



ACOUSTICS part - 1 Sound Engineering Course

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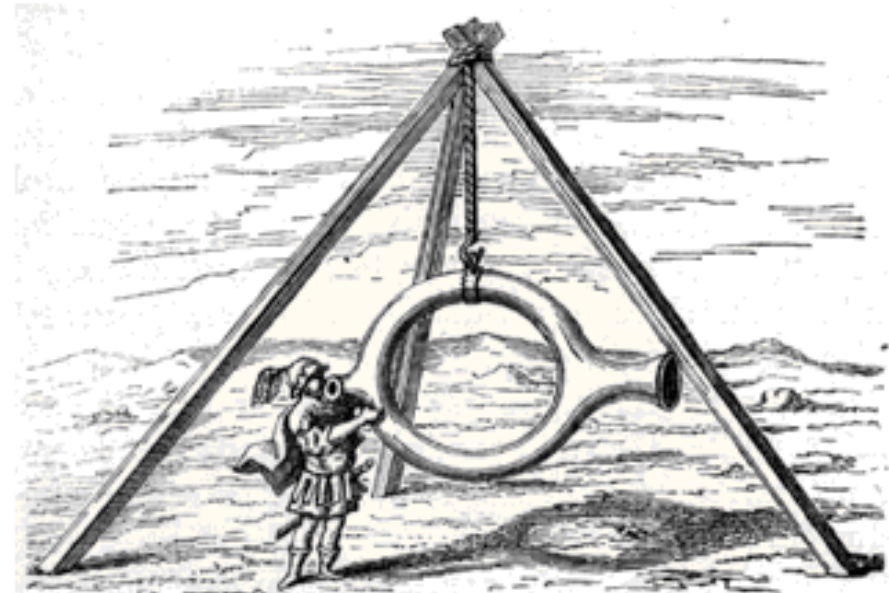


Nature of Sound



What is SOUND

- Sound is generated by **pressure fluctuations** inside a medium (fluid or solid), which propagates **without mass transfer**
- It is characterized by some fundamental quantities, such as **amplitude, frequency, period, wavelength** and “speed of sound”, or **celerity** (the speed of the wave traveling in the medium, not to be confused with the “particle velocity”, that is the motion of air particle around their original position due to pressure fluctuations)



The horn of Alexander the Great



Ingredients of sound

Sound can be seen as a form of energy propagation due to rapid repetition of compression and expansion of an elastic medium; the energy is originated from a **sound source**, and propagates in the medium with finite speed.

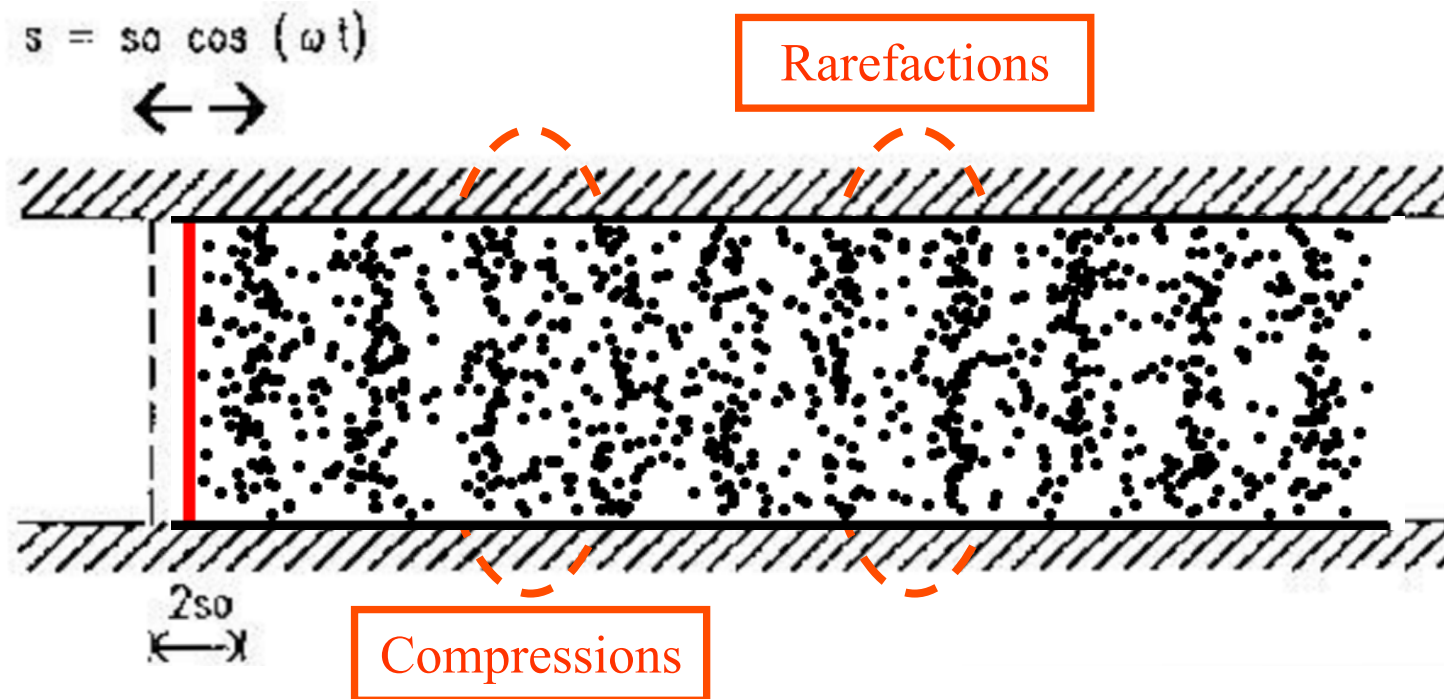
The sound phenomenon requires two “ingredients”:

