FORUM ACUSTICUM EURONOISE 2025

SUMMER SCHOOL

Fundamentals in Acoustics

The lecturers

- Maarten Hornikx, Eindhoven University of Technology (NL)
- Francesco Martellotta, Politecnico di Bari (IT)
- Silvin Willemsen, Eindhoven University of Technology (NL)

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About me

Full Professor of "Building Physics and Building Energy Systems" at Polytechnic University of Bari.
Graduated with honors in Building Engineering at the Polytechnic University of Bari in 1998, in 2001 got a PhD at the University of Ancona with a dissertation on the Acoustics of Apulian Churches.
Research interests include architectural acoustics, material and meta-material acoustics, sound field modeling, noise and its effects, as well as indoor environmental quality, building energetics and sustainability applied to buildings and materials.
Author/co-author of over 150 scientific works, half of them in international journals, 3 books and several contributions to books.
General Secretary of the Italian Association of Acoustics, and full member of the Acoustical Society of America and of the Audio Engineering Society.
Associate Editor for the "Journal of Acoustical Society of America"

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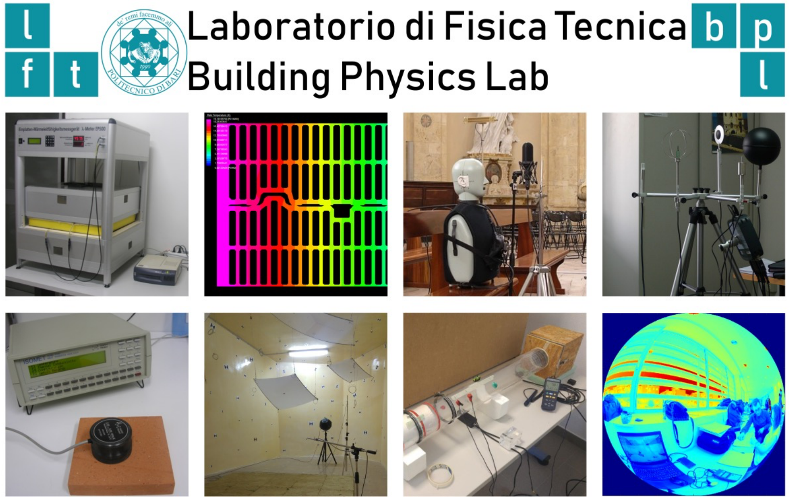
About me



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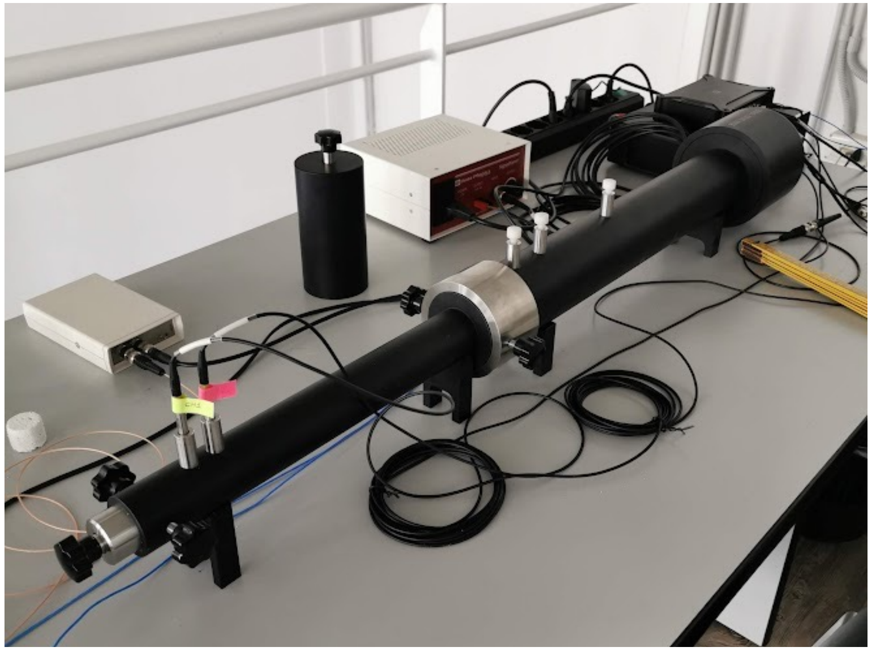

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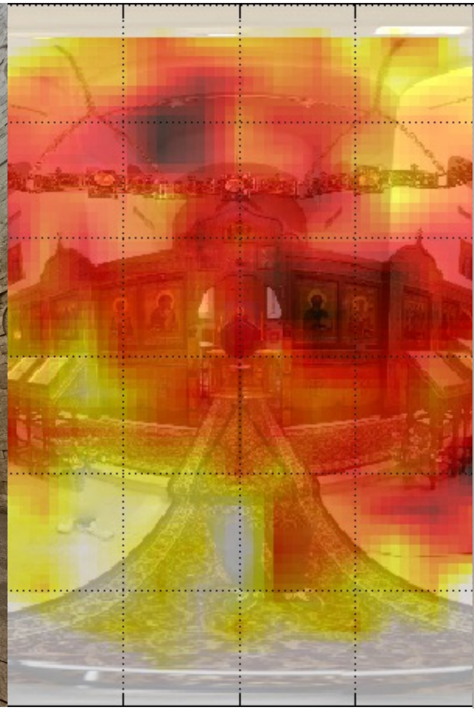

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Course outline (day 1)

SEA
EAA

DAY 1 - 21/06/2024	
8:30-9:00 h	Registration
9:00-10:30 h	**Lecture**: Introduction (why do we study acoustics) Basic signal properties: Period, wavelength and frequency. Definitions, and fundamental equations for propagation of sound.
10:30-11:00 h	Coffee break
11:00-12:00 h	**Tutorial:** Tools for acoustic analysis, Recording of recorded sound, Manipulation of sound
12:00-13:00 h	Plenary session I. Deep learning, AI and acoustics (Prof. Hamid Krim. North Carolina State University) **(All the topics)**
13:00-14:00 h	Lunch
14:00-15:30 h	**Lecture:** More advanced signal properties: Pure and complex sounds, frequency decomposition and sound spectrum. Acoustic quantities: levels and their manipulation, Octave bands and physiology of hearing, binaural hearing.
15:30-16:00 h	Coffee break
16:00-17:00 h	**Lecture**: Wave-surface interactions, 1D wave equation solution including reflection cofficient Sound absorption, types of sound absorption materials

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Course outline (day 2)

SEA EAA

DAY 2 - 22/06/2024	
9:00-10:30 h	**Lecture**: Sound insulation, governing principles. **Tutorial**: sound absorption and insulation
10:30-11:00	Coffee break
11:00-12:00 h	**Lecture**: Sound propagation in open and enclosed spaces.
12:00-13:00 h	Plenary session II. Carrier paths in Acoustics **(All the topics)**
13:00-14:00 h	Lunch
14:00-15:30 h	**Tutorial**: Sound propagation in open and enclosed spaces
15:30-16:00	Coffee break
16:00-17:00 h	Lectures / test

Why do we study acoustics?

