KTH ROYAL INSTITUTE
OF TECHNOLOGY

DT2212: Music Acoustics

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Sound is all around us

What is it? How does it work? How do we sense it?

Music acoustics is an ancient study

500 BC

Music acoustics is an ancient study

1425 BC

Music acoustics is an ancient study

10000 BC

Music acoustics is an ancient study

Hohle Fels Flute

35000 BC

Music acoustics is an ancient study

100000 BC

Motivating questions

How does this thing work?
What defines its acoustic properties?
Why does it sound the way it does?

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ILOs of Music Acoustics

After completing the course you should be able to:

- **explain** the acoustical function of musical instruments and the singing voice from basic physical principles
- **calculate** and **measure** basic acoustical properties of musical sounds and instruments
- **design** and **calculate** the dimensions of prototypes for string and wind instruments
- **describe** and **use** different methods for modeling of musical instruments and for synthesis of musical sounds
- **extract** and **present** the main content of a selection of scientific articles on music acoustics

Outline of course

Lecture 1: Introduction; basic acoustics

Lecture 2: Modes of vibration

Lecture 3: The ear, critical bands, and masking;

Lecture 4: tuning and temperament and audio analysis

Lecture 5: Vibrating strings

Lecture 6: Guitar and piano

LAB 1: Guitar

Lecture 7: Synthesis methods

Lecture 8: Singing voice

LAB 2: Singing voice

Lecture 9: Bowed strings

Lecture 10: Wind instruments

Lecture 11: Other instruments + Project workshop

Lecture 12: Final project presentations

DT2212 Laboratories (P/F)

Group-based work (pairs)

FEB 3-7?

1. **Guitar modes**
   hands-on measurements of a guitar and a string

FEB 10-14?

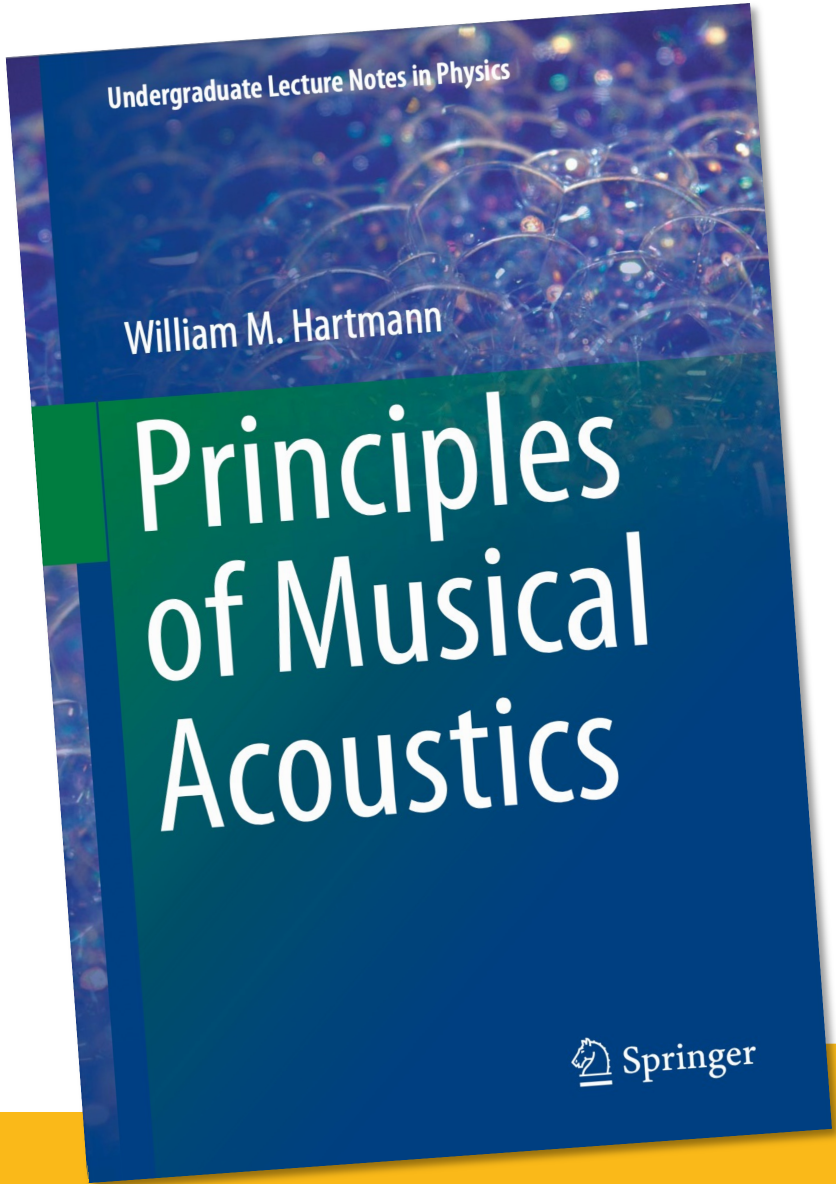
2. **Voice analysis**
   Measure your own voice

TA: Helena Linder
htlm@kth.se

Assignments

1. **Literature summary:** Summarize a scientific acoustics paper
2. **Modal synthesis:** Experiment with analysis and synthesis
3. **Singing synthesis:** Experiment with modelling a singing voice
4. **Application of Theory:** Answer technical questions

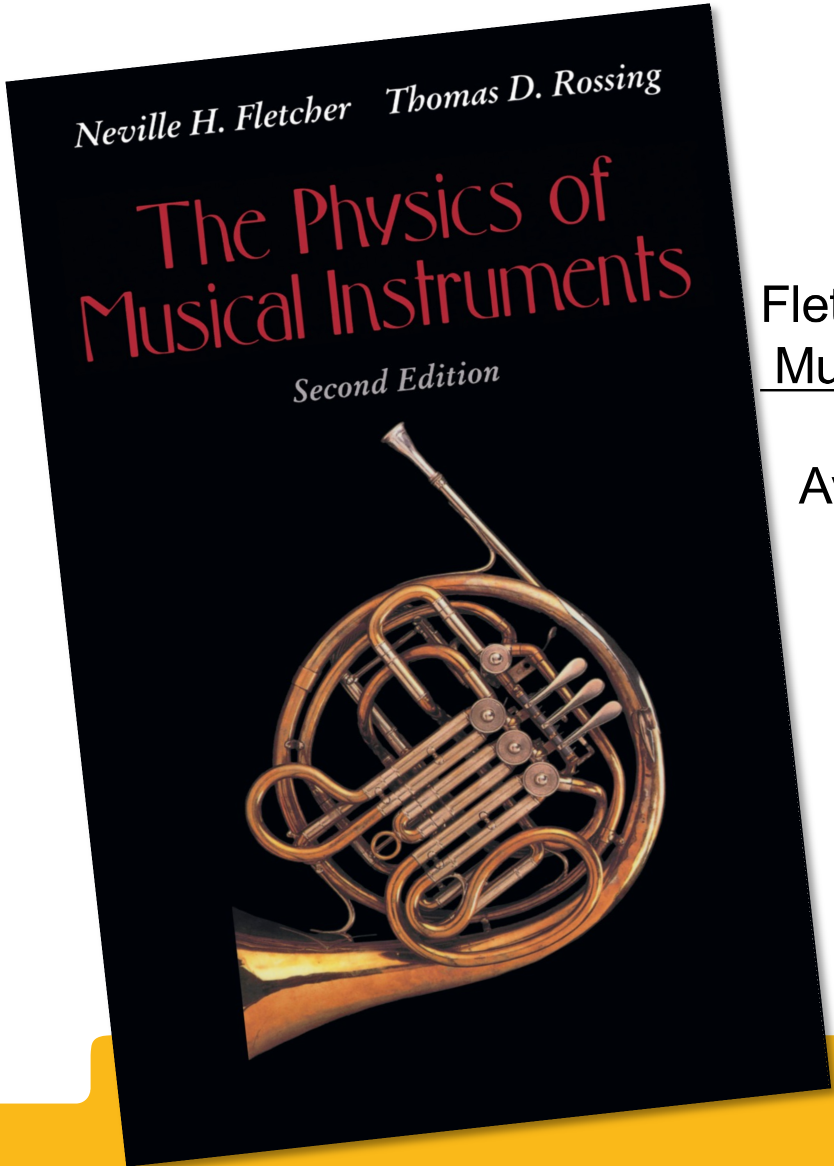
Main Course Text



Hartmann, <u>Principles of musical acoustics</u>, Springer, 2013.

Available through *KTH Biblioteket*

Main Course Text (more advanced)



Fletcher and Rossing, The Physics of Musical Instruments, 2nd ed., Springer, 1998.

Available through *KTH Biblioteket*

Course Resources

A variety of handouts will be distributed

Online demos and material

http://www.acs.psu.edu/drussell/demos.html

http://www.falstad.com/mathphysics.html

https://newt.phys.unsw.edu.au/music/

https://www.whyyouhearwhatyouhear.com/

https://ccrma.stanford.edu/~jos/

Project

Group work

- An opportunity to demonstrate how well you meet ILOs of the course
- Approximately 40 hours (one week full time)
- Project workshop on Feb 18, 2025
- Presentation on Feb 25, 2025
- Attendance required!
- Written project report due Mar 7, 2025

Some project ideas (more information will be presented later):

- Build an instrument and study its properties
- Synthesize an instrument
- Investigate the acoustical properties of an instrument

Breakdown of Grading

Task	Max points	Pass limit
1. Assignment A Literature	20	10
2. Assignment B Modal synthesis	20	10
3. Assignment C Voice synthesis	20	10
4. Assignment D Theory	20	10
5. Lab exercise 1	10 (P/F)	10 (P/F)
6. Lab exercise 2	10 (P/F)	10 (P/F)
7. Project report and presentation	30	15
Total	130	75

Final Grade	Points
A	119
B	108
C	97
D	86
E	75
F	< 75

You must pass all assignments and lab exercises to get a final grade

Who are you?

1. What’s your degree program?
2. Why are you interested in music acoustics?

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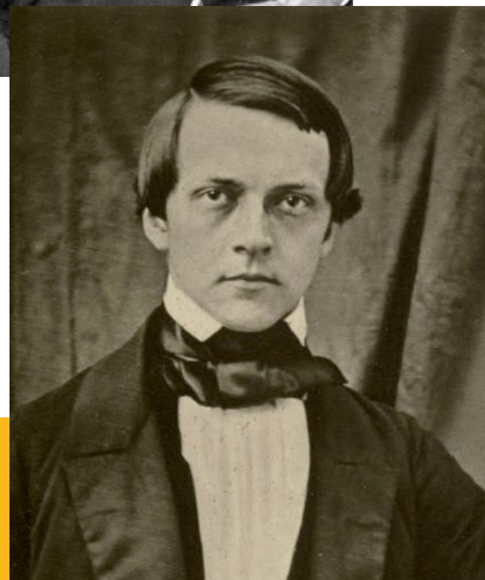
Introduction to Acoustics

Chapters 1, 5, 6 in Hartmann

What is acoustics?

A branch of physics dealing with mechanical waves in gases, liquids and solids (e.g., sound in air).

Much discussed since ancient times (e.g., Pythagoras and Aristotle)



- *Sir Charles Wheatstone (1820s)*
- *John William Strutt, 3rd Baron Rayleigh*

  The Theory of Sound (1877)
- *Hermann von Helmholtz*

  On the Sensations of Tone (1863)

What is a sound wave?

