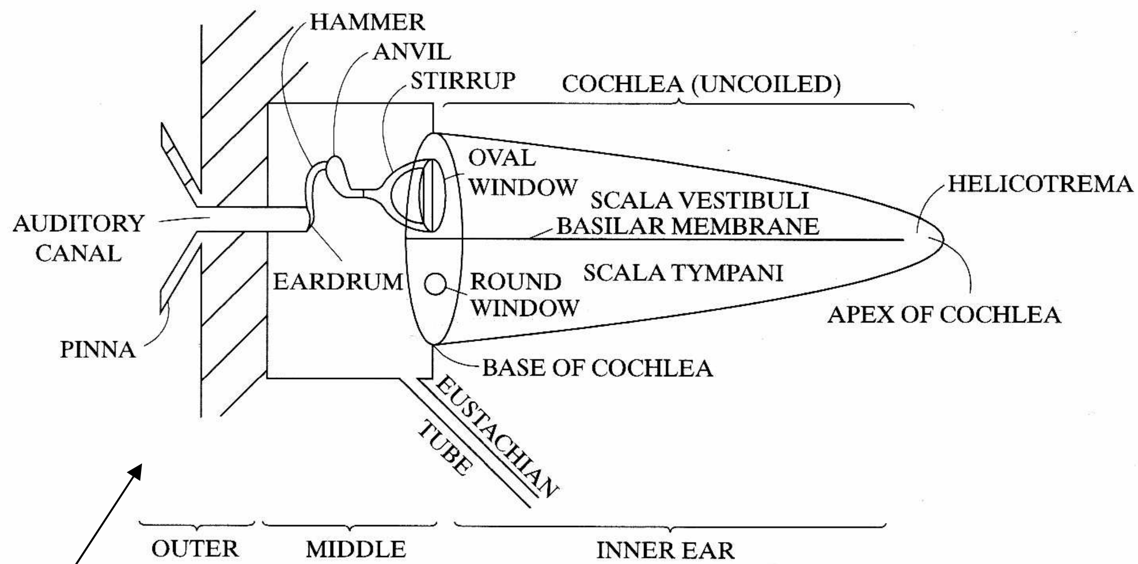
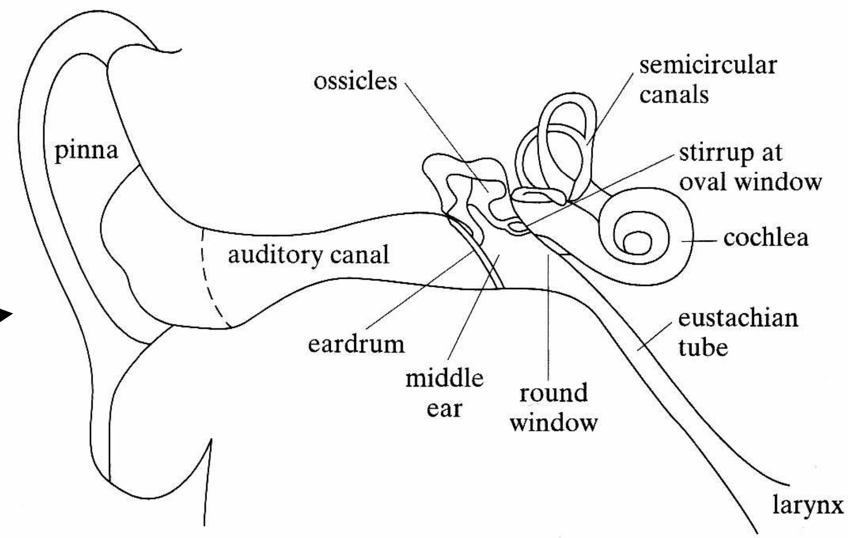
7 – Hearing

Human ear is, probably, the most remarkable organ. It has a very sophysticated construction, is sensitive to the sound of frequency from 20 Hz to 20 KHz, that is, in the range of three decades in frequency, and of intensity from 10^{-12} W/m^2 to 1 W/m^2, that is, twelve decades in the intensity! Ears of some animals are even better.



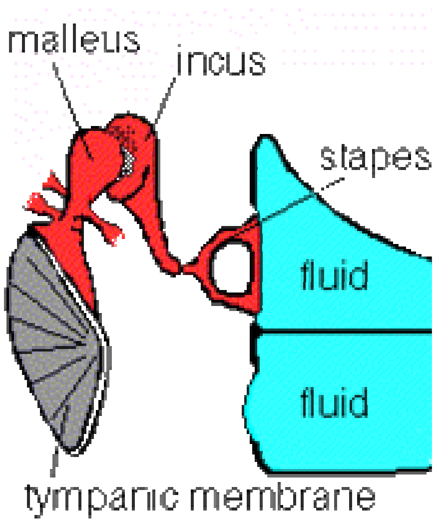
Human ear (schematic)

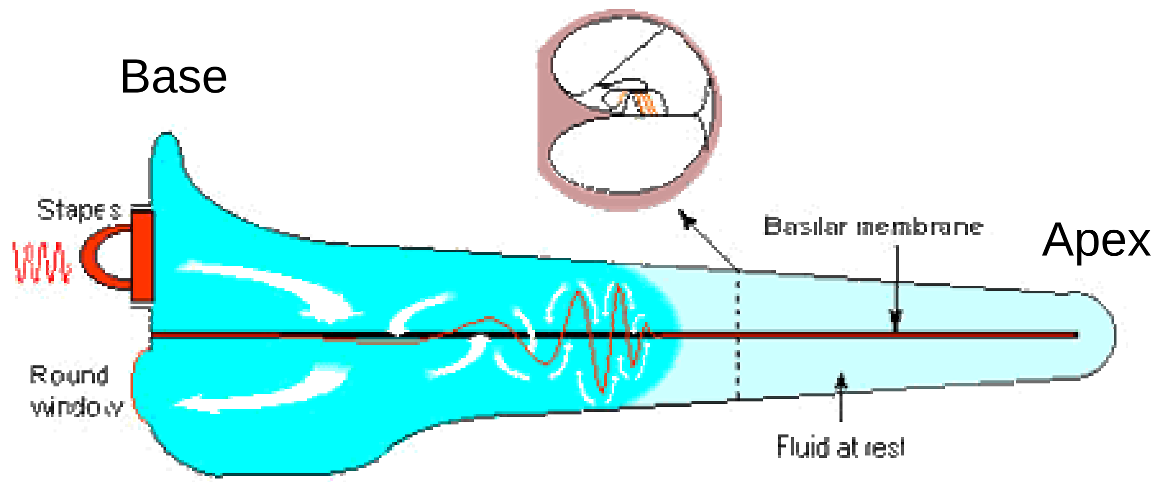


Human ear (realistic)

