SMS-204: Physical solutions of everyday problems in aquatic sciences.

Lecture 6: a fast survey through light, vision, sound and Hearing.

Light

Light is electromagnetic radiation. It provides energy for photosynthesis, is a source of heat, and is used by animals to obtain information about their surrounding (sensing). We use the term "light" to refer to electromagnetic radiation that can be perceived by an organism.
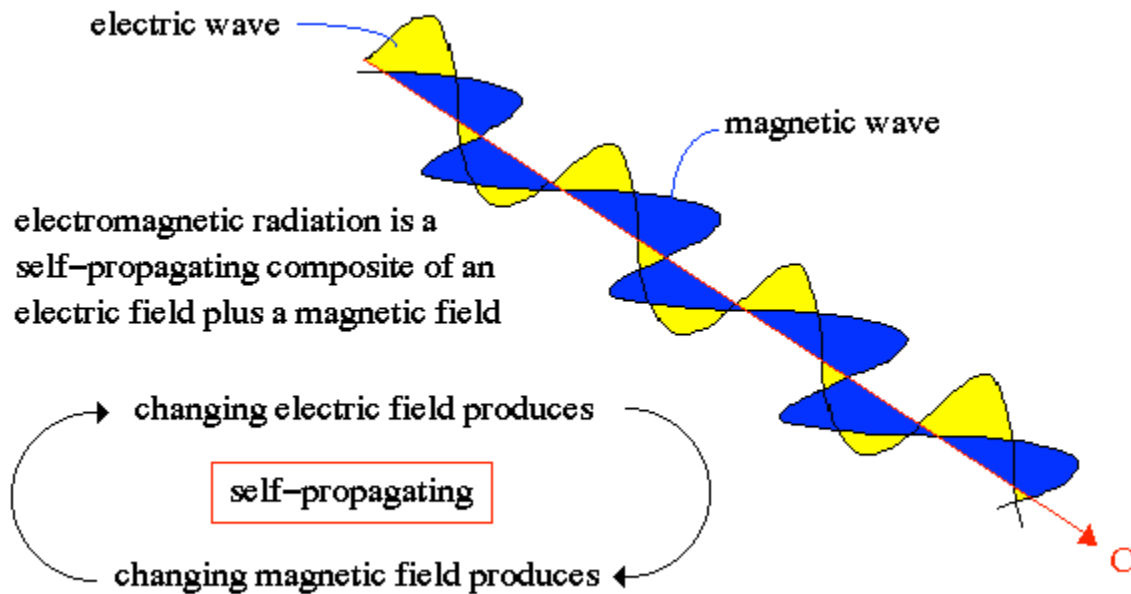

Figure 1. Light is energy carried in the form of perpendicular electric and magnetic fields in the shape of waves. Figure from:
http://zebu.uoregon.edu/~js/ast123/lectures/lec03.html

Electromagnetic radiation is classified according to the frequency, f [sec^{-1}], or wavelength, λ [m], with which the electric (and magnetic) field oscillate. The two are related by the speed of propagation in the medium (c): $c=f\lambda$.

In a vacuum, the speed of light, c=299,800km/sec (propagation speed in air is similar to vacuum). We refer to the wavelength of light as the wavelength in vacuum (λ_{vac}) because it changes between media (by a factor of 1.34 smaller in water compared to air), while its frequency is constant in all media (a consequence of energy conservation which is proportional to the frequency).

Light is comprised of elementary particles (energy packets), called photons. The energy of a photon of light is proportional to the frequency of its associated electrical and magnetic fields, $E_{photon}=\hbar f$, where ħ is the Plank constant, $6.626*10^{-34}$J sec. Thus, a blue photon ($\lambda\approx450$nm, 1nm$=10^{-9}$m) has about 1.5 times the energy of a red photon ($\lambda\approx680$nm).

Light behaves like waves as well; it has a wavelength (and a frequency), which we associate with color. It is attenuated as it propagates due to spherical spreading. Light interacts with other light waves producing constructive and destructive interference patterns (diffraction, see below).

'Visible' light refers to the range of light visible to humans (400-740nm). It is not surprising that it is in the region of maximum radiant energy flux [Joules m^{-2} s^{-1} = W m^{-2}] of the sun, by far the dominant source of light used by plants and animals.
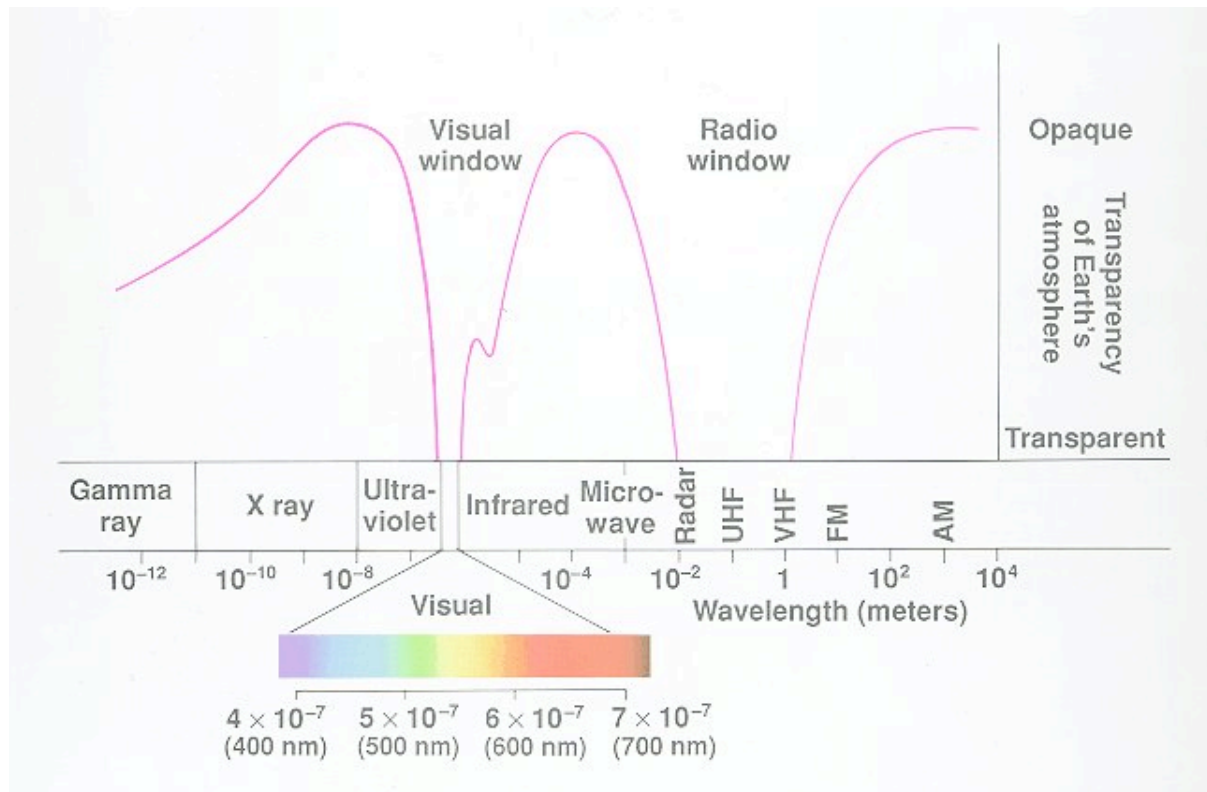

