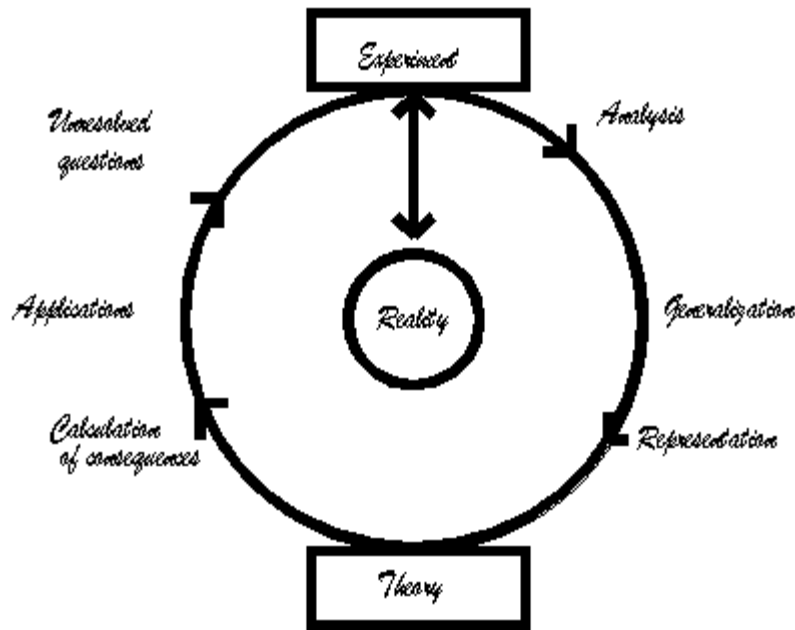


It is impossible to put everything down that we have discussed in lecture and that you have read in the text. However, the idea here is to give you a list of the general topics that we have covered along with some comments. Hopefully this will be a help to you when you study for the exam. Some words that may be new to your vocabulary are in *italics*.

I **Physics** produces descriptions of things through a process of doing and thinking (experiment and theory). It tells you the shape of things, but not their meaning.



**Figure 1**

II Physics measures things in terms of **standard units**. For acoustics, which is a branch of mechanics, we need the fundamental units of mass (*Kilogram*), length (*meter*), and time (seconds). Furthermore there are combined units. For example, force is measured in units called the *Newton*=Kg\*m/s<sup>2</sup>=(N). Energy in (*Joule*=N\*m), power in (*Watt*= J/s), speed in m/s, acceleration in m/s<sup>2</sup>, frequency in (Hertz=1/s), *String Impedance* in Kg/s, etc. **Both sides of an equation must have the same units.** You can multiply or divide things that have different units but you can't add or subtract two things that have different units. In physics measurements and equations **you must keep track of both the numbers and the units.**

**Equations and graphs** are used to represent relationships between different things. It is important to learn how to read and interpret them. To represent sound we often use a graph of the *waveform*. This is a plot of the *wave displacement* verses time. The simplest wave is a *harmonic wave* which is described by a sine or cosine function. Because of the relation between harmonic waves and uniform motion around a circle, you can keep track of where you are in a waveform by using a *phase angle* that goes from zero to 360

degrees (zero to  $2\pi$  radians). Vibration frequencies  $f$  are measured in cycles-per-second (Hertz) or in phase-angle per second  $\omega$  (angular frequency in radians per second)  $\omega=2\pi f$ . The time it takes for one cycle of a vibration is called its period. The period is related to the frequency by the simple formula  $T=1/f$ . The most complicated graph that we have considered is the *spectrogram*. The spectrogram is an *analysis* of the sound power at various frequencies as a function of time. Analysis means you take apart the total sound into its component waves at various frequencies. For the spectrogram the horizontal axis is time and the vertical axis is frequency. Sound power is indicated by the color on the plot. See the Friday 4 worksheet for an example.