*Anywhere there is matter and energy, there is vibration, and any vibration can **transfer energy and information to a receiver** who is listening.*
And the wide range of vibration perceivable by living things, from the single thud of a footstep that shuts up a frog chorus to the incredibly high-frequency sounds that form a dolphin's natural ultrasound, requires a sensory system thousands of times faster than its slower cousins, vision, smell, and taste.

Seth Horowitz
The Universal Sense: How Hearing Shapes the Mind

Why do we study acoustics?

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Why do we study acoustics?

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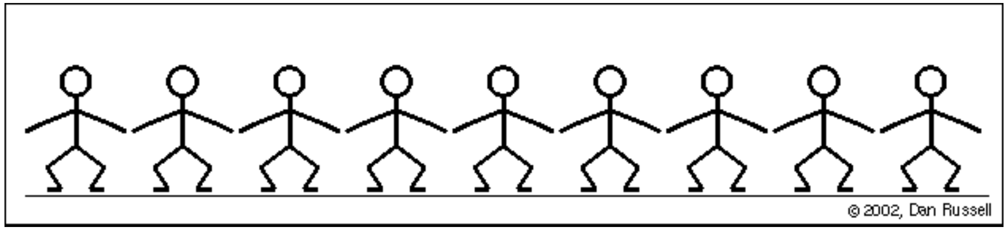
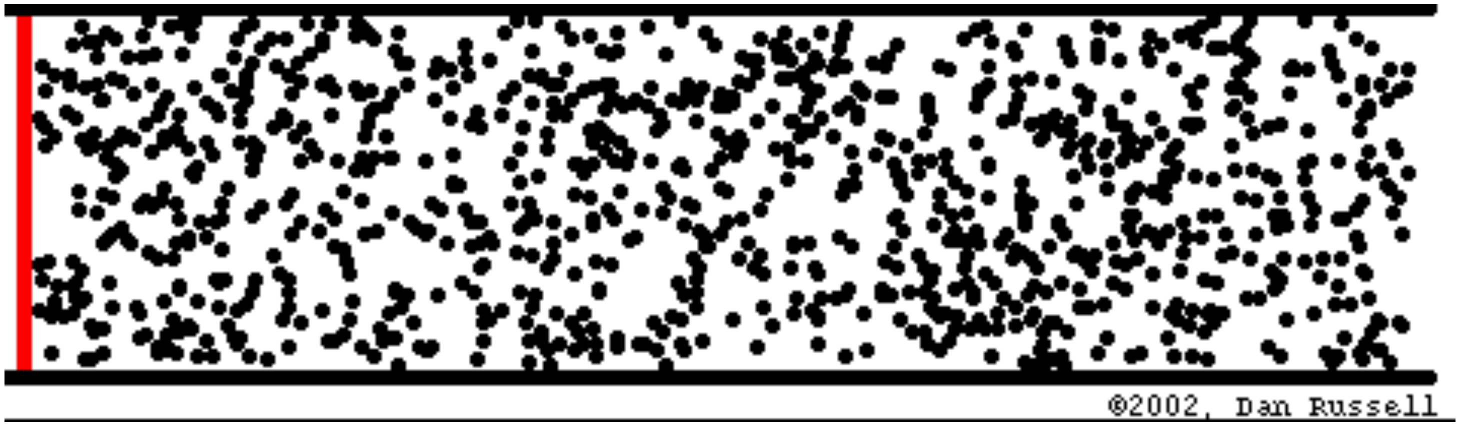
Why do we study acoustics?