Figure 2. Light is some time referred to only a small part of the electro-magnetic spectrum, that perceived by the human eye. It is one of the regions of the spectrum where the atmosphere is transparent, and thus can propagate relatively unattenuated from the top of the atmosphere to the surface of the earth.

Polarization refers to whether the magnetic and electric fields occupy a preferential plane relative to the axis of propagation (as in figure 1, for the case of linear polarization) or whether they are equally likely to be in all direction relative to the propagation axis (unpolarized light). Sun light is unpolarized while scattering from particles and surfaces

usually results in the reflected light being, at least, partially polarized light (see below). Laser light sources produce linearly polarized light.

Scattering, absorption, and attenuation.

Light interacting with matter can either be absorbed or scattered. The oscillation of the associated electrical and magnetic fields causes the material light encounters to vibrate. These vibrations cause, in turn, secondary electrical and magnetic fields, which propagates from the encountered material. In other words the energy of the incident light is scattered by the interaction with matter. The frequency of the secondary wave is usually the same as that of the incident light (termed elastic scattering).

The scattered light propagates in all directions but with an intensity that varies with the angle between the incident and scattered light. The angular distribution of the scattered light depends primarily on the ratio of the size of the particle interacting with light and the wavelength.

Air and water scatter light with a strong dependence on wavelength; the intensity of the scattered light is (nearly) proportional to λ^{-4}. The scattering is predominantly due to microscopic fluctuations in the density of the material in water and air molecules in air. This means that blue light (shorter λ) is scattered preferentially (nearly by a factor of 9!) compared to red light (longer λ) and explains the predominant blue color of the sky and water (in water an additional contribution comes from Raman scattering, see below).

Photons incident upon matter can also be absorbed; this occurs when the energy of the incident light matches the difference between distinct energetic states of an atom within the matter. In this case rather than exciting a vibration within an energy state (as in the case of scattering), an electron jumps to a higher energy level, and the energy of the photon is retained (at least temporarily) within the atom. The absorbed energy can be converted to other energy (as in photosynthesis where it is converted to chemical energy), dissipated as heat, or re-emitted at a different (shorter) wavelength (fluorescence). The last is called inelastic scattering. The chlorophyll molecule used in photosynthetic organisms (plants, and responsible to their green color) absorbs preferentially in the blue and red (and thus looks green). It also fluoresces at a band centered at 686nm, a lower energy wavelength. The probability of chlorophyll fluorescence is low; only between 1→3% of the photon absorbed are emitted as fluorescence. Water itself causes a frequency shift in some photon it emits following absorption, called Raman scattering. This radiation is partially responsible for the purple-blue color of open-ocean water.

The frequencies that are likely to get absorbed (and fluoresced) depend on the nature of the absorbing material and can be predicted from the laws of quantum mechanics.

Attenuation is the sum of all processes which result in loss of photon along its path, and is thus the sum of absorption and scattering. Light intensity (I) obeys the following relationship (Lambert's law):

$$dI/dz = -cI,$$

where z is the distance traveled and c the attenuation coefficient $[m^{-1}]$. It means that a constant *proportion* of light is lost per unit length. The solution of this equation for a medium with constant attenuation is:

$$I = I_0 \exp(-cz),$$

Where I_0 is the light intensity at the source. Transmission=I/I_0*100 denotes the percent light that makes it to a detector at a distance z (it is a function of c and z). The attenuation coefficient, c, is a property of the fluid, varies with wavelength, and can be found by measuring the transmission, $c = -1/z*ln(I/I_0)$. It is often used to quantify how turbid a given water body is.

The (diffuse) attenuation of light by water and other materials in the oceans/lake result in a (nearly) exponential decay of light with depth. Phytoplankton, the microscopic photosynthetic 'grasses' of oceans/lake can only survive near the surface, where there is sufficient light for photosynthesis (in the open ocean in the summer the upper 130m, while in very turbid lake only the upper meter!, Fig. 3).
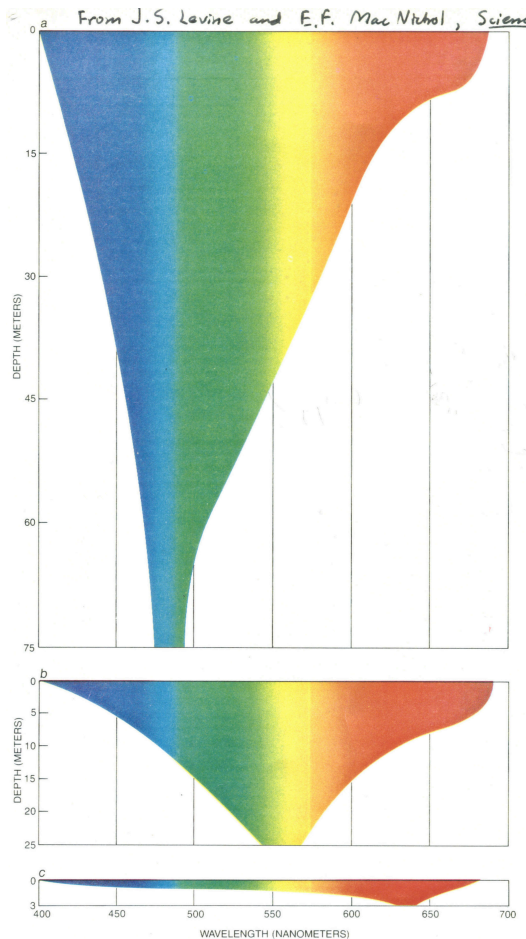

Figure 3. A cartoon depicting light penetration at different wavelengths as function of depth in clear open ocean waters (top), coastal waters (middle) and shallow inland pond (bottom). The attenuation is due to a combination of absorption by water (strongly absorbing near infra red) and varying amount of absorption by dissolved organic material (material similar to tea, absorbing strongly in the UV and blue) and phytoplankton (absorbing mostly in the blue and red).