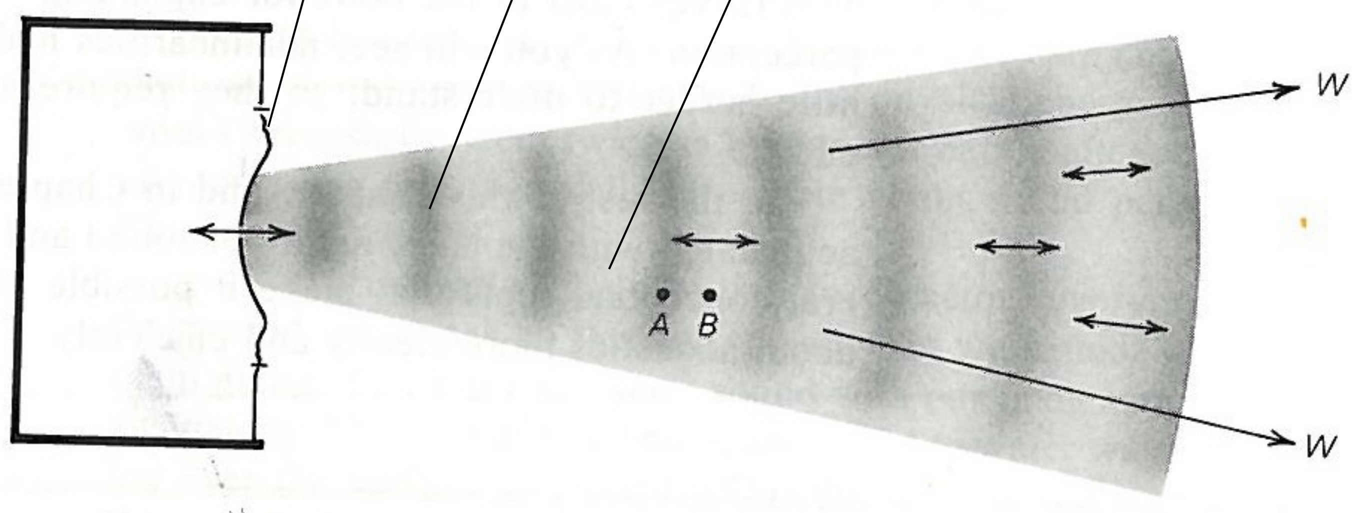
A longitudinal propagation of energy.

Vibrating surface

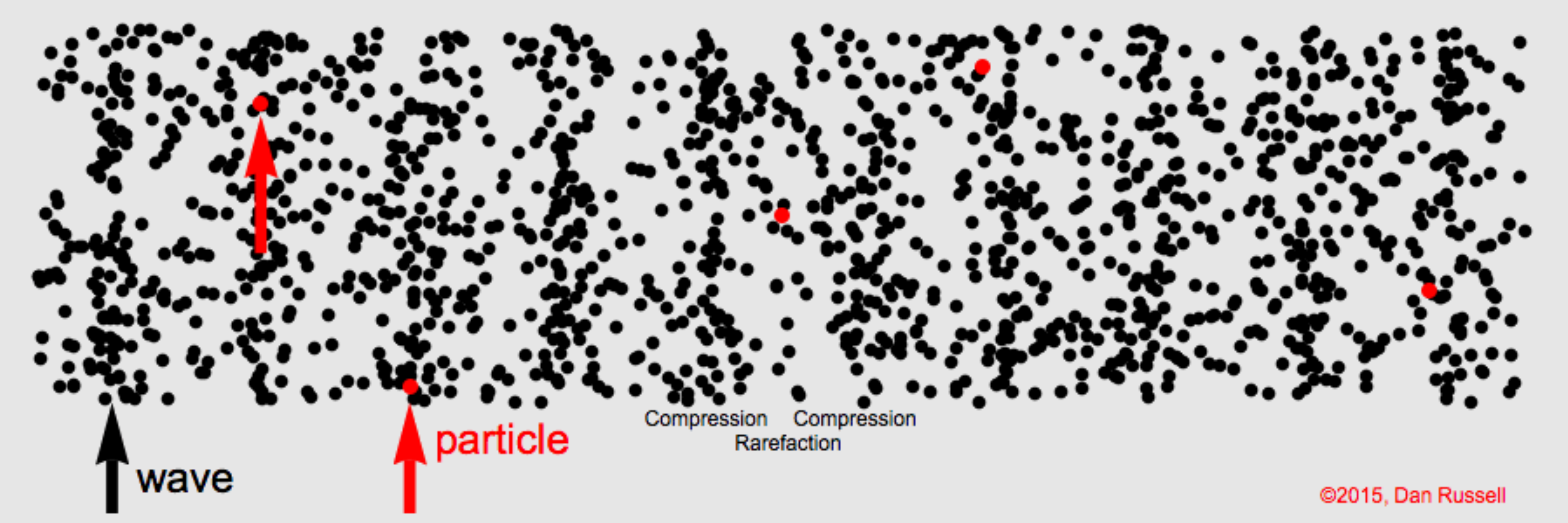
loudspeaker membrane
violin body, trumpet bell
(pipe end)

condensation

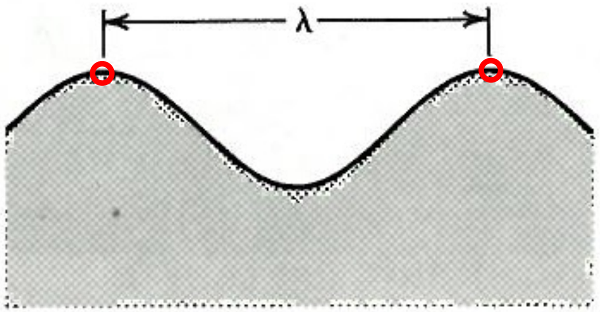
rarefaction
(decompression)

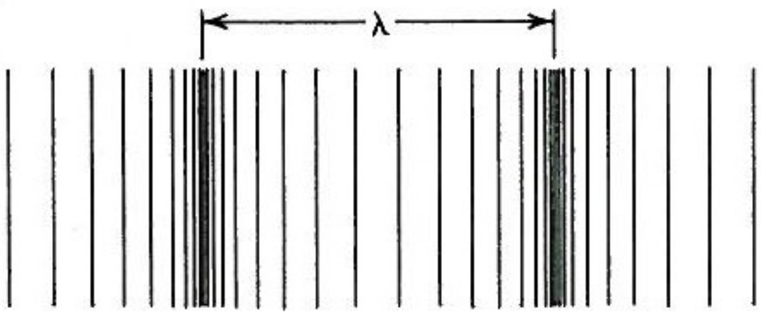


What is a *longitudinal wave*?



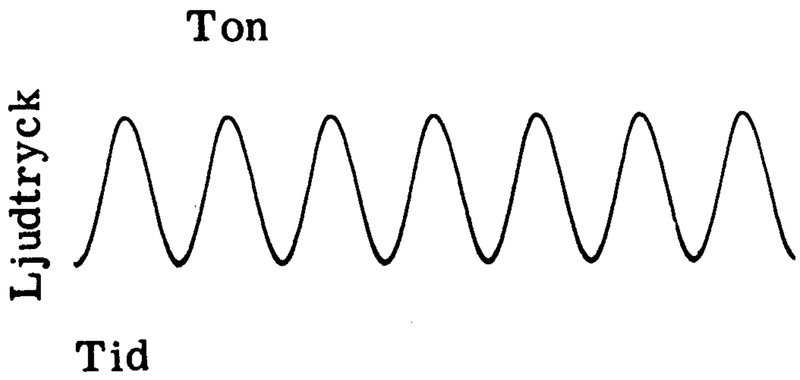
Displacement is in direction of wave travel instead of orthogonal to it.

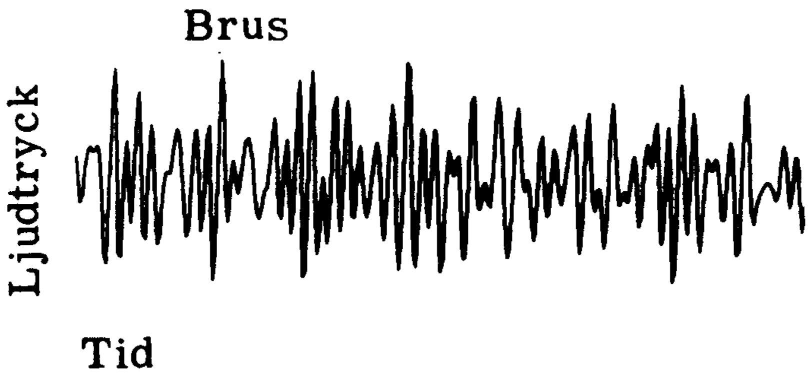




What is a waveform?

The form of a wave!

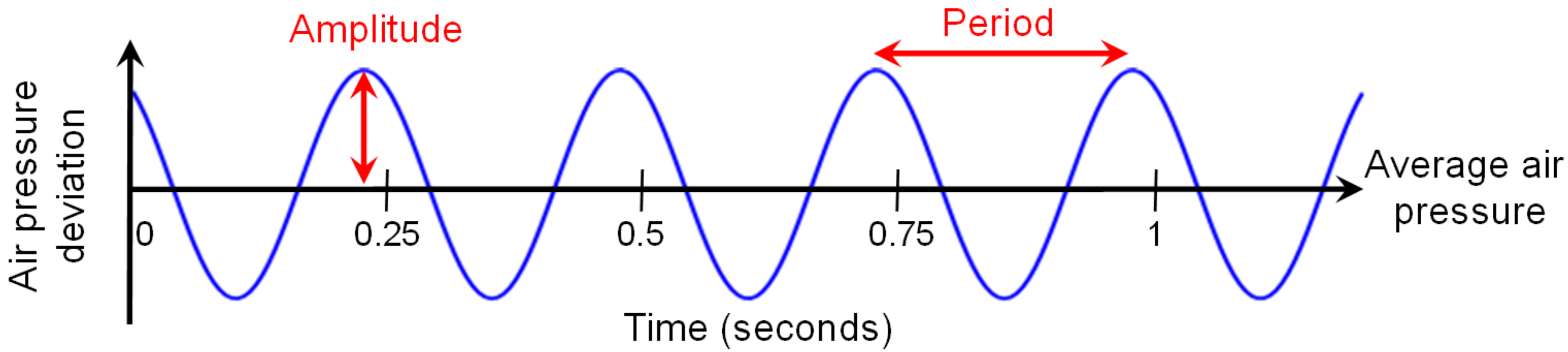




A function of amplitude vs. time (continuous)

An indexed sequence of real numbers (discrete)

What is *frequency*?



A quantitative characteristic of a periodic waveform, e.g., 440 Hz

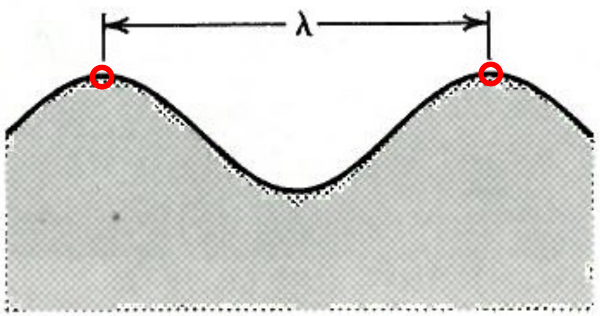
The repetition rate of a waveform

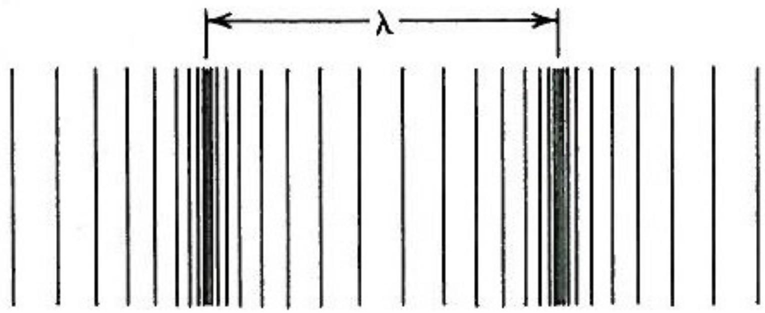
Units are cycles per second

Inverse of frequency is seconds per cycle (*period*)