How the ear works

- The sound enters the auditory canal from the outside and reaches the eardrum
- The eardrum vibrates and sets the three ossicles, hammer, anvil, and stirrup in motion
- The stirrup pushes at the oval window in the cochlea and produces waves in its liquid
- The waves propagate in the scala vestibuli along the basilar membrane, reach the apex of the cochlea, enter through the helicotrema into the scala tympani and propagate back in the scala tympani along the other side of the basilar membrane
- Waves reach the round window and are being damped there
- The travelling waves in the cochlear liquid excite the nerve endings located at the basilar membrane, and the signals go to the brain that decodes them as signals of particular frequency and particular loudness. The length of the basilar membrane is about 3.5 cm and it contains about 35000 nerve endings called „hair cells“.
- In fact, the magnification of the region of the basilar membrane shows another two membranes, and the whole process is more complicated

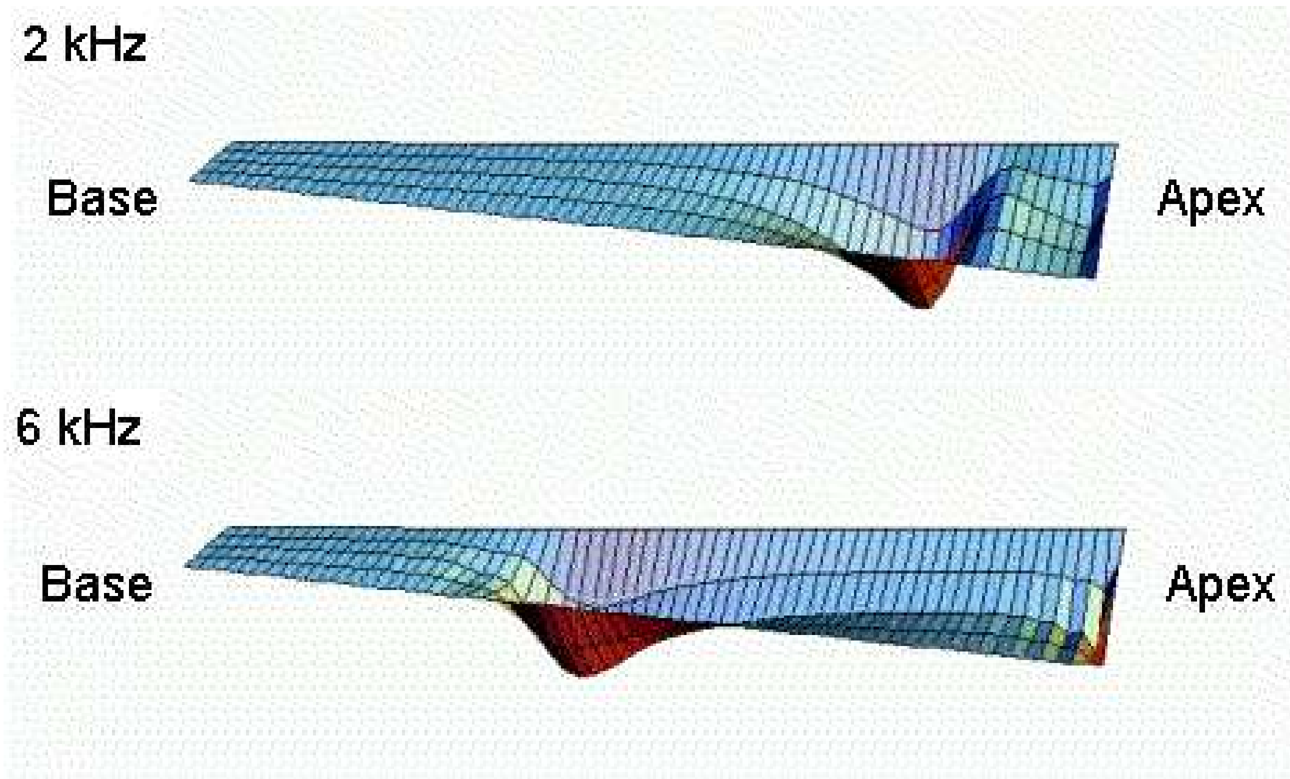




Place theory of hearing

Computer simulations by the WADA lab at the Tohoku University
http://www.wadalab.mech.tohoku.ac.jp/

Simulated vibrations of the basilar membrane of the guinea pig cochlea caused by the sound of different frequency:



Place theory of hearing

It was proven experimentally that the sound of a particular frequency creates waves in the cocklear liquid that have antinodes at particular well-defined places of the basilar membrane along its length. That is, each particular frequency excites the hair cells at a particular distance from the base of the basilar membrane. The brain knows from where the nerve signals are coming and decodes the positions along the basilar membrane into the sensation of frequency. It was shown that equal distances between the sensitive points for any two sounds correspond to equal ratios of the frequencies of the two sounds. That is, the frequency coding is logarithmical that is the explanation of a large frequency range the ear is sensitive to.

