universität wien

Musicological Department

Musicological Department of the University of Vienna

Christoph Reuter

The Musicological Department

- One of the oldest and most longstanding musicological institutes worldwide
- 4 Chairs:
  - Historical Musicology (Music before 1600)
  - Historical Musicology (Music after 1600)
  - Ethnomusicology
  - Systematic Musicology

- At the moment:
  16 researchers, 5 administrative/technical department members,
  15 project members in 14 third-party funded projects,
  34 lecturers, and about 850 students

The Musicological Department

Research discipline	**->**	**Methods, strategies and perspectives**
Historical Musicology		humanities, philology, and cultural studies
Ethnomusicology		anthropology, sociology, and (world-)cultural studies
Systematic Musicology		natural science, statistical methods, and empiricism

The Musicological Department

Infrastructure

- Two lecture halls and two seminar rooms

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- Recreational break room with exhibitions of selected instruments of the institutes musical instruments collection
- Semi-anechoic chamber, repair shop, and archive in the basement
- Equipment: Measurement Microphones, High-Speed Camera, Dodecahedron room acoustic measurement system, Nexus 10 Biotrace device, Vidivoice voice field measurement system, Oculus Rift VR Touch, 360-Degree Cameras, 3D-Camera, Acoustical Camera, Artificial Head etc.

The Musicological Department

Research Topics in the field of Systematic Musicology

- Timbre and noise perception / Analysis / Synthesis
  (Focus: Music Information Retrieval / Signal analysis)

- Music, sound and noise impact in everyday life
  (Focus: Chill Experiences, Audiologo / Music Advertisement, Background music, Concert pitch etc.)

- Everyday legends about music (impact of music, and noises on plants, animals, intelligence, social behaviour etc.)

- Acoustics of musical instruments and rooms, psycho-acoustics,
- Music Informatics, Music Machines, Virtual Reality

Good Vibrations

Fundamentals of musical acoustics

1 Fundamentals of Musical Acoustics

1.1 Sound Propagation
1.2 Pitch and Periodicity
1.3 Frequency and Wavelength
1.4 Timbre
1.5 Resonance

2 Voice

2.1 Source (Vocal Folds)
2.2 Deviation (Vocal Tract)
2.3 Radiation (Mouth/Nose)

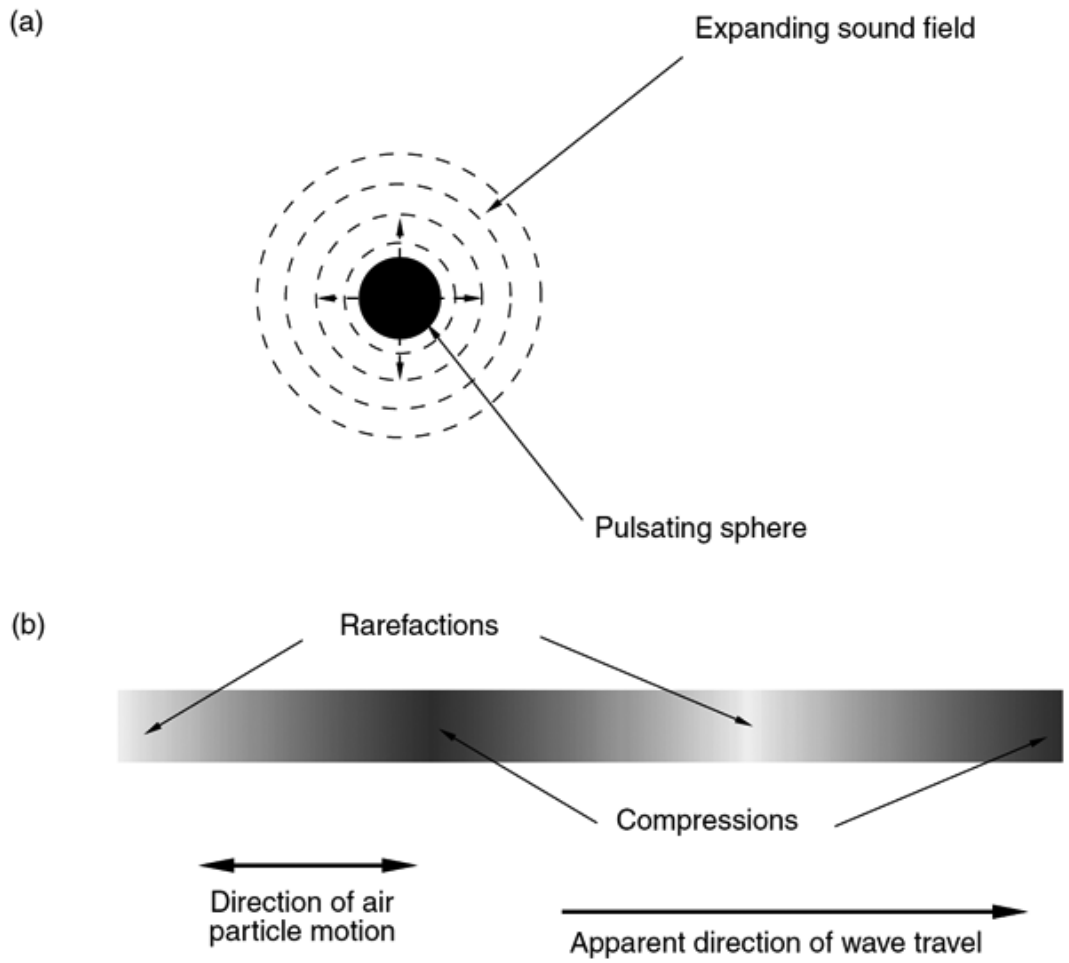
3 Ear

3.1 Outer Ear
3.2 Middle Ear
3.3 Inner Ear

Good Vibrations

Sound Propagation

If a material swings **back and forth**, the air directly in front of it is correspondingly **compressed and diluted** in the frequency of this vibration.



Sound propagation of a spherical wave, compression and dilution of the air particles in the period of the sound source (Rumsay, McCommick 2006, p. 2)

Good Vibrations

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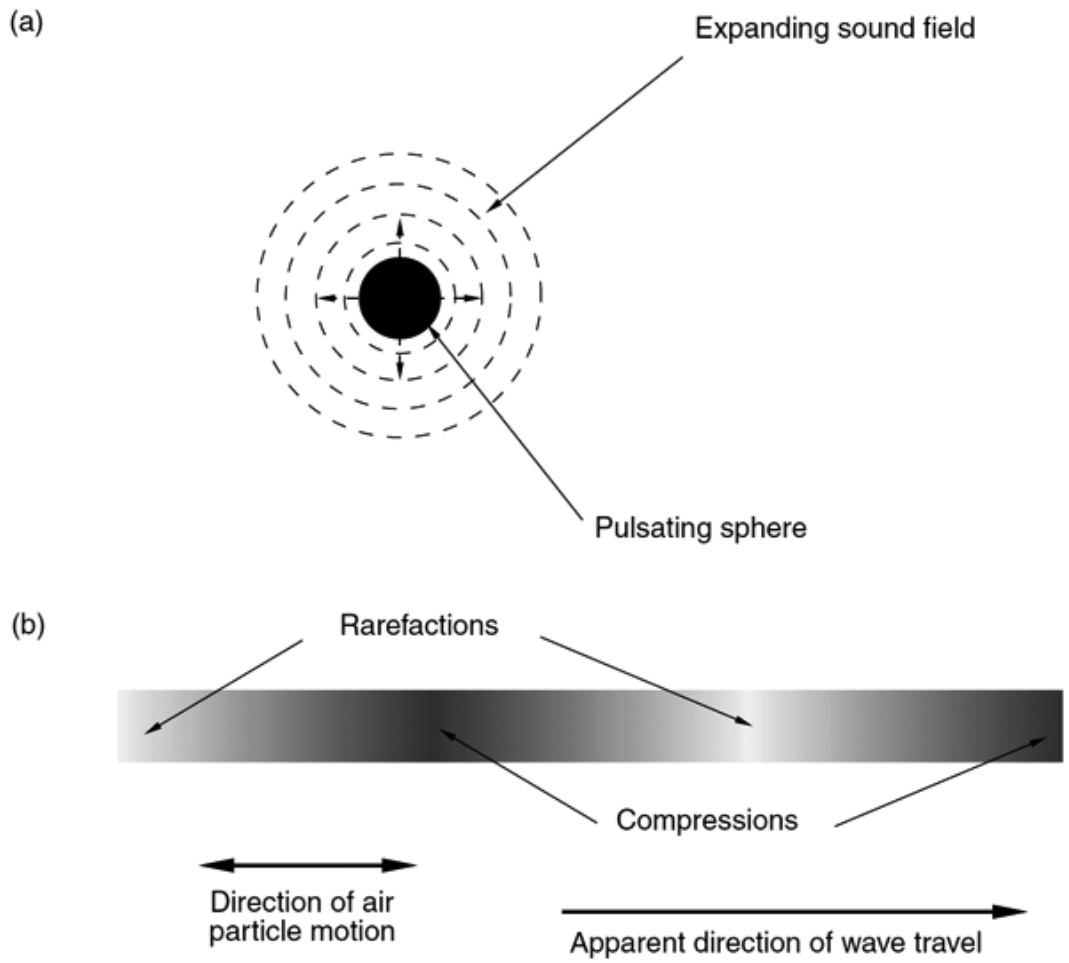
Compression / dilution shifts to **neighboring air molecules**.



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Good Vibrations

Sound Propagation

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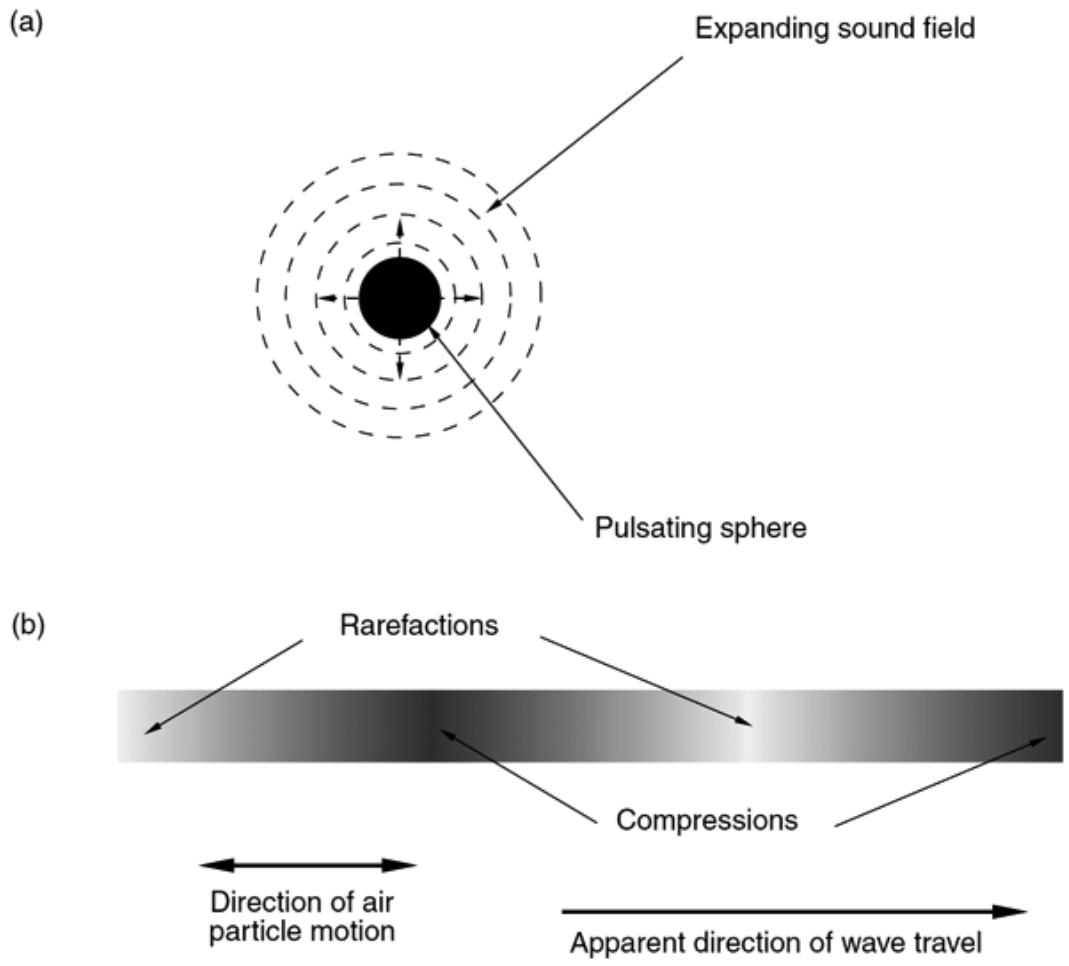
Compression / dilution shifts to **neighboring air molecules**.

-> It leads to a **disturbance of the equilibrium state of the air pressure**, which spreads **spherically** into space.

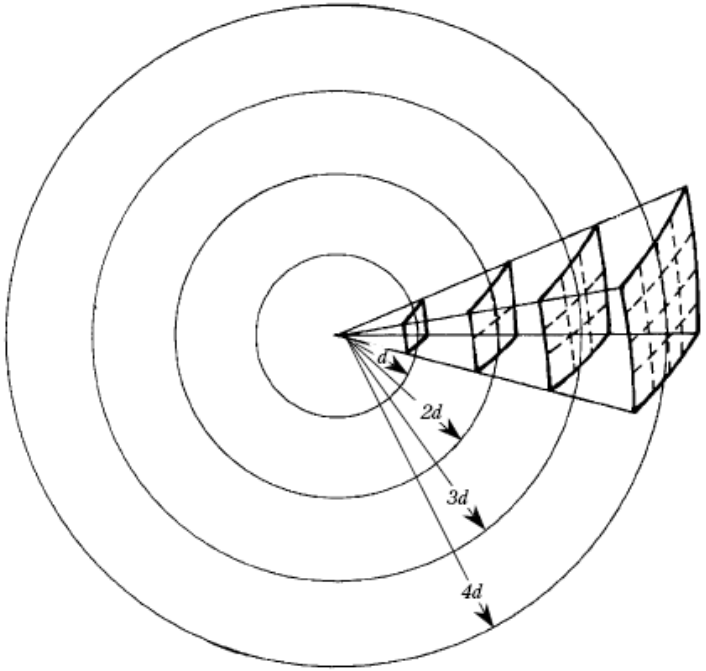


Sound propagation of a spherical wave, compression and dilution of the air particles in the period of the sound source (Rumsay, McCommick 2006, p. 2)

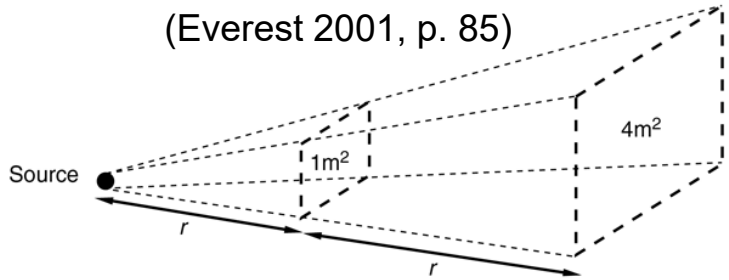
Good Vibrations

Sound Propagation

The **extend** of the air pressure disturbance (**amplitude in %** or **sound pressure level in dB**) leads to the impression of **sound intensity** or **volume**.



Sound propagation in acoustic free-field conditions (Everest 2001, p. 85)



Doubling the distance (r) leads to a squared decrease of the sound level (Rumsay, McCommick 2006, p. 17)

Good Vibrations

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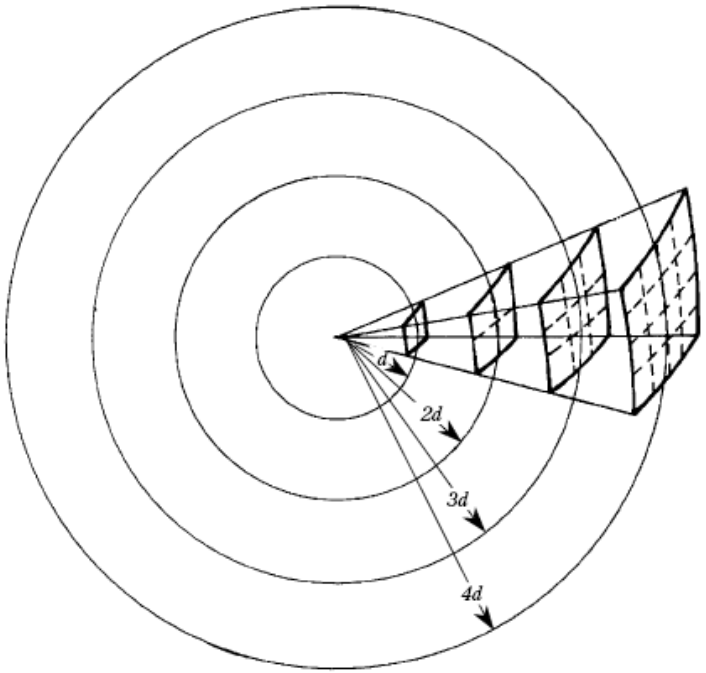
The **extend** of the air pressure disturbance (**amplitude in %** or **sound pressure level in dB**) leads to the impression of **sound intensity** or **volume**.

When the **distance** from the sound source is **doubled**, the **sound pressure level decreases** by **half** (by -6 dB), since the energy is distributed over an **increasing squared** area.



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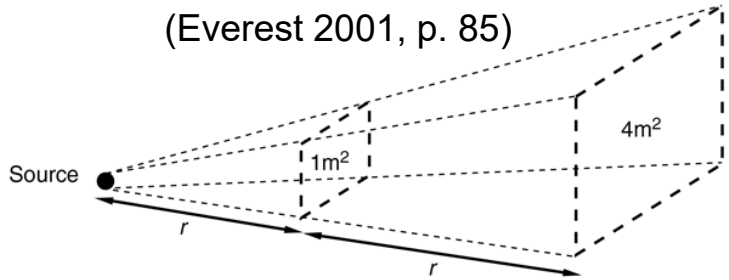

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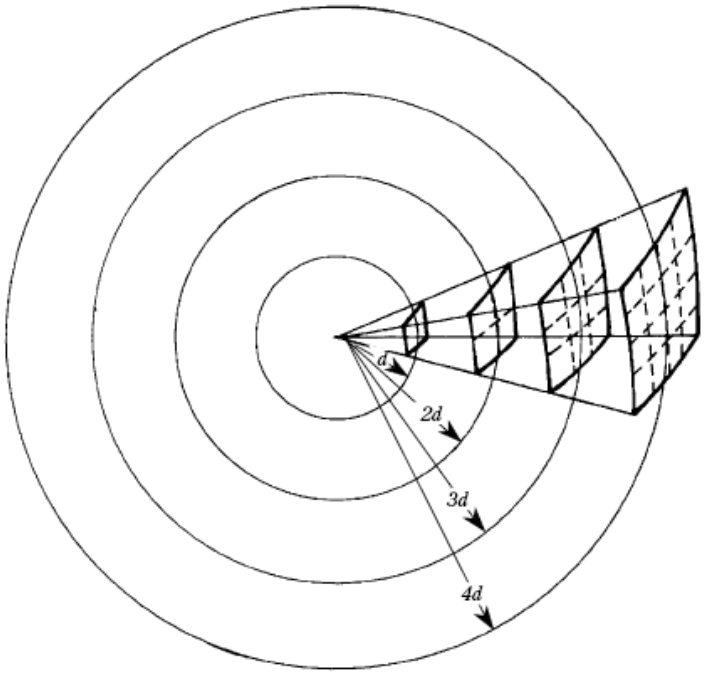
When the **distance** from the sound source is **doubled**, the **sound pressure level decreases** by **half** (by -6 dB), since the energy is distributed over an **increasing squared** area.

So the perceived sound volume gets **lower and lower** with **increasing** distance.



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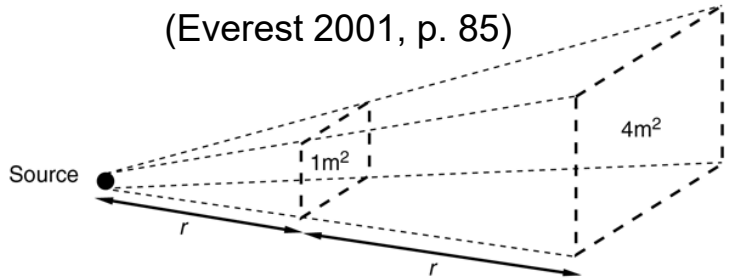


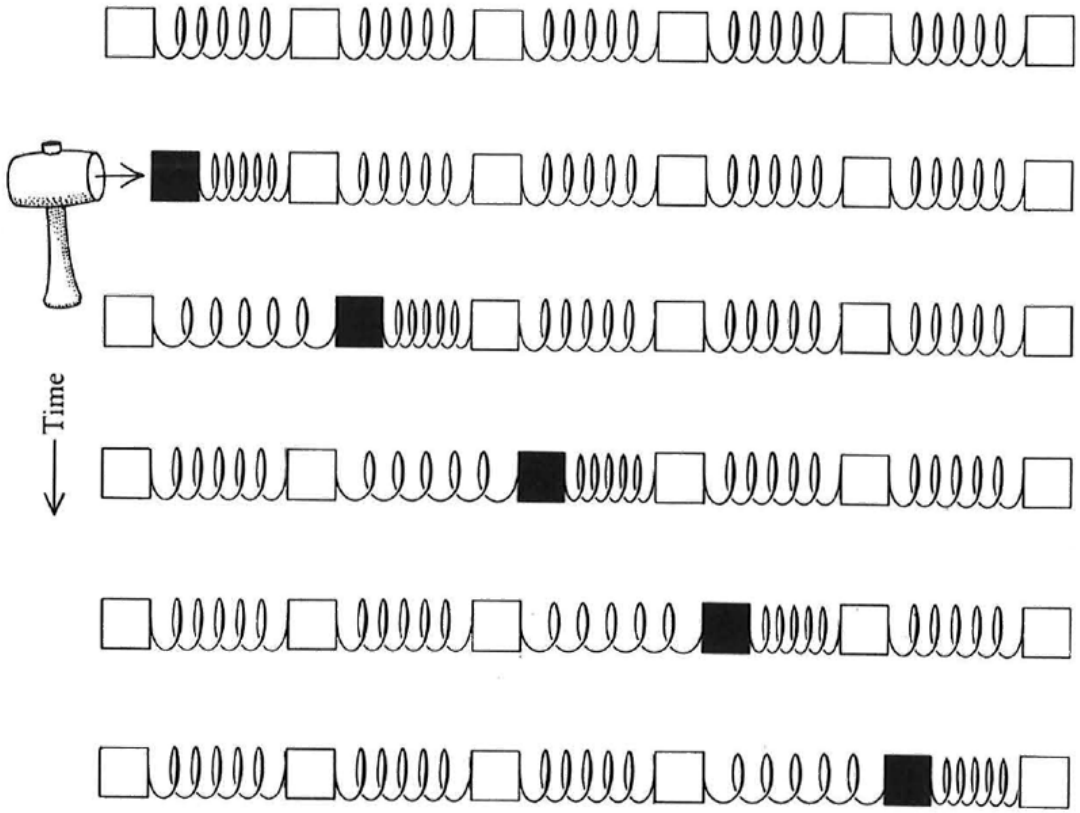
Doubling the distance (r) leads to a squared decrease of the sound level (Rumsay, McCommick 2006, p. 17)

Good Vibrations

Sound Propagation

Sound propagation by the example of a **spring-mass system**:

Always **only the impulse spreads**, while the individual **elements** more or less **remain firmly** in their position.



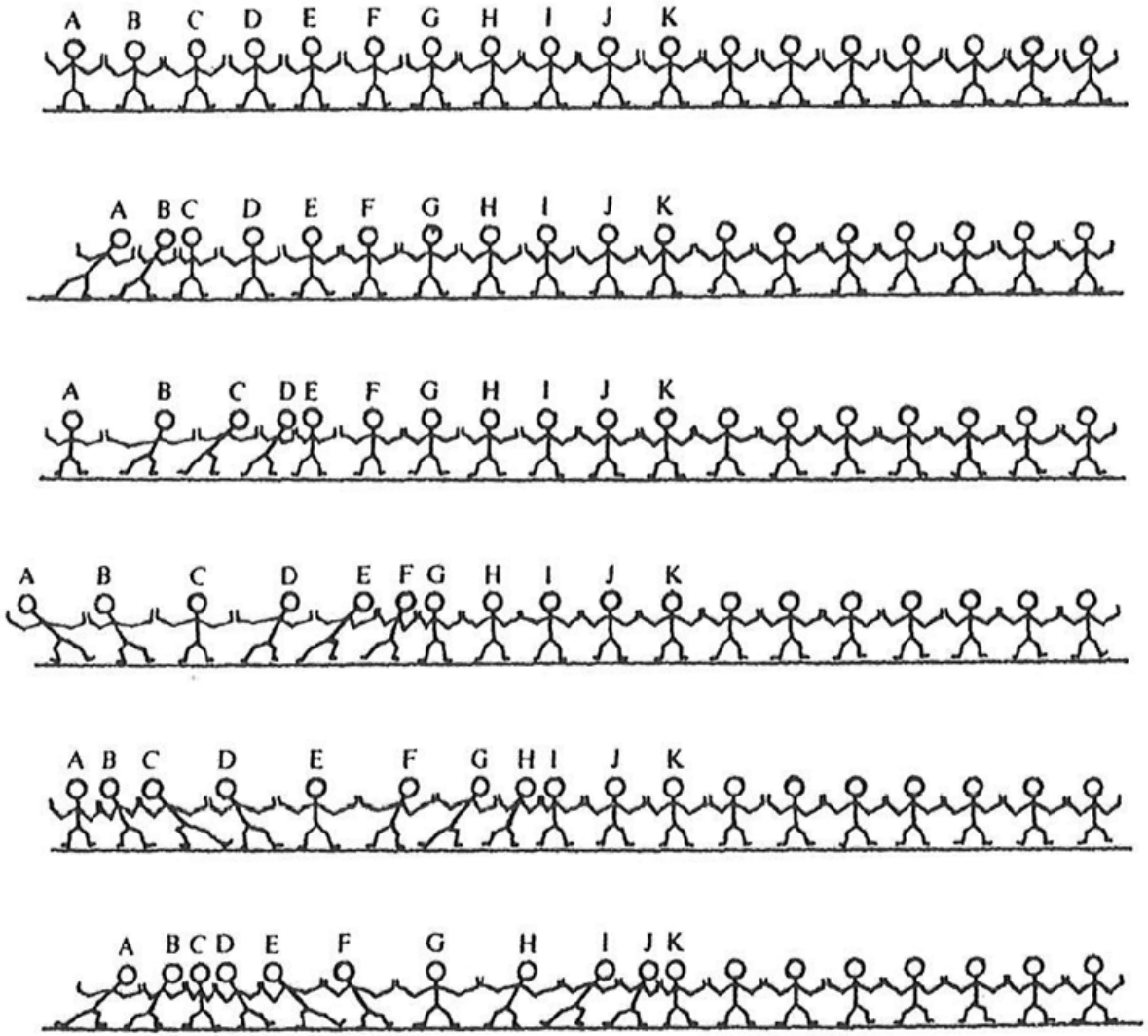
Sound propagation by the example of a spring-mass system
(Pierce 1992, p. 26)

Good Vibrations

Sound Propagation

This can also be observed when pushing someone in a chain of people, to trigger an impulse.