Wavelength and Frequency

Wavelength λ distance between 1 period



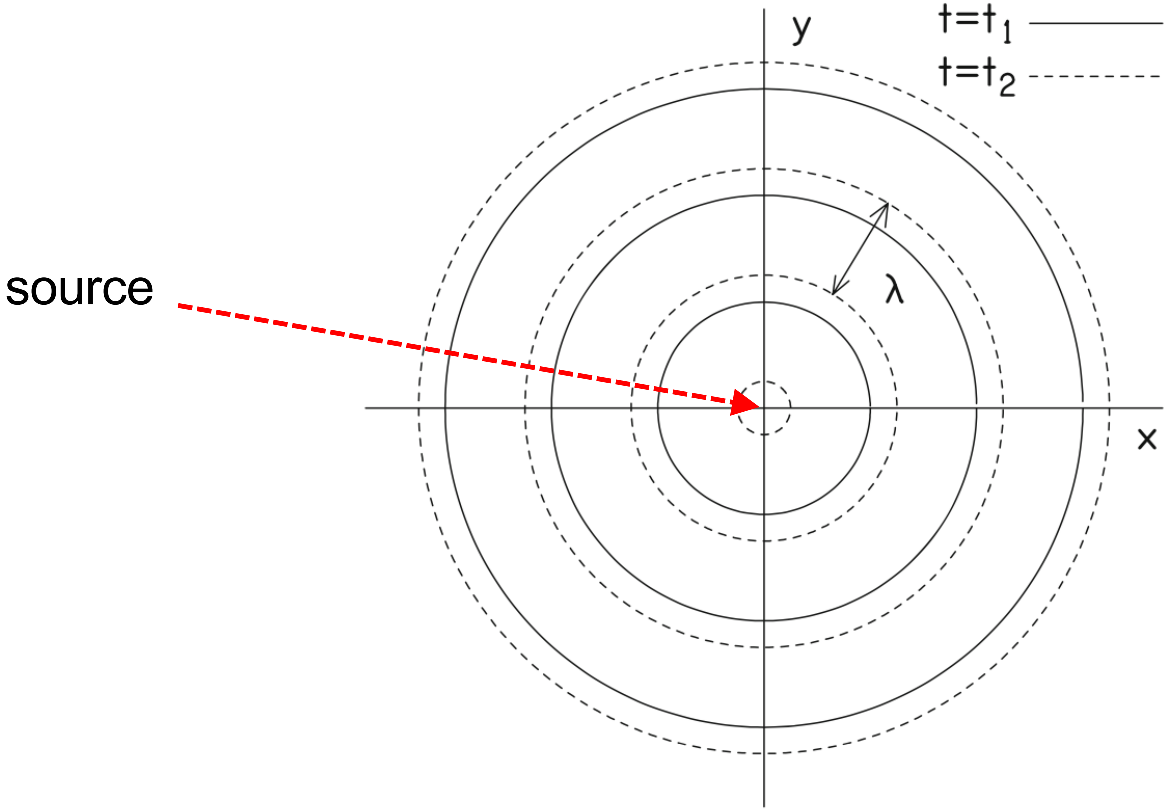


Frequency f is the number of periods per unit time

wavelength times frequency is velocity: $c = \lambda f$

Notice: Frequency and wavelength are inversely proportional given velocity is constant

Sound in two dimensions



Velocity of sound

Velocity c depends on the medium in which sound waves propagate. In a gas:

Universal gas constant

Adiabatic index

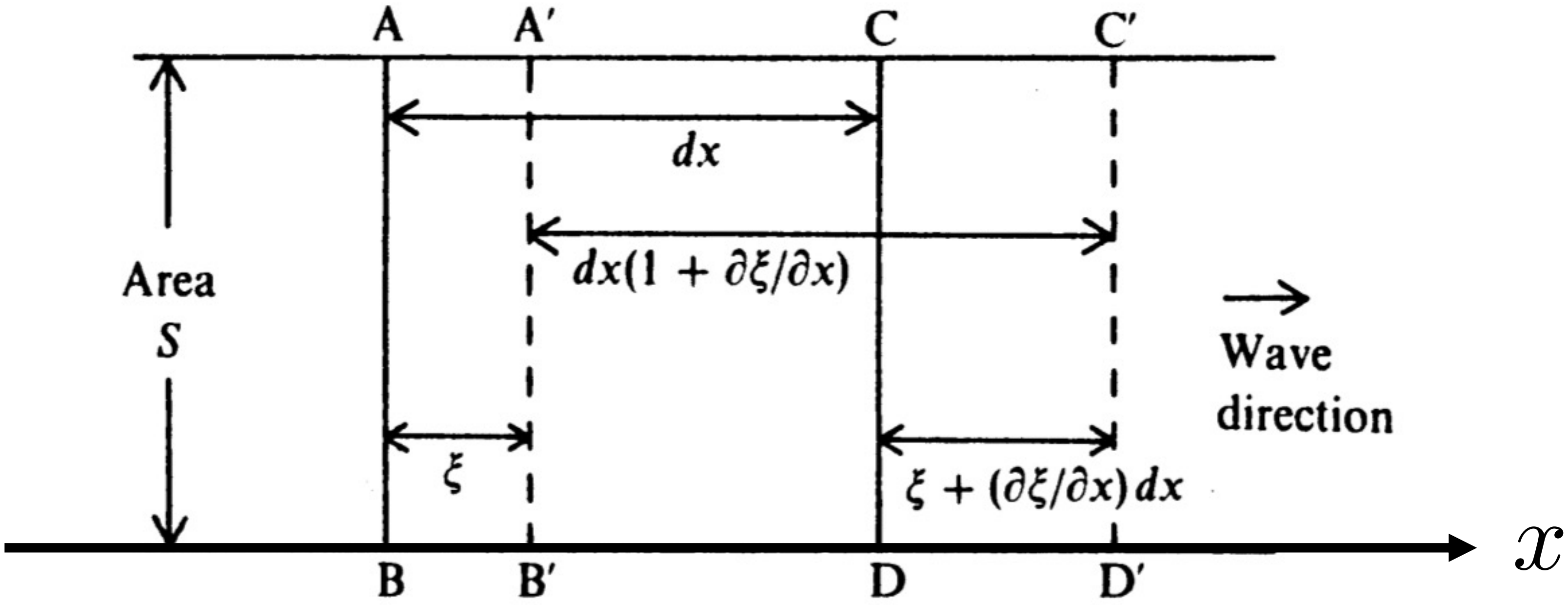
Temperature of medium (Kelvin)

$$c^2 = \frac{\gamma R T}{M}$$

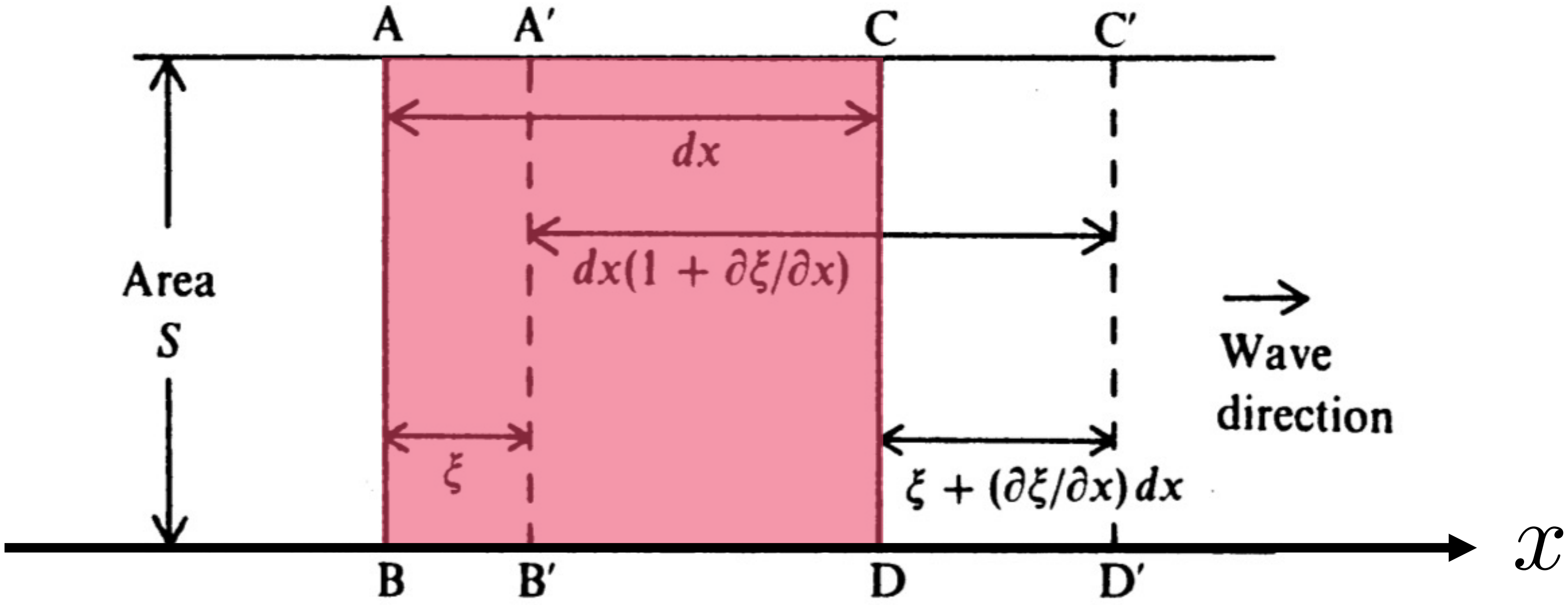
Molar mass of medium

See sec. 6.1 in Fletcher and Rossing

Deriving the velocity of sound in air

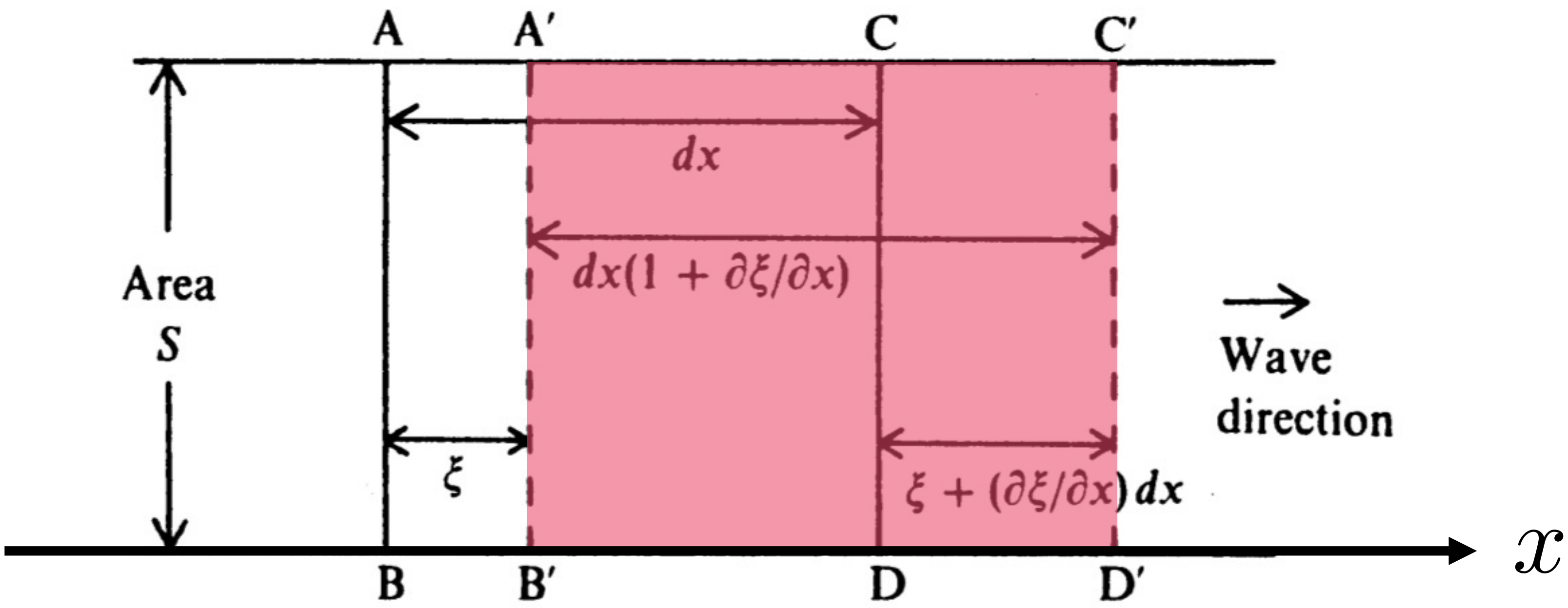


Deriving the velocity of sound in air



$$V = Sdx$$ The volume of the shaded region

Deriving the velocity of sound in air



A displacement of this volume by ξ changes its length by $\frac{\partial \xi}{\partial x} dx$

$$V + dV = S dx + S \frac{\partial \xi}{\partial x} dx$$

The volume of the new shaded region

Deriving the velocity of sound in air

From before: $$V + dV = S dx + S \frac{\partial \xi}{\partial x} dx$$

The bulk modulus of the air K (resistance to compression) is defined:

$$K = -V \frac{dp}{dV}$$

Pressure due to sound, which we will notate as p_s

With substitution: $$= -S \frac{p_s}{S dx \partial \xi / \partial x} dx$$

$$p_s = -K \partial \xi / \partial x$$

Deriving the velocity of sound in air

The force opposing compression is given by

$$F = -S\frac{\partial p_s}{\partial x}dx$$

(Remember the definition of pressure: P = F/A)

