I. WHAT ARE WAVES?

Everyone has seen examples of waves on the surface of an ocean or lake. Those little ripples that are generated by dropping a pebble in water are waves (Figure I.1). Light and other components of the electromagnetic spectrum have wave properties. Medical imaging is a familiar example of using observations of waves (x-rays) to deduce properties of the material in which the waves propagate [the human body!]. Most of us are able hear and utilize the properties of sound waves constantly in our daily lives. Perhaps the ultimate waves from a human perspective are those that are generated in the earth during large earthquakes, those that can topple buildings and collapse bridges in mere seconds.

Figure I.1 Waves from a pebble

But what exactly are waves, and what are the **characteristics** that are used to describe all these different types of waves? Waves are a form of kinetic energy, the energy of motion. Let's look at that example of the pebble dropped into a pool of water. The falling pebble slows down dramatically when it hits the water's surface, yet the energy that the falling pebble had must go somewhere because it cannot simply vanish. (Remember that energy can be transferred to different forms but cannot be destroyed.) Upon impact, the kinetic energy of the falling pebble is transferred to the water and begins to travel (or **propagate**) away from the point of impact in the form of waves.

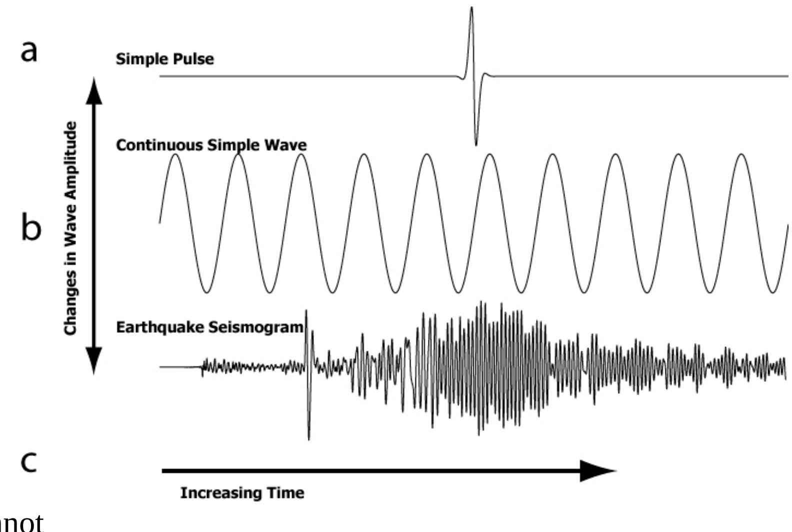

Figure I.2 Different Types of Waves

There are many different types of waves, but they often can be represented as graphs. Figure I.2 shows graphs of simple types of waves. A short pulse of a single note of music, a continuous tone of music, and an earthquake will each generate waves. In Figure I.2, the graphs show the variation of these waves in time. The single pulse appears as a short-lived change in amplitude as it passes the observation point (your ear!). The continuous tone, on the other hand, varies with time in a very simple way (and always sounds the same to your ear). The earthquake also varies in time, but in a more complex way. Instead of being heard, it would be felt by the person observing it as motion that varied with time.

WAVE CHARACTERISTICS

Even though there are many types of waves, all waves have very similar characteristics:

- amplitude
- velocity
- period
- frequency
- wavelength

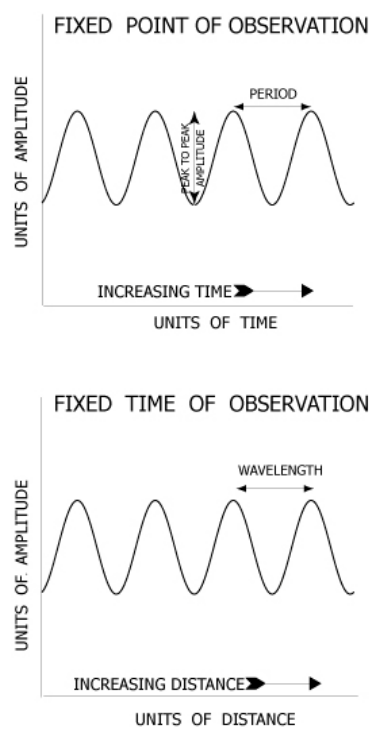

Figure I.3 Two ways to observe the effects of waves

Some of the various wave characteristics can be seen in the diagram of a simple wave shown in Figure I.3. Graphing wave motion is a good place to start when trying to understand wave characteristics. Graphs can be drawn that represent waves in the two ways that are normally observed. First, the waves can be observed during a single instant in time to determine how they behave in space (spatial variations). Figure I.1 and the bottom frame of Figure I.3 are examples of observing waves at an instant in time. The photograph of the pebble dropped in water captures the characteristics of that wave at that particular instant in time. Second, they can be observed from a single point in space to determine how they change with time (temporal variations). A person listening to music or experiencing an earthquake is observing variations of these waves from a single observation point as time changes. Thus, Figure I.2 and the top frame of Figure I.3 are examples of graphing the temporal variations in wave characteristics at a single observation point.