Swimmers in a wave pool

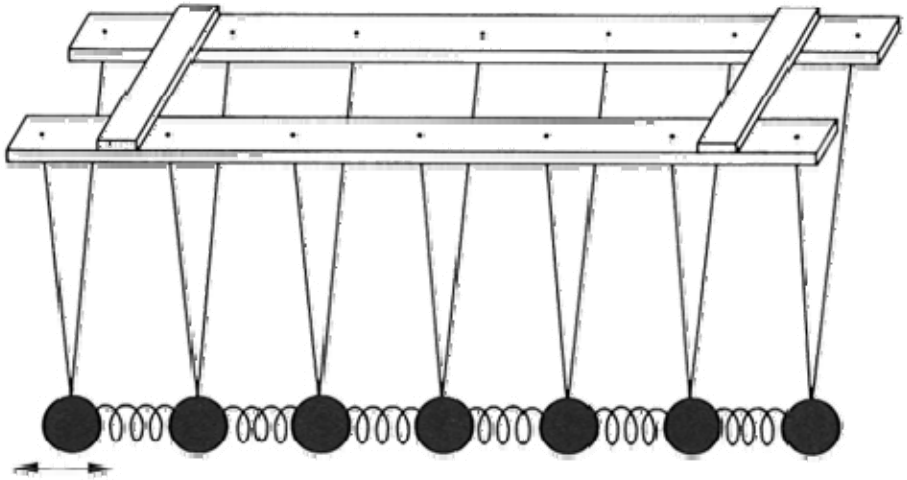


Impulse propagation in a chain of people
(Campbell, Greated 2001, p. 24)

Good Vibrations

Sound Propagation

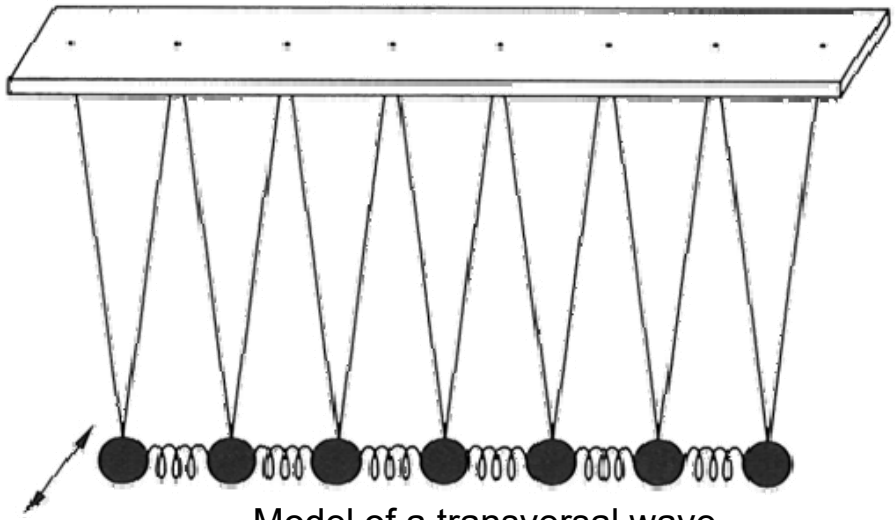
Longitudinal waves



Model of a longitudinal wave
(Bergmann, Schäfer 2008, p. 480)

The particles oscillate **in the direction** of sound propagation
(e.g. voice, wind instruments)

Transversal waves



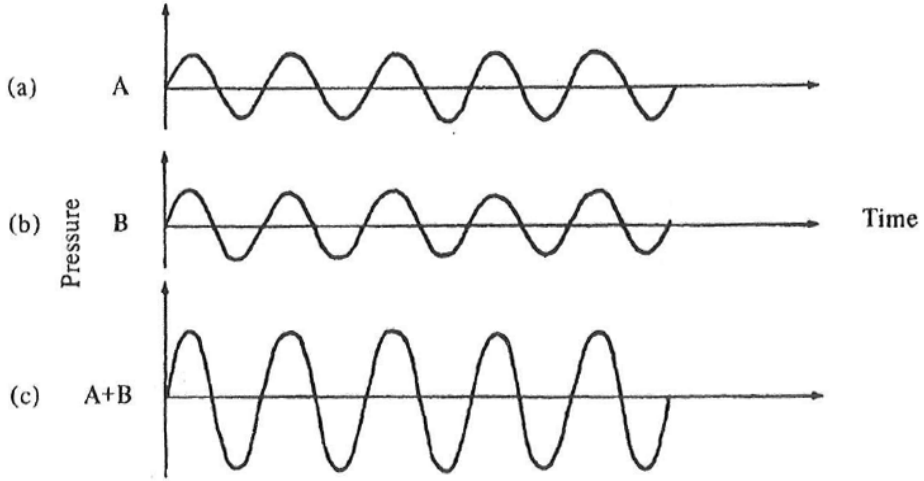
Model of a transversal wave
(Bergmann, Schäfer 2008, p. 480)

transversal: The particles oscillate **perpendicular to the direction** of sound propagation
(e.g. string instruments, percussion instruments)

Good Vibrations

Sound Propagation

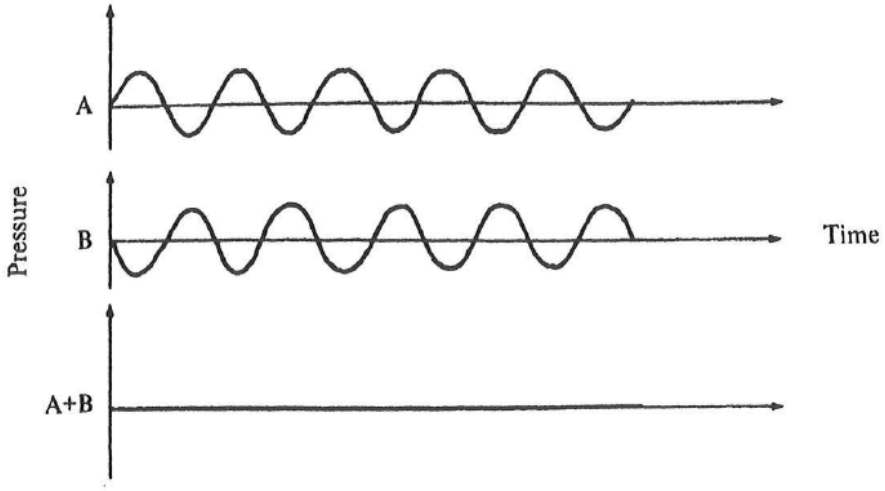
Constructive Interference



Constructive Interference
(Campbell, Greated 2001, p. 34)

Two **equal waves** in the **same phase reinforce** each other.

Destructive Interference



Destructive Interference
(Campbell, Greated 2001, p. 34)

Two **equal waves** in **opposite phase weaken** or **annihilate** each other.

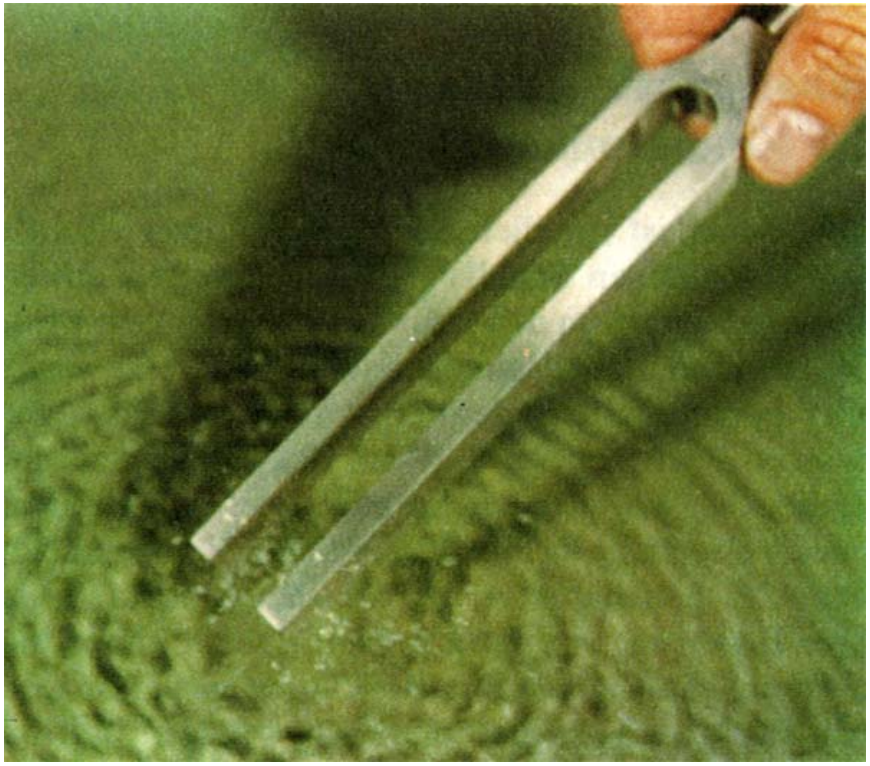
Good Vibrations

Sound Propagation

With the help on a **tuning fork** and an illuminated **glas of water** filmed with a high speed camera, it is possible to make sound propagation as well as interference effects **visible**.

Highspeed Video:
Sound propagation in water made visible with a tuning fork

(Recording: Mühlhans, Reuter, Esper 2014)



Sound propagation made visible
(picture: Pütz 1973, p. 10)

Good Vibrations

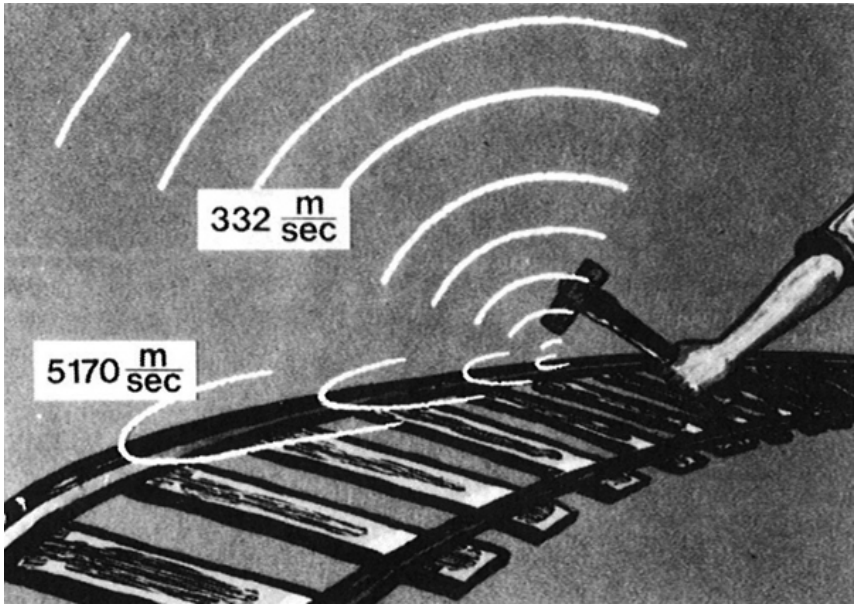
Sound Propagation

The propagation of a vibrational state (= sound) **takes time**, because masses have to be accelerated.

The **speed of sound in air** takes **340 m/s** (at a temperature of 15°, or 332 m/s at a temperature of 0°)

Video: Propagation of sound vs. light in case of a volcano eruption

Blowing into a recorder (flute) with air, helium and carbon dioxide
(Schwarzenbacher, Reuter, Czedik-Eysenberg, Oehler 2016)



Speed of sound in air (at a temperature of 0°) and in iron
(Pütz 1973, p. 12)

Good Vibrations

Sound Propagation

Sound needs a **medium** for propagation.

Rule of thumb: The **denser** the molecules are together (the more **solid** the medium) the **faster** is the speed of sound.

Inside a **vacuum no sound propagation** is possible.

A bell inside a vacuum can not be heard (Pütz 1973, p. 11)

Good Vibrations

Take Home Message

Sound needs a **medium** to propagate.

Sound propagation happens in a **spherical wave** from the source.

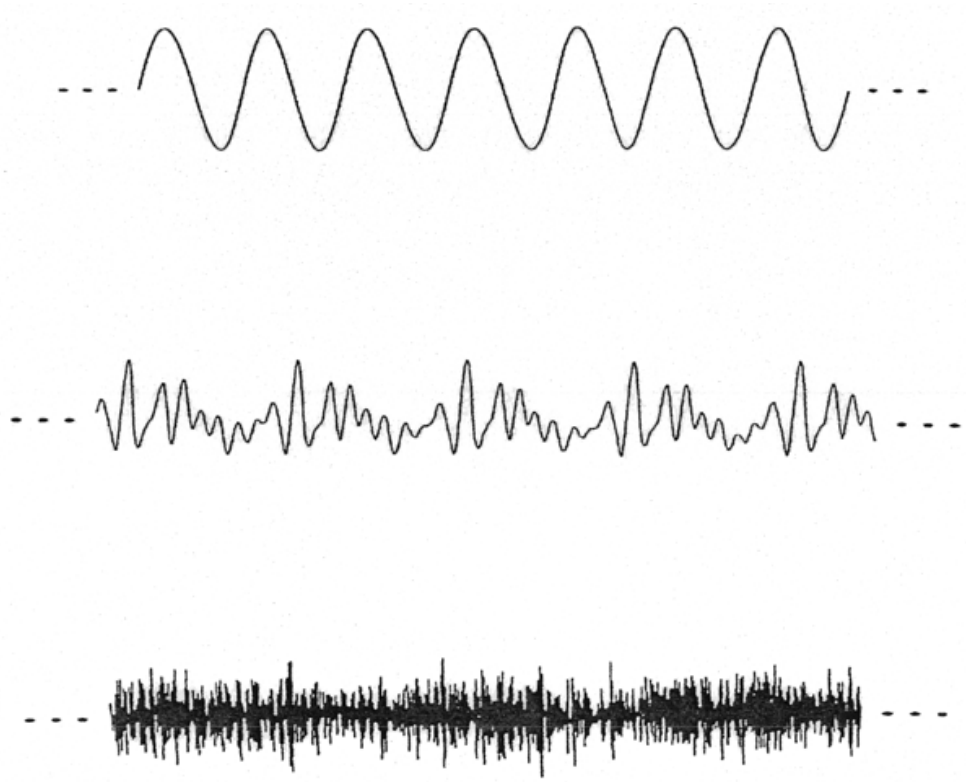
The **speed of sound** in air is **340 m/s**.

At **twice** the **distance** from the sound source, the **amplitude** is **halved**.

Interfering sound waves of the same frequency can **amplify** each other (**constructive interference**, if **in phase**) or **attenuate/annihilate** each other (**destructive interference**, if in **opposite phase**).

Good Vibrations

Pitch and Periodicity



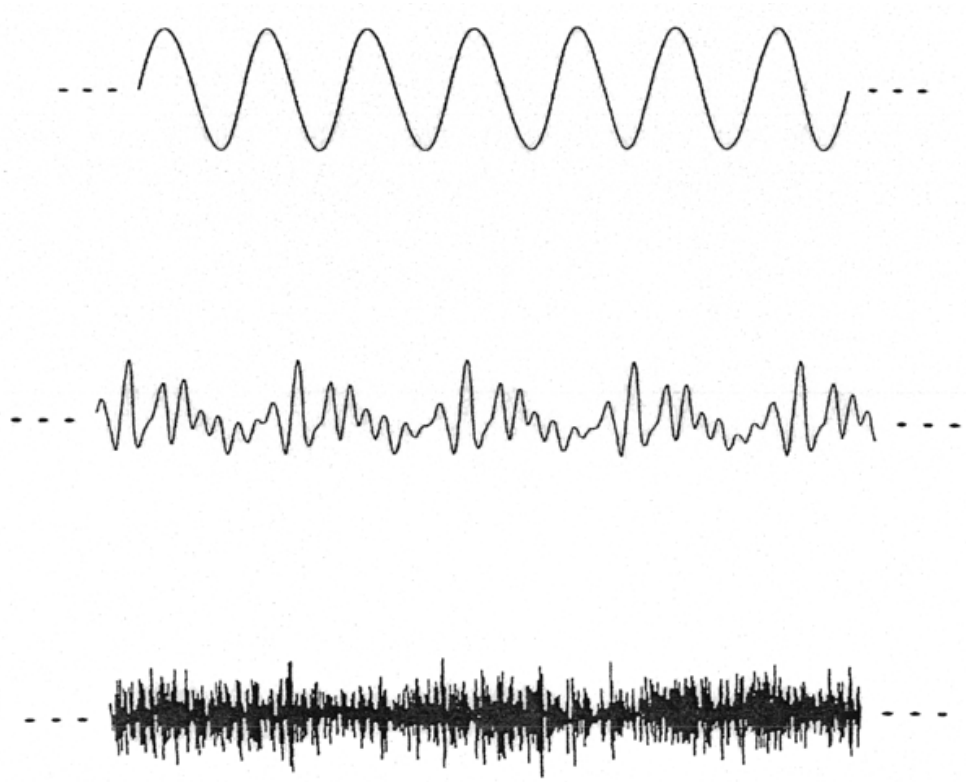
Tone (periodical sine wave),
timbre (periodical complex wave) and
noise (unperiodical waveform) in comparison
(Hellbrück et al. 2004, p. 55)

Good Vibrations

Pitch and Periodicity

Pitch

Whenever something **oscillates periodically** in a frequency between 20 and 20.000 times per second (**in Hz**), we perceive it as a pitch.



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Good Vibrations

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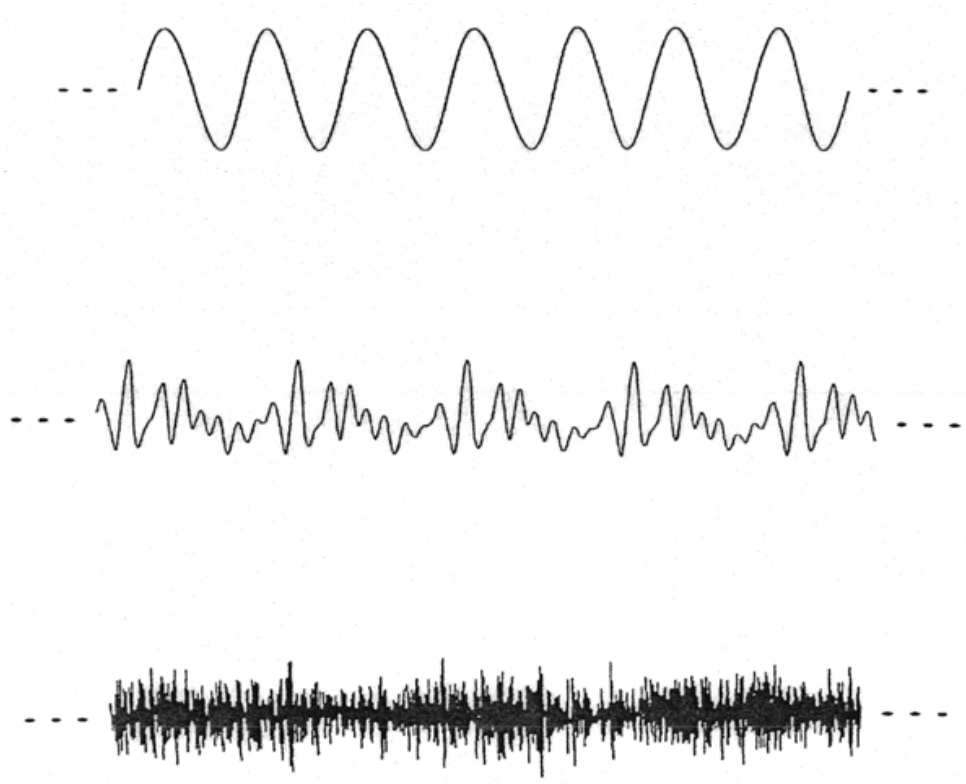
Periodicity

(main reason for pitch perception): Whenever a **repetition** is recognizable inside a waveform, it can be measured as periodicity (**in milliseconds, ms**).



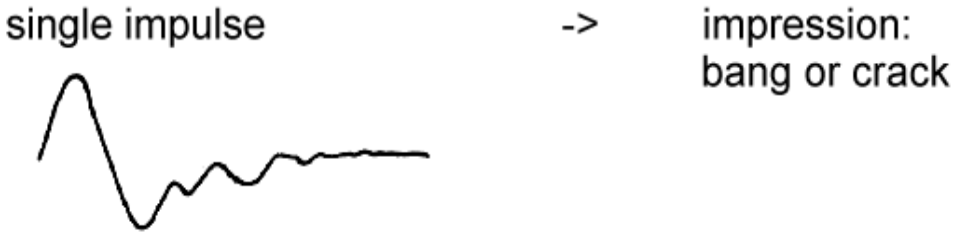
Tone (periodical sine wave), timbre (periodical complex wave) and noise (unperiodical waveform) in comparison (Hellbrück et al. 2004, p. 55)

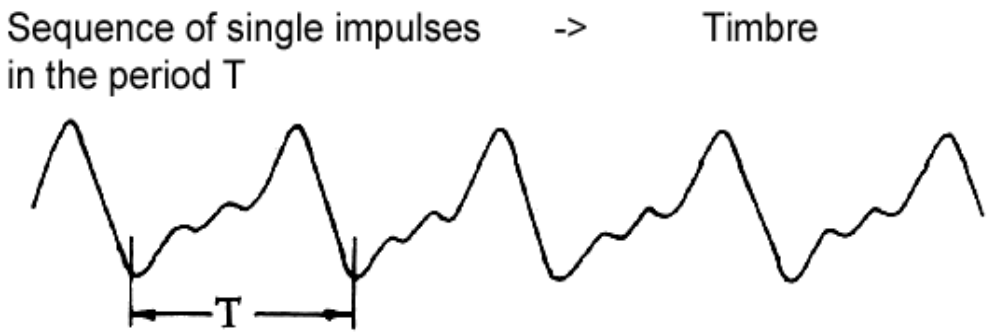
Good Vibrations

Pitch and Periodicity

Single impulse

a single impulse has **no periodicity**. It leads to a sound impression of a **crack** or a **bang** without any pitch.





Single impulse vs. periodical sequence of impulses
(Gieseler, Lombardi, Weyer 1985, p. 15)

Good Vibrations

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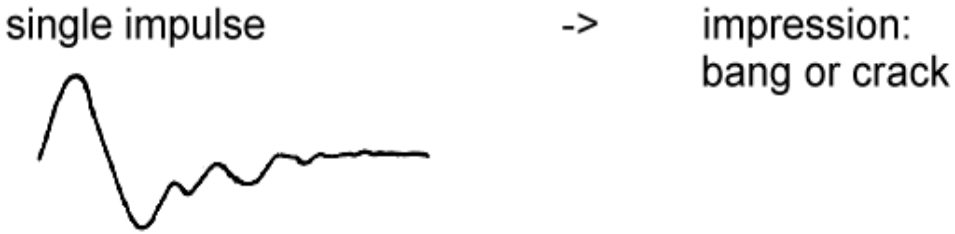
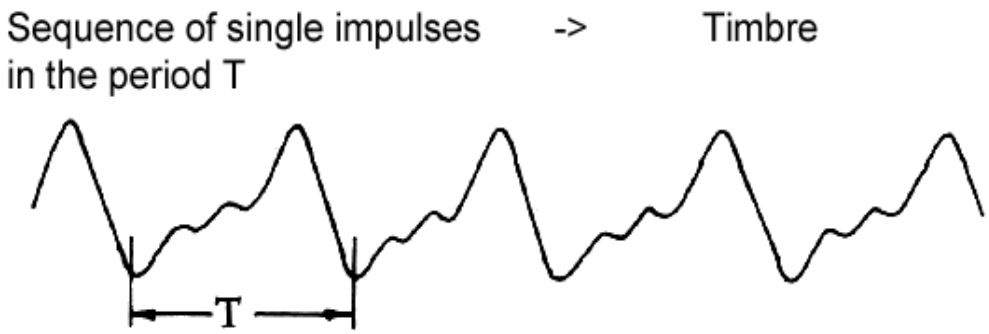


Sequence of single impulses

In a **periodical sequence** of single impulse (all with the same time lag T) a **pitch** is perceptible.



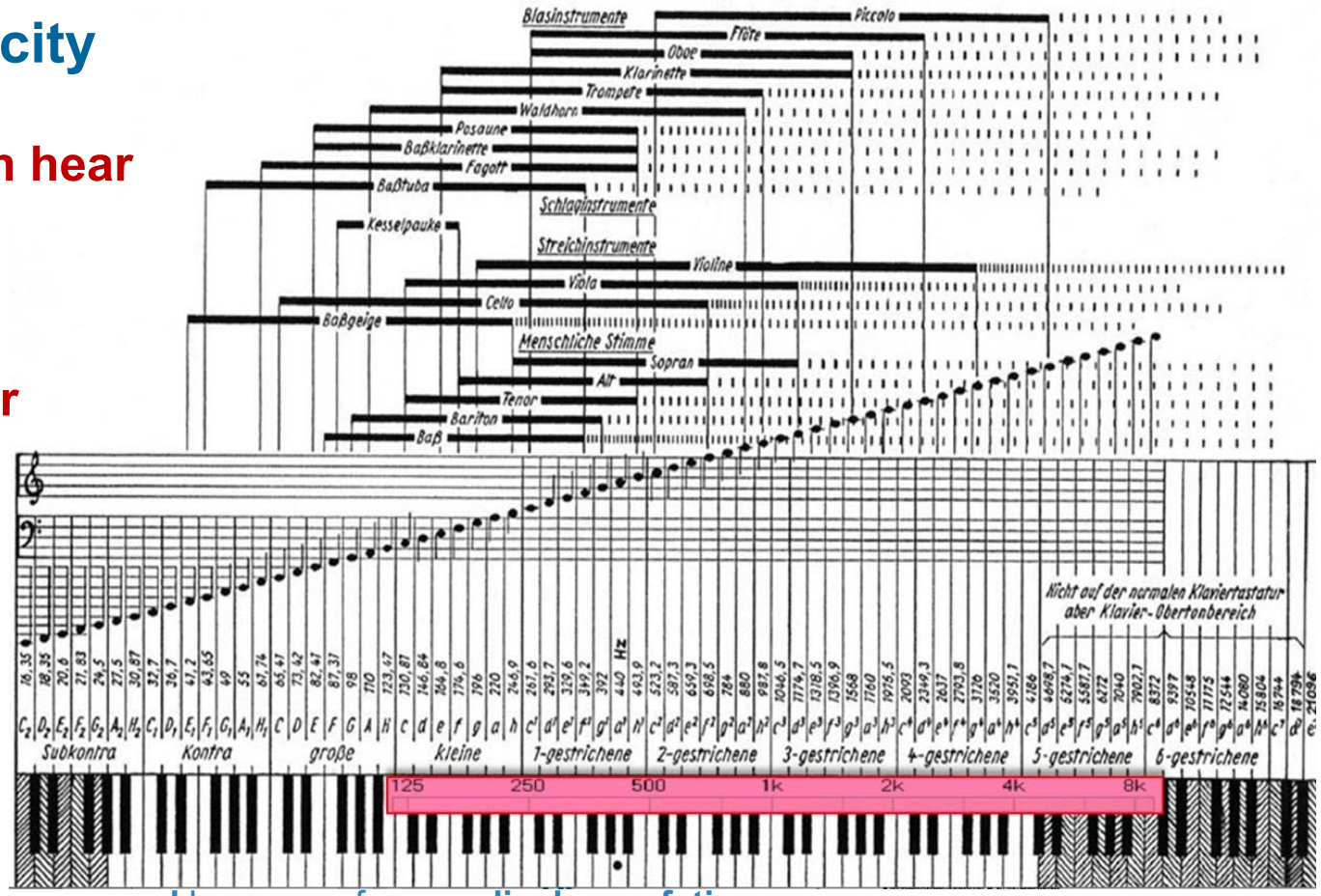
Single impulse vs. periodical sequence of impulses
(Gieseler, Lombardi, Weyer 1985, p. 15)

Good Vibrations

Pitch and Periodicity

Frequencies we can hear
(theoretically)
20 - 20.000 Hz

Pitches we can hear
(musically useful):
50 - 5.000 Hz



Pitches of musical instruments:
50 – 5.000 Hz

Above 5.000 Hz
Our pitch perception **gets compressed** because of **nerve discharge fatigue,** so we are **not able to perceive intervals correctly** in this frequency area.