Now recall Newton's second law:

$$F = ma$$

The mass of the volume of air with density ρ being displaced:

$$m = \rho S dx$$

Deriving the velocity of sound in air

Finally:

$$-S\frac{\partial p_s}{\partial x}dx = \rho S dx \frac{\partial^2 \xi}{\partial t^2}$$

$$-\frac{\partial p_s}{\partial x} = \rho \frac{\partial^2 \xi}{\partial t^2}$$

Substituting $p_s = -K\partial\xi/\partial x$

$$\frac{\partial^2 \xi}{\partial x^2} = \frac{\rho}{K}\frac{\partial^2 \xi}{\partial t^2}$$

One-dimensional wave equation

Deriving the velocity of sound in air

Notice too: $p_s = -K\partial\xi/\partial x$

$$\frac{\partial^2 p_s}{\partial t^2} = -K\frac{\partial^2}{\partial t^2}\frac{\partial\xi}{\partial x}$$

From before: $$-\frac{\partial p_s}{\partial x} = \rho\frac{\partial^2\xi}{\partial t^2}$$

$$-\frac{\partial}{\partial x}\frac{\partial p_s}{\partial x} = \rho\frac{\partial}{\partial x}\frac{\partial^2\xi}{\partial t^2}$$

Deriving the velocity of sound in air

$$\frac{\partial^2 p_s}{\partial t^2} = -K \frac{\partial^2}{\partial t^2} \frac{\partial \xi}{\partial x}$$

$$-\frac{\partial}{\partial x} \frac{\partial p_s}{\partial x} = \rho \frac{\partial}{\partial x} \frac{\partial^2 \xi}{\partial t^2}$$

$$\frac{\partial^2 p_s}{\partial x^2} = \frac{\rho}{K} \frac{\partial^2 p_s}{\partial t^2}$$

One-dimensional wave equation

Deriving the velocity of sound in air

$$\frac{\partial^2 p_s}{\partial x^2} = \frac{\rho}{K} \frac{\partial^2 p_s}{\partial t^2}$$

Notice the dimensionality of the constant: (time/distance)^2

$$c^2 = \frac{K}{\rho} = \frac{\gamma RT}{M}$$

In the case of an adiabatic medium

Velocity of sound

$$c = \sqrt{\frac{\gamma R T}{M}}$$

In air with c_0 = 331 m/s (0° C)

$$c = c_0 \sqrt{1 + \tfrac{T_C}{273}}$$

Rule of thumb. $c \approx 331 + 0.6 \cdot T_C$

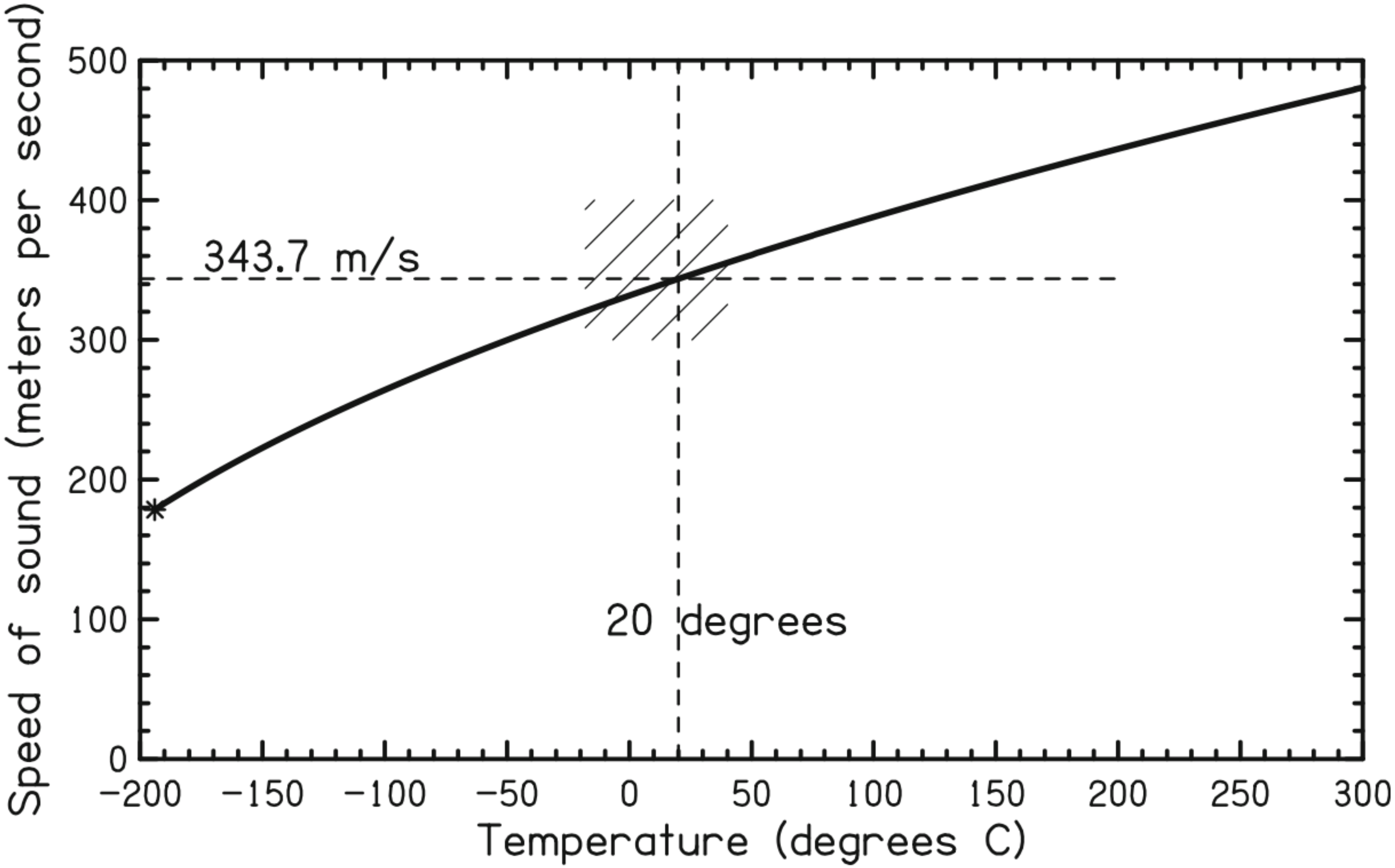
(increase by 0.6 m/s per degree temperature Celcius)

At room temperature (20°C) c = 343.7 m/s

In wind instruments (average 28°C) c = 346 m/s

See sec. 5.2 in Hartmann

Velocity of sound



Hartmann, pg. 44

Acoustical sizes

Is an object large or small from an acoustical perspective?
Depends on the wavelength! In STP:

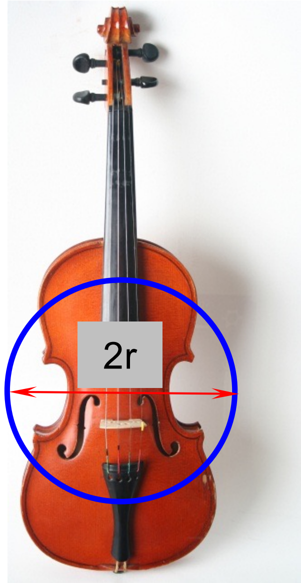
Sound Frequency f (Hz)	Wavelength λ (m)	Wavelength comparable to
20	17	Semi Truck
41	8	Small Yacht
110	3	Sofa
440	0.8	Cello
660	0.5	Chair
1000	0.3	Violin
10 000	0.03	Outer ear

Comparison of sizes

Assume object is like a sphere of radius r
with circumference $C = 2\pi r$

Define "He" as the ratio of this circumference
and the sound wavelength

$$\mathrm{He} = \frac{C}{\lambda}$$



- If He > 1, then the object is larger than the wavelength of a sound (it is "acoustically large")
- If He < 1, it is "acoustically small"

Given a wavelength, the r such that He = 1 is the "acoustical limit" between large and small

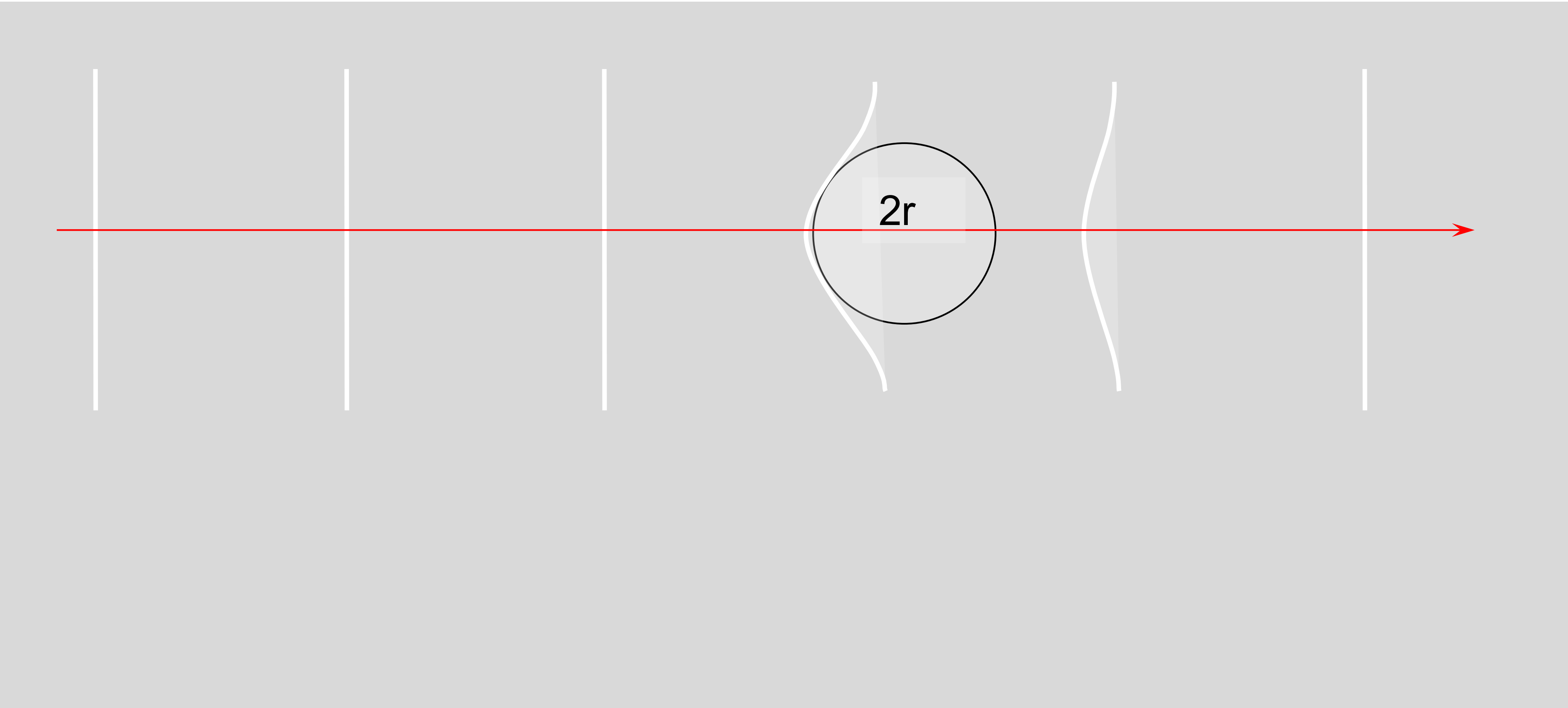
Acoustical sizes

Is an object large or small from an acoustical perspective?
Depends on the wavelength! In STP:

Sound Frequency *f* (Hz)	Wavelength λ (m)	Wavelength comparable to	Acoustical limit large – small object $He = 2\pi r/\lambda = 1$
20	17	Semi Truck	r = 3 m
41	8	Small Yacht	1 m
110	3	Sofa	50 cm
440	0.8	Cello	10 cm
660	0.5	Chair	8 cm
1000	0.3	Violin	5 cm
10 000	0.03	Outer ear	5 mm

Diffraction

When an object is acoustically smaller than the wavelength, the longitudinal wave bends around it



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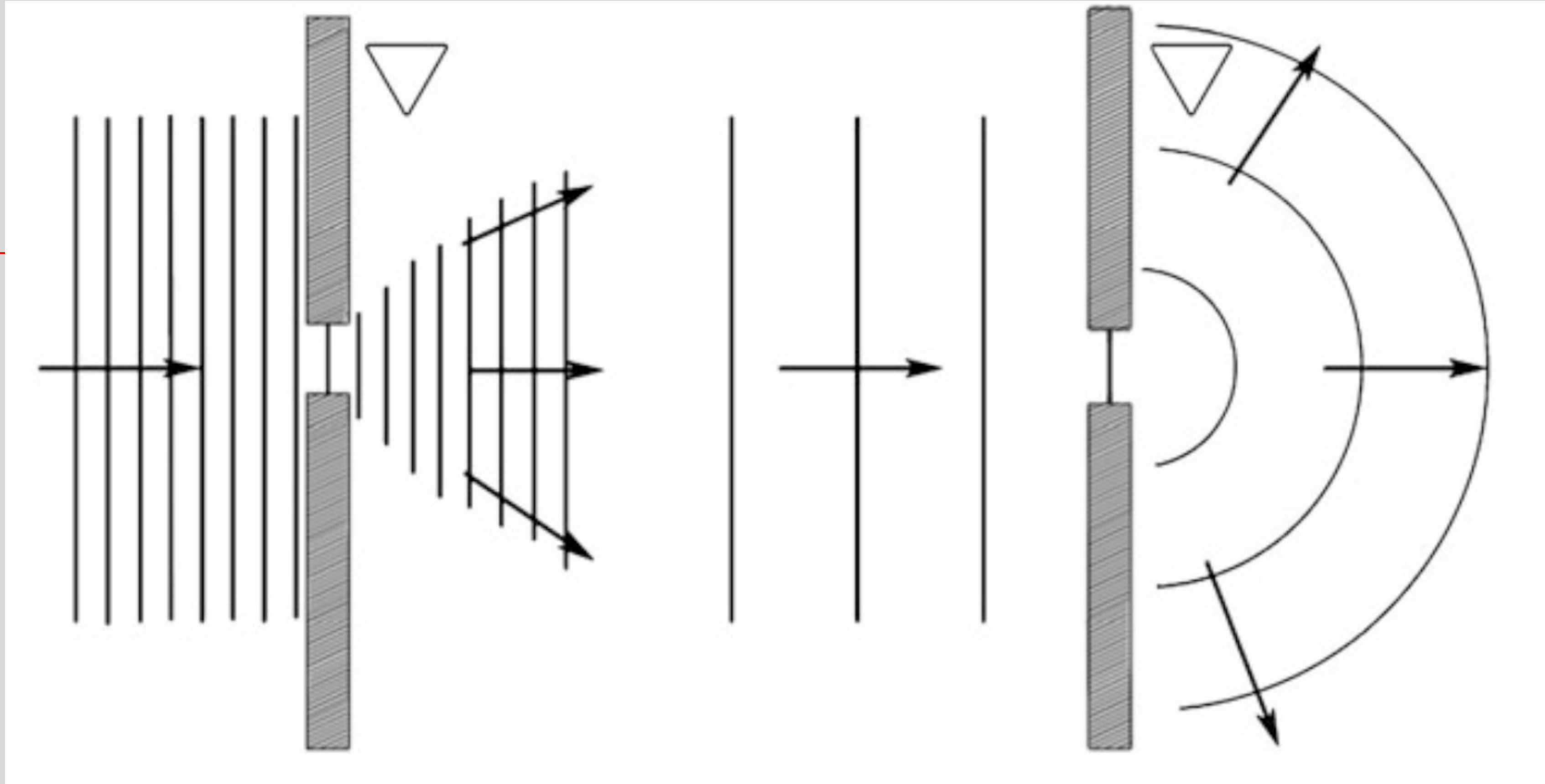

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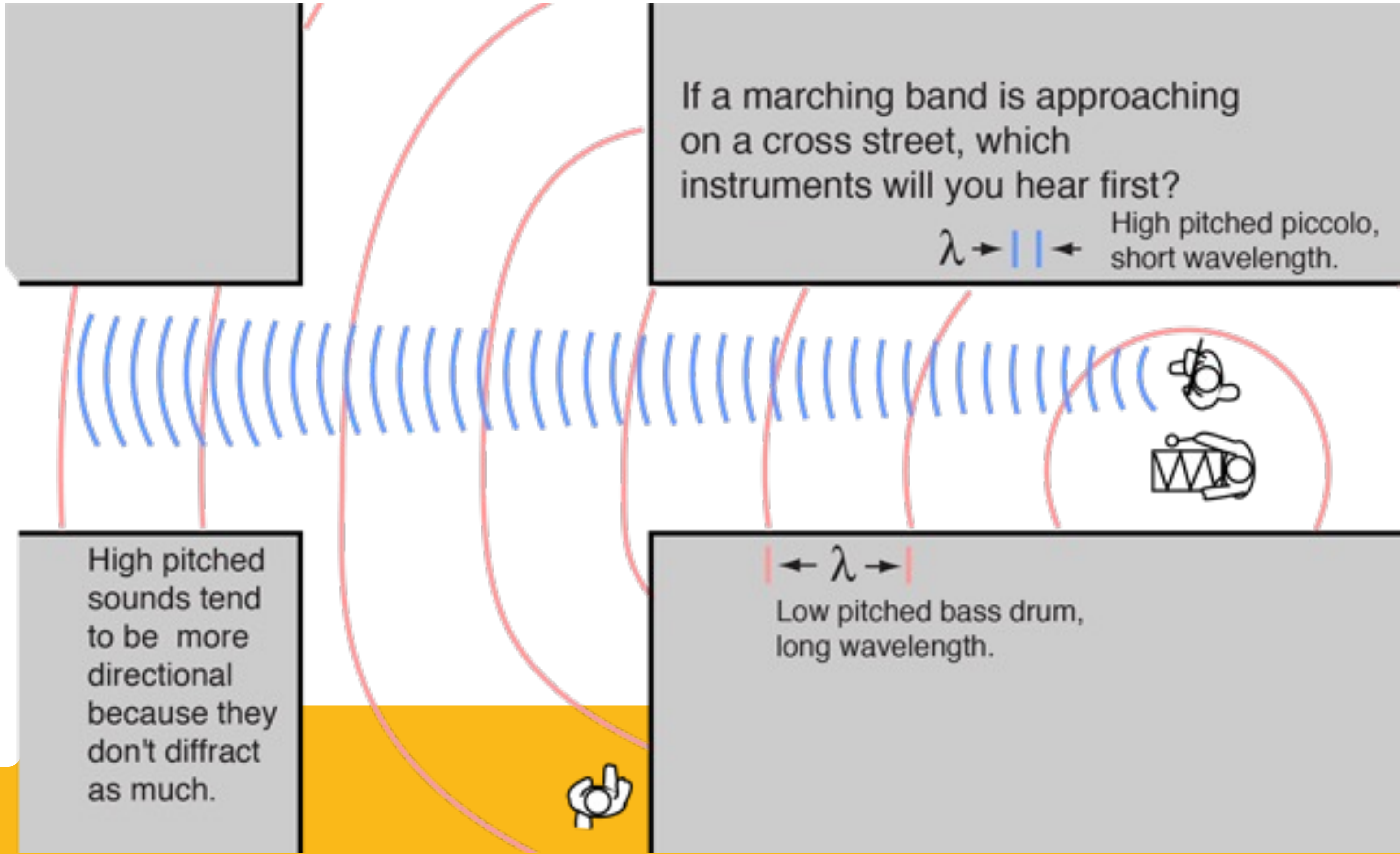
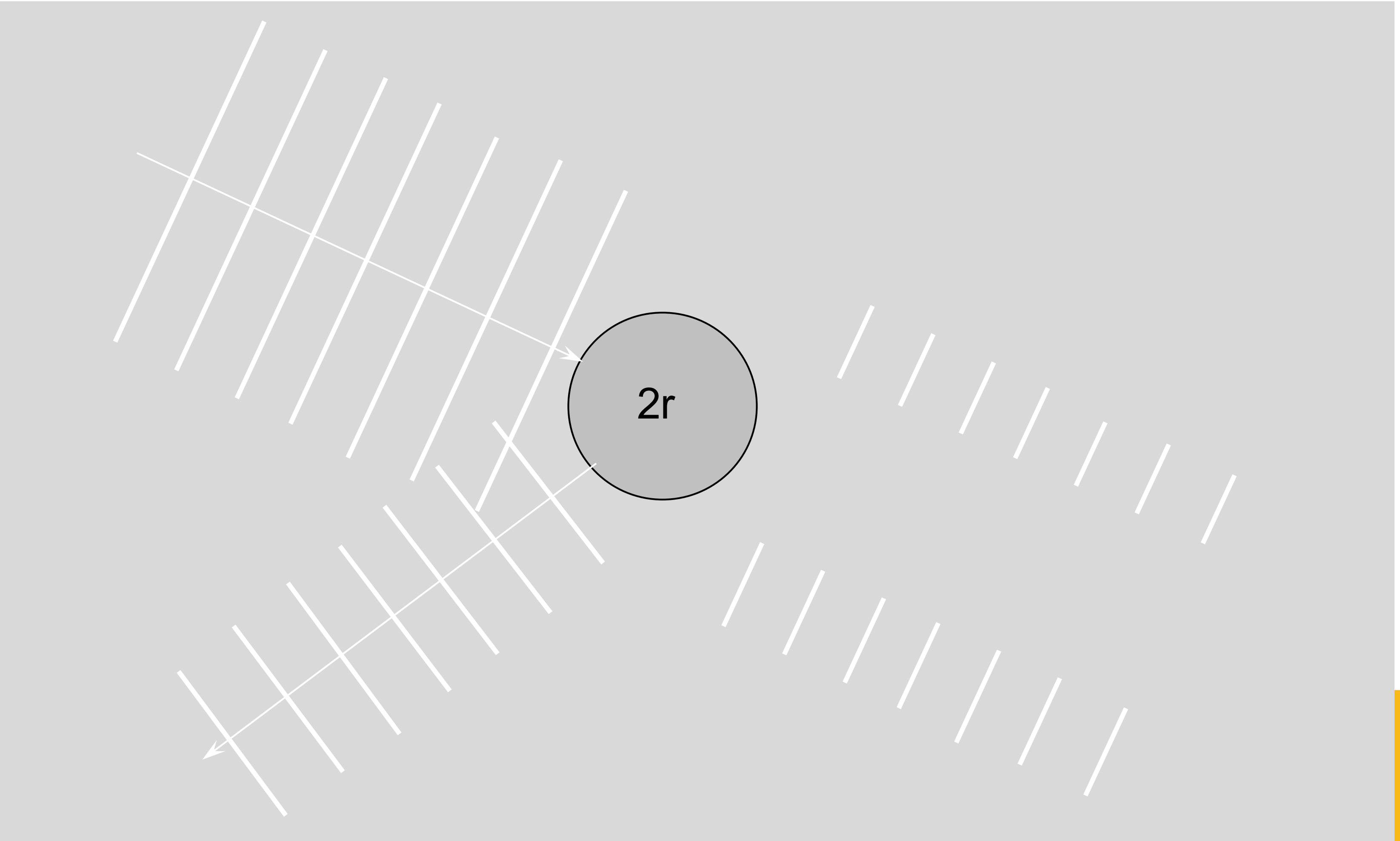