- a “*sound source*”
- an “*elastic medium*”



Sound sources (1):

Sound source: the simplest case is a rigid piston moving back and forth with harmonic law, placed at the end of a duct of infinite length filled with a steady leastic medium.





Sound source (2):

The harmonic motion of the piston is characterized by the *frequency* “ f ” of the alternative motion.

“ f ” = **frequency**, number of cycles performed by the planar surface in one second, measured in “Hertz”; 1 Hz = 1 cycle per second

“ T ” = **period**, time required to complete a cycle, in s;

“ ω ” = **angular velocity, in rad/s**;

Relationships among these quantities:

$$f = 1/T \quad \text{and} \quad f = \omega / 2\pi \quad (\text{Hz})$$

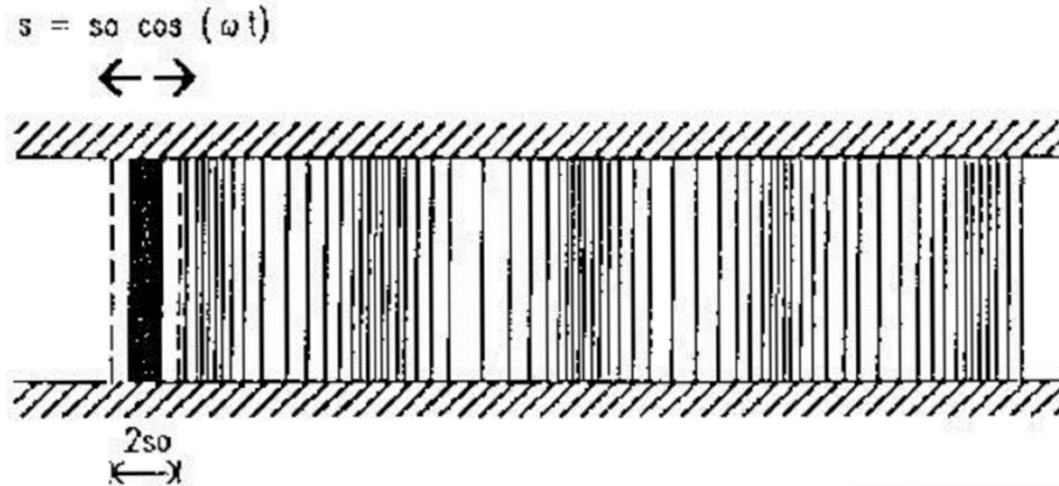
If the frequency is between 20 and 20.000 Hz, the sound can be perceived by humans, and the phenomenon is called “sound”; below 20 Hz it is called “infrasound”, and above 20 kHz it is called “ultrasound”.