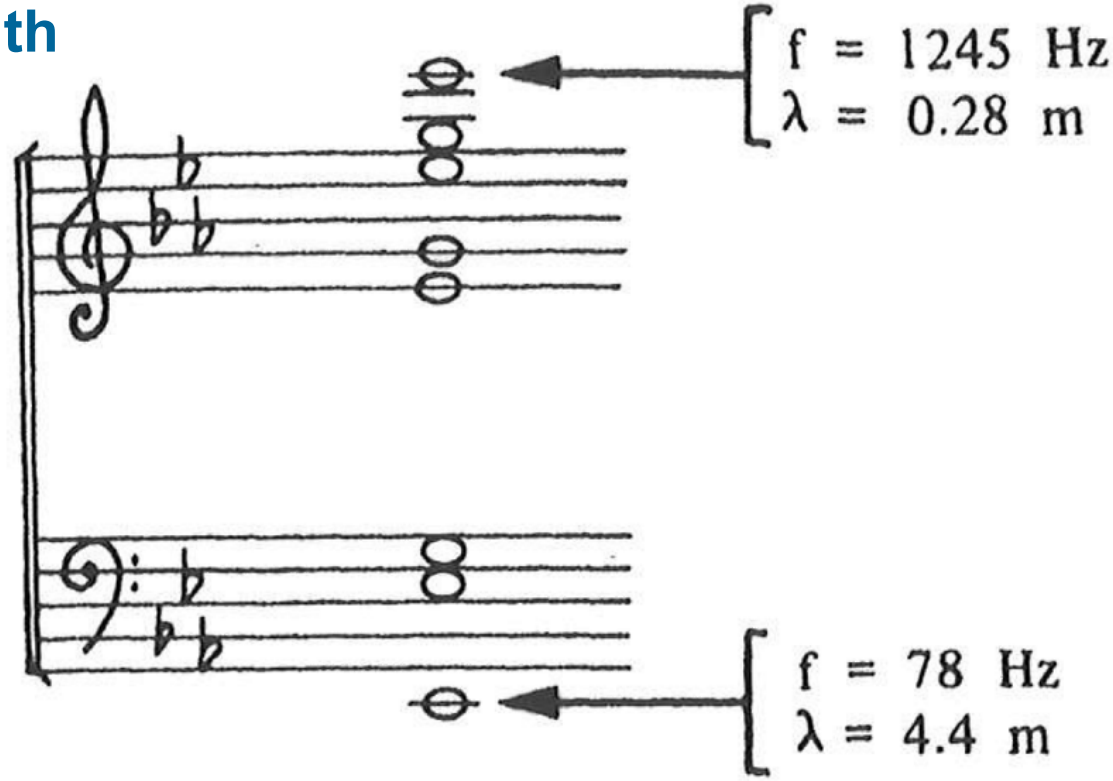
Good Vibrations

Frequency and Wavelength

Since the speed of sound in the air is **340 m/s** at room temperature, the wavelength of **1 Hz ≙ 340** m.

The **wavelengths** of higher frequencies are correspondingly shorter:

10 Hz ≙ 34 m,
100 Hz ≙ 3,4 m,
1.000 Hz ≙ 34 cm,
10.000 Hz ≙ 3,4 cm



Wavelengths and frequencies of the lowest and highest notes in the first chord of Beethoven's Piano Concerto No. 5 (Campbell, Greated 2001, p. 33)

Good Vibrations

Frequency and Wavelength

Relation between speed of sound (c), frequency (f), wavelength (λ), and period (T)

At **340 m/s**: **1 Hz** (frequency) ≙ **1000 ms** or **1 s** (period) ≙ **340 m** (wavelength)

- **Speed of sound (c)** = speed at which a sound pressure fluctuation propagates (**340 m/s**)
- **Period (T)** = time span inside a wave form after the vibration can be mapped back onto itself (**in ms**).
- **Frequency (f)** = Number of periods per second (**in Hz, 1 Hz = 1 period per second**)
- **Wavelength (λ)** = Spatial distance of a period (**in m**)

Period (T)	Wavelength (λ)	Frequency (f)
1 s	340 m	1 Hz
0,1 s (100 ms)	34 m	10 Hz
0,01 s (10 ms)	3,4 m	100 Hz
0,001 s (1 ms)	34 cm	1.000 Hz
0,0001 s (0,1 ms)	3,4 cm	10.000 Hz

Converting the entities:

c = f * λ	or	**c** = λ / T
T = λ / c	or	**T** = 1 / f
f = c / λ	or	**f** = 1 / T
λ = c / f	or	**λ** = c * T

Good Vibrations

Take Home Message

Periodical oscillations between **20 and 20.000** times per second (**Hz**) are perceived as **pitch**

Musically useful pitches and intervals are between **50 and 5.000 Hz**

With the help of the **speed of sound (340 m/s)**, **wavelength and frequency** can be converted into each other.

Rule of thumb: **1 Hz ≙ 340 m, 1.000 Hz ≙ 34 cm**

Period (T)	Wavelength (λ)	Frequency (f)
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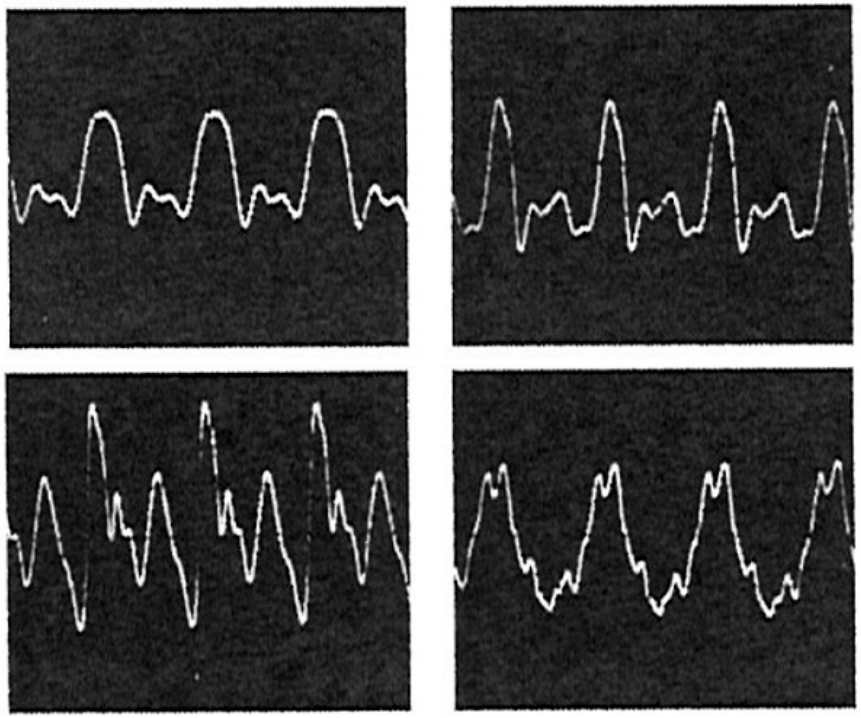
Converting the entities:

$c = f * \lambda$	or	$c = \lambda / T$
$T = \lambda / c$	or	$T = 1 / f$
$f = c / \lambda$	or	$f = 1 / T$
$\lambda = c / f$	or	$\lambda = c * T$

Good Vibrations

Timbre

While in **textbooks** acoustic processes are mostly represented by **sine waves**, in **nature** one is almost exclusively confronted with **complex waveforms**.



Waveforms of the timbres of different musical instruments played in A4 (440 Hz):
a) Flute, b) Trumpet, c) Saxophone, d) Violine
(Hall 1997, p. 39)

Good Vibrations

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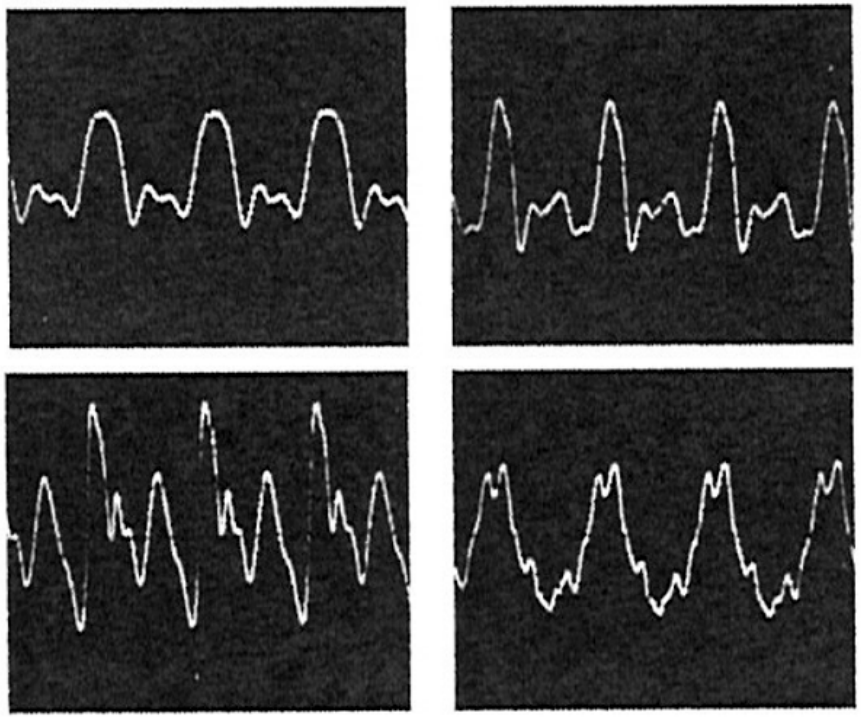
Different **timbres** are more or less represented by different **waveforms** (while pitch, amplitude and durations are **remaining the same**).



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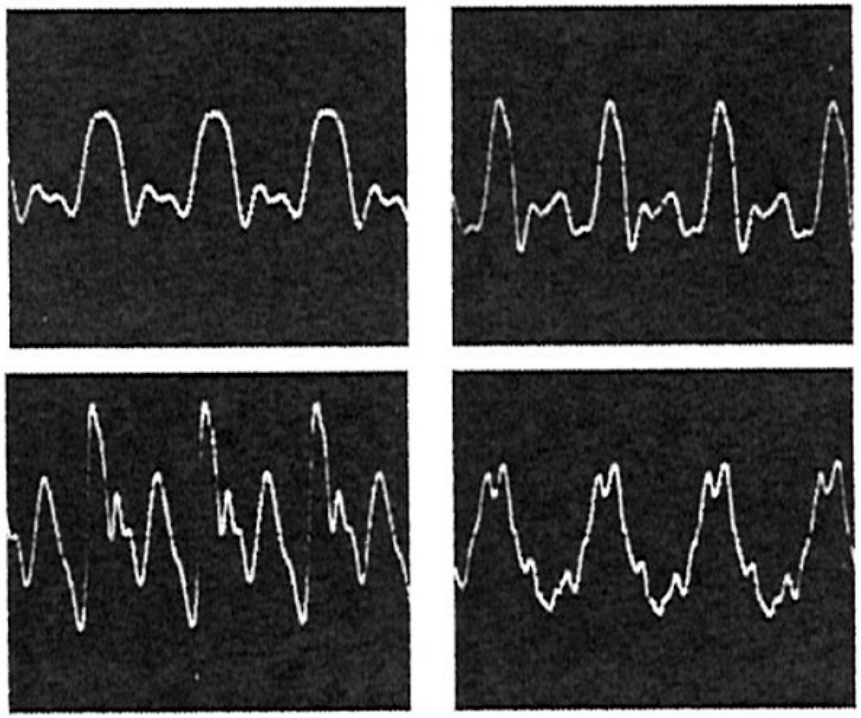
Different **timbres** are more or less represented by different **waveforms** (while pitch, amplitude and durations are **remaining the same**).

These **complex waveforms** can be computationally **decomposed** into a **number of sine waves** with different amplitudes and phase relationships.



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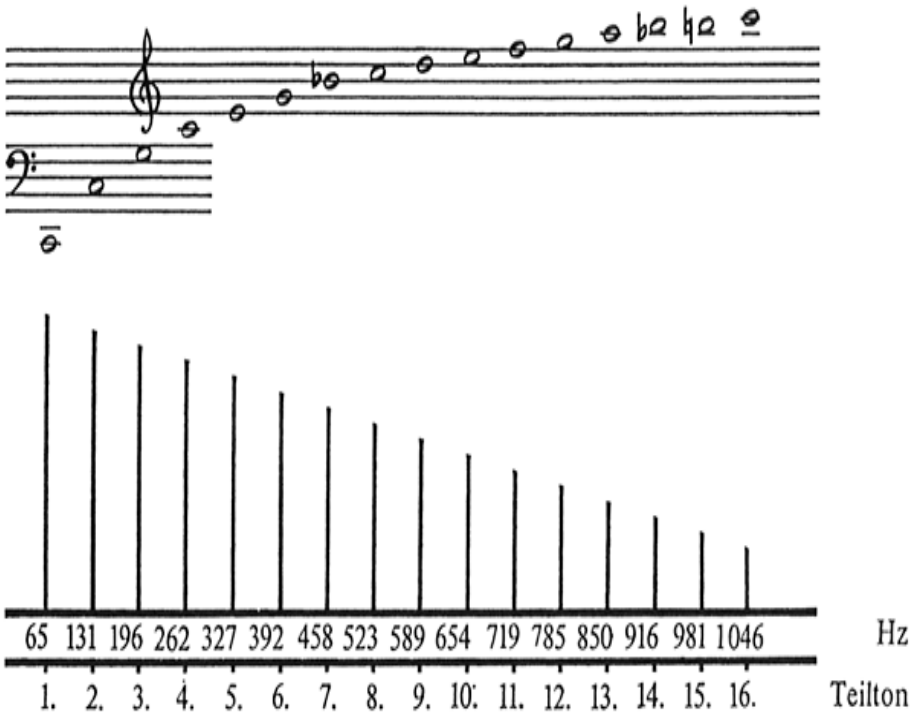
Good Vibrations

Timbre

Each **complex periodic waveform** can be decomposed into its **individual partials** with their respective amplitudes.

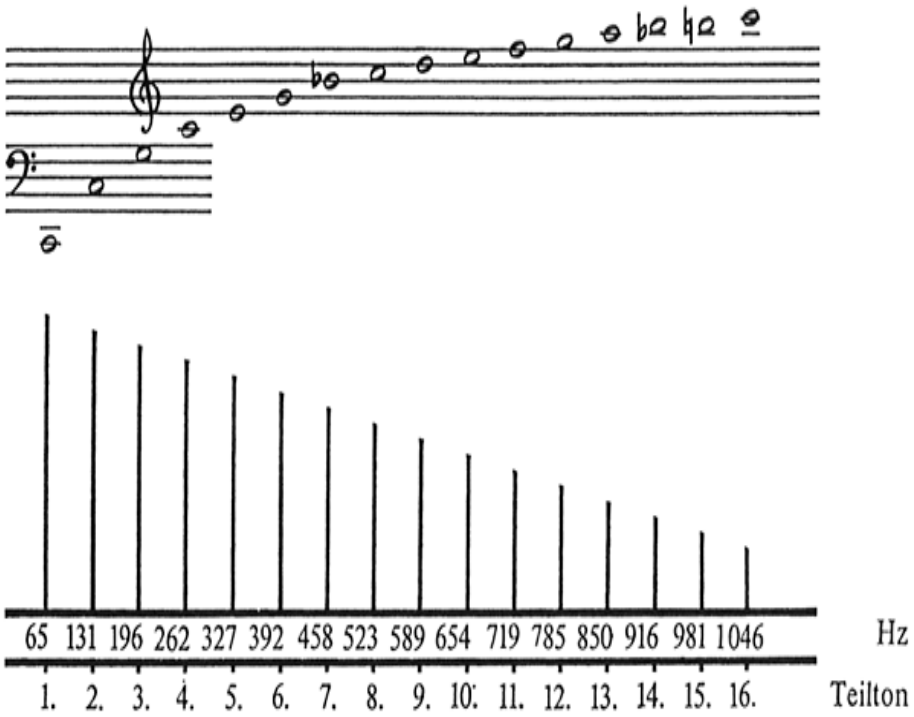


Series of partials in a schematic line spectrum built up as integer multiples of a fundamental of 65 Hz (Winckel 1960, p. 12; Seidner, Wendler 1997, p. 34)

Good Vibrations

Timbre

Each **complex periodic waveform** can be decomposed into its **individual partials** with their respective amplitudes. For **periodic waveforms**, these partials are **integer multiples** of the **fundamental frequency**.



Series of partials in a schematic line spectrum built up as integer multiples of a fundamental of 65 Hz (Winckel 1960, p. 12; Seidner, Wendler 1997, p. 34)

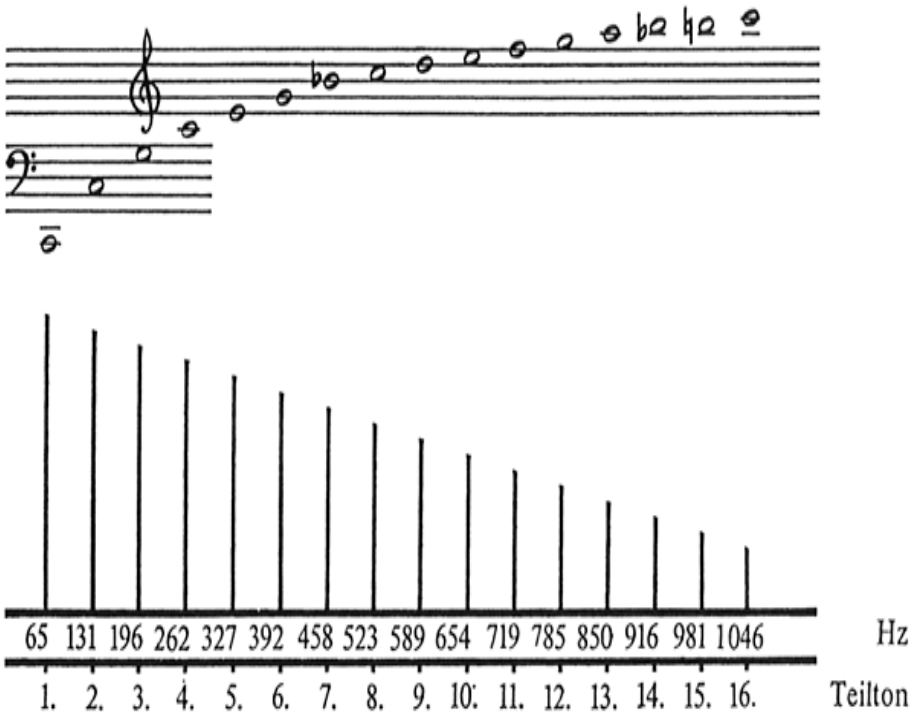
Good Vibrations

Timbre

Each **complex periodic waveform** can be decomposed into its **individual partials** with their respective amplitudes. For **periodic waveforms**, these partials are **integer multiples** of the **fundamental frequency**.

Timbre is – strictly speaking – the result of the **number** and **amplitudes** of the **partials** of a sound (**sound spectrum**).

(of course, there is even more to it such as amplitude envelopes, modulations, roughness and dynamic changes, but when it comes to timbre on the first hand the spectrum is mentioned)



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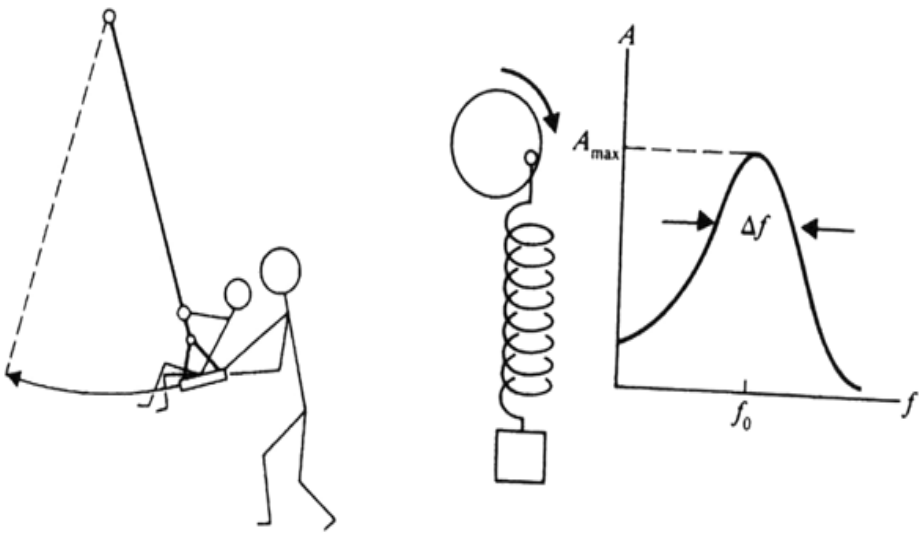
Good Vibrations

Resonance

Resonance is a process in which an oscillatory system is excited externally via its **natural frequency**, whereby the **systems amplitude** can **increase** as many times **higher** than the **amplitude of the exciting oscillation**.



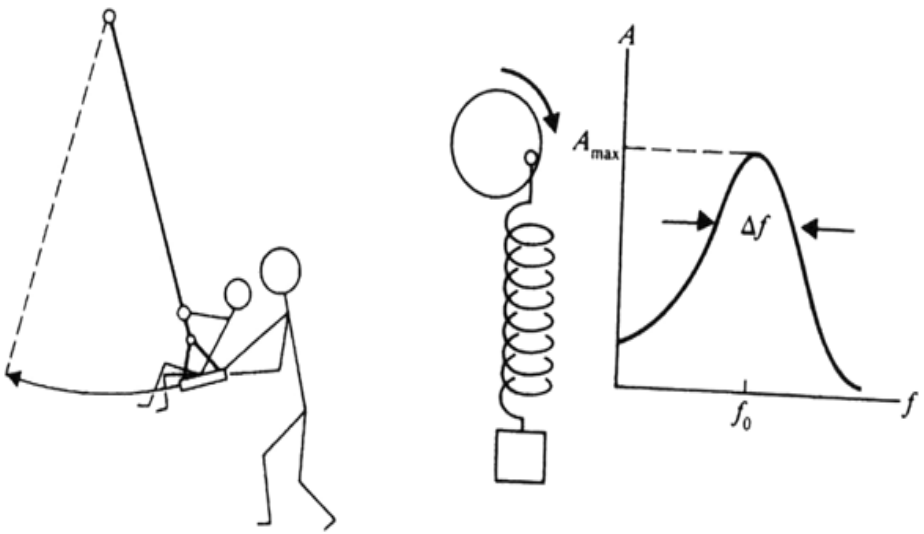
Classic example for resonance excitation:
The child in the swing. Periodically excited spring-mass system with a natural (= resonance) frequency f_0
(Rossing, Moore, Wheeler 2002, p. 60-61)

Good Vibrations

Resonance

Resonance is a process in which an oscillatory system is excited externally via its **natural frequency**, whereby the **systems amplitude** can **increase** as many times **higher** than the **amplitude of the exciting oscillation**.

The greater the difference between the exciting frequency and resonant frequency, **the weaker the resonance**.



Resonance at a wine glass sung from close up
(Acoustic Camera, Vienna Musicology 2019)

Classic example for resonance excitation:
The child in the swing. Periodically excited spring-mass system with a natural (= resonance) frequency f_0
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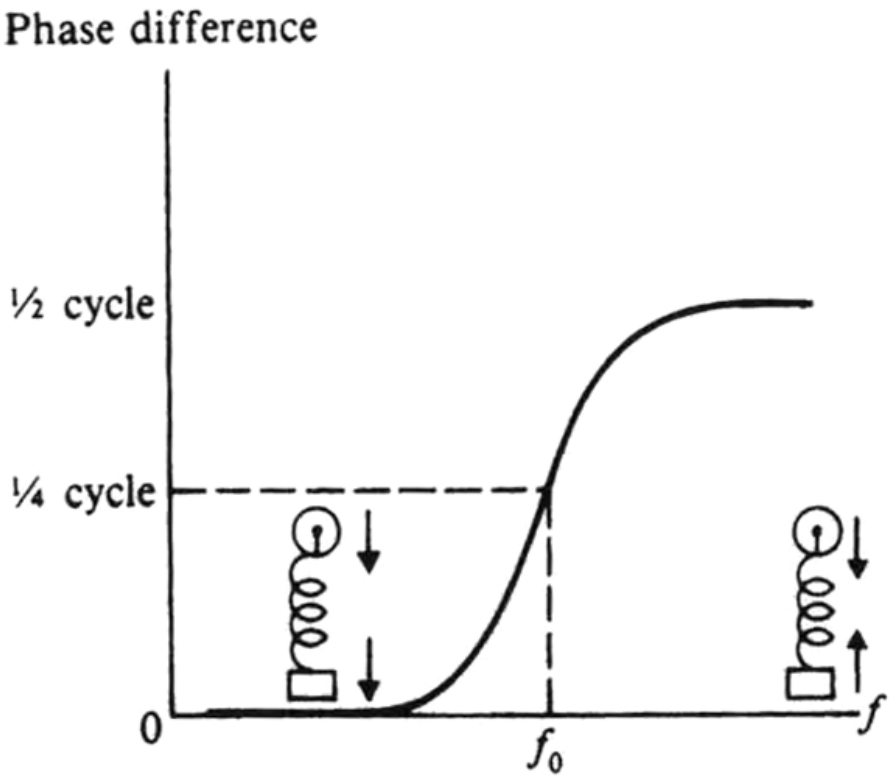
Good Vibrations

Resonance

Maximum excitation or energy transfer occurs at a **phase difference of 90°** between exciting frequency and natural frequency.



The best energy transfer occurs with a delay of one quarter of the circular motion = a phase shift of 90° between exciting frequency and resonance frequency f_0 (Rossing, Moore, Wheeler 2002, p. 60-61)

Resonance catastrophe in a wine glass (Reuter, Eder, Krayncz 2019, P.M. Wissen)

Good Vibrations

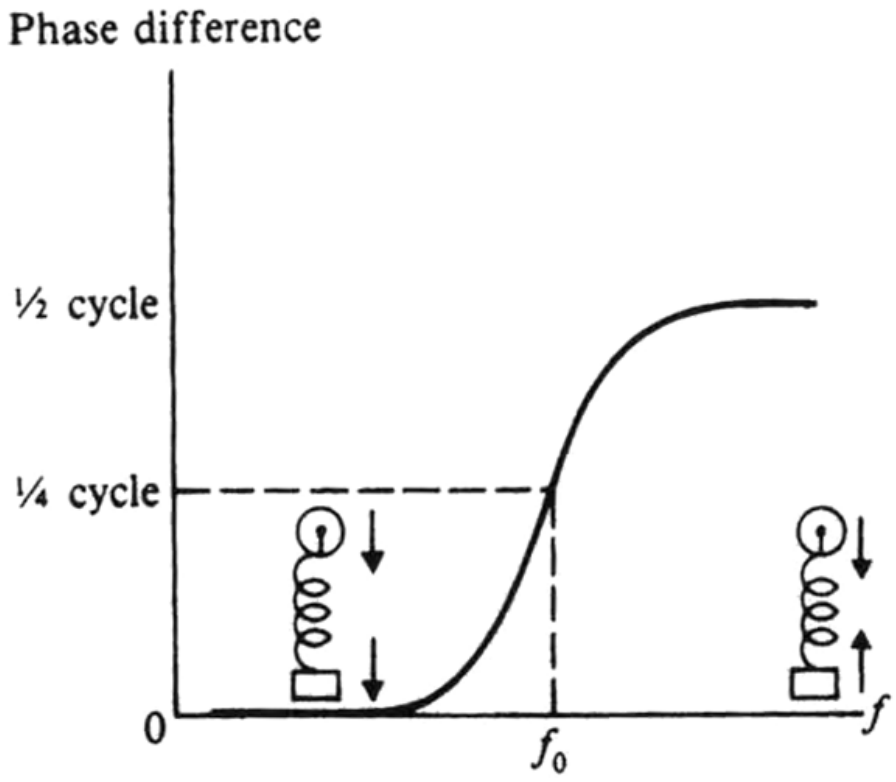
Resonance

Maximum excitation or energy transfer occurs at a **phase difference of 90°** between exciting frequency and natural frequency.

Excitation frequency < resonance frequency
-> **no resonance**: **in-phase** resonators oscillation in the **same amplitude**.

Excitation frequency = resonance frequency
-> **Resonance**: resonators oscillation builds up more and more, **phase delay** between excitation and resonance frequency by **90°**.

Excitation frequency > resonance frequency
-> **no resonance**: **anti-phase** resonators oscillation in a **much lower amplitude**.