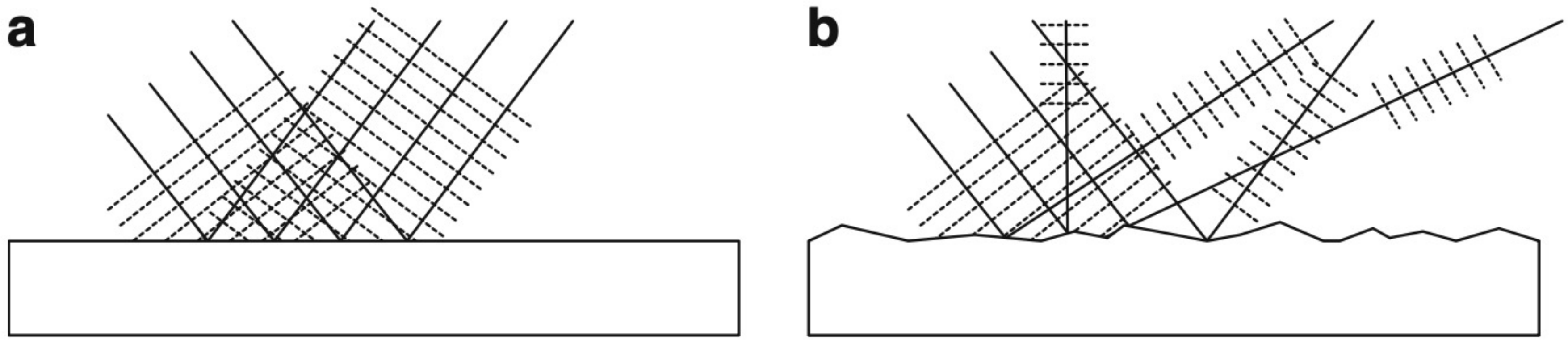
Reflection

When object is acoustically bigger than the wavelength, the longitudinal wave reflects



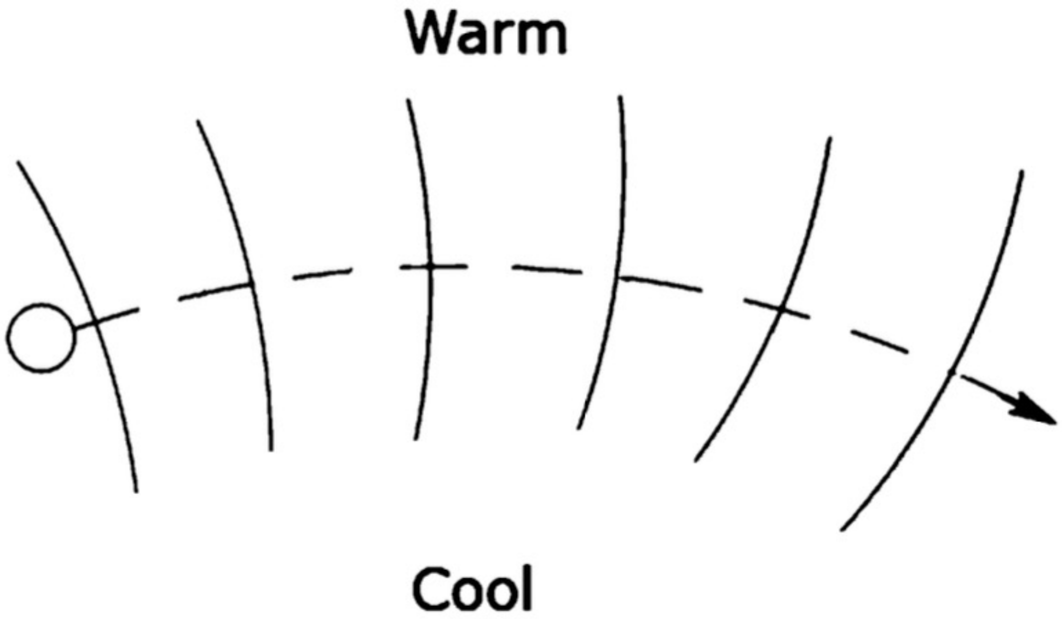
Reflection

When object is acoustically bigger than the wavelength, the longitudinal wave reflects

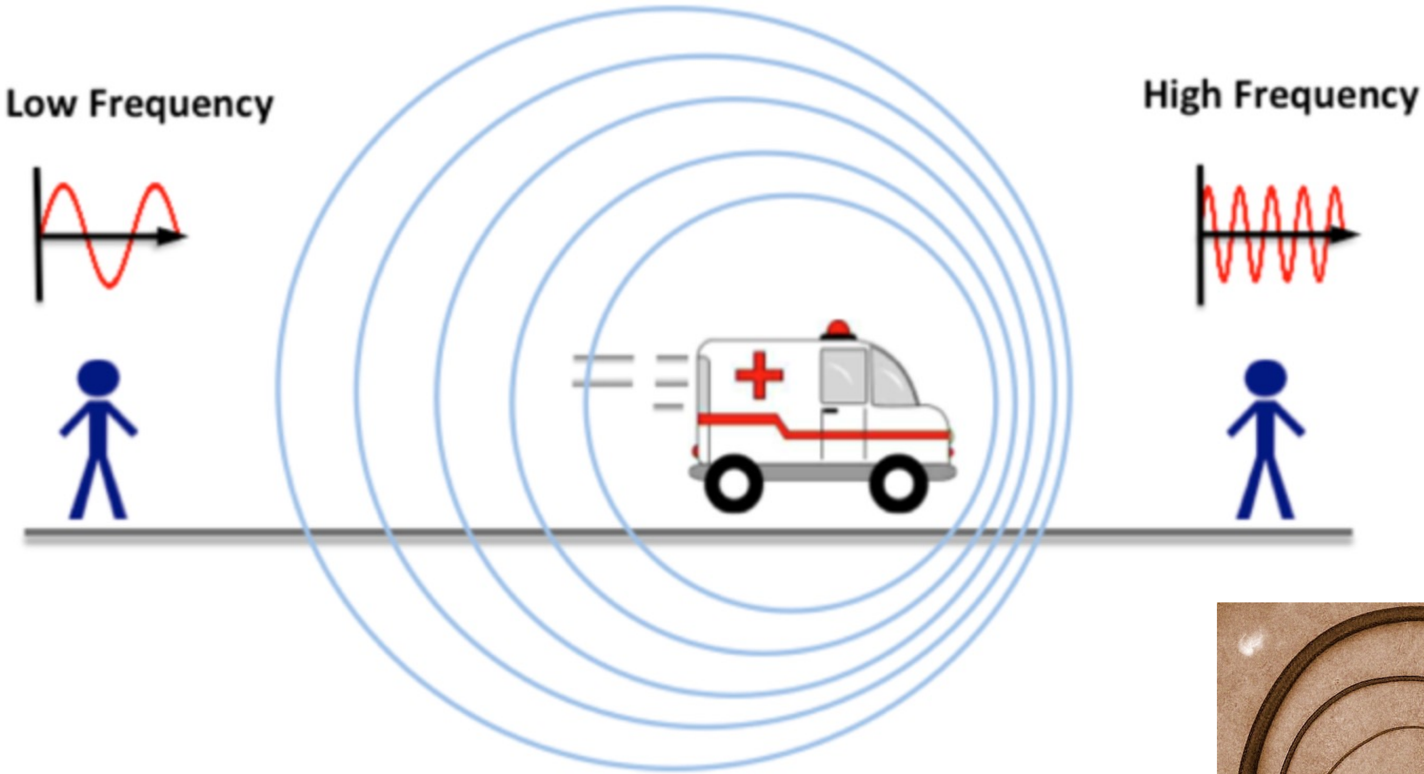


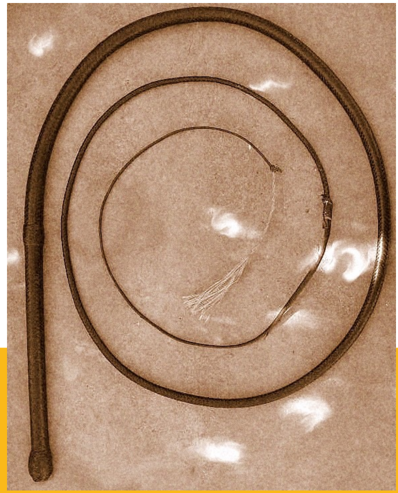
Refraction

When temperature/density varies in a medium, acoustic waves refract.