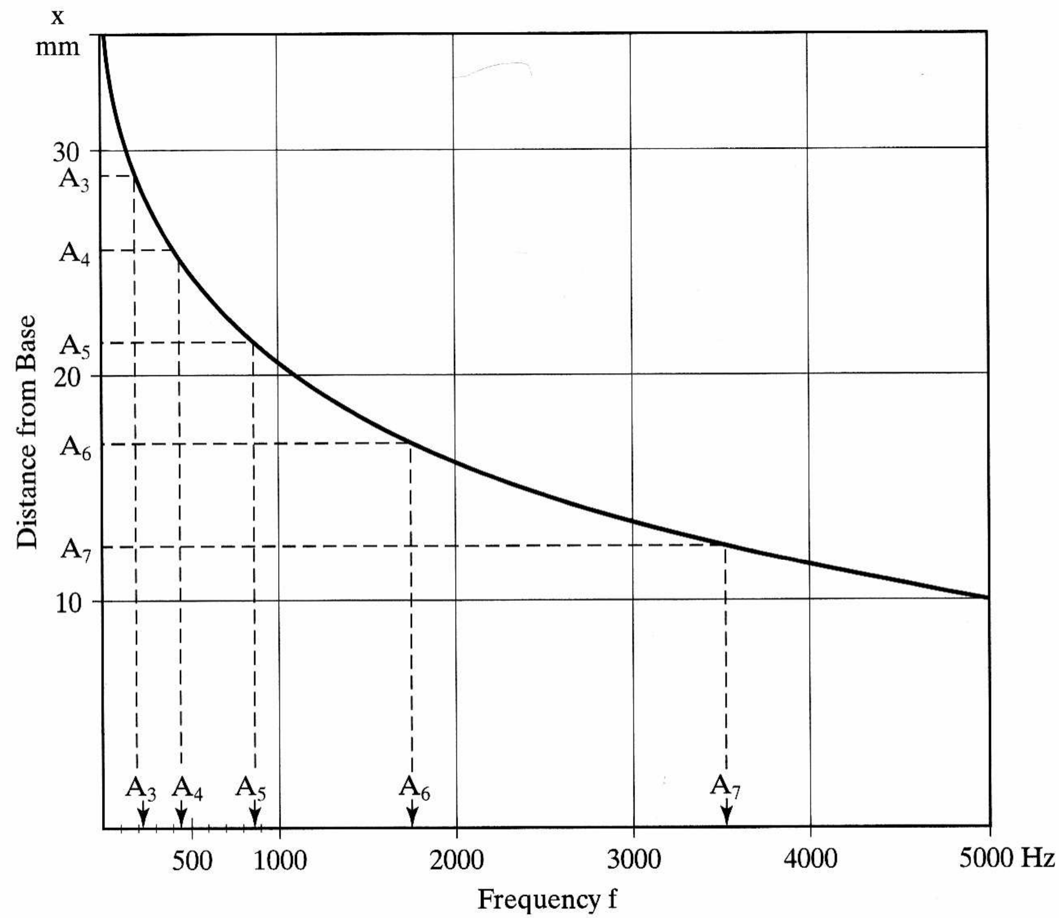
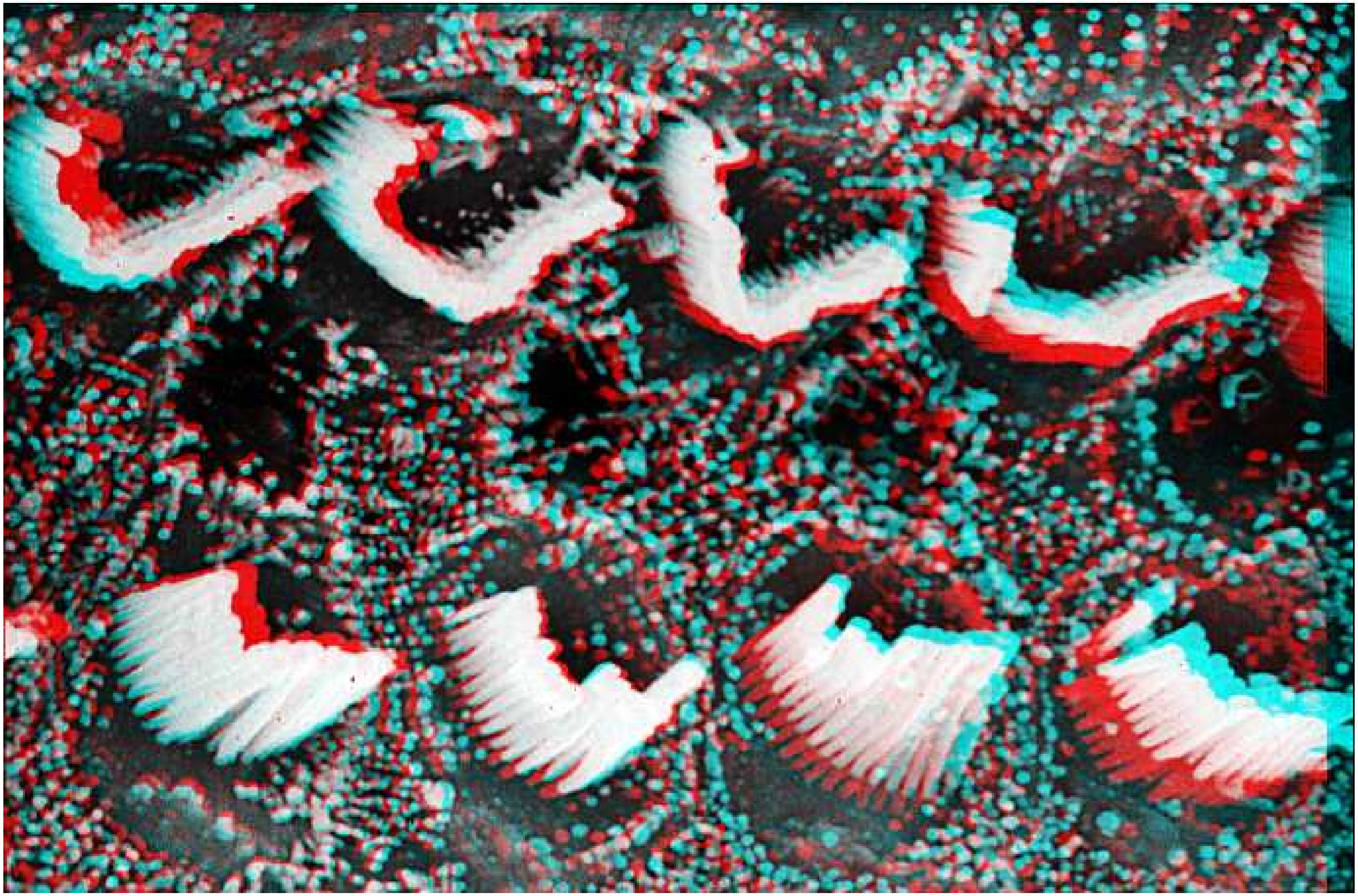