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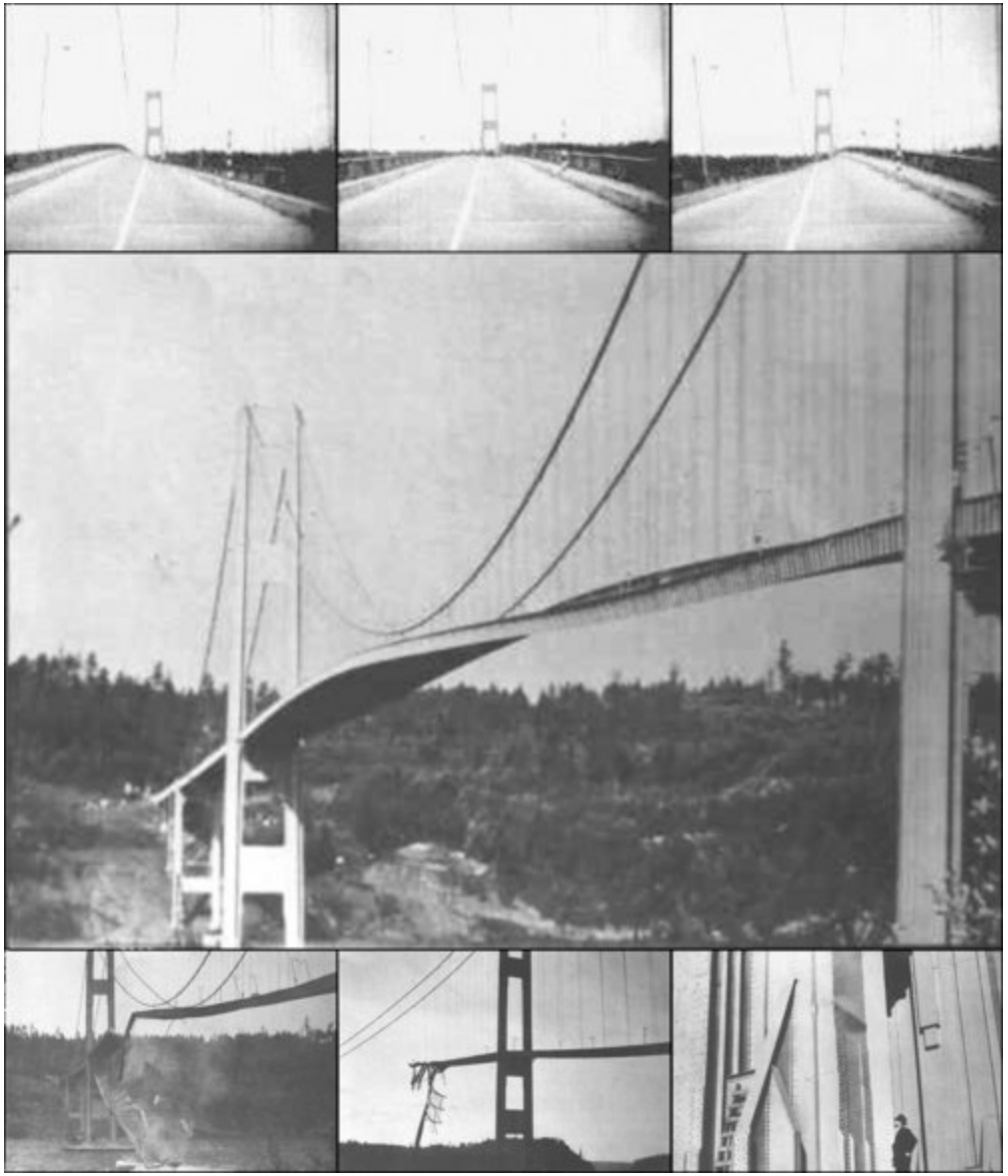
Resonance catastrophe in a wine glass (Reuter, Eder, Krayncz 2019, P.M. Wissen)

Good Vibrations

Resonance

If the **resonance is too strong**, a whole system can be **destroyed** only by oscillations, such as the Tacoma Narrows Bridge.



Resonance catastrophe at the Tacoma Narrows Bridge (7.11.1940)

Good Vibrations

Take Home Message

Tone = (periodical) **sine wave** between 20 and 20.000 Hz

Noise = **unperiodical** wave **without** pitch, **without** periodicity.

Timbre = mainly characterized by the shape of a **periodic complex waveform**, which can be decomposed mathematically into a number of **partials** (integer multiples of the fundamental frequency) with different **distinctive amplitudes**.

Resonance = vibrating systems have **natural frequencies**, which can be excited by external oscillations in the **same frequency**. During a resonance process a systems **amplitude** can **increase as many times higher** than the amplitude of the exciting oscillation.

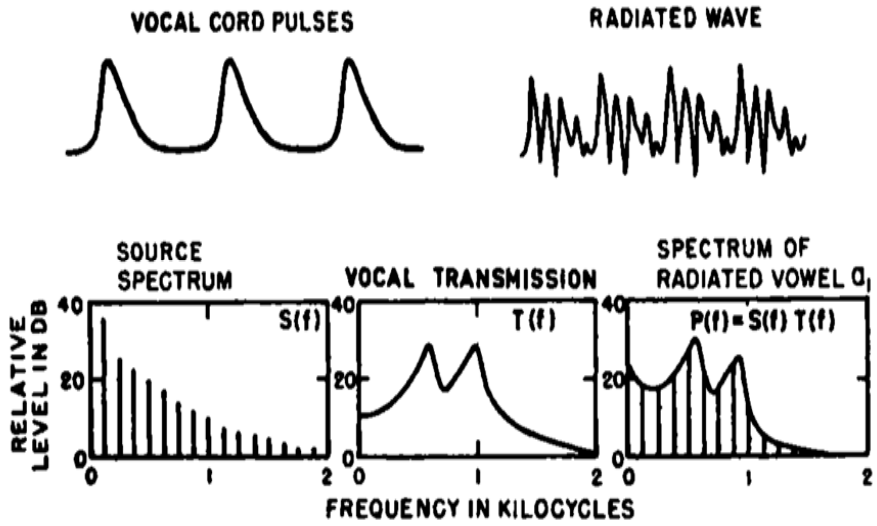
Resonance is able to **destroy** a whole system just by **oscillation**.

Good Vibrations

Voice

Basic principle of sound production in voices and musical instruments is the **Source-Filter-Model**:

$$S_{(f)} * D_{(f)} * R_{(f)} = A_{(f)}$$



Simplified source-filter decomposition of the spectrum of a two-formant voiced speech sound (Fant 1960, p. 19)

Good Vibrations

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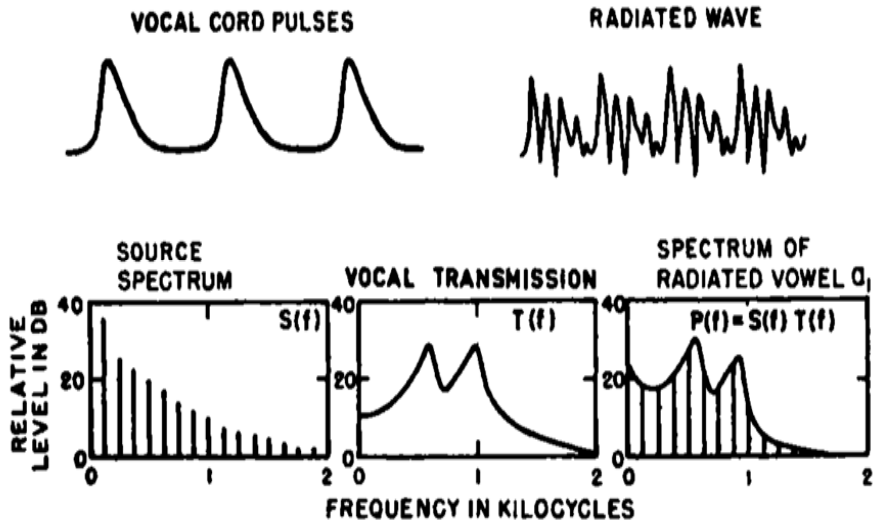

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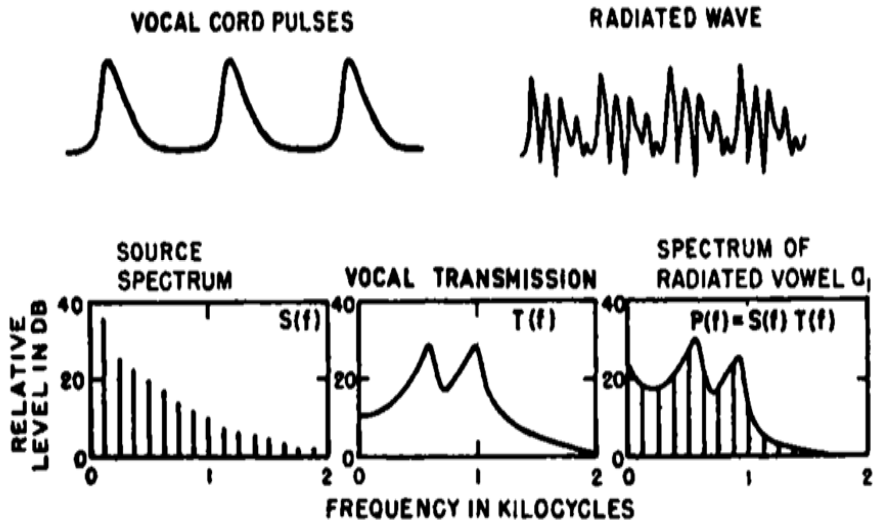

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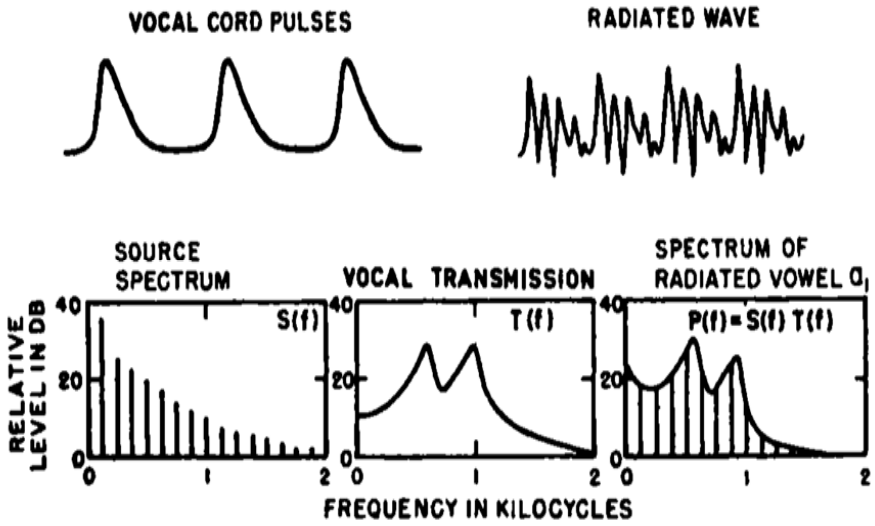

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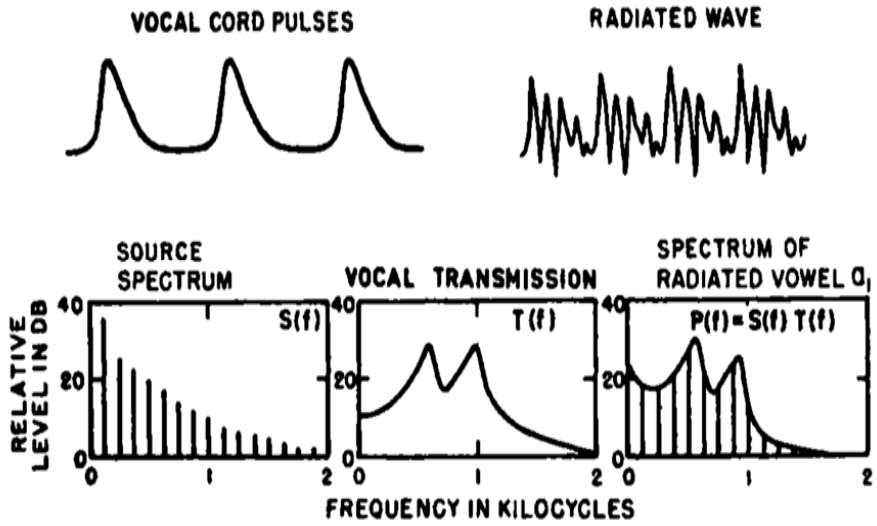
A = resulting **Amplitude** of one **single frequency f** of a spectrum



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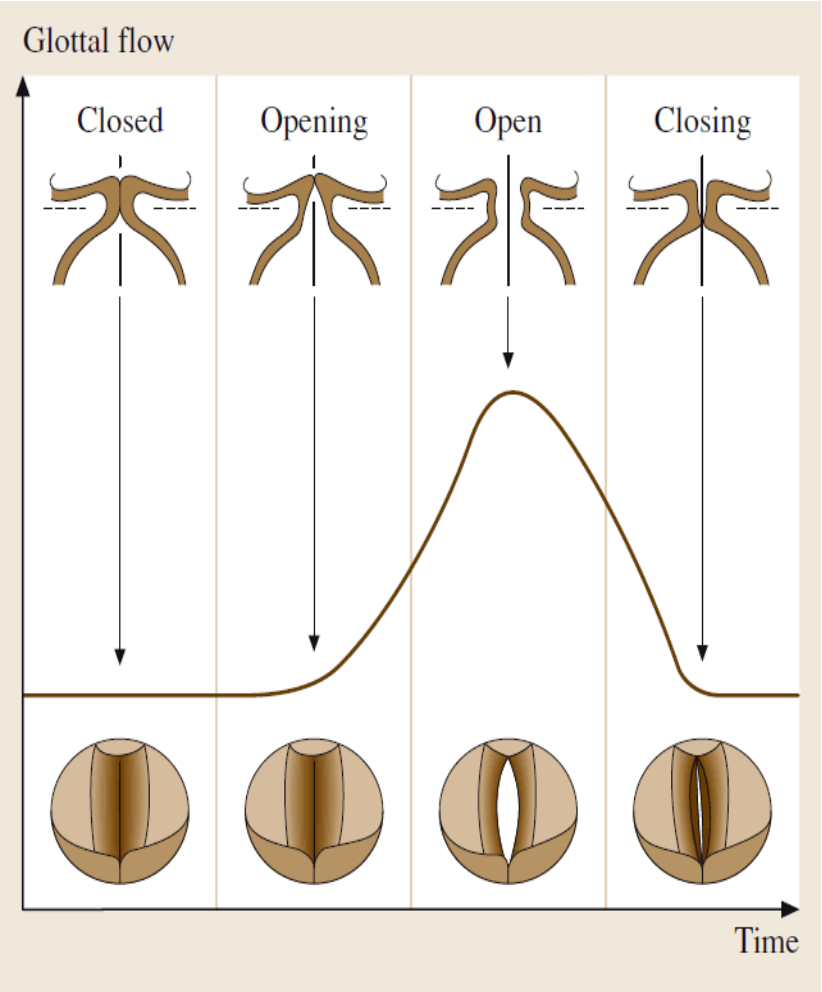
Voice - Source

1.) In the larynx: An **airflow** is forced from the lungs between two **almost closed vocal folds** (to generate the source spectrum for vowels and voiced sounds).



Vocal chords movement and air flow
(as seen from the side and from above)
(Rossing 2007, p. 677)

Good Vibrations

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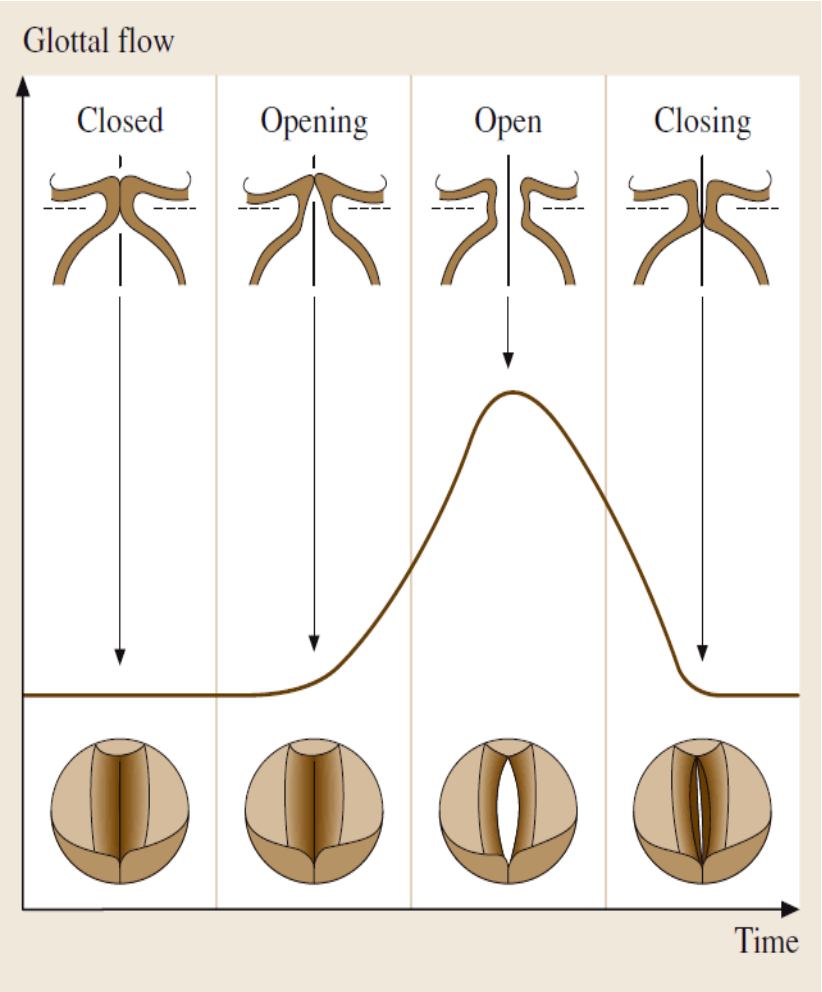
2.) **Large pressure** in the trachea escapes through a **small opening**
–> **Bernoulli Effect:** air escapes at **high speed**, causing a **negative pressure** between the vocal folds, which contract again –> air flow is **interrupted**.



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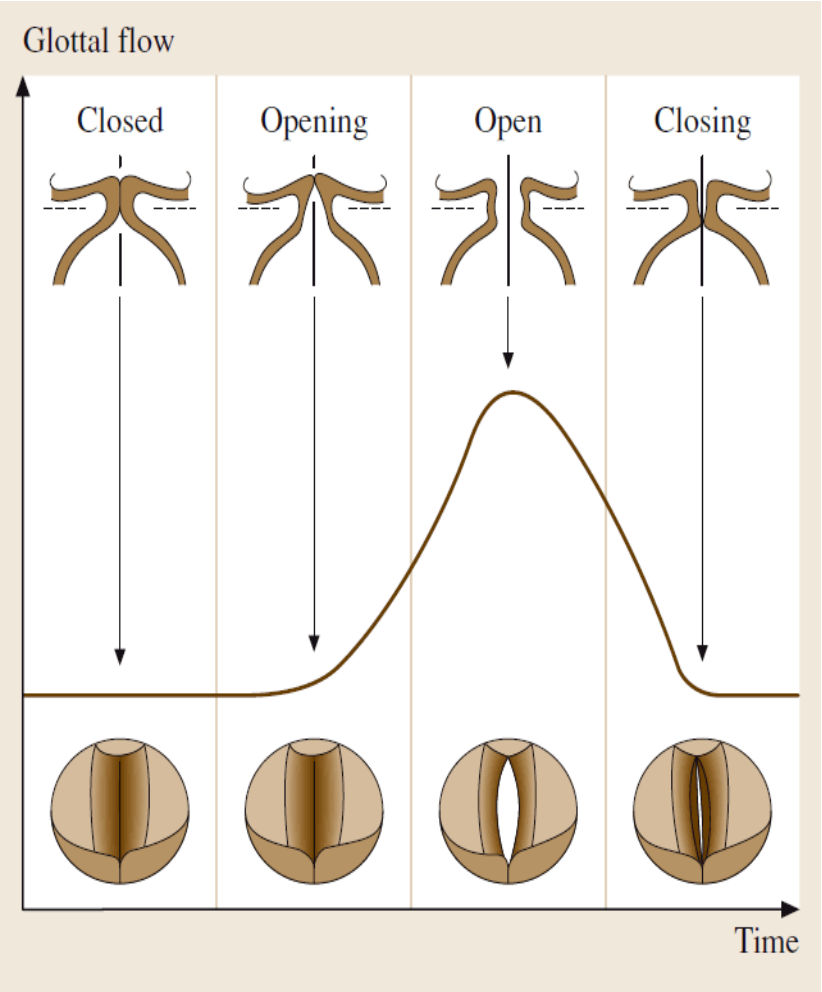
3.) **Higher pressure** develops in the larynx between the contracted vocal folds again
-> vocal folds open again, new air flows out, **repetition** of the process, etc.



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Good Vibrations

Voice - Deviation

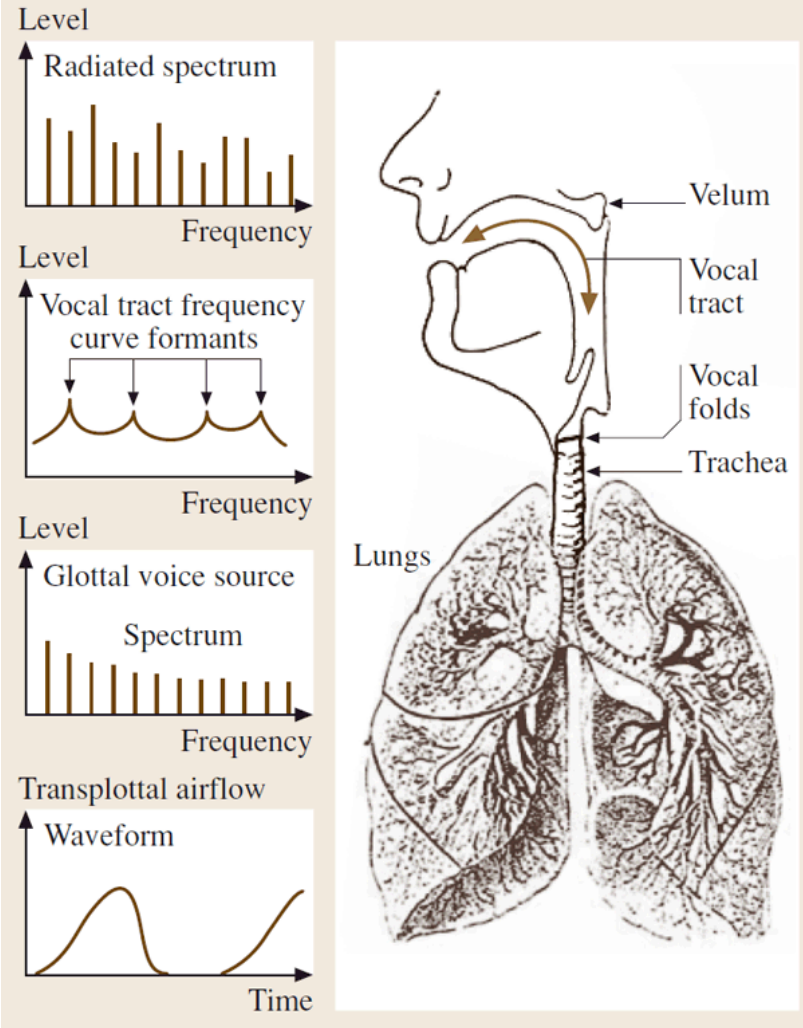
Vocal tract in relaxed mode works **like a stopped organ pipe** with a length of **17 cm**.

One can calculate the **resonance frequencies** (and all **uneven multiples**) of a stopped pipe via the speed of sound:

$$f = c/4L$$

(frequency (f) = speed of sound (c) devided by 4 times the length (L) of the pipe)

f = 340 m/s / 4*17 cm
= 34.000 cm/s / 68 cm
= 500 * 1/s = **500 Hz** (and all uneven multiples)



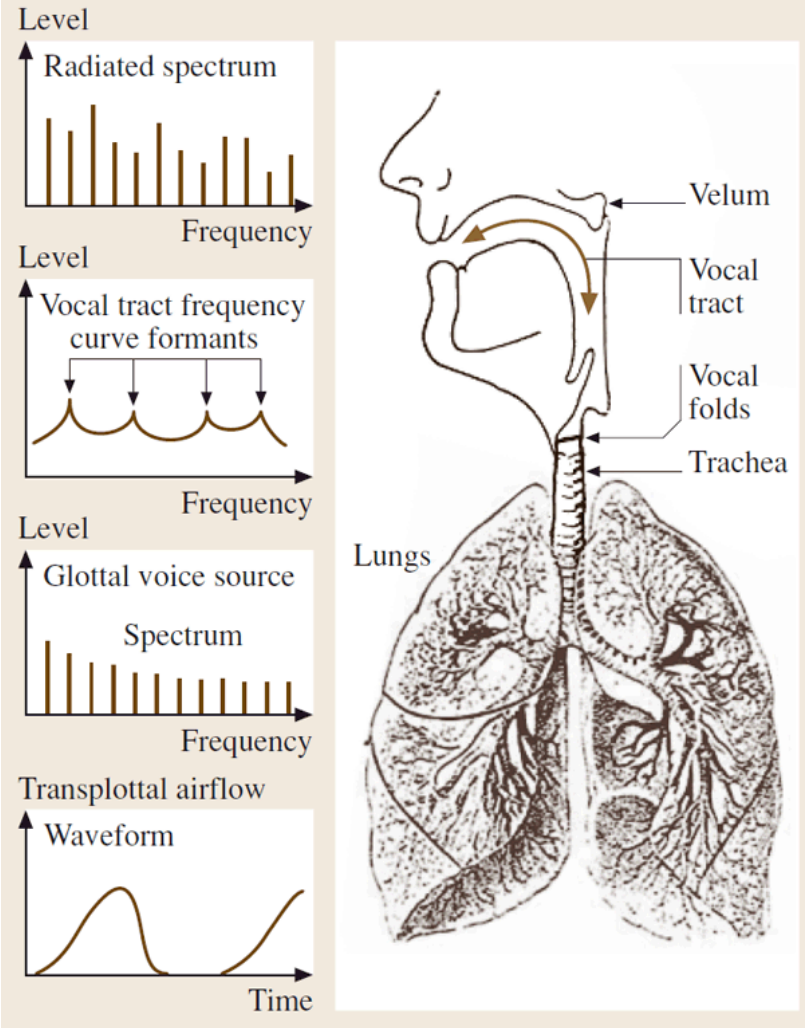
Source-filter theory in voice production: shaping the sound in the vocal tract (Sundberg 1994, p. 46; Rossing 2007, p. 682)

Good Vibrations

Voice - Deviation

Resonance frequencies in the vocal tract produce the **formant frequencies** in the vowel spectrum.

With any **deformation of the vocal tract** the resonance frequencies (≙ formant frequencies) **get shifted** in the corresponding direction.



Source-filter theory in voice production: shaping the sound in the vocal tract (Sundberg 1994, p. 46; Rossing 2007, p. 682)

Good Vibrations

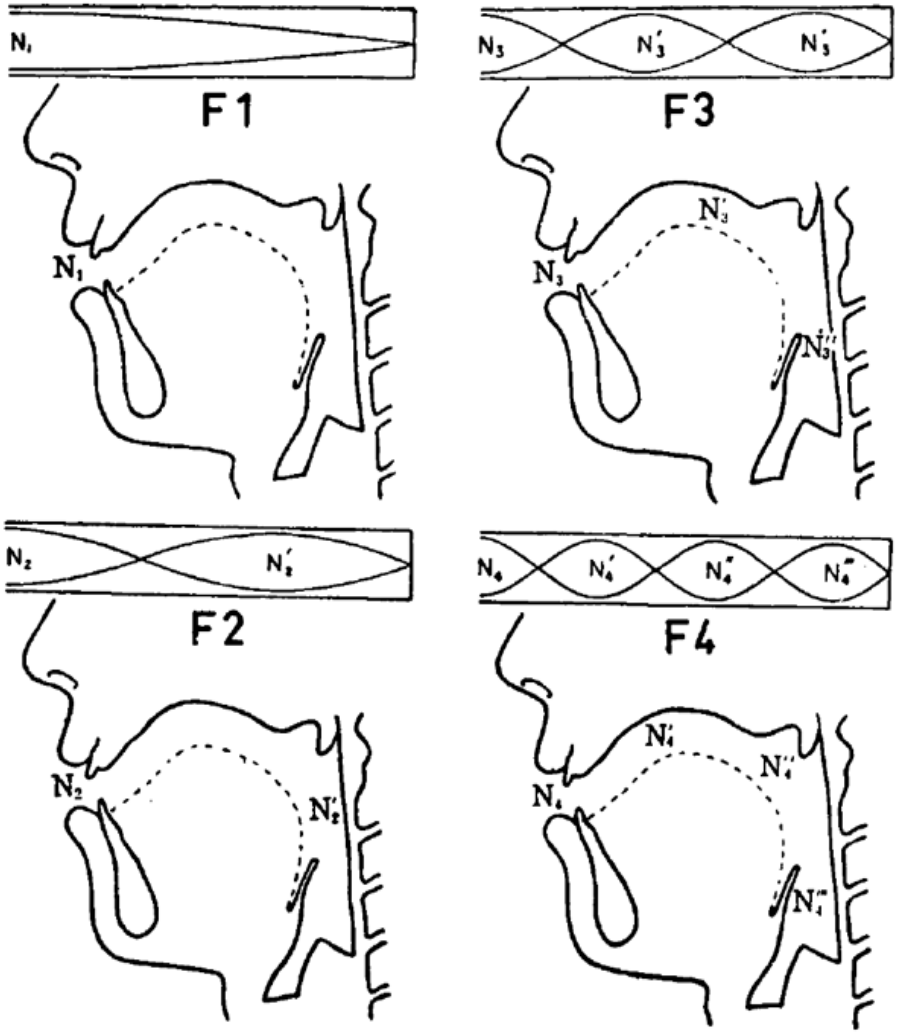
Voice - Deviation

Vowels can be distinguished on the basis of the first **two formants** (F1 and F2) only:

F1 = depends on the position of the **lower jaw**: the lower the jaw, the higher F1

F2 = depends on **jaw** and **tongue** position: the further forward the tongue, the higher F2

With the help of the software **VTDemo**
(by Mark Huckvale, University College London)
it is possible to synthesize vowels and consonants via altering the cross section of an artificial vocal tract.