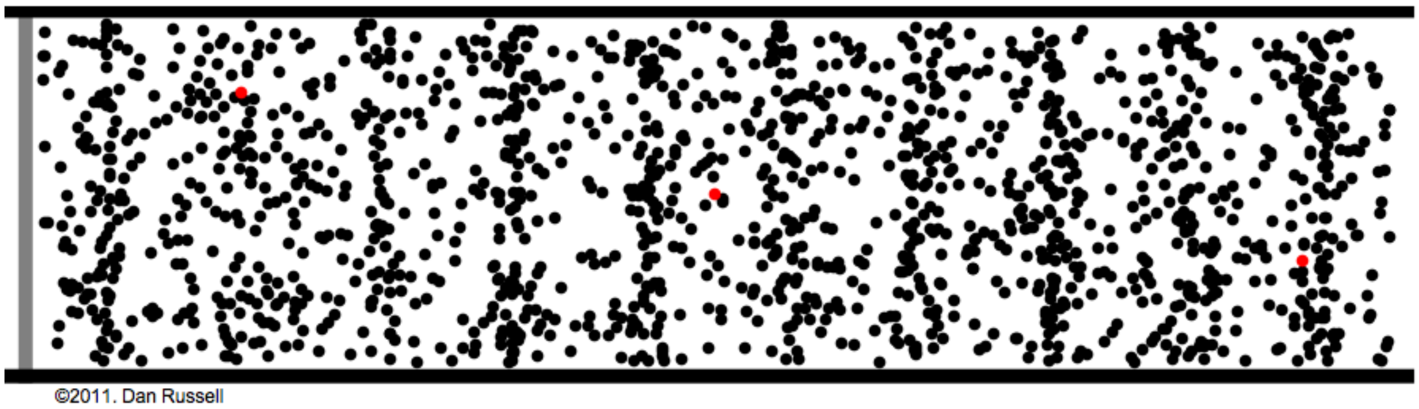
Basic sound properties



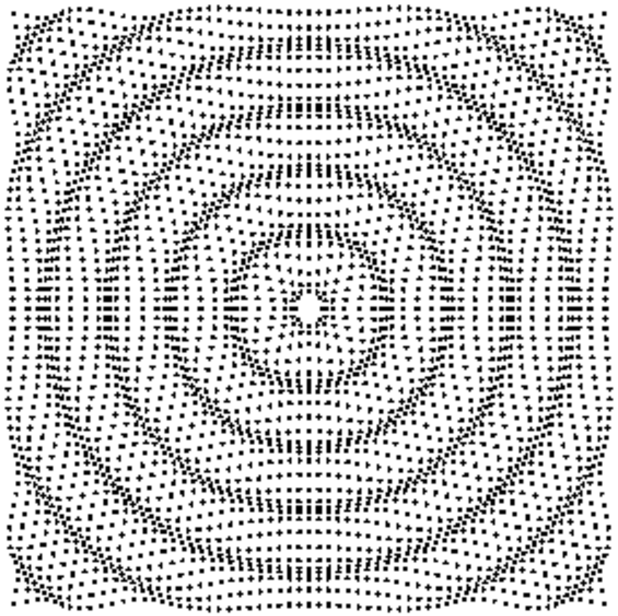
Basic sound properties



Basic sound properties



Basic sound properties

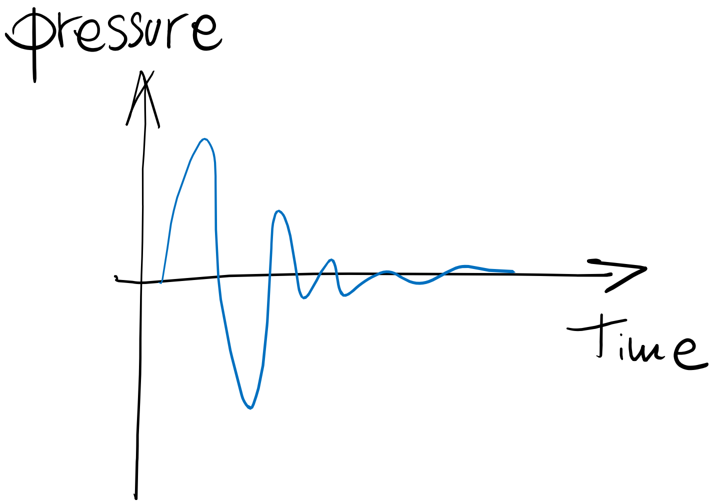


Basic sound properties

To describe the acoustic phenomena we use «**Sound pressure**» defined as:

$$p(x, y, z, t) = P(x, y, z, t) - P_0 \quad \text{[Pa]}$$

The smallest pressure variation we humans may hear (on average) is about $2x10^{-5}$ Pa, which is named «hearing threshold»



The wave equation

Newton's equation of motion: $F = \rho \cdot dx \cdot dy \cdot dz \dfrac{dv}{dt} = -\dfrac{\partial p}{\partial x} dV \rightarrow -\dfrac{\partial p}{\partial x} = \rho \dfrac{\partial v}{\partial t}$

Ideal gas equation: $\dfrac{1}{p_0} \dfrac{\partial p}{\partial t} = -\dfrac{k}{V_0} \dfrac{\partial \tau}{\partial t}$

Conservation of mass equation: $\dfrac{\partial \tau}{\partial t} = \dfrac{\partial^2 \xi_x}{\partial x \partial t} V_0 = \dfrac{\partial v}{\partial x} V_0$

Combining them yields: $\dfrac{\partial^2 p}{\partial x^2} = \dfrac{\rho}{k P_0} \dfrac{\partial^2 p}{\partial t^2}$

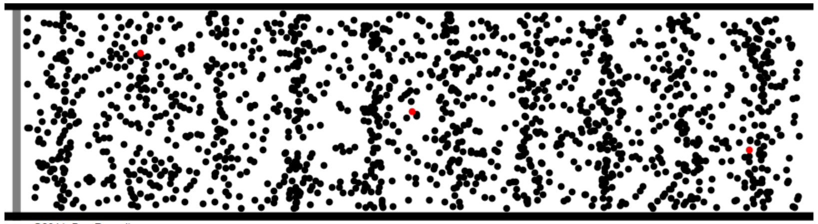
And replacing $c^2 = k \cdot p_0 / \rho$ ➔ $\dfrac{\partial^2 p}{\partial x^2} = \dfrac{1}{c^2} \dfrac{\partial^2 p}{\partial t^2}$

The wave equation

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

The wave equation

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \qquad c^2 = k \cdot p_0 / \rho \quad [\mathrm{m^2/s^2}]$$



The general solution is: $p(x,t) = F(ct - x) + G(ct + x)$

In an arbitrary position… $F_{(t0,x0)} = F(ct_0 - x_0)$

In the same position after a time Δt… $F_{(t0+\Delta t,x0)} = F(ct_0 + c\Delta t - x_0)$

Meanwhile at position x_0 + cΔt… $F_{(t0+\Delta t,x0+c\Delta t)} = F(ct_0 + c\Delta t - x_0 - c\Delta t) = F(ct_0 - x_0) = F_{(t0,x0)}$

…thus *c* must be the *speed of sound*

The wave equation

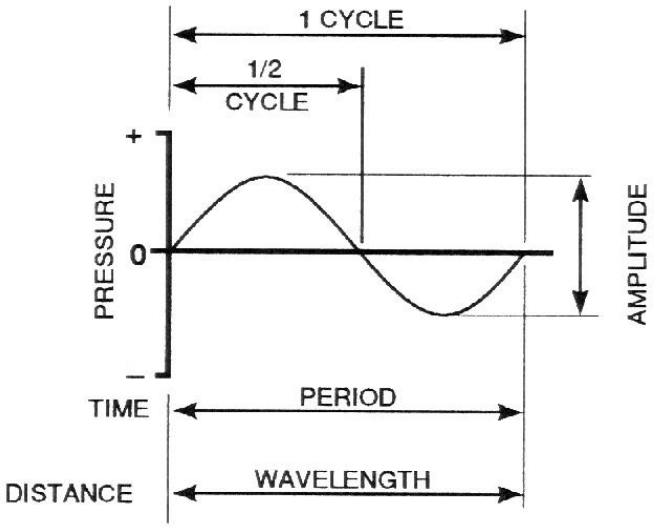
$$p(x,t) = F(ct - x) + G(ct + x)$$

$$p(x,t) = A \cdot cos(ct - x)$$

$$p(x,t) = A \cdot cos\left(\frac{2\pi}{cT}ct - \frac{2\pi}{cT}x\right)$$

$$\omega = \frac{2\pi}{T}\left[{}^{rad}/_{s}\right] = 2\pi f \qquad k = \frac{2\pi}{\lambda}\left[{}^{rad}/_{m}\right]$$