Speed of Sound and Wavelength



Sound source (3):



The surface of the piston is moving according to harmonic laws:

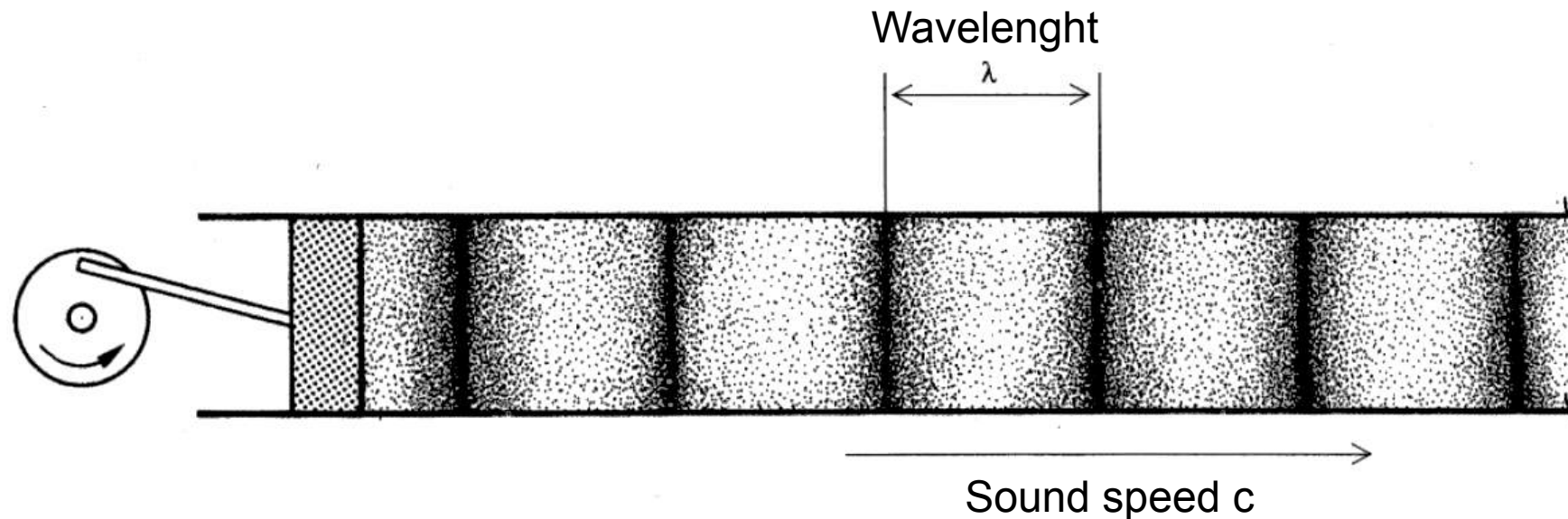
- displacement : $s = s_0 \cos(\omega t)$,
- velocity : $v = ds/dt = -\omega s_0 \sin(\omega t)$,
- acceleration : $a = dv/dt = -\omega^2 s_0 \cos(\omega t)$,

where s_0 is the maximum excursion of the piston, in either direction, from the rest position.



Elastic medium:

The “speed of sound” is determined by the elastic and massive properties of the medium, which descend from thermodynamic relationships. These quantities also affect the capability of the emdium to carry energy (a dense and rigid medium carries more energy than a light and soft medium)





Sound speed and wavelength:

The pressure perturbation propagates from the source in the medium, with a **sound speed** “ c ” which in air depends from the temperature t , following the relationship:

- $$c_0 = \sqrt{\gamma \cdot R \cdot T}$$

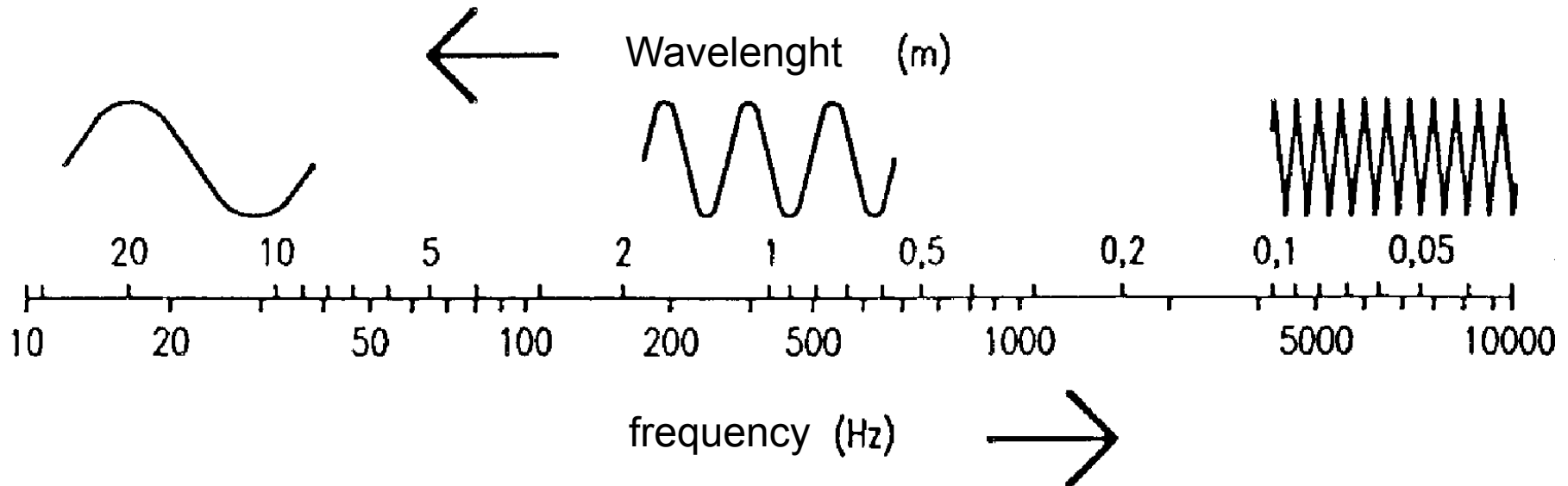
$$\gamma = 1.41 \quad R = 287 \quad (J/kgK) \quad T = t + 273 \quad (K)$$

the **wavelength** “ λ ”, is related to the frequency of harmonic motion by the relationship:

- $$\lambda = \frac{c_0}{f} = c_0 \cdot T \quad (\text{m})$$



Relationship between frequency and wavelength:



When frequency increases, the wavelength becomes smaller and smaller...



Sound speed in different mediums:

- sound speed in air @ 20°C

$$c_0 \approx 340 \text{ m/s}$$

- sound speed in water:

Temperature T_c [°C]	Sound Speed c [m/s]
0	1407
10	1449
20	1484
30	1510

- sound speed in different solids

Material	Density ρ_0 [kg/m ³]	Sound Speed c [m/s]
Acciaio	7800	5000
Alluminio	2700	5820
Calcestruzzo	2000 – 2600	3500 – 5000
Gomma	1010 – 1250	35 – 230
Legno	400 – 700	3300
Marmo	2600	3800
Mattoni pieni	2100	3600
Piombo	11300	1260
Rame	8900	4500
Sabbia	1600	1400 – 2600
Stagno	7280	4900
Sughero	240	480
Vetro	2300 – 5000	4000 – 5000
Zinco	7100	3750

$$c = \sqrt{\frac{E}{\rho}}$$

$E = \text{elastic modulus} \quad (N/m^2)$

$\rho = \text{density} \quad (kg/m^3)$



Measurable Physical Quantities



Physical quantities related to sound:

The more relevant physical quantities involved in characterizing sound are:

• Sound pressure		p	} Field Quantities
• Particle velocity	v	m/s	
<hr/>			
• Sound energy density	D	J/m³	} Energetic quantities
• Sound Intensity	I	W/m²	
• Sound Power	W	W	



Sound pressure, particle velocity, acoustic impedance

When the acoustic wave travels in the elastic medium (air), many physical quantities are simultaneously perturbed (pressure, density, temperature).

And the air particles **move**.