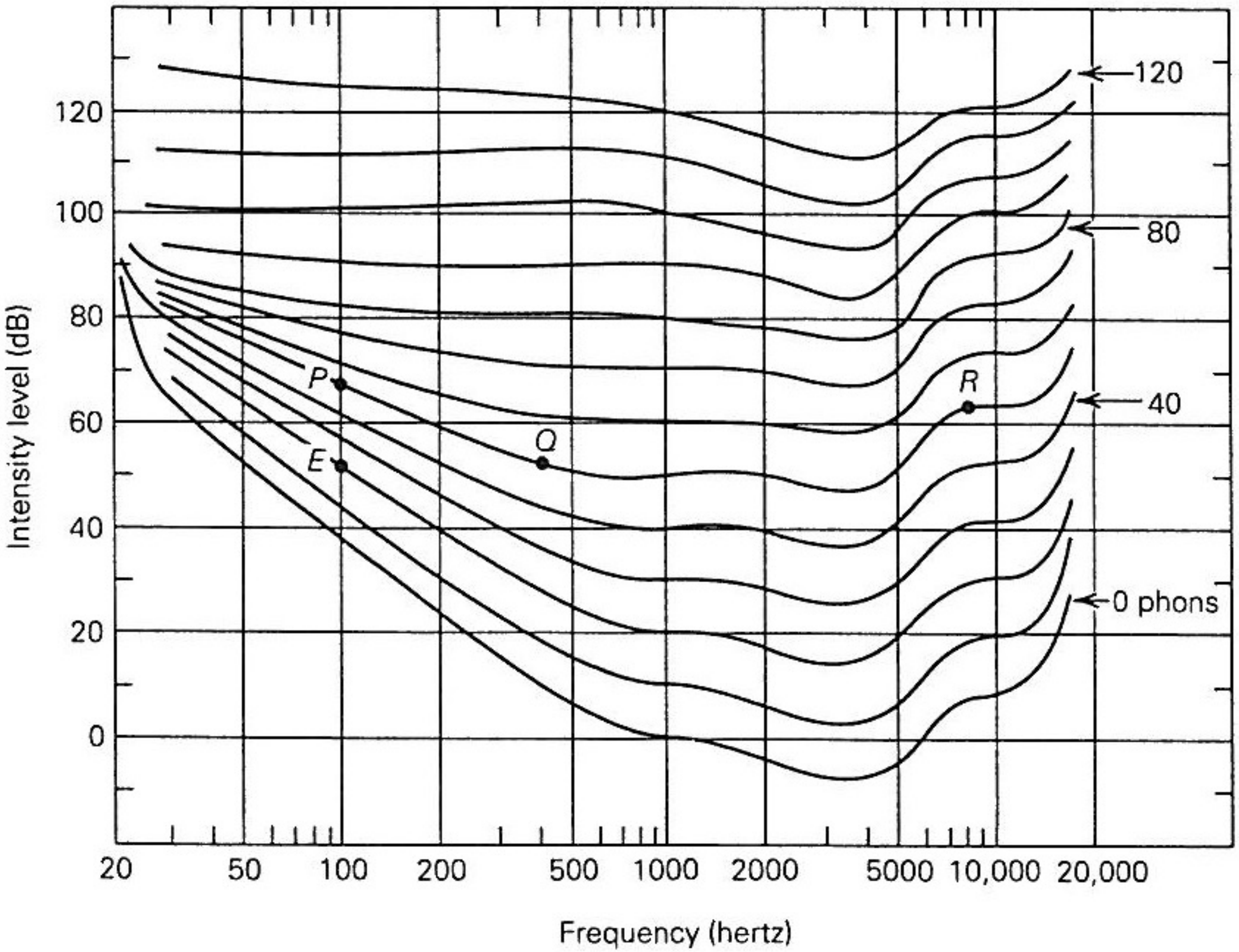


Doppler Effect

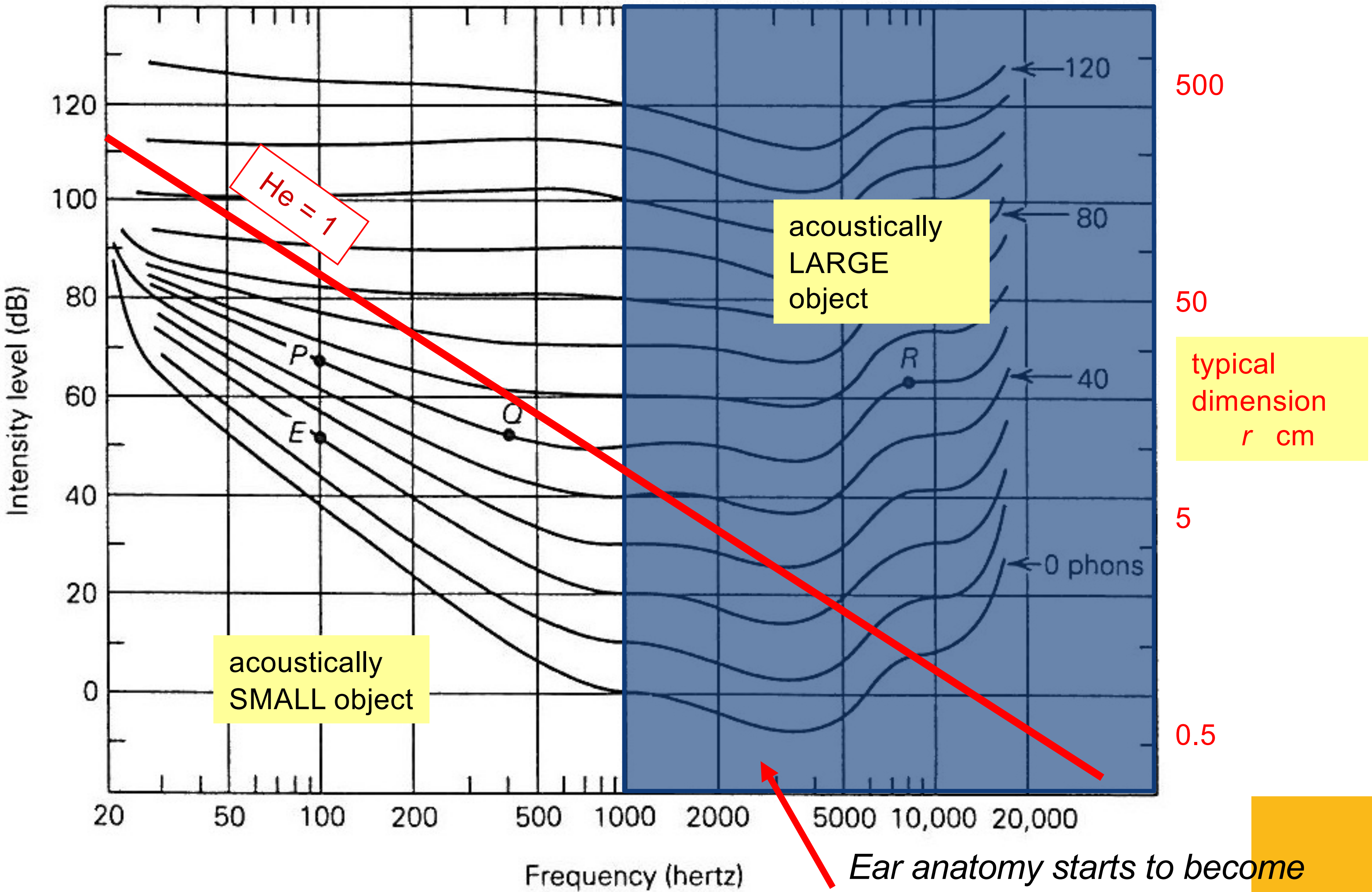




Helmholtz Number and perception



Helmholtz Number and perception



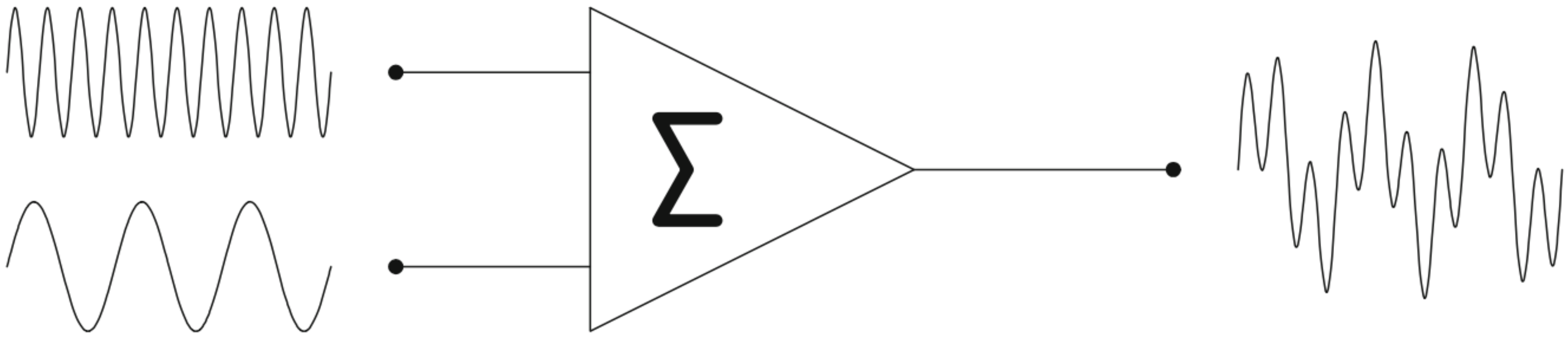
Ear anatomy starts to become acoustically large

Spatial-temporal acoustic properties of the human

HRTF databases: https://www.sofaconventions.org/mediawiki/index.php/Files

Properties of sound

Additive

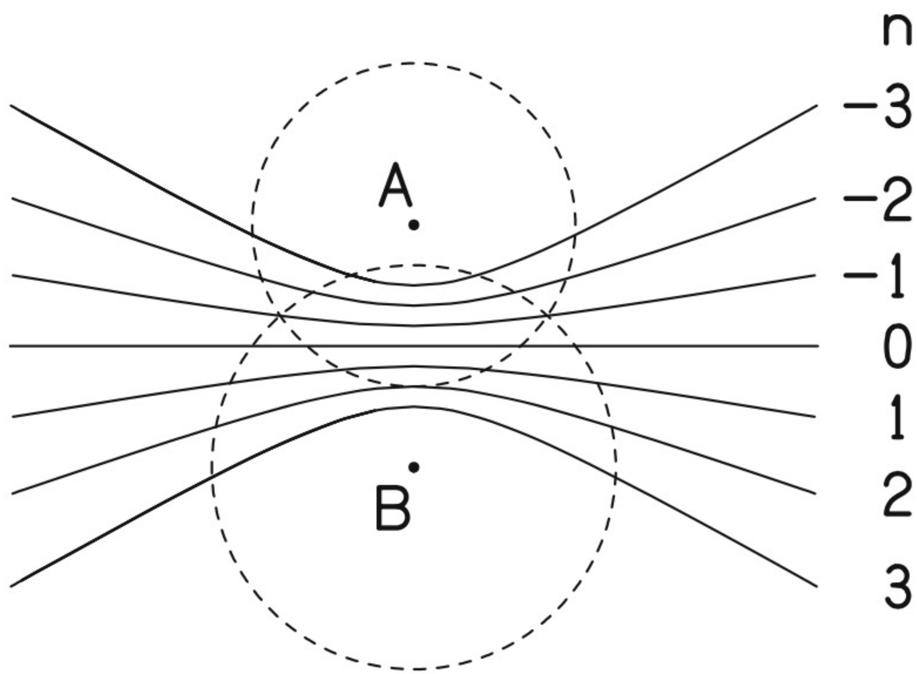


Properties of sound

Additive

Properties of sound

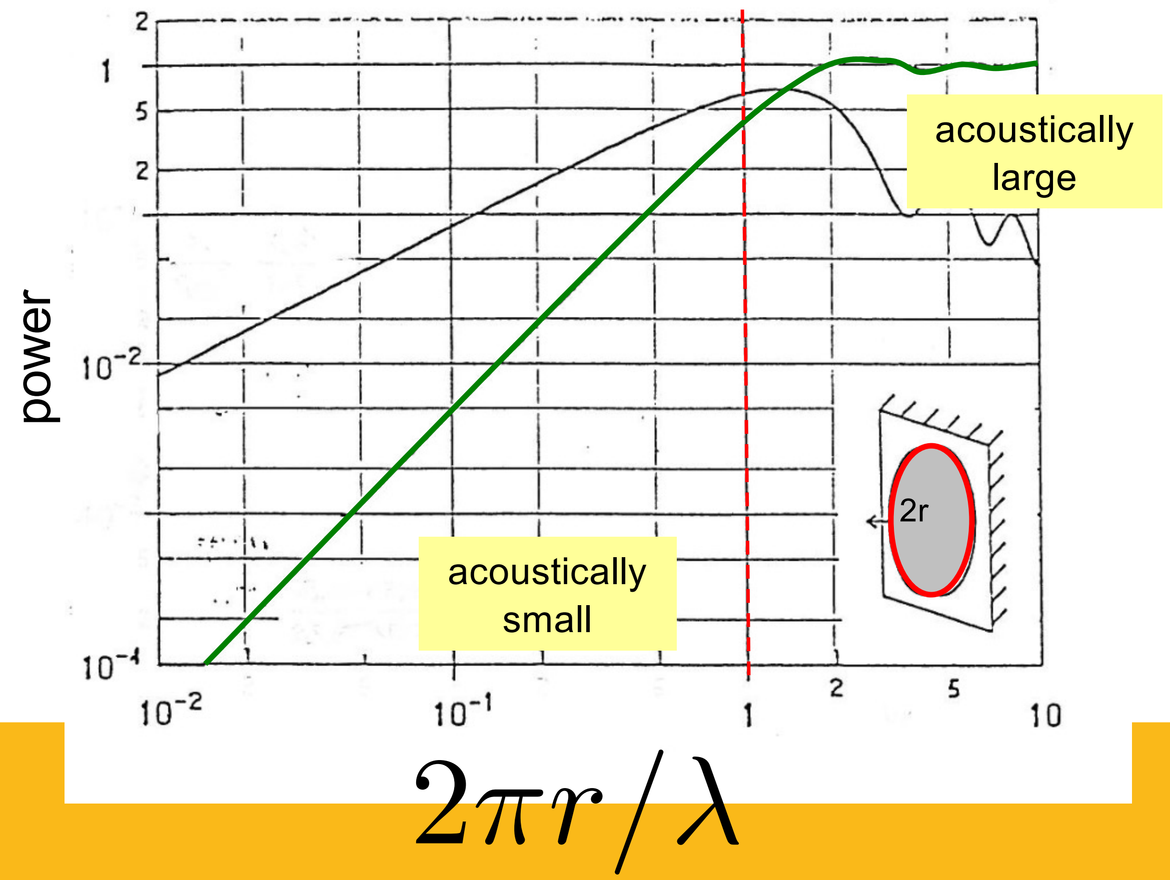
Additive (constructive and deconstructive interference)