In oceans and lakes a white plate (Secchi disk) is often used to quantify water transparency. One records the maximum depth at which the disk is visible. This depth depends relates primarily on the average optical properties down to that depth and to a lesser extent on the observer and illumination conditions. Another method is to use black disk viewed horizontally (through a periscope).

Vision

 Vision consists of a series of events:
a. Light from the environment arrives to the vision organ (may pass via lenses and be reflected).
b. The image is formed in a vision organ and is detected by light sensitive cells.
c. Nerve cells pass the detected information to the brain.

Light travels in straight lines from the source to the sensor apparatus. In the absence of a lens, a small pinhole can be used to provide a sharp image on the retina. The smaller the pinhole, the sharper the image, but the fewer photons hit the retina, decreasing the signal.
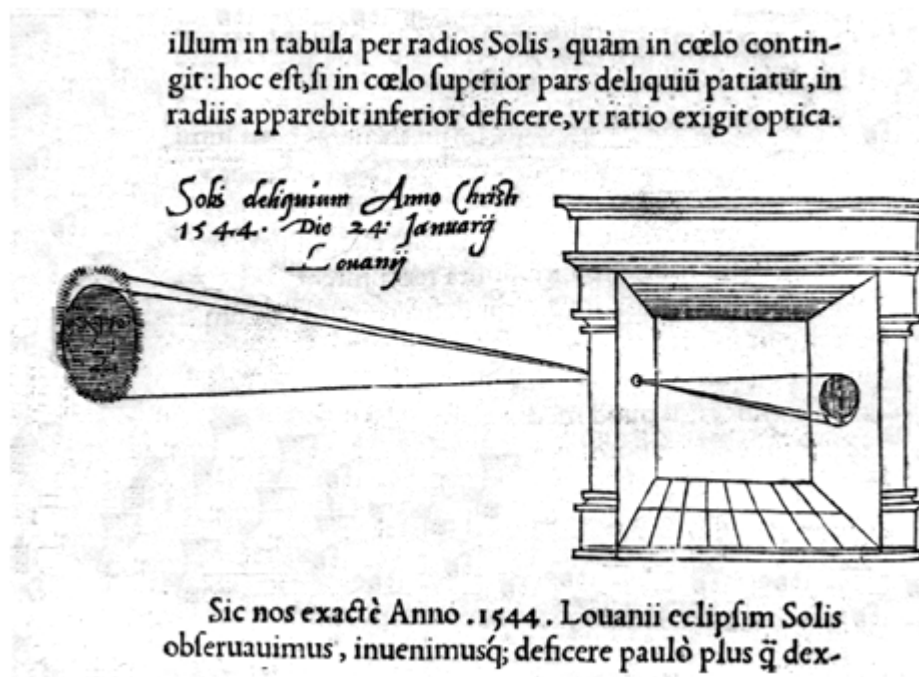

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Figure 4. Example of pinhole optics from 1544. The solar eclipse is inverted in the view through the hole as it passes. Figure from:
http://www.pixeldetective.org/Optics/COIE/pinhole/pinhole01.html

Using a lens, both a sharp image and larger signal throughput are possible. All image-forming eyes in nature use lenses. The same issues associated with taking pictures with cameras have to be solved by the eyes of organisms, namely: focus, sensitivity, and contrast. Eye shape and size are dynamically adjusted for level of light in the environment as well as to focus on targets at different distances. As an aside, you may

have noticed that prey eyes are often mounted on the sides of the head for wide-angle vision, whereas predator eyes are often mounted in front for pursuit.
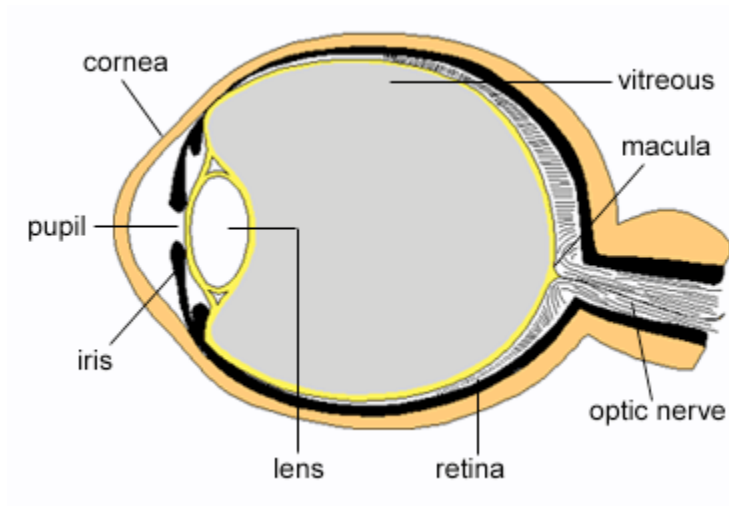

Figure 5. The human eye. The iris regulates the amount of light that enters the eye (to avoid saturation). The lens and cornea focus the light and send it to the retina where it is captured, an image is formed and color is perceived.

