Sound is a wave. It is introduced into a medium such as water or air by the vibration of an object. The vibration causes molecules around the vibrating object to be compressed and expanded, which is why sound is termed a pressure wave. The compressions and rarefactions (expansions) create a longitudinal displacement of particles as the energy of a sound wave passes through some medium with the motion of the particles being both parallel and anti-parallel to the direction of the energy transport. Reciprocally, a sound wave moving through some medium can cause a stationary object (e.g., your eardrum or a piezoelectric crystal – see text box below) to vibrate, so that a sonar system can sit on the ocean floor and record sound waves passively, that is, without emitting any sounds.

Piezoelectric transducers are now commonly used in sonars.

### PIEZOELECTRICITY - DISCOVERY AND INSIGHTS


The first experimental demonstration of a connection between macroscopic piezoelectric phenomena and crystallographic structure was published in 1880 by Pierre and Jacques Curie. Their experiment consisted of a conclusive measurement of surface charges appearing on specially prepared crystals (tourmaline, quartz, topaz, cane sugar and Rochelle salt among them) which were subjected to mechanical stress. These results were a credit to the Curies’ imagination and perseverance, considering that they were obtained with nothing more than tinfoil, glue, wire, magnets and a jeweler’s saw.

In the scientific circles of the day, this effect was considered quite a "discovery," and was quickly dubbed as "piezoelectricity" in order to distinguish it from other areas of scientific phenomenological experience such as "contact electricity" (friction generated static electricity) and "pyroelectricity" (electricity generated from crystals by heating).

The Curie brothers asserted, however, that there was a one-to-one correspondence between the electrical effects of temperature change and mechanical stress in a given crystal, and that they had used this correspondence not only to pick the crystals for the experiment, but also to determine the cuts of those crystals. To them, their demonstration was a confirmation of predictions which followed naturally from their understanding of the microscopic crystallographic origins of pyroelectricity (i.e., from certain crystal asymmetries).

The Curie brothers did not, however, predict that crystals exhibiting the direct piezoelectric effect (electricity from applied stress) would also exhibit the converse piezoelectric effect (stress in response to applied electric field). This property was mathematically deduced from fundamental thermodynamic principles by Lippmann in 1881. The Curies immediately confirmed the existence of the "converse effect," and continued on to obtain quantitative proof of the complete reversibility of electro-elasto-mechanical deformations in piezoelectric crystals.
When waves emanate from more than one source they can interfere constructively and destructively. Here are examples in two dimensions. The red and blue lines represent the original waveforms and the black line is the result of them interfering with each other:

![Wave Interference Diagram](http://scienceworld.wolfram.com/physics)

In the case of spherical spreading waves from points sources, the interference pattern generated by two point sources looks like this:

![Spherical Wave Interference](http://www.olympusmicro.com/primer/lightandcolor/interference.html)

When sonar transducers are built, they effectively string lots of point sources into one array where the maximum strength of the outgoing signal is concentrated in the center of the array through constructive interference, and at the ends of the array the outgoing signal strength is low because of destructive interference. We can measure the intensity of sound produced by the sonar above in special tanks or outdoor testing facilities to produce a sonar beam pattern:

![Sonar Beam Pattern](http://www.olympusmicro.com/primer/lightandcolor/interference.html)
The intensity of a sound wave is the amount of energy transported past a given area in some medium per unit time:

\[
\text{Intensity} = \frac{\text{Energy}}{\text{Time} \times \text{Area}} \quad \text{or} \quad \frac{\text{Power}}{\text{Area}} \quad (\text{Watts/m}^2)
\]

Because the human ear can detect a very large range of intensities, a logarithmic scale is used to measure intensity. This is the decibel scale.

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**Decibel**

*Extracted from Wikipedia, the free encyclopedia.*

Although it is widely used as a measure of the loudness of sound, the **decibel (dB)** is more generally a measure of the ratio between two quantities, and can be used to express a wide variety of measurements in acoustics and electronics. The decibel is a "dimensionless unit" like percent.

**Definition**

The intensity of a sound \( I \) can be expressed in decibels with the standard equation:

\[
I_{dB} = 10 \log_{10} \left( \frac{I}{I_0} \right)
\]

where \( I_0 \) is the quietest sound most people can hear, the threshold of hearing. Neither eardrums nor microphones can convert sound intensity. We hear the pressure variations.