**III Basic mechanics.** Work is force times distance and has the same units as energy. Power is force times speed. Impedance is the ratio of force divided by speed. You can do the same work either with a large force and a small displacement or with a small force and a large displacement as long as the product of force times displacement is the same. An *impedance transformer* (like a lever) does not do work for you, but it can change the way that you do work – by changing the ratio of force to motion.

The basic equation of mechanics is  $F=ma$  : to accelerate a mass  $m$  with acceleration  $a$  you need a force  $F$ . Mechanics is the science of understanding force and motion.

**IV Simple harmonic motion.** Many sounds are produced by vibrations. The simplest and most common kind of vibration is *simple harmonic motion*. It requires two ingredients: mass and a linear restoring force. A simple harmonic oscillator, when struck, will oscillate with harmonic motion. That means it has a waveform given by a sine or cosine function at a special frequency called its *natural frequency*. All simple harmonic oscillators can be described by a return force per unit displacement (in mechanics this is the spring constant for a spring  $k$  in N/m) and by a mass ( in mechanics  $m$  in Kg). Given these you can calculate the natural frequency using:

$$\omega_{res} = 2\pi f_{res} = \sqrt{\frac{k}{m}}$$

Even a small force can produce a large motion for a simple harmonic oscillator if the force oscillates at the natural frequency. This is called *resonance*. At resonance you can easily transfer energy to a simple harmonic oscillator – as in the case of the glass beaker broken by sound from a loudspeaker. In simple harmonic motion there are two forms of energy: *kinetic energy* – the energy of motion – which is  $PE= \frac{1}{2} mv^2$  and *potential energy* (stored energy in the spring) which is  $KE=\frac{1}{2} kx^2$ . During oscillation energy is exchanged back and forth between these two forms and only slowly escapes through friction and becomes heat in the environment (this is called *damping*).

**V Wave motion.** Wave motion occurs when you have the right kind of *medium*. For sound, you need a medium which is like many small simple harmonic oscillators connected together. Media that support sounds waves have a certain density of mass and a certain restoring force that depends on how you have compressed or decompressed the material. Because there are many kinds of wave motion there are a number of concepts that have been invented to describe waves. We discussed *speed*, *polarization* ( ! warning,

I call longitudinal and transverse two kinds of polarization- which sadly is not the definition given in the textbook), impedance, frequency and wavelength, amplitude, and intensity (power). As in the case of the simple harmonic oscillator, wave motion at a definite frequency has a definite wavelength and is described by a waveform that is a sine or cosine wave in both time and in space. Also, because of *linearity* (this means that restoring force is linearly proportional to the wave displacement) you can analyze complex waveforms in terms of simple parts. Also, the net result of two sounds is simply to add the displacement caused by each one separately (this is called *superposition*). The speed of a wave is related to the mass and restoring force in much the same way that the natural frequency of a simple harmonic oscillator depends of the mass and spring constant. For example, for a string, the restoring force is due to the tension force  $F$  (in Newtons), and the mass is in the density  $W$  (in Kg/m) of the string. The wave speed for these *transverse waves* is  $S = \sqrt{\frac{F}{W}}$ . However, waves can travel at many frequencies and

have a wavelength that varies depending on the speed of sound and the frequency  $f \lambda = S$ . Wave power depends on the wave impedance and the square of the particle velocity according to  $P = Zv^2$ . The wave impedance for a string is

$$Z = \sqrt{F \cdot W}$$

Where the mass density (mass per unit of length) of the string is its mass divided by its length  $W = \frac{M}{L}$ .