The perception of distance from an eye can be effected by the use of two eyes (stereoscopic image) as well as the difference in the angles of the incoming rays on one eye (Fig. 6).
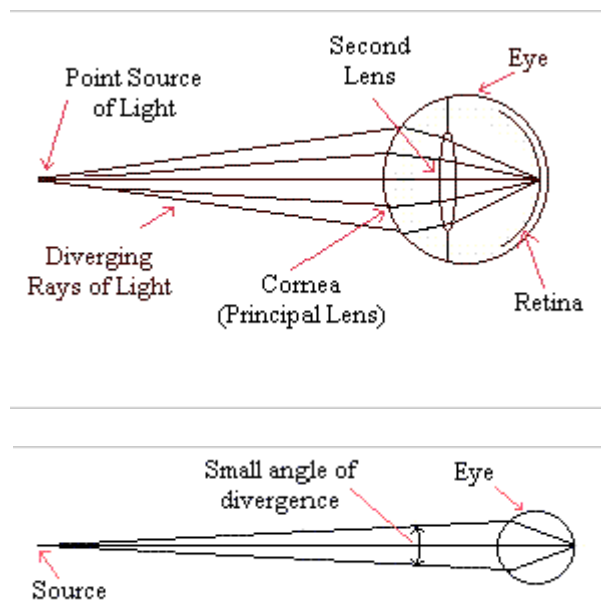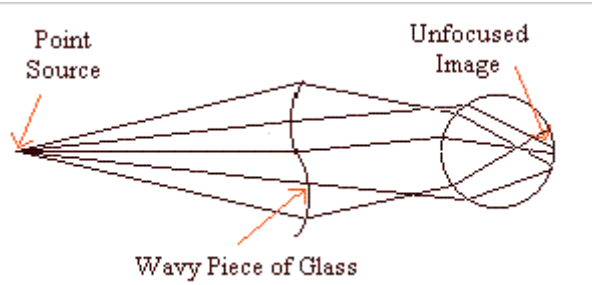
Figure 6. Optics of an eye. Notice the change of path with distance, allowing distance perception. When a wavy piece of glass is introduced (or there is a problem with the lenses) the resulting image is not focused on the retina and appears blurred. From:
http://www.wfu.edu/~brehme/space.htm

Cones and rods in the retina are responsible for the perception of light intensity (Fig. 7). Rods are responsible for light perception at the lowest light intensities while cones allow us to differentiate colors. Notice that our ability to observe and differentiate colors and hues in the light is based on three broad filters (receptors).
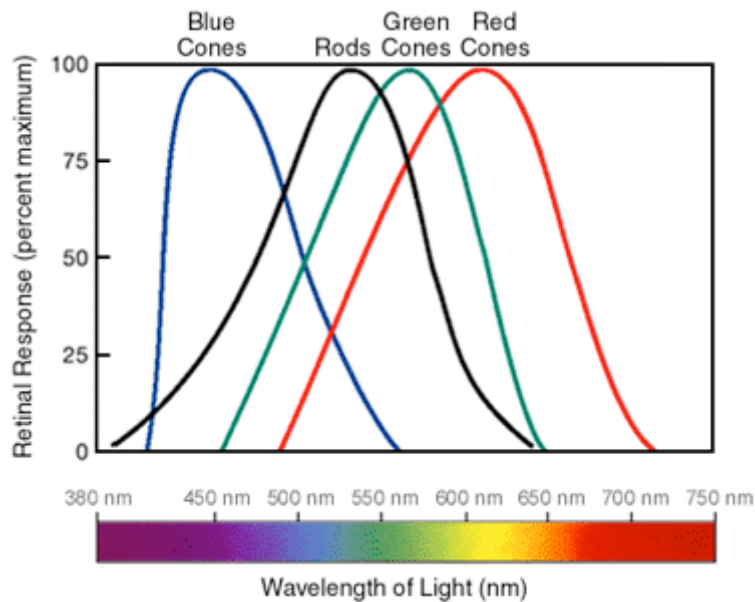

Figure 7. Spectral response of rods and cones cells on the retina. From:
http://www.planetary.org/rrgtm/emspectrum.html

Principle of reciprocity (or inversion):

In geometric optics, one can retrace light rays from receiver to source to predict how light would propagate between the two (that is if light makes it from source to receiver light could travel on the same paths from receiver to source). This is a very powerful law and of great help when designing instruments. It means that one can study the eye by putting a light source at the retina and seeing where it propagates to. Light will only go to the

locations that can be viewed by this specific spot on the retina (assuming all else in its way stays the same). In modeling of light propagation it saves a lot of time because only rays that emanate from the receiver need to be studied as opposed to all the rays going out of a source.

Polrization

In recent years several studies have showed that polarized vision (e.g. vision that perceives only the part of the electromagnetic spectrum that travels with a given polarization) is utilized by many marine organisms (varying from shrimp to marine birds) to sense their environment. For example, predators using polarized vision are better able to perceive the prey (enhanced contrast) or avoid glare (marine birds). For more information see:
http://oceanexplorer.noaa.gov/explorations/05deepscope/background/polarization/polarization.html

Sound

Acoustics is the science of sound and its propagation in varied media. Sound is a mechanical disturbance of alternating expansion and contraction that propagates through an elastic medium. It travels as waves of alternating high and low pressure, accompanied by back-and-forth movement of the medium in the direction of wave propagation.
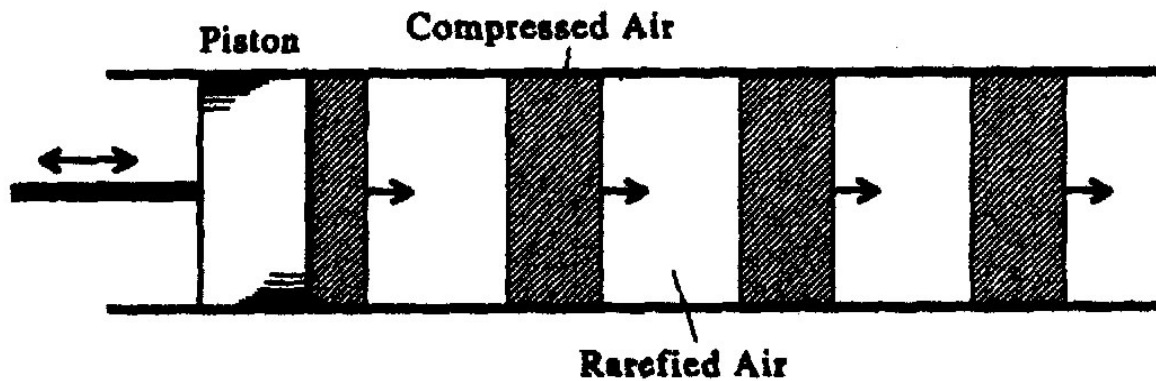

Figure 8. Sound wave propagating in air. The displacement of particles is in the same direction as the wave propagation (unlike water gravity waves). From Denny (1993).