A and B: sound sources vibrating at the same rate

Radiation impedence

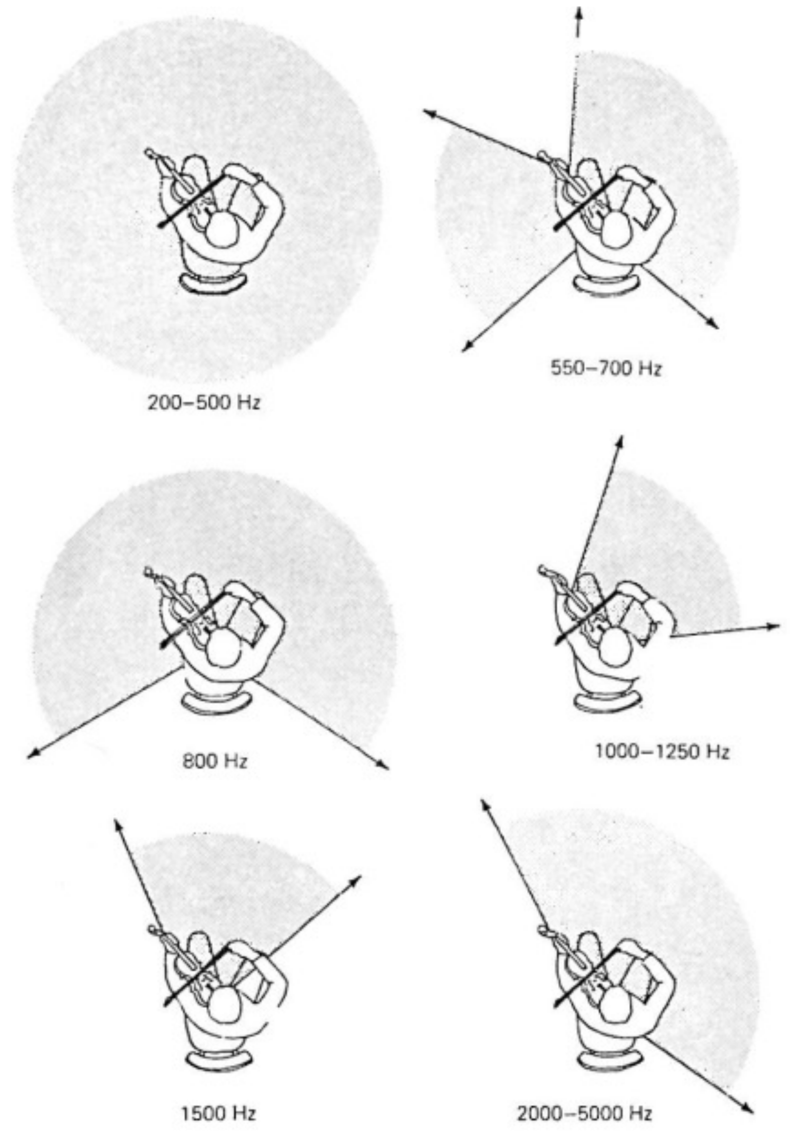
General rule: A sound source that is small compared to the wavelength ($2\pi r \ll \lambda$) is an **inefficient** sound radiator



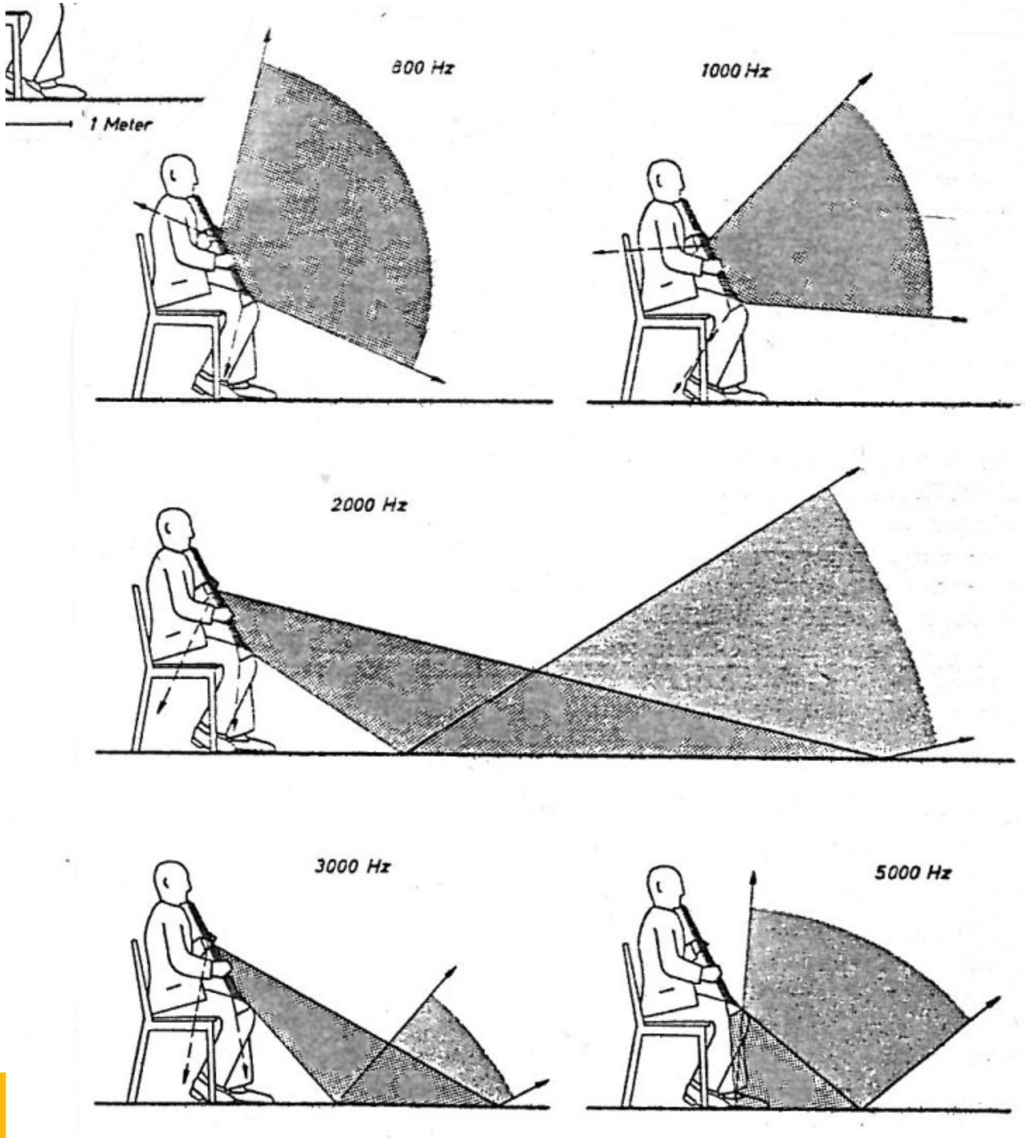
Sound radiation in musical instruments

Instrument specific!

Frequency specific!



Sound radiation in musical instruments



radiation through open tone holes

Near-field mic is problematic

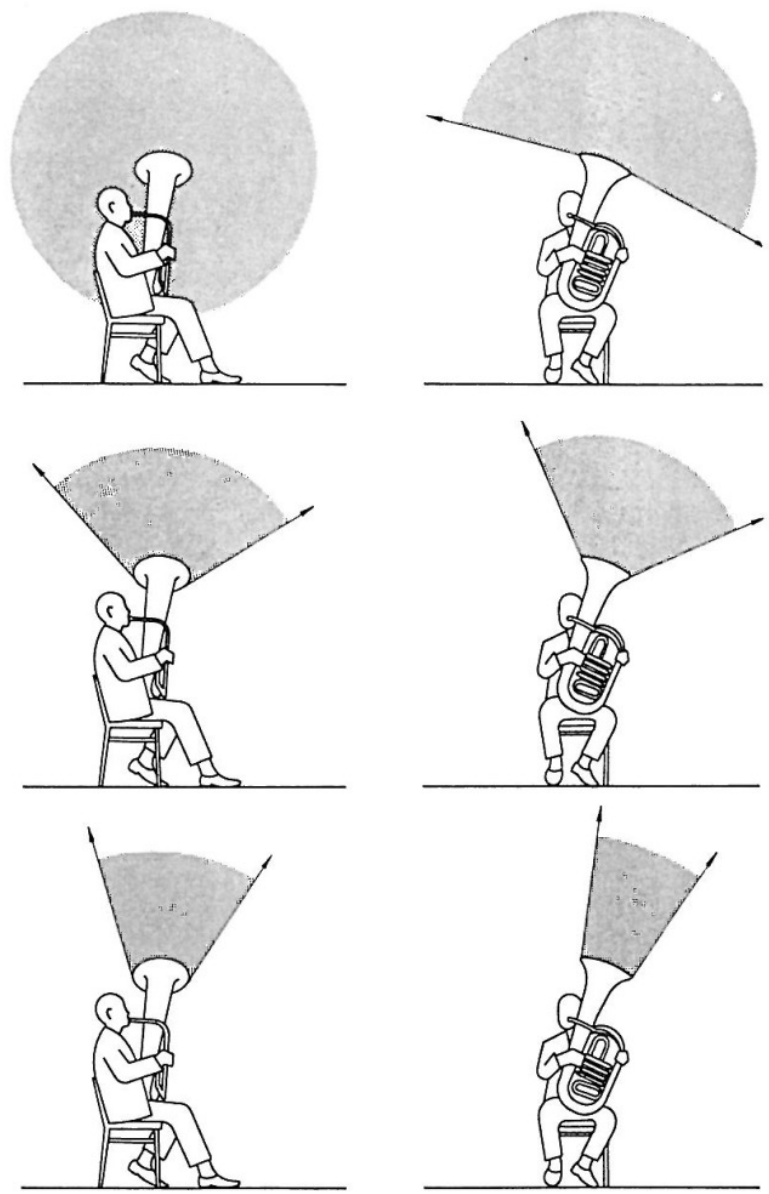
radiation through bell

Sound radiation in musical instruments

90 – 180 Hz

300 – 500 Hz

1200 – 3500 Hz

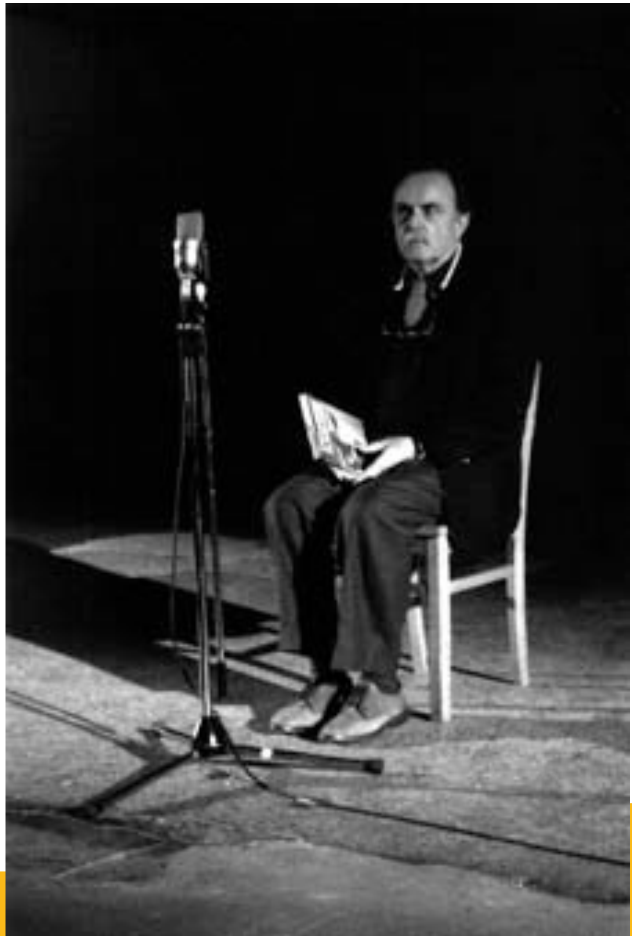


And what about the room?

And what about the room?

Music doesn’t have to come from “traditional musical instruments”

“I am sitting in a room” by Alvin Lucier (1970)



“Recording was made by Alvin Lucier on October 29th and 31st, 1980, in the living room of his home … recorded on a Nagra tape recorder with an Electro-Voice 635 dynamic microphone and played back on one channel of a Revox A77 tape recorder, Dynaco amplifier and a KLH Model Six loudspeaker.”
http://www.lovely.com/titles/cd1013.html

https://youtu.be/bhtO4DsSazc

Before next lecture

Read:

1. Chapters 2, 3, 26 in Hartmann