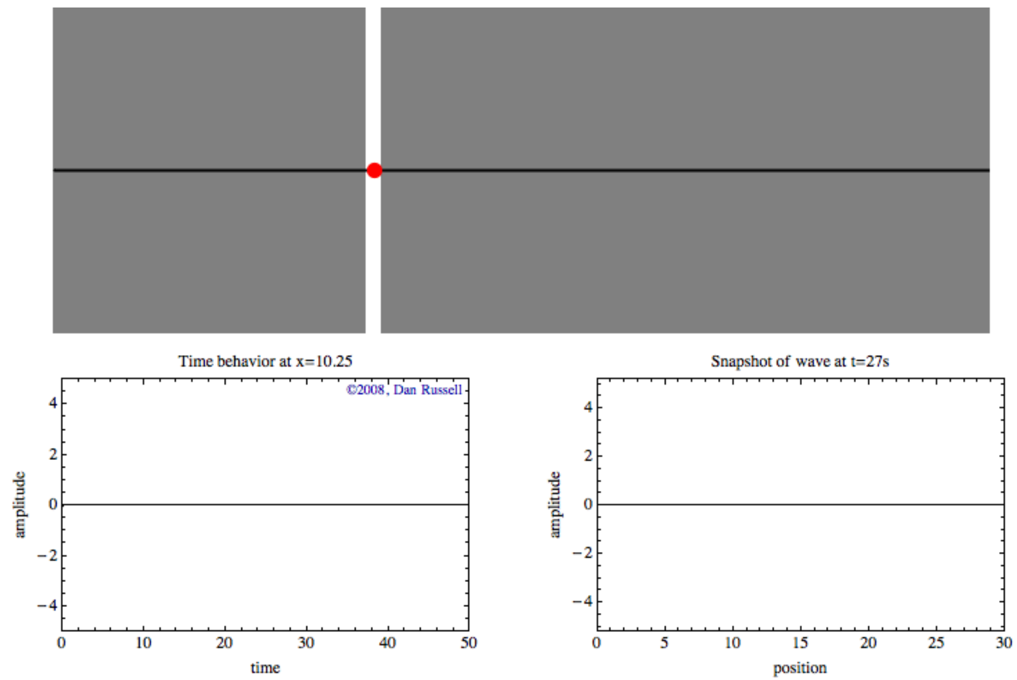
$$p(x,t) = A \cdot cos(\omega t - kx)$$



$$\lambda = \frac{c}{f} = c \times T$$

Basic sound properties

$$p(x,t) = A \cdot cos(\omega t - kx)$$



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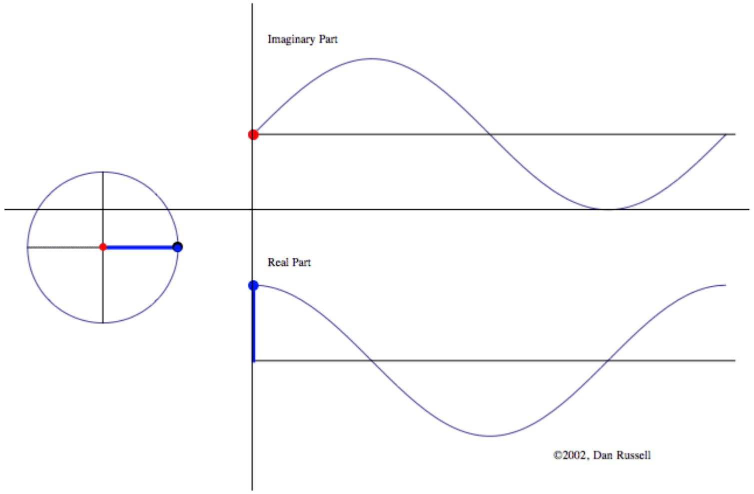
The complex notation

$$p(x,t) = A \cdot cos(\omega t - kx)$$

$$z = x + jy, \qquad j = \sqrt{-1}$$

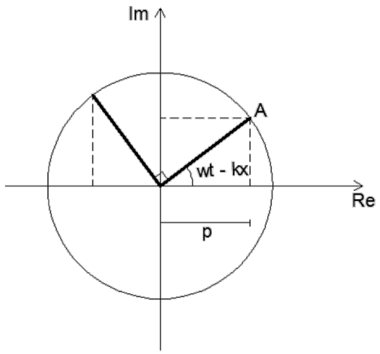
$$z = x + jy = r(cos\phi + j\ sin\phi) = \mathrm{r\ ej}^{\phi}$$

$$p(x,t) = Re\ [A\ e^{j(\omega t - kx)}]$$



The complex notation

$p(x,t) = A \cdot cos(\omega t - kx)$	$p(x,t) = Re\,[A\, e^{j(\omega t - kx)}]$
$p(x,t) = A \cdot cos(\omega t - kx + \phi)$	$p(x,t) = Re\,[A\, e^{j(\omega t - kx)} e^{j\phi}]$
$\frac{dp(x,t)}{dt} = -\omega A sin(\omega t - kx)$ $= \omega A cos(\omega t - kx + \frac{\pi}{2})$	$\frac{dp(x,t)}{dt} = Re\left[j\omega A e^{j(\omega t - kx)}\right]$ $= Re[\omega A e^{(\omega t - kx)} e^{\frac{j\pi}{2}}]$
$\int p(x,t)dt = \frac{A}{\omega} sin(\omega t - kx)$ $= \frac{A}{\omega} cos(\omega t - kx - \frac{\pi}{2})$	$\int p(x,t)dt = Re\,\left[(A/j\omega) e^{j(\omega t - kx)}\right]$ $= Re[\frac{A}{\omega} e^{j(\omega t - kx)} e^{-\frac{j\pi}{2}}]$



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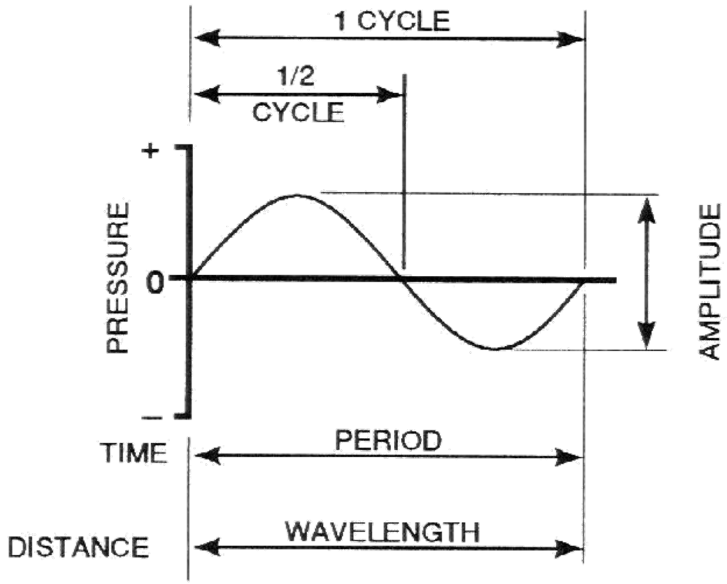
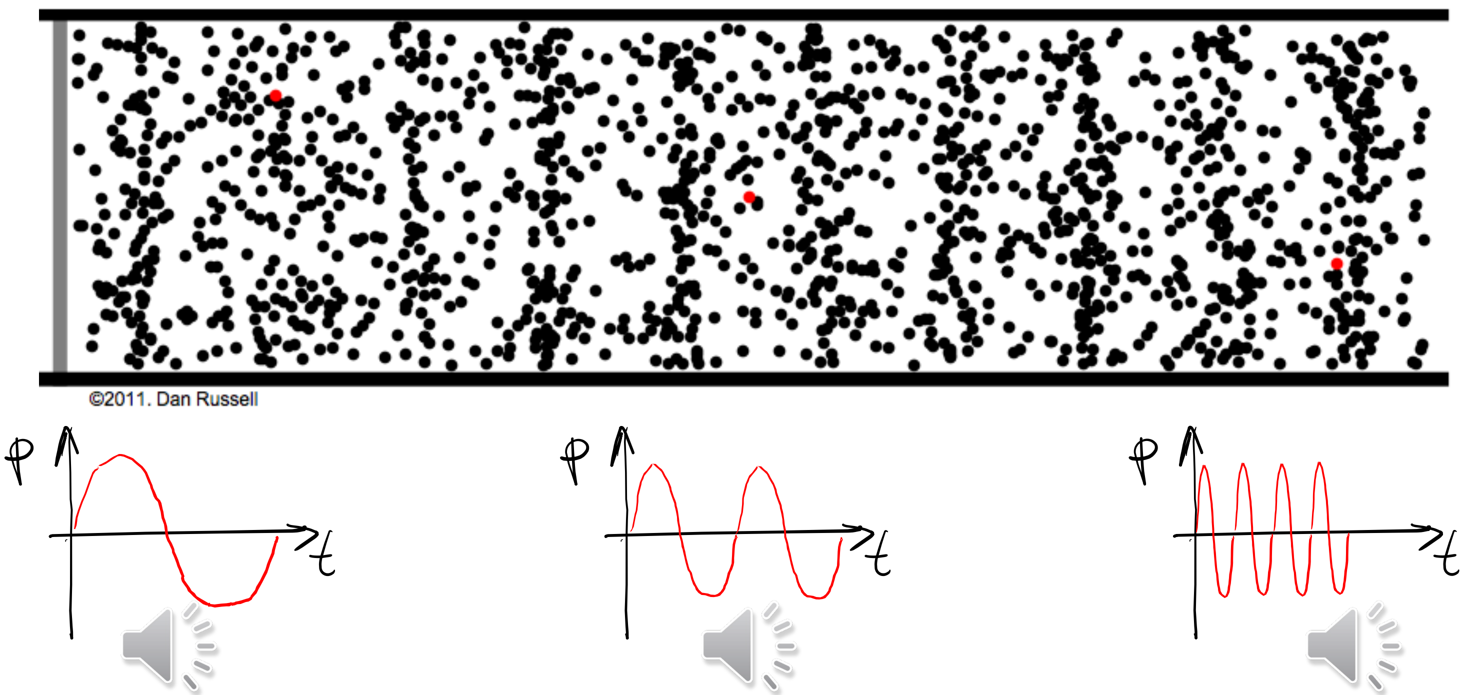