Since sound involves a change of pressure and density, we can arrive at the sound speed simply from dimensional analysis (0 denote state in which the medium is at rest):

Change in pressure due to wave: $\Delta p = p - p_0$ [M T^2 L^{-1}]. Change in density due to wave: $\Delta \rho = \rho - \rho_0$ [M L^{-3}]

From dimensions alone: $c = (\Delta p/\Delta \rho)^{1/2}$

In air, sound speed is nearly 350m/s whereas in water it is nearly 1400m/s. Sound Speed in both media increase with temperature (about 10% from 0 to 40) and in water sound speed increase with salinity (about 3% for 30psu) and pressure (about 16 m/s per 1000 m depth). Notice that light, on the contrary, travels faster in air than in water. The speed of sound in solids is higher, about 6000 m/s (granite), because they are less compressible (smaller $\Delta\rho$ for the same Δp).

As with any wave, the frequency ($f = 1/T$, where T is the period) of sound relates to the wavelength (λ) and speed (c) through: $c = f\lambda = \lambda/T$. As with light waves, the frequency is preserved when crossing media. Thus a 1000 Hz sound wave is about 1.4 m long in water while 0.3 m in air. A frequency of 1 Hz (or Hertz) means 1 crest of the wave is observed per second. Wavelength is important as it is what of the determinants of the scattering of sound and light with matter. Both interact most intensely (e.g. providing the maximal scattering per mass) with objects having the same size as the wavelength.

Sound intensity $I = (\Delta p_{max})^2/(\rho_0 c)$, is the sound energy per unit time that passes a unit area perpendicular to its propagation direction [W m^{-2}].

Sound intensity is often measured relative to a reference intensity to give a loudness scale: dB(decibel) = 10 log$_{10}$ (I/I$_{ref}$). For human hearing often I_{ref} = 10^{-12} W m^{-2} - the intensity of barely audible sound. In terms of pressure dB = 20 log$_{10}$ ($\Delta p/\Delta p_{ref}$), Δp_{ref} = 2·10^{-5}N m^{-2} is the threshold for human hearing at 1 kHz. In water Δp_{ref} = 0.1 N m^{-2} is most often used.

Similarly to electro-magnetic (or water) waves, sound waves reflect, refract and diffract when going through changes in the media in which they propagate. Sound is attenuated due to viscous dissipation and is converted to heat. Attenuation increases with frequency. Air attenuates sound much more rapidly than salt water (~factor of 1000000!), which attenuates sound more rapidly than fresh waster (~factor of 100). In air sound propagates better in some directions than in others, depending on the thermal structure and wind speed of the gaseous medium. In water, because of the much faster sound speed, reciprocity is a much better assumption, i.e., that a sound of a given intensity set off in position A and heard in position B would be heard in position B just as well if it were set off in position A.
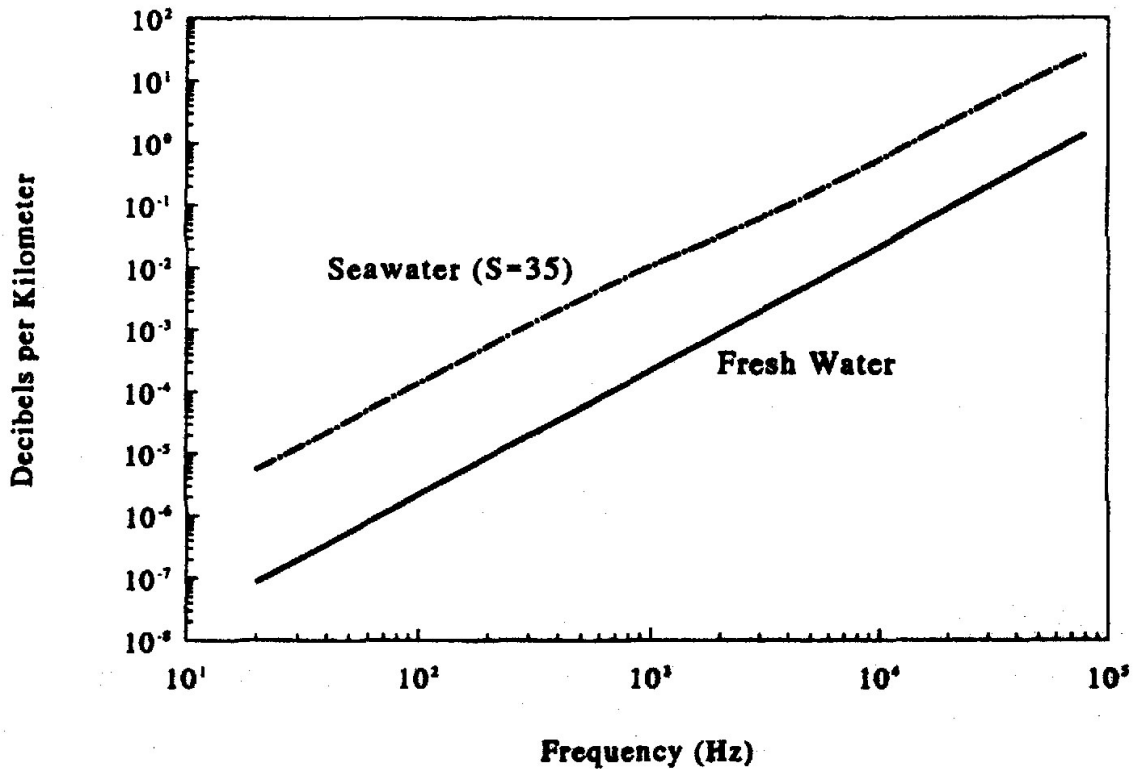
Figure 9: Sound attenuation as function of frequency in fresh and salt water. Notice the increase of attenuation with salinity as well as with frequency. From Denny (1993).

Hearing organs do not form an image due to size constraints. Each sensor has to be of similar dimension to the wave and one would need thousands of such sensors to form an image. At 50 kHz the image forming ear would need to be O(10 m), impractically large. Thus ears are used as point detectors of sound.