Positions of resonance frequencies for F1-F4 in relaxed vocal tract
(Fant 1960, p. 85, after Chiba & Kajiyama 1941)

Good Vibrations

Voice - Deviation

Fun Fact ☺

How does the voice change under helium?

Good Vibrations

Voice - Deviation

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How does the voice change under helium?

The **speed of sound becomes faster** under helium.

Good Vibrations

Voice - Deviation

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That means: **Resonance frequencies** in the vocal tract shift **upwards** -> Voice changes in **Timbre**
Vocal cord vibration remains the same (oscillates independent from the gas in the vocal tract) -> **Pitch does not change**.

Good Vibrations

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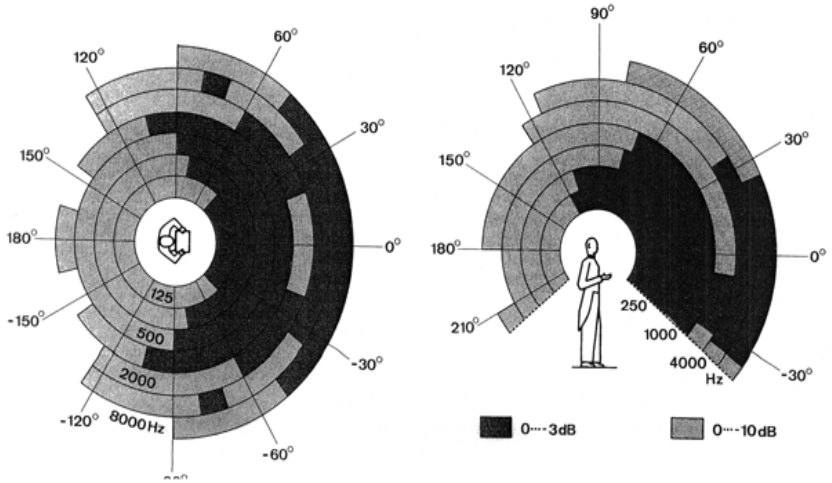
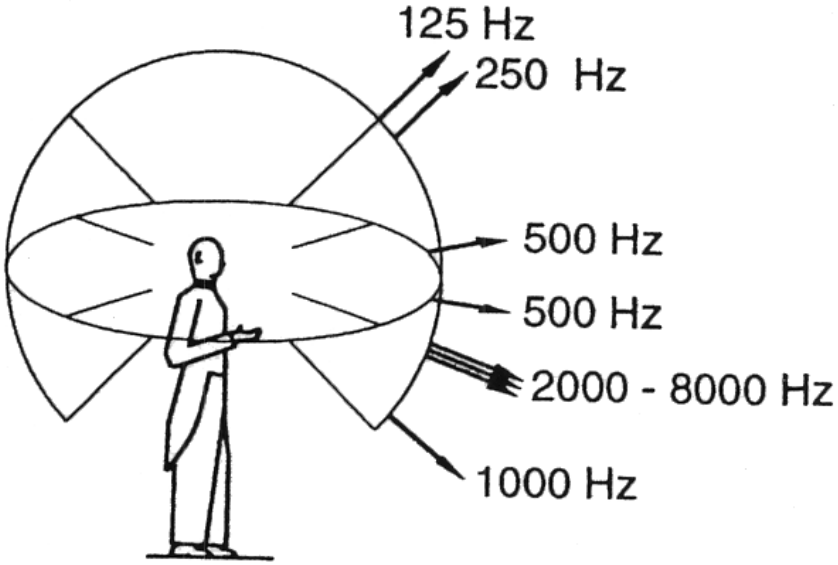
Fun Fact II: Similar results (but in opposite direction) one can get with Sulfurhexaflourid

Good Vibrations

Voice - Radiation

Rule of thumb: Musical instruments are far **too small** for the radiation of their **lowest frequencies**.





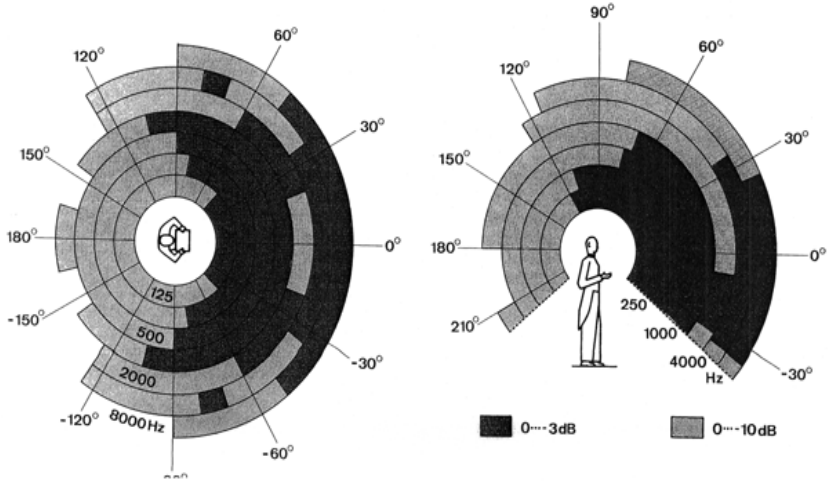
Sound radiation of the human voice
(Meyer 2015, p. 141 and 142)

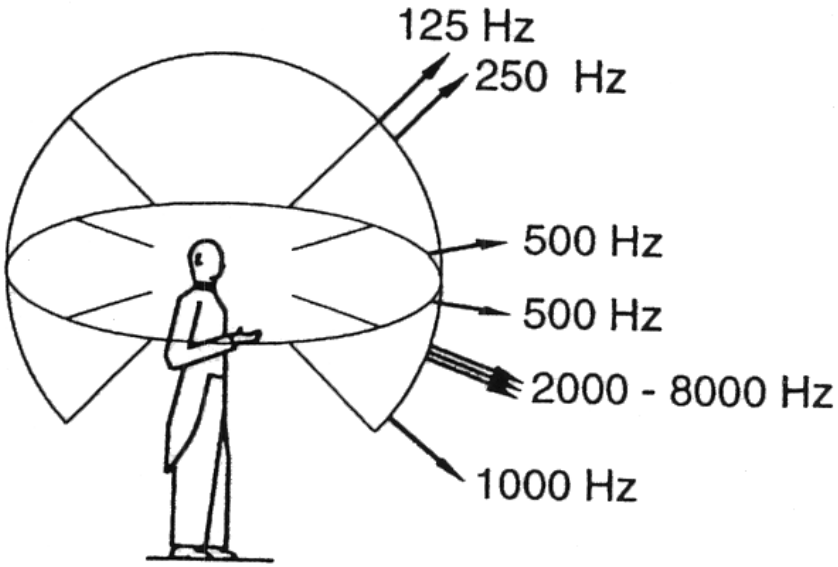
Good Vibrations

Voice - Radiation

Rule of thumb: Musical instruments are far **too small** for the radiation of their **lowest frequencies**.

Same holds for the human voice:
- **Low frequencies** are radiated spherically in **all directions**.
- **Medium / high frequencies** are radiated more and more **directionally** with increasing value





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Good Vibrations

Take Home Message

Source-Filter-Model: Basic principle of sound production in voices and musical instruments: $\mathbf{S_{(f)} * D_{(f)} * R_{(f)} = A_{(f)}}$

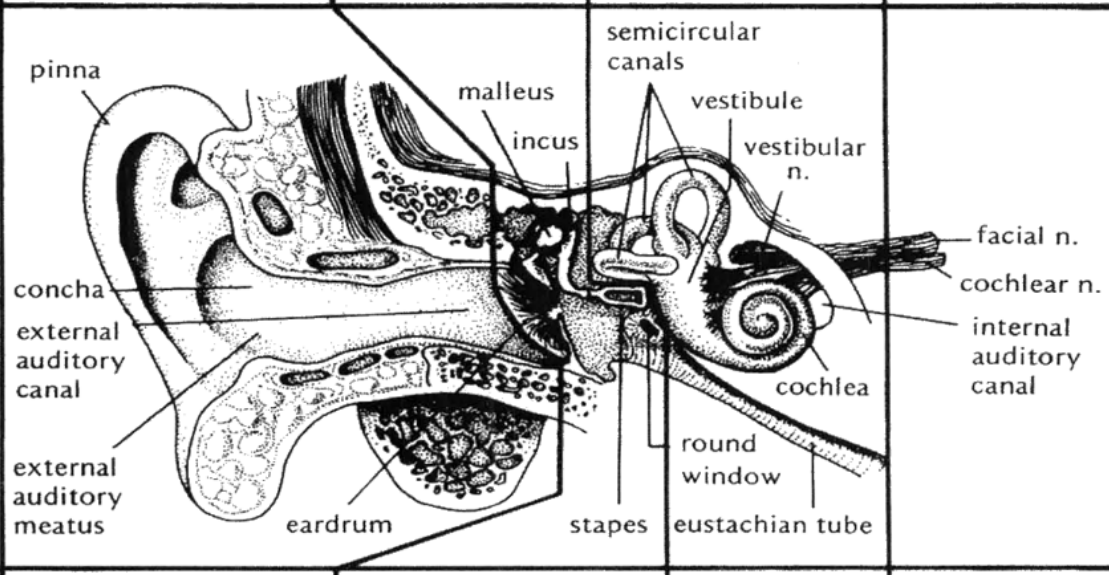
Bernoulli Effect at the sound source **(S)**: inversely proportional ratio of **pressure** and **flow velocity**, leads to a closing of the vocal folds because of **negative pressure**, when air flows between them in a **high velocity** (common effect observable at **nearly all wind instruments**, also at aircraft wings etc.).

Vocal tract resonances shape the spectrum of the glottal voice source = forming **formant regions** (**F1 and F2** are enough to identify/synthesize **vowels**).

Radiation of the sound is **frequency dependent**: the **higher** the frequency the **more directional** is the sound radiation

Good Vibrations

Ear

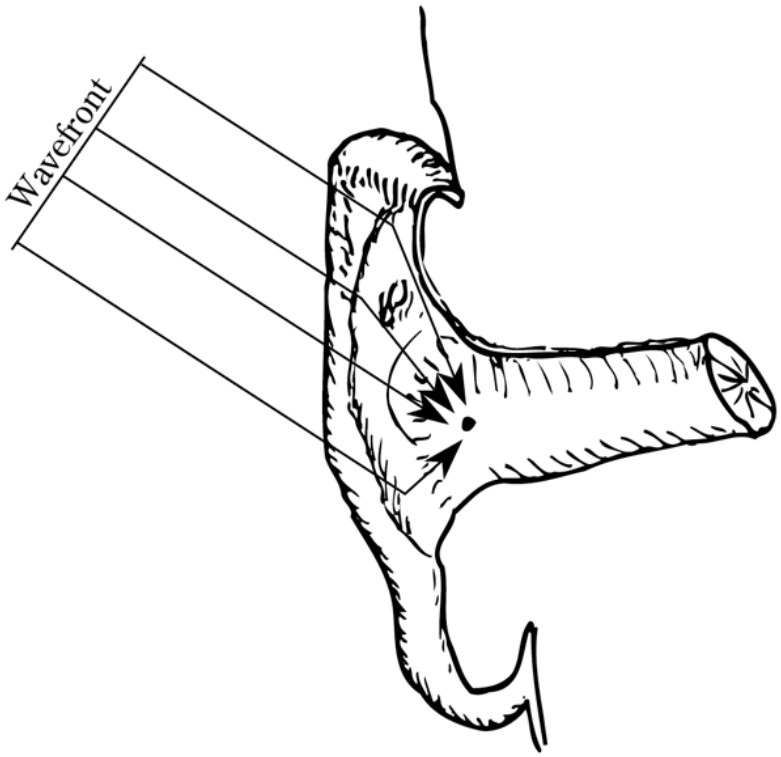
Gross division	*Outer ear*	*Middle ear*	*Inner ear*	*Central auditory nervous system*
Anatomy				
Mode of operation	*Air vibration*	*Mechanical vibration*	*Mechanical, Hydrodynamic, Electrochemical*	*Electrochemical*
Function	*Protection, Amplification, Localization*	*Impedance matching, Selective oval window stimulation, Pressure equalization*	*Filtering distribution, Transduction*	*Information processing*

Anatomy, operational mode and function of the outer, middle and inner ear
(Yost 2007, p. 68)

Good Vibrations

Ear - Outer Ear

The task of the **auricle** is to **conduct** the sound from the environment to the eardrum.



Outer ear viewed from the side with direct and indirect sound path to the auditory canal. (Everest 2001, p. 65)

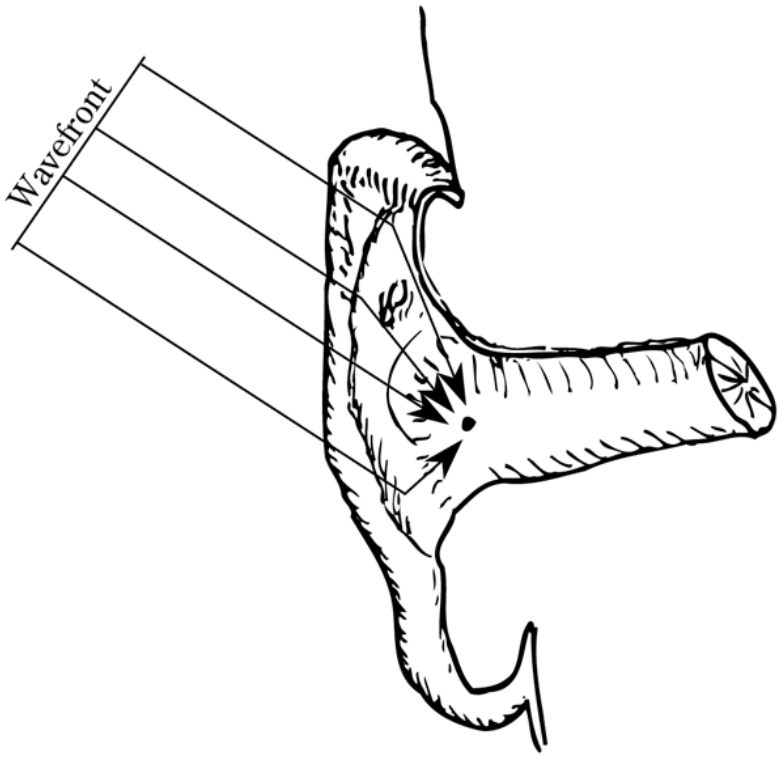
Good Vibrations

Ear - Outer Ear

The task of the **auricle** is to **conduct** the sound from the environment to the eardrum.

Due to the **funnel-like shape** of the ear canal and the auricle, the **sound conduction** works
- **frequency-dependent**
- **directionally**

(Basis for spatial hearing, it is more or less a directional filter)



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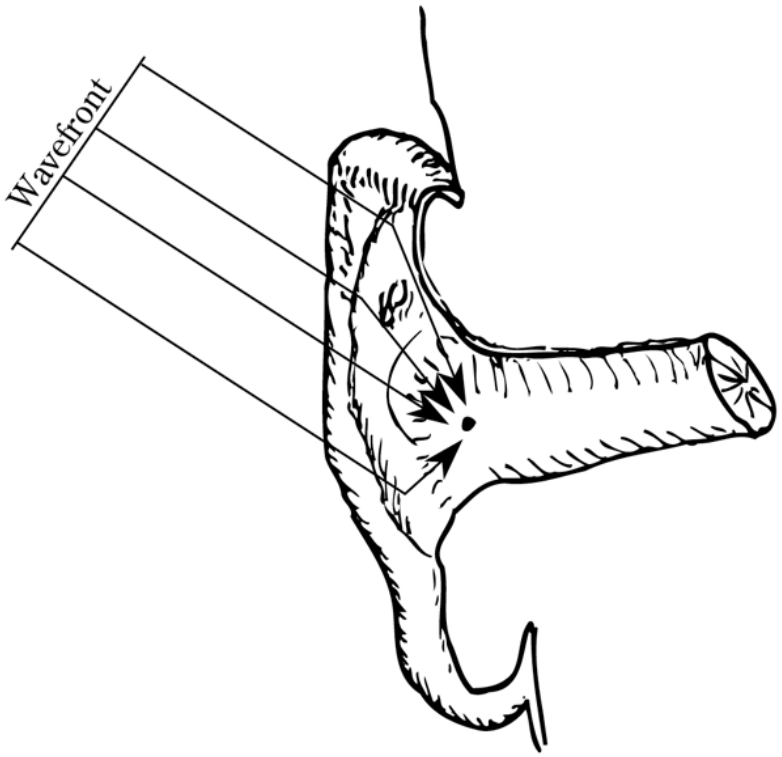
The auricle is responsible for
- **Front-back** localization
- **Top-bottom** localization



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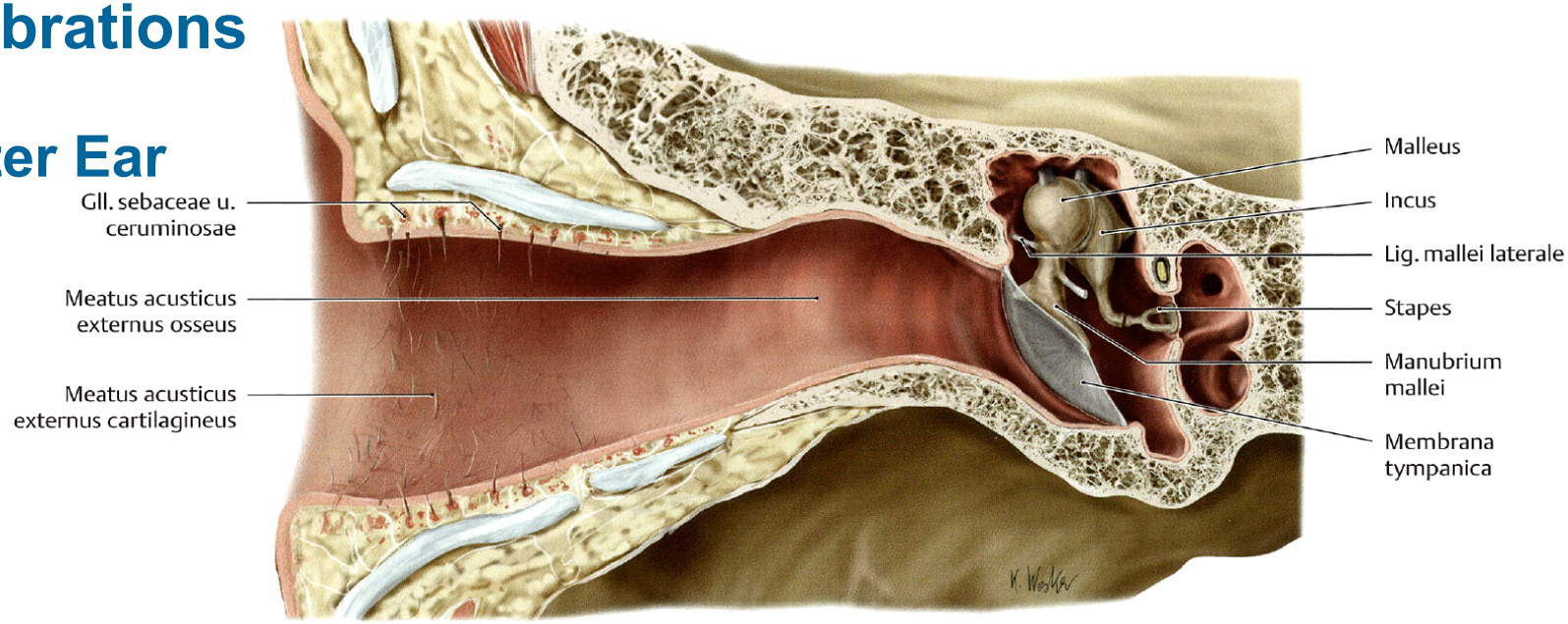
Good Vibrations

Ear - Outer Ear

Cross section of the ear canal with ear drum and timpanic cavity (Schünke et al. 2009, p. 127)

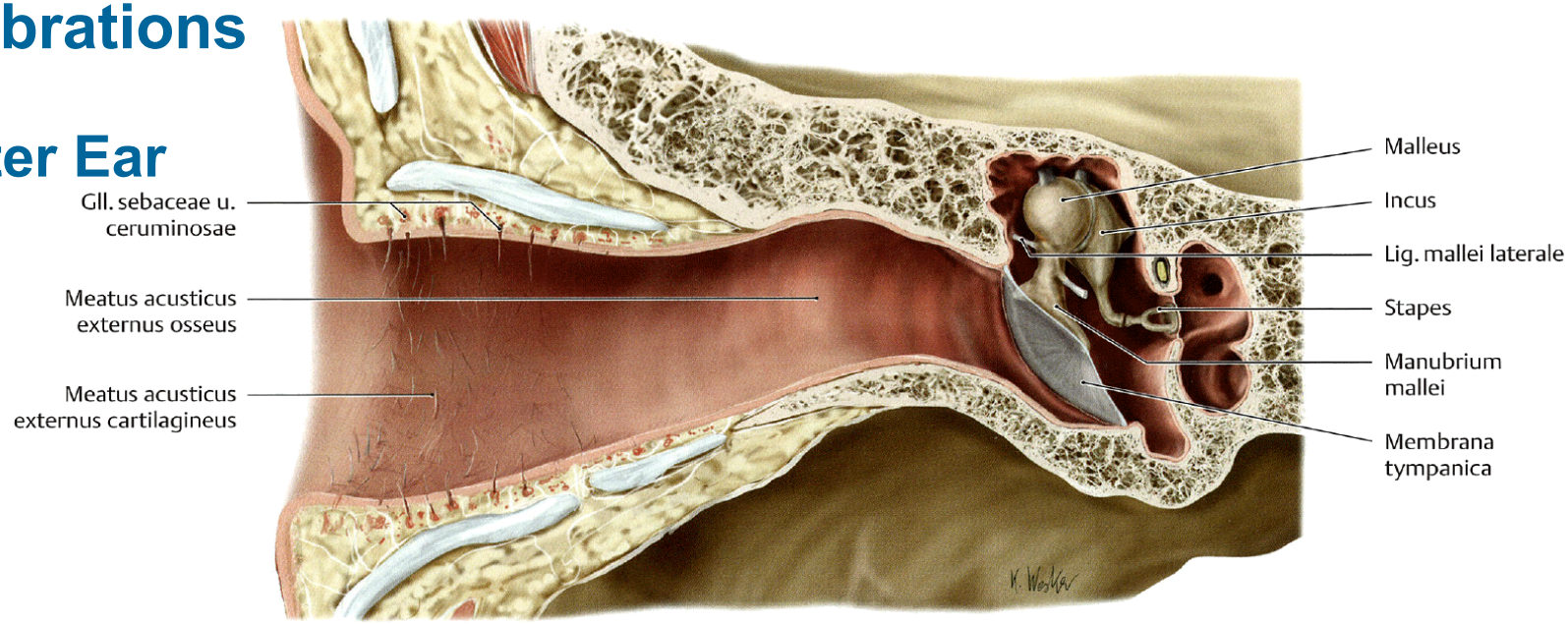


The ear canal acts as a **27 mm long stopped pipe**.

Good Vibrations

Ear - Outer Ear

Cross section of the ear canal with ear drum and timpanic cavity (Schünke et al. 2009, p. 127)



The ear canal acts as a **27 mm long stopped pipe**. Via the speed of sound it is possible to calculate its **resonance frequency** (and uneven multiples):

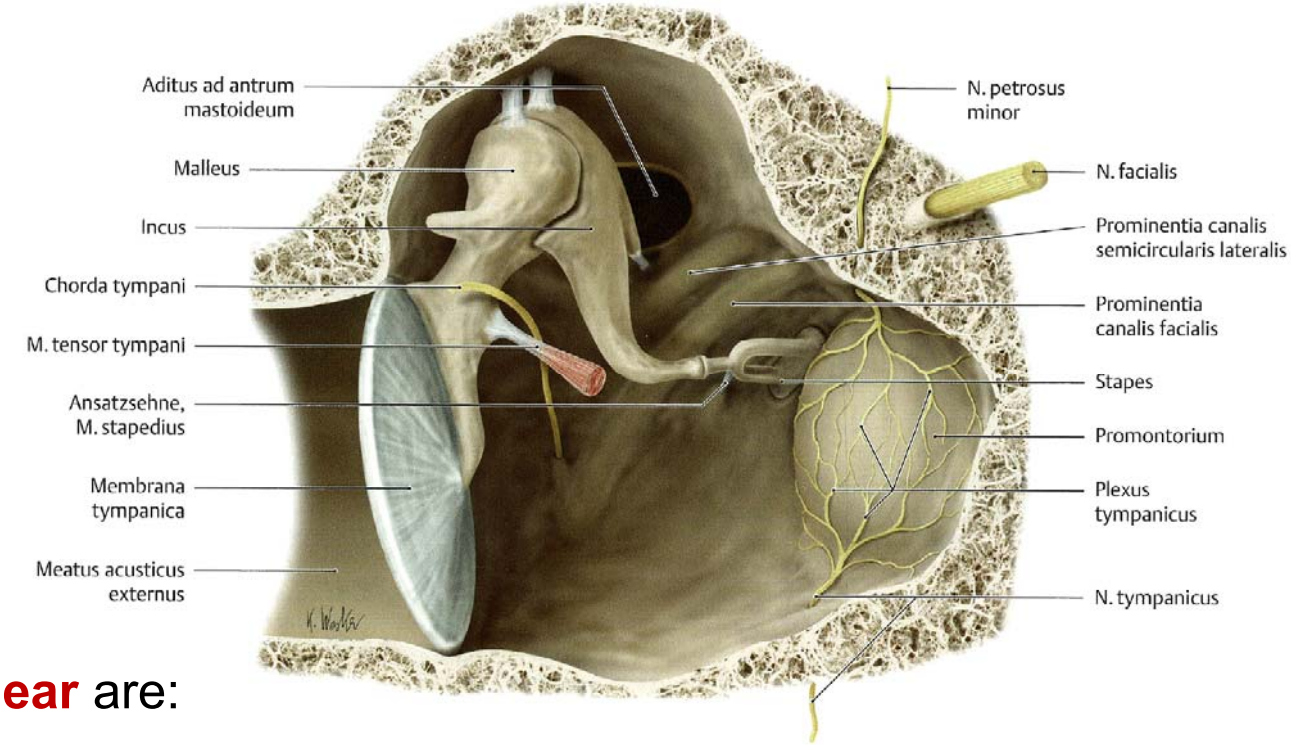
f = c/4L (frequency (f) = speed of sound (c) divided by 4 times the length (L) of the pipe)

f = 340 m/s / 4 * 0,027 m = **3148 Hz** (and all uneven multiples)

-> Our ear is **particularly sensitive** between **2000 and 4000 Hz**.