FREQUENCY = 1 / PERIOD

$$\lambda = \frac{c}{f} = c \times T$$

Basic sound properties



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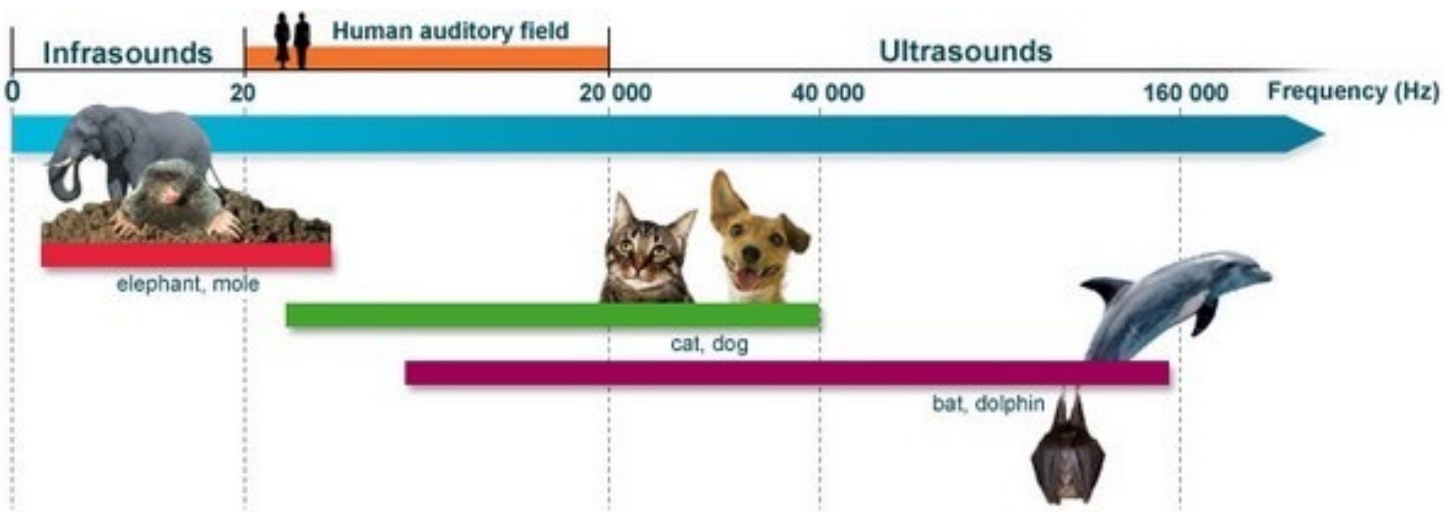

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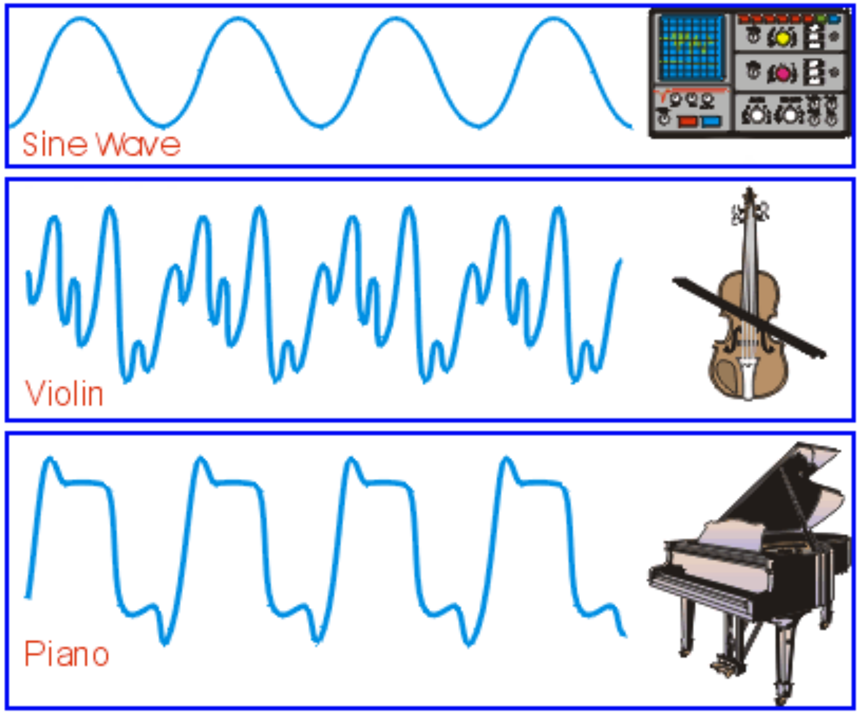