Figure 6-3 Position of the resonance maximum on the basilar membrane for a pure tone of frequency f (after von *Békésey*, 1960). (From *The Physics and Psychophysics of Sound* by Juan G. Roederer, Figure 2.8, page 25, © 1995 by Springer-Verlag, New York. Used with permission.)

Here the frequencies double each time, and this results to the same shift down along the vertical axis

Hair cells



Physical sound intensity

The physical the sound intensity I is defined as the energy of the sound wave that goes through a unit area (1 m^2 in SI) during one second, or, equivalently, as the sound power (that is, the energy per second) that goes through the unit area. For any wave, the physical sound intensity I is proportional to the square of the amplitude of the sound, for instance, to the square of the amplitude of the pressure oscillations δP in the sound wave,

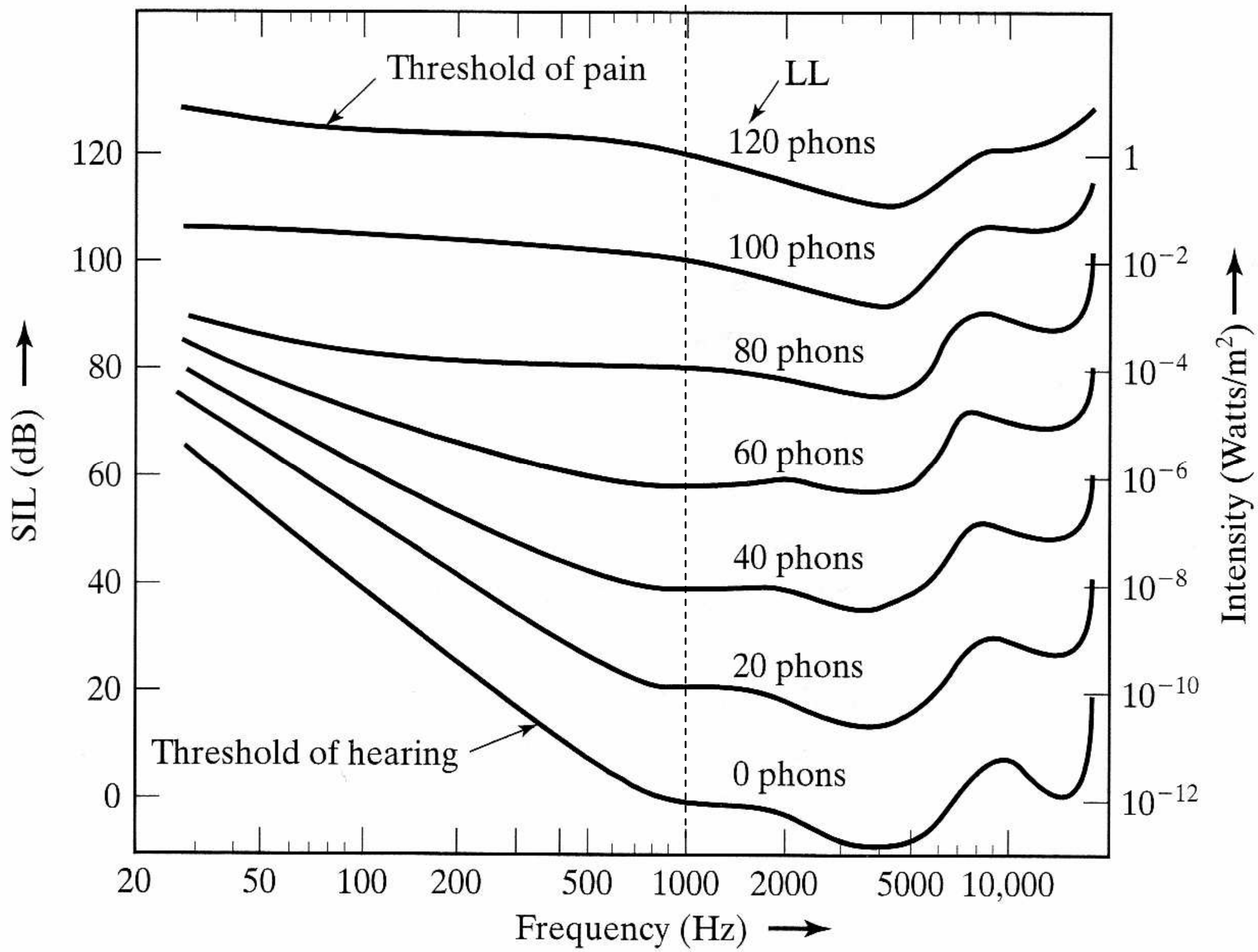
$$I \propto A^2, \quad \text{in particular,} \quad I \propto (\delta P)^2$$

If the two sound waves are incoherent, that is, they have non-equal frequencies or a random relative phase shift, there is no interference and the intensities of both sound waves add. In this case, if both sound waves have intensity I, their sum will have the intensity $2I$. If the two sound waves are coherent (have the same freqiency and the same phase) then there is a constructive interference, both amplitudes A add resulting in the amplitude $2A$, so that the resulting intensity is $(2A)^2 = 2^2A^2 = 4I$. For many incoherent signals, the resulting intensity is

$$I = I_1 + I_2 + I_3 + I_4 + \dots$$

Sound intensity response of the ear

The response of the ear to the sound intensity is even more remarkable than its frequency response, so that we can hear both very quiet and very loud sounds. The intensity response of the ear is logarithmic, too. Below the sound-intensity level (SIL) in decibel is shown on the left and the physical sound intensity in W/m^2 is shown on the right. The curves are the sould intensity levels that are percepted by an average person with normal hearing as equally loud.