Source	Frequency (Hz)	Power (W)	Attenuation (km^{-1})	Noise intensity (W m^{-2})
Human speech	1000	10^{-5}	30	10^{-9}
Human yell	1000	10^{-3}	30	10^{-9}
Dolphin click	25000	10^{5}	1.3	10^{-15}
Dolphin whistle	10000	10^{-4}	0.25	10^{-14}
Finback whale	20	10	0.0007	10^{-11}

Table 1. Frequency, power, attenuation and intensity of sound generated by various marine mammals. From Dusenbery (1994).
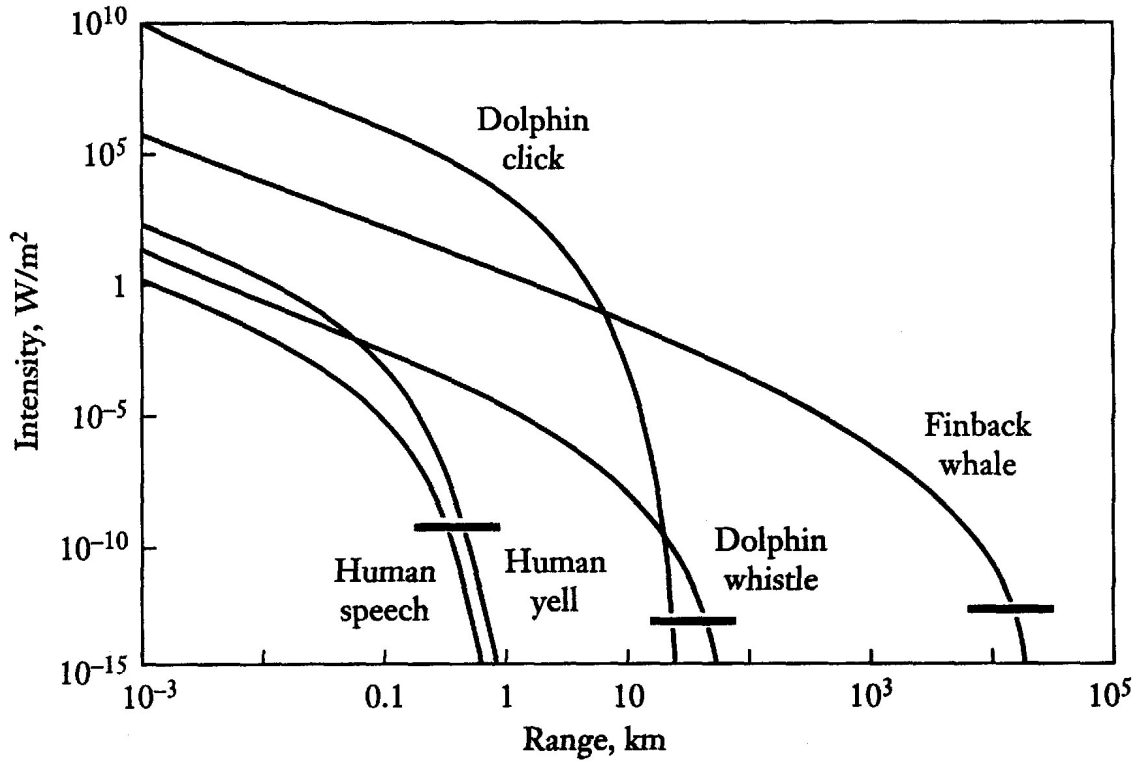
Figure 10. Intensity and range of detection of marine mammals (based on data from table 1). From Dusenbery (1994).

Scattered sound that returns to its source is called an *echo*. Echolocation with click frequencies from 30-150 kHz is used by dolphins to locate prey. The amount of sound scattered back from a target depends on the on the ratio $\pi D/\lambda$, where D is the target's diameter and λ the wavelength of sound. For $\pi D/\lambda \ll 1$, backscattered intensity from a rigid spherical target at a distance l, is given by:

$$I_s = I_0 \, 4\pi^4 \, D^6/(9\lambda^4 \, l^2)$$

Where I_0 is the intensity of the source. Notice the strong wavelength dependence. The signal at low wavelength (high-frequencies) is preferentially backscattered. Also, large targets (those of similar size with the acoustic wavelength) scatter much more than smaller ones. This fact makes muddy suspensions practically transparent to sound produced by aquatic organisms, allowing them to 'see' in waters that are highly absorbing to light.

In contrast, when $\pi D/\lambda \gg 1$ the backscattered intensity from a rigid spherical target at a distance l, is given by:

$$I_s = I_0 \, D^2/(16l^2),$$

which is not dependent on wavelength. It is proportional to the cross-sectional area of the target.

In terms of energy reflected per mass (or volume), targets that are of similar size as the acoustic wavelength, reflect the most.

Sound detection of direction: Animals use one or a combination of the following strategies to locate the direction of sound sources:

1. Difference in intensity between two sensing organs (ears) at two different locations on the body.

2. Difference in arrival time to two sensing organs (ears) at two different locations on the body.

3. Detection of phase shift between pressure waves at two sensing organs (ears) at two different locations on the body.

Detection of echoes allows organisms such as dolphins to locate the distance of a target:

Range = (time interval)*(sound speed)/2

Moving the sensors to get cues of direction is also a frequent tactic employed, for example, by birds.

The Doppler Effect

The range detection above assumed both source and target to be stationary. In that case the frequency of sound is given by $f = c/\lambda$

When the source and receiver move relative to each other, the perceived frequency of sound changes. Moving towards a sound source increases the number of waves perceived per unit of time, and thus the frequency increases. Moving away from a sound source creates the opposite effect, with the frequency decreasing. As a result the frequency heard by a moving organism is:

$f' = (c + u_r)/\lambda = f(c + u_r)/c$

where c is the sound speed and u_r the velocity of the receiver relative to a stationary source, positive when moving towards the source. The shift in frequency is given by:

$\Delta f = f' - f = f u_r/c,$

and is called the Doppler shift. This shift happens with water and light waves as well. When the source is moving (velocity u_s, positive towards receiver) and the receiver is at rest,

$\Delta f = f\, u_s/(c - u_s)$,

as long as u_s and $u_r \ll c$ (case for oceanic organisms) it does not matter whether the source or receiver moves, and the Doppler shift is proportional to $f(u_r + u_s)/c$

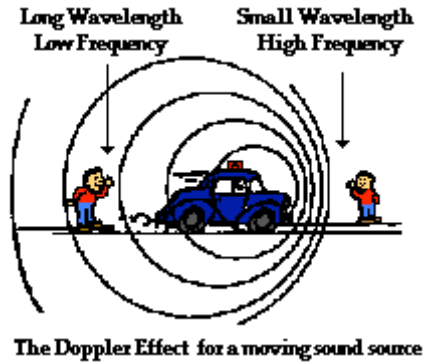The Doppler shift allows organisms to get information about the motion of their prey.