There is a cause-effect relationship between pressure differences and air motion. Thus, under simple conditions (plane wave propagating inside the duct), there is perfect proportionality between Sound Pressure and Particle Velocity :

- $$\frac{p'}{v'} = \rho_0 \cdot c_0 \quad (\text{kg/m}^2 \text{ s})$$

where ρ_0 is the density of the elastic medium and the product $\rho_0 c_0$ is called **acoustic impedance (Z)** of the plane wave ($\text{kg/m}^2 \text{ s}$)(rayl).



RMS value of p and v

For complex waveforms, the definition of amplitude of the signal becomes ambiguous, and the evaluation of the maximum instantaneous value of pressure is not anymore significant in terms of human perception.

Instead, the “average” amplitude of the pressure fluctuations is evaluated by means of the RMS (root mean squared) value:

$$P_{rms} = \sqrt{\frac{1}{T} \cdot \int_0^T [p(\tau)]^2 \cdot d\tau}$$



Energy contained in the elastic medium:

In the case of plane, progressive waves, the sound energy density “ D ” contained in a cubic meter of the elastic medium is given by two contributions:

$$D_k = \frac{E}{V} = \frac{1}{2} \cdot \rho_0 \cdot v_{eff}^2 \quad (\text{J/m}^3) \quad - \text{Kinetic Energy}$$

where v_{eff} is the RMS value of the particle velocity (or the velocity of the piston, which is the same).

$$D_p = \frac{1}{2} \cdot \frac{p_{eff}^2}{\rho_0 \cdot c_0^2} \quad (\text{J/m}^3) \quad - \text{Potential Energy}$$

Which expresses the energy stored due to the elastic compression of the medium, and again is evaluated by the RMS value of sound pressure

Hence, the RMS value has an energetic meaning.



Energy contained in the elastic medium:

In the particular case of plane, progressive waves, the two energy contributions are equal. However, in the generic sound field, the two contributions are not generally equal, and one has to evaluate them separately, and sum for getting the total energy density:

$$D = \frac{E}{V} = \frac{1}{2} \cdot \left[\rho_0 \cdot v_{\text{eff}}^2 + \frac{p_{\text{eff}}^2}{\rho_0 \cdot c_0^2} \right] \quad (\text{J/m}^3)$$

In the general case it is therefore required to know (measure or compute) 4 quantities: the sound pressure p and the three Cartesian components of the particle velocity v (v_x, v_y, v_z)



Sound Intensity:

Sound Intensity “ I ” measures the flux of energy passing through a surface.

I is defined as the energy passing through the unit surface in one second (W/m^2).

Sound Intensity is a vectorial quantity, which has direction and sign, and which varies, in the general case, with the position of the point in the sound field (x, y, z) and with time t :

$$\vec{I}(x, y, z, t) = p(x, y, z, t) \cdot \vec{v}(x, y, z, t)$$

In case of plane waves, the computation of sound intensity is easy:

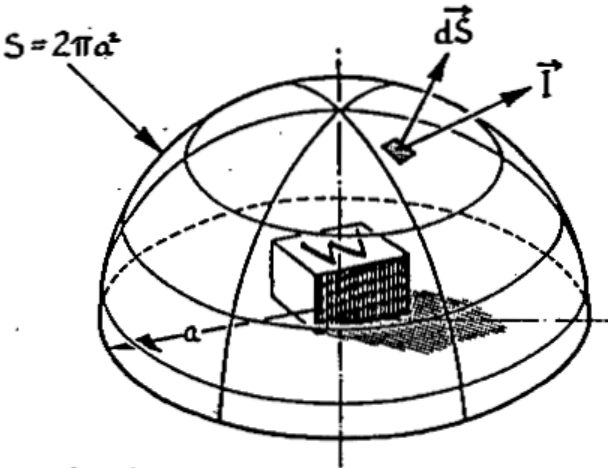
$$I = D \cdot c_0 \quad (\text{W}/\text{m}^2)$$



Sound Power (1):

The Sound Power describes the capability of a sound source to radiate sound, and is measured in Watt (W). It is not possible to measure directly the radiated sound power, hence, an indirect method is employed, based on Intensity measurements.