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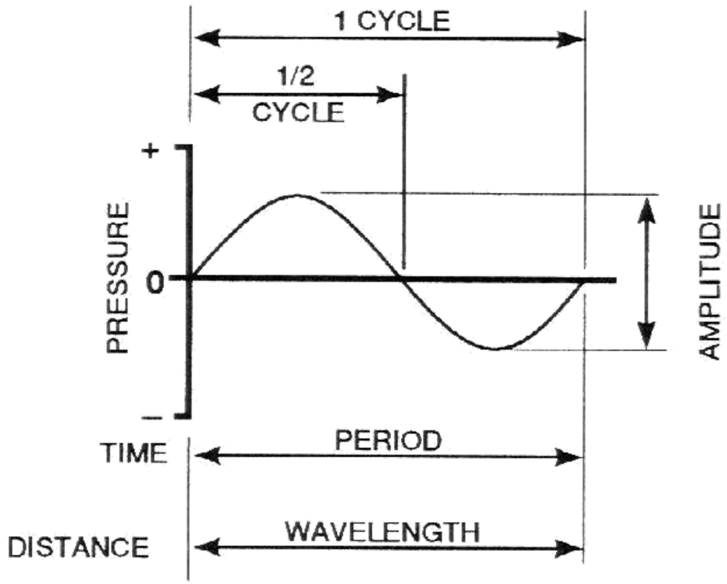

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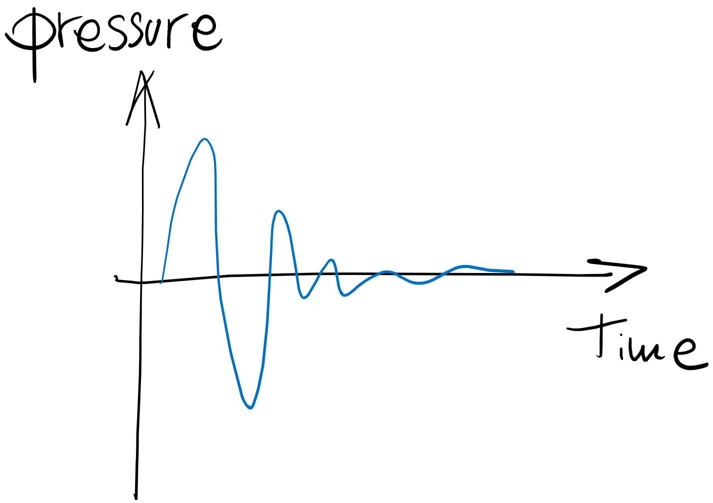


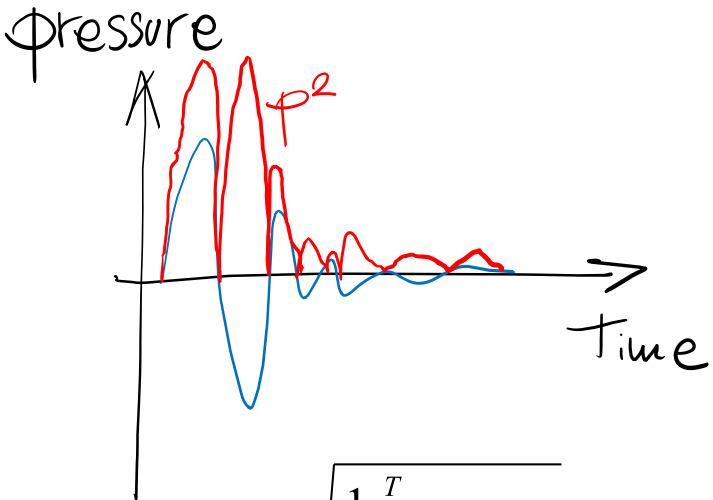
Basic sound properties

To take into account the wide range of magnitudes, and also account for subjective perception, «**sound pressure level**» has been introduced:

$$L_p = 10\,Log_{10}\frac{p_{rms}^2}{p_{ref}^2} \quad \text{[dB]}$$

$$p_{ref} = 2 \cdot 10^{-5}\,[Pa]$$

In this way, the lowest audible sound pressure corresponds to a level of 0 dB



$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt}$$

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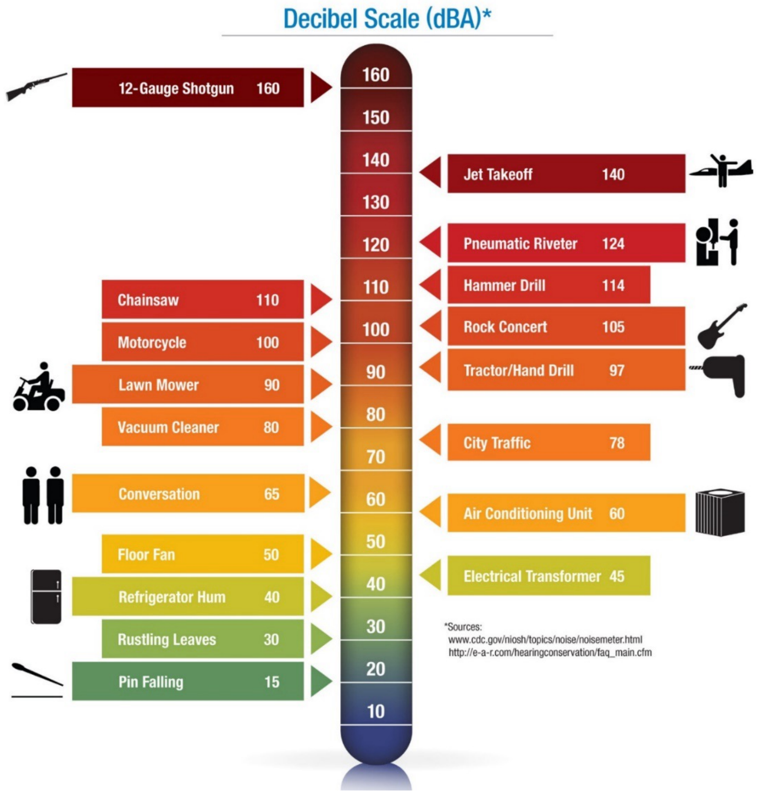
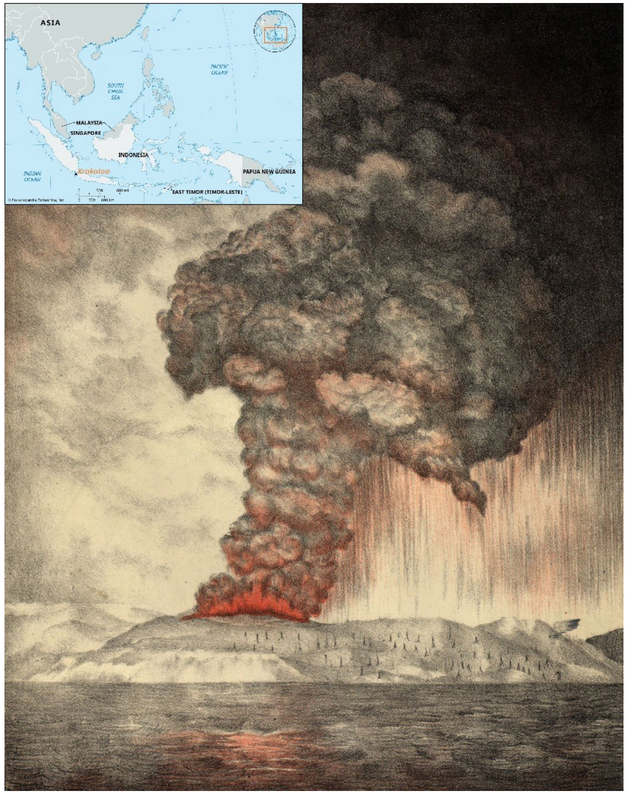