Logarithms

$$\text{Let } y = 10^x, \quad \text{then } x = \log_{10} y$$

$$\text{Examples}: \log_{10} 1 = 0, \quad \log_{10} 10 = 1, \quad \log_{10} 100 = \log_{10} 10^2 = 2$$

Properties:

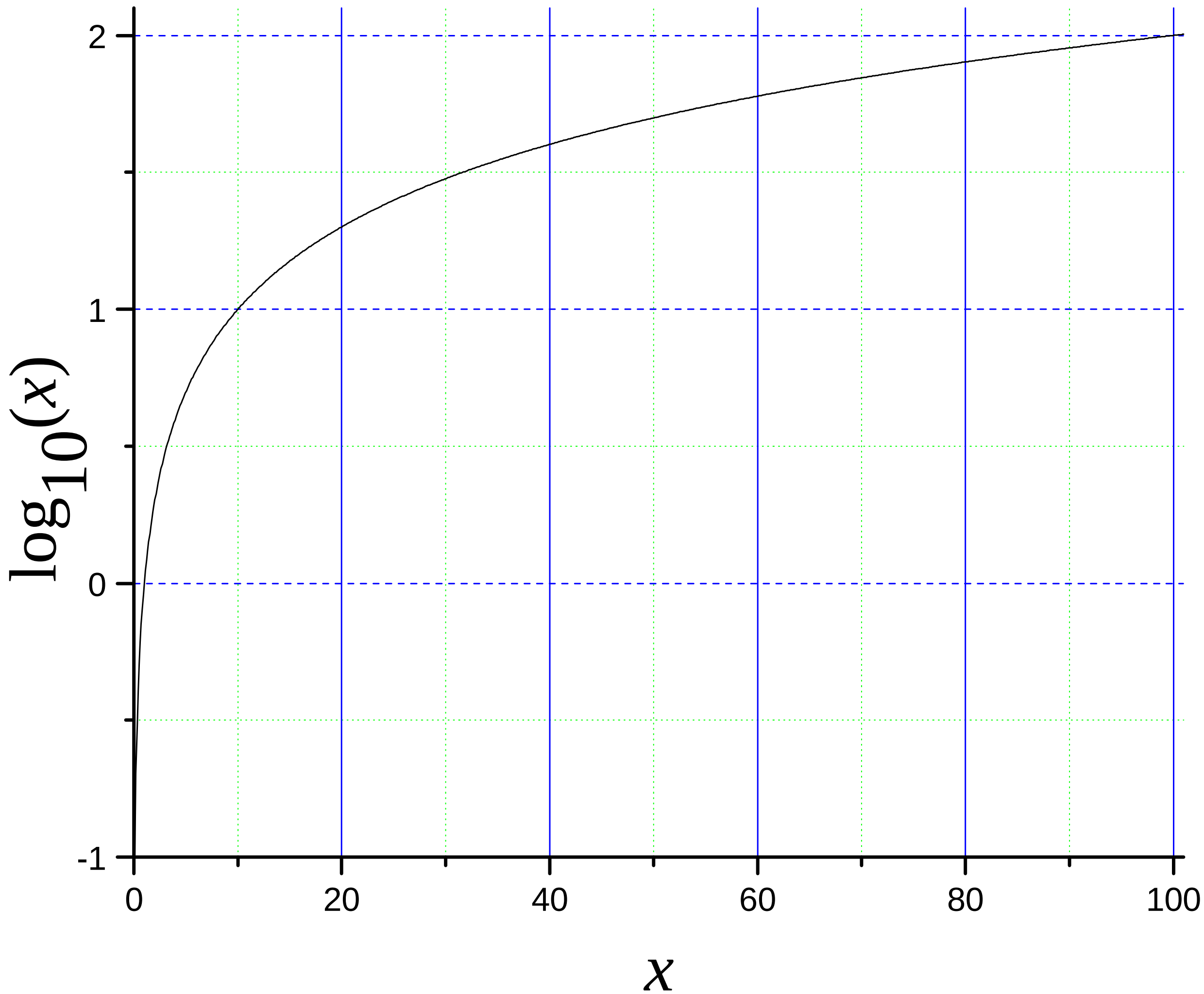
$$\log(ab) = \log(a) + \log(b)$$

$$\log(a^\alpha) = \alpha \log(a)$$

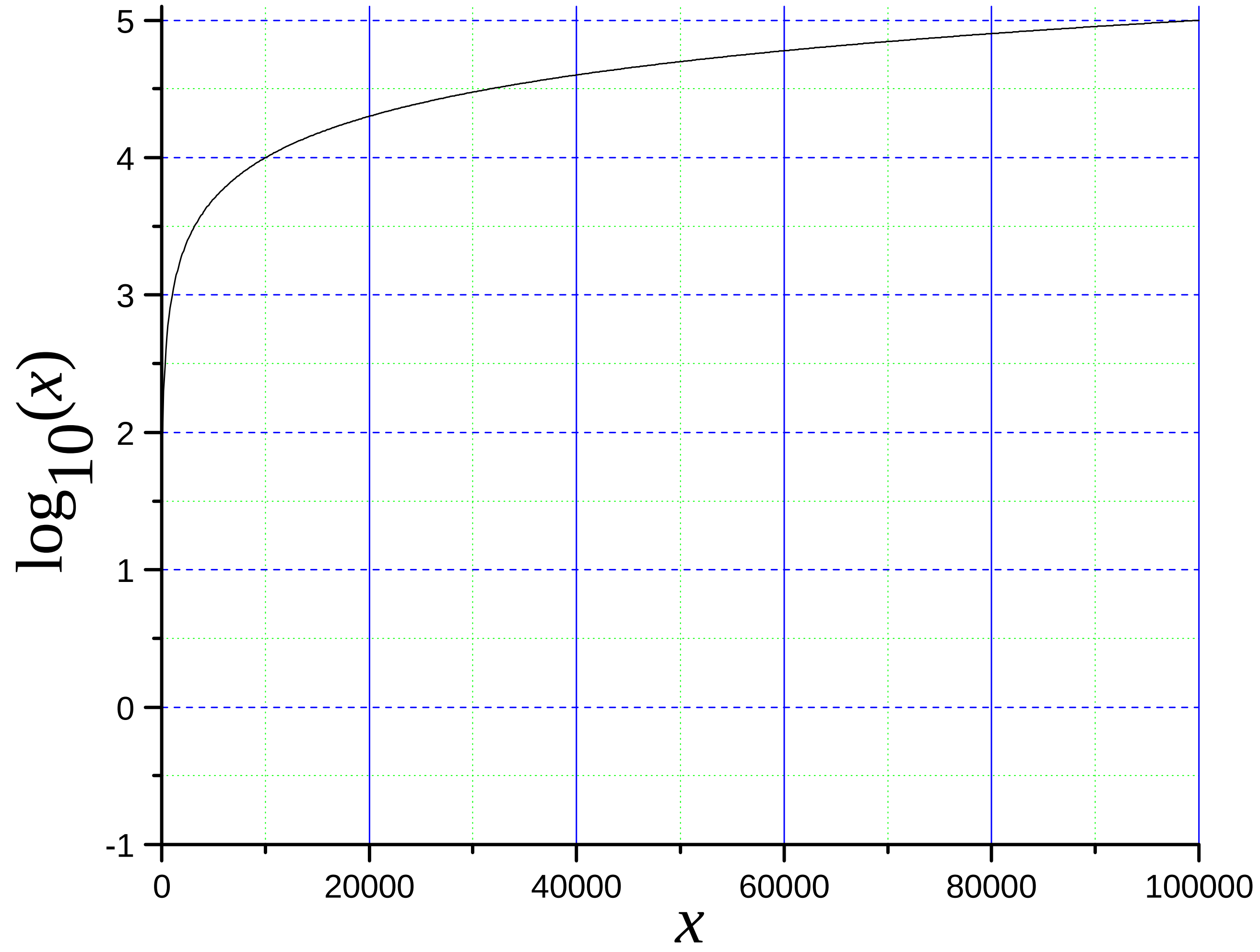