Figure 11. From: [www.glenbrook.k12.il.us/gbssci/ phys/Class/sound/u1l3b.html](www.glenbrook.k12.il.us/gbssci/phys/Class/sound/u1l3b.html)

Hearing

Two basic mechanisms:
1. Otolith - a relatively heavy object (e.g., a calcareous ball) in contact with cilia (little hairs) which are attached to nerve cells. When a pressure wave (sound) propagates through the otolith it displaces the fluid surrounding the cilia and ball. The cilia themselves move (having nearly the same density as water) differently than the heavier ball, resulting in a change in the force that the ball exerts on the cilia. This organ also provides directional information to fish with respect to gravity (up vs down).
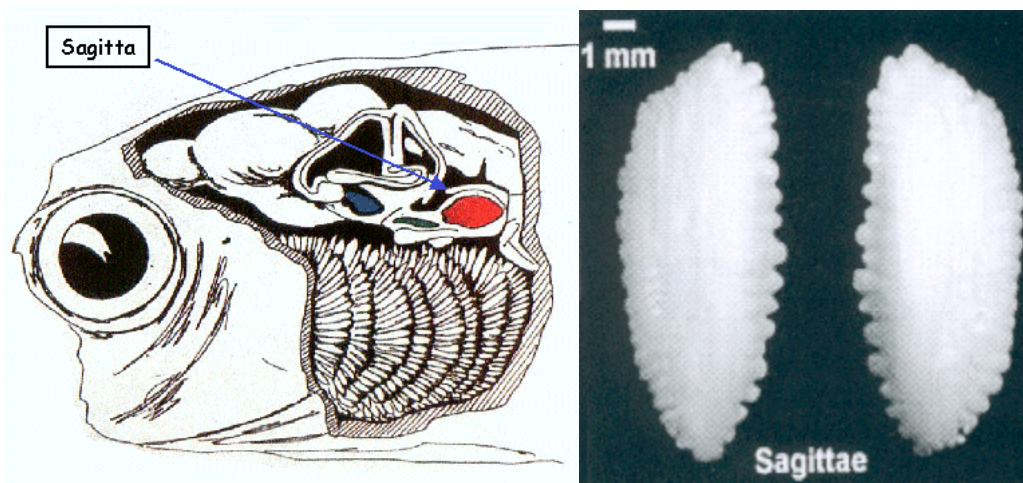

Figure 12. One of three pairs of fish otoliths. From: http://perso.club-internet.fr/jflhomme/otolithes/desc_otolithe.html

2. Mammals and typical insects perceive sound by directly sensing pressure. Arrival of a sound forces an oscillation on a membrane (similar to drums, the eardrum). These oscillations move cilia attached to nerve cells.

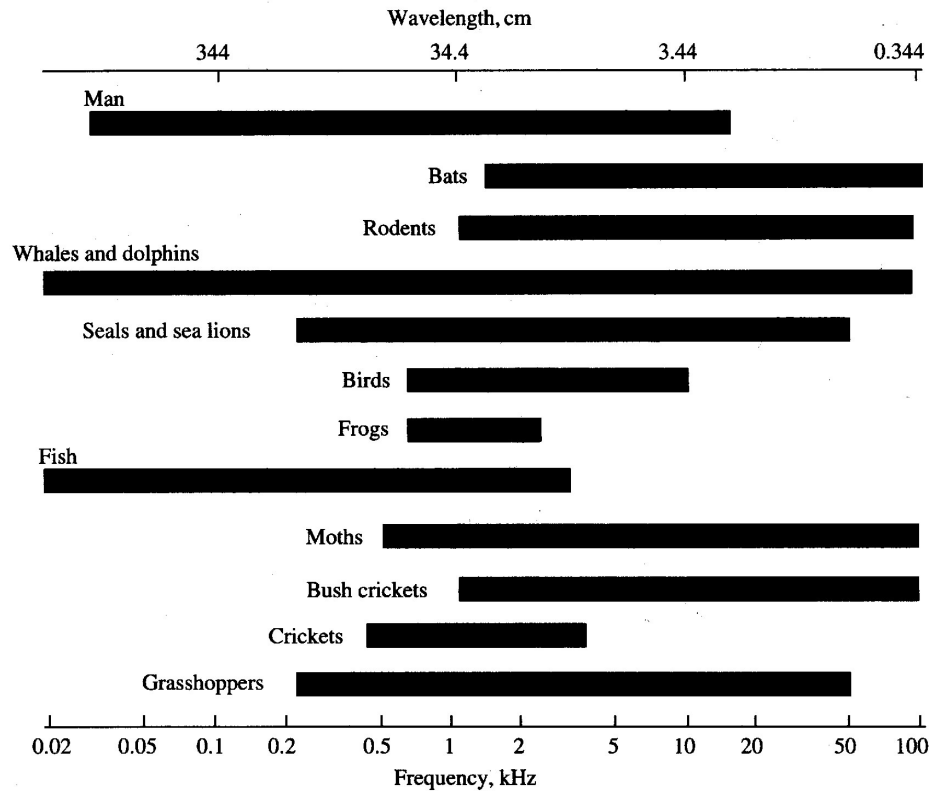Different organisms are sensitive to different frequency ranges:

Figure 13. Animal sensitivity to sounds at different frequencies. From Dusenbery (1994).

The frequency of marine organisms is shifted to low frequency due to the high attenuation of higher frequency in water (Fig. 9).