At first approximation, the sound power of a given sound source is univocally fixed, and does not depend on the environment.

$$W = \int_S \vec{I} \cdot d\vec{s} = \int_S I_n ds$$

$$L_w = 10 \log_{10} \left[\frac{W}{W_0} \right]$$
$$W_0 = 10^{-12} \text{ Watt}$$



Sound Power (2):

Taking into account a closed surface S surrounding the source, the **sound power W** emitted by the sound source is given by the surface integral of the **sound intensity I** :

$$W = \int_S \vec{I}(P, t) \cdot n dS$$

In the case the total surface S can be divided in N elementary surfaces, and a separate sound intensity measurement is performed on each of them, the integral becomes a summation:

$$W = \sum_{i=1}^N I_i \cdot S_i$$



Decibels



The Decibel scale (1):

What are decibels, and why are they used?:

The physical quantities related to sound amplitude have an *huge dynamic range*:

- 1 pW/m^2 (hearing threshold) \div 1 W/m^2 (pain threshold)
[10^{12} ratio]
- $p = 20 \cdot \mu\text{Pa}$ (hearing threshold) \div 20 Pa (pain threshold)
[10^6 ratio]

$$L_p = 20\text{dB}$$

The human perception compresses such wide dynamic ranges in a much lesser variable perception. Hence a logarithmic compression is employed, for mimicking the human perception law.

The advantage of employing a logarithmic scale is to “linearize” the perceived loudness perception (roughly, the loudness doubles every increase of intensity of a factor of 10);



The Decibel scale (2):

The **sound pressure level** “ L_p ” or *SPL*, is defined as:

- $L_p = 10 \log p^2/p_{\text{rif}}^2 = 20 \log p/p_{\text{rif}}$ (dB) @ $p_{\text{rif}} = 20 \mu\text{Pa}$

The **particle velocity level** “ L_v ” is defined as:

- $L_v = 10 \log v^2/v_{\text{rif}}^2 = 20 \log v/v_{\text{rif}}$ (dB) @ $v_{\text{rif}} = 50 \text{ nm/s}$.

The **sound intensity level** “ L_I ” is defined as:

- $L_I = 10 \log I/I_{\text{rif}}$ (dB) @ $I_{\text{rif}} = 10^{-12} \text{ W/m}^2$.

The **energy density level** “ L_D ” is defined as:

- $L_D = 10 \log D/D_{\text{rif}}$ (dB) @ $D_{\text{rif}} = 3 \cdot 10^{-15} \text{ J/m}^3$.

In the simple case (plane progressive wave) ($\rho_o c_o = 400 \text{ rayl}$):

- $p/v = \rho_o c_o \quad I = pv = p^2/\rho_o c_o = D \cdot c_o \quad \Rightarrow \text{hence} \quad L_p = L_v = L_I = L_D$



The Decibel scale (3):

The **sound power level** “ L_W ” is defined as:

- $L_W = 10 \log W/W_{\text{rif}} \quad (\text{dB}) \quad @ W_{\text{rif}} = 10^{-12} \text{ W.}$

But, while the first 4 levels have all the same meaning (how loud a sound is perceived), and assume the very same value in the simple case of the plane, progressive wave, instead the Sound Power Level value is generally different, and possibly much larger than the first 4 values!

In the simple case of plane, progressive wave (piston having area S at the entrance of a pipe), the relationship among sound power level and sound intensity level is::

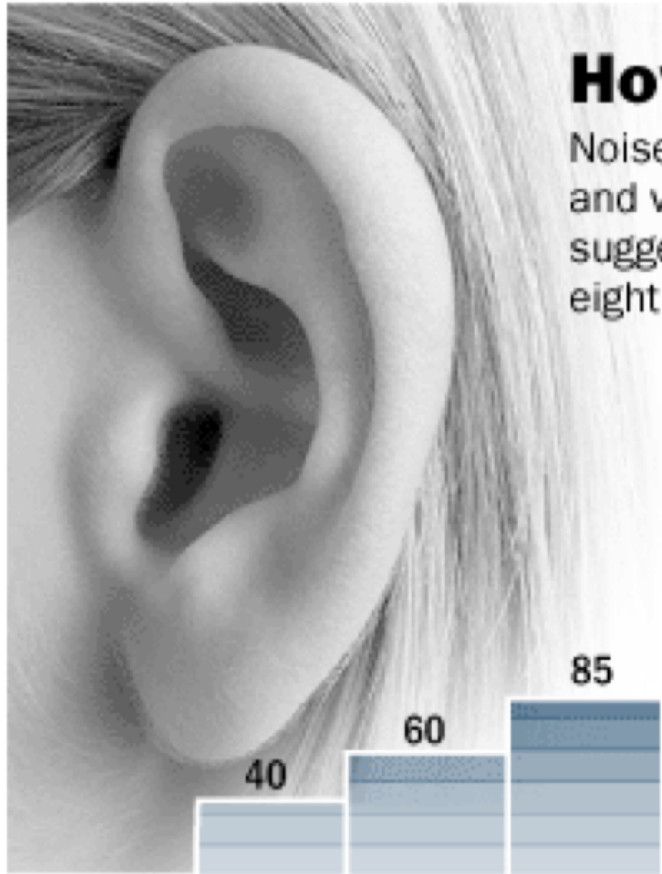
- $L_W = L_I + 10 \log S/S_0 = L_I + 10 \log S \quad (\text{dB})$