$$\log\left(\frac{1}{a}\right) = \log(a^{-1}) = -\log(a)$$

Particular values:

log 1	=	0.00
log 2	=	0.3
log 3	=	0.5
log 4	=	0.6
log 5	=	0.7
log 6	=	0.8
log 7	=	0.85
log 8	=	0.9
log 9	=	0.95
log 10	=	1.00

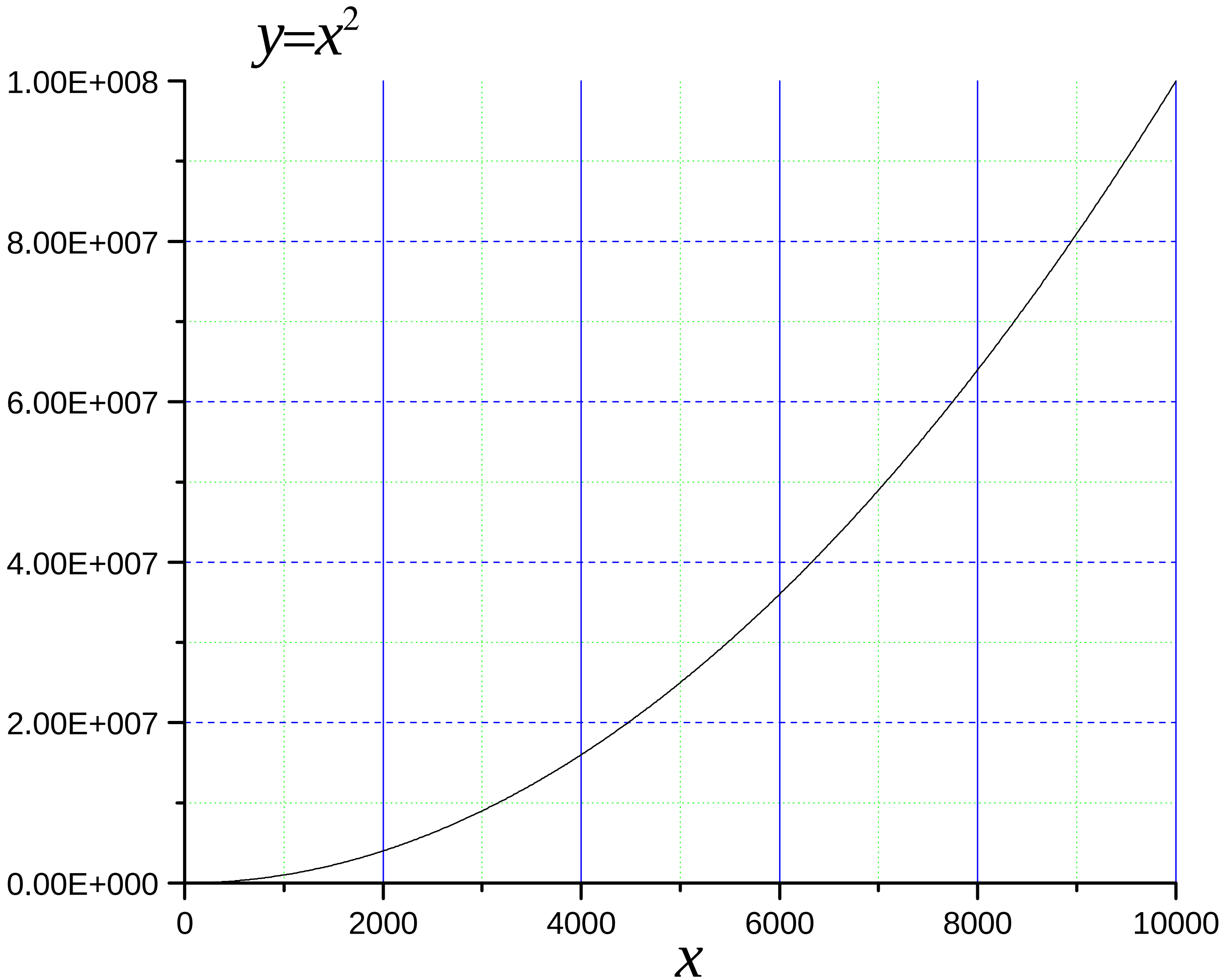


One more plot of the logarithmic function in a greater range of x.