Good Vibrations

Ear - Middle Ear



Cross section of the timpanic cavity with malleus (hammer), incus (anvil) and stapes (stirrup) (Schünke et al. 2009, p. 130)

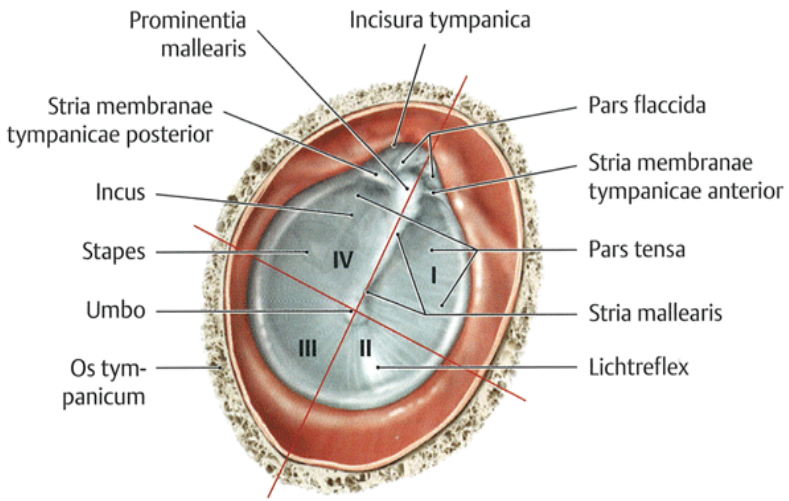
The tasks of the **middle ear** are:

- **Sound transmission** from outer to inner ear
- **Impedance conversion** between outer and inner ear
- **Expanding** the dynamic range of the ear
- **Frequency-selective sensitivity** change of the hearing
- **Protection** of the inner ear from loud sounds (stapedius reflex)

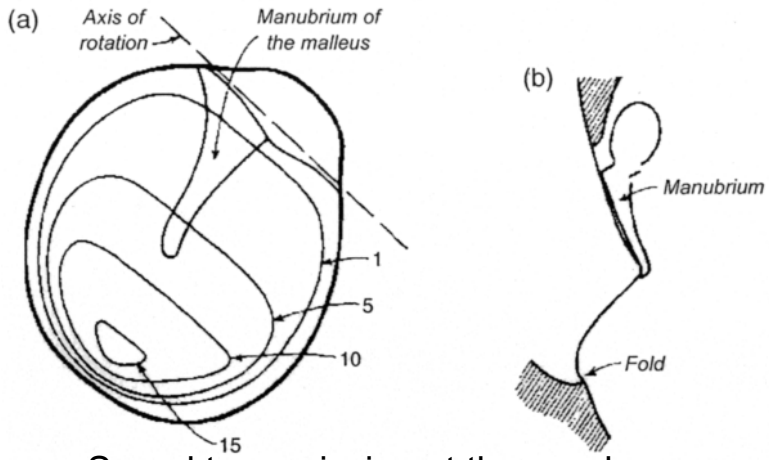
Good Vibrations

Ear - Middle Ear

The **eadrum** is a membrane with a size of 64 mm^2 .



Ear drum, view from the ear canal side
(Schünke et al. 2009, p. 129)



Sound transmission at the ear drum
(numbers: amplitudes at 2000 Hz)
(Bekesy 1943, p. 13)

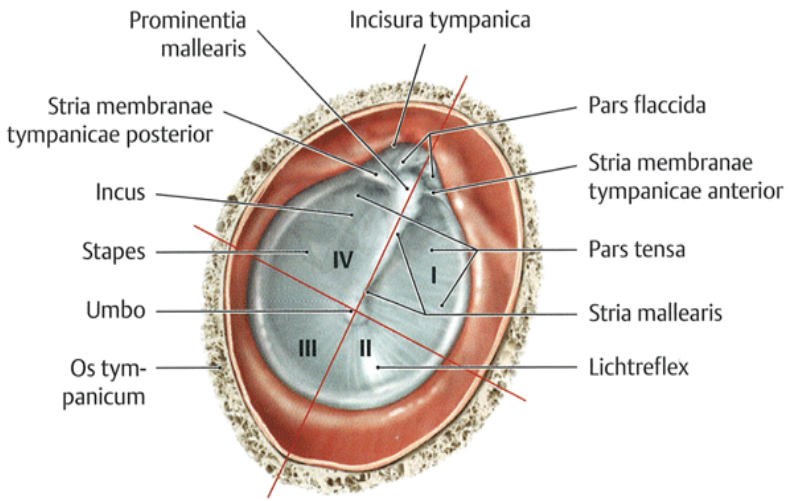
Good Vibrations

Ear - Middle Ear

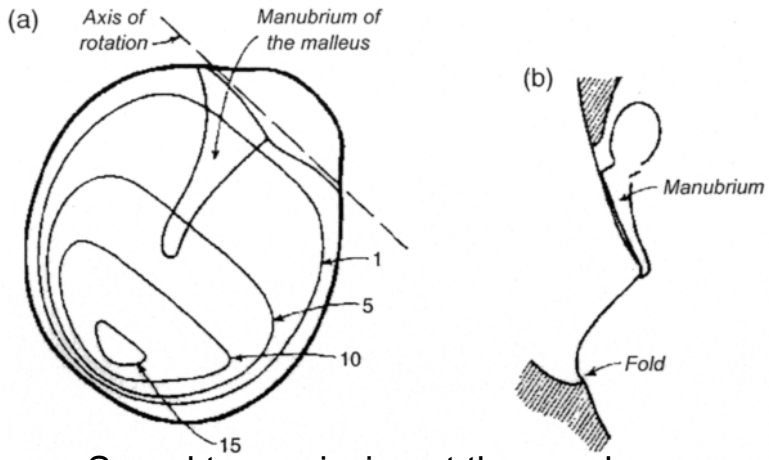
The **eadrum** is a membrane with a size of 64 mm^2 .

The **movement of the ear drum** depends on the frequency:

- **below** ca. 2400 Hz: Eardrum oscillates as a **rigid surface.**
- **over** ca. 2400 Hz: **Parts** of the eardrum oscillate **differently strong**.



Ear drum, view from the ear canal side (Schünke et al. 2009, p. 129)



Sound transmission at the ear drum (numbers: amplitudes at 2000 Hz) (Bekesy 1943, p. 13)

Good Vibrations

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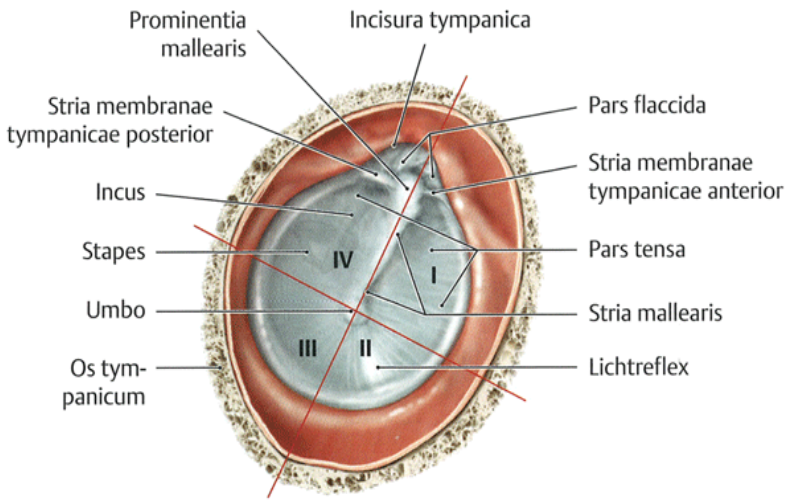
The **resonance frequency of the middle ear** is at **1200 Hz** (as well as a smaller resonance at **800 Hz**)



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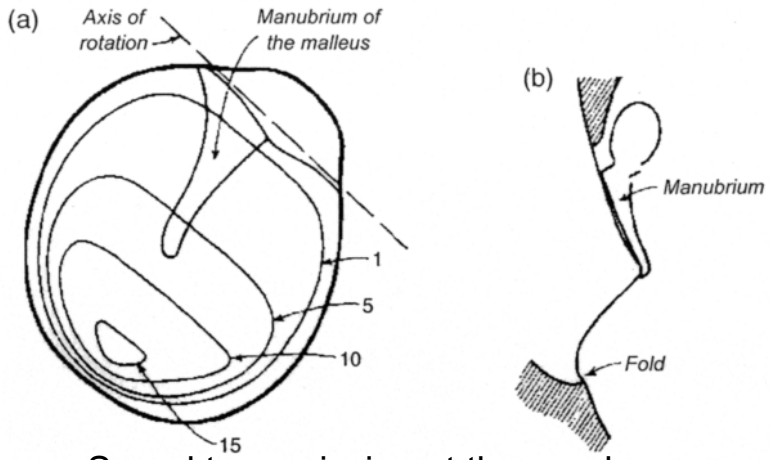

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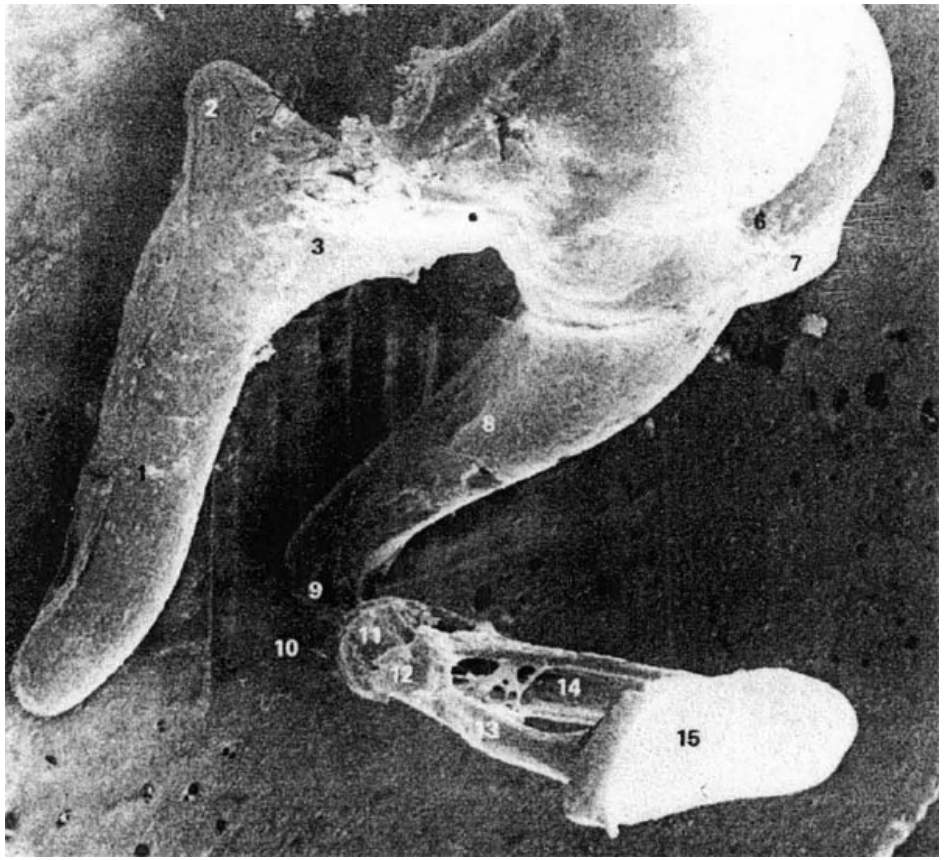
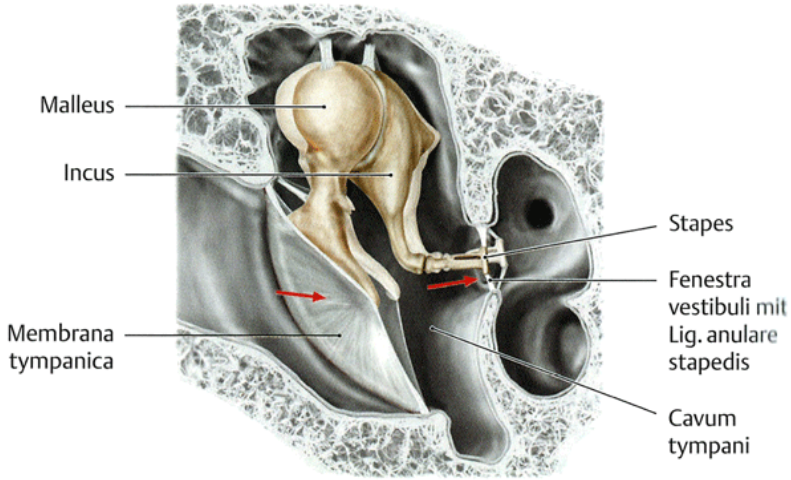
Good Vibrations

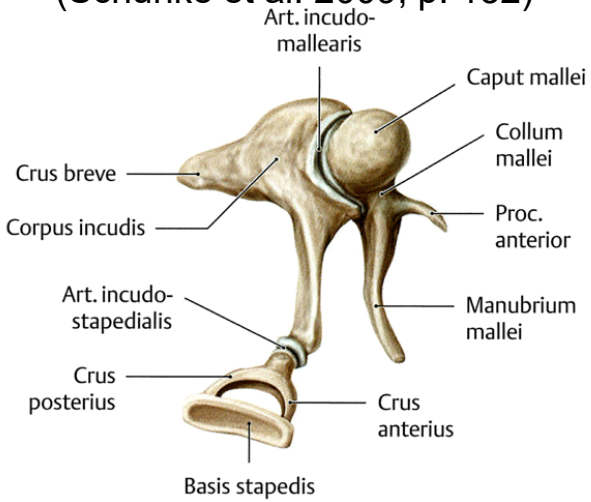
Ear - Middle Ear



middle ear bones in the timpanic cavity
(Yost 2007, p. 70)



Sound conduction at the middle ear bones
(Schünke et al. 2009, p. 132)

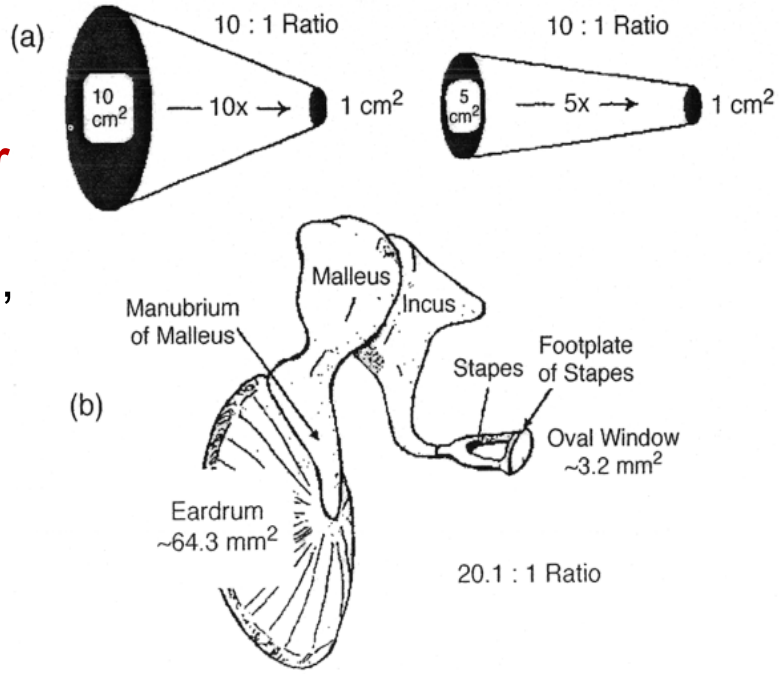


Stapes, incus and malleus
(Schünke et al. 2009, p. 132)

Good Vibrations

Ear - Middle Ear

Outer ear receives sound in **air**, while the **inner ear** receives sound in **water**.
Air and water have **different compressibilities**, which lead to **different impedances**.



Transfer function of the outer and middle ear (Yost 2007, p. 73)

Good Vibrations

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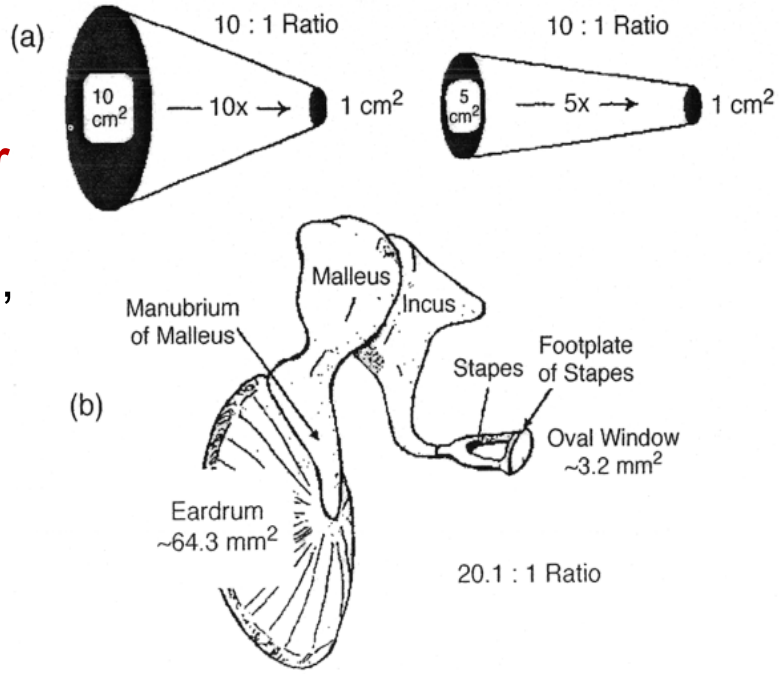
In a **direct transition** between air and water about **98%** of the sounds' amplitude would be reflected and only **2%** could be transferred.



Transfer function of the outer and middle ear (Yost 2007, p. 73)

Good Vibrations

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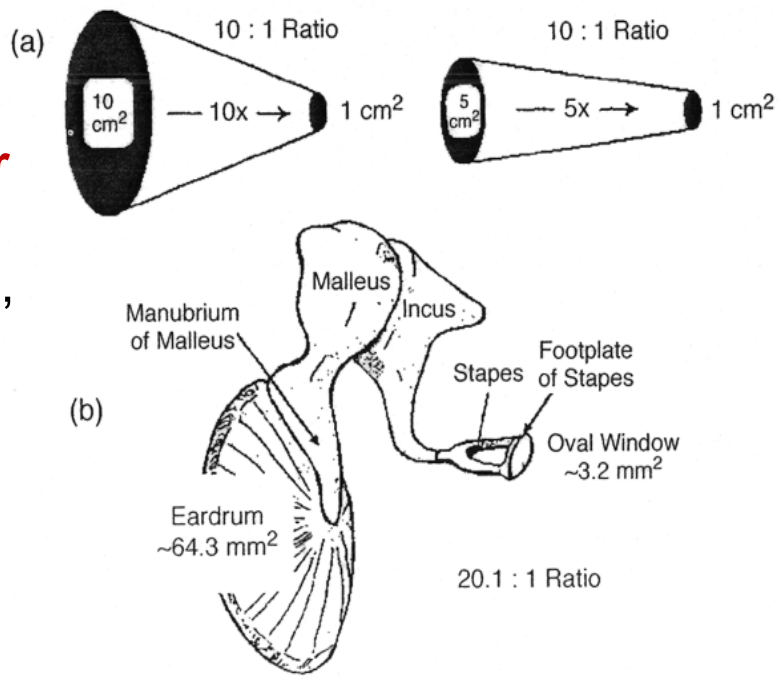
Impedance matching in the middle ear

The ratio between the **ear drum membrane (64,3 mm²)** to the **stapes footplate (3,2 mm²)** leads to an **amplification of 20,1:1**
(-> **60%** can be transferred)

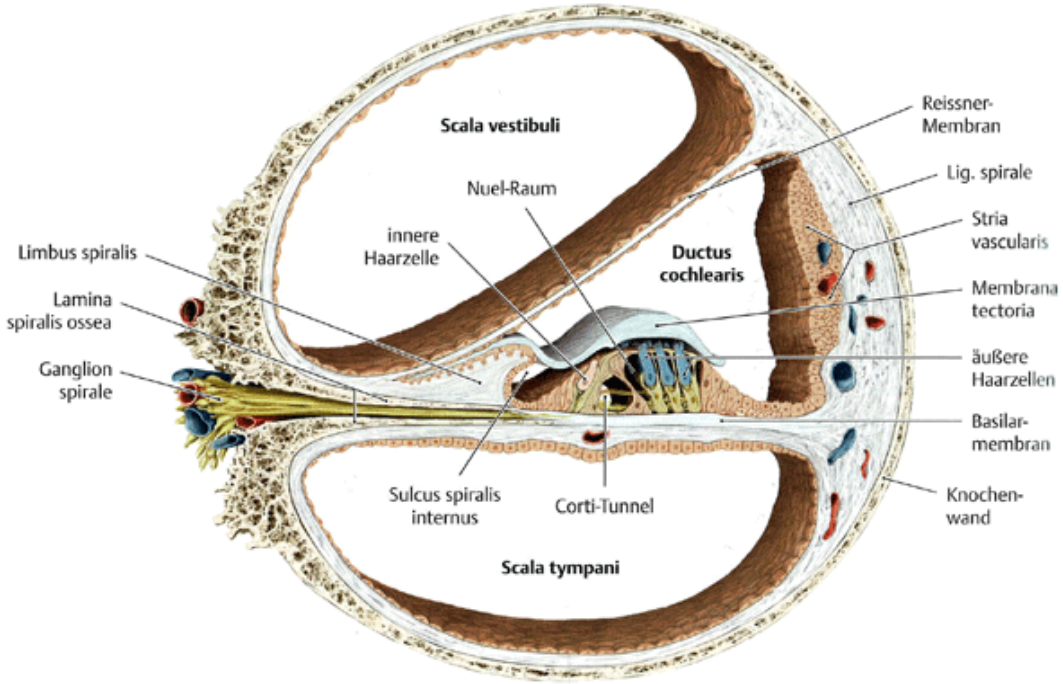


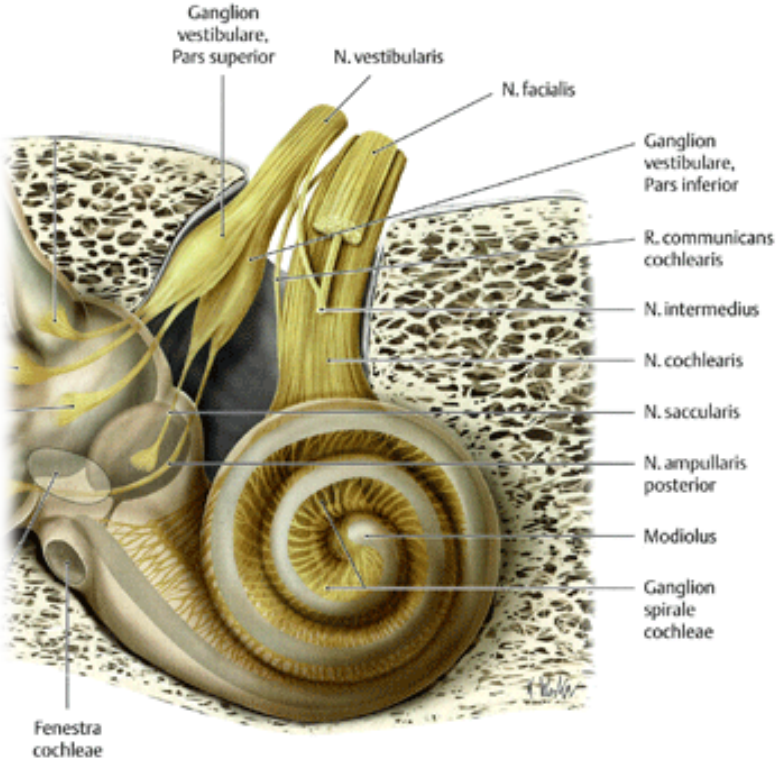
Transfer function of the outer and middle ear (Yost 2007, p. 73)

Good Vibrations

Ear - Inner Ear

Snail-wound, lymph-filled, 32 mm long tube with **three superimposed sections**





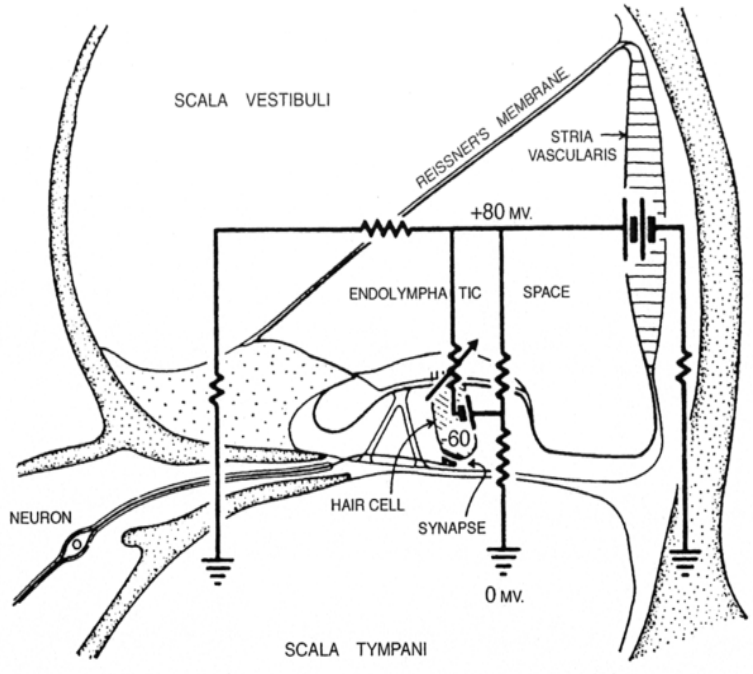
Top: nerves of the inner ear (Cochlea)
(Schünke et al. 2009, p. 135)

Left side: cross section of the cochlea
(Schünke et al. 2009, p. 136)

Good Vibrations

Ear - Inner Ear

Scala vestibule: perilymph, sodium-rich.