Basic sound properties

On August 27th 1883 the Krakatoa volcano in Indonesia exploded producing an estimated sound pressure level of 230 dB.
The explosion was clearly heard in India and Australia at 3500 km…

$$L_p = 10\ Log_{10} \frac{p_{rms}^2}{p_{ref}^2} \quad \text{[dB]}$$

$$p_{rms} = p_{ref} 10^{\frac{Lp}{20}} \quad \text{[Pa]}$$



Energy quantities

$$Acoustic\ intensity = \frac{\text{Energy}}{\text{Surface Area} \cdot \text{Time}} \quad [\frac{W}{m^2}]$$

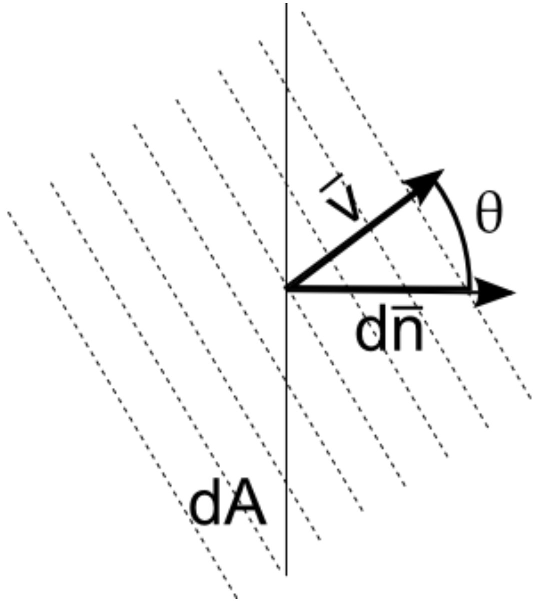
$$I(t,\theta) = \frac{dE}{dA\,dt} = \frac{p\,dA\,d\xi\,cos\theta}{dA\,dt}$$

$$\frac{d\xi}{dt} = v \Rightarrow \quad I(t,\theta) = p \cdot v\cos\theta$$

$$-\frac{\partial p}{\partial x} = \rho\frac{\partial v}{\partial t} \rightarrow v = -\frac{1}{\rho}\int\frac{\partial p}{\partial x}dt$$

$$v(x,t) = -\frac{1}{\rho}\int -jkAe^{j(\omega t-kx)}dt = \frac{1}{\rho}\cdot\frac{jk}{j\omega}Ae^{j(\omega t-kx)} = \frac{1}{\rho c}p(x,t)$$

$Z = \dfrac{p(x,t)}{v(x,t)}$ Acoustic impedance $\quad Z_0 = \rho c\,, for\ a\ plane\ wave$



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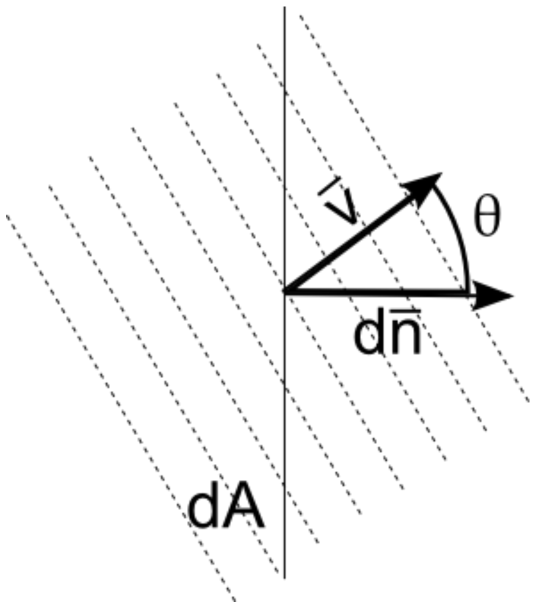
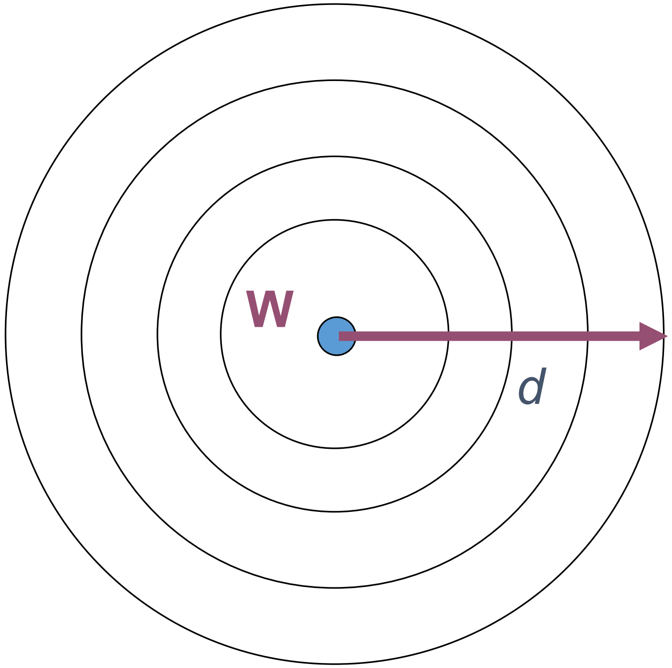
$$\frac{d\xi}{dt} = v \Rightarrow \quad I(t,\theta) = p \cdot v \cos\theta$$

$$I(t,\theta) = \frac{p^2}{\rho c} cos\theta$$

$$\bar{I}(\theta) = \frac{1}{T}\int_0^T I(t,\theta)dt = \frac{p_{rms}^2}{Z_0}\cos\theta = \frac{p_{rms}^2}{\rho c}\cos\theta$$



Sound propagation



$$L_W = 10\log\frac{W}{W_{RIF}}$$

$$I = \frac{W}{4\pi d^2} \quad (Wm^{-2})$$

$$L_I = L_W - 10\log(4\pi) - 10\log d^2$$

$$L_p = L_W - 20\log d - 11$$

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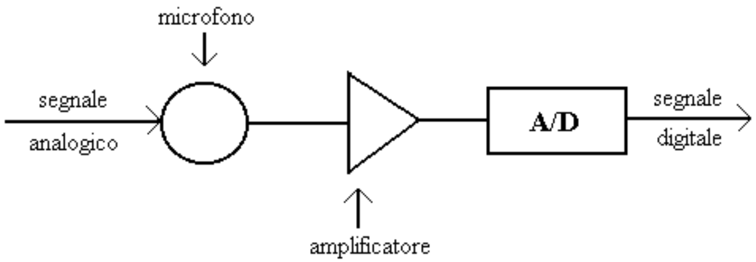
Tutorial #1:
from analog to digital
(and vice versa)

https://www.audacityteam.org/

Audacity®

Tutorial #1:
from analog to digital
(and vice versa)