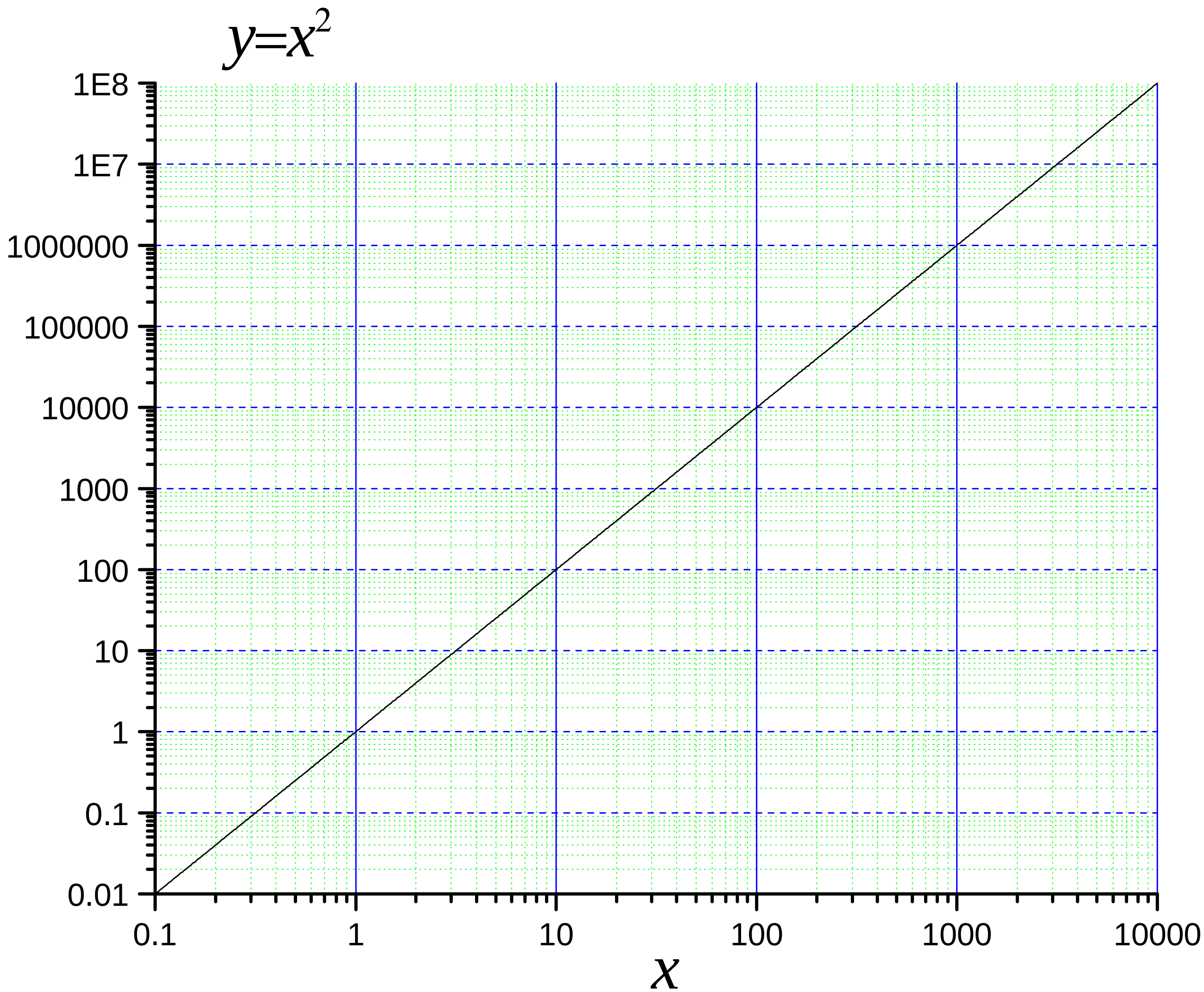


The normal scale is inconvenient for plotting functions over many decades of their argument. In this case the logarithmic scale is more convenient. Examples on the next page

Standard plot of a quadratic function. Drawback: The region of small x is not well represented



Double logarithmic (log-log) plot of the same function. All ranges of x, small and large, are equally well represented. The ear was constructed to hear both very quiet and very loud sounds of very small and very large frequencies. This is why the ear hears logarithmically.



Decibel scale of sound intensity level

The scale of the sound intensity level introduced by Alexander Graham Bell (1847-1922) uses the logarithms of the physical sound intensities I in W/m^2, with the minimal audible sound intensity at 1000 Hz $I_0 = 10^{-12}$ W/m^2 taken as the reference point. The basic unit for the SIL is Bell, and SIL in Bells is given by the formula

$$SIL^{(\mathrm{Bells})} = \log_{10} \frac{I}{I_0}$$

Practically we use the 10 times smaller unit than Bell that is called decibel (dB), so that the formula for the SIL in decibels is

$$SIL = 10 \log_{10} \frac{I}{I_0}$$

One can see that increasing I by a factor of 10 results in the increase of SIL by 10 dB. The threshold of hearing, $I=I_0$, corresponds to 0 dB, whereas the pain threshold I_{max} = 1 W/m^2 corresponds to

$$SIL_{\mathrm{max}} = 10 \log_{10} \frac{I_{\mathrm{max}}}{I_0} = 10 \log_{10} \frac{1}{10^{-12}} = 10 \log_{10} 10^{12} = 10 \times 12 \times \log_{10} 10 = 10 \times 12 = 120 \text{ dB}$$

Aural harmonics

The response of the ear is nonlinear, so that loud sounds get distorted in the ear. This phenomenon is similar to the „clipping“ in electric circuits. As a result, the signal remains periodic but it is no longer pure sinusoidal. Its Fourier spectrum contains harmonics of the main tone. Since these harmonics are produced by the ear, they are called aural harmonics.

