end of a rope and jiggle it up and down in simple harmonic motion, you will generate harmonic waves. If you were to take a picture of the waves, it might look like this:

We can represent this wave with a graph like the one below. Here \(x\) is the distance along the rope, and \(y\) is how far the rope is displaced from equilibrium. The curve is the shape of the rope at one particular instant \(t=0\).

Like the wave pulse, a repeating wave has an **equilibrium position** (the location of the rope when no wave is present) and an amplitude \(A\). In addition a repeating wave has two additional parameters. The first is the **wavelength** \(\lambda\) which tells us the distance (along the direction of wave motion) between identical pieces of the wave. The second is the **period** \(T\); a wave completes one period if it enough time \(T\) has passed that the wave looks exactly the same. Pulse-type waves, which do not repeat, do not have periods or wavelengths. In other words, the wavelength \(\lambda\) tells us how the wave repeats in space, while the period \(T\) tells us how the wave repeats in time.

Notice that the graph above shows the wave for a fixed time, so it gives us no information about the period. For that we need a new graph; if we were to paint a red dot on the rope at some fixed \(x\) value, and then plot the position of only that dot against time, we would find that particular point moves in simple harmonic motion.
It takes the same amount of time for the dot to return to an initial position as it does for the whole wave to return to an initial configuration. That means $T$ is the period of both the simple harmonic motion of the red dot on the rope and of the wave itself. Just like in simple harmonic motion, the period is the reciprocal of the frequency:

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

Typically, $T$ is measured in seconds and $f$ is measured in Hertz (1 Hz = 1 s$^{-1}$). $T$ is the time between the arrival of adjacent crests of the wave, while $f$ is the number of crests that pass by per second. This means the red dot completes an $f$ number of up-and-down cycles every second, or the rope returns to an initial configuration an $f$ number of times every second.

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**Dimensionality**

The examples seen above are called one-dimensional waves because the displacement discussed in each only changes in one direction. We arbitrarily called that direction the $y$-axis.

If a wave spreads out on a surface then we will define it as a two-dimensional wave. For example a water wave spreads out on the surface of the water, so water waves are two-dimensional.

A wave that spreads outward in all directions is three-dimensional. Examples of three-dimensional waves are typical sound and light waves.

An important distinction between these waves is that, as we described them above, the amplitude $A$ of the waves is only constant for one-dimensional waves. Two-dimensional and Three-dimensional waves have amplitudes that depend on the distance from the source of the disturbance. Recall how ripples in a pond become smaller as they spread out, or how the brightness and loudness of something increases as you get closer to it. This is a consequence of conservation of energy; as a wave propagates outward in multiple dimensions, the energy it carries must be spread over a region of increasing size.

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Polarization

Material waves and electromagnetic waves have a characteristic called polarization. The polarization describes how the displacements due to a wave occur in the medium. For material waves, we are going to define two types of polarization:

- **Transverse Waves**: A material wave is transverse if the displacement from equilibrium is perpendicular to the direction the wave is traveling. Note that if we consider a wave traveling to the right of the page then an oscillation in-and-out of the page or towards the top-and-bottom of the page would both be considered transverse. Below is a transverse wave in a spring. The horizontal line represents the spring’s equilibrium position and the displacement is explicitly labeled.

![Transverse Wave](image1)

- **Longitudinal Waves**: A material wave is longitudinal if the displacement from equilibrium is in the same direction that the wave is traveling. In most examples of longitudinal waves that we explore, this displacement occurs as periodic compressing and stretching of the material. The picture below shows the spring in its equilibrium position (top spring) and a longitudinal wave (bottom spring). The displacement from equilibrium $y(x,t)$ can be found by comparing the two pictures. Note that in this case, $y(x,t)$ is not vertical!

![Longitudinal Wave](image2)

Exercise

Which of the following can be seen in waves above: amplitude, wavelength, period? Which cannot be seen on these pictures?
Wave Speed

The wave speed \(v_{wave}\) is the speed at which the disturbance propagates through the medium. It is not the speed of the individual particles making up the medium. One way of thinking about the wave speed is that it is the speed someone who was riding the wave on a surfboard would travel.

To a good approximation \(v_{wave}\) depends only on properties of the medium, not on wave amplitude \(A\) or frequency \(f\). For large waves, or for waves with extreme frequencies, this approximation breaks down. For now, we simplify our discussion by ignoring dependence of wave speed on amplitude (we don't work with big waves in 7C). We will also ignore dependence of speed on frequency until we discuss refraction of light waves.

As an example of how the medium determines the wave speed we can look at a material wave on a stretched medium. Both transverse waves and longitudinal waves are possible on a stretched string or wire. The speed, \(v_{wave}\), of transverse waves on a stretched string depends on the properties of the string that affect its elasticity and its inertial properties. For a string that is thin compared to its length, the relation connecting the wave speed to the string properties is

\[
v_{wave} = \sqrt{\frac{\tau}{\mu}}
\]

where \(\tau\) is the tension in the string and \(\mu\) is its mass per unit length. Notice that this formula makes some sense considering the picture we discussed in What is a Wave?. The tension is (roughly) the force that one piece of string exerts on another – the tighter the string the higher the tension. As we learned that a material wave is a disturbance that propagates by one piece of the medium exerting a force on its neighbors, it makes sense that when the tension increases the wave speed also increases. When the string is particularly heavy, the forces between pieces of the string result in less acceleration, so it also makes sense that as \(\mu\) increases the wave speed decreases. The ability to control the wave speed is critical for stringed instruments like the guitar, which is why they have tuning knobs at one end (to control \(\tau\)) and the strings are of different mass (for different \(\mu\)). We will discuss the guitar in more detail later when in Standing Waves.

Note that the speed is independent of the time and, if the string is homogeneous, independent of position as well. Notice also that the wave speed does not depend on how long the string is, the amplitude of the wave, the frequency of the wave (if it is a repetitive wave), nor the shape of the pulse (if it is a pulse-type wave).

Hands-On

The simulation below models a string as a series of individual points that each exert a force on their neighbor to maintain their preferred separation distance (as in Primitive Wave Concepts). After reading this chapter, adjust the settings of the string and try creating waves using different methods. Can you predict which methods produce which kind of wave? Can you predict which settings will affect which properties (speed, wavelength etc.) of the wave?
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