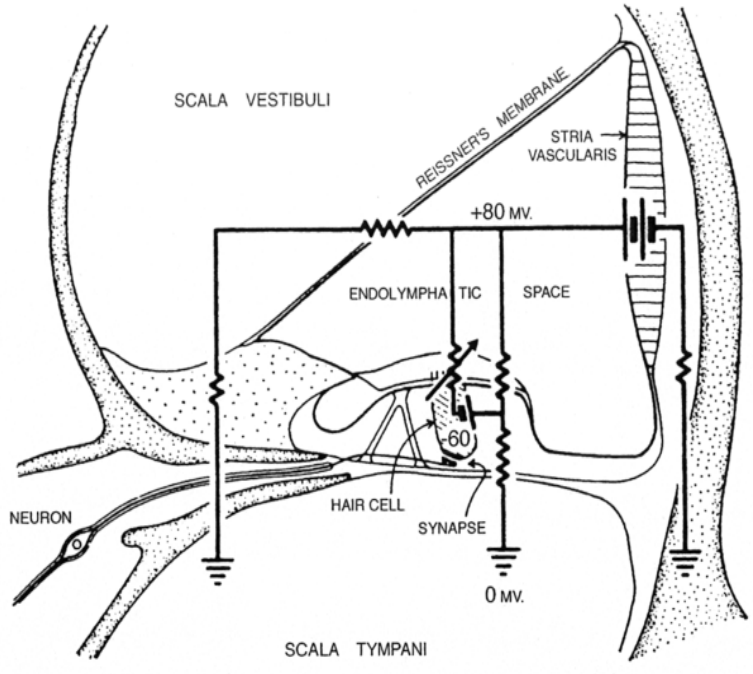
Cross section of the cochlea with voltage differences between the tube sections (Gelfand 2004, p. 140)

Good Vibrations

Ear - Inner Ear

Scala vestibule: perilymph, sodium-rich.

divided by: **Reissner‘s membrane**



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Good Vibrations

Ear - Inner Ear

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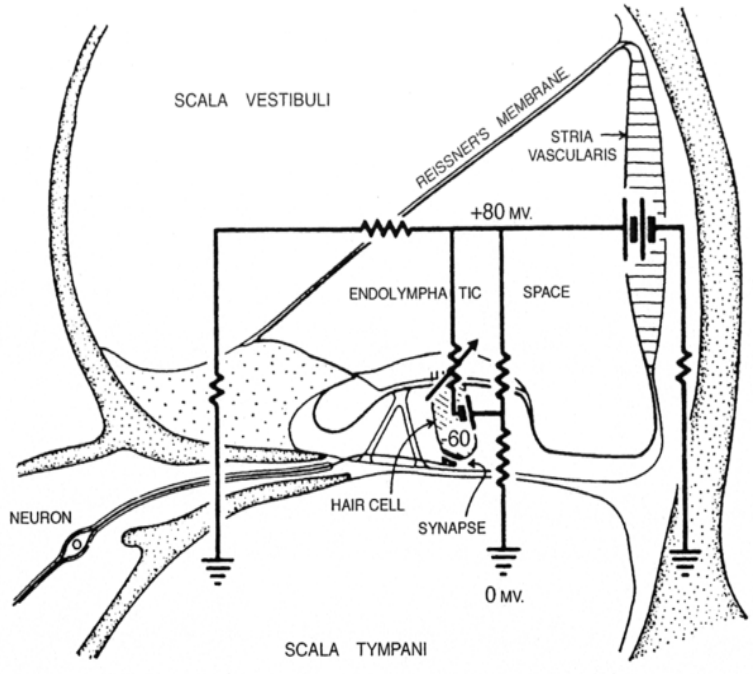
Scala media: endolymph, potassium rich, **+80 mV**



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Good Vibrations

Ear - Inner Ear

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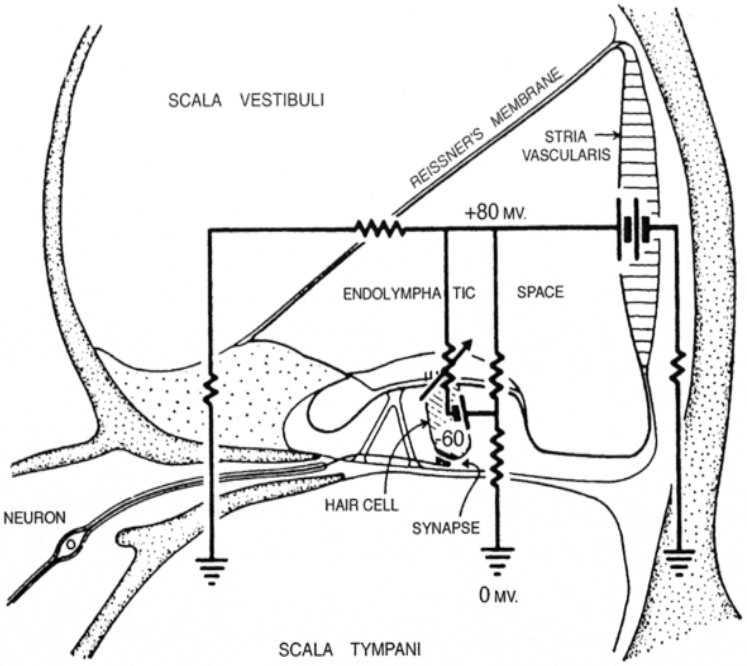
divided by: **basilar membrane with organ of Corti**: resting potential of the haircells: **-40 to -70 mV**



Cross section of the cochlea with voltage differences between the tube sections (Gelfand 2004, p. 140)

Good Vibrations

Ear - Inner Ear

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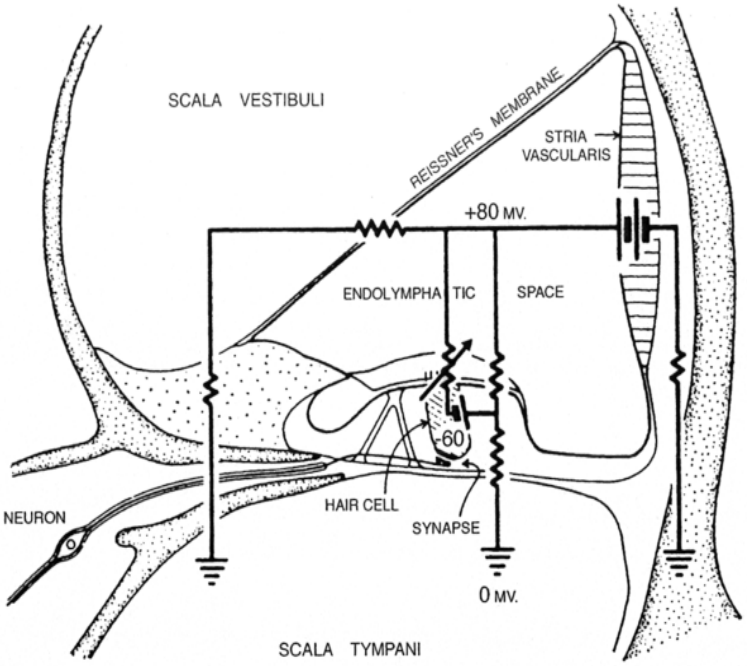
Scala Tympani: perilymph, sodium-rich



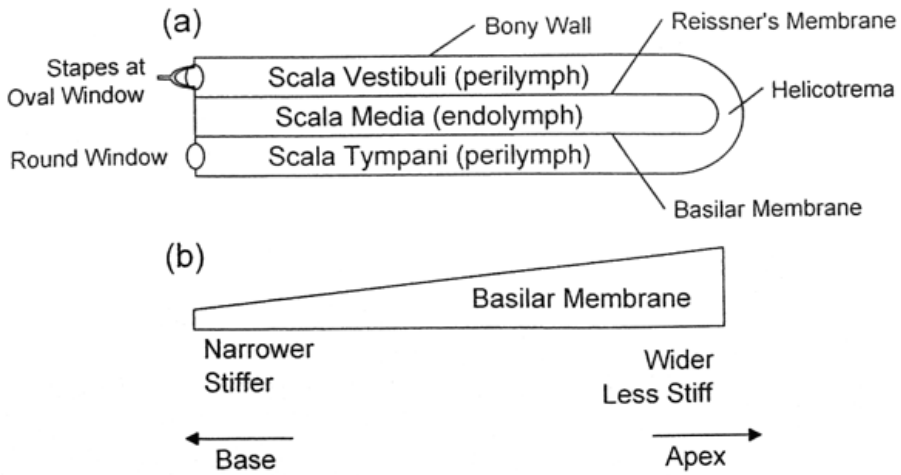
Cross section of the cochlea with voltage differences between the tube sections (Gelfand 2004, p. 140)

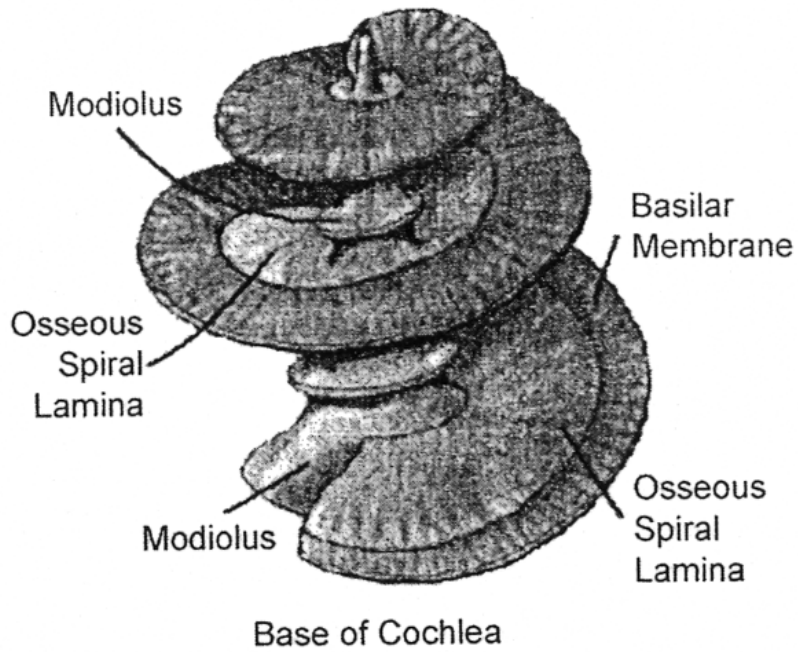
Good Vibrations

Ear - Inner Ear

Basilar membrane is more a plate then a membrane:

- At **oval window**: **narrow** and **stiff**
- At **apex** (Helicotrema): **wide** and **loose**

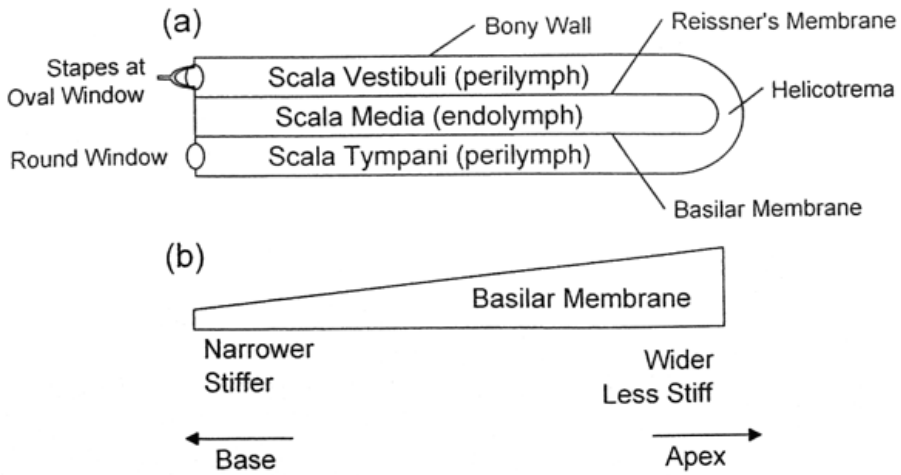




From top to down: (a) unrolled cochlea (b) nature of the basilar membrane (c) basilar membran gets wider at the apex (Gelfand 2004, p. 55 & 55)

Good Vibrations

Ear - Inner Ear



Basilar membrane is more a plate then a membrane:

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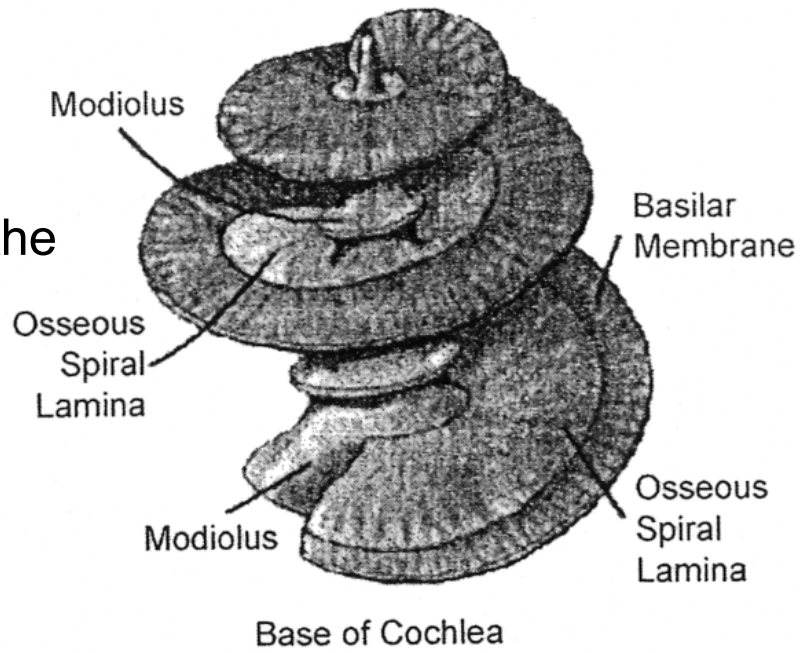
Because of these properties:
the basilar membrane has **slowly changing resonance characteristics** on the path from the base to the apex.



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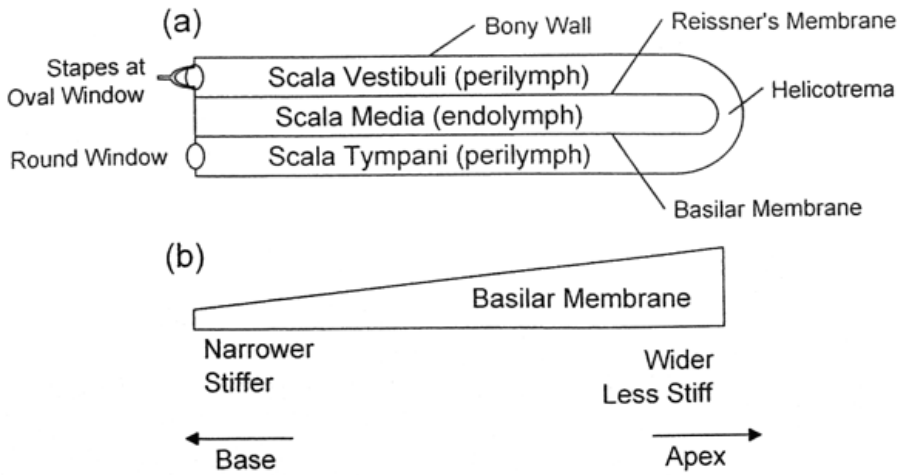
Good Vibrations

Ear - Inner Ear



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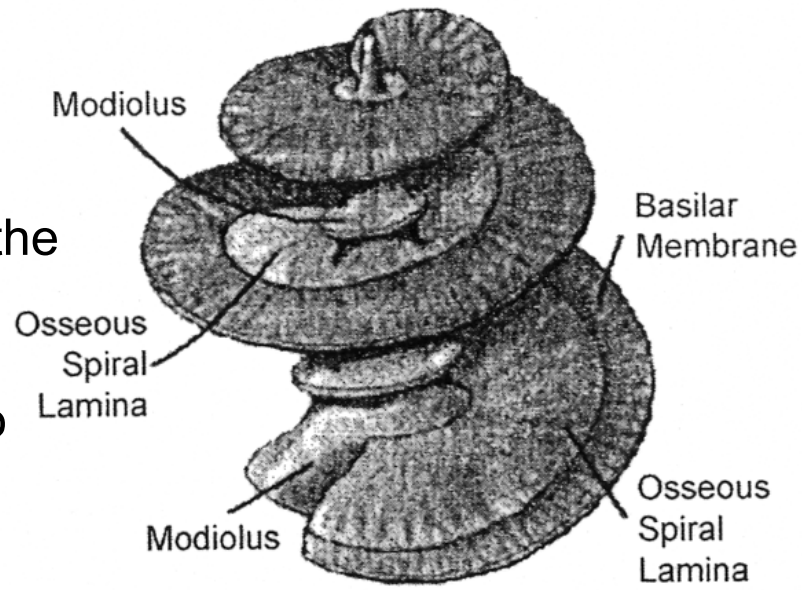
At **Helicotrema**: Scala Vestibuli goes over into Scala Timpany



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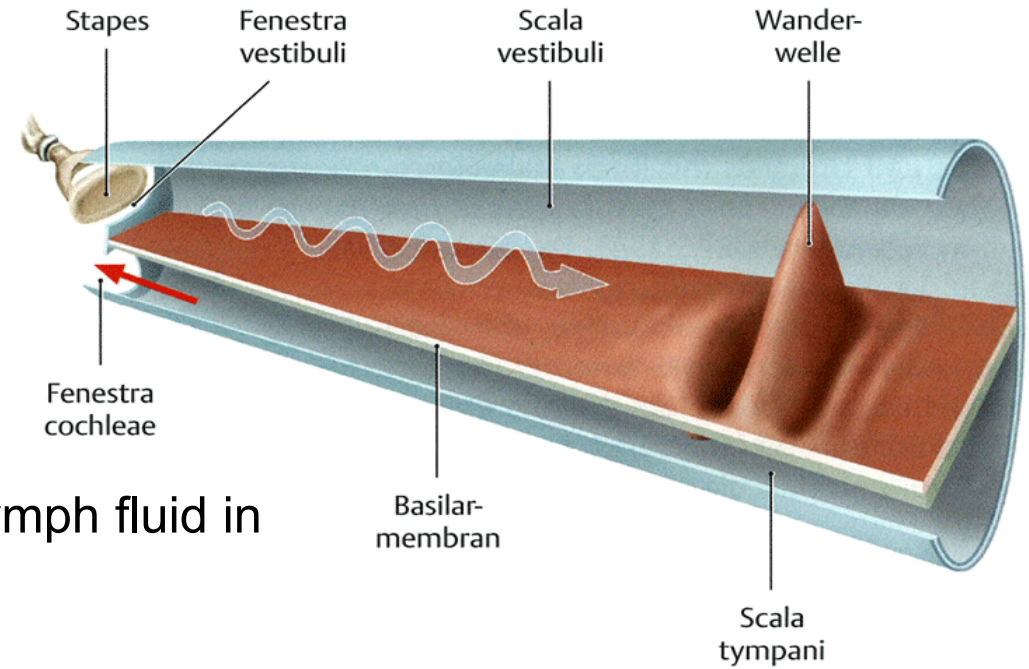
Good Vibrations

Ear - Inner Ear

Traveling wave theory

With **slow stapes movements**:
opposed displacement of the endolymph fluid in Scala Vestibuli and Scala Tympani.

With **fast stapes movements**: Basilar membrane is set in vibration, a **traveling wave** is induced

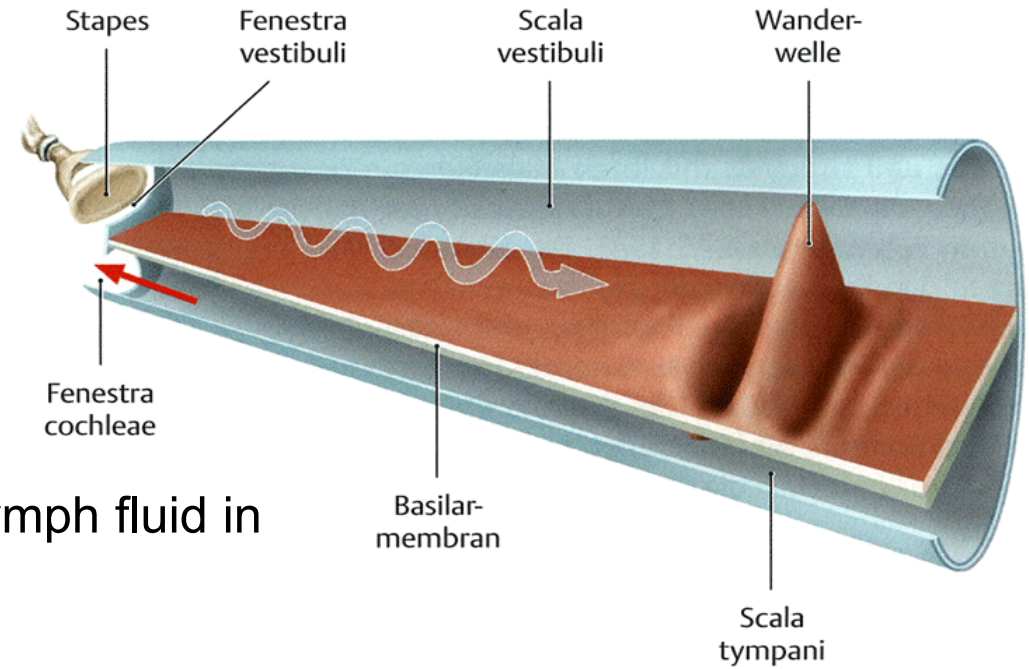


Induction of a traveling wave on the basilar membrane (Schünke et al. 2009, p. 137)

Good Vibrations

Ear - Inner Ear

Traveling wave theory



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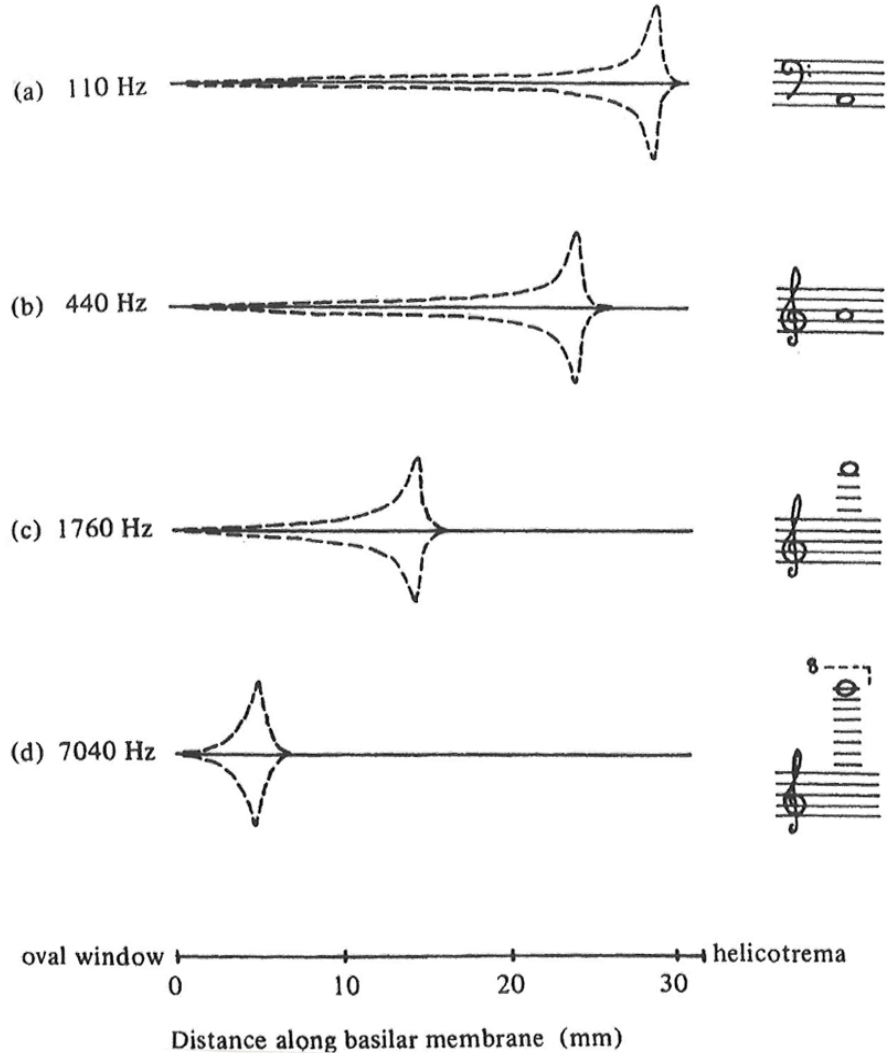
Traveling wave has a **frequency-dependent amplitude maximum**:
- the **higher** the frequency, the closer to the **oval window (base)** the maximum is.
- the **lower** the frequency, the closer to the **helicotrema (apex)** the maximum is.

Good Vibrations

Ear - Inner Ear

Traveling wave theory

Due to the resonance characteristics of the basilar membrane, a rough **mechanical frequency analysis** takes place on it.



Amplitude maxima at different frequencies (Campbell, Greated 2001, S. 55)

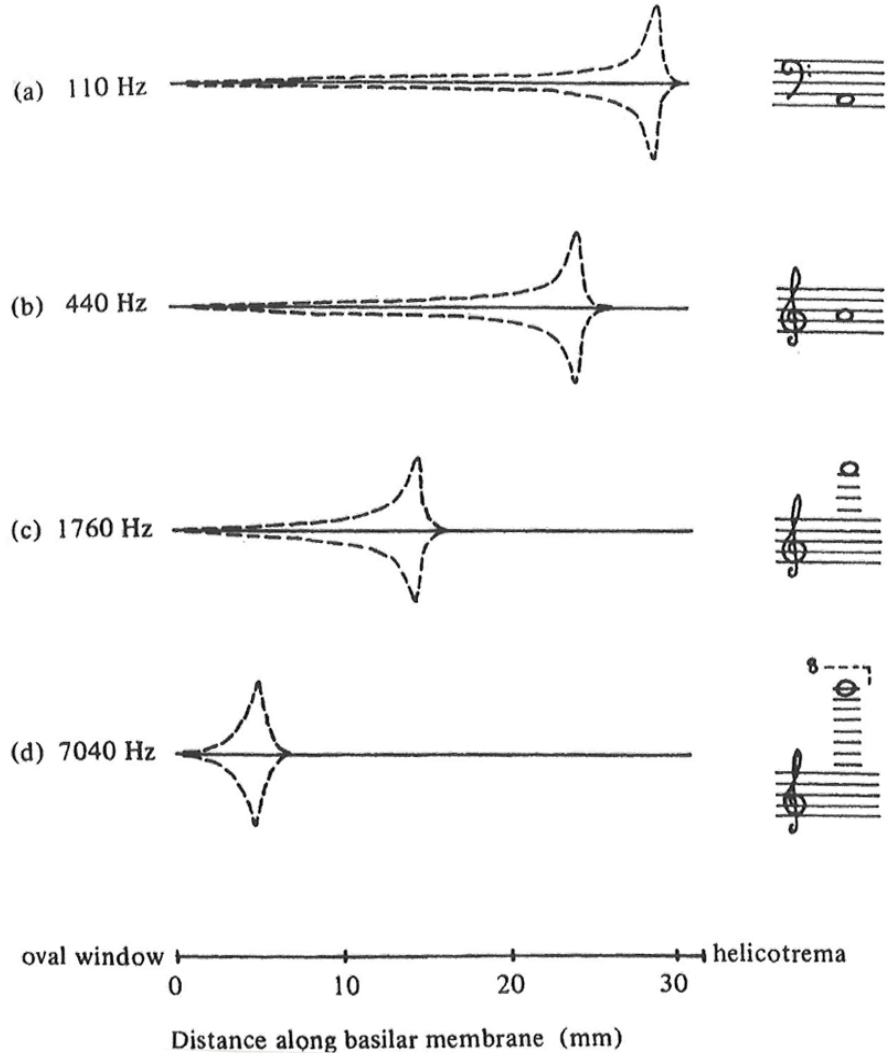
Good Vibrations

Ear - Inner Ear

Traveling wave theory

Due to the resonance characteristics of the basilar membrane, a rough **mechanical frequency analysis** takes place on it.

The basilar membrane works like as a **series of low-pass filters** whose upper frequency decreases successively from oval window (base) to helicotrema (apex).



Amplitude maxima at different frequencies (Campbell, Greated 2001, S. 55)

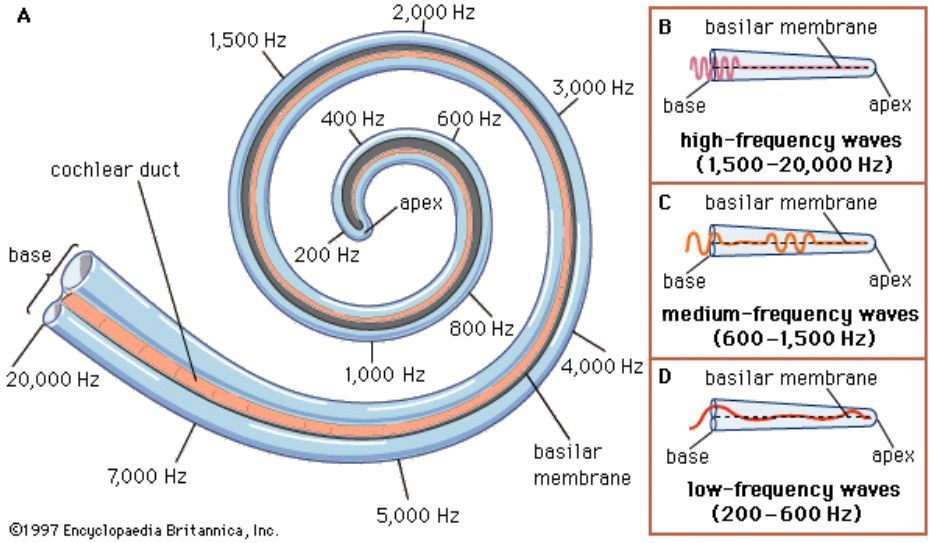
Good Vibrations

Ear - Inner Ear

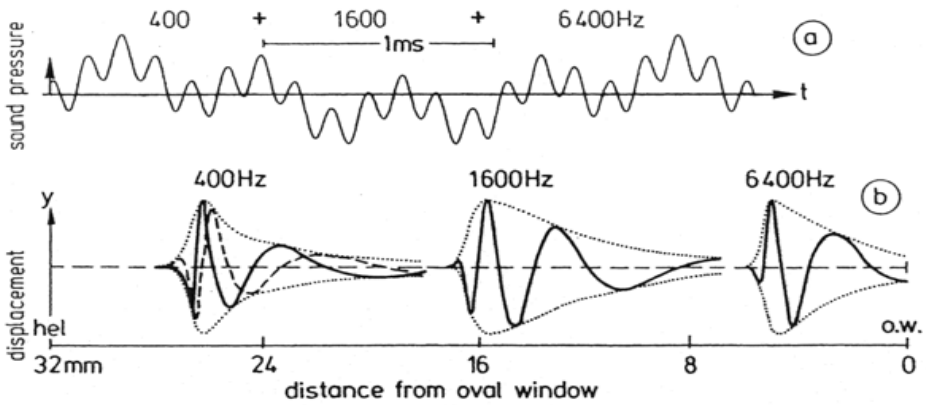
Traveling wave theory

Tonotopy = each frequency is characterized by a certain place on the basilar membrane.