WAVE AMPLITUDE

In the example of the pebble falling into water, some simple arguments can be used to draw two important conclusions about waves. Vibrations of individual water particles cause the ripples seen on the surface of the water as energy propagates outward from where the pebble entered the water. In Figure I.4, the motion of an individual particle is tracked during the passage of the water wave.

As the wave passes this point, it induces the water particles to move in a circular pattern. However, there is no net motion of the water particle! After the wave passes, the individual water particles have not experienced any net motion … they are right back where they were when the wave arrived. This is because the wave is propagating energy, not propagating matter! The energy induces vibrations as it is transferred from particle to particle through the material, but the particles themselves return to their original position. The displacement of an individual particle during the passage of a wave is called the **wave amplitude** (see Figure I.1).

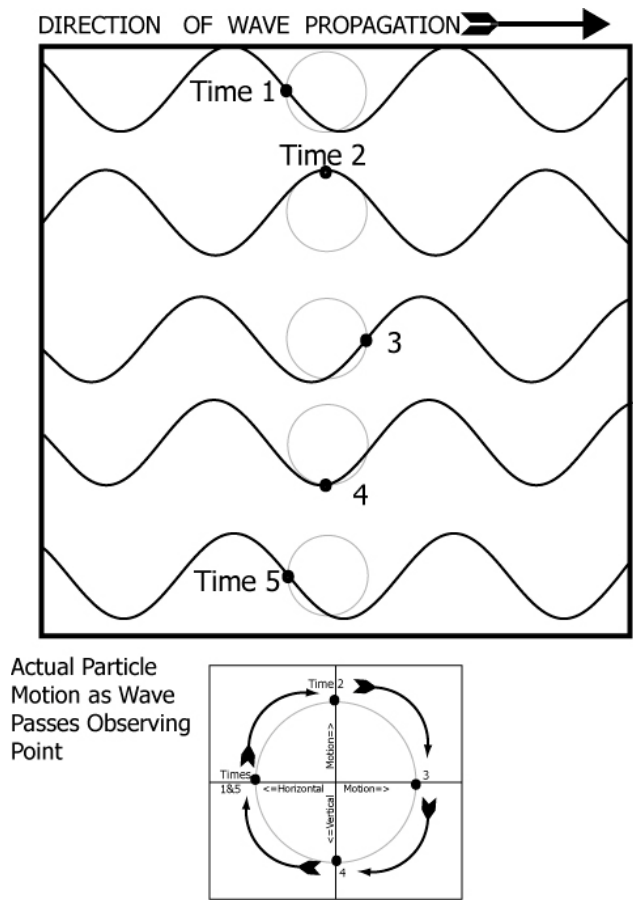

Figure I.4 Actual particle motion as wave passes observing point

If a larger pebble was dropped into the water, one would expect to see larger waves. The reason for this is that there is more energy in the larger pebble, and therefore, more energy is transmitted into wave motion. Since the amplitude of the wave increases as the mass of the pebble increases, it is logical to conclude that the amplitude of a wave is controlled, at least in part, by the energy in that wave.

If the small pebble were dropped onto hard ground rather than into water, would one expect to see waves along the surface of the ground? Probably not! But the energy in the pebble was still transformed into some other form because the pebble is no longer moving. What if larger and larger boulders were dropped onto the ground? Eventually, a person would begin to feel and, at some point, even see the waves that are generated by progressively larger and larger boulders. Do the boulders only begin generating waves when they get to be a certain size or is there a minimum size wave that can be detected by humans? In fact, there are ways of detecting waves that are much more sensitive than our bodies are to feeling and seeing the wave vibration. Even a small pebble generates waves when it strikes solid ground.

The amplitude of the waves generated when a pebble is dropped into water is much larger than when the same pebble is dropped onto solid ground. Therefore, a conclusion might be that the amplitude is also controlled, in part, by properties of the material through which the wave is propagating.

From this, it has been concluded that just one characteristic of a wave, its amplitude, could generate much information about the amount of energy in a wave. An example of the first conclusion is the use of recordings of earthquake waves to deduce the amount of energy released in that earthquake. In addition, it is possible to infer information about the properties of the material through which the wave propagated. For example, waves from earthquakes, called **seismic waves**, are commonly used to determine the internal structure of the earth. In later modules in this series seismic waves will be used to discuss wave properties.

The variations of wave amplitude with time for three different types of waves were shown in Figure I.2; the axes of the graph are TIME on the horizontal axis and AMPLITUDE on the vertical axis. There are no specific units on the graphs, but when observing individual waves this information will be needed to study their characteristics. In the case of Figure I.2.b (the continuous simple wave or tone), the larger the amplitude, the louder the sound. But without units a determination of just how loud the tone is cannot be made. The graph also does not show from where the sound is coming, just the variation of the sound with time. Similarly, without units, the graph of the earthquake waves (Figure I.2.c) doesn't reveal which way the ground is moving or how much. It just illustrates the change in relative size of the wave motion with time.