Although wave motion can be complicated, you can use simple principles to predict what is going to happen. If the wavelength of a wave is short compared to the objects encountered you can use the *ray theory* – this says that sound spreads out along lines. According to ray theory, large objects will have a sound shadow. The ray theory is useful when you want to understand *refraction* – the deflection of sound due to a temperature gradient. However, it does not work when you have *diffraction*. If an object or a doorway is about the same size or smaller than the wavelength then the waves will diffract around corners and there will not be a shadow. One way to understand diffraction is in terms of *Huygen's principle*. *Interference* does not mean that one wave blocks another, but rather that the total wave amplitude at any location will be the sum of the amplitudes of several waves that may have taken different paths or be at different frequencies. *Beats* are one example of an interference effect.

The *Doppler effect* occurs when either the source or the receiver of sound is moving. Although the net effect is similar (for example the frequency heard increases if the sender moves toward the receiver or if the receiver moves toward the sender) the two kinds of Doppler effect are very different. The formula relating frequency to wavelength only works in the frame of reference of the air (the wave medium). When the source moves, both the frequency and the wavelength of the sound in the air change. When the receiver moves, nothing changes in the air, but the receiver hears an altered frequency. See the notes from Friday 4.

For a moving source the Doppler effect is described by:  $f_{air} = f_{source} \frac{1}{(1 - \frac{v_{source}}{v})}$

where  $v$  (without a subscript) is the speed of sound. You can see that if a source moves at the speed of sound this equation fails (you divide by zero) – this means that the theory breaks down. What happens is that you get a shock wave if a source moves that fast.

For a moving receiver you have:  $f_{receiver} = f_{air} (1 + \frac{v_{receiver}}{v})$

## VI Waves in Air

Sound travels as a *longitudinal wave* in air with a velocity given by

$S = \sqrt{\frac{\gamma kT}{m}} \approx (331.1 + 0.6 T_{Celsius}) \frac{m}{s}$ . The second part is an approximate formula that

works well for most of the temperatures that you will experience. The speed depends on the mass of the molecules  $m$ , their shape  $\gamma$ , and their temperature  $kT$ . The main thing that affects the sound speed on earth is a change in temperature. Because water molecules have a different shape and mass from oxygen and nitrogen (the gasses that make up most of the atmosphere), there is a slight dependence on humidity. The specific wave impedance of air, however, depends on the pressure and on the density of air.

**VII The slinky** is a special medium that supports both transverse and longitudinal waves. When you stretch it out you change both the mass density and the tension. See Friday 3 worksheet.

## VIII Impedance and reflections.

A sudden change in impedance causes a reflection. Energy transfer is perfect when impedances are matched. See the notes on Impedance from the lectures notes. In addition there are supplementary lecture notes on impedance.

$$A_R = A_I \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

This equation tells you the amplitude of the reflected wave  $A_R$  if you know the amplitude of the incident wave  $A_I$  and the impedances of the incident wave medium  $Z_1$  and the impedance of the medium that the wave runs into  $Z_2$ .

Equation summary sheet:

Some definitions: angular frequency  $\omega=2\pi f$  , period  $T=1/f$  ( $f$  is frequency)

Basic mechanics :  $F=ma$  Newton's second law.

Simple harmonic motion:  $\omega_{res} = 2\pi f_{res} = \sqrt{\frac{k}{m}}$  PE=  $\frac{1}{2} mv^2$  KE= $\frac{1}{2} kx^2$

Waves:  $f\lambda = S$

$$\text{Waves on Strings: } S = \sqrt{\frac{F}{W}} \quad W = \frac{M}{L} \quad Z = \sqrt{F \cdot W}$$

Waves in Air:  $S = \sqrt{\frac{\gamma kT}{m}} \approx (331.1 + 0.6 T_{Celsius}) \frac{m}{s}$  Pressure is force per unit area and density is mass per unit volume.

Doppler Effect (moving source):  $f_{air} = f_{source} \frac{1}{(1 - \frac{v_{source}}{v})}$

Doppler Effect (moving receiver):  $f_{receiver} = f_{air} (1 + \frac{v_{receiver}}{v})$

Impedance and reflections:

$$A_R = A_I \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad P = Zv^2$$