If the surface area S represent the total surface over which the power flows away from the source, the above relationship is substantially always valid, even if the radiated sound field is NOT a plane progressive wave.



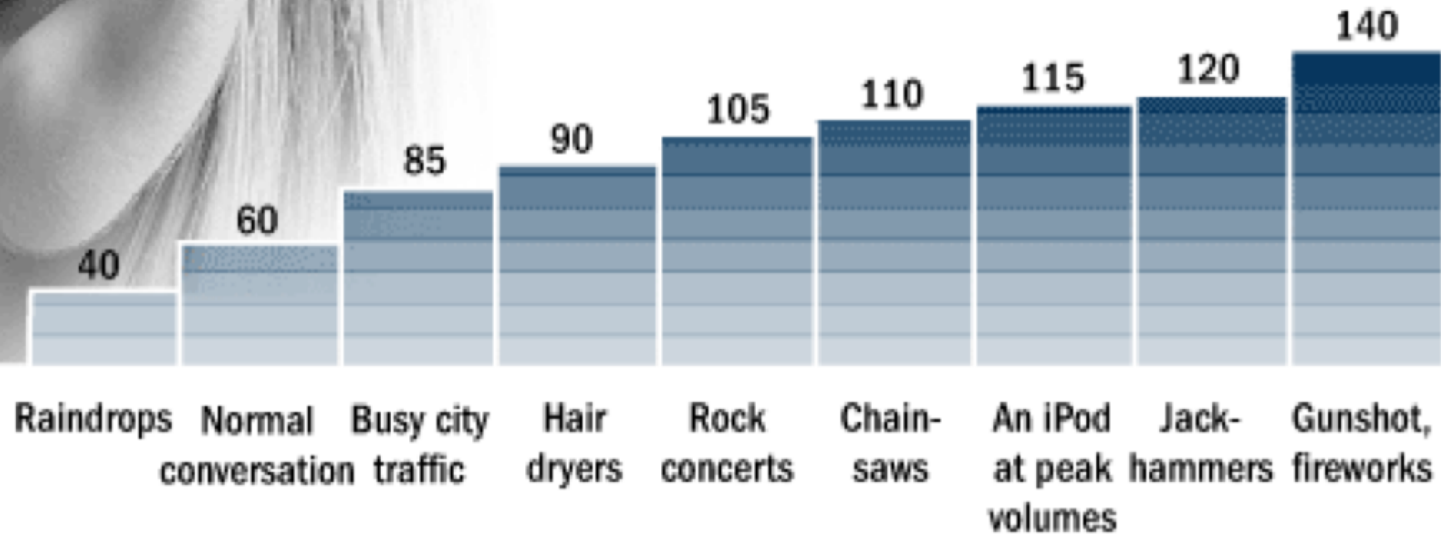
Human perception of SPL

PictureQuest



How Loud Is Too Loud?

Noise-induced hearing damage is related to the duration and volume of exposure. Government research suggests the safe exposure limit is 85 decibels for eight hours a day. Some common decibel levels:



Sources: dangerousdecibels.org; WSJ research



Human perception of SPL

- Roughly, human perception doubles every 10 dB
- The minimum perceived sound variation is 1 dB
- No sound is perceived below 0 dB
- Sound pressure levels above 85 dB are dangerous