This **tonotopic arrangement** can be found throughout the **entire hearing path** from the inner ear to the auditory cortex



Tonotopy on the basilar membrane
(Encyclopedia Britannica 1997; Stickel 2003, p. 55)



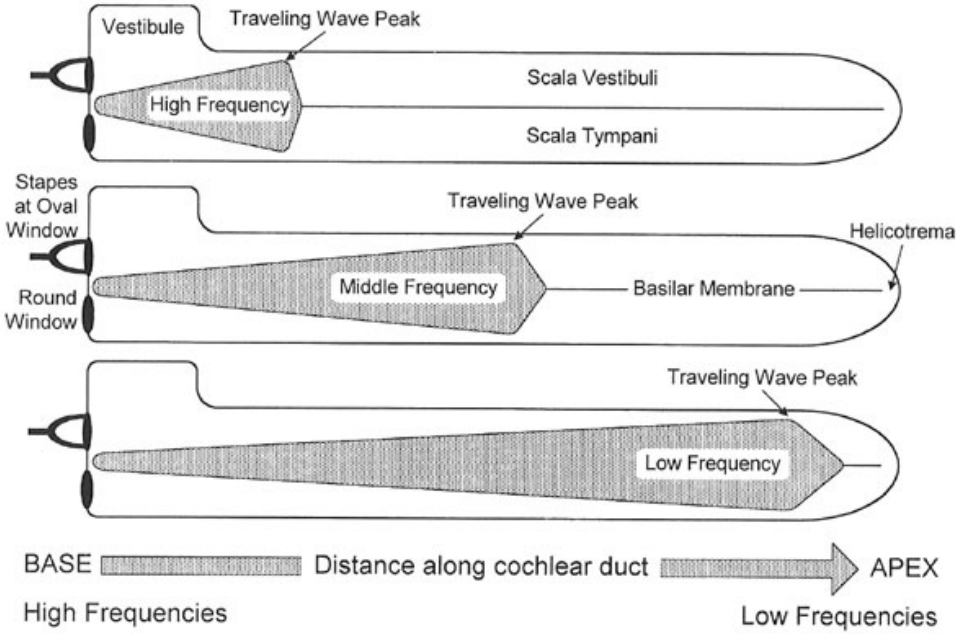
Basilar movements for different frequencies
(Fastl, Zwicker 2006, p. 29)

Good Vibrations

Ear - Inner Ear

Traveling wave theory

Consequences for the hearing process caused by the traveling wave from high to low frequencies:



Traveling Wave with frequency-dependent peaks on the basilar membrane (Gelfand 2009, p. 67)

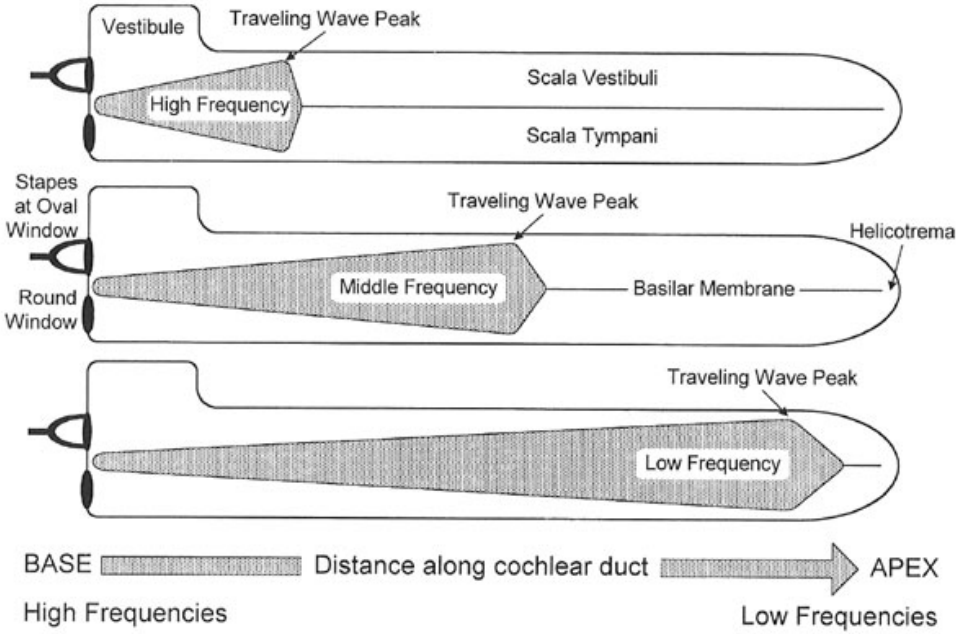
Good Vibrations

Ear - Inner Ear

Traveling wave theory

Consequences for the hearing process caused by the traveling wave from high to low frequencies:

- Presbyacusis: Age-related hearing loss starts at the **high frequencies**



Traveling Wave with frequency-dependent peaks on the basilar membrane (Gelfand 2009, p. 67)

Good Vibrations

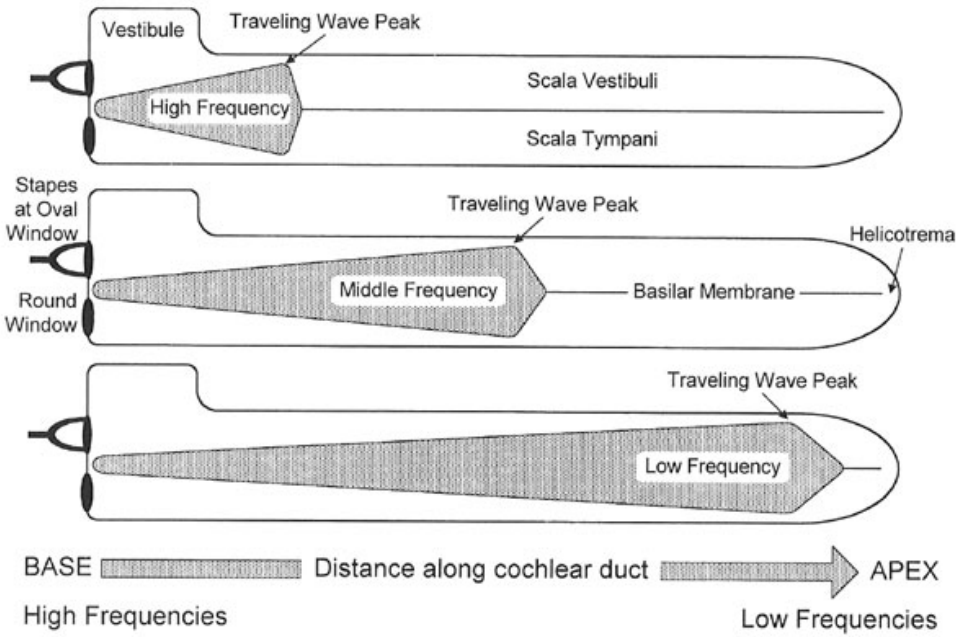
Ear - Inner Ear

Traveling wave theory

Consequences for the hearing process caused by the traveling wave from high to low frequencies:

- **Presbyacusis:** Age-related hearing loss starts at the **high frequencies**

- **Masking: Low** frequencies mask high frequencies **more** than **high** frequencies the low ones.



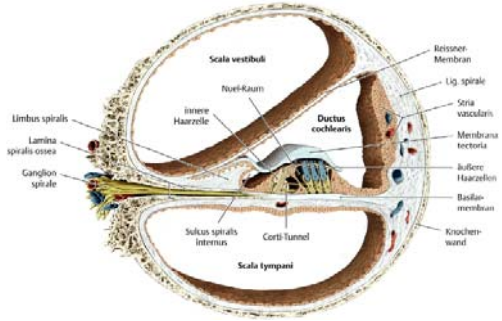
Traveling Wave with frequency-dependent peaks on the basilar membrane (Gelfand 2009, p. 67)

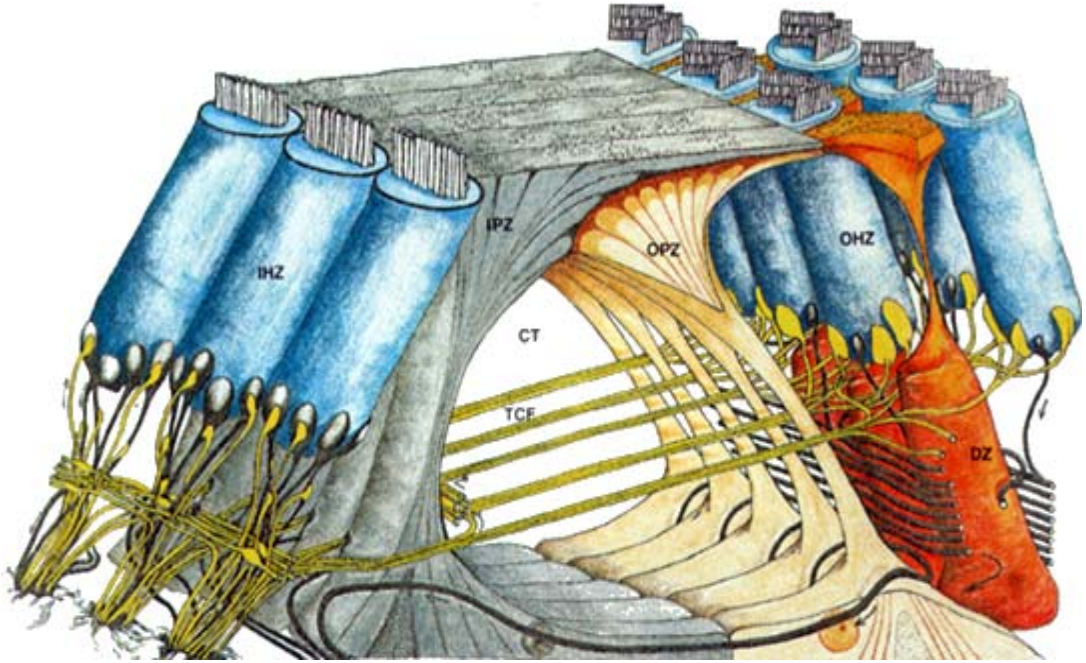
Good Vibrations

Ear - Inner Ear

Organ of Corti

On the basilar membrane the **organ of Corti** is located.
Its task is to transform the **mechanical vibrations** of the basilar membrane into **nerve impulses**





Organ of Corti of a guinea pig,
with outer (OHZ) and inner hair cells (IHZ)
(Reiss et al. 1989, p. 50)

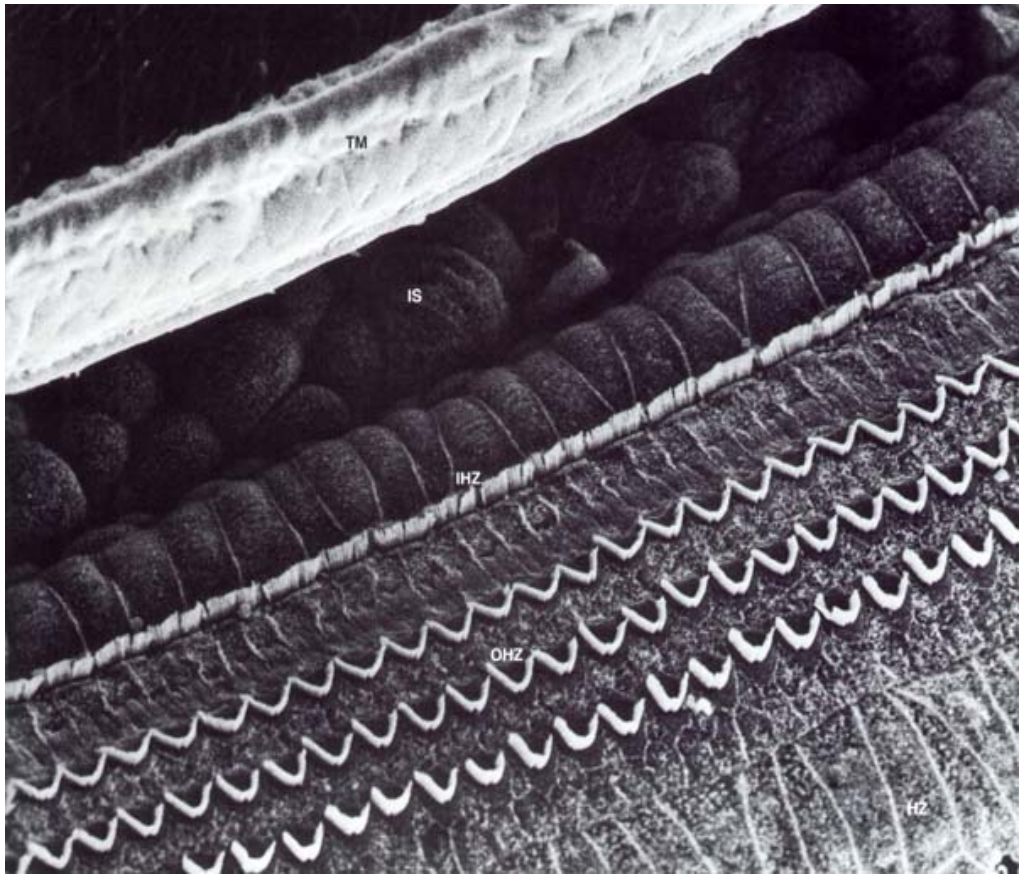
Good Vibrations

Ear - Inner Ear

Organ of Corti

Hair cells on the organ of Corti:

1 row of about 3.500 **inner hair cells** -> firing nerve impulses synchronized by the heard frequency



Inner (IHZ) and outer hair cells (OHZ) on
a human organ of Corti on the basilar membrane
with outer (OHC) and inner hair cells (IHZ)
(Reiss et al. 1989, p. 51)

Good Vibrations

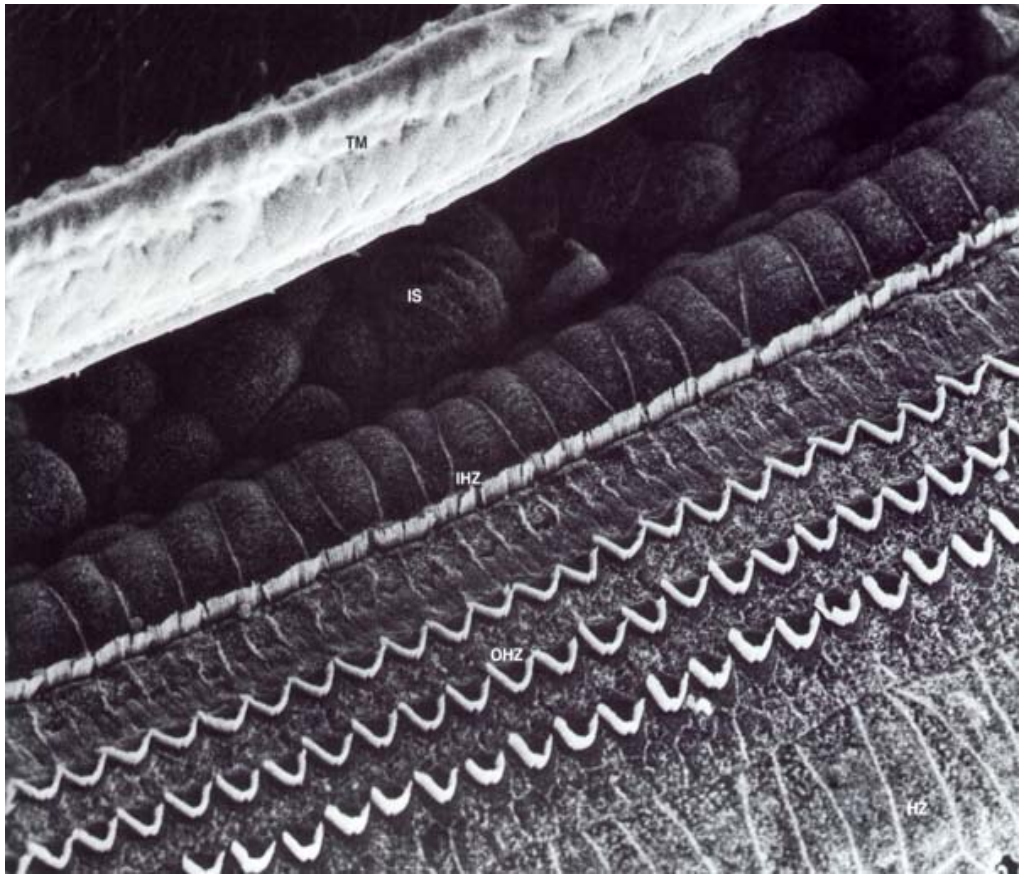
Ear - Inner Ear

Organ of Corti

Hair cells on the organ of Corti:

1 row of about 3.500 **inner hair cells** -> firing nerve impulses synchronized by the heard frequency

3 rows of about 12.000 **outer hair cells** -> reinforcing the basilar membrane movement by changing their size synchronized by the heard frequency



Inner (IHZ) and outer hair cells (OHZ) on a human organ of Corti on the basilar membrane with outer (OHC) and inner hair cells (IHZ) (Reiss et al. 1989, p. 51)

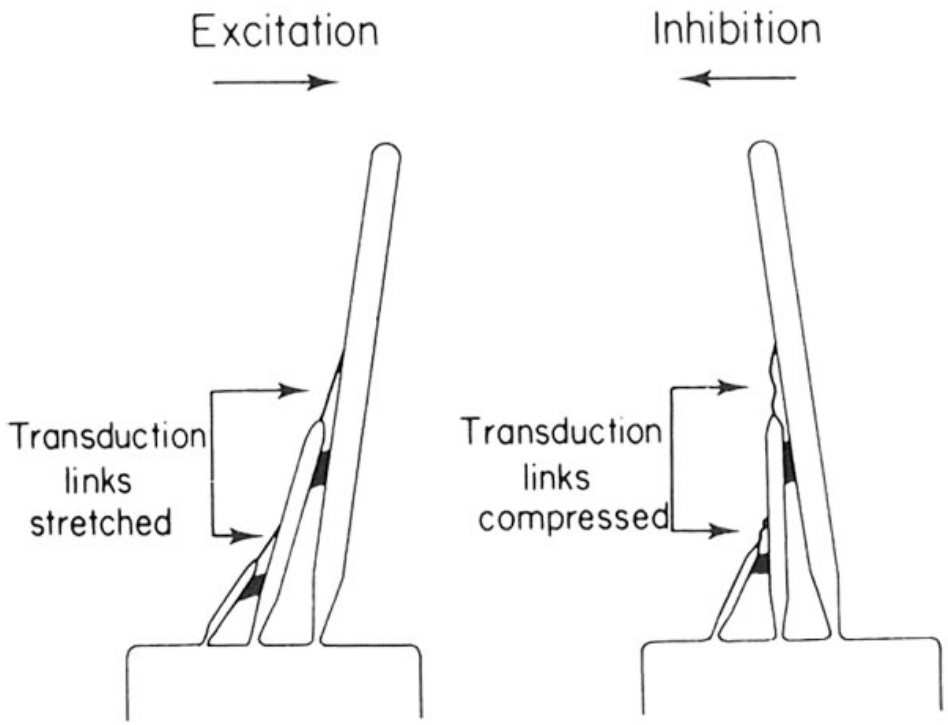
Good Vibrations

Ear - Inner Ear

Organ of Corti

Hair cells on the organ of Corti:

Stereocilia are located on top of the hair cells, moving **synchronously** to the basilar membrane motion.



Excitation and inhibition of hair cells caused by the stereocilia movement (Gelfand 2009, p. 60)

Outer hair cells changing their size synchronously to music

Dancing Hair Cell I

Dancing Hair Cell II

Good Vibrations

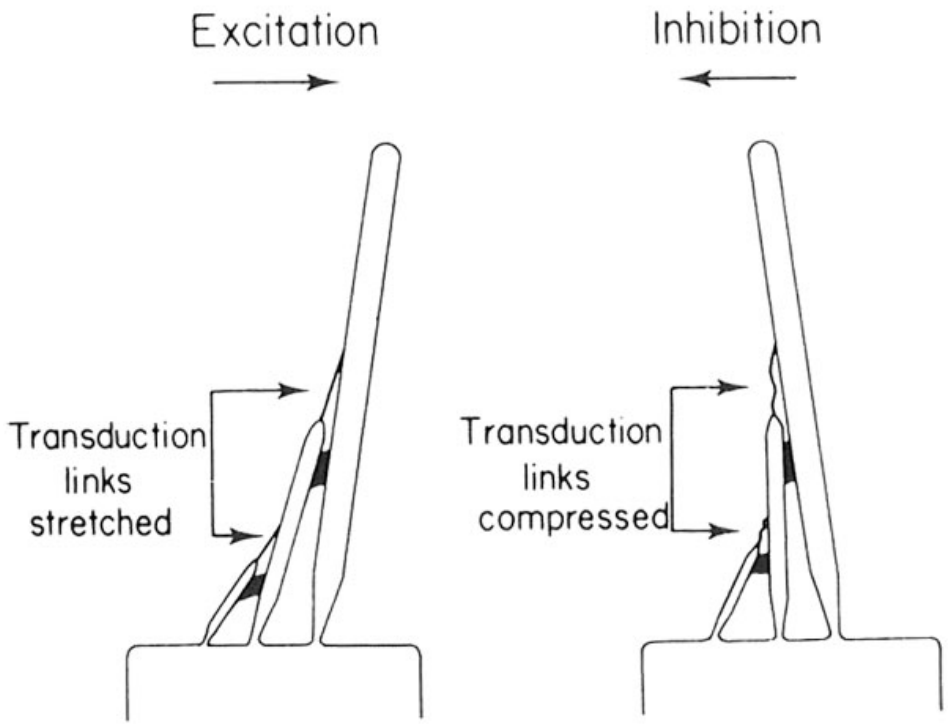
Ear - Inner Ear

Organ of Corti

Hair cells on the organ of Corti:

Stereocilia are located on top of the hair cells, moving **synchronously** to the basilar membrane motion.

When stretched: electro-chemical processes lead to:
-**firing neurons** synchronous to the frequency (**inner hair cells**)
-**changing their size** synchronous to the frequency (**outer hair cells**)



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Outer hair cells changing their size synchronously to music

Dancing Hair Cell I

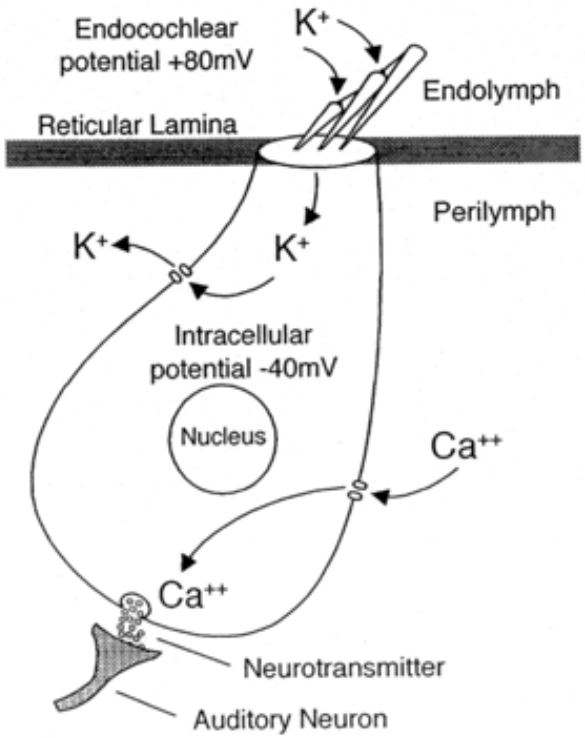
Dancing Hair Cell II

Good Vibrations

Ear - Inner Ear

Organ of Corti

Electrochemical process inside the hair cell:
(happens synchronously to the heard frequency)



Depolarization of the hair cell in the rhythm of the received frequency (Gelfand 2004, p. 135)

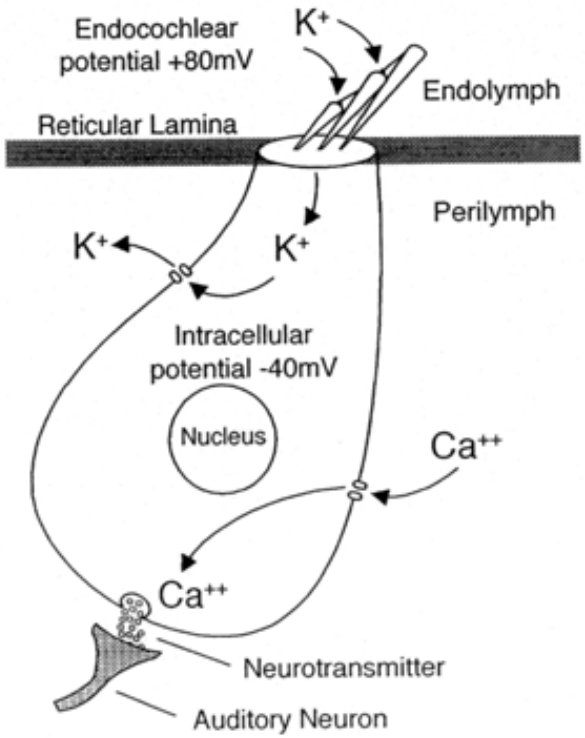
Good Vibrations

Ear - Inner Ear

Organ of Corti

Electrochemical process inside the hair cell:
(happens synchronously to the heard frequency)

Positive charged **Potassium Ions (K+)** flow inside the negative charged hair cell, **depolarizing** it.



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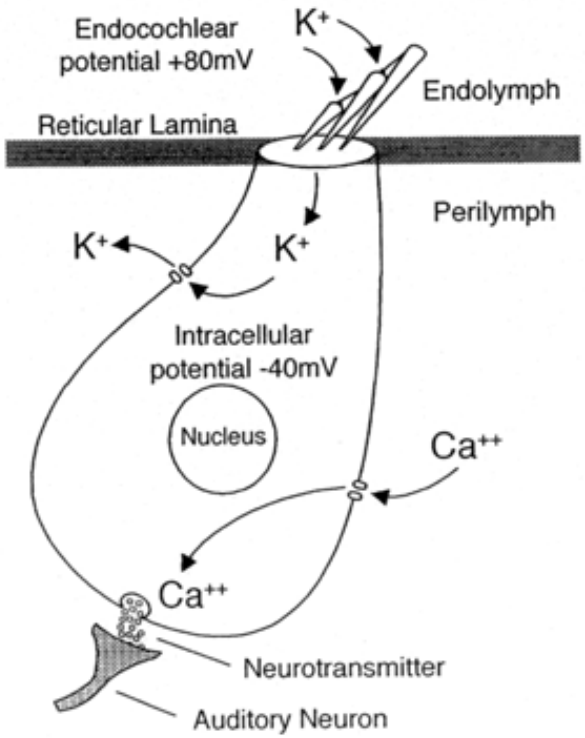

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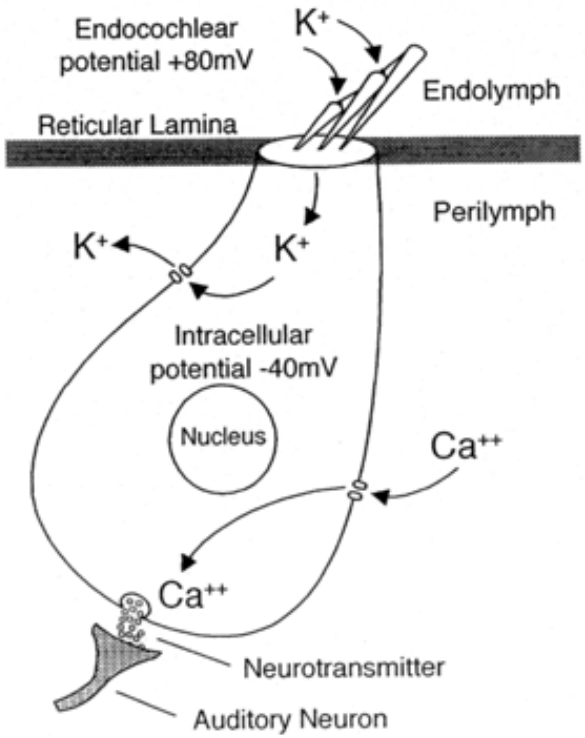
-> Depolarization gets transmitted to **auditory neuron** as an **electric discharge**



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Good Vibrations

Take Home Message I

The Ear consists of **outer**, **middle** and **inner ear**.

Outer Ear: enables us to **top-bottom-front-back-localization**, hearing gets particularly **sensitive between 2000 and 4000 Hz** because of the resonance frequency of the outer ear canal.

Middle Ear: **Impedance conversion** between outer (sound in **air**) and inner ear (sound in **water**) with the help of the **middle ear bones** (**ossicles**).

Inner Ear: the vibrations of the stapes causes a **traveling wave** on the basilar membrane with an **amplitude maximum** at a **frequency-depentent place**. Caused by their decreasing resonance frequency from base to apex, the basilar membrane is a **rough frequency analysator**.

Good Vibrations

Take Home Message II

Inner Ear: On top of the basilar membrane the organ of Corti is located with two kinds of hair cells:

1 row of **inner hair cells**: generating **nerve firing patterns** via **stereocilia**, synchronous to the basilar membrane movement -> auditory pathway **to** auditory cortex.

3 rows of **outer hair cells**: influencing **basilar membrane movement** (connected with tectorial membrane via **stereocilia**)
<- **changing size** by messages **from** the auditory cortex.

谢谢