Combinational tones

In the case of two incoming signals with frequencies f_1 and f_2, nonlinearities in the ear result in the appearance in the Fourier spectrum of the signal (in the ear!) of many combinational tones with frequencies

$$f_+ = mf_1 + nf_2 \quad \text{(sum tones)}$$

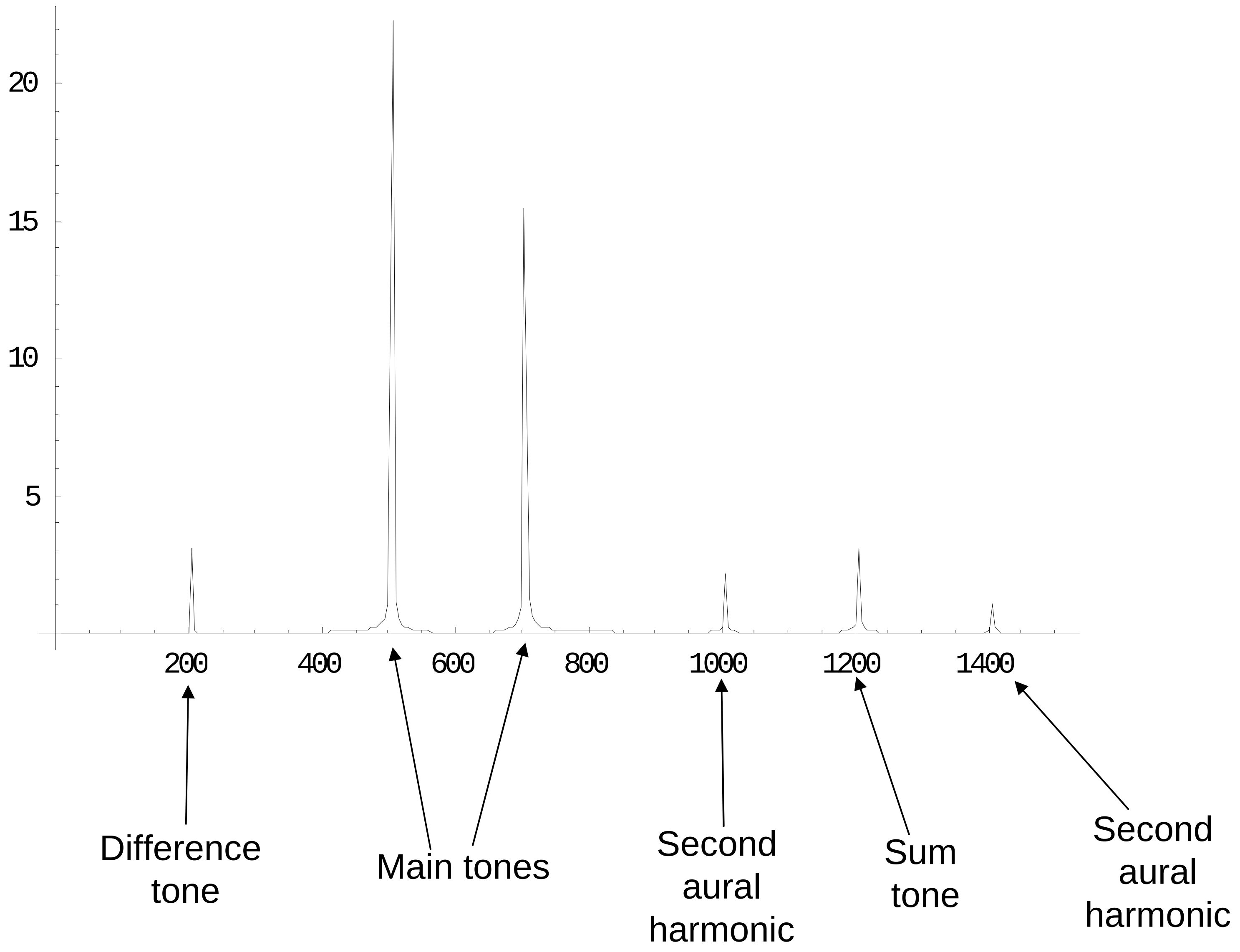
$$f_- = |mf_1 - nf_2| \quad \text{(difference tones)}$$

where m and n are natural numbers. The combinational tones are weaker than the main tones but they can be made apparent by adding a weak tone with the frequency close to one of the combinational tones to produce beats.

Fundamental tracking

Our brain does an additional job of (mis)interpreting the incoming sound wave. In the case of two sounds with frequencies that can be different harmonics of one fundamental, our brain adds this nonexistent fundamental to our perception of the sound. For instance, f_1=500 Hz and f_2=700 Hz, we also hear the „fundamental“ 100 Hz. The same happens for f_1=600 Hz and f_2=700 Hz, of course. But for f_1=550 Hz and f_2=700 Hz, we do not hear this „fundamental“.

Fourier spectrum of the signal consisting of the two pure tones f_1=500 Hz and f_2=700 Hz distorted by a nonlinearity in the ear (or in the speakers!)



Binaural effects

Binaural effects are effects arising due to the differences of the signals received by the two ears. Processing these differences, the brain can figure out the direction from which the sound comes.

The two main mechanisms behind the binaural effects are 1) phase shifts of the sound; 2) differences in loudness. Importance of the phase shifts in the binaural hearing is probably the reason why otherwise the brain does not distinguish phase effects (Ohm‘s law of hearing).