Resonance

Musical instruments emit sounds of given narrow frequency although they are forced at a broad range of frequencies (think of a drum, a string instrument or a wind instrument). The specific dimension of the instrument selects for specific sound wavelengths that are amplified while other frequencies are damped. The specific wavelengths that are chosen are those that fit within the instrument's boundaries in some discrete (and often small-integer, or an integer+1/2) way.
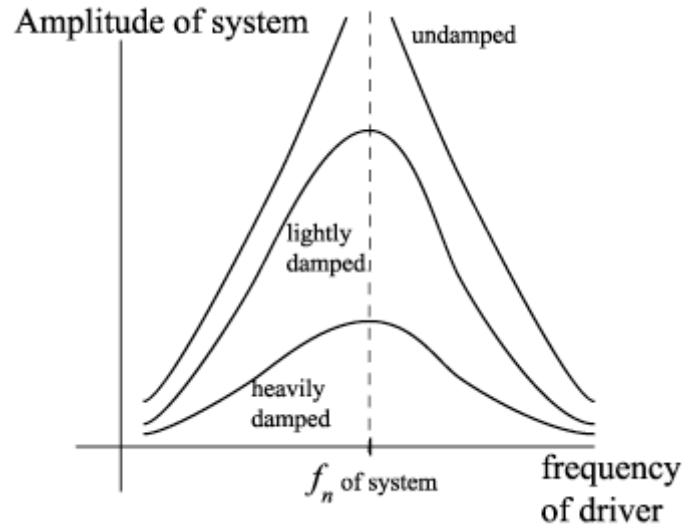
Figure 14. A system can be made to oscillate by means of a periodic external driving force. When a system oscillates without the constant application of an external driving force, the system is said to be oscillating at its natural frequency, f_n. Suppose that such a system is driven with varying frequencies and the resultant system amplitude plotted against driving frequency. Resonance occurs when the driving frequency most easily transfers its energy to the driven system. Systems exhibit resonance when the driving frequency is equal to their natural frequency. From: http://www.jcphysics.com/toolbox_indiv.php?page=10&cat_id=2

Resonance is a phenomenon encountered by many oscillatory systems (systems that produce or are influenced by waves). Production of a laser light (collimated and polarized) involves resonance as do the biggest tides in the world found at the Bay of Fundy.

Snell's law and refraction

When a wave encounter an environment with a different wave speed it refracts (the wave crest/trough appear to change direction, Fig. 15). Snell's law states that: $n_1 sin(\theta_1) = n_2 sin(\theta_2)$ where θ is the angle is between the ray and the normal to the surface in each medium (1 or 2). The refractive index of a medium is inversely proportional to the wave's propagation speed, so we can rewrite Snell's law as: $c_2 sin(\theta_1) = c_1 sin(\theta_2)$. Some consequences of this law are:

1. Waves do not refract when propagating perpendicular to the boundary between medium with different wave speeds.
2. Total internal reflection, when waves cannot cross across the boundary, can occur only when crossing from a slow to a fast environment.

Note: when encountering a boundary between media with different wave speeds some energy is reflected within the medium with the angle of reflection being equal to the angle of incidence (Fig. 15).
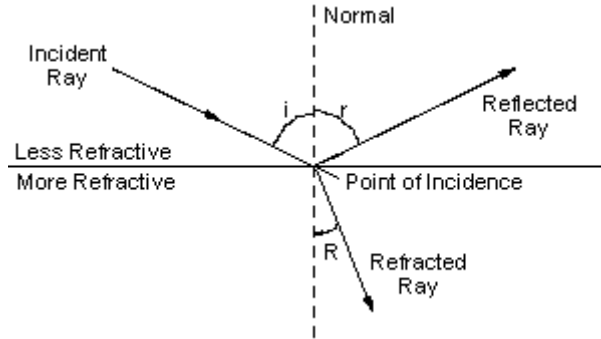
Figure 15. Snell's law provides the direction of waves as they cross interfaces. Arrows denotes direction of propagation of the waves. From: http://www.sasked.gov.sk.ca/docs/physics/images/u3c12_1.gif

Sound propagation in the ocean

Sound rays (lines tracing the direction of the energy propagation) do not propagate straight in the ocean. They are refracted due to changes in sound speed. When encountering a change in sound speed refraction results in a bigger angle to the plane of the waves when the speed is increased (as with light going from water to air) and vice versa when speed is decreased (Snell's law, Fig. 15). Total internal reflection for rays propagating in certain angles result in a wave guide in the ocean called the SOFAR channel (Fig. 16). Organisms such as whales have been found to communicate with low frequency sound across the world's ocean by using the SOFAR channel (where there is less loss to spherical spreading than out of it).
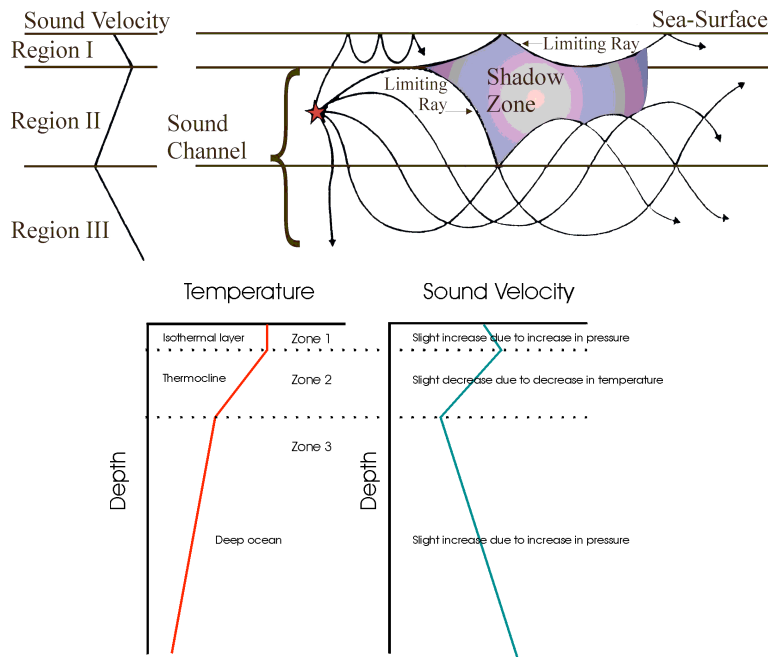
Figure 16. Sound propagation in an ocean with a typical distribution of temperature and pressure. Sound refracts as the speed of sound changes, resulting in a sound channel (SOFAR channel) where sound propagates very well. Note that here and in other layered media that vary in sound speed, sound tends to get trapped in the layers where sound velocity is slowest. It is this sound channel that allows long-distance communication between whales. From:
http://freespace.virgin.net/mark.davidson3/propagation/propagation.html

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References and additional reading:

Denny, M. W., 1993, Air and Water, Princeton U. Press, Chapters 10-11.
Dusenbery, D. B., 1992, *Sensory Ecology*: How Organisms Acquire and Respond to Information. New York: Freeman. Chapters 8-9.
Mobley, C. D., 1996, Light and water, Academic Press, Ch 1-4.

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