WAVELENGTH

One other wave characteristic that is commonly used to describe waves is its **wavelength** (measured in units of distance per cycle**)**. For example, the *distance* between successive crests of the waves in Figure I.3.a is the wavelength of this simple wave. The distance between wave crests on the snapshot shown in Figure I.1 can be used to obtain an estimate of the wavelength of the water wave caused by pebble dropped in the water. It should be pointed out however, that the wavelength does not have to be measured from crest to crest or trough to trough. Wavelength can be measured from any two equivalent points on waves.

WAVE VELOCITY

Seismic waves, like those shown in Figure I.2.c, can be used to illustrate another wave characteristic. Figure I.5 shows the movement of seismic waves past an observing station in a simple time-amplitude graph. This type of diagram is known as a **seismogram.** The TIME axis records the time in seconds from the time of occurrence, or origin time, of the earthquake until the waves are recorded at this observing station. Earthquakes generate three basic types of waves, **P-waves, S-waves and surface waves**. The first wave arriving from most earthquakes is the P-wave. In Figure I.5.a, the P-wave takes a little over 500 seconds to reach this station. If the length of the path that the P-wave took was known, it would be possible to determine the speed of this wave.

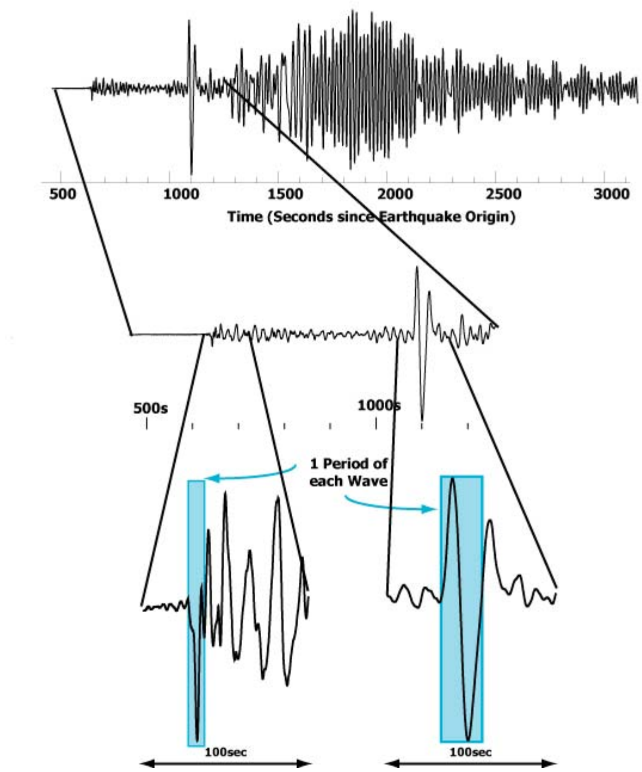

Figure I.5 Properties of Earthquake Waves

The wave speed (measured in units of distance divided by time) is controlled by two factors. The first is the type of wave. The second is the type of material in which the wave is propagating. Thus, the P-wave and the later-arriving S-wave travel in the same material but at different speeds. One practical application of wave speed is to use the variations in arrival-times of seismic P- and S-waves to calculate the location of the earthquake that generated these waves. Because these waves originate from the same place and travel at different speeds, the difference in their arrival times can be used to estimate the distance between the observing station and the earthquake.

WAVE PERIOD AND WAVE FREQUENCY

Another important characteristic of waves can be easily observed on Figure I.5. Note in Figures I.5.c and I.5.d that the time it takes for one full cycle of the P-wave and S-wave to pass a given point (the width of the shaded area) is different. The time of one cycle of a wave is called its **period** (measured in units of time per cycle)**.** For simple waves such as those shown in Figures I.2.b and I.3.b, the period is determined by measuring the time between the passage of two wave crests by our point. However, it is not always this simple for the other waves, such as the two waves shown in Figures I.2.a and I.2.c or for any complex "real-world" wave. The duration of one period of the P-wave and S-wave is shown in Figures I.5.c. & I.5.d Another way to describe this characteristic is termed the **frequency** (measured in units of cycles per unit of time)**,** which is the inverse of the **period.** The units of frequency are cycles/sec or Hertz. If you are observing a wave at some point and count the number of cycles of a wave over a fixed time interval, you can determine the wave's frequency. For the particular waves in Figure I.5, the P-wave is said to have a "shorter period" or "higher frequency" than the S-wave.

The wave characteristics described above are inter-related by a simple formula:

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

where **v** is the wave speed, ***f*** is the wave frequency, and λ is the wavelength of the wave. Thus, if you could measure both the frequency and wavelength of an individual wave, then you could calculate the speed of that wave. Similarly, if you knew both the velocity and the frequency of an individual wave, then you could calculate its wavelength.

Be aware when applying this equation that these parameters are often determined by other factors for "real-world" waves. For instance, the velocity of the wave is most often fixed by the properties of the material through which the wave is propagating. This is the case for sound, water, and seismic waves.