**Merits**

The use of decibels has three different merits:

- It is more convenient to add the decibel values of, for instance, two consecutive amplifiers rather than to multiply their amplification factors.
- A very large range of ratios can be expressed with decibel values in a range of moderate size, allowing one to clearly visualize huge changes of some quantity.
- In acoustics, the decibel as a logarithmic measure of ratios fits well to the logarithmic dependence of perceived loudness on sound intensity. In other words, a doubling in decibel level creates approximately a doubling in perceived intensity level.

**History of bels and decibels**

A **bel** (symbol B) is a unit of measure of ratios, such as power levels and voltage levels. It is mostly used in telecommunication, electronics, and acoustics. Invented by engineers of the Bell Telephone Laboratory to quantify the reduction in audio level over a 1 mile length of standard telephone cable, it was originally called the *transmission unit* or *TU*, but was renamed in 1923 or 1924 in honor of the laboratory's founder and telecommunications pioneer Alexander Graham Bell.

The bel was too large for everyday use, so the **decibel (dB)**, equal to 0.1 B, became more commonly used. The bel is still used to represent noise power levels in hard drive specifications.

**Acoustics**

The **decibel** unit is often used in acoustics to quantify sound levels relative to some 0 dB reference. The reference may be defined as a sound pressure level (SPL), commonly 20 micropascals (20 µPa). To avoid confusion with other decibel measures, the term dB (SPL) is used for this. The reference sound pressure (corresponding to a sound pressure level of 0 dB) can also be defined as the sound pressure at the threshold of human hearing, which is conventionally taken to be \(2 \times 10^{-5} \text{ newton per square metre}, 2 \times 10^{-5} \text{ N/m}^2 \) or 20 micropascals. That is roughly the sound of a mosquito flying 3 m away. The ears are only sensitive to sound **pressure** deviations.

The reason for using the decibel is that the ear is capable of detecting a very large range of sound pressures. The
ratio of the sound pressure that causes permanent damage from short exposure to the limit that (undamaged) ears can hear is more than a million. Because the power in a sound wave is proportional to the square of the pressure, the ratio of the maximum power to the minimum power is more than one (short scale) trillion. To deal with such a range, logarithmic units are useful: the log of a trillion is 12, so this ratio represents a difference of 120 dB. Psychologists have found that our perception of loudness is roughly logarithmic — see the Weber-Fechner law. In other words, you have to multiply the sound pressure by the same factor to have the same increase in loudness. This is why the numbers around the volume control dial on a typical audio amplifier are related not to the voltage amplification, but to its logarithm.

Sound levels above 85 dB are considered harmful, while 120 dB is unsafe and 150 dB causes physical damage to the human body. Windows break at about 163 dB. Jet airplanes cause A-weighted levels of about 133 dB at 33 m, or 100 dB at 170 m. Eardrums rupture at 190 dB to 198 dB. Shock waves and sonic booms cause levels of about 200 dB at 330 m. Sound levels of around 200 dB can cause death to humans and are generated near bomb explosions (e.g., 23 kg of TNT detonated 3 m away). The space shuttle generates levels of around 215 dB (or an A-weighted level of about 175 dB at a distance of 17 m). Even louder are nuclear bombs, earthquakes, tornadoes, hurricanes and volcanoes.

By arranging individual transducer elements into specific patterns such as circles, single rows, double rows, etc., scientists and engineers are able to build systems such as echo-sounders, Acoustic Doppler Current Profilers (ADCPs), sidescan sonars, multibeam swath mapping sonars, etc. The transducers are usually mounted on a towbody or the hull of a ship with an acoustically transparent material protecting the sonar arrays (Figures 5 and 6). We will discuss various types of systems in more detail over the next few lectures.

Figure 5 - (Left) EM1002 transducers mounted on the hull of the R/V Kilo Moana and (right) EM3002 transducers mounted on the hull of the Hi'ialakai.

Figure 6 - (Left) Hawaii MR1 shallow-towed sonar (transducers located below the double black runners along the side of the vehicle) and (right) deep-towed IMI-30 with transducers on the two downward pointing legs of the vehicle.
Assigned Reading