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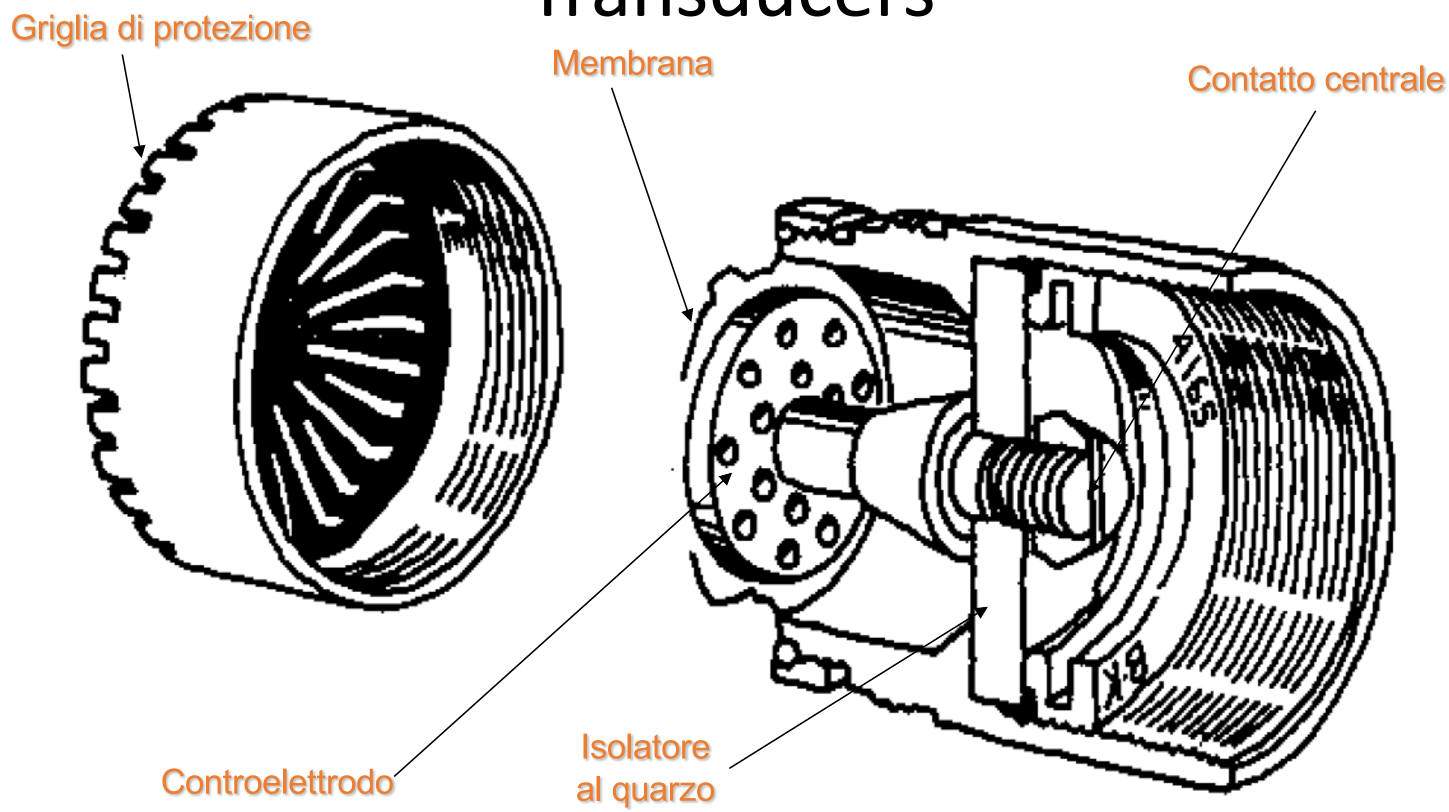
Transducers



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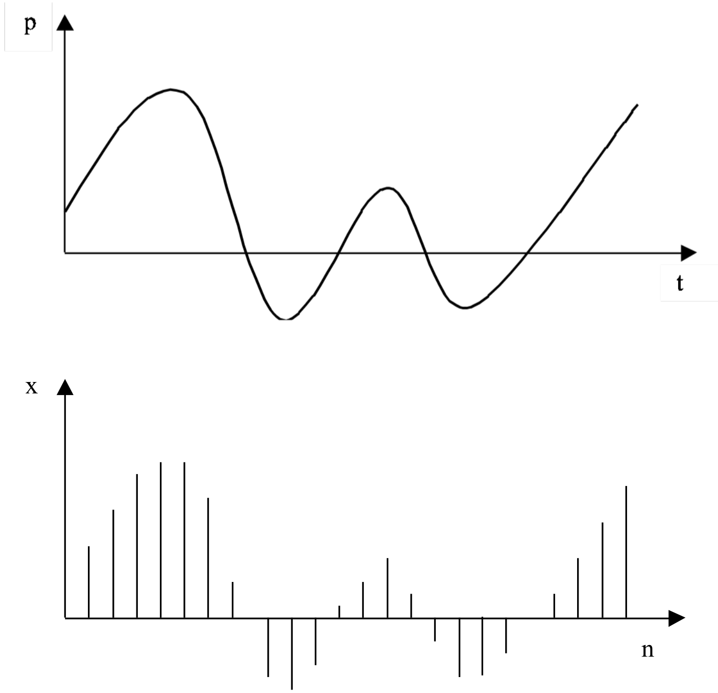
Tutorial:
from analog to digital



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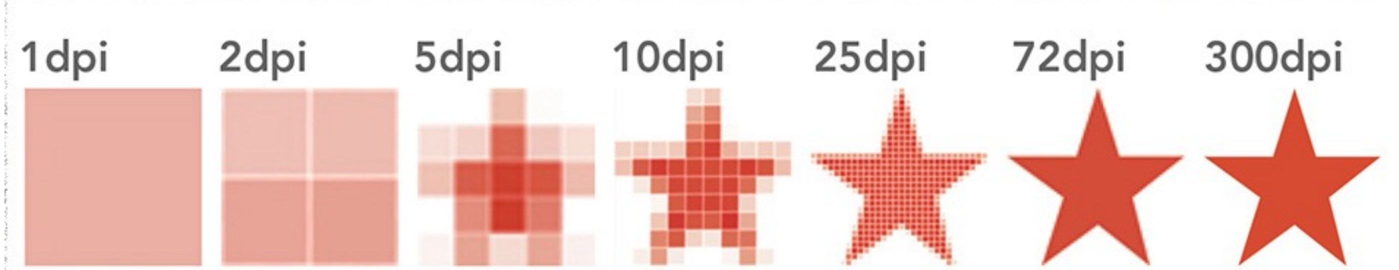
Tutorial:
from analog to digital



Tutorial:
from analog to digital

The Nyquist theorem states that an analog signal **must be sampled at least twice as fast as the bandwidth of the signal** to accurately reconstruct the waveform; otherwise, the high-frequency content creates an alias at a frequency inside the spectrum of interest (passband). An alias is a false lower frequency component that appears in sampled data acquired at too low a sampling rate.